INVESTIGATION OF FLOW PATTERNS USING GEOCHEMICAL TRACERS IN THE FLORIDAN AQUIFER SYSTEM, NAPLES, FLORIDA

By

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This Thesis was prepared under the direction of the candidate's thesis advisor, Dr. David L. Warburton, Department of Geosciences, and has been approved by the members of his supervisory committee. It was submitted to the faculty of The Charles E. Schmidt College of Science and was accepted in partial fulfillment of the requirements for the degree of Master of Science.

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ABSTRACT

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Title: Investigation of Flow Patterns Using Geochemical Tracers in the Floridan Aquifer System, Naples, Florida

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This study investigated flow patterns in the FAS and tested Kohout's theory of "cyclic flow" in the vicinity of Naples, Florida. Temperature logs were analyzed to identify a reverse geothermal gradient in the Floridan aquifer system. The geochemical analysis consisted of inorganics (major cations and anions), stable isotopes (^{2}H, ^{18}O), radiocarbon (^{14}C), and noble gas (He, Ne, Ar, Kr, Xe) data. The temperature logs were inconclusive in identifying a reverse geothermal gradient in the study area. The geochemical analysis suggests that within the FAS relatively old meteoric freshwater circulates in the UFA over relatively young seawater of the MCU and LFA. The analysis also supports the possibility of vertical flow from the LFA to the UFA in the study area along with ancient meteoric recharge into the UFA during the last glacial period. The study was inconclusive in identifying "cyclic flow" in the study area.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

^{0}C	Degrees Celsius
%	Percent
‰	Per Mil
Δ	Delta
^{1}H	Protium
^{2}H	Deuterium
^{12}C	Carbon-12
^{13}C	Carbon-13
^{14}C	Radiocarbon
^{16}O	Oxygen-16
^{18}O	Oxygen-18
6’	LAT6 Feet Lateral
16”	RES16-Inch Resistivity
64”	RES64” Resistivity
AD	After Death
AMS	Accelerator Mass Spectrometer
Ar	Argon
Avg.	Average
Bls	Below Land Surface
Ca	Calcium
CaCO3	Calcium Carbonate
Cali	Caliper
cc stp/g	Cubic Centimeters of Dissolved Gas at Standard Temperature and Pressure per Gram of Water
Cl	Chlorine
CO_2	Carbon Dioxide
CO_3	Carbonate
c.p.s	Counts Per Second
dec	Decimal
DegF	Degrees Fahrenheit
DIC	Dissolved Inorganic Carbon
DT	Delta Time
EIL	Environmental Isotope Laboratory
EPA	Environmental Protection Agency
FAS	Floridan Aquifer System
F & G	Fontes and Garnier
ft. bls.	Feet Below Land Surface
FGS	Florida Geological Survey
Fm	Formation
FR	Fluid Resistivity
gAPI	Gamma American Petroleum Institute
GMWL	Global Meteoric Water Line
GR	Gamma Ray

HCO_3	Bicarbonate
He	Helium
HOxl	Oxalic Acid Standard
IAS	Intermediate Aquifer System
ILD	Induction Log Deep
ILM	Inductuction Log Middle
in.	Inches
IW	Injection Well
K	Potassium
Kr	Krypton
LFA	Lower Floridan Aquifer
LGM	Last Glacial Maximum
LGP	Last Glacial Period
MCU	Middle Confining Unit
Mg	Magnesium
Mg/L	Milligrams Per Liter
MIU	Marco Island Utilities
MP	Marking Point
MW	Monitor Well
mV	Milli Volt
MZ	Monitoring Zone
N_2	Nitrogen
Na	Sodium
NCRWRF	North Collier Regional Water Resource Facility
Ne	Neon
NBS	National Bureau of Standards
ND	Not Determined
NPHI	Neutron Porosity
ohm.m	Ohm Per Meter
PDB	Pee Dee Belemnitella Standard
pmC	Percent of Modern Carbon
PT	Packer Test
Rn	Radon
SAS	Surficial Aquifer System
SCRWRF	South Collier Regional Water Resource Facility
SFR	Short Formation Resistivity
SFWMD	South Florida Water Management District
SMOW	Standard Mean Ocean Water
SP	Spontaneous Potential
SPHI	Sonic Porosity
SO_4	Sulfate
TDS	Total Dissolved Solids
TEMP	Temperature
Th	Thorium
TW	Test Well
U	Uranium

us/ft	Micro-Seconds Per Foot
UFA	Upper Floridan Aquifer
Xe	Xenon
years BP	Years Before Present

CHAPTER 1.0 – INTRODUCTION

1.1 Objectives

This study investigated flow patterns and tested Kohout's theory of "cyclic-flow" in the Floridan aquifer system (FAS) within the south western Florida Peninsula of Naples Florida. Cyclic flow means ocean water enters the lower Floridan aquifer, flows inland, migrates upward into the upper Floridan aquifer, and then flows back to the ocean. Kohout (1967) was the first to identify cyclic groundwater flow from his anomalous temperature measurements in the Floridan aquifer. He suggested that cold, dense seawater flows inland through the cavernous dolomite in the deep part of the lower Floridan aquifer, where it becomes progressively heated by geothermal heat flow. The reduction in density produces an upward convective circulation which brings seawater into contact with freshwater.

The study area covers approximately 175 square miles around the city of Naples, Collier County, Florida. Four Floridan monitoring wells were used for this investigation. The tri-zone Floridan monitor well (I75-TW), property of the South Florida Water Management District (SFWMD), was the core monitor well used for this investigation. Three nearby dual-zone Floridan monitor wells, property of Collier County, Florida, were used to support the data from the I75-TW.

This investigation attempts to identify groundwater flow patterns with a geochemical analysis of groundwater samples from the FAS in the vicinity of Naples, Florida. These groundwater samples were analyzed for major cations (Na^+, K^+, Ca^{2+} and Mg^{2+}), anions (Cl^-, HCO_3^-, and SO_4^{2-}), stable isotopes (^2H, ^{18}O), radiocarbon (^{14}C), and noble gas data collected from monitor wells located within the study area. Temperature logs were also conducted in the aforementioned monitor wells and analyzed to aid in identifying the possibility of cyclic flow in the FAS.

1.2 Location and Geomorphology of Study Area

The state of Florida is the above-sea-level part of a large peninsular landmass called the Floridan Plateau. The Plateau in south Florida is approximately 240 miles in width (Kohout, 1967). This platform is flanked on the west by abyssal depths greater than 12,000 feet in the Gulf of Mexico (Kohout, 1967). This platform is truncated on the east and south by the Florida Straits (Kohout, 1967). The study area is located in the vicinity of Naples, Florida within northeastern Collier County near the Gulf of Mexico (Figure 1).

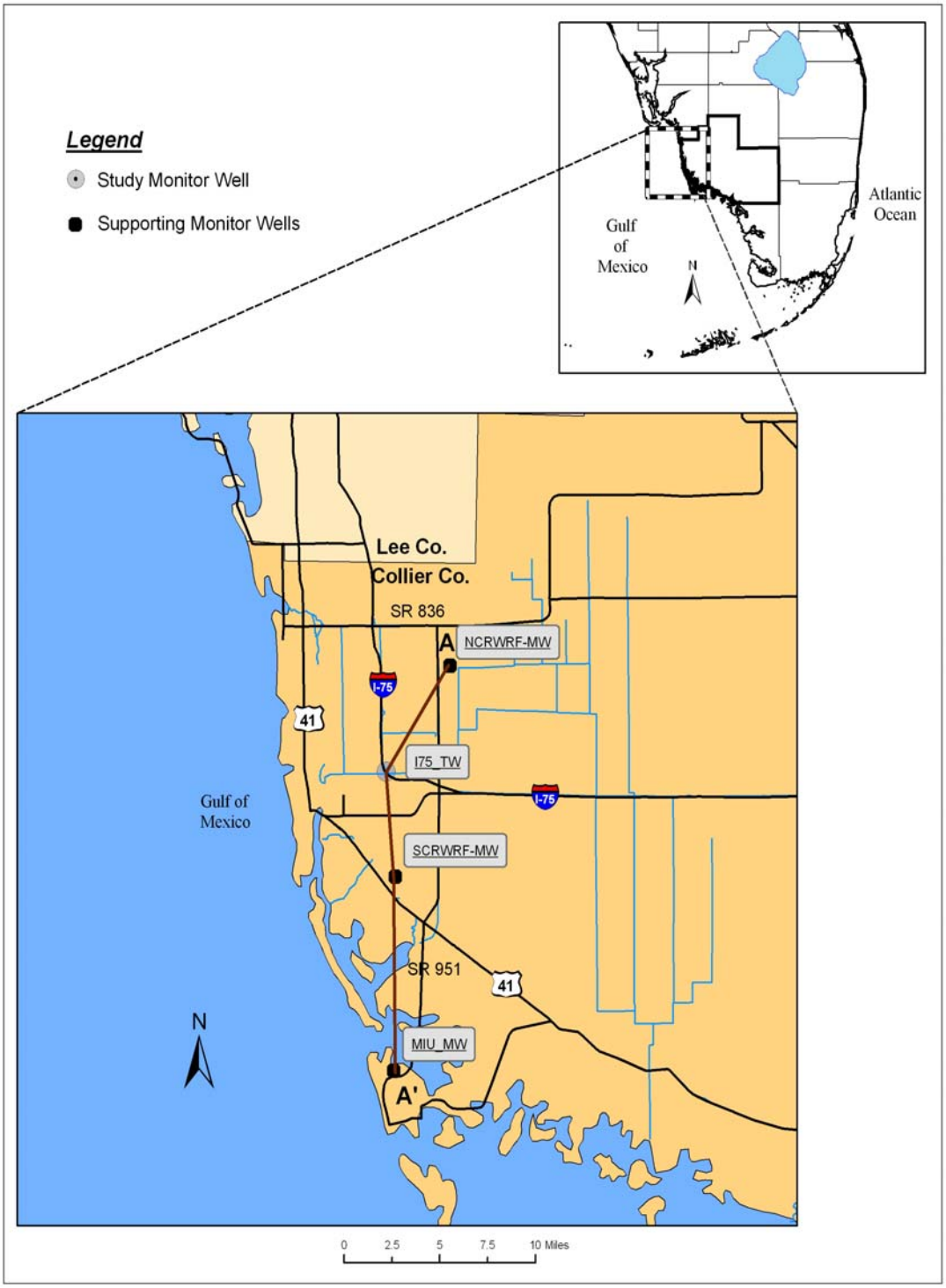

Figure 1. Study area with well locations and line for Hydrostratigraphic cross-section (A - A').

Southwestern Florida terrain is characterized by broad, flat, gently sloping and poorly drained topography (Klein *et al*., 1964). The topography of this area can be divided into two regions, the Immokalee Rise and the Big Cypress Swamp. These two features have not been appreciably affected by the deposition of post-Flandrian peat, lime mud, shell, or sand (White, 1970). The Immokalee Rise was built in Pamlico time as a submarine shoal that lies north of the Big Cypress Swamp, west of the Everglades and south of the Caloosahatchee Valley (White, 1970). The Big Cypress Swamp is a flat plain that slopes very gently to the south.

1.3 Climate

The climate in this region is subtropical and the temperature rarely falls below freezing (White, 1970). This tropical climate that covers nearly all of southern Florida is referred to as a subtropical savanna (savanna being a grassland with scattered trees) or subtropical wet-and-dry climate (Henry *et al.*, 1994). During the rainy season, conditions are similar to equatorial rainy climates, with frequent cloudy skies, warm temperatures, high humidity, and frequent afternoon thunderstorms (Henry *et al*., 1994). Conversely, during the dry season, conditions usually include abundant sunshine, much lower humidity, and often a lack of rain for several weeks or even months (Henry *et al*., 1994).

1.4 Well Descriptions

The geochemical data were obtained from one FAS test well (I75-TW) owned by the SFWMD. The monitor well is located in the Golden Gates Estate area on

Florida Department of Transportation property along the I-75 Canal in the northwestern quarter of Section 29, Township 49S, Range 26E. Geochemical data was also collected from three FAS monitor wells operated by various Wastewater Treatment facilities, owned by the city of Naples and Marco Island, within the study area. The locations of these wells are shown on Figure 1.

Groundwater samples were collected at various depth intervals within the Floridan aquifer system from the aforementioned wells. They were collected during open hole packer tests in test wells or from completed monitor wells. Appendix 1 lists the owners, well names, and intervals that the samples were collected from for this study.

CHAPTER 2.0 - HYDROGEOLOGY OF SOUTHWESTERN FLORIDA

2.1 Stratigraphic Framework

The study area of southwestern Florida is underlain by rocks of Cenozoic age to a depth of about 5,000 ft (Meyer, 1989). These rocks are composed of carbonates, with minor amounts of evaporates in the lower part and clastics in the upper part (Reese, 2000). In this Chapter, the stratigraphy of these rocks and identified aquifer systems in the study area of Naples, Florida will be discussed from youngest to oldest.

The SFWMD collected geologic formation samples (well cuttings) from the pilot hole during drilling operations for a tri-zone monitor well (I75-TW) and separated them based on their dominant lithologic or textural characteristics, and, to a lesser extent, color (Bennett, 2004). The representative formation samples were split into two sets and distributed to the SFWMD and the Florida Geological Survey (see FGS lithologic description in Appendix 2). This chapter of the investigation presents a detailed discussion of the geologic framework of the study area based on interpretations from the FGS. A lithologic summary of the site is listed on Figure 2.

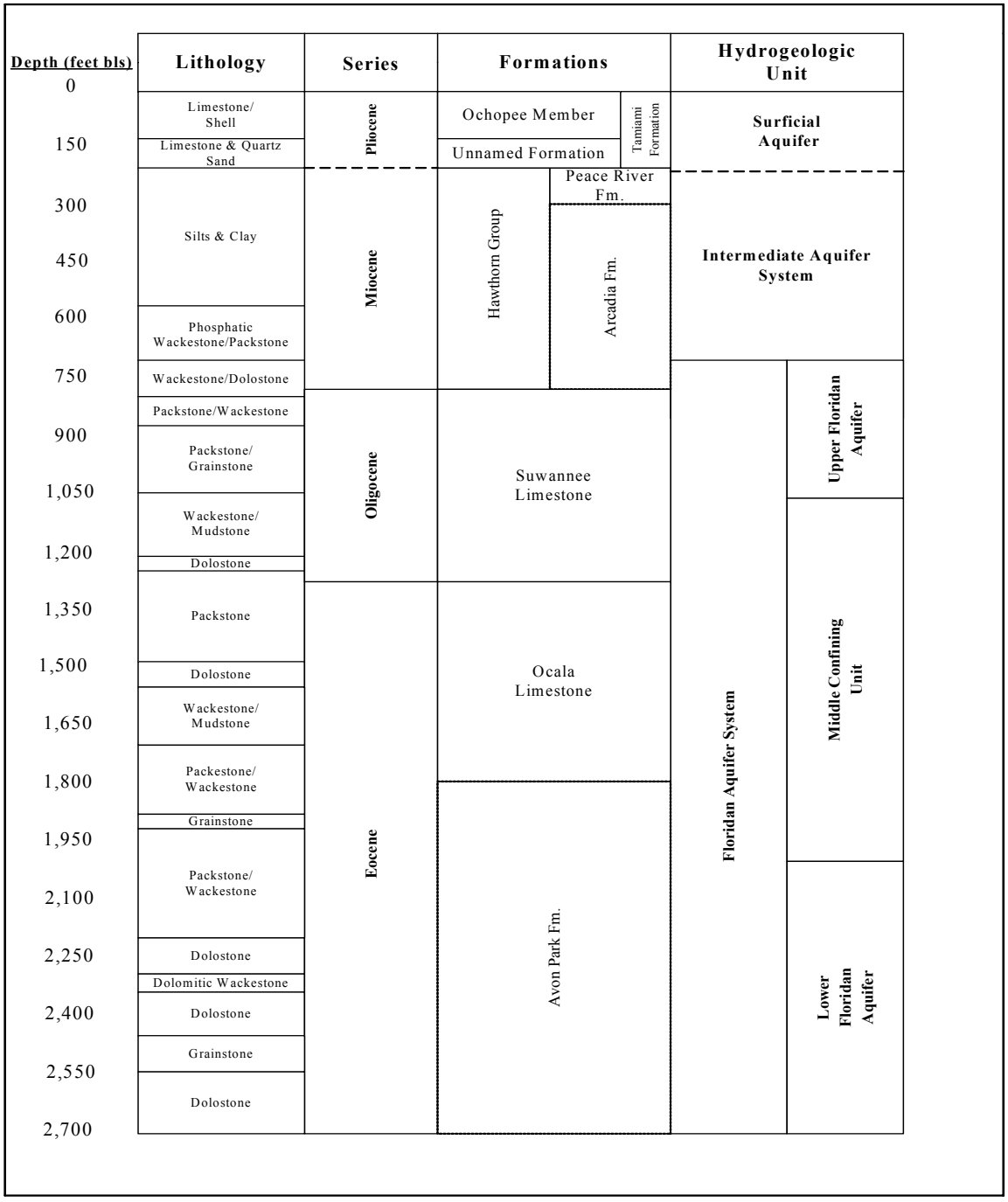

Figure 2. Stratigraphic Section and Hydrogeologic Framework of the I75-TW Site.

2.1.1 Pliocene Series

In the study area, the Tamiami Formation of Pliocene Age occurs from 10 to 195 feet below land surface (feet bls.) (Cunningham, 1997, Weedman *et al.*, 1999, Reese, 2000 and Cunningham, *et al.*, 2001). The Tamiami Formation at the I75-TW site is divided into the Ochopee Limestone Member (Cunningham, *et al*., 2001) and the Unnamed Formation (Weedman *et al*., 1999). The "Unnamed Sand Member" (Cunningham, *et al*., 2001), that is identified as the upper lithostratigraphic unit of the Tamiami Formation in the southern most peninsula of Florida, is not present in the study area (Cunningham *et al*., 2001).

An unconsolidated shell/limestone bed was identified from a depth of 10 to 90 feet at this site. The shell bed consists of mollusks, yellowish gray to grayish olive in color inter-fingered with grayish limestone. This unconsolidated shell/limestone bed represents the Ochopee Member of the Pliocene aged Tamiami Formation. Unconsolidated, fine to very coarse-grained quartz sands/limestone beds occur from 90 to 195 feet bls. These sediments may be the Pliocene aged Unnamed Formation (Weedman *et al*., 1999). While these sediments of the Unnamed Formation may seem similar to the Peace River Formation of the Hawthorn Group, Weedman *et al*. (1999) identified differences that warrant separation into different lithostratigraphic units. In general, the Unnamed Formation has lower concentrations of phosphate grains, more coarse sand and gravel, less silt and clay, and in some areas, less carbonate facies than the Peace River Formation (Weedman *et al*., 1999). This description by Weedman *et al*. (1999); corresponds to the lithostratigraphy of the study area.

2.1.2 Miocene Series

2.1.2.1 Hawthorn Group

The Hawthorn Group occurs from 195 to 768 feet bls. (Bennett, 2001), the formation acts as a confining unit for the surficial aquifer system and the underlying Floridan aquifer system. In the study area of Naples, Florida, the Hawthorn Group is divided into the Peace River Formation and Arcadia Formation in the lower part (Reese, 2004). Both formations are thought to be Miocene in age (Reese, 2000).

The Hawthorn Group is composed of a heterogeneous mixture of silt, clay, calcareous clay, dolosilt, quartz sand, phosphate, limestone, and dolomite (Bennett, 2004). In the study area, the Hawthorn Group can be subdivided into two litho stratigraphic units. The upper unit, the Peace River Formation is composed of predominately fine grained siliciclastic material from 195 to 430 feet bls at the I75-TW site. The lower unit, the Arcadia Formation is composed principally of carbonates, such as limestones and marls (Scott, 1988) and is approximately 430 to 768 feet bls.

A regional disconformity (Cunningham, *et al*., 2001) separates the Peace River Formation from the Arcadia Formation (Scott, 1988 and Missimer, 1997, 2002). The contact between these two units can often be distinguished by the occurrence of a rubble bed of coarse to pebble-size quartz sand, phosphatic sand, and gravel (Bennett, 2004). The lower 500 feet of the unit consists of 3 to 4 large scale, transgressive- regressive cycles **(**Missimer**,** 1984**)**. Each cycle consists of a lower

thick limestone unit and an upper mixture of minor carbonate and clastic units (Missimer, 1984).

2.1.3 Oligocene Series

The Floridan aquifer system consists of the Suwannee Limestone of early Oligocene age, Ocala Limestone of late Eocene age, Avon Park Formation of middle Eocene age, Oldsmar Formation of early Eocene age, and the Cedar Keys Formation of Paleocene age (Reese, 2000).

2.1.3.1 Suwannee Limestone

The Suwannee Limestone of Oligocene Age (Reese, 2000) at this site occurs from 768 to 1,299 feet bls. The FGS and SFWMD identified the contact between the Hawthorn Group and the Suwannee Limestone at a depth of 768 feet bls based on interpretations from the lithology and geophysical logs (refer to Appendices 2 and 3). A regional disconformity separates the Hawthorn Group from the Suwannee Limestone (Reese, 2000 and Bennett, 2001). The contact between the these two formations in the study area is described as going from a phosphatic gray mudstone to a yellowish gray, fossiliferous, medium grained packstone with trace amounts of quartz sand (Reese, 2000). Geophysically, the contact between the Hawthorn Group and the Suwannee Limestone is marked by an attenuation of the natural gamma activity, as depicted in Appendix 3 (log run 2), primarily due to the decrease in phosphate content in the upper Suwannee Limestone (Bennett, 2001 and 2004).

2.1.4 Eocene Series

2.1.4.1 Ocala Limestone

At the I75-TW site, the Ocala Limestone of late Eocene Age (Reese, 2000) occurs from 1,299 to 1,785 feet bls, consisting primarily of yellowish gray packstone and wackestone units. In southwestern Florida it is difficult to distinguish the Suwannee Limestone from the Ocala Limestone based solely on lithologic descriptions. The Ocala Limestone shares the same lithology (yellowish-gray packstones/wackestones) and the same geophysical log responses with the Suwannee Limestone (Bennett, 2004). The FGS primarily used a biostratigraphic designation for identifying the top of the Ocala Limestone at depth 1,299 feet bls, with the first occurrence of the diagnostic benthic foraminifer Lepidocycina ocalana (Applin and Applin, 1944). The lack of lithologic differences between the two units may indicate similar depositional environments were present at this location (Bennett, 2004).

2.1.4.2 Avon Park Formation

The deepest unit drilled into at the I75-TW site is the Avon Park Formation of middle Eocene Age (Reese, 2000). The FGS identified the top of the Avon Park Formation at a depth of 1,785 feet bls. The lithology changes with depth from a yellowish gray packstone/wackestone to a yellowish brown to brownish gray dolostone. In addition, this formation boundary coincides with a change in fossil assemblage and an increase in natural gamma activity. The first occurrence of Dictyoconus americanus (Chen, 1965), a diagnostic foraminifera (used

extensively as a bio-stratigraphic indicator for the Avon Park Formation) occurs at 1,800 feet bls, 15 feet below the identified top of the formation.

