

**OPTICAL DATING OF PALEOSHORELINE
FEATURES IN FLORIDA**

**PLEISTOCENE STRATIGRAPHY AND OPTICAL DATING OF
SURFICIAL SANDS IN FLORIDA'S COASTAL PLAIN AND CENTRAL
HIGHLANDS: IMPLICATIONS FOR SEA-LEVEL AND SHORELINE AGES**

By

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ABSTRACT

Optical dating of siliciclastic sediments in various locations throughout Florida was conducted to obtain a better understanding of Cenozoic climates and sea-level fluctuations. 44 optically stimulated luminescence (OSL) ages and 22 electron spin resonance optical dating (ESROD) ages were collected from various sediment types in Florida including, coquina, beach ridge, aeolian, shallow marine, and estuarine. OSL is widely used by geoscientists in aeolian and beach ridge environment, because past findings that indicate its reliability for these applications, however it has rarely been applied on coquina, shallow marine, and estuarine deposits which is attempted here. ESROD is a new technique used a handful of times on fluvial and aeolian environments but never on shallow marine or estuarine, as done here. This project focused on 3 concentrated areas, Merritt Island, Anastasia Formation, and the Gulfport Formation, to conduct high resolution studies, and one broader study that enabled us to obtain an understanding of Cenozoic sea-levels in eastern Florida. These areas were chosen based on previous works' determination that 3 major terraces represent 3 major sea-level highstands.

The Anastasia Formation is a coquina ridge that is believed to be deposited during the marine isotope stage (MIS) 5. It is culturally very important because the first Spanish fort, Castillo de San Marcos, is built completely out of the coquina. Three OSL samples were collected to determine the validity of this hypothesis and to begin to understand the relationship of the Anastasia Formation to the lowest terrace. OSL dating of a coquina has only been performed a handful of times around the world and never in Florida. The results support the hypothesis that the Anastasia was formed during MIS-5 and contributed by confirming the Anastasia is in fact not a single depositional event but multiple events cemented together post-deposition. Associated fossils also support the OSL results.

Merritt Island is located just west of Cape Canaveral, and the eastern part of the island is composed of a sand ridge set. Four and a half kilometers of ground penetrating radar (GPR) and 10 OSL ages were combined to determine the depositional history of these beach ridges. Direct-push electrical conductivity was tested in two locations to determine the effectiveness of this new technique as a quick stratigraphic tool. Also a new graphical way to illustrate grain size distribution was utilized. Particle size distribution (PSD) plots allow the reader to visualize any minute changes in grain size such as a slight increase in clay content that may be overlooked if just using mean grain size. These changes are very important for interpretation of luminescence characteristics. Radar facies indicate that the ridges at Merritt Island are a classic example of beach ridges with an approximately 1-2 m aeolian cap on them. A new OSL model was used for the first time in an attempt to obtain more accurate luminescence ages on the ridges. This model, called the aeolian cap removal model (ACRM), removes the aeolian cap and then recalculates the burial depth using a shallower overburden to calculate the cosmic dose rate. After using this model the OSL ages for the beach ridges made more sense

geologically and stratigraphically. The results indicate that the Merritt Island beach ridge set formed during MIS-5c. Globally this sea-level highstand did not reach above present, but the results add to mounting evidence that in the southeastern United States MIS-5c sea-level was higher than present.

Five direct-push cores, five vibracores, and twenty-eight OSL ages (using the ACRM) were collected, as well as seven kilometers of GPR, in an attempt to determine the depositional history of the Gulfport Formation. The Gulfport Formation is a 1-3 km wide discontinuous barrier ridge belt that hugs the edge of the Florida panhandle. It is believed to have been deposited during the later stages of MIS-5 and sits atop the Biloxi Formation, which is hypothesized to be marine in origin deposited during the earliest stages of MIS-5. The GPR data clearly defined the Gulfport Formation and the Biloxi Formation, but the OSL ages suggest that the Biloxi was deposited before MIS-5, possibly MIS-7 or MIS-9. Sitting directly above the Biloxi Formation is a mica rich sediment that was deposited during MIS-6, a contradiction to previous works. It is believed that as sea level dropped the paleo-Apalachicola River began depositing this sediment as it meandered through the area. As sea levels began to rise again, beach ridges (the Gulfport beach ridges) were deposited in the field area. LiDAR was used for the first time in the area to determine high resolution elevations. These elevations coupled with the precision of the GPR allowed us to conclude that MIS-5e sea levels were approximately 3.5 m above present.

ESROD, a new optical dating technique, was used at 10 locations across north-central and peninsular Florida in an attempt to better understand Pleistocene sea-level fluctuations and establish age constraints on three regional scale geomorphic sequences characterized by ridges and terraces at distinct elevation ranges. These are believed to have formed at the different elevations in connection with past higher sea levels. A total of twenty-two ESROD samples were collected in these three sequences: the Trail Ridge Sequence, the Effingham Sequence, and the Chatham Sequence. ESROD was conducted for the first time in Florida and on marine sediments. Our results indicate that Trail Ridge began depositing on the Hawthorn Group around 2.2 Ma and continued in several stages until 6 ka. The Effingham Sequence, which contains the Osceola Cape, was deposited around 1.5 Ma. The Chatham Sequence is a multi-depositional terrace with at least three events preserved. The majority of the sequence was deposited between 0.86 Ma and 1.09 Ma, with surficial aeolian features deposited between 0.41 Ma and 0.61 Ma.

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PREFACE

This dissertation compiles a collection of research papers that were either published at different stages of this Ph.D., are presently in press (i.e. proof corrected), or are under review or in the process of being submitted. The objectives and relationship among the various papers are described in the introductory chapter. The final chapter, Conclusions, summarizes the major contributions obtained during this research. The different research papers presented herein are the following:

Chapter Two:

BURDETTE, K., RINK, W.J., MEANS, G.H., PORTELL, R.W., 2009. Optical Dating of the Anastasia Formation, Northeastern Florida, USA. *Southeastern Geology* 46 (4), 173-185.

Chapter Three:

BURDETTE, K., RINK, W.J., MALLINSON, D.J., PARHAM, P.R., REINHARDT, E.G. Geologic Investigation and Optical Dating of the Merritt Island Sand Ridge Sequence, Eastern Florida, USA. *Southeastern Geology*, (submitted June 2010; accepted with minor reviews, September 9, 2010).

Chapter Four:

BURDETTE, K.E., RINK, W.J., LOPEZ, G.I., MALLINSON, D.J., PARHAM, P.R., REINHARDT, E.G. Geologic Investigation and Optical Dating of the Gulfport Formation near Apalachicola, Northwest Florida, USA. (prepared for *Sedimentology*; submitted August 17, 2010; under review).

Chapter Five:

BURDETTE, K.E., RINK, W.J., MALLINSON, D.J., MEANS, H.G., PARHAM, P.R. Electron Spin Resonance Optical Dating of Marine, Estuarine, and Aeolian Sediments in Florida, USA. (prepared for *Geology*; ready for submission September 2010).

All work conducted, involving every aspect of each manuscript, was led by the first author (i.e. the doctoral candidate). Dr. Rink provided professional guidance with respect to research, discussion of results, manuscript writing, editing, and submission. All authors have reviewed, edited, and approved each manuscript before submission. All the manuscripts were co-authored and the remaining authors contributed to varying degrees. In Chapters 2, 3, and 4, Dr. Dave Mallinson allowed the use of instrumentation as well as very helpful edits and comments on the manuscripts. In Chapters 2, 3, 4, and 5, Dr. Pete Parham contributed by assisting the research team in the field and editing the manuscript drafts. In Chapters 3 and 4, Dr. Eduard Reinhardt allowed the use of lab equipment and also advised on manuscript drafts. In Chapters 2 and 5, Harley Means contributed to the manuscripts by editing and advising on the geology of Florida. In Chapter 4, Dr. Gloria Lopez, contributed by allowing the candidate to use samples collected for her research and also edited the manuscript. In Chapter 2, Roger Portell assisted with the identification of invertebrates and assisted with the editing of the manuscript.

The formatting of each chapter is noticeably different based on the required format of the journal they will or have been submitted to. Also because each chapter is an individual publication the reader will notice repetition in sections such as methods and previous works. McMaster University copyright regulations require permission to reproduce research papers already published and/or in press. Copies of the reproduction permissions are given at the beginning of the chapters requiring it.

CHAPTER 1

INTRODUCTION

The lack of datable material exceeding the range of C^{14} has been an ever-present problem with researchers in Florida. This is evident in the State of Florida Geological Map where many of the units are placed in large age groups or defined as undifferentiated. Previous coastal researchers had to rely on collecting cores in transect and filling in the gaps with best guesses, which is nearly impossible in complex coastal systems. To place absolute ages on the units, researchers were forced to use trace amounts of carbon, which could have been reworked from older deposits or far worse contaminated. This led to much confusion and misinterpretation of the data.

Most available direct sea-level indicators, such as shoreline deposits, are for the period after the last deglaciation, because earlier records were mostly destroyed by rising sea levels at the onset of the early Holocene deglaciation in tectonically stable areas (Lambeck and Chappell, 2001). Although it is considered by many to be tectonically stable, Adams et al. (2010) suggest that Florida is in fact uplifting by karstification of underlying carbonate rocks. This uplift has increased the availability of preserved ancient deposits.

With the advent of technologies, such as ground penetrating radar (GPR), optically stimulated luminescence dating (OSL), and electron spin resonance optical dating (ESROD), geoscientists can now define the depositional environments and chronostratigraphy of siliciclastic coastal deposits and place them in the context of sea level and climate change.

Optical dating, whether it be OSL or ESROD, of quartz grains is based on a few key assumptions: a) the signal can be zeroed or reduced to a residual background by exposure to sunlight, b) the signal, natural and laboratory dosed, can be measured, c) moisture content effects on dose rates can be reasonably modeled with sufficiently conservative error estimates, d) the cosmic dose rate can be calculated, e) the accumulation rate of the sediment has been either constant or instantaneous throughout time, f) the uranium decay chain has remained in equilibrium, g) in the aeolian cap removal model (ACRM) there is no missing sequence that was deposited and remained for a significant amount of time and then eroded. If any of these assumptions are not true, the researcher must justify how he/she overcame them.

OSL dating is a form of geochronology that measures the output of photons being released by insulator minerals such as quartz and feldspars (Aitken, 1998). In natural settings, exposure to the weak flux of ionizing radiation from uranium (U), thorium (Th), and potassium-40 (K) in the sediment, as well as by cosmic rays and by rubidium-87 to a minor extent, produce emitted energy in the form of δ -photons, β and α particles that are absorbed and stored in defects inside the crystal lattice of quartz and feldspar (Aitken,

1998). This stored energy dose can be evicted with optical stimulation, either by heat or light, and released as luminescence.