The Avon Park Formation from 1,785 to 2,694 feet bls consists predominately of moderately indurated, yellowish gray packstones/wackestones with thick interbeds of dolostone (approximately 30 feet or greater in thickness). This lithologic sequence goes with Reese's (2000) investigation, identifying dolomite occurring in the lower part of the Avon Park Formation as thick interbeds in Lee County and western Collier County.

2.1.4.3 Oldsmar Formation

A review of the borehole data indicates that the Oldsmar Formation was not present to a depth of 2,694 feet bls at the I-75 Canal site, based on established lithologic and paleontologic criteria (Applin and Applin, 1944; Chen, 1965; Miller, 1986; Duncan *et al*., 1994). Although the I75-TW was not drilled into the Oldsmar Formation, the formation will still be discussed briefly in this study because it makes up the lower Floridan aquifer (LFA).

The top and bottom of the Oldsmar Formation of late Eocene Age (Reese, 2000) is often difficult to identify. Its diagnostic microfossils are often obliterated by diagenetic effects and its lithological character is similar to the overlying Avon Park Formation (Bennett, 2004). The formation is predominately an alternating sequence of dolomites and limestones with some evaporates (Missimer, 1984). In the study area of southwestern Florida, the Oldsmar Formation ranges from 800 to 1,500 feet in thickness (Missimer, 1984). A common characteristic of the

formation is the occurrence of massive caverns and high transmissivity zones, which caused drillers to call it the "boulder zone" (Missimer, 1984).

2.2 Hydrogeologic Framework

Three major aquifer systems underlie the study area: the Surficial Aquifer System (SAS), the Intermediate Aquifer System (IAS), and the Floridan Aquifer System (FAS), with the FAS being the focus of this study. These aquifer systems are composed of multiple, discrete aquifers separated by low permeability "confining" units that occur throughout this Tertiary/Quartenary age sequence (Bennett, 2001). Figure 2 shows the hydrogeologic section underlying the I75-TW site. Figure 3 shows a generalized hydrostratigraphic cross-section from north to south (A – A', shown on Figure 1) with wells used in this investigation.

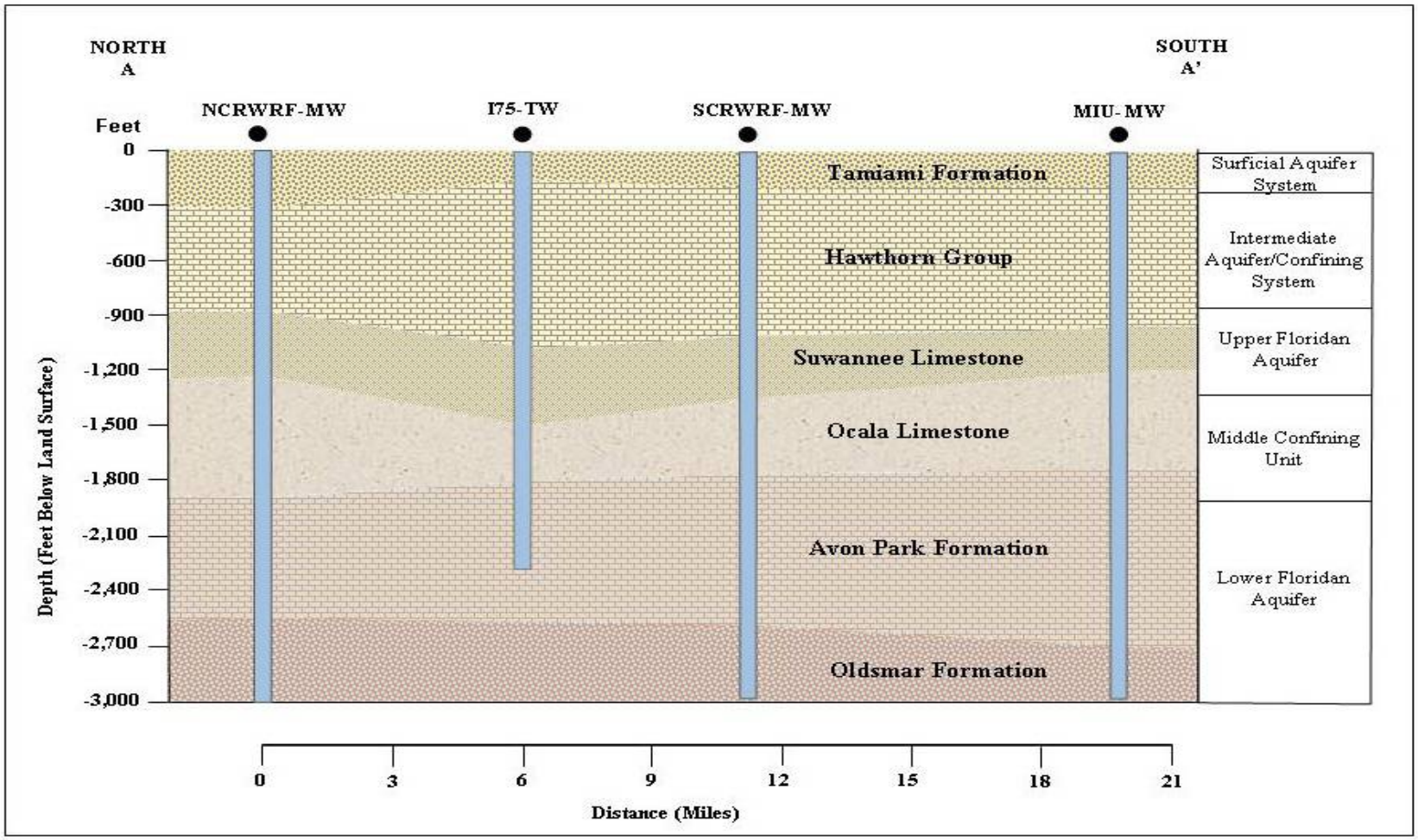

Figure 3. Generalized Hydrostratigraphic Cross-Section From A – A' through the Study Area (Line of Cross-shown in Figure 1).

2.2.1 Surficial Aquifer System

The SAS consists of the water-table aquifer and hydraulically connected units above the top of the first occurrence of laterally extensive and vertically persistent beds of much lower permeability (Southeastern Geological Society, 1986).

At the I-75 Canal site, depicted in Figures 2 and 3, the SAS consists of Pliocene aged Tamiami Formation; divided into the Ochopee Limestone Member and the Unnamed Formation (Weedman *et al*., 1999). A low permeability poorly indurated olive green, silty clay unit of the Peace River Formation at 206 feet bls forms the base of the SAS (Bennett, 2001).

2.2.2 Intermediate Aquifer System

Aquifers that lie beneath the SAS and above the FAS in southwestern Florida are grouped within the IAS (Southeastern Geological Society, 1986). The IAS does not crop out and contains water under confined conditions (Miller, 1986). The IAS lies within the Hawthorn group and may include multiple production horizons.

At the study area (Figure 2), the IAS extends from 206 to 690 feet bls. The Peace River and Arcadia Formations of Miocene age Hawthorn Group (Scott, 1988) act as semiconfining units separating the FAS from the SAS. Multiple productive horizons separated by low permeability interaquifer confining units where identified during drilling and testing operations for the I75-TW. The first moderately productive unit occurs from 220 to 280 feet bls and consists of moderately indurated biogenic limestone with up to 5 percent phosphatic sands,

identified as the carbonate facies of the Sandstone Aquifer (Smith and Adams, 1988). A second productive horizon occurs from 322 to 370 feet bls, composed of moderately indurated wackestone containing 30 to 40 percent allochems consisting of mollusks and bryozoans (Bennett, 2001). This unit was correlated to the mid-Hawthorn aquifer, which underlies the area (Knapp *et al.*, 1986).

2.2.3 Floridan Aquifer System

The Floridan Aquifer System is defined as a vertically continuous sequence of permeable carbonate rocks of Tertiary age that are hydraulically connected in varying degrees, and whose permeability is generally several orders of magnitude greater than that of the rocks that bound the system above and below (Miller, 1982). The Floridan aquifer in the study area of southwestern Florida is composed predominately of limestone with dolomitic limestone and dolomite. The system includes the lower Arcadia Formation, Suwannee and Ocala Limestones, Avon Park Formation, and the Oldsmar Formation. The Paleocene age Cedar Keys Formation with evaporitic gypsum and anhydrite forms the lower boundary of the FAS (Miller, 1986).

2.2.3.1 Upper Floridan Aquifer

The top of the FAS, as defined by the Southeastern Geological Society Ad Hoc Committee on Florida Hydrostratigraphic Unit Definition (1986), coincides with the top of a vertically continuous permeable carbonate sequence at Miocene to Oligocene Age. As shown in Figure 2, the upper Floridan aquifer in southwestern

Florida occurs from 690 to 1,050 ft bls. and chiefly consists of permeable zones in the lower Hawthorn Group and Suwannee Limestone (Reese, 2000). Generally the upper Floridan aquifer consists of several thin water-bearing zones of high permeability interlayered with thick zones of much lower permeability (Reese, 1994). The lithologic and hydraulic properties of most of the rocks in the lower part of the upper Floridan aquifer are similar to those of the middle-confining unit of the Floridan aquifer system (Reese, 1994). The salinity and temperature of the upper Floridan aquifer generally increases with increasing depth. However, temperatures along the southeastern coast are lowest (about 70.0 ^{0}F) owing to heat transfer to the Atlantic Ocean (Straits of Florida) (Sproul *et al*., 1972) and (or) to heat transfer to cooler saltwater in the Lower Floridan aquifer (Kohout, 1965). At this study area, the top of the FAS occurs at a depth of 690 feet bls, which coincides with the lower portion of the Arcadia Formation (Basal Hawthorn Unit, Reese, 2000).

Generally, two predominant permeable zones exist within the upper Florida aquifer (Bennett, 2001). The uppermost permeable zone typically lies between 700 and 1,300 feet bls. The most transmissive part of this upper zone usually occurs near the top, coincident with an unconformity at the top of the Oligocene or Eocene age formations (Miller, 1986).

The productive zones in the upper Floridan aquifer at the I-75 Canal site were identified using geophysical logs (i.e. fluid resistivity, flowmeter and temperature), borehole video survey (evidence of vuggy porosity), and loss of circulation during mud rotary drilling. The first transmissive horizon includes the

lower portion of the Basal Hawthorn Unit (Reese and Memberg, 2000), and occurs from 690 to 780 feet bls (Bennett, 2001). Through this interval, the flowmeter log indicates increased upward water flow at 745 feet bls, the fluid resistivity trace shows a sharp deflection at 735 feet bls, (refer to geophysical logs Run 2 in Appendix 3), and combined with the lost circulation from 725 to 737 feet bls during mud rotary drilling, suggests a highly transmissive horizon (Bennett, 2001).

The second productive interval within the upper Floridan aquifer was identified from 905 to 1,050 feet bls in the Suwannee Limestone. The flowmeter log was of limited use in identifying this productive horizon due to the large borehole muting evidence of water production (Bennett, 2001). However, the signature of the temperature log trace (refer to geophysical logs Run 2 in Appendix 3), and the result of the borehole video survey were invaluable in identifying this productive interval (Bennett, 2001).

2.2.3.2 Middle Confining Unit

The middle-confining unit of the Floridan aquifer system, as shown in Figure 2, occurs from 1,050 to 1,990 ft. bls (Reese, 2000 and Bennett, 2001). The unit has relatively low permeability, and it generally separates the brackish ground water of the upper Floridan aquifer, from the ground water that closely resembles seawater in the lower Floridan aquifer (Meyer, 1989). Hydraulic connection between the upper and lower aquifer is inferred from sinkholes and fractures that transect the middle-confining unit (Kohout, 1965, 1967). Ground water

movement in southern Florida is estimated to be primarily upward from the lower Floridan aquifer through the middle-confining unit, then horizontally toward the ocean through the Upper Floridan aquifer (Kohout, 1965, 1967). Salinity varies greatly at the top of the middle-confining unit as the upward moving saltwater is blended with seaward-flowing freshwater in the upper Floridan aquifer (Meyer, 1989).

The top of the middle confining unit at the I-75 Canal site was identified at 1,050 feet bls. The top was found by examining a positive deflection from the resistivity log trace conducted on the borehole (refer to geophysical logs Run 2 or Run 3 in Appendix 3). This positive deflection suggests lower porosities and/or lower formation water TDS concentrations from 1,050 1,090 feet bls. (Bennett, 2001). The middle confining unit consists of the lower section of the Suwannee Limestone, Ocala Limestone, and the upper portion of the Avon Park Formation.

Small productive zones were identified in the middle confining unit of the Suwannee Limestone using production type geophysical logs (i.e. fluid resistivity, flowmeter and temperature). Minor water production was primarily above and below a dolostone unit from 1,204 to 1,231 feet bls; it was indicated by deflections in the temperature differential log trace (see geophysical logs Run 3 in Appendix 3).

The Ocala Limestone from 1,299 to 1,785 feet bls forms in large part an interaquifer confining unit within the FAS at this site (Bennett, 2001). This interval consists of low permeability mudstones and wackestones. Formation samples from this interval do not show evidence of large-scale secondary porosity

development (Bennett, 2001). In addition, the production type geophysical log traces indicate limited production horizons, which support the confinement in this interval (Bennett, 2001). Intervals with high permeability have been documented within the middle confining unit ranging in depth from 1,400 to 1,600 feet bls (Miller, 1986). In this interaquifer confining unit, a minor flow zone is present within a crystalline dolomite unit at a depth of 1,481 to 1,500 feet bls (Bennett, 2001). Through this interval, the induction, sonic and density/neutron log traces indicate a well indurated, low porosity unit. Near the center of this unit, the caliper log identifies an enlarged borehole with a diameter exceeding 20 inches, and deflections in the temperature and flowmeter logs indicate minor water production (see Geophysical Log Run 3 in Appendix 3).

The upper Avon Park Formation from 1,785 to 1,986 feet bls is in part also an interaquifer confining unit within the FAS at this site. Miller (1986) observed that portions of the lower Avon Park Formation are fine grained and have low permeability, thereby acting as interaquifer confining units within the FAS. Based on well cuttings, well indurated, low porosity mudstone and packstone units with intermittent dolostones occur in the subsurface from 1,986 to 2,213 feet in depth (Bennett, 2001). This lithologic change was also identified by geophysical logs with the caliper log measuring a relatively gauged borehole, an increase in both resistivity and bulk density values, and shorter sonic time (see Geophysical Log Run 3 in Appendix 3).

2.2.3.3 Lower Floridan Aquifer

In the study area, the lower Floridan aquifer consists of the lower part of the Avon Park Formation, Oldsmar Formation, and the upper part of the Cedar Keys Formation (Meyer, 1989 and Bennett, 2001). Ground water in the lower Floridan aquifer is compared closely to the chemical nature of modern seawater. There are three permeable dolostones units within the lower Floridan aquifer that are separated by less permeable limestones (Meyer, 1989). The transmissivity of the lower dolostone (locally called the Boulder Zone; Miller, 1986) is slightly higher than the overlying dolostones (Meyer, 1989). The high permeability in the Boulder Zone is due to the cavernous porosity and extensive fracturing present (Reese, 1994). In southwestern Florida, drilling data suggests that the dolostones are hydraulically connected, although head data and aquifer tests to confirm this interpretation are lacking (Meyer, 1989). There is a pronounced temperature anomaly present in the lower Floridan aquifer; the geothermal gradient is reversed at a depth below 3,000 feet below sea level (Kohout, 1965). Temperatures increase generally from the Straits of Florida inland toward the center of the Floridan Plateau (Meyer, 1989), and, as previously mentioned, Kohout (1965) hypothesized circulation of cold seawater inland from the Straits of Florida through the lower part of the Floridan aquifer system driven by geothermal heat flow.

At the I75-TW site, shown in Figure 2, the lower Floridan aquifer was identified from 2, 213 to 2,694 feet bls. The lower Floridan aquifer may extend deeper than

2,694 feet into the subsurface at this site, although, the I75-TW project stopped drilling at that depth due to budget constraints.

A significant lithologic change occurs at a depth of 2,213 feet bls, and continues to the total depth of the borehole at 2,694 feet bls (Bennett, 2001). Well indurated dolostones dominate this interval with only minor stringers of wackestone and packstone limestone units (Bennett, 2001). This change in lithology is indicated by an increase in resistivity and a decrease in sonic travel times (see Geophysical Log Run 3 in Appendix 3). Based on Myers (1989) and Reese (2000), the interval from 2,213 to 2,694 feet bls was identified as the upper dolostone units of the lower Floridan aquifer. From a stratigraphic perspective, the Oldsmar Formation was not found at this site, based on lithologic criteria defined by Miller (1986), the lack of a glauconite marker bed used by Duncan *et al.* (1994), and the absence of early Eocene index fossils such as *Helicostegina gyralis* (Chen, 1965).

CHAPTER 3.0 – GEOCHEMICAL TRACERS AND FLOW DIRECTION IN AQUIFERS

3.1 Previous Investigations

The following sections will discuss previous investigations which establish the importance of using geochemical tracers (i.e. temperature, inorganics, stable isotopes, radiocarbon, and noble gases) when investigating the flow systematics archived in groundwater systems. Geochemistry is needed to separate the effects of mixing of groundwater masses with different histories presumably caused by cyclic flow within the study area of Naples, Florida (Clark *et al*., 1998).

Temperature logging measures characteristics related to the fluid column in the borehole; no direct signal is derived from the surrounding rocks and their contained fluids (Keys, 1989). Temperature logs may provide useful information on the movement of water through a borehole, including the location of depth intervals that produce or accept water (Keys, 1989). Thus they aid in providing information related to permeability distribution and relative hydraulic head (Keys, 1989).

Geochemical and isotope tracer data may be used to estimate groundwater ages and help to discern circulation patterns within a hydrologic system (Bennett, 2004). These multi-tracers can be successfully applied to describe complicated hydrologic systems with travel time of a thousand years (Bennett, 2004;

Bottemley *et al.*, 1984; Clark *et al.*, 1997 and 1998; Stute *et al.*, 1995). The chemical composition of groundwater reflects both the source(s) of water and process(es) that modify the inorganic and isotopic compositions; each source and process leaves a distinctive geochemical "signature" on the water (Bennett, 2004). Radiocarbon analysis and dating often complements the stable isotope data and may also be used to estimate regional flow velocities (Hanshaw *et al.*, 1964). Noble gas paleo-thermometry has become an acceptable method for determining continental temperatures of past climates recorded in groundwater systems based on the temperature dependence of the solubility of noble gases in water (Bennett, 2004). This method may help to determine the paleo-temperatures of water entering the Floridan aquifer, thus providing constraints to the determined radiocarbon ages (Stute *et al.*, 1995; Clark *et al.*, 1997 and Bennett, 2004).

3.1.1 Temperature

Kohout (1965, 1967) hypothesized the cyclic flow of salt water related to geothermal heating in the Floridan aquifer. He suggested that cold, dense seawater flows inland through the cavernous dolomite in the deep part of the aquifer, where it becomes progressively heated by geothermal heat flow. The reduction in density produces an upward convective circulation which brings seawater into contact with freshwater.

Meyer (1989) studied the Alligator Alley Test Well, located in Broward County, Florida and identified a reverse geothermal gradient with coldest groundwater ($24^{0}C$) occurring at the bottom of the well (2,811 feet). Meyer supported

Kohout, that colder seawater from the Atlantic Ocean flows inland (west) into the Oldsmar Formation (Eocene age) of southern Florida.

3.1.2 Inorganic Chemistry

Inorganics are employed primarily to identify changes in salinity with depth within the Floridan Aquifer System (FAS). Meyer (1971), studied variations in water quality with depth in the FAS of southern Floridan and used this study to assist local governments in the proper management of this groundwater resource. He showed that chloride content increases with depth in the FAS of southern Florida. Meyer's study also found that the Floridan aquifer is composed of several artesian water-bearing zones which are hydraulically connected and may function as a single aquifer in karst regions.

Hanshaw and Back (1979) conducted a study on the geochemical processes in the evolution of a carbonate aquifer system. They studied the changes in groundwater chemistry of carbonate aquifers from the time of their inception in the shallow marine environment, through their functioning as emergent aquifer systems. Hanshaw and Back suggested that the mixing of groundwaters of different chemical compositions seem to be the major control on groundwater alteration processes including porosity and permeability distribution.

Frazee (1982), developed a geochemical pattern analysis using the Piper trilinear diagram to describe regional hydrologic systems. His method involves eight parameters (Ca, Mg, Na, K, Cl, SO_4, HCO_3 and CO_3) and pH which compares acidity to conductive rates of recharge and SO_4 – HCO_3 dominance. These

parameters are plotted on the Piper trilinear diagram and then compared with patterns developed using a selection of known water types tested by statistical correlation methods. Grouped waters include recharge, fresh formation, interface, ocean, saline formation and relict in situ. Frazee used this technique to geochemically describe the southeastern limestone regional aquifer system relating recharge, interface, and intruded groundwaters in Florida.

Sprinkle (1989), published a comprehensive geochemical study of the Floridan aquifer. He identified several processes that control the chemistry of major dissolved species in groundwater of the FAS. The processes described in Sprinkle's study were carbonate dissolution, gypsum dissolution, ocean water intrusion, and mixing of long and short residence-time waters.

Reese (1994 and 1998) studied the vertical variations in water quality (salinity) in the FAS and related these variations in water quality to the local hydrogeologic framework of southern Florida. In his study, he defines areas of high salinity as having chloride concentrations greater than 3,000 milligrams per liter (mg/L). Most investigations of the Floridan aquifer in southern Florida, including this study, found the major anion-cation pair in the areas of high salinity is chloride and sodium. In Reese's studies of southern Florida, groundwater salinity in the Oldsmar Formation and in the lower part of the Avon Park Formation reaches that of ocean water.

3.1.3 Stable Isotopes

Stable isotopes are particularly useful because they provide additional criteria linking water chemistry with mineral mass transfer. This information may ultimately be used to better understand the geochemical processes within the FAS. Deuterium (^{2}H) and oxygen-18 (^{18}O) are two stable isotopes commonly used in hydrologic studies. These stable isotopes do not undergo radioactive decay, but, because of the difference in mass between them and the more common isotopes of their respective elements, protium (^{1}H) and oxygen-16 (^{16}O), they react differently with other atoms and molecules as they move through the hydrologic system (Swancar and Hutchinson, 1992). The higher mass of ^{2}H and ^{18}O causes them to bond more tightly in molecules (including water), thus requiring more energy to break the bonds when these molecules participate in chemical reactions (Swancar and Hutchinson, 1992). Consequently, these two isotopes become enriched in the reactants of chemical reactions requiring higher energy levels (Swancar and Hutchinson, 1992).