Numerous studies have been conducted on aeolian and coastal systems utilizing OSL of quartz, although many of these only deal with Holocene or recent sediments (Ollerhead et al., 1994; Stokes, 1999; Frechen et al., 2001; Murray-Wallace et al., 2002; Ballarini et al., 2003; Berger et al., 2003; Tatumi et al., 2003; Rink and Forrest, 2005). Ollerhead et al. (1994) used OSL to determine the formation chronology of a sequence of dunes on Buctouche Spit, a Holocene deposit on the northeast coast of New Brunswick. OSL ages, ranging from 5+/-30 BP for an embryo dune to 765+/-45 BP for the oldest dune, exhibit the expected seriation from youngest to oldest and are consistent with historical evidence coupled with an assumed constant sediment aggradation rate (Ollerhead et al., 1994). Murray-Wallace et al. (2002) dated quartz sand in bioclastic carbonate-quartz sediments from coastal relict foredunes (beach ridges) in Guichen Bay, South Australia, using OSL to evaluate the utility of the method for studies of dune dynamics and to quantify rates of coastal progradation. Banerjee et al. (2003) pushed OSL dating to extraordinary limits. Using coarse (106-200 μm) quartz grains, Banerjee et al. (2003) obtained OSL ages ranging from 61 ka to an impressive 710 ka for aeolian sands in southern Australia. The reason for such old dates is the extreme low dose environment ($\sim 0.5 \text{ mGy a}^{-1}$), compared to typical 2-2.5 mGy a^{-1} .

ESROD dating may allow us to evaluate the ages of detrital sediments from 20 ka to more than 2 Ma, which are difficult to obtain by other methods (Lin et al., 2006). The paramagnetic centers of quartz used in the dose determination (aluminum and titanium centers) are sensitive to light and ionizing radiations. These centers can be optically zeroed, or bleached, during fluvial and aeolian transport (Yokoyama et al., 1985; Voinchet et al., 2007). Although the Germanium center is the most easily bleached center in quartz, most workers have found the natural signal to be either weak or non-existent (Rink, 1997). Voinchet et al. (2007) concluded that the aluminum center was maximally, but not totally, bleached after an 800 h illumination time, equivalent to 6 months of natural light, which agreed with Laurent et al. (1998) earlier assumptions. However, Tissoux et al. (2007) concluded that 2 to 3.5 months of natural exposure was sufficient. Studies on Titanium (Ti) centers show promising results for using Ti-Li and Ti-H for optical dating (Tissoux et al., 2007; Toyoda et al., 2000). Bleaching experiments indicate that after ~ 520 hours of Ultra Violet (UV) exposure, no Ti-Li signal can be observed (Tissoux et al., 2007). Although Toyoda et al. (2000) concluded that the Ti-Li center is completely zeroed in 72 or 168 hours of sunlight, but 24 hours is sufficient for the Ti-H and Ti-Na centers.

The only minor drawback to ESR dating of quartz is that the Aluminum and Titanium centers can only be measured at $\sim 77.2 \text{ K}$. A complex spectrum arising, in both cases, from the interaction of the unpaired magnetic electron with nearby magnetic nuclei (Lin et al., 2006). The signal is composed of six ^{27}Al hyperfine structure lines, of which each is quadrupled and numbered 1-16 (Yokoyama et al., 1985). Lin et al. (2006) concluded that peak-to-peak heights of both 1–6 and 1–14 (the height from the top of the

first peak to the end of the last peak) can be used for ESR dating of the aluminum center. There is no saturation for any of the peak-to-peak heights for pure quartz even after being irradiated up to 60,000 Gy. This implies that the aluminum center in quartz has great potential for dating over 2 Ma (Lin et al., 2006). Rink et al. (2007) suggested a strict criterion when dating siliciclastic sediment using ESROD. Many researchers used the Al signal or the Ti signal individually but Rink et al. (2007) requires for an age to be valid, both signals must overlap statistically.

Ground penetrating radar has become a vital tool for depositional environment determination in coastal environments (van Heteren et al., 1994; Jol et al., 1995; Bristow et al., 2000; Jol et al., 2002). GPR systems use electromagnetic radiation in the VHF-UHF bands (usually in the frequency range of 16 MHz to 2000 MHz) in the same way that seismic systems use acoustic energy to produce high resolution images of subsurface stratigraphy (Brill, 1996). GPR works best where clean (free of silt and clay), quartz-rich, thick, clastic sediments allow the signal to penetrate without attenuation. The main causes of attenuation in GPR are silts and clays and saltwater, a constant variable when dealing with coastal environments.

Initial application of GPR to coastal stratigraphy was in connection with placer prospecting of fluvial deposits in Canada and in Australia in the early 1990's (Brill, 1996 and references therein). Van Heteren et al. (1994) used GPR to investigate sandy to gravelly barrier beaches and spits along the New England coast. They had some difficulty with salt-water attenuation, but were still able to separate Holocene beaches from Quaternary glacial deposits. They also developed one of the first tables that characterized various geometries and their relationship to the modern facies. Bristow et al. (2000) conducted a similar GPR study of the foredunes in Norfolk, UK and identified seven different radar facies. These facies can be used in Florida's coastal systems to determine past depositional environments.

1.1 Research Justification

Florida is an area where minimal absolute age dating has taken place. The areas that have been studied are usually confined to Holocene sediments using OSL. Therefore any additional absolute ages are important. The success of previous applications of OSL in Florida (work by Dr. Gloria Lopez) demand the continuation and pursuit to push the limits of materials and environments dated. Most researchers tend to apply OSL on younger sediments that are sure to have been optically zeroed. This is only a small amount of material. This project focuses directly on Pre-Holocene mainland marine and aeolian features that may not have been optically zeroed or that may have been altered post deposition. It is crucial that researchers continue to develop new techniques and new models for OSL.

ESROD has never been conducted on Florida sediments, or on shallow marine sediments. After discussing our research ideas with the Florida Geological Survey, it

became clear that Florida would be the perfect testing grounds for ESROD. The criterion of Rink et al. (2007) was used in the dating of all the Florida samples. Some of the deposits studied in this project have been debated for decades. Trail Ridge is the prime example. At least a dozen articles have been published about its age and depositional environment. For the first time, we will be able to place absolute ages, using ESROD and OSL, on the formation and once and for all settle the debate about how old is Trail Ridge.

1.2 Research Design and Objectives

The project described herein focuses on mainland geology and geomorphology in an effort to define the geologic record of the Pleistocene sea level and climate fluctuations in Florida. This project will contribute to our knowledge of the Florida coastal system by defining the stratigraphic framework, identifying the depositional environments, and dating coastal deposits at critical localities. This project was designed from the onset to be a very broad study of several locations, sediment types, and depositional environments. It was to be a pilot project in which later studies could take pieces of this project and conduct high-resolution studies. This project was to be a “guinea pig” for the use of ESROD on marine sediments in Florida.

The main objective of this project is to define the stratigraphy, geochronology, and geologic history of Pleistocene deposits in critical Florida localities. Defining GPR facies, correlating them to lithofacies defined in vibracore/direct-push core stratigraphy, placing absolute chronology on these facies using the most state of the art dating methods available, and defining climatic and depositional environments will help achieve this goal.

Specific sub-objectives are:

1. To determine the ages of these deposits using multiple chronological tools, emphasizing the need to compare results from different methods wherever possible.
2. To reconstruct the depositional history of these deposits in a chronostratigraphic framework in order to define the history of Pleistocene relative sea-level changes in the region.
3. To integrate the record of the evolution of these surficial landforms into the overall history of the Florida coastal plain during the Pleistocene, using combined geophysical, luminescence, and stratigraphic information.
4. To discuss the implications of the history of these shallow landforms for the future evolution of the low-gradient, low elevation Florida coastal plain in the context of rising global sea level.

1.3 Dissertation Structure

Based on the variety of micro-studies conducted in this dissertation, it was possible to divide the dissertation into several research papers, which are fused back

together as chapters. Being a “sandwich thesis”, this dissertation begins with an introduction about the ideas and thinking behind this project and ending with a conclusion that summarizes the major accomplishments of this work. The body of the dissertation is the chapters mentioned above. Since peer reviewed manuscripts do not contain raw data, appendices were added to inform the reader of specifics, including detailed locations, criteria for sampling, and program files used.

The chapters presented here that make up the body of this dissertation is based on four peer-reviewed manuscripts. One of these papers has already been published in *Southeastern Geology*, one is currently under review in *Southeastern Geology*, and the other two are ready to be submitted to *Quaternary Science Review* and *Quaternary Geochronology*.

Chapter 2

“Optical Dating of the Anastasia Formation, Northeastern Florida, USA”

This chapter solely focuses on the Anastasia Formation of northeastern Florida. It is a coquina ridge that many researchers believed to have been deposited during marine isotope stage (MIS) 5. We collected 3 cores, using a technique never used before by the AGE laboratory, a diamond tipped corer. Optical dating of coquina had only been performed around the world a handful of times, and never in Florida. This paper examines the difficulties and possible problems with dating a coquina. The age of the Anastasia Formation will begin the process of unraveling the depositional history of the Chatham Sequence.

Chapter 3

“Geologic Investigation and Optical Dating of the Merritt Island Sand Ridge Sequence, Eastern Florida, USA.”

Chapter 3 looks at a classic beach ridge set in eastern Florida. GPR and OSL dating were utilized to determine the environment and timing of deposition. A new type of grain size visualization, particle size distribution, was used coupled with electric-conductivity graphs to produce high-resolution logs that show slight variations in grain size percentages. A new OSL model was used for the first time in this article. All the sands of the Merritt Island sequence contained an aeolian cap that was deposited well after the ridges were deposited. The new model, named the aeolian cap removal model (ACRM), removes this cap and recalculates the cosmic dose, yielding more accurate OSL ages. The age of the Merritt Island sequence also contributes to the knowledge of the Chatham Sequence.

Chapter 4

“Geologic Investigation and Optical Dating of the Gulfport Formation near Apalachicola, Northwest, Florida, USA.”

Until Chapter 4 the research was based on very small areas of unique depositional regimes. Seven kilometers of GPR and 28 OSL, using the ACRM, were used in two distinctly different areas in the Gulfport Formation to determine its age and environment of deposition. The first area is two beach ridge sets, much like Merritt Island, but the second area is geomorphically mottled with no recognizable structure. GPR became very important in Chapter 4 to determine the extent of the beach ridges and therefore the extent of sea level. This study is the first to use shallow-surface geophysics to determine the maximum elevation of sea level in this area.

Chapter 5

“Electron Spin Resonance Optical Dating of Marine, Estuarine, and Aeolian Sediments in Florida, USA”

Chapter 5 is a revolutionary advancement into electron spin resonance optical dating (ESROD). 22 samples from 10 sites were collected to determine the depositional age of the Trail Ridge Sequence, the Effingham Sequence, and the Chatham Sequence. This is the first time ESROD was conducted on marine and estuarine samples in Florida or anywhere. This study will assist the Florida Geologic Survey in updating the Florida State Map and will also assist other researchers working on uplift caused by karstification.

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CHAPTER 2

OPTICAL DATING OF THE ANASTASIA FORMATION, NORTHEASTERN FLORIDA, USA

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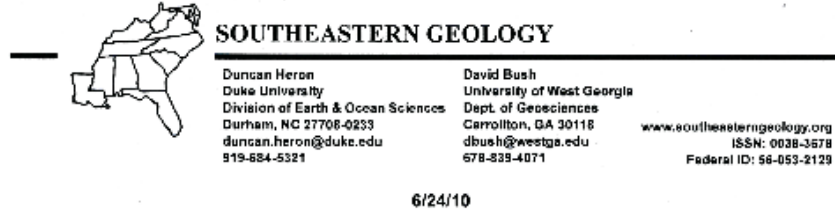
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Dear Kevin,

As Editor of Southeastern Geology, I am glad to grant you permission to reprint your article in your dissertation at McMaster University. The paper to which you refer is:

BURDETTE, K., RINK, W.J., MEANS, G.H., PORTELL, R.W., 2009. Optical Dating of the Anastasia Formation, Northeastern Florida, USA. Southeastern Geology 46 (4), 173-185.

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Sincerely,

David M. Bush
Editor

ABSTRACT

The single-aliquot regenerative-dose (SAR) procedure was used to obtain optically stimulated luminescence ages to determine the depositional age of the upper part of the Anastasia Formation. This unit, which crops out along the east coast of Florida, is one of the most culturally and economically important coquina deposits in North America. Rock samples from the upper three meters of exposure at three locations were collected. Additional materials for paleontological analysis were also taken. Based on our samples, the luminescence ages of the Anastasia Formation are well within marine isotope stage 5, which supports the Osmond et al. (1970) results. Furthermore, associated vertebrate fossils fall within the Rancholabrean North American Land Mammal Age (300 ka to 10 ka) and the fossil mollusk assemblage; consisting entirely of modern species, support the luminescence age determinations.

2.1 INTRODUCTION

Optically stimulated luminescence dating (OSL) has now become a well-established chronological tool for dating aeolian and other coastal siliciclastic deposits around the world (Stokes, 1999; Murray-Wallace et al., 2002; Ballarini et al., 2003; Madsen et al., 2005; Buynevich et al., 2007; Mallinson et al., 2008) and more authors are now trying to use optical dating techniques on coquina, beachrock, and aeolianites (French et al., 2001; Tatumi et al., 2003; Bateman et al., 2004; Frechen et al., 2004; Armitage et al., 2006; Tatumi et al., 2006; Hearty and O’Leary, 2008). Those who have attempted to date these materials using optical dating have had encouraging results, with ages corresponding within error to other dating techniques or geologic context.

This paper analyzes three OSL samples collected in the Anastasia Formation in Northeastern Florida in an attempt to place absolute geochronological constraints on the deposition of this unit. These constraints will allow us to define sea levels at a time in geologic history when sea level was at or above present.

2.2 REGIONAL SETTING

2.2.1 *Anastasia Formation*

Along the eastern coast of Florida, exists one of the most culturally and economically important coquina deposits in North America, the Anastasia Formation. The building blocks for Castillo de San Marcos, a 17th century Spanish fort near St. Augustine, Florida, were quarried from this coquina. The present study attempts to place numeric ages on the upper part (0-3 m) of the Anastasia Formation using OSL dating techniques.

The Anastasia Formation, named by Sellards (1912), consists of various admixtures of sand, shell, and coquinoid limestone. It occurs along the east coast of Florida from St. Johns to Palm Beach counties (Scott et al., 2001) and underlies the

Atlantic Coastal Ridge geomorphic province (Scott, 2004). The formation extends inland up to 32 km (20 miles). The dominant lithology in coastal exposures is a coquinoid limestone. In the subsurface the formation can consist of unconsolidated shell and shelly sands of nearshore marine facies. The Anastasia Formation interfingers laterally with the Fort Thompson Formation and the Miami Limestone (both late Pleistocene) in the southern extent of its distribution. The Anastasia Formation can attain up to 30 m (100 feet) in thickness (Parker et al., 1955).

Lovejoy (1987) recognized two facies within the Anastasia Formation in Martin and Palm Beach counties. These are a coquinoid limestone facies and a shellrock facies. The coquinoid limestone facies consists of calcite cemented whole and fragmented mollusk shells and varying percentages of quartz sand and a small percentage of heavy minerals. The shellrock facies contains less fragmented mollusk shells and is not as well cemented as the coquinoid limestone facies. These facies formed due to meteoric diagenesis. The coquinoid limestone facies formed in the phreatic zone (saturation zone) and the less cemented shellrock facies formed in the vadose zone (aeration zone). A number of sedimentary structures have been observed in the Anastasia Formation including cross-bedding, horizontal bedding and infilled burrows. All sedimentary structures suggest that the Anastasia Formation was deposited in a near-shore, marine environment.

2.2.2 Paleontology of the Anastasia

Fossil marine macro-invertebrates from the Anastasia Formation include sponges, bryozoans, corals, mollusks (Johnson, 1993; Lovejoy, 1992), crabs (Portell et al., 2003), and echinoids (Portell and Oyen, 2002). Mollusks dominate the unit with the other taxa being a minor component. Bivalves are most abundant and consist primarily of infaunal species. Typically, mollusk shells occur as abraded fragments (loose or calcite-cemented) although whole shells can often be found.

Vertebrate fossils typically are uncommon in the Anastasia Formation but have been recovered most often from the Anastasia Formation in Brevard and St. Johns counties. In Brevard County, taxa collected consist of abraded teeth of sharks and bones of turtles, tapir, horse, armadillo, and whales (Portell et al., 2003).

2.2.3 Previous Geochronology Work

Osmond, et al. (1970) using $^{230}\text{Th}/^{234}\text{U}$ age determination and working with shell and beachrock from the Cape Kennedy (Canaveral) barrier and lagoon complex, concluded two major depositional events in the Merritt Island area. The first occurred between 25-50 ka with a majority of the shell samples (5 of 7) falling on a 30 ka isochron. The second occurring between 85-120 ka, with a majority of the shell and coquina samples (8 of 11) falling near a 110 ka isochron.

2.3 METHODS

2.3.1 Sample Strategy and Acquisition

Three locations were chosen to sample the Anastasia Formation due to their location along strike of the formation and their exposure (Figure 1). WCQ-01 (Wilson Coquina Quarry) was collected in a commercial coquina quarry, HCC-01 (Haulover Canal Coquina) was collected in a navigation canal in northern Merritt Island connecting Mosquito Lagoon and Indian River, and DRC-01 (Dalbora Road Coquina) was collected from an exposure in a drainage ditch on Dalbora Road (Figure 2). Although DRC-01 is not directly located within the Anastasia Formation boundaries on the State of Florida Geological map, it is believed that this coquinoid limestone is part of the Anastasia Formation (Scott, T., personal communication).

Two samples (HCC-01 & WCQ-01) were collected using a hand-held diamond core drill with a three-inch core barrel. The cores were placed from the core barrel directly into an opaque black photograph paper bag to minimize exposure to sunlight. DRC-01 was collected at night using a red-filtered flashlight and was hand excavated using a wrecking bar. For the latter sample, exposed coquina on the outcrop was removed using a rock hammer, and an unexposed sample from inside the outcrop was removed and placed into an opaque black bag.

2.3.2 Sample Preparation and Dose-Rate Measurements

All samples were processed at the School of Geography and Earth Sciences at McMaster University under subdued orange light with ultra-violet filtration. Pure quartz grains were obtained using a slightly modified OSL preparation method. The recovered cores of solid coquina were placed in 50% HCl until approximately 2 cm was removed from the outside of the core. This was to insure that any zeroed grains from the drilling process were removed. After discarding the waste sand, the remaining core was digested in 50% HCl. Once the cores were digested, the typical OSL preparation method followed, which include 30% H₂O₂ digestions to remove organics, sieving to obtain proper grain size, heavy liquid separation using Lithium Polytungstate to remove heavy minerals and feldspars, HF digestion for 40 minutes to remove the outer alpha effected layer and to remove any plagioclase, another HCl digestion for 40 minutes to remove any fluorides that may have precipitated during the HF digestion, and finally resieving to remove any grains that no longer fall in the desired size range.

Some dose rates were based on neutron activation analysis (NAA) of ²³²Th and ⁴⁰K and delayed neutron counting (DNC) analysis of ²³⁸U (conducted at the McMaster University Nuclear Reactor). Determination of the elemental concentrations of radioactive ²³⁸U, ²³²Th and ⁴⁰K were from untreated subsamples of the original samples (Table 1). NAA-based dose rates were calculated assuming radioactive equilibrium in the ²³⁸U and ²³²Th decay chains. Dose rates for all three sites were also measured using in situ gamma spectrometry. Moisture contents are usually measured in the lab from the

recovered sediment and used for the dose rate calculation. Due to the constant wetting of the corer, the moisture contents calculated would not represent true field moisture, therefore moisture contents of 5% and 10% were assumed for all samples. Cosmic ray dose rates were calculated using the burial depth (assuming an instant sedimentation rate) and a 2 g/cm^3 of overburden density using calculations by Prescott and Hutton (1988) with the ANATOL program version 0.72B (provided by N. Mercier, CNRS, Paris). The internal ^{238}U and ^{232}Th dose rates were calculated using the average concentration of those radioisotopes in granitic quartz (Rink and Odom, 1991), using an alpha efficiency factor of $0.04 \pm 10\%$.

2.3.3 OSL Measurements and Equivalent Dose Determination

Luminescence measurements were conducted on a RISØ OSL/TL-DA-15 reader using blue light LED stimulation (470 nm) and a 7 mm-thick Hoya U-340 filter (270–400 nm). A calibrated ^{90}Sr beta source was used to perform laboratory irradiations. The single aliquot regeneration (SAR) protocol (Murray and Wintle, 2000) was conducted on a minimum of 24 aliquots to determine a final equivalent dose (De). Quartz grains were mounted on aluminum discs using a 8mm mask and silicon spray. Samples were illuminated for 100 seconds at 125°C . The background (the last 4 s) of the OSL decay curve was subtracted from the “fast” component (first 0.4 s) to determine the samples luminescence signal. Only aliquots whose recycling ratios were within 10% were accepted for De determination.

Thermal transfer and dose recovery tests were performed to determine final De preheat temperature (Madsen et al., 2005). For both tests, twelve aliquots from each sample were optically bleached by blue light illumination for 40 seconds, followed by a 10,000 second pause and another 40 second illumination. For the dose recovery test, the aliquots were given a known dose (29Gy for HCC-01, 29Gy for WCQ-01, and 33Gy for DRC-01). Both tests continued with the standard SAR protocol except the preheat temperatures varied (160, 200, 240, 280°C), with 3 aliquots from each sample receiving a different preheat temperature.