Mixing within regional groundwater flow systems has the effect of averaging the isotopic composition of ^{2}H and ^{18}O in various groundwaters from different recharge environments. The isotopic composition of deep or well-mixed groundwater in such cases converges on the mean weighted value of all recharge contributions (Clark and Fritz, 1997). Such regional scale mixing can be observed in deep groundwater as well as in shallow but confined systems with a long subsurface flowpath (Clark and Fritz, 1997). In such cases, stable isotopes are used as indicators of regional flow, rather than to identify discrete areas of recharge (Clark and Fritz, 1997). Stable

isotope ratios in this study, such as oxygen and hydrogen ratios will be used to indicate local recharge as well as to date the groundwater.

The use of isotopes as tracers in studies of groundwater movement in the FAS began in the early 1960's. Hanshaw and Back (1971), in studies of the origin of dolomite in the FAS, used stable isotope ratios ($\delta^{13}C$ and $\delta^{18}O$) to interpret the origin of dolomite. Hanshaw and Back employed isotopic composition to distinguish between marine (primary) dolomite and nonmarine (stoichiometric) dolomite.

Meyer (1971, 1974, and 1989) used geologic, isotopic and hydraulic data to describe the hydrogeology and the flow characteristics in the FAS of southern Florida. Meyer (1989) analyzed naturally occurring isotopes of carbon, oxygen, and uranium in south Florida to assess their potential as tracers of groundwater movement within the Florida aquifer system.

3.1.4 Radiocarbons

The most important method for dating groundwater is carbon-14 (^{14}C), which has a half-life of 5,730 years (later half of the Pleistocene), making it a useful tool for dating waters as old as 50,000 years. Due to complex groundwater chemistry that affects carbon isotopes, it is unlikely that ^{14}C ages can be obtained with an accuracy of +/- 2,000 years (Stute and Sonntag, 1992).

The dating of groundwater is difficult due to dispersion processes in the aquifer that limit the time resolution of the record (Stute and Sonntag, 1992). There are some other complications within the FAS for the dating of groundwaters. This may

be due to the presence of vertical fractures and dissolution channels which could cause the ascent of deep-seated brines mixing with the groundwater of a different origin. Also, the dissolution of carbonate minerals may add dead carbon (i.e. devoid of ^{14}C) to the water, giving it an inaccurate old age (Drever, 1982). The contribution of the stable carbon ratio $^{13}C/^{12}C$ is a good potential tracer and is used in determining more accurate ^{14}C dates within the Floridan aquifer (Drever, 1982).

Studies began with estimates of groundwater velocities using ^{14}C in the upper part of the aquifer system in central Florida by Hanshaw *et al.* (1965). In their study, carbon-14 ages were analyzed from wells monitoring the Floridan aquifer, each well progressively farther down gradient on the piezometric surface. Hanshaw *et al*. were able to calculate a horizontal velocity for the Floridan aquifer groundwater of 7 meters per year from Darcy's Law. Plummer (1977) in the same area, examined transient changes in water chemistry in relation to the earlier ^{14}C ages, and new ages (slightly younger) were assigned to Hanshaw's samples on the basis of mass-transfer reaction coefficients. Plummer's calculated flow velocities were in close agreement Hanshaw's *et al*., derived from carbon-14 ages and ranged from approximately 2 – 10 meters per year.

Pearson and Hanshaw (1970) employed the stable carbon isotope composition of Floridan aquifer groundwater to correct ^{14}C ages. Their study identified a relationship between stable carbon isotope composition and degree of saturation with respect to calcite indicating that stable carbon could be used to correct for the degree of ^{14}C dilution produced by carbon aquifer dissolution (Kaufmann and Bennett, 2004). Pearson and Hanshaw's estimates indicated modern ages for

groundwater in recharge areas, but as old as 22,600 years in deeper portions of the aquifer suggesting the validity of their approach.

Meyer (1989) also employed carbon-14 in his investigation of the Floridan aquifer. He noted that radiocarbon activities of several groundwater samples suggest that seawater-like groundwater at 2,560 feet bls. is younger than brackish water at 1,030 feet bls. Meyer's comparison of the ^{14}C activity of the 2, 560 foot zone with that from wells with comparable depth in Ft. Lauderdale and Miami, approximately 45 miles east from his test well, suggested that the saltwater is younger at the coast, and that the direction of flow is inland.

Plummer and Sprinkle (2001) evaluated geochemical reaction models to improve radiocarbon dating of dissolved inorganic carbon (DIC) in groundwater from confined parts of the Upper Floridan aquifer in central and northeastern Florida. The chemical and isotopic data in their study were interpreted using NETPATH (Plummer *et al*., 1994) in order to adjust initial ^{14}C activities for geochemical reactions. The adjusted radiocarbon ages of DIC show that most of the groundwater in confined parts of the Upper Floridan Aquifer was recharged during the last 15,000 – 30,000 years ago, indicating that most of the freshwater recharged the aquifer occurred during the last glacial period (approximately 18,000 radiocarbon years before present).

Kaufmann and Bennett (2004) used ^{14}C activity to support Kohout's theory of cyclic flow in the FAS. They found the age range of the upper Floridan groundwater correlated with low sea level stands during the last Ice Age, which may have induced aquifer recharge from above. On average, Kaufmann and

Bennett identified the age of water in the lower Floridan is younger than the upper Floridan. There was only one portion of Kaufmann and Bennett's study that supported the hypothesis of cyclic flow, the area between Ft. Lauderdale and Naples. Additional work is necessary to uniformly apply the cyclic flow theory in all of southern Florida.

This study will consider three methods to estimate absolute ^{14}C ages. The three methods which will be used for correcting ^{14}C ages of the groundwater in the study area are Tamers (1967), Mook (1976), and Fontes and Garnier (1979). All three methods used stable ^{13}C to correct for carbonate dissolution and soil gas exchange (Pearson, Fontes and Garnier, and IAEA). Evaluation of these methods indicate that selection of age estimate methods for the Floridan aquifer must be done on a case by case basis because of effects of ocean water recharge and soil zone exchange are heterogeneous.

3.1.5 Noble Gases

Measurements of atmospheric noble gases, Helium (He), Neon (Ne), Argon (Ar), Krypton (Kr), and Xenon (Xe) dissolved in groundwater, originate from the atmosphere (Cook and Herczeg, 2000). Whenever water comes into contact with the atmosphere, gases are exchanged and gas concentrations of the individual phases record some characteristics of these processes due to the lack of chemical reactions that affect them (Cook and Herczeg, 2000). These atmospheric noble gases dissolved in groundwater yield valuable information on paleoclimate, in

particular temperature at the time of recharge and dynamics of groundwater flow (Cook and Herczeg, 2000).

The physical principle of the noble gas thermometer uses the temperature dependency of the solubility of the noble gases (Figure 4), especially Ar, Kr, and Xe, in water (Stute *et al*., 1992). Noble gases are used mostly in conjunction with ^{14}C and other chemical tracer data to develop continental paleotemperature records (Clark *et al*., 1997). Meyer (1989) employed noble gases along with ^{14}C to track groundwater movement in the Florida aquifer of southern Florida. Noble gases can identify paleotemperatures between the times in the beginning of the Holocene and the last glacial period, approximately 18,000 years ago (Clark *et al*., 1998).

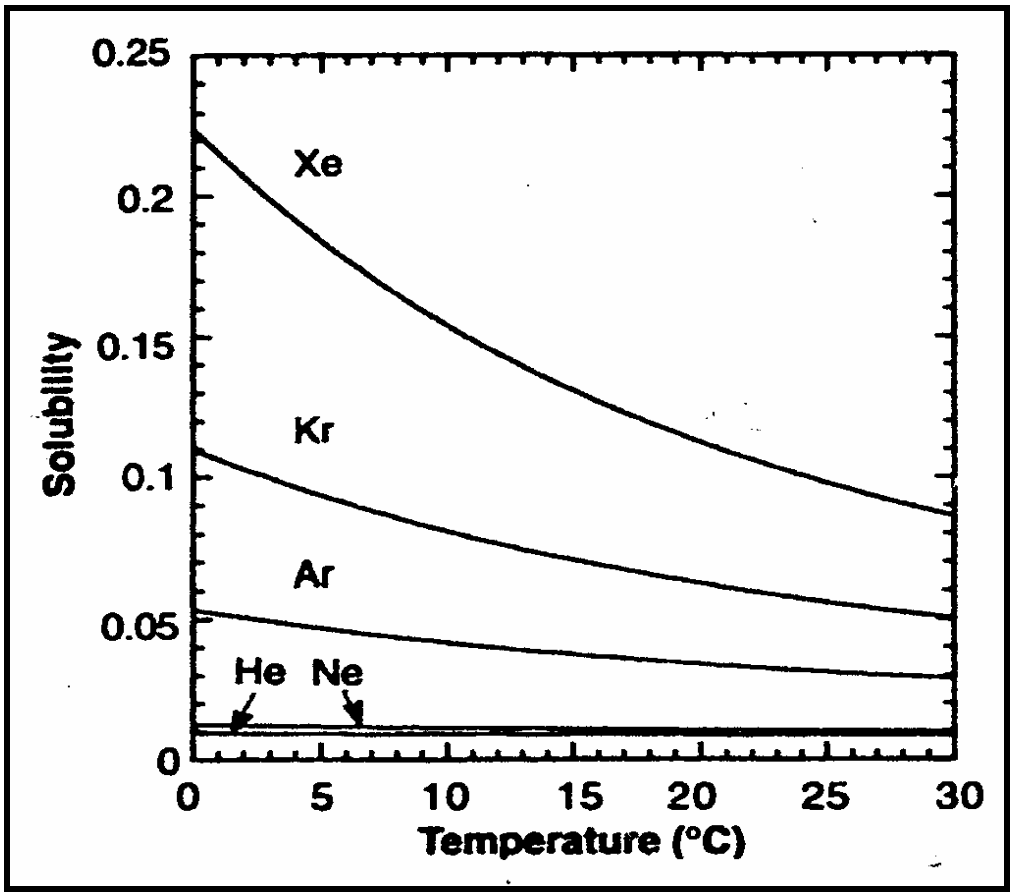

Figure 4. Temperature dependence of the noble gas solubilities in distilled water expressed as the Bunsen coefficient (Stute *et al*., 1992).

The advantage of the noble gas thermometer, as compared to other paleothermometers, is that it is based on physical principles and measures an annual mean temperature with high accuracy (Stute *et al*., 1992). It averages the seasonal temperature fluctuations and smoothes out variability occurring on time scales of several years to about a thousand years (Stute *et al*., 1992). The gases can also be used to calibrate high resolution records obtained by other methods that have weaknesses determining the accuracy of the absolute temperature determination (Stute *et al*., 1992).

The climate signals recorded by noble gases are also used to study groundwater flow dynamics (Cook and Herczeg, 2000). For example, the seasonal cycle of nitrogen (N_2) and Ar, in groundwater recharged by a stream aid, in determining flow velocities within the aquifer (Cook and Herczeg, 2000). The climate signal derived from noble gases may also be used as a stratigraphic marker for situations where radiocarbon ages have large uncertainties due to complicated hydrochemistry (Cook and Herczeg, 2000).

Clark *et al*. (1997) conducted a tracer study of the Floridan aquifer in southeastern Georgia to identify groundwater flow and paleoclimate. The analysis of stable isotopes, radiocarbons, noble gases, and chlorides in groundwater from the upper Floridan aquifer suggested that it contained waters representative of both regional and local groundwater flow systems. The noble gas temperatures were used to differentiate between groundwaters of Holocene and Pleistocene origin and also to constrain mixing processes. The data suggested that this region of Georgia was $4.0 \pm 0.6^{o}C$ cooler during the LGM.

Clark *et al*. (1998) analyzed chemical and isotope tracers (i.e. dissolved noble gases, stable isotopes, radiocarbon, and chlorine) along a flow path in the Dakota Aquifer System, located in south-eastern Colorado and western and central Kansas. The study was done to determine likely recharge sources, groundwater residence times, and the extent of mixing between local and intermediate flow systems. Three water types were distinguished with the water tracers, each having a very different history. The tracer data suggested that the type of groundwater recharged locally during the last few thousand years. The second type of groundwater identified was composed of groundwater that recharged earlier during a cooler climate, presumably during the last glacial period (LGP) and mixed aged groundwater. The paleotemperature record indicated that south-eastern Colorado was about $5\,^{0}C$ cooler during the LGP than during the late Holocene. The third groundwater type showed a residence time on the order of 10^4-10^5 years and its recharge location is near the Colorado and Kansas border down gradient of the other groundwater types.

Clark (2002), in cooperation with the South Florida Water Management District conducted a study to determine groundwater ages and circulation patterns using geochemical tracers. Groundwater samples were collected from the Upper and Lower Floridan aquifers at seven different locations south of Lake Okeechobee. The groundwater samples were analyzed for noble gases, stable isotopes, chlorinity and radiocarbons. The isotope and salinity data indicated that the groundwater in the two aquifers were different, although some evidence did show Lower Floridan aquifer (LFA) groundwater upwelling and mixing with the Upper

Floridan aquifer (UFA). The data suggested that within this system relatively old meteoric freshwater circulates in the UFA over relatively young seawater of the LFA. The data identified the seawater origin as Straits of Florida bottom water and indicated the circulation time to be less than 10,000 years in the LFA. The multiple geochemical tracers depicted the UFA groundwater must have recharged during the last glacial period, when sea levels fell some 400 feet.

CHAPTER 4.0 – METHODOLOGY

4.1 Geophysical Methods

The four Floridan monitor wells were geophysically logged with the temperature probe to assist in identifying movement of groundwater. This type of logging is called fluid logging and includes techniques that measure the characteristics related to the fluid column in a borehole (Keys, 1989). In fluid logging, there is no direct signal derived from the surrounding rocks and their contained fluids (Keys, 1989). This type of logging provides information related to the movement of water and will be used to examine the possibility of cyclic flow in the FAS of the study area.

4.1.1 Temperature Logs

The temperature logs that will be used in this study will record temperature versus depth. As depicted in Figure 5, temperature probes commonly used in groundwater studies are approximately 6 feet in length and utilize a glass bead thermometer mounted in a tube that is open at both ends to protect it from damage and to channel water flow past the sensor (Keys, 1989). A small electrical current is conducted through the glass-bead thermistor to measure the changes in resistance that occurs as a function of temperature (Keys, 1989). The changes in

resistance of the thermistor are converted to a varying pulse rate to eliminate the effect of changes in resistance of the logging cable (Keys,

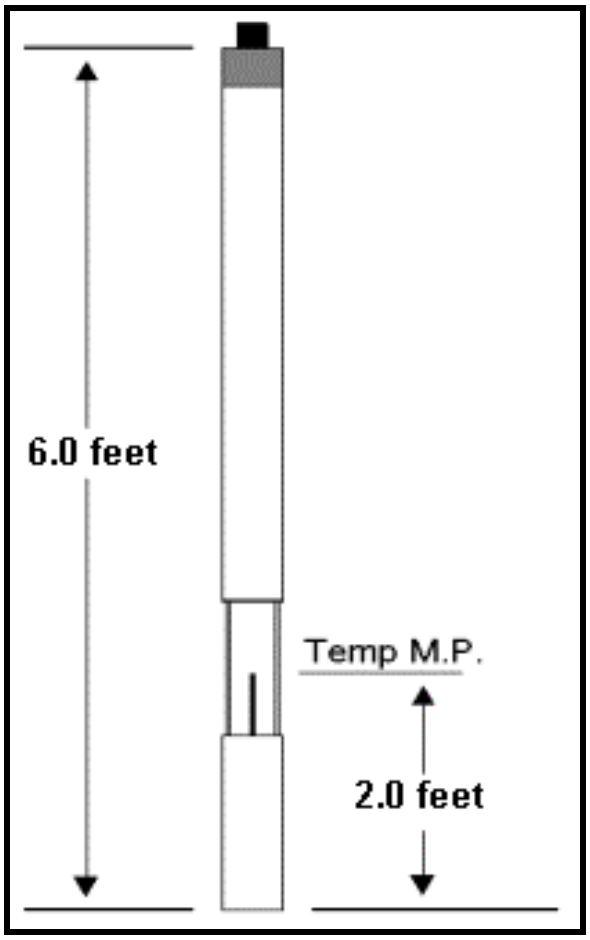

Figure 5. Schematic of a temperature probe employed during down hole fluid logging.

1989). Thermistor-type temperature probes generally used have an accuracy, repeatability, and sensitivity of about 0.02 ^{0}C (Keys, 1989).

One of the major problems encountered in the interpretation of temperature logs is convection, particularly in large diameter boreholes and in areas of substantial thermal gradient (Keys, 1989). Convection is defined as the flow of groundwater around and through heated zones adjacent to plutons in response to thermal gradients (Bates and Jackson, 1984). Convective cells in large diameter boreholes may cause temperature anomalies unrelated to groundwater movement (Keys, 1989). Krige (1939) developed an expression for the critical temperature gradient above which convection occurs (K), as indicated in equation (1):

$$Cvk/g\alpha a^4 + g\alpha T/cp = K \qquad (1)$$

Where:

g = acceleration of gravity; in centimeters per second squared ($cm^2\ sec^{-1}$)

T = absolute temperature (Kelvin)

α = coefficient of thermal expansion of water; in $Kelvin^{-1}$

cp = specific heat at constant pressure; in $Kelvin^{-1}$

v = kinematic viscosity; in $cm^2\ sec^{-1}$

k = thermal conductivity; in $cm^2\ sec^{-1}$

a = radius of the borehole; cm

C = a constant, which is 216 for most boreholes

Because of the effect of convective movement, small diameter boreholes provide more useful temperature logs under most conditions (Keys, 1989).

Temperature data from wells have many applications. In this study, the data will be used to trace the movement of water. The temperature data may also be used to calculate water density, viscosity, thermal conductivity, and to develop heat flow maps (Keys, 1989).

4.2 Geochemical Methods

At four locations in the Naples vicinity throughout southwestern Collier country, Florida, groundwater samples were collected from monitoring wells open to the Upper Floridan, middle confining unit, and Lower Floridan aquifers following the sampling procedures listed in the South Florida Water Management District (SFWMD) Quality Assurance Manual for the Chemistry Laboratory and Field Sampling. All samples were collected using a suction pump after purging the well of approximately five well volumes.

4.2.1 Inorganic Chemistry

The water samples collected from the monitor wells in this study were analyzed by the SFWMD water quality laboratory for major cations and anions using Environmental Protection Agency (EPA) and/or Standard Method Procedures (SFWMD, Quality Assurance Manual for the Chemistry Laboratory and Field Sampling, 2001).

More than 90% of the dissolved solids in groundwater can be attributed to eight ions: sodium (Na^+), calcium (Ca^{2+}), potassium (K^+), magnesium (Mg^{2+}), sulfate (SO_4^{2-}), chlorine (Cl^-), bicarbonate (HCO_3^-), and carbonate (CO_3^{2-}) (Fetter, 2001). A cation-anion balance will be performed on the chemical analysis. This is accomplished by converting all ionic concentrations to units of equivalents per liter (Fetter, 2001). The anions and cations are summed separately, and the results are compared (Fetter, 2001). If the sum of the cations is not within a few percent of the sums of the anions, then there is either a problem with the chemical analysis or one or more ionic species that have not been identified are present in significant amounts (Fetter, 2001).

An alternative method is to calculate the charge balance error (CBE) (Fetter, 2001). The charge balance error can be found from equation (2).

$$\text{CBE\%} = \frac{\sum z \times m_c - \sum z \times m_a}{\sum z \times m_c + \sum z \times m_a} \qquad (2)$$

Where:

z = is the charge on an ion

m_c = is the molality of a cation

m_a = is the molality of an anion

If there is a zero balance error, then $\sum z \times m_c$ would equal $\sum z \times m_a$ (Fetter, 2001). Any charge balance errors identified in the data will be noted in the Results Chapter and not used for this study.

A trilinear diagram, commonly known as a Piper diagram, will be used to show the different chemical composition of groundwater in the different aquifers. For

this study, Frazee's (1982) geochemical pattern analysis will be applied with the Piper diagram. Frazee's method will substantiate the geochemical analysis relating recharge, interface, and intruded waters within the FAS.

The differences in chemical composition are known as hydrochemical facies (Fetter, 2001). Figure 6 depicts the form of the trilinear diagram and how the hydrochemical facies are classified on the basis of the dominant ions in the groundwater (Fetter, 2001). The facies are a function of the lithology, solution kinetics, and flow patterns of the aquifer (Back, 1960, 1966 and Fetter, 2001).

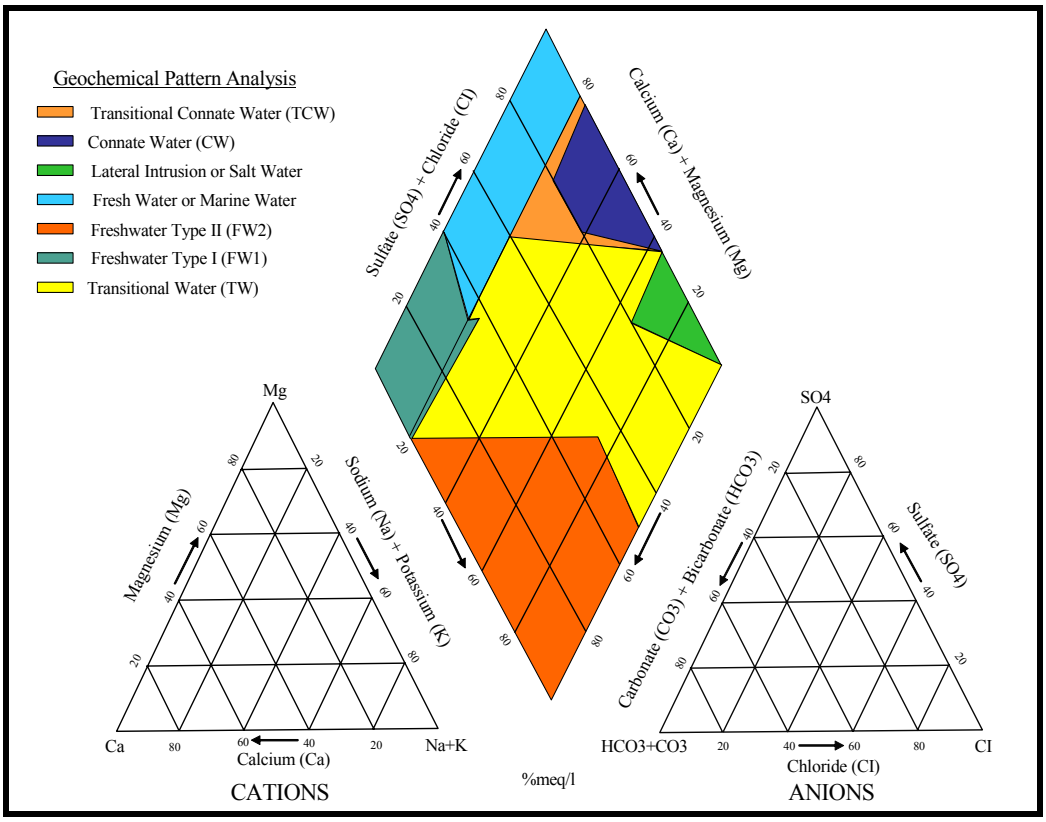

Figure 6. Hydrogeochemical classification system for natural waters using the Piper trilinear diagram applying Frazee's geochemical pattern analysis.