A feldspar contamination check, as outlined by Thompson et al. (2007), was also performed on each sample to insure purity of the quartz grain separates. An initial De was estimated by comparing the natural OSL signal (preheat $T = 200^\circ\text{C}$) of 3 aliquots to the regenerated OSL given by a single dose. A second identical regeneration dose was applied to the same aliquots and the IRSL signal was measured. If a ratio of IRSL to regenerated OSL signal was less than 1% for all aliquots, it is assumed there is no significant feldspar contamination (Forrest, 2003).

De data were analyzed using an exponential plus linear function in the RISØ Luminescence Analyst program (version 3.15b). A weighted mean and standard error was calculated using the Central Age Model spreadsheet (provided by S. Hout & B. Roberts). The central age model explicitly determines the extent of paleodose over-

dispersion between aliquots, and takes this into account when estimating the mean paleodoses (Galbraith et al., 2005). Over-dispersion is defined as the dispersion remaining after photon counting statistics have been taken into account (Galbraith et al., 2005).

2.4 RESULTS

2.4.1 Optical Dating Results

The thermal transfer and dose recovery tests were used to determine the preheat temperature that would give the most accurate De estimates. For each sample the dose recovery test was used to determine which preheat temperature produced a De closest to the given dose (Figure 3). Once this preheat temperature was determined the thermal transfer test was analyzed to insure there was no induced charge transfer at that given temperature. For each of the samples, the thermal transfer at the chosen preheat temperatures was insignificant. Twenty-four aliquots for each sample were used to determine a final De. The De distributions with a 3 mm mask show no conclusive evidence of mixing or incomplete zeroing and radial plots indicate a relatively high individual precision of the SAR equivalent doses (Figure 4). This precision illustrated by the radial plots further adds to the confidence that using the SAR protocol on beachrock is a reliable method of dating.

When the NAA/DNC and the gamma spectrometry dose rates are within error of each other, we believe that the gamma spectrometry dose rate should be used to calculate the OSL age (Table 2). For WCQ-01 and HCC-01 there are minor discrepancies between the ages using the NAA dose rate and the in situ gamma dose rates. We attribute the discrepancy from WCQ-01 to water trapped in the hole from the coring process. The discrepancy for HCC-01 cannot be attributed to water in the coring hole and, in fact, cannot be determined. Therefore, for WCQ-01 and HCC-01, the dose rates calculated from the NAA/DNC data were used in the interpretations of the deposit, while the gamma spectrometry dose rates were used for DRC-01.

OSL ages were calculated for each sample, using appropriate NAA/DNC dose rates or in situ Gamma Spectrometry dose rates or both, 5% moisture content, and 10% moisture content (Table 2). The ages were calculated using the instant accumulation model assuming instantaneous accumulation of sediment with minimal overburden accumulation. The weighted mean ages are given and the error is calculated using one standard error.

2.4.2 Paleontology Results

At the study site, WCQ-01 (Florida Museum of Natural History IP locality SJ002) currently known as Lakeview Dirt Company, 35 marine bivalve species, 15 marine gastropod species, and one species each of freshwater and terrestrial snails were identified from bulk sampling of the shellrock facies just below the coquinooid limestone

facies. Here the bivalves, both in diversity and abundance, far outweigh that of the gastropods. Most abundant were *Donax variabilis*, *Anomalocardia cuneimeris*, *Anadara transversa*, *Stewartia floridana*, and *Mulinia lateralis*. All of the marine mollusks identified from the site have living cognates that today inhabit nearshore, shallow water environments of Florida.

At the study sites, paleontologists from the Florida Museum of Natural History (FLMNH) collected abundant remains of cartilaginous and bony fishes, amphibians, reptiles (especially turtles), birds, and mammals (e.g., rodent, camel, horse). Collectively the invertebrate fauna, consisting of still living species, and the vertebrate fauna, determined to represent the Rancholabrean North American Land Mammal Age (300 ka to 10 ka) (R. Hulbert, per. comm.), indicates that the time of deposition at the study site was restricted to the late Pleistocene.

2.5 DISCUSSION

Coquina may not be an ideal material to optically date since there are possible problems determining the dose rate over the entire burial period. Since OSL dates the deposition of the quartz sand grains and not the cementation of the sediment, ages obtained by OSL would represent the time when sea level was near that location. There is little doubt the quartz grains have been optically bleached, due to its nearshore/shoreface depositional environment (Rink & Pieper, 2001).

One issue of concern about dating beachrock is the dose rate. The issue of dose rate is actually two-fold. The first issue is whether mollusks in whole matrix are closed systems with respect to U-migration after burial and the second issue is if there is any change in dose rate associated with the cementation event which might increase the dose rate significantly if the cementation event occurred much later than the depositional event associated with uncemented sediment dose rates. Previous authors have assumed that coquina acts as a closed system with respect to Uranium and can be treated as a closed system (French et al., 2001; Tatumi et al., 2003; Bateman et al., 2004; Armitage et al., 2006; Tatumi et al., 2006).

The OSL ages of Anastasia Formation, from the three samples that were collected, are well within marine isotope stage (MIS) 5, which is believed to be the last time sea level rose as high as present (Szabo, 1985; Muhs et al., 2002; Potter and Lambeck, 2003; Wehmiller et al., 2004). Sea-level position during MIS-5 is controversial (Mallinson et al., 2008). As such the results are in good agreement with some of Osmond et al.'s (1970) previous work. Figure 5 illustrates global sea level heights during the three MIS-5 substages and suggests that only during MIS-5e did sea levels reach as high as present.

Along the U.S. Atlantic Coast there are several examples that dispute the global sea level curves (Cronin et al., 1981; Potter and Lambeck, 2003; Burdette, 2005; Mallinson et al., 2008; Parham et al., 2008). Based on the elevations of the Key Largo

Limestone at Windley Key and Key Largo, sea level during the last interglacial period (MIS-5e) must have been at least 5-8 m above present (Muhs et al., 2004). Cronin et al. (1981) using uranium series ages of fossil corals concluded that sea level was 7.5 +/- 1.5 m above present sea level at 120 ka. Cronin et al. (1981) also argued that sea level was 6.5 +/- 3.5 m above present sea level at 94 ka, while Potter and Lambeck (2003) modeled sea level during MIS-5c to be ~10 m below MSL. Relative to present, MIS-5a sea levels range from -19 m to more than +3 m between Barbados, Haiti, the Bahamas, Florida, Bermuda and the U.S. Atlantic Coast (Potter and Lambeck, 2003). Geochronological studies of reefs and speleothems in the Bahamas, Bermuda, Haiti, and Barbados reconstructed MIS 5a sea level from -18 to -13 m MSL (Toscano and Lundberg, 1999), but Cronin et al. (1981) argued that 72 ka sea level was 7 +/- 3 m above present sea level. Mallinson et al. (2008) concluded, based on several OSL ages in the coastal plain of North Carolina, that sea level during MIS-5a was at or above present.

DRC-01, approximately 2 m above sea level, probably represents either a MIS-5e or a MIS-5c nearshore deposit. The age range of DRC-01 is 100.3 – 119.4 ka considering all age uncertainties. The γ -dose rates from the in situ measurements and the gamma spectrometer measurements are statistically indistinguishable, and give us the highest confidence in this sample. WCQ-01, approximately 8 m above sea level, also probably represents either a MIS-5e or a MIS-5c nearshore deposit. The age range of WCQ-01 is 106.9 – 128.3 ka using the NAA/DNC γ -dose rates. The in situ γ -dose rates were problematic as mentioned above and therefore not considered in age determination.

Although it cannot be definitively determined when sea level raised, either MIS-5e or MIS-5c, the argument can be made that sea level rose to approximately 8 m above present based on the approximate elevation of WCQ-01 and the depositional environment of WCQ-01, a nearshore deposit. At DRC-01, there are Anastasia Formation deposits located to the west of Merritt Island along the shore of the mainland (Figure 1). This suggests that if these date to the same age range, sea level rose higher than the elevation of DRC-01 (2 m) and possibly to the elevation of WCQ-01 (8 m).

HCC-01, approximately 2 m above sea level, is the youngest of the three samples and probably represents a shoreline deposit during MIS-5a. The age range of HCC-01 is 66.8 – 91.6 ka considering all age uncertainties. The variations in these ages are mainly due to the choice of γ -dose rate. The counting rate of the in situ gamma spectrometer was very close to minimal confidence relative to instrument background. The counts per unit time were barely above 3x internal instrument background, which decreases our confidence in the use of the in situ γ -dose rate and therefore is leading us to favor the NAA/DNC ages (76.7 – 91.6 ka).

However, Cronin et al. (1981), Szabo (1985), and Wehmiller et al. (2004) who used closed-system assumption $^{230}\text{Th}/^{234}\text{U}$ dating of corals and Mallinson et al (2008) and Parham et al. (2008) using OSL on nearshore deposits indicate ages in the 70 – 80 ka range. Therefore if this deposit is related to nearshore sedimentation in less than a few

meters of water and reflects sea level as would corals, we wish to leave open the possibility that the strip of land hosting the HCC-01 dates potentially to our youngest possible age of 66.8 ka, but could also date to as old as 91.6 ka. Also, HCC-01 is located east of DRC-01, and if DRC-01 represents a MIS-5e or MIS-5c shoreline, the MIS-5a time frame would fit geomorphically.

2.6 CONCLUSION

OSL dating of the upper part of the Anastasia Formation confirms the finding of Osmond et al. (1970) that some of the Anastasia dates to MIS-5 and the estimates of McNeill (1985) that the surficial deposits of this coquina were deposited around 100 ka. The results presented also confirm Brooks' (1972) idea that "the Anastasia was formed during several depositional events..." based on the two groups of MIS-5 OSL ages. The first group of OSL ages, based on two samples, groups in MIS-5e (~112 ka) or MIS-5c (~105 ka) and suggests that sea level during one of these times reached approximately 8 m above present, assuming our interpretation of nearshore deposition is correct and that none of these units constitute dune facies of the Anastasia, though these have not been clearly recognized in the past. The second group, based on one sample, dates to MIS-5a (~83 ka) and suggests that sea level during MIS-5a reached to slightly above present sea level.

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Table 2.1. Location, approximate elevation, and U, Th, and K values of Anastasia Formation samples, which were determined by NAA/DNC on sub-samples derived from the OSL samples prior to chemical treatments.