Each apex of a triangle represents a 100% concentration of one of the three constituents (Fetter, 2001). When two constituent groups are present in a sample, the point representing the percentage of each would be plotted on the line between the apexes for those two groups (Fetter, 2001). When all three constituent groups are present, the analysis would fall in the interior of the triangle (Fetter, 2001). The diamond shaped field between the two triangles will be used to represent the composition of groundwater with respect to both cations and anions of the FAS in the study area.

4.2.2 Stable Isotopes

Stable isotope data complements inorganic chemistry and physical hydrogeology in groundwater investigations. In this study, the isotopic data collected from the monitoring wells will be used to better understand groundwater circulation patterns in the FAS (Kohout, 1965 and 1967) and to identify possible recharge and discharge areas.

These groundwater samples were collected in 2 liter plastic containers during packer tests in test wells and from completed monitor intervals in southeastern Collier County. The groundwater samples were sent to the Environmental Isotope Laboratory (EIL) at the University of Waterloo in Ontario, Canada for stable isotope determinations. The analytical services included the determination of the stable isotope compositions for the following parameters: ^{18}O, ^{2}H, and $\delta^{13}C$.

^{18}O values were determined by CO_2 equilibration using standard procedures outlined by Epstein and Mayeda (1953) and Drimmie and Heemskerk (1993).

Hydrogen isotope concentrations were determined using the methods of Coleman *et al.* (1982) and Drimmie *et al.* (1991). The results are presented as per mil ($^{0}/_{00}$) derivations from a water standard using the δ-notation (delta) in equation (3):

$$\delta_x = \delta_{x\text{-std}} = 1000\left(\frac{R_x}{R_{\text{Rstandard}}} - 1\right) \qquad (3)$$

Where:

R_x = the isotope ratio of the sample (i.e., $^{2}H/^{1}H$)

$R_{standard}$ = the isotopic standard.

The standard related to $\delta^{2}H$ and $\delta^{18}O$ is standard Mean Ocean Water (SMOW) (Clark, 2002). The reproducibility for $\delta^{18}O$ and $\delta^{2}H$ were ±0.05 $^{0}/_{00}$ and ±0.5 $^{0}/_{00}$, respectively (Clark, 2002). This investigation will plot $\delta^{2}H$ as a function of $\delta^{18}O$ so that it may compare groundwater in the FAS to the SMOW.

Water samples received by EIL for $\delta^{13}C$ determinations are acidified under vacuum with phosphoric acid. The released CO_2 produced from dissolved inorganic carbon (DIC) in the sample was then purified using cold distillation and analyzed by a mass spectrometry (Drimmie *et al.*, 1990). These results are then compared to a carbon standard. The carbon standard is the isotope ratio derived from CO_2 liberated from beleminites of the Cretacious-aged Pee Dee Formation (PDB) of South Carolina. The results are permitted as per mil ($^{0}/_{00}$) derivations with respect to the standard using the δ-notation (delta) in equation (4):

$$\delta^{13}C\ (^{0}/_{00}, \text{PDB}) = 1000\left(\frac{^{13}C/^{12}C_{sample}}{^{13}C/^{12}C_{\text{Standard}}} - 1\right) \qquad (4)$$

The $\delta^{13}C$ of dissolved inorganic carbon in the ocean is approximately $0^{0}/_{00}$ PDB (Fetter, 2001). In the study area, the FAS is composed of carbonate rocks that

were precipitated by the ocean. The $\delta^{13}C$ of the FAS groundwater will be compared to the $\delta^{13}C$ from the ocean.

4.2.3 Radiocarbons

In this study, radiocarbon data collected from the monitoring wells will be used to determine an age of the groundwater and complement the isotope data in better understanding groundwater circulation patterns of the FAS in the study area. The groundwater samples were collected in 250 milliliter glass bottles during packer tests in test wells and from completed monitor intervals in southeastern Collier County. The radiocarbon ages were correct by Ron Kaufmann and GW Holmes and Associates (2005).

Estimates of groundwater age depend in part on knowing the initial activity of ^{14}C (A_o), no small constraint if atmospheric carbon activity at time of recharged differed from the present, or if the carbon of the water mixed with other sources of carbon (Wigley, 1975; and Kaufmann and Bennett, 2004). The estimates of ^{14}C age for this investigation consider only effects in mixing in as much as atmospheric variations of ^{14}C are beyond the scope of the study. But they have been analyzed, and corrections can be applied.

An accelerator mass spectrometer (AMS) at the Rafter Radiocarbon Laboratory (Institute of Geological and Nuclear Sciences, New Zealand) was used to determine radiocarbon age, Del ^{14}C, and percent of modern carbon (pmC). The ^{14}C activities or pmC values are absolute percent of modern carbon, relative to the National Bureau of Standards (NBS) oxalic acid standard (HOxl) corrected for

decay since 1950. The activity of "modern carbon" is 95% of the ^{14}C in the 1950 NBS oxalic acid standard, which is close to the activity of 1890 wood produced in a fossil-fuel free environment (Clark and Fritz, 1997). Del ^{14}C is the relative difference between the absolute standard activity and the sample activity, as indicated in equation (5):

$$\text{Del } ^{14}C = 1000(A_s/A_{abs} - 1) \quad (5)$$

Where:

A_s = activity of the sample

A_{abs} = activity of the standard

The modern activity of ^{14}C is set as 13.56 decays-per-minute per gram of carbon. The "zero year" for this activity is 1950 AD (pre thermonuclear testing) with an activity of 100 pmC. The conventional radiocarbon age (^{14}C Age) is determined in the following manner in equation (6):

$$T = -8033 \ln (A_{sn}/A_{on}) \quad (6)$$

Where:

A_{sn} = normalized sample activity

A_{on} = normalized oxalic acid activity(count rate)

T = calculated time that elapsed represented by the difference in activities between the standard and sample.

Time (T) however is not the actual date of recharge because ^{14}C is either removed or added as the water moves through the system. In order to calculate time since recharge, equation 4 is modified in equation (7):

$$T = -8267 \ln (A_t/A_o) \quad (7)$$

Where:

T = the time since recharge,

A_t = the current ^{14}C activity of the sample

A_o = the initial ^{14}C activity.

Calculating time since recharge requires the current ^{14}C activity of the sample, which is measured, and the initial activity (A_o), which must be estimated.

The three methods which will be used for correcting ^{14}C ages of the groundwater in the study area are Tamers (1967), Mook (1976), and Fontes and Garnier (1979). The method that best complements the isotope data will be used in the results section of this paper.

Tamers method accounts for mixing of recent atmospheric carbon, which enters the aquifer with the recharge water, and dead carbon dissolved from aquifer material (Kaufmann and Bennett, 2004). Tamers method considers the chemical balance of carbon (disregarding CO_2) in calculating initial ^{14}C activity (A_o) with equation (8):

$$A_o = A_T = [(a + 0.5b)\, A_g + 0.5bA_c]/(a + b) \quad (8)$$

Where:

A = represents ^{14}C activity,

g = stands for soil gas,

c = stands for solid carbonate,

a = stands for H_2CO_3

b = stands for HCO^-_3

T = stands for total dissolved inorganic carbon

Tamers method may overcorrect A_o for exchange between total dissolved inorganic carbon and the gas phase, and under correct for exchange with the solid phase (Fontes and Garnier, 1979 and Kaufmann and Bennett, 2004).

Mook (1980) quantified a mass balance-isotope approach based with a combined calculation that modifies the Tamer method as indicated in equation (9):

$$A_o = A_o(\text{Tamers}) + k \qquad (9)$$

With (k) given by equation (10):

$$k(\text{Mook}) \sim 0.5(A_g - A_c)\,[\delta_T(a+b)-(a+0.5b\delta_c]/[0.5(\delta_g - \delta_c) - \epsilon_{gb}](a+b) \qquad (10)$$

Where:

$\delta =$ represents $\delta^{13}C$ stable isotope ratio

Where ϵ_{Ij} is the stable isotope enrichment factor between species i and j ($\epsilon_{Ij} \sim \delta_i - \delta_j \sim - \epsilon_{Ij}$) (Kaufmann and Bennett, 2004). Temperature dependencies in Kelvin are given by Mook *et al.* (1974) as $\epsilon_{ag} = -0.373 \times 10^3/T + 23.89$; $\epsilon_{cb} = -4.232 \times 10^3/T + 15.10$ (calcite). This equation is most effective where carbonates are not dominant in the system (Kaufmann and Bennett, 2004).

Fontes and Garnier (1979) developed a correction model that considers soil processes, carbonate dissolution, and carbon exchange. They proposed a modification of Mook's method, as shown in equation (11):

$$k(\text{Fontes \& Garnier}) \sim (Ag - Ac)\,[\delta_T(a+b)-(a+0.5b)\,\delta_g - 0.5b\delta_c]/[(\delta_g - \epsilon_{gb} - \delta c)](a+b) \qquad (11)$$

Fontes and Garnier describe a complete exchange of a fraction of total dissolved inorganic carbon with either the gas or solid phase (Kaufmann and Bennett, 2004). When change occurs with the solid phase, equation (11) may be used with

the substitution of ϵ_{gb} with ϵ_{cb} = +0.9‰ (Rubinson and Clayton, 1969; Kaufmann and Bennett, 2004)

4.2.4 Noble Gases

Noble gas samples were collected at two locations in each well, from the upper and lower portions of the FAS. These samples were collected in approximately 15 ml copper tubes connected to a peristaltic pump and regulator, which reduced aeration of the groundwater sample. Once the copper tubing was flushed with formation water at high pressure, it was sealed at each end with steel pinch-off clamps. The groundwater samples were sent to the Lamont-Doherty Observatory of Columbia University and noble gas concentrations including He, Ne, Ar, Kr, Xe were determined on a MAP 215-50 noble gas mass spectrometer using the method outlined by Stute *et al*. (1995). The system was calibrated using known quantities of air and water standards. Absolute noble gas concentrations were determined with a precision of +/- 1% for Ar and Xe and +/- 2% for He, Ne and Kr.

As water recharges and flows down gradient within the aquifer, there is no longer exchange with other fluid phases and the heavier noble gas concentrations remain unchanged, making them suitable for paleoclimate studies. Helium concentrations in groundwater however change due to radioactive decay of uranium/thorium nuclides within the aquifer (Bottemley *et al*., 1984; Torgersen and Ivey, 1985, and Bennett, 2004). Helium concentrations increase with time and vary between aquifers making it a useful tool as an approximate chronometer

(Clark, 2002). Noble gas temperatures were calculated from concentration data using the inversion method of Aeschbach-Hertig *et al.* (1999).

CHAPTER 5.0 – RESULTS AND DISCUSSION OF THE GEOPHYSICAL AND GEOCHEMICAL ANALYSES

5.1 Geophysical

Temperature logs were analyzed in the monitor wells of this investigation to see if Kohout's (1965 and 1967) theory of "cyclic flow" could be identified in the study area. Kohout studied temperature surveys in oil and oil exploratory wells and suggested that a geothermal heat flow may induce a cyclic flow of seawater in the FAS.

Kohout (1965 and 1967) suggested that cold, dense seawater flows inland through the cavernous dolomite in the deep part of the LFA, where it becomes progressively heated by geothermal heat flow. The reduction in density produces an upward convective circulation which brings seawater into contact with freshwater. Meyer (1989) identified a reverse geothermal gradient with the coldest groundwater occurring at the bottom of the Alligator Alley Test Well in Broward County, Florida. He supported Kohout with evidence that colder seawater from the Atlantic Ocean flows inland (west) into the Oldsmar Formation (Eocene age) of southern Florida.

5.1.1 Temperature Logs Analysis

The temperature logs analyzed from the monitor wells within the study area did not support the evidence given by Kohout (1965 and 1967) or Meyers (1989) of a reverse geothermal gradient with increasing depth or cyclic flow within the study area (Figure 7). This study identified two out of the four monitor wells (NCRWRF and MIU) in the area with a noticeable increase in geothermal gradient as the depth increases in the FAS. The I75-TW did not identify any change in geothermal gradient and there was too much noise and/or interference in the temperature survey run on the SCRWRF-MW.

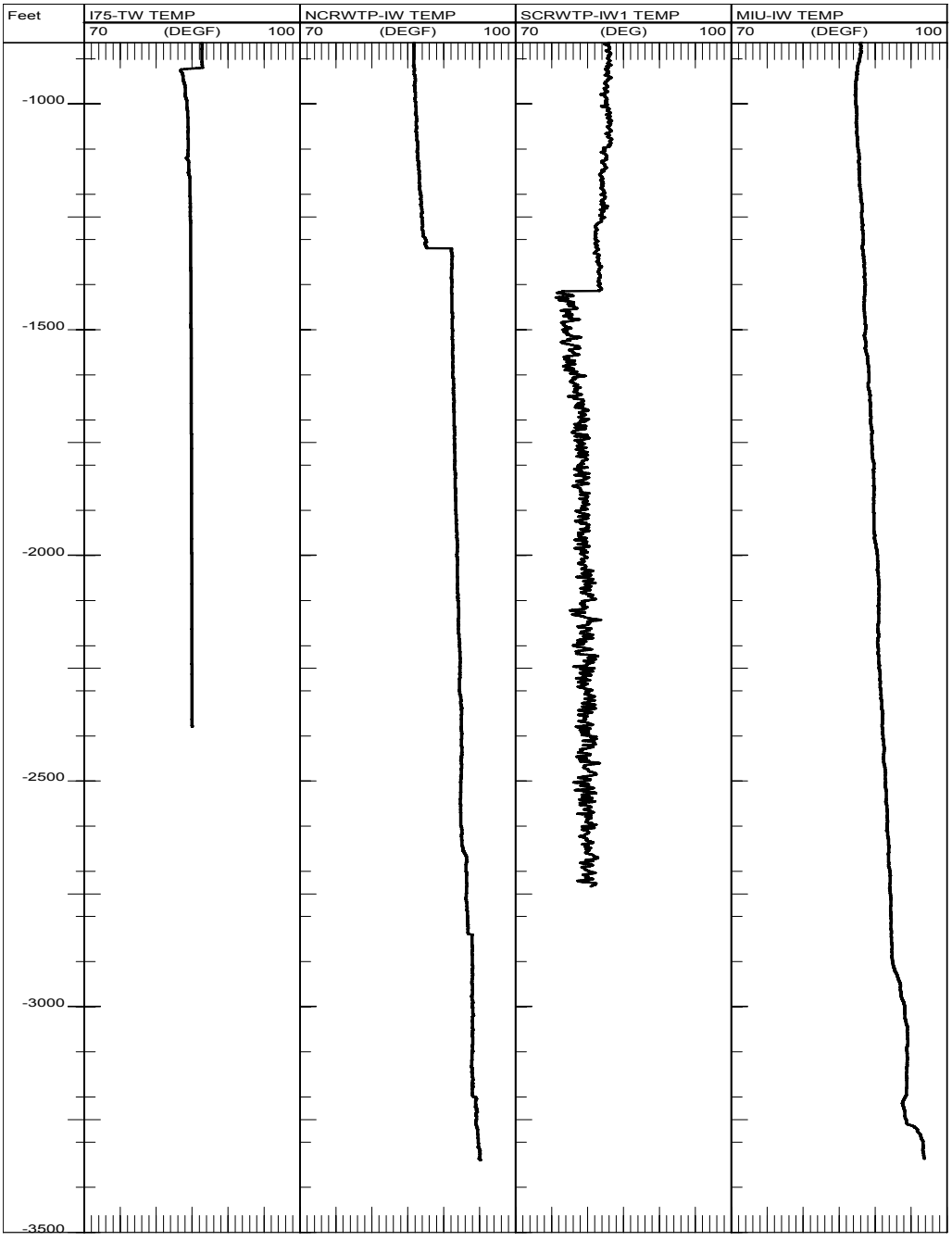

Figure 7. Graph showing temperature-depth profiles of monitor wells in the Floridan aquifer system analyzed within the study area.

It could be that there is no reverse geothermal gradient in the study area or there may be a few reasons, perhaps why the temperature logs may not have supported the evidence of cyclic flow or identified a reverse geothermal gradient with depth in the monitor wells. First, the hydrogeologic conditions within the study area may be different than the areas investigated by Kohout (1965 and 1967) and Meyer (1989). Meyer (1989) did an investigation that supported Kohout's theory on a Floridan test well located off I75 (Alligator Alley) near the center of the state approximately 40 miles west of the area of investigation. The test well Meyer (1989) employed has a total depth 2,811 feet. The monitor wells for this investigation may not have been drilled deep enough to identify the change in geothermal gradient. A second possibility could be borehole conditions (i.e. borehole development, logged under static or pumping conditions, or convection) while logging. Foreign waters (i.e. surface water bodies near the drill site) may have been used while drilling the well and if not developed out properly could cause the temperature log to not show evidence of a reverse geothermal gradient. The best way to run a temperature log is under static conditions (i.e. well is shut in and not allowed to flow) when trying to identify a geothermal gradient. However, if the well was pumped or allowed to flow by artesian pressure while logging this could cause a mixing of groundwater throughout the borehole. This is because there may be one or two highly productive zones in the borehole that when stressed by pumping or allowed to flow by artesian means may produce the majority of groundwater. The third possibility may have been problems with the tool itself recording temperature (i.e. calibration of the tool).

The four wells logged within the study area were not able to identify a reverse geothermal gradient. Considering all possibilities, the wells may need to be drilled much deeper to support Kohout's (1965) hypothesis to identify the reverse geothermal gradient within the area of investigation.

5.2 Geochemical

In this section, a multi-parameter approach using inorganics, stable isotopes, radiocarbons and dissolved noble gases will be discussed in detail. Multi-parameter analyses have been very successful when interpreting flow systems in complicated hydrological systems with flow times of thousands of years (Clark *et al.*, 1997, 1998; and Clark, 2002). This approach is often needed because, for each parameter, multiple factors can result in similar changes (Clark, 2002). According to Clark's (2002) regional investigation of the FAS in southern Florida, interpretations of ^{14}C ages and stable isotopes in groundwater can often be ambiguous. This is because decreases in ^{14}C concentrations can occur as a result of both water-rock interactions and radioactive decay; and the composition of stable isotopes vary as a function of a number of factors including continentality, elevation, temperature, and long-term climate. With the multi-parameter approach, erroneous interpretations are minimized because of the complimentary nature of the isotopic systems.

5.2.1 Inorganic Chemistry Analysis

The groundwater samples for packer tests and completed monitor zones were analyzed by the SFWMD water quality laboratory for major cations (Na^+, K^+, Ca^{2+} and Mg^{2+}) and anions (Cl^-, HCO_3^-, and SO_4^{2-}). Table 1, contains the major cation and anion data from the groundwater samples (refer to Appendix 1 for well construction information). Ionic balance ratios were calculated from each groundwater sample to determine the accuracy of the data. The percentages of error calculated from the ionic balance of each groundwater sample were below 10% making the results acceptable for this study (McGinnes, 2005).

Table 1. Summary of major cation and anion results

		Cations (mg/L)				Anions (mg/L)			Ionic Balance %	
Well Name	Aquifer	Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	HCO_3^-	SO_4^{2-}	Error	TDS (mg/L)
I75 MZ-1	UFA	902	37	157	152	1,529	212	486	3.8	3,410
I75 MZ-2	UFA	1,820	65	246	263	3,558	194	630	-0.6	6,750
SCRWRF-MZU	UFA	1,573	56	206	214	2,858	191	686	0.1	5,894
NCRWRF-MZ1	UFA	1,161	50	191	164	2,206	214	700	-3.1	4,690
MIU-MZ1	UFA	8,412	392	461	906	14,602	158	2,034	1.8	26,900
I75 PT-4	MCU	6,050	200	400	638	10,151	201	1,336	3.6	17,600
MIU-MZ2	MCU	10,534	514	571	1,061	18,022	133	2,475	2.2	33,200
I75 PT-3	MCU	11,460	432	620	1,368	19,037	134	2,259	5.4	35,100
NCRWRF-MZ2	MCU	10,218	528	1,013	1,403	19,084	165	2,740	2.2	33,000
SCRWRF-MZL	MCU	11,618	356	767	1,194	18,280	181	2,800	6.1	31,880
I75 PT-2	MCU	11,260	418	600	1,334	19,281	131	2,136	4.1	34,900
I75 PT-1	LFA	11,520	428	620	1,354	19,262	131	2,511	4.6	34,600
I75 MZ-3	LFA	11,200	407	533	1,235	19,398	129	2,531	2.0	35,700

mg/L - milligrams per liter
% - percent
MZ - Monitor Zone
PT - Packer Test
UFA - upper Floridan Aquifer
MCU - middle confining unit
LFA - lower Floridan aquifer

In the study area of Naples, Florida, the data in Table 1 indicates that sodium and chloride are the dominant ions and that the concentrations of these ions and total dissolved solids (TDS) increase with depth. The data suggests that groundwater

below a depth of 1,400 feet bls is similar in concentration to seawater, with the exception of MIU-MW. The monitor well, MIU-MZ1, is located on Marco Island (refer to Figure 1) and monitors the UFA between 1,000 – 1,089 feet bls also shows concentrations similar to seawater. This may suggest that the UFA outcrops in the Gulf of Mexico near the monitor well's location or the possibility of a vertical fractures within the FAS where the monitor well is drilled causing seawater to be the dominant source of groundwater for MIU-MZ1.

The data from the inorganic analysis and Frazee's (1985) geochemical pattern analysis (Figure 8) indicates that sodium and chloride are the dominant ions and suggests that seawater is the dominant recharge source of groundwater for the FAS within the study area. The inorganic data also shows the possibility of the lower Floridan groundwater upwelling and mixing with the upper Floridan groundwater.