Sample Name	Coordinates (WGS 84)	Approx Elevation above MSL (m) [a]	U ²³⁸ (ppm)	Th ²³² (ppm)	K (%)
HCC-01	28 44.158'N 80 45.228'W	2	0.70	0.63	0.0397
WCQ-01	29 52.889'N 81 21.147'W	8	0.51	0.86	0.0674
DRC-01	28 28.694'N 80 40.535'W	2	1.48	1.16	0.0607

[a] Elevations were estimated using the Florida digital elevation model (USGS, 2005).

Table 2. Luminescence Dating Results

Sample Name	Sample Depth (cm)	De (Gy)	Cosmic Dose Rate ($\mu\text{Gy/a}$) [a]	Water Content (%) [b]	NAA/DNC Gamma Dose ($\mu\text{Gy/a}$)	In Situ Gamma Dose ($\mu\text{Gy/a}$)	Beta Dose ($\mu\text{Gy/a}$)	Total Internal Dose ($\mu\text{Gy/a}$)	Annual Dose ($\mu\text{Gy/a}$) [b]	SAR-OSL age (ka) [c]	Marine Isotope Stage
HCC-01	244	33.2 $\pm$ 1.2	151.02 $\pm$ 15.1 (IA)	10.0	108.8 $\pm$ 10.7		119.2 $\pm$ 12.5	10.5 $\pm$ 2.3	389.5 $\pm$ 16.6	78.8 – 91.6	MIS-5a
				10.0		171.8 $\pm$ 8.5	119.2 $\pm$ 12.5	10.5 $\pm$ 2.3	452.6 $\pm$ 15.3	77.9 – 68.7	MIS-5a
				5.00	113.5 $\pm$ 11.1		119.2 $\pm$ 12.5	10.5 $\pm$ 2.3	400.0 $\pm$ 17.4	89.1 – 76.7	MIS-5a
				5.00		179.3 $\pm$ 8.9	119.2 $\pm$ 12.5	10.5 $\pm$ 2.3	465.7 $\pm$ 16.0	75.6 – 66.8	MIS-5a
WCQ-01	266	45.6 $\pm$ 1.9	146.76 $\pm$ 14.6 (IA)	10.0	105.3 $\pm$ 10.8	N/A	120.4 $\pm$ 11.6	10.5 $\pm$ 2.3	383.1 $\pm$ 16.0	128.3 – 109.7	MIS5e-MID5c
				5.00	109.9 $\pm$ 11.2	N/A	120.4 $\pm$ 11.6	10.5 $\pm$ 2.3	393.4 $\pm$ 16.7	124.9 – 106.9	MIS5e-MID5c
DRC-01	60	73.0 $\pm$ 3.0	194.43 $\pm$ 19.4 (IA)	10.0	217.3 $\pm$ 11.1		233.1 $\pm$ 11.8	10.5 $\pm$ 2.3	655.4 $\pm$ 16.3	119.4 – 103.4	MIS5e-MID5c
				10.0		222.4 $\pm$ 10.4	233.1 $\pm$ 11.8	10.5 $\pm$ 2.3	660.5 $\pm$ 15.9	117.5 – 103.5	MIS5e-MID5c
				5.00	226.8 $\pm$ 11.5		233.1 $\pm$ 11.8	10.5 $\pm$ 2.3	676.0 $\pm$ 17.1	115.7 – 100.3	MIS5e-MID5c
				5.00		232.1 $\pm$ 10.8	233.1 $\pm$ 11.8	10.5 $\pm$ 2.3	681.3 $\pm$ 16.6	113.8 – 100.4	MIS5e-MID5c

[a] Cosmic dose rate value calculated using an instant accumulation model (IA) and an overburden density of 2 g/cm³.

[b] All β and γ dose rates were calculated based on U, Th, and K concentrations of each sample accounting for moisture values of the sample.

[c] Datum for SAR-OSL ages is A.D. 2008.

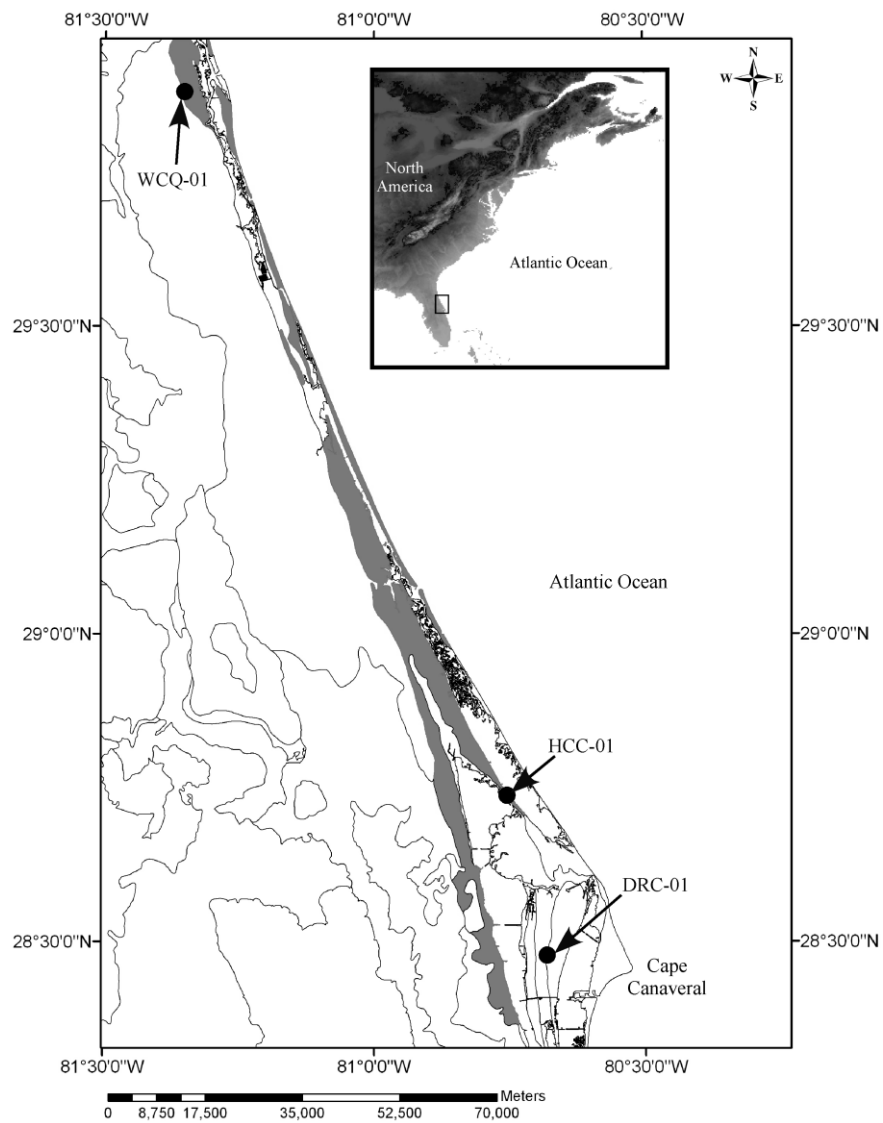


Figure 2.1. Geologic map of Florida showing core locations. The Anastasia Formation is represented by the shaded polygons.

HCC-01



WCQ-01



DRC-01

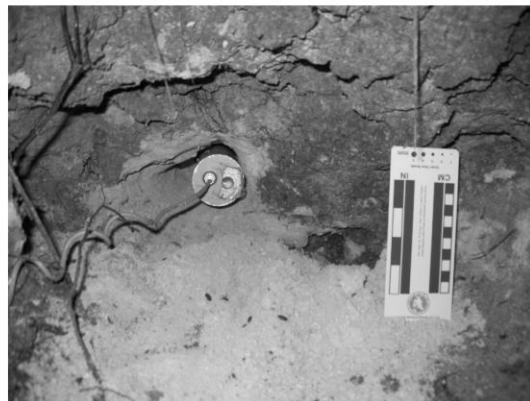


Figure 2.2. Photographs of each sample location.

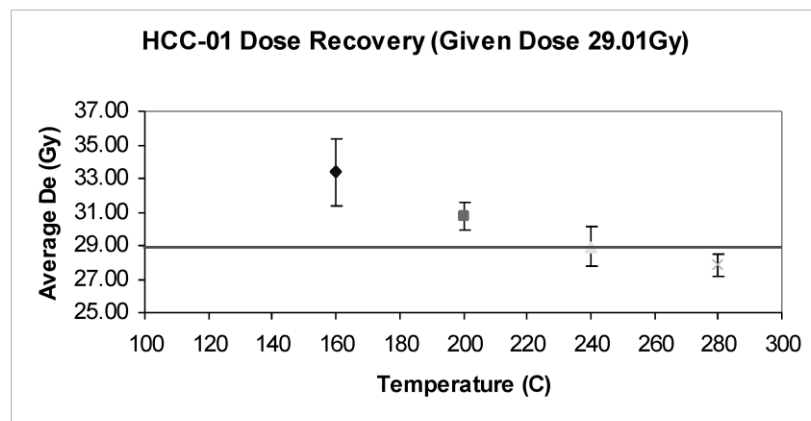
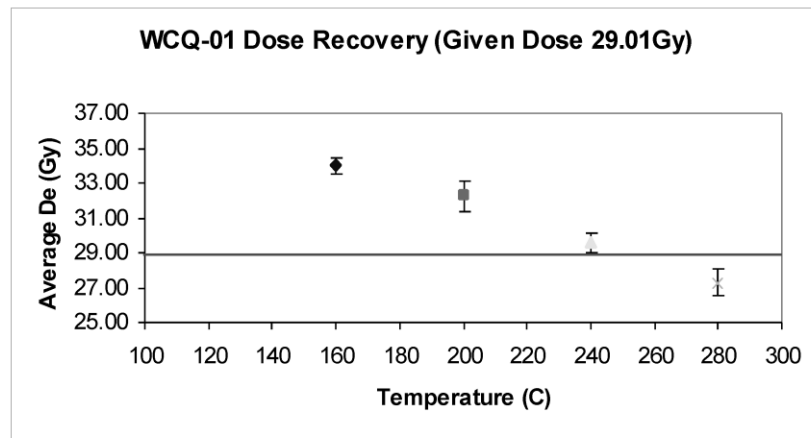
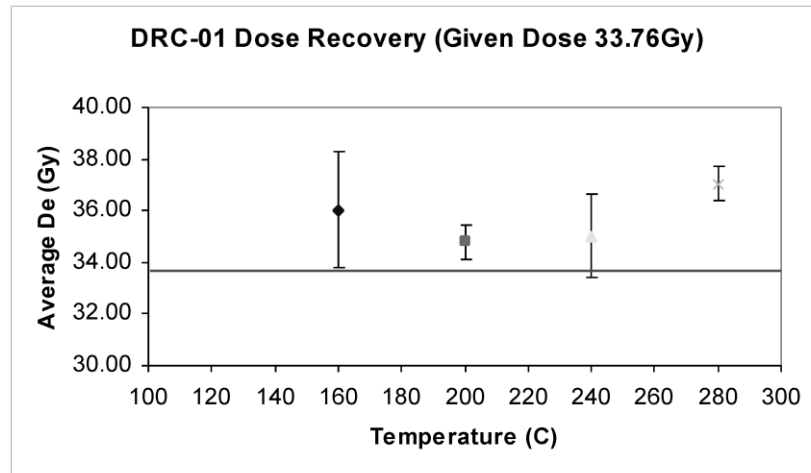


Figure 2.3. Dose recovery tests for each sample. The line drawn represents the known dose given to each laboratory bleached sample.