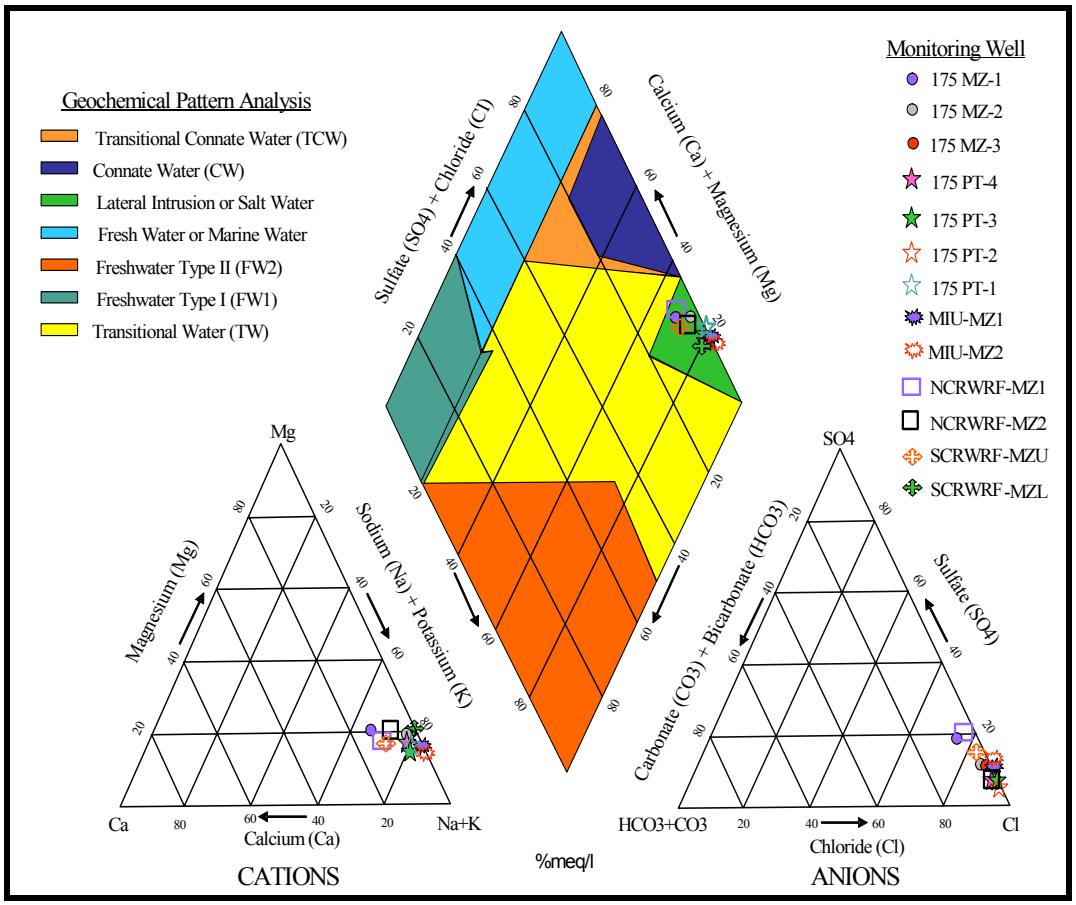

Figure 8. Piper trilinear diagram of inorganic constituents applying Frazee's (1985) geochemical pattern analysis of the Floridan aquifer system in Naples, Florida.

The analysis for this study supports previous investigations by Meyer (1971), Hanshaw and Back (1979), Sprinkle (1989), Reese (1994 and 1998), Clark (2002), and Bennett (2001 and 2004). Inorganics were insufficient to identify possible recharge sources or circulation patterns of the FAS. Stable isotope and noble gas data were also employed in this investigation to provide additional information on possible recharge sources as discussed in the next section of this chapter.

5.2.2 Stable Isotopes and Radiocarbons Analysis

Stable isotope data (^{18}O and ^{2}H) complements inorganic chemistry and physical hydrogeology investigations (Bennett, 2004). Isotopic data were used to better understand the groundwater circulation patterns of the FAS (Kohout, 1965, 1967) and to identify recharge and discharge areas. Table 2 contains the stable isotope data and ^{14}C values of the groundwater samples.

Table 2. A summary of the stable isotope and radiocarbon results for the study.

Well Name	Aquifer	Sample Date	^{18}O ‰ SMOW	^{2}H ‰ SMOW	$\delta^{13}C$ ‰ PDB[c]	^{14}C ‰	^{14}C (pmc)	Uncorrected ^{14}C (year BP)
I75 MZ-1	UFA	Apr-95	-1.05	-6.51	-3.97	-993.30	0.67	40,130
I75 MZ-2	UFA	Apr-95	-1.05	-6.45	-2.64	ND	ND	ND
SCRWRF-MZU	UFA	Jun-99	-1.19	-5.53	-3.05	-998.20	0.17	>46,300
NCRWRF MZ-1	UFA	Feb-96	-1.14	-1.53	-3.70	-991.40	0.82	38,520
MIU-MZ1	UFA	Feb-96	-0.08	-5.17	-3.00	-984.10	1.53	33,530
I75 PT-4	MCU	Dec-94	0.57	2.61	-1.87	ND	ND	ND
MIU-MZ2	MCU	Feb-96	-0.35	0.28	-3.80	-979.20	1.99	31,420
I75 PT-3	MCU	Dec-94	0.67	2.97	-1.42	ND	ND	ND
NCRWRF MZ-2	MCU	Jun-96	0.40	9.00	-1.77	-988.50	1.09	36,220
SCRWRF-MZL	MCU	Jun-99	0.55	5.33	-1.18	-1000.00	0.00	>50,000
I75 PT-2	MCU	Dec-94	0.54	4.28	-1.59	ND	ND	ND
I75 PT-1	LFA	Dec-94	0.60	2.46	-1.35	ND	ND	ND
I75 MZ-3	LFA	Apr-95	0.65	1.16	-1.78	-809.30	19.70	13,429

‰ - per mil
SMOW - Standard Mean Ocean Water Standard
δ - delta
PDB - Pee Dee Belemnitella Standard
pmC - percent modern Carbon
Years B.P. - Years Before Present (1950)
ND - not determined
MZ - Monitor Zone
PT - Packer Test
UFA - upper Floridan aquifer
MCU - middle confining unit
LFA - lower Floridan aquifer

Precipitation or meteoric water contains very little dissolved constituents and the oxygen and hydrogen isotope composition of world-wide rainfall fall along a documented line called the Global Meteoric Water Line (GMWL, Craig, 1961). Plots of $\delta^{2}H$ and $\delta^{18}O$ (Figure 9) indicate two different types of water within the FAS; consistent with findings in previous studies (Meyer, 1989; Swancar and Hutchinson, 1992, and Bennett, 2001 and 2004). The UFA values are isotopically lighter than ocean water. These values, shown in Figure 9, parallel the Global Meteoric Water Line (GMWL), which suggest the source of the water is precipitation from recharge areas in central Florida. The UFA values, although more enriched in $\delta^{18}O$, plot close to the GMWL which is similar to the mean isotopic

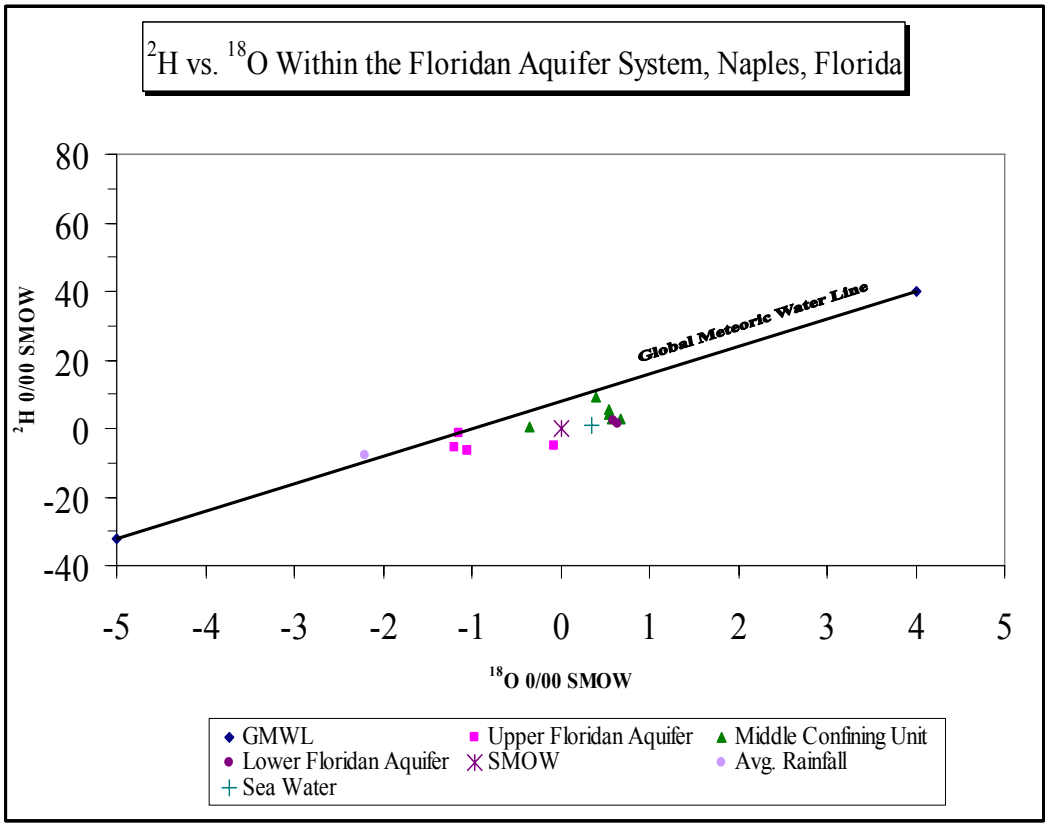

Figure 9. Relationship between Stable Isotopes Deuterium (^{2}H) and Oxygen-18 (^{18}O).

composition of recent Everglades rainfall, which is $\delta^{18}O$ = -2.2 ‰ and $\delta^{2}H$ = -7.6 ‰ (Meyers *et al.*, 1993). The enriched $\delta^{18}O$ values of the UFA may indicate that climatic conditions and/or meteoric water that recharged the UFA were slightly different than present day conditions. In addition, evaporation may have been minimal before meteoric recharge, which caused the UFA waters to plot near the GMWL.

The stable isotopic results from the study area show that the MCU and LFA waters are slightly enriched in both $\delta^{2}H$ and $\delta^{18}O$, as compared to the SMOW (Figure 8). The inorganic water quality results (Table 1) from the majority of wells monitoring the MCU and LFA are brackish to saline in composition. The stable isotope data from the LFA samples are similar to seawater samples collected in the Straits of Florida (off the coast of Ft. Pierce – 27° 00' 26.7"N, 79 °26' 47.3"W) at depths greater than 1,700 feet below mean sea level (Clark, 2002). These isotopically heavier values may suggest that the source of the LFA, which plots close to 0.0 $^{0}/_{00,}$ is ocean water migrating in from the Gulf of Mexico and/or Straits of Florida. In addition, the $\delta^{18}O$ data from MCU and LFA are different from glacial ocean water where the isotopic composition was significantly different than SMOW, $\delta^{18}O$ was 1 $^{0}/_{00}$ heavier than present (Schrag *et al.*, 1996 and Mashisotta *et al.*, 1999), suggesting that water may have entered the MCU and LFA after the last glacial period (less than 10,000 years before present).

However, there is one discrepancy to the data at the dual zone monitor well located on Marco Island (MIU-MZ1 and MZ2). The stable isotopic results in the

UFA (1,000 – 1,089 feet bls.) and the MCU (1,490 – 1,600 feet bls.) monitoring zones are slightly depleted in both δ^2H and $\delta^{18}O$, as compared to the SMOW. The inorganic water quality results (Table 1) are saline in composition which suggests that both the UFA and MCU at this location have been intruded by seawater. There are several reasons that there is such a difference in the stable isotope and water quality data on Marco Island from the other monitor wells located in the vicinity of Naples, Florida. The first cause may have been a laboratory error (EIL, University of Waterloo in Ontario, Canada) during the analysis of both intervals for δ^2H and $\delta^{18}O$. A second reason could be that the water quality data collected during the construction of the monitor well is not accurate. The drilling contractor will at times use heavy brines (i.e. salt) mixed with water from a different source (i.e. nearby water body) to suppress the artesian flow in the borehole during drilling operations. After the monitor well was completed the drilling contractor may not have properly developed the well which may have left some of the brines and non-native water in the well causing the skewed groundwater quality results. Another cause may be in part due to the location of the monitor well. There could be the possibility that the UFA outcrops near the floor of the Gulf of Mexico or there could be vertical fractures present allowing seawater from below to enter the UFA.

This is the only monitor well in the study that is located on a barrier island approximately 10 miles off the coast of Naples in the Gulf of Mexico. The inorganic water quality results in other Floridan aquifer monitor wells off the coast of Florida; for example, Key West (CH2M HILL, 2000), also shows

intrusion of seawater into the UFA and are also slightly depleted in both ^{2}H and ^{18}O, as compared to the SMOW. The anomalous results for both ^{2}H and ^{18}O at the Marco Island Utilities dual-zone monitor well will be noted but not used in this study, because of the reasons mentioned above.

The data suggests the UFA, although brackish, appears to have a meteoric origin. The source of this brackish composition may be due to upward migration of groundwater from the underlying units of the MCU and LFA. The MCU and LFA do not have a meteoric origin and are saline and close in composition to seawater. This suggests that both zones are recharged from the sea. These results support previous investigations by Meyer (1971, 1974, 1988, and 1989), Clark and Fritz (1997), and Bennett (2001 and 2004).

The ^{14}C activities or pmC (Table 3) listed in this study are absolute percent of modern carbon relative to the National Bureau of Standards oxalic acid (HOxl) standard corrected for decay since 1950. These apparent (uncorrected) radiocarbon ages were corrected using three methods (Tamer's, 1967; Mook, 1976; and Fontes and Garnier, 1979) as depicted on Table 3.

Table 3. Corrected ^{14}C results for the Floridan aquifer monitor wells in the study area.

Well Name	Monitoring Interval (feet bls.)	Aquifer	Uncorrected ^{14}C (years BP)	Tamers (1967) (Years BP)	Mook (1976) (years BP)	Fontes and Garnier (1979) (years BP)
I75 MZ-1	690-760	UFA	40,130	37,836	43,333	9,878
SCRWRF-MZU	850-910	UFA	>46,300	50,195	56,235	40,956
NCRWRF-MZ1	910-1,146	UFA	38,520	36,423	42,118	29,210
MIU-MZ1	1,000-1,089	UFA	33,530	31,679	37,712	22,628
MIU-MZ2	1,490-1,600	MCU	31,420	29,694	35,661	22,140
NCRWRF-MZ2	1,815-1,930	MCU	36,220	34,085	40,459	21,880
SCRWRF-MZL	1,820-1,950	MCU	>50,000	67,091	73,462	52,513
I75 MZ-3	2,300-2,350	LFA	13,429	10,275	16,617	-1,987
years BP - years Before Present					UFA - upper Floridan aquifer	
feet bls. - feet below land surface					MCU - middle confining unit	
MZ - monitoring zone					LFA - lower Floridan aquifer	

The apparent (uncorrected) ^{14}C data show very distinct differences in age within the FAS of the study area (Table 3). From the data in this study, the average age of the groundwater in the UFA is about 39,000 years BP, about 25,000 years older than the LFA groundwater. Generally in groundwater systems, water moves downward and becomes older; this investigation depicts the reverse circumstance. Our results support previous studies (Meyer, 1989; Bennett, 2001 and 2004; and Kaufmann and Bennett, 2004). Kohout's hypothesis of cyclic flow also implies that groundwater in the UFA would be older than the LFA.

Spatial distribution of ^{14}C data could also be used to support the hypothesis in the study area (Clark, 2002; and Kaufmann and Bennett, 2004). However, this investigation covered a small area, within the vicinity of Naples, Florida which would make it difficult to identify the spatial distribution of ^{14}C. However, there have been larger regional investigations completed which have identified the possibility of cyclic flow within the area of investigation (Clark, 2002; and

Kaufmann and Bennett, 2004). The radiocarbon data from these regional investigations, specifically Kaufmann and Bennett (2004), suggest, within the study area, that ocean water from the Gulf of Mexico moves east (inland) into the LFA, migrates into the UFA and moves west (back out) to the Gulf of Mexico.

This study also plotted δ^2H against uncorrected ^{14}C ages and the outcome supported the radiocarbon data. The shallow water of the UFA and MCU was older than the deeper water of the LFA. In most aquifers the age of the groundwater increases with depth, the reverse circumstance is noticed in this investigation. Figure 10 depicts this relationship between δ^2H and uncorrected ^{14}C data from the FAS in the study area.

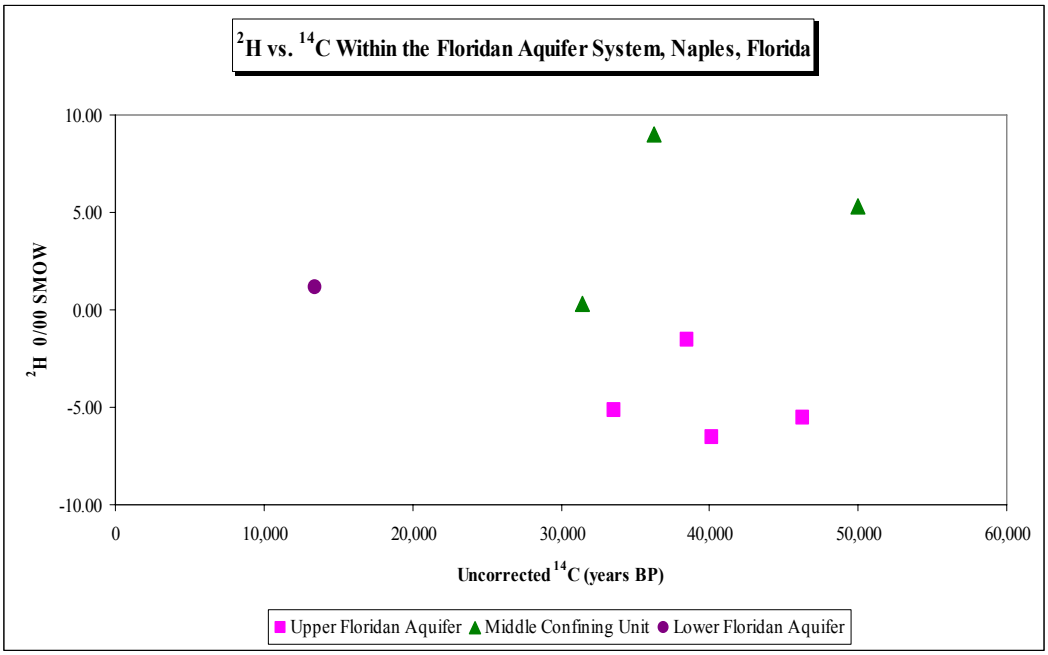

Figure 10. Relationship between Deuterium (^{2}H) and Uncorrected Carbon-14 (^{14}C) ages.

Water rock interactions within the FAS make it difficult to interpret ^{14}C data. An attempt was made to also correct the ^{14}C ages by applying three different methods (Tamers, 1967; Mook, 1976; and Fontes and Garnier, 1979). The results are shown on Table 3. From the three correction methods used in this study, Fontes and Garnier (F & G) (*Equation 11*), which accounts for carbonate dissolution and CO_2 gas in the soil (open system), appears to be the most accurate which is supported by previous studies from Plummer and Sprinkle, 2001 and work from Kaufmann and Bennett, 2004.

F&G estimates used in this study and presented in Table 3 indicate that the ages are similar within each monitor well, but differ among wells. The differences identified are as follows:

- Monitor well I75 has relatively young water (F&G of 9,878 years BP in the upper zone and -1,987[1] in the lower zone).
- Monitor well SCRWRF has relatively old water (F&G of 40,956 years BP in the upper zone and 52,513 years BP in the lower zone).
- Ages of NCRWRF and MIU are intermediate (F&G of 29,210 years BP in the upper zone and 21,880 years BP in the lower zone of monitor well NCRWRF, and 22,628 years BP in the upper zone and 22,140 years BP in the lower zone of Well MIU).

The future value of I75-TW in the lower zone, as well as the inconsistent trends between zones (i.e. I75-TW, NCRWRF-MW and MIU-MW decrease in age with

[1] A negative date indicates a date in the future.

increasing depth, SCRWRF increases in age with increasing depth) may indicate one or more of several issues according to Kaufmann (2005):

1. Suitability of F&G for these wells
2. Exchange of water within the bore hole
3. Exchange of water between zones outside of the bore hole

^{14}C activity is liable to change through chemical processes as well as radioactive decay (Kaufmann, 2005). The half-life of ^{14}C is constant with respect to time, but the chemical processes (including rock/water interactions, concentrations and dilution of ^{14}C, precipitation, as well as advective mixing, dispersion and diffusion) that occur along the flow path of groundwater are not constant with respect to space (Kaufmann, 2005). As a result, the corrected *absolute* age (i.e. the age estimate that takes gains and losses of ^{14}C into account) of groundwater is not always proportional to the *relative* age as estimated from ^{14}C activity without any correction (Kaufmann, 2005). Calculation of groundwater velocity from ^{14}C activity requires evaluation beyond ^{14}C activity distribution (Kaufmann, 2005). Estimated ages presented in Table 3 using the F&G method do agree with other regional data collected by the SFWMD for the Floridan aquifer in Collier County (Kaufmann, 2005). Thus, most of the results probably reflect real values for the ages of the groundwater (Kaufmann, 2005). Only the deep sample from I75-TW appears to be in error (Kaufmann, 2005). ^{14}C data is difficult to interpret in this system because of water rock interactions.

The stable isotopes and radiocarbon data do show the possibility of Kohout's theory of cyclic flow within the study area. However, there is a possibility that

ancient recharge may have occurred because the UFA is fresher and much older than the MCU and the LFA. During the Last Glacial Maximum, 10,000 to 20,000 years ago, sea level dropped approximately 430 feet from current levels. This time frame coincides with the older ages of the UFA (Meyer, 1989; and Balsillie and Donoghue, 2004).

5.2.3 Noble Gases Analysis

Important to the multi-tracer approach is the analysis of dissolved noble gases (He, Ne, Ar, Kr, and Xe). Noble gas paleo-thermometry has become an accepted method for determining continental temperatures of past climates archived in groundwater systems (Stute *et al.*, 1992, 1995; Clark *et al.*, 1997, 1998; and Clark, 2002). This method was utilized to determine the paleo-temperatures of water entering the Floridan aquifer within the study area, thus providing constraints to the determined radiocarbon ages (Stute *et al.*, 1995; Clark *et al.*, 1997; Clark, 2002; and Bennett, 2004).

Noble gas samples were collected from the UFA, MCU, and LFA from two of the monitor wells within the study area (Table 4). On average, the LFA water has higher salinities, higher ^{14}C concentrations, lower helium concentrations, lighter $\delta^{18}O$ values, and lower noble gas temperatures than those of the UFA (Clark, 2002).

Table 4. Summary of noble gas results and calculated paleo-temperatures.

Well Name	Monitoring Interval (ft. bls)	Aquifer	He (cc stp/g)	Ne (cc stp/g)	Ar (cc stp/g)	Kr (cc stp/g)	Xe (cc stp/g)	Temp. (^{0}C)
I75-MZ1	690-760	UFA	2.47E-07	2.13E-07	3.35E-04	7.32E-08	9.84E-09	19.00
MIU-MZ1	1,000-1,089	UFA	1.37E-07	1.66E-07	3.12E-04	7.32E-08	1.06E-08	18.20
MIU-MZ2	1,490-1,600	MCU	1.68E-07	1.79E-07	3.16E-04	7.24E-08	1.03E-08	9.10
I75-MZ3	2,300-2,350	LFA	7.16E-08	1.81E-07	3.21E-04	7.54E-08	1.08E-08	7.70

ft. bls – feet below land surface
cc stp/g - cubic centimeters of dissolved gas at Standard Temperature and Pressure per gram of water
^{0}C - degrees Celsius
UFA - upper Floridan aquifer
MCU - middle confining unit
LFA - lower Floridan aquifer

The noble gas paleo-temperature in the UFA samples averaged 18.6° C, 5° C cooler than the present day mean annual air temperature in South Florida (23.6° C), and about 10° C warmer than the LFA samples. These cooler noble gas temperatures suggest that the freshwater recharged the UFA during the cooler glacial period 15,000 to 25,000 years ago (Clark, 2002).

The relatively high helium concentrations (>13 x 10^{-8} cc STP/gr; cubic centimeters of dissolved gas at Standard Temperature and Pressure per gram of water) and low $\delta^{14}C$ (Table 2**)** concentrations in the UFA support the interpretation based on the noble gas data that the UFA groundwater recharged during the glacial period (Clark, 2002). It is important to note that in the Floridan aquifer from southern Georgia, Clark *et al.* (1997) showed that glacial aged groundwater had helium concentrations greater than 10 x 10^{-8} cc STP/gr (Clark, 2002). The calculation of absolute ages with the helium data requires detailed measurements of U and Th concentrations in the aquifer material. Unfortunately, few measurements exist and it is likely that most of the U is contained in relatively thin apatite-rich layers (Clark, 2002). A detailed analysis of the core

material collected from the FAS is needed before He ages can be calculated (Clark, 2002).

Clark (2002), recognized samples analyzed for stable isotope composition and noble gas temperature (Tables 2 and 4) of the groundwaters in the MCU and LFA in southern Florida were similar to seawater (9.36ºC) collected from depths greater than 1,800 feet in the Straits of Florida. This indicates that post glacial seawater entered the LFA near the bottom of the Straits of Florida and/or Gulf of Mexico as suggested by Kohout (1965). Because the isotope composition of the glacial ocean water (15,000 to 25,000 years ago) was significantly different ($\delta^{18}O_{glacial} - \delta^{18}O_{Holocene} > 1‰$; Schrag *et al.* 1996; Mashisotta *et al.*, 1999), the seawater must have entered the aquifer after sea level rose to near present day levels subsequent to the last glacial period (Clark, 2002). Hence, the groundwater ages of the seawater circulating through the LFA aquifer must be less than 10,000 years (Clark, 2002). This inference is supported by the relatively low helium concentrations and high $\delta^{14}C$ concentrations found in most LFA samples, both of which suggest short circulation times (Clark, 2002). Absolute ^{14}C ages are difficult to calculate because water rock interactions are difficult to quantify in carbonate aquifers (Clark *et al.*, 1997 and Clark, 2002). Furthermore, standard models are inappropriate because they assume that the groundwater recharged through a soil zone (Clark, 2002).

The noble gas data (Table 4) complements the stable isotope (Table 2) and radiocarbon (Table 3) data for this investigation by identifying two different sources of recharge within the FAS of the study area. The data suggests that

within this system relatively old meteoric freshwater circulate in the UFA over relatively young seawater of the LFA (Clark, 2002). The cooler noble gas temperatures, high helium concentrations, and low ^{14}C concentrations suggest that meteoric freshwater recharged the UFA during the last glacial period. The relatively low helium concentrations and high ^{14}C concentrations infer that groundwater in the MCU and LFA is recharged by recent (post-glacial) seawater entering in from the Gulf of Mexico. These results slightly contradict Kohout's (1965) conjecture that seawater entered the LFA from the Straits of Florida and depicts the possibility that recharge into the LFA is not from one particular location. These results support previous investigations by Clark and Fritz (1997), Clark (2002), and Bennett (2004).

CHAPTER 6.0 – CONCLUSIONS DRAWN FROM INVESTIGATION

This study investigated groundwater flow patterns and tested Kohout's "cyclic flow" theory of the FAS in the in the vicinity of Naples, Florida. Temperature logs and a geochemical analysis of the groundwater samples from monitor wells within the study area were collected to identify circulation patterns in the FAS. The groundwater samples collected within the study area were analyzed for inorganics (Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, HCO_3^-, and SO_4^{2-}), stable isotopes (^2H, ^{18}O), radiocarbon (^{14}C), and noble gases (He, Ne, Ar, Kr, and Xe).

The temperature logs analyzed from the monitor wells in this study did not support evidence of a reverse geothermal gradient as specified by Kohout (1965 and 1967) or Meyers (1989). The reverse geothermal gradient observed by Kohout (1965) in a monitor well, is what first gave evidence of cyclic flow within the FAS in southern Florida. The temperature logs may not have identified the reverse geothermal gradient because it may not be present or the wells were not drilled deep enough and recharge of seawater into the LFA may be deeper in this particular area.

The geochemical analysis employed for this investigation identified vertical flow patterns along with ancient recharge in the FAS of the study area. The data suggests that the hydrogeologic units of the FAS are connected through vertical fractures and/or solution channels. This supports previous investigations of

vertical mixing in the FAS where groundwater from the LFA is migrating upwards into the UFA (e.g., Kohout, 1965; Meyer, 1989; Jordan, 2002).

The geochemical tracers analyzed were inorganics (major cations and anions), stable isotopes (^{18}O and ^{2}H), radiocarbons (^{14}C), and noble gases (He, Ne, Ar, Kr, and Xe), together help to better understand groundwater flow patterns in the FAS of the study area. The inorganic analysis indicated that salinity of the groundwater increased with depth and suggested that lower Floridan groundwater may be upwelling and mixing with the upper Floridan groundwater. Stable isotopes and radiocarbon analysis indicated upper Floridan groundwater to be meteoric in origin and the groundwater in the MCU and LFA is recharged by seawater from the Gulf of Mexico. The noble gas analysis was employed to support and add constraints to the radiocarbon data. The data suggested that meteoric freshwater recharged the UFA during the last glacial period and young seawater from the Gulf of Mexico is recharging the MCU and LFA. This geochemical analysis proved to be an essential method to employ when understanding the complex groundwater circulation patterns of the FAS.

In summary, the geochemical analysis does support vertical flow and identified ancient recharge in the FAS within the study area of Naples, Florida. This investigation was inconclusive in identifying Kohout's hypothesis of cyclic flow. Additional research must be conducted on a larger, regional scale area; such as modeling the effects of sea level changes, evaluating the potentiometric head data of the FAS in detail, determining areas of vertical connection between the lower

and upper Floridan aquifer, and having more inland monitor wells from the study area will help better explain groundwater circulation patterns within the FAS.

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APPENDICES

Appendix 1 - Location and Well Construction Information of Monitor Wells

Well Name	Owner	County	Latitude	Longitude	Well Construction Details		
					Total Depth (feet)	Casing Depth (feet)	Casing Diameter (inches)
I75-TW (MZ-1)	SFWMD	Collier	261013	814350	760	690	2
I75-TW (MZ-2)	SFWMD	Collier	261013	814350	1,050	905	12
I75-TW (MZ-3)	SFWMD	Collier	261013	814350	2,350	2,300	2
MIU-MZ1	MIU	Collier	255733	814324	1,089	1,000	12
MIU-MZ2	MIU	Collier	255733	814324	1,600	1,490	6
NCCWTMZ-1	NCRWRF	Collier	261444	814041	995	900	12
NCCWTMZ-2	NCRWRF	Collier	261444	814041	1,930	1,815	6
SCC-MZU	SCRWRF	Collier	260544	814324	910	850	12
SCC-MZL	SCRWRF	Collier	260544	814324	1,950	1,820	6

Appendix 2 - Lithologic Description of the I75-TW

LITHOLOGIC WELL LOG PRINTOUT SOURCE - FGS

WELL NUMBER: W-17405
TOTAL DEPTH: 2694 FT.
331 SAMPLES FROM 10 TO 2694 FT.

COMPLETION DATE: 03/26/96
OTHER TYPES OF LOGS AVAILABLE - ELECTRIC

COUNTY - COLLIER
LOCATION: T.49S R.26E S.29
LAT = 26D 10M 12S
LON = 81D 43M 51S
ELEVATION: 10 FT

OWNER/DRILLER:RST CO. (SFWMD)

WORKED BY:__MARTIN BALINSKY (9/19/96)
SFWMD GEOPHYSICAL # 021-000066, I75-TW
SFWMD ID# FOR CUTTINGS IS 021-26
WELL IS LOCATED IN SEC 33, T49S, R26E, SECT. 29
BELLE MEADE SW QUADRANGLE, COLLIER COUNTY

0.	-	10.	000NOSM	NO SAMPLES
10.	-	195.	121PCPC	PLIOCENE-PLEISTOCENE
195.	-	1126.	122HTRN	HAWTHORN GROUP
1126.	-	1500.	123SWNN	SUWANNEE LIMESTONE
1500.	-	1800.	124OCAL	OCALA GROUP
1800.	-	.	124AVPK	AVON PARK FM.
0.	-	10.	000NOSM	NO SAMPLES
280.	-	287.	000NOSM	NO SAMPLES
482.	-	490.	000NOSM	NO SAMPLES
1795.	-	1796.	000NOSM	NO SAMPLES

0 - 10 NO SAMPLES

10 - 30 SHELL BED; YELLOWISH GRAY TO WHITE
25% POROSITY: INTERGRANULAR, POSSIBLY HIGH PERMEABILITY
UNCONSOLIDATED
ACCESSORY MINERALS: CALCILUTITE-05%
FOSSILS: MOLLUSKS

30 - 90 SHELL BED; VERY LIGHT ORANGE TO GRAYISH OLIVE
25% POROSITY: INTERGRANULAR, POSSIBLY HIGH PERMEABILITY
UNCONSOLIDATED
ACCESSORY MINERALS: CALCILUTITE-15%, PHOSPHATIC SAND- 01%
FOSSILS: MOLLUSKS

90 - 195 SAND; YELLOWISH GRAY TO MODERATE LIGHT GRAY
30% POROSITY: INTERGRANULAR, POSSIBLY HIGH PERMEABILITY
GRAIN SIZE: COARSE; RANGE: VERY FINE TO COARSE
HIGH SPHERICITY; UNCONSOLIDATED

195 - 210 WACKESTONE; LIGHT OLIVE GRAY TO WHITE
15% POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: CALCILUTITE, SKELETAL

40% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: COARSE; RANGE: VERY FINE TO COARSE
MODERATE INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
ACCESSORY MINERALS: QUARTZ SAND-25%
FOSSILS: MOLLUSKS
THE SAND FOUND HERE IS DOMINANTLY FINE-GRAINED. POSSIBLE TOP OF MIOCENE HAWTHORN FORMATION

210 - 220 SAND; MODERATE OLIVE BROWN TO WHITE
20% POROSITY: INTERGRANULAR
GRAIN SIZE: COARSE; RANGE: VERY FINE TO COARSE
HIGH SPHERICITY; POOR INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
ACCESSORY MINERALS: SILT-30%, CALCILUTITE-20%
FOSSILS: MOLLUSKS

220 - 280 SHELL BED; MODERATE LIGHT GRAY TO WHITE
25% POROSITY: INTERGRANULAR, POSSIBLY HIGH PERMEABILITY
POOR INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
ACCESSORY MINERALS: PHOSPHATIC GRAVEL-02%
PHOSPHATIC SAND-01%
FOSSILS: MOLLUSKS
SOME RECRYSTALLIZATION (5 %)

280 - 287 NO SAMPLES

287 - 305 SAND; LIGHT OLIVE GRAY TO WHITE
25% POROSITY: INTERGRANULAR, POSSIBLY HIGH PERMEABILITY
GRAIN SIZE: FINE; RANGE: VERY FINE TO FINE
MEDIUM SPHERICITY; POOR INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
ACCESSORY MINERALS: CALCILUTITE-10%, SHELL-85%
FOSSILS: MOLLUSKS
SHELLY SAND

305 - 335 WACKESTONE; WHITE TO LIGHT GRAY
20% POROSITY: INTERGRANULAR
GRAIN TYPE: SKELETAL, CALCILUTITE
15% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: VERY FINE; RANGE: VERY FINE TO COARSE
POOR INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
ACCESSORY MINERALS: PHOSPHATIC SAND-01%
FOSSILS: MOLLUSKS

335 - 370 WACKESTONE; WHITE TO MODERATE LIGHT GRAY
15% POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: SKELETAL, CALCILUTITE
40% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: VERY FINE; RANGE: VERY FINE TO VERY COARSE
MODERATE INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
ACCESSORY MINERALS: PHOSPHATIC SAND-01%

BRYOZOANS

370 - 430 MUDSTONE; WHITE
POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: CALCILUTITE, SKELETAL
05% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: VERY FINE; RANGE: VERY FINE TO COARSE
MODERATE INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
ACCESSORY MINERALS: PHOSPHATIC SAND-01%
FOSSILS: MOLLUSKS

430 - 482 MUDSTONE; YELLOWISH GRAY
POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: CALCILUTITE, SKELETAL
03% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: VERY FINE; RANGE: VERY FINE TO COARSE
MODERATE INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
ACCESSORY MINERALS: PHOSPHATIC SAND-01%
FOSSILS: MOLLUSKS

482 - 490 NO SAMPLES

490 - 635 MUDSTONE; VERY LIGHT ORANGE TO YELLOWISH GRAY
POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: CALCILUTITE, SKELETAL
05% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: VERY FINE; RANGE: VERY FINE TO COARSE
MODERATE INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
ACCESSORY MINERALS: PHOSPHATIC SAND-01%
FOSSILS: MOLLUSKS
PARTIALLY RECRYSTALLIZED

635 - 660 MUDSTONE; VERY LIGHT GRAY TO LIGHT OLIVE GRAY
POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: CALCILUTITE, SKELETAL
05% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: VERY FINE; RANGE: VERY FINE TO COARSE
MODERATE INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
FOSSILS: MOLLUSKS

660 - 735 MUDSTONE; YELLOWISH GRAY
POROSITY: LOW PERMEABILITY, INTERGRANULAR, VUGULAR
GRAIN TYPE: CALCILUTITE, SKELETAL
03% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: VERY FINE; RANGE: VERY FINE TO COARSE
GOOD INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
ACCESSORY MINERALS: PHOSPHATIC SAND-01%
FOSSILS: MOLLUSKS

735 - 764 WACKESTONE; WHITE TO DARK GRAYISH YELLOW

12% POROSITY: LOW PERMEABILITY, INTERGRANULAR, VUGULAR
GRAIN TYPE: CALCILUTITE, SKELETAL
12% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: VERY FINE; RANGE: VERY FINE TO COARSE
GOOD INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
ACCESSORY MINERALS: DOLOMITE-15%, PHOSPHATIC SAND-01%
FOSSILS: BRACHIOPOD
VUGGY EUHEDRAL DOLOSTONE EXISTS AS SEPARATE FRAGMENTS FROM CALCILUTITE

764 - 777 PACKSTONE; VERY LIGHT ORANGE TO YELLOWISH GRAY
12% POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: CALCILUTITE, SKELETAL
70% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: MEDIUM; RANGE: VERY FINE TO COARSE
GOOD INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
FOSSILS: MOLLUSKS
GASTROPODS. SOME PARTIAL RECRYSTALLIZATION OBSERVABLE

777 - 806 MUDSTONE; WHITE TO PINKISH GRAY
POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: CALCILUTITE, CRYSTALS
05% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: VERY FINE; RANGE: VERY FINE TO COARSE
MODERATE INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
FOSSILS: MOLLUSKS

806 - 860 WACKESTONE; VERY LIGHT ORANGE TO WHITE
12% POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: CALCILUTITE, SKELETAL
30% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: VERY FINE; RANGE: VERY FINE TO COARSE
MODERATE INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
FOSSILS: MOLLUSKS
GASTROPODS. ABOUT 80% RECRYSTALLIZED

860 - 912 PACKSTONE; VERY LIGHT ORANGE TO WHITE
12% POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: CALCILUTITE, SKELETAL, CRYSTALS
80% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: COARSE; RANGE: VERY FINE TO COARSE
MODERATE INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
FOSSILS: MOLLUSKS
DOMINANTLY PELOIDS. ABOUT 90% RECRYSTALLIZED

912 - 996 PACKSTONE; GRAYISH ORANGE TO VERY LIGHT ORANGE
15% POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: CALCILUTITE, SKELETAL
70% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: COARSE; RANGE: VERY FINE TO COARSE

MODERATE INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
FOSSILS: MOLLUSKS
ABOUT 30% RECRYSTALLIZED

996 - 1030 WACKESTONE; VERY LIGHT ORANGE TO YELLOWISH GRAY
11% POROSITY: LOW PERMEABILITY, INTERGRANULAR, VUGULAR
GRAIN TYPE: CALCILUTITE, SKELETAL
40% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: VERY FINE; RANGE: VERY FINE TO COARSE
GOOD INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
FOSSILS: BENTHIC FORAMINIFERA, MOLLUSKS
ABOUT 90% RECRYSTALLIZED

1030 - 1033 GRAINSTONE; DARK GRAYISH YELLOW TO WHITE
17% POROSITY: INTERGRANULAR, POSSIBLY HIGH PERMEABILITY
GRAIN TYPE: CALCILUTITE, SKELETAL, CRYSTALS
95% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: COARSE; RANGE: VERY FINE TO COARSE
GOOD INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
FOSSILS: BENTHIC FORAMINIFERA, MOLLUSKS
GASTROPODS. ABOUT 95% RECRYSTALLIZED. PELOIDS AND FORAMINIFERA. IDENTIFICATION OF TYPES OF FORAMINIFERA INDETERMINATE

1033 - 1040 PACKSTONE; WHITE TO VERY LIGHT ORANGE
14% POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: CALCILUTITE, SKELETAL
65% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: COARSE; RANGE: VERY FINE TO COARSE
GOOD INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
THIS SAMPLE CONSISTS OF ABOVE UNIT (1030-1033 FEET) AND A MATRIX-SUPPORTED UNIT (PARTIALLY RECRYSTALLIZED) CONTAINING FORAMINIFERA AND PELOIDS

1040 - 1045 WACKESTONE; WHITE TO VERY LIGHT ORANGE
10% POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: CALCILUTITE, SKELETAL
35% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: VERY FINE; RANGE: VERY FINE TO COARSE
GOOD INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
FOSSILS: MOLLUSKS, CORAL
GASTROPODS

1045 - 1060 WACKESTONE; VERY LIGHT ORANGE TO WHITE
15% POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: CALCILUTITE, SKELETAL
15% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: VERY FINE; RANGE: VERY FINE TO COARSE
MODERATE INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX

FOSSILS: MOLLUSKS

1060 - 1070 MUDSTONE; YELLOWISH GRAY TO WHITE
POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: CALCILUTITE, SKELETAL
05% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: VERY FINE; RANGE: VERY FINE TO COARSE
MODERATE INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
FOSSILS: MOLLUSKS

1070 - 1073 MUDSTONE; WHITE TO VERY LIGHT ORANGE
POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: CALCILUTITE, SKELETAL
05% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: VERY FINE; RANGE: VERY FINE TO COARSE
MODERATE INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
FOSSILS: MOLLUSKS

1073 - 1092 MUDSTONE; VERY LIGHT ORANGE TO WHITE
POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: CALCILUTITE, SKELETAL
03% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: VERY FINE; RANGE: VERY FINE TO COARSE
MODERATE INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
FOSSILS: MOLLUSKS

1092 - 1122 PACKSTONE; YELLOWISH GRAY TO WHITE
15% POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: CALCILUTITE, SKELETAL, BIOGENIC
85% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: MEDIUM; RANGE: VERY FINE TO COARSE
MODERATE INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
FOSSILS: MOLLUSKS, BENTHIC FORAMINIFERA
EXTENSIVE RECRYSTALLIZATION (95%). SKELETAL FRAGMENTS OF MOLLUSKS, FORAMINIFERA AND PELOIDS.