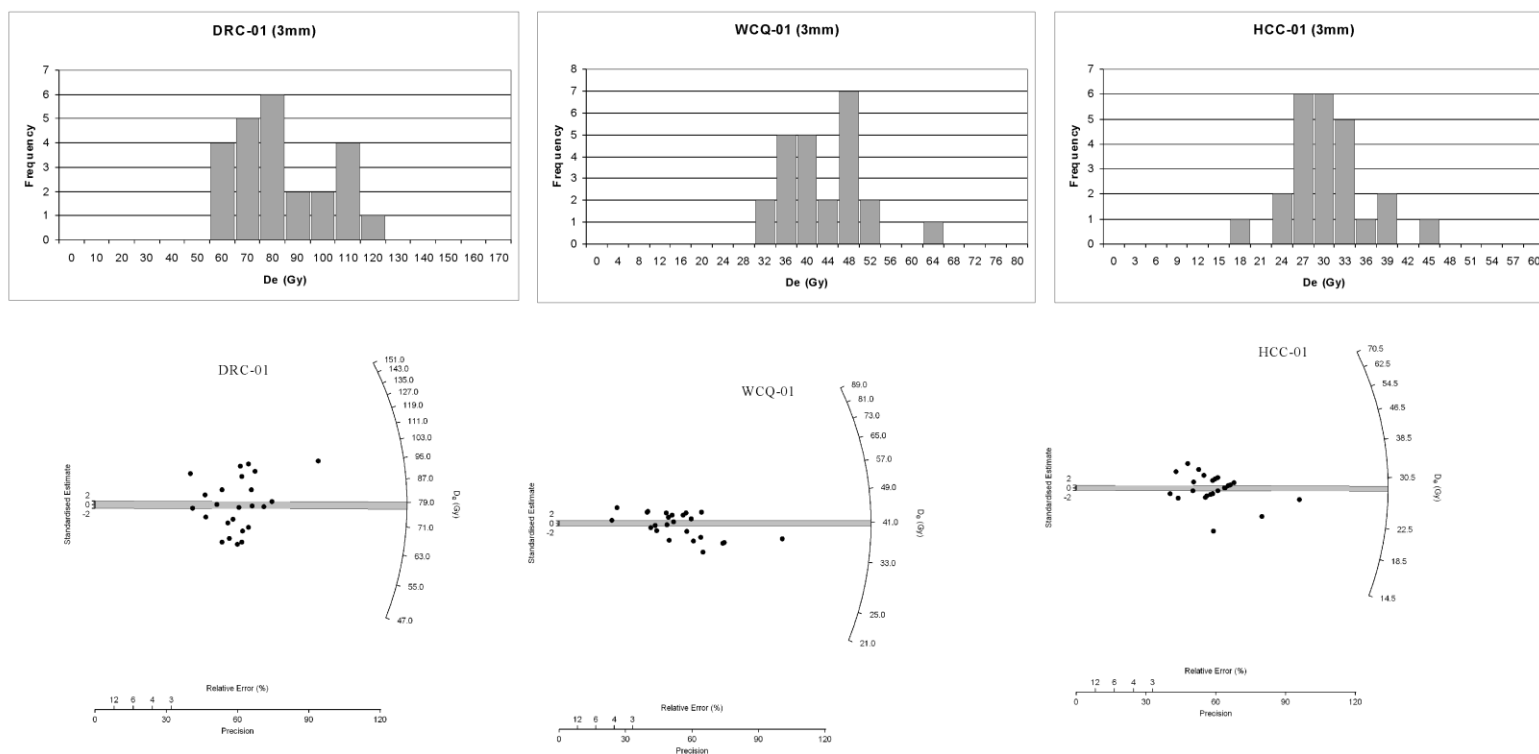


Figure 2.4. Radial Plots and De distributions for each sample using an 3 mm mask. All aliquots were included.

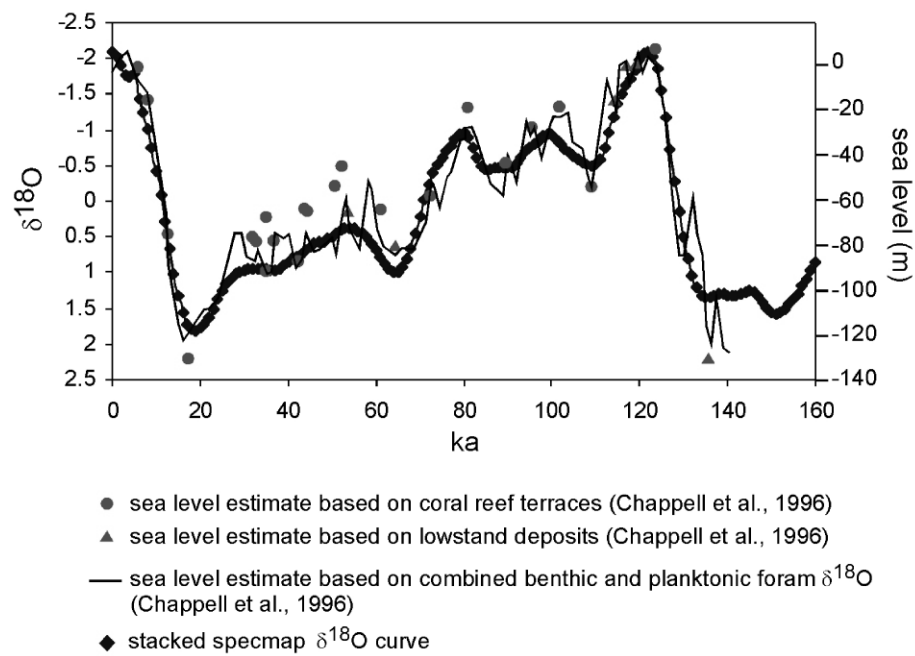


Figure 2.5. Comparison of the SPECMAP marine $\delta^{18}\text{O}$ curve (Imbrie et al., 1989; MacIntyre et al., 1989), coral reef terraces (Chappell et al., 1996; Cabioch and Ayliffe, 2001), and foraminiferal $\delta^{18}\text{O}$ data (Chappell et al., 1996; Linsley, 1996).

CHAPTER 3

GEOLOGIC INVESTIGATION AND OPTICAL DATING OF THE MERRITT ISLAND SAND RIDGE SEQUENCE, EASTERN FLORIDA, USA.

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ABSTRACT

Ground penetrating radar (GPR) and the single-aliquot regenerative-dose (SAR) was used to determine the depositional environments and age of the Merritt Island sand ridge sequence. Five direct-push cores and ten OSL ages were collected. A new model of cosmic dose rate calculation, which removes the much younger aeolian cap, was utilized for the first time and helped produce more consistent OSL ages. Based on our data and samples, the Merritt Island sand ridges are a classic beach ridge set that was deposited during the MIS-5c sea-level highstand. This is supported by the results of Osmond (1970) based on U/Th ages and Burdette et al. (2009) based on OSL ages of a coquinoid limestone west of the beach ridge sequence.

3.1 INTRODUCTION

A multi-proxy approach was undertaken to determine the depositional history of a sand ridge sequence on Merritt Island, Florida. Ground penetrating radar (GPR) surveys allowed for the identification of radar facies that when coupled with defined lithofacies can be indicative of certain depositional environments (Burdette et al., 2009; Mallinson et al., 2010). Optically stimulated luminescence (OSL) dating allowed for burial age calculation of selected samples within the sequence and defined facies. Direct-push electrical conductivity (DPEC) allowed for high-resolution characterization of hydrostratigraphic features in the unconsolidated sediment.

Improved techniques in subsurface visualization utilizing GPR have led to an increase in its use in coastal environments (Van Heteren et al., 1994; Jol et al., 1996; Bristow et al., 2000; Jol et al., 2002; Mallinson et al., 2010). GPR can image high-resolution (cm scale) stratigraphy in shallow subsurface sand, gravel, and organic-rich material with the best results obtained in clean (free of silt and clay), quartz-rich, thick, clastic sediments (Smith and Jol, 1995). Van Heteren et al. (1994) developed one of the first tables that characterized various geometries and their relationship to the modern coastal facies. Bristow et al. (2000) conducted a similar GPR study of the foredunes in Norfolk, UK and identified seven different radar facies.

Luminescence dating methods encompass a range of techniques which, based on a radiation-produced charge population trapped within crystalline sedimentary materials, are capable of determining the period of time that has elapsed since the last time the trapped charge population was reset (Stokes, 1999). OSL fills an important niche in coastal geochronology where datable carbon or carbonates are absent or deposits of interest are beyond the range of radiocarbon dating. Numerous studies have been conducted on aeolian and coastal systems utilizing OSL with very encouraging results (Murray-Wallace et al., 2002; Berger et al., 2003; Tatumi et al., 2003, Frechen et al., 2004; Rink & Forrest, 2005; Lian & Roberts, 2006; Burdette, 2005; Mallinson et al., 2008a; Mallinson et al., 2008b; Wintle, 2008).

The measurement of the electrical resistivity (the inverse of conductivity) has long been used as a logging tool in open boreholes for both water well and oil well applications (Christy et al., 1994). The electrical conductivity associated with sedimentary materials varies with particle size, mineralogy, and matrix properties (Schulmeister et al., 2003). Silt- and sand-sized particles of covalently bonded minerals, such as quartz, mica, and feldspar, are generally nonconductive, as opposed to clay-sized particles, which tend to be very conductive (Schulmeister et al., 2003). Therefore minute vertical changes in lithology and clay-sized particles can easily be detected and characterized using DPEC. In coastal sediments, the freshwater/saltwater interface may also be noted due to the contrast in resistivity.

By combining the use of these techniques, an accurate assessment of coastal evolution in response to process variables is possible. This manuscript presents data that reveal the accretion of a mixed carbonate-siliciclastic coastal system during multiple sea-level cycles of the late Pleistocene.

3.2 PREVIOUS REGIONAL WORK

The majority of the geologic work conducted in the Merritt Island/Cape Canaveral area predates or coincides with the development of the John F. Kennedy Space Center. Brown et al. (1962) conducted the first thorough geologic investigation of Brevard County and produced a table of the stratigraphic units of Brevard County, Florida (Table 1). Schmalzer and Hinkle (1990) used this table as well as core data from a preexisting National Aeronautics and Space Administration (NASA) report to generate two cross-sections on Merritt Island. The cross sections indicate that the upper ~40 ft (~12 m) is unconsolidated fine to medium sands of Pleistocene and Pliocene age.