1122 - 1126 SAND; VERY LIGHT ORANGE
30% POROSITY: INTERGRANULAR, POSSIBLY HIGH PERMEABILITY
GRAIN SIZE: MEDIUM; RANGE: VERY FINE TO MEDIUM
HIGH SPHERICITY; UNCONSOLIDATED
THIS SAMPLE IS DOMINANTLY MEDIUM-GRAINED SAND. THIS IS SUSPICIOUS, AND MOST LIKELY REPRESENTS A CAVING

1126 - 1173 PACKSTONE; YELLOWISH GRAY TO WHITE
12% POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: CALCILUTITE, SKELETAL
60% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: COARSE; RANGE: VERY FINE TO VERY COARSE
GOOD INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
DICTYOCONUS (FIRST OCCURRENCE). POSSIBLE OLIGOCENE

SUWANNEE LIMESTONE. GASTROPODS

1173 - 1195 MUDSTONE; VERY LIGHT ORANGE
15% POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: CALCILUTITE, SKELETAL
05% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: VERY FINE; RANGE: VERY FINE TO COARSE
MODERATE INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX

1195 - 1204 WACKESTONE; VERY LIGHT ORANGE TO WHITE
10% POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: CALCILUTITE, SKELETAL
05% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: VERY FINE; RANGE: VERY FINE TO COARSE
MODERATE INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
ABOUT 80% RECRYSTALLIZED

1204 - 1207 DOLOSTONE; OLIVE GRAY TO LIGHT OLIVE GRAY
10% POROSITY: LOW PERMEABILITY, INTERGRANULAR
90-100% ALTERED; ANHEDRAL
GRAIN SIZE: FINE; RANGE: VERY FINE TO FINE
GOOD INDURATION
CEMENT TYPE(S): DOLOMITE CEMENT
ACCESSORY MINERALS: CALCILUTITE-05%
FOSSILS: ALGAE
CALCILUTITE AND DOLOSTONE EXIST AS SEPARATE FRAGMENTS

1207 - 1227 DOLOSTONE; YELLOWISH GRAY
10% POROSITY: LOW PERMEABILITY, INTERGRANULAR, VUGULAR
90-100% ALTERED; EUHEDRAL
GRAIN SIZE: FINE; RANGE: VERY FINE TO FINE
GOOD INDURATION
CEMENT TYPE(S): DOLOMITE CEMENT
ACCESSORY MINERALS: CALCILUTITE-02%
MINOR REMNANT CALCILUTITE. MINOR VUGS, LINED WITH EUHEDRAL DOLOMITE RHOMBS

1227 - 1231 DOLOSTONE; MODERATE LIGHT GRAY
10% POROSITY: LOW PERMEABILITY, INTERGRANULAR
90-100% ALTERED; EUHEDRAL
GRAIN SIZE: FINE; RANGE: VERY FINE TO FINE
GOOD INDURATION
CEMENT TYPE(S): DOLOMITE CEMENT
ACCESSORY MINERALS: CALCILUTITE-05%
SEPARATE CALCILUTITE AND DOLOSTONE FRAGMENTS

1231 - 1267 WACKESTONE; MODERATE LIGHT GRAY TO YELLOWISH GRAY
12% POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: CALCILUTITE, SKELETAL
25% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: VERY FINE; RANGE: VERY FINE TO COARSE
GOOD INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX

ACCESSORY MINERALS: DOLOMITE-40%
OTHER FEATURES: DOLOMITIC
FOSSILS: MOLLUSKS, ECHINOID
SEPARATE FRAGMENTS OF CALCILUTITE AND DOLOSTONE.
DICTYOCONUS ABOUT 70% RECRYSTALLIZED. SOME FRAGMENTS ARE HIGH IN SKELETAL MATERIAL

1267 - 1287 PACKSTONE; YELLOWISH GRAY TO WHITE
15% POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: CALCILUTITE, SKELETAL
70% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: COARSE; RANGE: VERY FINE TO COARSE
MODERATE INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
FOSSILS: MOLLUSKS, ECHINOID

1287 - 1299 PACKSTONE; YELLOWISH GRAY
15% POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: CALCILUTITE, SKELETAL, BIOGENIC
85% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: COARSE; RANGE: VERY FINE TO COARSE
MODERATE INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
DOMINANTLY PELOIDS

1299 - 1413 WACKESTONE; YELLOWISH GRAY TO MODERATE LIGHT GRAY
10% POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: CALCILUTITE, SKELETAL
40% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: COARSE; RANGE: VERY FINE TO COARSE
MODERATE INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
FOSSILS: CRUSTACEA, MOLLUSKS
SIMILAR TO PRECEDING LITHOLOGY, BUT BETTER INDURATED, AND LOWER AMOUNT OF PELOIDS. GASTROPODS

1413 - 1481 WACKESTONE; YELLOWISH GRAY TO WHITE
15% POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: CALCILUTITE, SKELETAL
15% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: VERY FINE; RANGE: VERY FINE TO COARSE
MODERATE INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
FOSSILS: MOLLUSKS

1481 - 1483 DOLOSTONE; DARK GRAYISH YELLOW
12% POROSITY: LOW PERMEABILITY, INTERCRYSTALLINE
90-100% ALTERED; EUHEDRAL
GRAIN SIZE: MEDIUM; RANGE: VERY FINE TO MEDIUM
GOOD INDURATION
CEMENT TYPE(S): DOLOMITE CEMENT
ACCESSORY MINERALS: CALCILUTITE-01%

1483 - 1485 MUDSTONE; VERY LIGHT ORANGE TO YELLOWISH GRAY
POROSITY: LOW PERMEABILITY, INTERGRANULAR

GRAIN TYPE: CALCILUTITE, SKELETAL
01% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: VERY FINE; RANGE: VERY FINE TO COARSE
MODERATE INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
ACCESSORY MINERALS: DOLOMITE-20%
FOSSILS: MOLLUSKS
PARTIALLY DOLOMITIZED FRAGMENTS INTERBEDDED WITH CALCILUTITE

1485 - 1500 DOLOSTONE; GRAYISH BROWN TO MODERATE YELLOWISH BROWN
13% POROSITY: LOW PERMEABILITY, INTERCRYSTALLINE, VUGULAR
90-100% ALTERED; EUHEDRAL
GRAIN SIZE: FINE; RANGE: VERY FINE TO FINE
GOOD INDURATION
CEMENT TYPE(S): DOLOMITE CEMENT
ACCESSORY MINERALS: CALCILUTITE-10%
OTHER FEATURES: CALCAREOUS
MINOR VUGS

1500 - 1527 WACKESTONE; WHITE TO GRAYISH BROWN
10% POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: CALCILUTITE, SKELETAL
30% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: VERY FINE; RANGE: VERY FINE TO COARSE
GOOD INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
ACCESSORY MINERALS: DOLOMITE-15%
OTHER FEATURES: DOLOMITIC
FOSSILS: MOLLUSKS
SEPARATE FRAGMENTS OF DOLOSTONE AND WACKESTONE. LEPIDOCYCLINA PRESENT. POSSIBLE TOP OF LATE EOCENE OCALA LIMESTONE

1527 - 1532 MUDSTONE; YELLOWISH GRAY
POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: CALCILUTITE, SKELETAL
01% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: VERY FINE; RANGE: VERY FINE TO COARSE
MODERATE INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
FOSSILS: MOLLUSKS

1532 - 1545 MUDSTONE; WHITE
POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: CALCILUTITE, SKELETAL
01% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: VERY FINE; RANGE: VERY FINE TO COARSE
GOOD INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
FOSSILS: MOLLUSKS

1545 - 1610 MUDSTONE; VERY LIGHT ORANGE
POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: CALCILUTITE, SKELETAL

05% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: VERY FINE; RANGE: VERY FINE TO COARSE
MODERATE INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
FOSSILS: MOLLUSKS
LEPIDOCYCLINA

1610 - 1620 WACKESTONE; VERY LIGHT ORANGE TO YELLOWISH GRAY
15% POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: CALCILUTITE, SKELETAL
12% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: VERY FINE; RANGE: VERY FINE TO COARSE
MODERATE INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
ACCESSORY MINERALS: DOLOMITE-05%
FOSSILS: MOLLUSKS
CALCILUTITE-BEARING DOLOSTONE EXISTS AS SEPARATE FRAGMENTS FROM CALCILUTE. NUMMULITES COMPRISE ABOUT 10% OF SAMPLE.
DICTYOCONUS

1620 - 1690 WACKESTONE; VERY LIGHT ORANGE
15% POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: CALCILUTITE, SKELETAL
40% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: VERY FINE; RANGE: VERY FINE TO COARSE
MODERATE INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
LEPIDOCYCLINA

1690 - 1747 PACKSTONE; YELLOWISH GRAY
15% POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: CALCILUTITE, SKELETAL
85% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: COARSE; RANGE: VERY FINE TO COARSE
MODERATE INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
NUMMULITES DOMINATE. LEPIDOCYCLINA

1747 - 1777 WACKESTONE; YELLOWISH GRAY
10% POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: CALCILUTITE, SKELETAL
20% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: VERY FINE; RANGE: VERY FINE TO COARSE
GOOD INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
FOSSILS: MOLLUSKS
NUMMULITES MINOR (1%)

1777 - 1795 PACKSTONE; YELLOWISH GRAY TO WHITE
10% POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: CALCILUTITE, SKELETAL
60% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: COARSE; RANGE: VERY FINE TO COARSE
GOOD INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX

FOSSILS: CORAL, MOLLUSKS
NUMMULITES

1795 - 1796 NO SAMPLES

1796 - 1800 WACKESTONE; DARK GRAYISH YELLOW
15% POROSITY: LOW PERMEABILITY, INTERCRYSTALLINE
GRAIN TYPE: CALCILUTITE, SKELETAL
15% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: VERY FINE; RANGE: VERY FINE TO COARSE
MODERATE INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
FOSSILS: MOLLUSKS, ECHINOID
SAMPLE CONSISTS OF DOMINANTLY RECRYSTALLIZED CALCITE FRAGMENTS, WITH SOME CALCILUTITE. EXTENSIVE SKELETAL FRAGMENTS FLOAT IN THIS MATRIX.

1800 - 1864 PACKSTONE; YELLOWISH GRAY
15% POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: CALCILUTITE, SKELETAL
65% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: COARSE; RANGE: VERY FINE TO COARSE
MODERATE INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
FOSSILS: MOLLUSKS, BENTHIC FORAMINIFERA, SPICULES
SOME RECRYSTALLIZATION (APPROXIMATELY 15%). MANY SKELETAL FRAGMENTS. IDENTITY UNCLEAR. DICTYOCONUS AMERICANUS.
POSSIBLE TOP OF MIDDLE EOCENE AVON PARK FORMATION

1864 - 1876 WACKESTONE; GRAYISH ORANGE TO WHITE
15% POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: CALCILUTITE, SKELETAL, CRYSTALS
35% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: VERY FINE; RANGE: VERY FINE TO COARSE
MODERATE INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
FOSSILS: MOLLUSKS, BENTHIC FORAMINIFERA
EXTENSIVE RECRYSTALLIZATION. MATRIX-SUPPORTED FRAGMENTS WITH RECRYSTALLIZED CALCITE AND REMNANT CALCILUTITE (15%) AND FLOATING SKELETAL FRAGMENTS. FORAMINIFERA TYPES INDETERMINATE

1876 - 1900 GRAINSTONE; VERY LIGHT ORANGE
18% POROSITY: LOW PERMEABILITY, INTERGRANULAR
POSSIBLY HIGH PERMEABILITY
GRAIN TYPE: SKELETAL, CALCILUTITE
95% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: FINE; RANGE: VERY FINE TO FINE
MODERATE INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
FOSSILS: BENTHIC FORAMINIFERA, MOLLUSKS
DOMINANTLY PELOIDS AND BENTHIC FORAMINIFERA WHOSE IDENTITY IS INDETERMINATE

1900 - 1905 WACKESTONE; VERY LIGHT ORANGE TO LIGHT OLIVE BROWN

20% POROSITY: INTERGRANULAR
GRAIN TYPE: SKELETAL, CALCILUTITE
40% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: VERY FINE; RANGE: VERY FINE TO COARSE
POOR INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
TWO DISTINCT COLORS OF FRAGMENTS ARE PRESENT--DARKER(ABOUT 70%) AND LIGHTER (ABOUT 30%). THE DARKER FRAGMENTS ARE POORLY INDURATED. NUMMULITES PRESENT--CAVINGS? (NOT IN MATRIX)

1905 - 1952 PACKSTONE; VERY LIGHT ORANGE TO GRAYISH BROWN
10% POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: SKELETAL, CALCILUTITE
60% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: VERY FINE; RANGE: VERY FINE TO COARSE
GOOD INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
SAMPLE IS ABOUT 20% RECRYSTALLIZED. DOMINANTLY VERY LIGHT FRAGMENTS, BUT MINOR PALE YELLOWISH-BROWN FRAGMENTS.
PELOIDS

1952 - 1986 WACKESTONE; VERY LIGHT ORANGE TO WHITE
15% POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: SKELETAL, CALCILUTITE, BIOGENIC
40% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: VERY FINE; RANGE: VERY FINE TO COARSE
MODERATE INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
FOSSILS: MOLLUSKS

1986 - 1997 WACKESTONE; VERY LIGHT ORANGE TO LIGHT OLIVE BROWN
15% POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: SKELETAL, CALCILUTITE
20% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: COARSE; RANGE: VERY FINE TO COARSE
MODERATE INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
FOSSILS: MOLLUSKS
TWO DISTINCT COLORS OF FRAGMENTS AGAIN, SIMILAR TO 1900-1905. MILDLY VUGGY. SKELETAL FRAGMENTS FLOAT IN MATRIX

1997 - 2084 WACKESTONE; YELLOWISH GRAY TO WHITE
15% POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: SKELETAL, CALCILUTITE
30% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: COARSE; RANGE: VERY FINE TO COARSE
MODERATE INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
FOSSILS: MOLLUSKS

2084 - 2127 WACKESTONE; VERY LIGHT ORANGE
13% POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: SKELETAL, CALCILUTITE, BIOGENIC

40% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: COARSE; RANGE: VERY FINE TO COARSE
MODERATE INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
FOSSILS: MOLLUSKS
PELOIDS, MOST OF WHICH HAVE BEEN RECRYSTALLIZED

2127 - 2155 WACKESTONE; GRAYISH YELLOW
10% POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: CALCILUTITE, BIOGENIC
30% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: COARSE; RANGE: VERY FINE TO COARSE
GOOD INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX

2155 - 2185 WACKESTONE; YELLOWISH GRAY TO LIGHT OLIVE GRAY
13% POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: CALCILUTITE, SKELETAL, BIOGENIC
35% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: VERY FINE; RANGE: VERY FINE TO COARSE
MODERATE INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
DICTYOCONUS

2185 - 2189 DOLOSTONE; OLIVE GRAY TO WHITE
17% POROSITY: LOW PERMEABILITY, INTERCRYSTALLINE, VUGULAR
50-90% ALTERED; ANHEDRAL
GRAIN SIZE: MEDIUM; RANGE: VERY FINE TO MEDIUM
GOOD INDURATION
CEMENT TYPE(S): DOLOMITE CEMENT
ACCESSORY MINERALS: CALCILUTITE-15%
OTHER FEATURES: CALCAREOUS
FOSSILS: BENTHIC FORAMINIFERA
DOLOSTONE WITH REMNANT SKELETAL CALCITE FRAGMENTS AND SOME CALCILUTITE FRAGMENTS. DOLOSTONE IS EXTENSIVELY VUGGY. DOMINANTLY ANHEDRAL AND SUBHEDRAL, BUT EUHEDRAL CRYSTALS ARE FOUND AS VUG LINERS AND DOMINATING A FEW PARTICULAR AREAS

2189 - 2210 DOLOSTONE; OLIVE GRAY TO WHITE
12% POROSITY: LOW PERMEABILITY, INTERCRYSTALLINE
50-90% ALTERED; SUBHEDRAL
GRAIN SIZE: FINE; RANGE: VERY FINE TO FINE
GOOD INDURATION
CEMENT TYPE(S): DOLOMITE CEMENT, CALCILUTITE MATRIX
ACCESSORY MINERALS: CALCILUTITE-35%
OTHER FEATURES: CALCAREOUS
PELOIDS AND REMNANT FORAMINIFERA. DIFFICULT TO DETERMINE THE IDENTITY OF THE FORAMINIFERA. CALCILUTITE IS INTERBEDDED WITH DOLOSTONE

2210 - 2213 DOLOSTONE; OLIVE GRAY TO WHITE
12% POROSITY: LOW PERMEABILITY, INTERCRYSTALLINE
50-90% ALTERED; SUBHEDRAL
GRAIN SIZE: FINE; RANGE: VERY FINE TO FINE

GOOD INDURATION
CEMENT TYPE(S): DOLOMITE CEMENT, CALCILUTITE MATRIX
ACCESSORY MINERALS: CALCILUTITE-35%
OTHER FEATURES: CALCAREOUS
WELL-INDURATED DOLOSTONE WITH REMNANT SKELETAL PIECES EXIST AS SEPARATE FRAGMENTS FROM MODERATELY INDURATED CALCILUTITE
WHICH RESEMBLES THAT SEEN FROM 2185 TO 2189 FEET. ABOUT 90% OF DOLOSTONE IS SUBHEDRAL AND 10% IS EUHEDRAL

2213 - 2215 DOLOSTONE; MODERATE YELLOWISH BROWN TO LIGHT OLIVE GRAY
10% POROSITY: LOW PERMEABILITY, INTERCRYSTALLINE
90-100% ALTERED; SUBHEDRAL
GRAIN SIZE: MEDIUM; RANGE: VERY FINE TO MEDIUM
GOOD INDURATION
CEMENT TYPE(S): DOLOMITE CEMENT, CALCILUTITE MATRIX
ACCESSORY MINERALS: CALCILUTITE-01%
APPROXIMATELY 35% EUHEDRAL CRYSTALS, AND 65% SUBHEDRAL. EUHEDRAL CRYSTALS DOMINATE CERTAIN AREAS ON THE SAMPLE, AND LINE VUGS

2215 - 2222 DOLOSTONE; LIGHT OLIVE GRAY TO MODERATE YELLOWISH BROWN
10% POROSITY: LOW PERMEABILITY, INTERCRYSTALLINE
90-100% ALTERED; EUHEDRAL
GRAIN SIZE: MEDIUM; RANGE: VERY FINE TO MEDIUM
GOOD INDURATION
CEMENT TYPE(S): DOLOMITE CEMENT
ACCESSORY MINERALS: SHELL-%
DOMINANTLY LARGE FRAGMENTS WITH SMOOTH FACES. POSSIBLE "FRACTURE ZONE" EUHEDRAL CRYSTALS ON FRACTURE SURFACES

2222 - 2235 DOLOSTONE; LIGHT BROWNISH GRAY
10% POROSITY: LOW PERMEABILITY, INTERCRYSTALLINE
90-100% ALTERED; SUBHEDRAL
GRAIN SIZE: FINE; RANGE: VERY FINE TO MEDIUM
GOOD INDURATION
CEMENT TYPE(S): DOLOMITE CEMENT
ACCESSORY MINERALS: SHELL-%
MOSTLY LARGE FRAGMENTS WITH ALMOST ALL SMOOTH FACES--POSSIBLE "FRACTURE ZONE" ROCK. MOST FRACTURE SURFACES DISPLAY FINE-GRAINED SUBHEDRAL AND ANHEDRAL CRYSTLAS, BUT MEDIUM-GRAINED EUHEDRAL RHOMBS DOMINATE A FEW
FACES OF THE ROCK

2235 - 2242 DOLOSTONE; LIGHT OLIVE GRAY TO MODERATE YELLOWISH BROWN
10% POROSITY: LOW PERMEABILITY, INTERCRYSTALLINE
90-100% ALTERED; SUBHEDRAL
GRAIN SIZE: FINE; RANGE: VERY FINE TO MEDIUM
GOOD INDURATION
CEMENT TYPE(S): DOLOMITE CEMENT
EXTENSIVE VUGS WHICH ARE LINED WITH EUHEDRAL CRYSTALS. EUHEDRAL CRYSTALS ARE ALSO FOUND ALONG SMOOTH SURFACES WHICH ARE LESS DOMINANT THAN IN ABOVE SAMPLE

2242 - 2244 DOLOSTONE; MODERATE LIGHT GRAY TO DARK GRAYISH YELLOW
12% POROSITY: LOW PERMEABILITY, INTERCRYSTALLINE, VUGULAR
90-100% ALTERED; SUBHEDRAL
GRAIN SIZE: FINE; RANGE: VERY FINE TO MEDIUM
GOOD INDURATION
CEMENT TYPE(S): DOLOMITE CEMENT
STILL DOMINANTLY LARGE FRACTURES WITH SMOOTH FACES. SOME FACES HAVE EUHEDRAL DOLOMITE CRYSTALS (FRACTURE FILL)

2244 - 2249 DOLOSTONE; MODERATE LIGHT GRAY TO GRAYISH OLIVE
12% POROSITY: LOW PERMEABILITY, INTERCRYSTALLINE, VUGULAR
90-100% ALTERED; SUBHEDRAL
GRAIN SIZE: FINE; RANGE: VERY FINE TO MEDIUM
GOOD INDURATION
CEMENT TYPE(S): DOLOMITE CEMENT
ACCESSORY MINERALS: CALCILUTITE-08%
CALCILUTITE AND DOLOSTONE EXIST AS SEPARATE FRAGMENTS.
ABOUT 15% EUHEDRAL CRYSTALS

2249 - 2265 WACKESTONE; VERY LIGHT ORANGE TO DARK YELLOWISH BROWN
15% POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: CALCILUTITE, SKELETAL
30% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: COARSE; RANGE: VERY FINE TO COARSE
MODERATE INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
ACCESSORY MINERALS: DOLOMITE-10%
OTHER FEATURES: DOLOMITIC
FRAGMENTS OF VERY PALE ORANGE MATRIX WITH UNIDENTIFIABLE COARSE-GRAINED WHITE ALLOCHEMS FLOATING IN THEM. DOLOSTONE AND CALCILUTITE EXIST AS SEPARATE FRAGMENTS. SOME OF THE DOLOSTONE FRAGMENTS HAVE THESE PALER FRAGMENTS FLOATING IN THEM. 20% OF

2265 - 2271 DOLOSTONE; LIGHT GRAY TO WHITE
10% POROSITY: LOW PERMEABILITY, INTERGRANULAR
50-90% ALTERED; EUHEDRAL
GRAIN SIZE: FINE; RANGE: VERY FINE TO MEDIUM
GOOD INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
ACCESSORY MINERALS: CALCILUTITE-35%, GYPSUM-05%
CALCILUTITE IS PRESENT AS REMNANT SPOTS IN DOLOSTONE, AND AS SEPARATE FRAGMENTS

2271 - 2277 DOLOSTONE; OLIVE GRAY TO WHITE
12% POROSITY: LOW PERMEABILITY, INTERCRYSTALLINE, VUGULAR
50-90% ALTERED; EUHEDRAL
GRAIN SIZE: FINE; RANGE: VERY FINE TO MEDIUM
GOOD INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
ACCESSORY MINERALS: CALCILUTITE-15%, GYPSUM-03%
SIMILAR TO ABOVE DESCRIPTION. ABOUT 40% OF DOLOSTONE IS SUBHEDRAL

2277 - 2298 LIMESTONE; YELLOWISH GRAY

12% POROSITY: LOW PERMEABILITY, INTERGRANULAR, VUGULAR
GRAIN TYPE: CRYSTALS, CALCILUTITE
GRAIN SIZE: VERY FINE; GOOD INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
ACCESSORY MINERALS: DOLOMITE-15%
ABOUT 35% OF SAMPLES ARE DOLOSTONE WITH LARGE PATCHES OF CALCILUTITE. ABOUT 65% OF FRAGMENTS ARE FAIRLY PURE CALCILUTITE. RECRYSTALLIZATION MAKES IT DIFFICULT TO ESTIMATE ALLOCHEMICAL PERCENTAGE. BOTH LITHOLOGIES ARE VUGGY.