Most of the arguments about the depositional age of Merritt Island are based on terrace location (Cooke, 1945; Kofoed and Gorsline, 1963; Alt and Brooks, 1965). It wasn't until Osmond et al. (1970) and later Rink and Forrest (2005) that absolute age controls were placed on the formation of Merritt Island/Cape Canaveral. Brooks (1972) argued the western portion of Merritt Island to be Yarmouth glacial period (~240,000 years ago) in age and the eastern sand ridge section to be Sangamon interglacial period (~132,000 – 71,000 years ago) in age. The Yarmouth age is based on the discovery of an *Archidiskodon haroldcooki* (a primitive mammoth that is distinctly found in the late Pleistocene Rancholabrean time) skeleton and teeth (Brooks, 1972). The Sangamon age is based on the open-system U- series dating with modeling of shallow-water mollusk shells conducted by Osmond et al. (1970).

Osmond et al. (1970) performed U-Th age analysis on samples from nine locations around Brevard County, Florida. The nine samples clustered into three isochrones; recent, 30,000 years before present (ybp), and 100,000 ybp. The two samples collected in southeastern Merritt Island fall into the 30,000 ybp and the 100,000 ybp isochrones, even though they are only located a few miles apart. Kaufman et al. (1971) argued that dates

obtained on mollusks by the U-series isotope methods are highly questionable and that isotope migration is a common phenomenon and occurs in ways which can neither be reliably corrected for, nor even detected. However, the ~30,000 ybp age of Merritt Island was later roughly confirmed by Rink and Forrest (2005), who used OSL dates on sands derived from samples collected from the crest of a beach ridge (Figure 2).

Burdette et al. (2009) used OSL to date the deposition of the Anastasia Formation at three locations (Figure 1, locations 1, 2, and 3). Results confirm the finding of Osmond et al. (1970) and Mc-Neill (1985) that the upper coquinoid limestone of the Anastasia Formation dates to marine isotope stage 5 (MIS-5) and the surficial deposits of this coquina were deposited around 100 ka. Two of Burdette et al.'s (2009) OSL ages group in MIS-5e (~112 ka) or MIS-5c (~105 ka): 1) at Wilson Coquina Quarry on the Atlantic Coastal Ridge west of St. Augustine and 2) on Merritt Island's Dalboro Road in the Atlantic Barrier Chain just west of our transect presented herein. The elevation of the Wilson Coquina sample suggests that relative sea level during one of these times reached approximately 8 m above present. The third location at Haulover Canal (location 3 on Figure 1) dates to MIS-5a (~83 ka) and suggests that relative sea level during MIS-5a reached to slightly above present sea level at that location in the Atlantic Barrier Chain. The results presented by Burdette et al. (2009) also confirm Brooks' (1972) idea that "the Anastasia was formed during several events..." based on three MIS-5 OSL ages. The first two OSL ages group in MIS-5e (~112 ka) or MIS-5c (~105 ka) and suggests that relative sea level during one of these times reached approximately 8 m above present. The third dates to MIS-5a (~83 ka) and suggests that sea level during MIS-5a reached approximately 2 m above present sea level.

Rink and Forrest (2005) also used OSL to place absolute age controls on the deposition of beach ridges on Cape Canaveral, Merritt Island, and mainland Brevard County. The majority of their study was conducted on Cape Canaveral with only one OSL age in Merritt Island. This sample was collected in the northeastern part of Merritt Island at a depth of ~100 cm below ground surface (Figure 2). The age of this sample (CC8) was $43,750 \pm 3,640$ ybp.

3.3 METHODS

3.3.1 Geophysical

Four and a half kilometers of GPR data were collected throughout the study area in order to define radar facies and reflectors that are indicative of specific depositional environments (Figure 2). Data were collected along a single shore-normal (east-west) transect.

GPR data were acquired using a truck traveling between 3-5 miles per hour. A Geophysical Survey Systems Inc.® (GSSI) 200 MHz antenna was towed behind the truck while the passenger monitored the readout on the Subsurface Interface Radar (SIR) 2000

and collected notes. Data were collected at 16 bits/sample, 512 samples/scan, and 8 scans/second (approximately 6 scans/meter). Navigation data, recorded in WGS84 format, were obtained using a WAAS enabled Garmin 76CSx Global Positioning System (GPS) unit, which the driver monitored. Waypoints were recorded simultaneously on the GPR and GPS systems.

The raw GPR data were processed using Radan software[®], which included bandpass filtering (75-225 MHz), gain adjustment, and stacking (3x). Processed data were exported as bitmap files into Canvas[®]. The major reflectors were traced and separated from the GPR line to help visualize depositional groups and define radar facies.

Two core locations (Tel-01 and Tel-04) were drilled using a direct-push EC logger (Figure 2). Data were collected every 0.015 m and depth was measured using a rig-mounted potentiometer. The data were stored in spreadsheet form, and then plotted on a graph of depth (m) vs. electrical conductivity (mS/m).

3.3.2 Sample Strategy & Acquisition

Five core locations were chosen using the GPR data in an attempt to recover multiple lithofacies in a single core (Figure 2). Core locations were documented using a Garmin 76CSx GPS unit. Four of the cores (Tel-01, Tel-02, Tel-03, & Tel-05) penetrated ~20 ft (~5.8 m) and Tel-04 penetrated ~24 ft (~7.0 m). After each core was collected and visually logged in the field, a second hole directly beside the original was drilled for optical dating samples. An opaque core liner was used and the desired depth was sampled. The core liners were then extracted directly into a 2.5 mm- thick black bag and taped closed.

3.3.3 Lithology

In the laboratory, the cores were opened, visually logged, photographed, and sampled for lithology. Laser diffraction particle size analysis was conducted on a Beckman-Coulter LS 230 (BC LS 230) at 10 cm intervals and mathematical computations were computed for each sample using the Fraunhofer optical model (Murray, 2002). Surface plots were constructed using Geosoft Oasis[®] for all cores as outlined by Beierle et al. (2002). Surface plots of grain size data allow qualitative interpretation of the characteristics of the entire particle size distribution (PSD) and thus can provide important insights into depositional processes and changing environmental conditions Beierle et al. (2002).

3.3.4 Optical Dating

All optically-dated samples were processed at the School of Geography and Earth Sciences at McMaster University under UV-filtered subdued orange light. Pure quartz grains were obtained using standard OSL preparation methods which include HCl and

H₂O₂ digestions to remove carbonates and organics respectively, sieving to obtain desired grain size, heavy liquid separation using Lithium Polytungstate to remove heavy minerals and feldspars, HF digestion to remove the outer alpha effected layer, a second H₂O₂ digestion to remove any remaining feldspars and any fluorides that may have formed during the HF digestion, and finally resieving to remove any grains that no longer fall in the desired size range (150 – 212 μ).

Dose rates were based on neutron activation analysis (NAA) of ²³²Th and ⁴⁰K and delayed neutron counting (DNC) analysis of ²³⁸U (conducted at the McMaster University Nuclear Reactor). Untreated subsamples of the original samples were used to determine the elemental concentrations of radioactive ²³⁸U, ²³²Th and ⁴⁰K (Table 2). NAA/DNC-based dose rates were calculated assuming radioactive equilibrium in the ²³⁸U and ²³²Th decay chains.

Luminescence measurements were conducted on a RISØ OSL/TL-DA-15 reader using blue light LED stimulation (470 nm) and a 7 mm-thick Hoya U-340 filter (270–400 nm). A calibrated ⁹⁰Sr beta source was used to perform laboratory irradiations. The single aliquot regeneration (SAR) protocol (Murray and Wintle, 2000) was conducted on a minimum of 24 aliquots to determine a final equivalent dose (De). Quartz grains, between 150-212 microns, were mounted with silicon spray on aluminum discs using a 3mm and a 1mm mask and were illuminated for 100 seconds at 125° C. The background (the last 4 s) of the OSL decay curve was subtracted from the “fast” component (first 0.4 s) to determine the samples luminescence signal. Only aliquots whose recycling ratios were within 10% were accepted for equivalent dose (De), also known as paleodose, determination.

Thermal transfer test and dose recovery test were performed to determine the final De preheat temperature (Madsen et al., 2005). For both tests, twelve aliquots from each sample were optically bleached by blue light illumination for 40 seconds, followed by a 10,000 second pause and another 40-second illumination. For the dose recovery test, the aliquots were given a known dose. Both tests continued with the standard SAR protocol except the preheat temperatures varied (160, 200, 240, 280° C), with 3 aliquots from each sample receiving a different preheat temperature. For each sample the dose recovery test was used to determine which preheat temperature produced a De closest to the given dose. Once this preheat temperature was determined the thermal transfer test was analyzed to insure there was no induced charge transfer at that given temperature.

A feldspar contamination check, as outlined by Thompson et al. (2007), was also performed on each sample to insure purity of the quartz grain separates. An initial De was estimated by comparing the natural OSL signal (preheat T = 200° C) of 3 aliquots to the regenerated OSL given by a single dose. A second identical regeneration dose was applied to the same aliquots and the IRSL signal was measured. If a ratio of IRSL to regenerated OSL signal was less than 1% for all aliquots, it is assumed there is no significant feldspar contamination (Forrest et al., 2003).

Moisture contents were measured in the lab from the recovered sediment and used for the dose rate calculations for the younger samples. If the samples were deposited before the last glacial maximum (LGM), then a moisture of 7% was used as an estimate of the moisture content throughout the samples burial history. The internal ^{238}U and ^{232}Th dose rates were calculated using the average concentration of those radioisotopes in granitic quartz (Rink and Odom, 1991), using an alpha efficiency factor of 0.04 +/- 10%. Cosmic ray dose rates were calculated using the burial depth and a 2 g/cm³ of overburden density using calculations by Prescott and Hutton (1988) with the ANATOL program version 0.72B (provided by N. Mercier, CNRS, Paris). Burial depth was determined by using the linear accumulation model or instant accumulation model. The linear accumulation model assumes sedimentation has been constant throughout its depositional history and not instantaneous. For the linear accumulation model, one half the true burial depth is used in the cosmic dose calculation.

De values and their associated errors for each aliquot were calculated using an exponential plus linear function in the RISØ Luminescence Analyst program (version 3.15b). Over-dispersion and De for each sample were calculated using the Central Age Model (written by S. Huot and provided by R. Roberts). The Central Age Model explicitly determines the extent of De over-dispersion between aliquots, and takes this into account when estimating the mean De values and their precisions (Galbraith et al., 2005). Over-dispersion is defined as the relative standard deviation of the De estimates, above and beyond that due to photon counting statistics and curve-fitting uncertainties (Roberts and Galbraith, in press).