2298 - 2302 LIMESTONE; VERY LIGHT ORANGE
11% POROSITY: LOW PERMEABILITY, INTERGRANULAR, VUGULAR
GRAIN TYPE: CRYSTALS, CALCILUTITE
GRAIN SIZE: VERY FINE; GOOD INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
ACCESSORY MINERALS: DOLOMITE-01%
EXTENSIVE RECRYSTALLIZATION (70%) LIMESTONE. AGAIN DIFFICULT TO ESTIMATE PERCENTAGE OF ALLOCHEMICAL CONSTITUENTS

2302 - 2323 LIMESTONE; VERY LIGHT ORANGE
11% POROSITY: LOW PERMEABILITY, INTERGRANULAR, VUGULAR
GRAIN TYPE: CRYSTALS, CALCILUTITE
GRAIN SIZE: VERY FINE; GOOD INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
ACCESSORY MINERALS: DOLOMITE-07%
OTHER FEATURES: DOLOMITIC
SEPARATE FRAGMENTS OF CALCILUTITE AND DOLOSTONE WITH CALCILUTITE

2323 - 2329 DOLOSTONE; MODERATE DARK GRAY TO MODERATE YELLOWISH BROWN
12% POROSITY: LOW PERMEABILITY, INTERCRYSTALLINE
90-100% ALTERED; SUBHEDRAL
GRAIN SIZE: FINE; RANGE: VERY FINE TO MEDIUM
GOOD INDURATION
CEMENT TYPE(S): DOLOMITE CEMENT
ACCESSORY MINERALS: CALCILUTITE-03%
CALCILUTITE EXISTS AS REMNANT AMONG DOLOSTONE. DOMINANTLY SUBHEDRAL CRYSTALS, BUT EUHEDRAL CRYSTALS ARE FOUND LINING VUGS AND CERTAIN SURFACES ON FRAGMENTS

2329 - 2331 DOLOSTONE; MODERATE LIGHT GRAY TO YELLOWISH GRAY
13% POROSITY: LOW PERMEABILITY, INTERGRANULAR
INTERCRYSTALLINE; 50-90% ALTERED; SUBHEDRAL
GRAIN SIZE: FINE; RANGE: VERY FINE TO MEDIUM
GOOD INDURATION
CEMENT TYPE(S): DOLOMITE CEMENT, CALCILUTITE MATRIX
ACCESSORY MINERALS: CALCILUTITE-30%
DOLOSTONE EXISTS AS SEPARATE FRAGMENTS FROM PARTIALLY DOLOMITIC LIMESTONE, AND NONDOLOMITIC LIMESTONE

2331 - 2337 DOLOSTONE; MODERATE YELLOWISH BROWN TO MODERATE GRAY
13% POROSITY: LOW PERMEABILITY, INTERCRYSTALLINE, VUGULAR

90-100% ALTERED; SUBHEDRAL
GRAIN SIZE: FINE; RANGE: VERY FINE TO MEDIUM
GOOD INDURATION
CEMENT TYPE(S): DOLOMITE CEMENT, CALCILUTITE MATRIX
ACCESSORY MINERALS: CALCILUTITE-01%
DOMINANTLY SUBHEDRAL CRYSTALS, BUT ABOUT 35% EUHEDRAL RHOMBS FOUND AS VUG LINERS, AND CONCENTRATED IN CERTAIN AREAS

2337 - 2352 DOLOSTONE; GRAYISH BROWN
12% POROSITY: LOW PERMEABILITY, INTERCRYSTALLINE
90-100% ALTERED; ANHEDRAL
GRAIN SIZE: FINE; RANGE: VERY FINE TO MEDIUM
GOOD INDURATION
CEMENT TYPE(S): DOLOMITE CEMENT
MINOR CALCILUTITE EXIST AS SEPARATE FRAGMENTS FROM DOLOSTONE. DOMINANTLY ANHEDRAL. MINOR AREAS (15%) OF EUHEDRAL AND SUBHEDRAL CRYSTALS. EUHEDRAL RHOMBS DOMINATE
SOME SURFACES

2352 - 2392 DOLOSTONE; DARK YELLOWISH BROWN TO MODERATE YELLOWISH BROWN
LX% POROSITY: VUGULAR; 90-100% ALTERED; SUBHEDRAL
GRAIN SIZE: FINE; RANGE: VERY FINE TO MEDIUM
GOOD INDURATION
CEMENT TYPE(S): DOLOMITE CEMENT
DOLOMITE RHOMBS (ABOUT 30%) EXIST AS VUG LINERS AND ALONG SURFACES.

2392 - 2412 WACKESTONE; YELLOWISH GRAY TO MODERATE LIGHT GRAY
10% POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: CALCILUTITE, BIOGENIC
30% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: VERY FINE; RANGE: VERY FINE TO FINE
GOOD INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
ACCESSORY MINERALS: DOLOMITE-35%
OTHER FEATURES: DOLOMITIC
CALCILUTITE AND DOLOSTONE EXIST AS SEPARATE FRAGMENTS. DOLOSTONE IS VUGGY--SIMILAR IN APPEARANCE TO THAT FOUND BETWEEN 2350 AND 2392 FEET

2412 - 2422 DOLOSTONE; MODERATE GRAY TO MODERATE YELLOWISH BROWN
11% POROSITY: LOW PERMEABILITY, INTERCRYSTALLINE, VUGULAR
90-100% ALTERED; SUBHEDRAL
GRAIN SIZE: FINE; RANGE: VERY FINE TO MEDIUM
GOOD INDURATION
CEMENT TYPE(S): DOLOMITE CEMENT, CALCILUTITE MATRIX
ACCESSORY MINERALS: CALCILUTITE-02%
ABOUT 70% SUBHEDRAL FINE-GRAINED DOLOMITE CRYSTALS, AND ABOUT 28% MEDIUM-SIZED EUHEDRAL RHOMBS

2422 - 2432 CALCILUTITE; VERY LIGHT ORANGE TO MODERATE DARK GRAY
14% POROSITY: LOW PERMEABILITY, INTERGRANULAR

INTERCRYSTALLINE
GRAIN TYPE: CALCILUTITE, BIOGENIC
01% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: VERY FINE; RANGE: VERY FINE TO FINE
GOOD INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX, DOLOMITE CEMENT
ACCESSORY MINERALS: DOLOMITE-35%
A MIX OF PARTIALLY DOLOMITIZED FRAGMENTS (30%), ALMOST ENTIRELY DOLOMITIZED FRAGMENTS (10%), AND CALCILUTITE FRAGMENTS (70%). THE CALCILUTITE IS MODERATELY INDURATED WHILE THE DOLOSTONE IS WELL-INDURATED

2432 - 2434 DOLOSTONE; MODERATE DARK GRAY TO WHITE
12% POROSITY: LOW PERMEABILITY, INTERCRYSTALLINE, VUGULAR
50-90% ALTERED; SUBHEDRAL
GRAIN SIZE: FINE; RANGE: VERY FINE TO MEDIUM
GOOD INDURATION
CEMENT TYPE(S): DOLOMITE CEMENT, CALCILUTITE MATRIX
SOME PARTIALLY DOLOMITITE CALCILUTITE FRAGMENTS (DOLOMITIZED AREAS ARE DISTINCT REGIONS OF FRAGMENTS) INTERBEDDED WITH FULLY DOLOMITIZED FRAGMENTS. DOLOSTONE HAS SAME CHARACTERISTICS AS THAT BETWEEN 2422 AND 2432 FRAGMENTS

2434 - 2436 DOLOSTONE; GRAYISH OLIVE TO MODERATE BROWN
11% POROSITY: LOW PERMEABILITY, INTERCRYSTALLINE, VUGULAR
50-90% ALTERED; SUBHEDRAL
GRAIN SIZE: FINE; RANGE: VERY FINE TO MEDIUM
GOOD INDURATION
CEMENT TYPE(S): DOLOMITE CEMENT, CALCILUTITE MATRIX
ACCESSORY MINERALS: CALCILUTITE-05%
OTHER FEATURES: CALCAREOUS

2436 - 2438 DOLOSTONE; MODERATE DARK GRAY TO VERY LIGHT ORANGE
12% POROSITY: LOW PERMEABILITY, INTERCRYSTALLINE, VUGULAR
90-100% ALTERED; SUBHEDRAL
GRAIN SIZE: FINE; RANGE: VERY FINE TO MEDIUM
GOOD INDURATION
CEMENT TYPE(S): DOLOMITE CEMENT
ACCESSORY MINERALS: CALCILUTITE-01%
VERY SIMILAR TO PRECEDING LITHOLOGIES OF DOLOSTONE--PARTIALLY EUHEDRAL, AND DOMINANTLY SUBHEDRAL

2438 - 2451 GRAINSTONE; YELLOWISH GRAY TO LIGHT OLIVE GRAY
12% POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: CALCILUTITE, BIOGENIC
90% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: FINE; RANGE: VERY FINE TO FINE
GOOD INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
ACCESSORY MINERALS: DOLOMITE-20%
DOMINANTLY PELOIDS. DOLOSTONE AND GRAINSTONE EXIST AS SEPARATE FRAGMENTS

2451 - 2458 DOLOSTONE; MODERATE DARK GRAY TO MODERATE

YELLOWISH BROWN
11% POROSITY: LOW PERMEABILITY, INTERCRYSTALLINE
90-100% ALTERED; SUBHEDRAL
GRAIN SIZE: FINE; RANGE: VERY FINE TO MEDIUM
GOOD INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX, DOLOMITE CEMENT
ACCESSORY MINERALS: CALCILUTITE-45%
OTHER FEATURES: CALCAREOUS
SIMILAR TO SAMPLES FOUND FROM 2436-2438 FEET

2458 - 2537 GRAINSTONE; YELLOWISH GRAY TO PINKISH GRAY
10% POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: CALCILUTITE, BIOGENIC
95% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: FINE; RANGE: VERY FINE TO FINE
GOOD INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
ACCESSORY MINERALS: DOLOMITE-45%
OTHER FEATURES: DOLOMITIC
DOMINANTLY PELOIDS. DOLOSTONE IS INTERBEDDED WITH
GRAINSTONE

2537 - 2541 DOLOSTONE; MODERATE LIGHT GRAY TO YELLOWISH GRAY
11% POROSITY: LOW PERMEABILITY, INTERCRYSTALLINE
INTERGRANULAR; 90-100% ALTERED; SUBHEDRAL
GRAIN SIZE: FINE; RANGE: VERY FINE TO MEDIUM
GOOD INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX, DOLOMITE CEMENT
ACCESSORY MINERALS: CALCILUTITE-45%
OTHER FEATURES: CALCAREOUS
GRAINSTONE AND DOLOSTONE EXIST AS SEPARATE FRAGMENTS

2541 - 2575 MUDSTONE; WHITE TO LIGHT GRAY
10% POROSITY: LOW PERMEABILITY, INTERGRANULAR
GRAIN TYPE: CALCILUTITE, BIOGENIC
05% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: VERY FINE; RANGE: VERY FINE TO FINE
GOOD INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX, DOLOMITE CEMENT
ACCESSORY MINERALS: DOLOMITE-15%
OTHER FEATURES: DOLOMITIC

2575 - 2581 DOLOSTONE; OLIVE GRAY TO LIGHT OLIVE GRAY
11% POROSITY: LOW PERMEABILITY, INTERCRYSTALLINE
90-100% ALTERED; SUBHEDRAL
GRAIN SIZE: FINE; RANGE: VERY FINE TO MEDIUM
GOOD INDURATION
CEMENT TYPE(S): DOLOMITE CEMENT
ACCESSORY MINERALS: CALCILUTITE-02%

2581 - 2585 DOLOSTONE; YELLOWISH GRAY TO LIGHT OLIVE GRAY
10% POROSITY: LOW PERMEABILITY, INTERGRANULAR
90-100% ALTERED; SUBHEDRAL
GRAIN SIZE: FINE; RANGE: VERY FINE TO MEDIUM
GOOD INDURATION

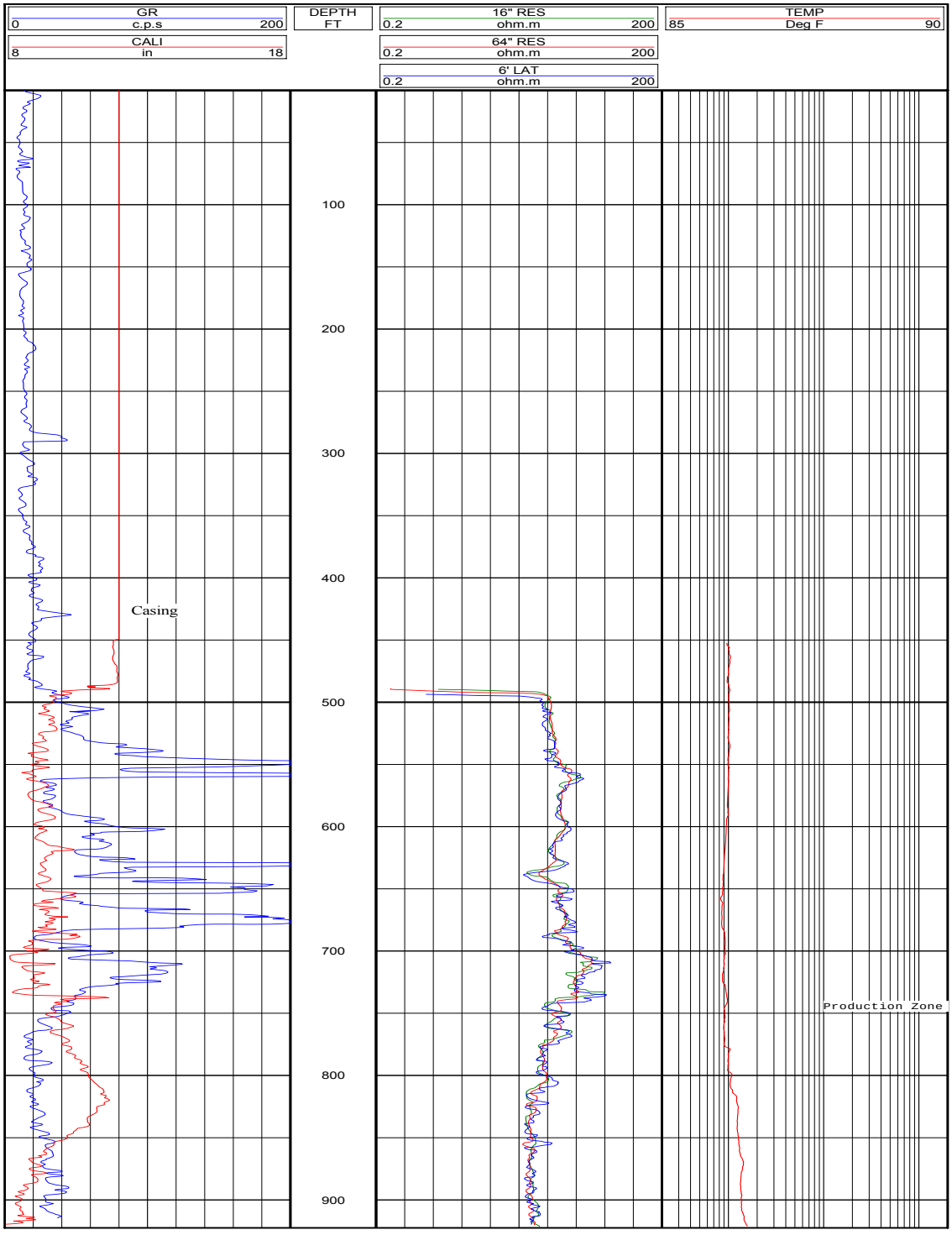
CEMENT TYPE(S): DOLOMITE CEMENT
ACCESSORY MINERALS: CALCILUTITE-15%
OTHER FEATURES: CALCAREOUS
LARGE SMOOTH-SIDED FRAGMENTS. TWO TYPES OF FRAGMENTS--YELLOWISH GRAY, WHICH ARE SLIGHTLY CALCAREOUS AND LIGHT OLIVE GRAY FAIRLY PURE DOLOSTONE). MINOR CALCILUTITE EXISTS AS SEPARATE FRAGMENTS FROM DOLOSTONE

2585 - 2694 DOLOSTONE; DARK YELLOWISH BROWN TO GRAYISH BROWN
10% POROSITY: LOW PERMEABILITY, INTERGRANULAR
INTERCRYSTALLINE; 50-90% ALTERED; SUBHEDRAL
GRAIN SIZE: FINE; RANGE: VERY FINE TO MEDIUM
GOOD INDURATION
CEMENT TYPE(S): DOLOMITE CEMENT, CALCILUTITE MATRIX
ACCESSORY MINERALS: CALCILUTITE-25%
OTHER FEATURES: CALCAREOUS
CALCILUTITE AND DOLOSTONE EXIST AS SEPARATE FRAGMENTS. DOLOSTONE FRAGMENTS SLIGHTLY CALCAREOUS

2694 TOTAL DEPTH

Appendix 3 - I75-TW Geophysical Logging

RUN 1



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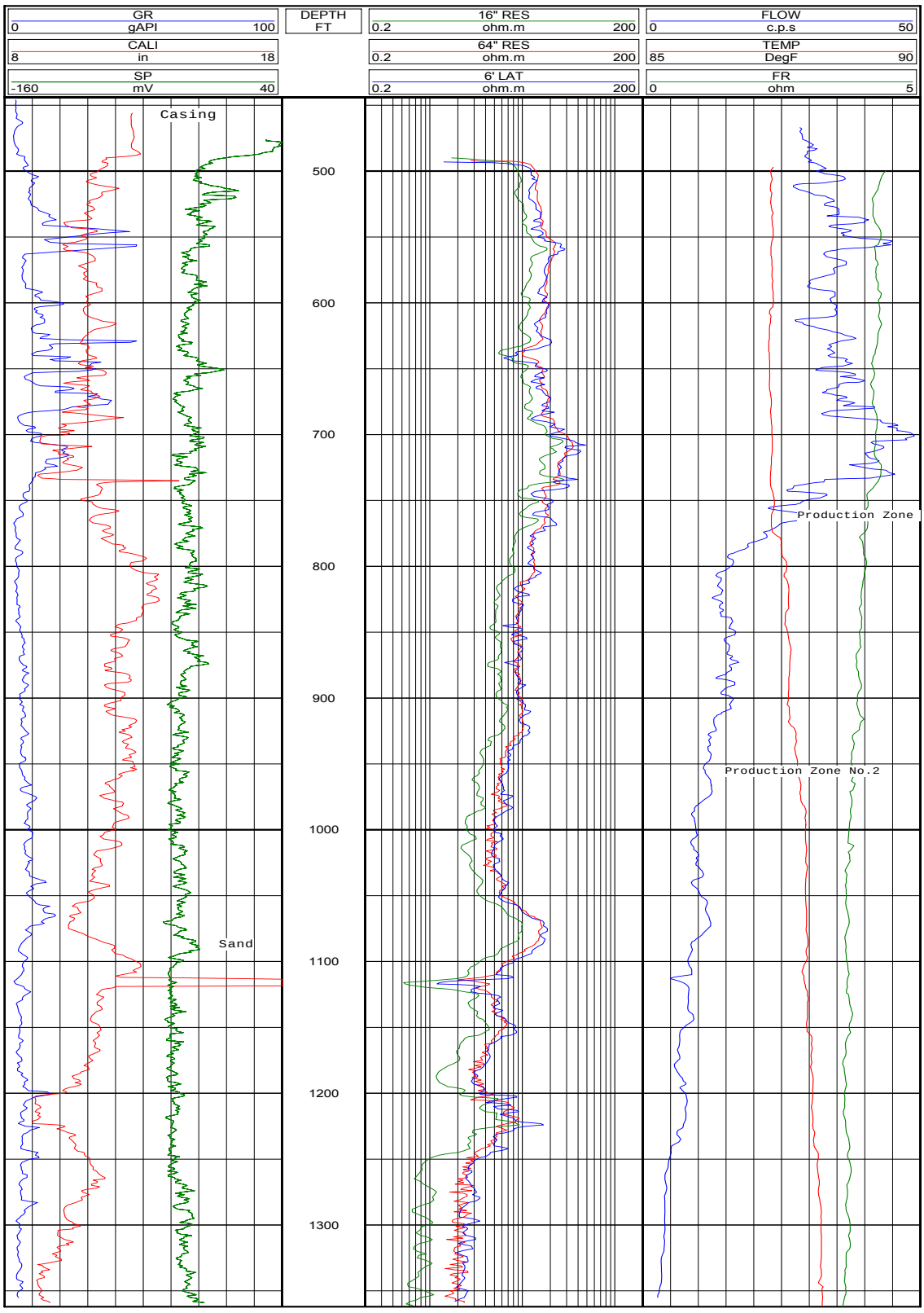
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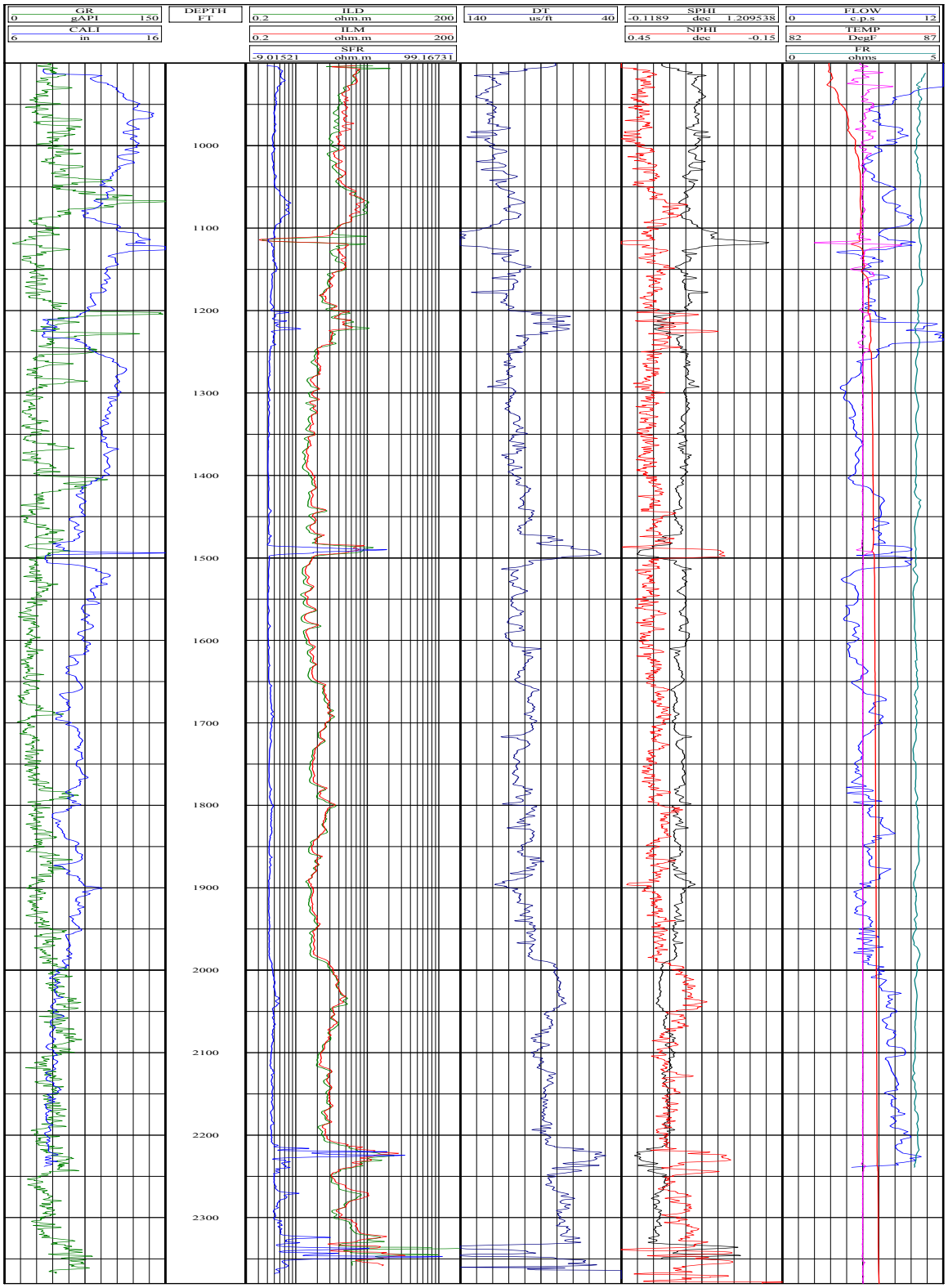
RUN 3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