Histograms, comparing the 3mm mask data and the 1mm mask data, and radial plots were constructed to graphically display the De distributions (Figure 3). Histograms are effective at illustrating the shape of a distribution (in addition to its location and spread), however they do not take into account the precision associated with each De value (Roberts and Galbraith, in press). Therefore, in addition to histograms, radial plots were constructed. A radial plot is a graphical display for comparing estimates that have differing precision (Galbraith, 2005). It is essentially a scatter plot that plots a standardized estimate on the y-axis against the precision (defined as the reciprocal of the standard error of the estimate) on the x-axis (Roberts and Galbraith, in press).

3.4 RESULTS

3.4.1 Geophysics

Ground penetrating radar and lithologic descriptions were used to define radar facies (RF). RF1 is characterized by continuous, high amplitude, horizontal reflectors and is uniformly one to two meters in thickness. RF1 is identified as remobilized sands or an aeolian sand sheet (Figure 6). RF2 is characterized by continuous (>10m), low-angle landward dipping (westward-dipping) clinoforms and is interpreted as an overwash fan or

and aeolian sand sheet. RF2 appears to begin around Tel-03 and end around Tel-04. RF3 is characterized by discontinuous, low to medium amplitude, seaward dipping (eastward-dipping) clinoforms and is interpreted as beach ridge foreslope accretion. RF3 has been identified by numerous authors in marine and lacustrine environments (Van Heteren, 1994; Jol et al., 1996; Bristow et al., 2000; Burdette, 2005; Mallinson et al., 2008a; Burdette and Mallinson, 2008).

3.4.2 Lithology

Figures 4 and 5 illustrate the homogeneity of the sediments that compose the upper ~6m of the Merritt Island sand ridge sequence. The PSD plots for Tel-01 and Tel-04 demonstrate clearly that although the mean grain size remains nearly constant downcore, variations in silt concentrations are partly responsible for differentiating lithofacies. Without the use of the PSD plots these variations may have gone unnoticed. The fluctuations in the EC mimic the PSD color variations and appear to be controlled largely by the abundance of clays. Conductivity is generally highest where clay content is high. It should be noted that EC graphs are a relative graph and can not independently determine grain size. Therefore EC graphs should always be ground-truthed with a separate method such as grain-size analysis or in this case PSD.

Four lithofacies were defined in the Merritt Island sequence. Rooted sands (rS) occurred in the upper 2m of each core and represent the modern topsoil. These rooted sands correlate with RF1. The EC record that corresponds to rS is highly variable, which is expected with the roots and clay variations that make up the modern soils. Massively bedded sands (mbS) occur in most cores; however Tel-04 contained a ~3m section. The EC record that corresponds to the mbS in Tel-01, suggests varying amounts of silts and clays, shown in the irregularity of the record (Figure 4). Based on modern environments, massively bedded sands could represent several depositional environments including flood-tidal deltas, overwash fans, back-barrier sand flats, and aeolian deposits (Susman and Heron, 1979; Reinson, 1992; Culver et al., 2005).

Laminated sand (lS) was recognized in all the cores, except Tel-03, usually in the lower portion of the core. The EC record that corresponds with the lS in Tel-01 and Tel-04 is quite different than the mbS. The EC record of the lS in Tel-04 is a relatively smooth record with a gradual decrease in signal with depth. Typically, in coastal environments, heavy minerals cause the laminations, but this area lacks significant heavy mineral sands, therefore the laminations are created by slightly muddier sands or sands of a very minute grain size difference. Laminated sands are typical of modern barrier island deposits in a variety of environments including flood-tidal deltas, distal overwash fans, foreshore and backshore deposits, aeolian dunes, and back-barrier berms (Susman and Heron, 1979; Culver et al., 2005).

Shelly sand (sS) was present in Tel-03 and at the base of Tel-04, Tel-02, and Tel-05. The shell and shell fragments were identified as *Donax sp.*, which live in the high

energy swash zones of Florida's modern beaches. The shelly sand in Tel-03 was quite different from that in the other cores. It graded from a nearly cemented, very limey, shelly sand with shell concentrations around 25% (~2.8m-3.5m) to a nearly 50% highly fragmented shelly sand (~3.75m) that slowly graded into a shelly sand with only 2-5% shell fragments at the bottom of the core. It should be noted that Tel-03 was collected less than 100 yards from the edge of the coquina described in Burdette (2009) (Figure 6).

3.4.3 Optical Dating

The OSL ages are defined by four groups. Group Four is defined by Tel04-02 (111.1-130.5 ka) and is interpreted as being deposited during MIS-5e. Group Three includes Tel01-01 (89.9-103.9 ka), Tel01-02 (89.9-103.9 ka), Tel02-01 (90.5-108.7 ka), and Tel04-01 (87.3-99.3 ka) and is interpreted as being deposited during MIS-5c. Group Two includes Tel02-02 (69.0-82.0 ka), Tel02-03 (81.6-96.4 ka), Tel03-01 (67.0-80.4 ka), and Tel05-01 (76.2-89.6 ka). Group Two is interpreted as being deposited during MIS-5a. Group One includes Tel03-03 (18.9-22.7 ka) and is interpreted as being deposited during the LGM.

As is typical of Florida coastal environments, the low content of U, Th, and K render the totally dose rate's composition to one with a large proportion of cosmic dose rate. We found it necessary to consider carefully the average burial depth for the entire history of burial in order to properly calculate the cosmic dose rate in these circumstances. In our sites there was an aeolian layer (RF1) that was conservatively estimated to be about 1m thick in all cores. This layer was probably deposited in the last 15,000 years or so, based on similar studies in the southeastern US (Ivester et al., 2001, Burdette, 2005, Mallinson et al, 2008a, Mallinson et al, 2008b). Therefore over the entire history of burial it was only present for a relatively short time and we had to adjust the depth of burial by employing a model that incorporated stripping off the overburden. We refer to this procedure used for the first time here the aeolian cap removal model (ACRM). Corrected sample depths are listed in Table 2. Until this model was used, the ages were found to exhibit much more scatter, and did not cluster into mainly MIS-5c, nor did they make sense with respect to the geology.

3.5 DISCUSSION

The base of the Merritt Island sand ridge sequence is composed of seaward dipping clinoforms labeled in the radargrams as RF3 and identified as a foreshore deposit (Figure 6 and Figure 7). This interpretation is consistent with the lithofacies found in cores. In the cores, RF3 generally coincides with the IS lithofacies and in some cores (Tel02, Tel04, and Tel05) this IS lithofacies grades into an sS with depth (~5-6 m). The one OSL age that can clearly be identified as RF3 (Tel04-02), dates between 111.1 Ka and 130.5 Ka and has an over-dispersion of 20%. Also the histograms show no evidence of mixing or incomplete zeroing based on the decrease of mask size from 3mm to 1mm.

Tel02 and Tel05 were located at the eastern end of the transect (Figure 2) and due to the low elevation (0-1 m above mean sea level) and intrusion of brackish water, the radar signal was slightly attenuated. Tel02-01, Tel02-03, and Tel05-01 all cluster in MIS-5c, while Tel02-02 appears to have an anomalously young age associated with MIS-5a. The over-dispersions of the four samples are 29%, 26%, 26%, and 25%, respectively.

Radar facies RF2 is composed of low-angle landward dipping clinoforms and may represent back-barrier sand flats, consisting of overwash or aeolian sand sheet facies (Figure 6 and Figure 7). Four OSL samples were collected in RF2 (Tel01-01, Tel01-02, Tel03-01 and Tel04-01) with over-dispersions of 23%, 15%, 31%, and 11%, respectively. Three samples (Tel01-01, Tel01-02, and Tel04-01) cluster within MIS-5c (105 – 95 Ka), while Tel03-01 dates to 67.0 Ka to 80.4 Ka.

MIS-5c was a sea-level high stand that globally was suggested not to be as high as MIS-5e and MIS-5a (Imbrie et al., 1989; MacIntyre et al., 1989; Chappell et al., 1996; Linsley, 1996; Cabioch and Ayliffe, 2001) (Figure 8), but regionally, evidence suggests that MIS-5c relative sea level did reach as high as MIS-5e and MIS-5a (Potter et al., 2004; Potter and Lambeck, 2004; Dumas et al., 2006; Coyne et al., 2007; Dutton et al., 2009; Parham, 2009). Therefore RF3 and RF2 are defined as a beach ridge and overwash sequence that was deposited during the MIS-5c highstand. The apparently anomalously younger MIS-5a ages for Tel03-01 and Tel02-02 both occur in the shelly sand unit. This suggests the possibility that there is a systematic problem with dating shelly sand with OSL (see also Burdette et al. 2009 for a discussion of the potential problems in dating coquina rock). The apparently anomalously old MIS-5e age for Tel04-02 comes from the laminated sand unit, and may be a result of upward mixing of older grains by bioturbation. However, the evidence of incomplete zeroing or mixing is not strongly supported by the overdispersion value of 20%, nor the histogram in Figure 3, though a few older aliquots were found at higher doses in the 1mm mask size than in the 3mm mask size.

Sea levels during cooler time periods (MIS 4 – MIS 2) were lower and sand became remobilized. This remobilized sand was deposited as an aeolian sand sheet and identified in the Merritt Island sand sequence as RF1. Similar types of this uppermost sand unit have been recognized over most of the southeastern United States from Florida to Delaware in late Pleistocene deposits (Ivester et al., 2001; Mallinson et al., 2008a; Mallinson et al., 2008b). Mallinson et al (2008a) describes one of these units in eastern North Carolina as an uppermost, remobilized aeolian sand averaging 2 meters in thickness. Tel03-03 and probably CC8 (Rink and Forrest. 2005) were collected in this unit and supports previous studies suggesting that this unit was deposited during late Quaternary cooler climates (Burdette, 2005; Mallinson et al., 2008a).

3.6 CONCLUSIONS

Our evidence suggests that RF3 and RF2 are components of a classic beach ridge deposit formed on the central eastern portion of Merritt Island at or near sea level during MIS-5c. Our OSL ages are in good agreement with the work of Osmond (1970), the hypothesis of Brooks (1972), and the work of Burdette et al. (2009). Although globally MIS-5c may not have reached the heights of MIS-5a or MIS-5e, in the southeastern United States there is mounting evidence that sea levels during MIS-5c did surpass present day sea level. The detailed lithologies and radar facies presented here form the first high-resolution transect for the Pleistocene of Merritt Island.

Capping the whole Merritt Island section is RF1, an aeolian sand sheet deposited as climate began to cool, sea level dropped, exposed sand became mobilized, and a sand sheet formed atop older deposits. This aeolian cap is recorded along the Atlantic coastal plain from Delaware to Florida. We found that use of the ACRM, described for the first time in this study, was essential for obtaining reliable OSL ages for environments with high proportions of cosmic dose rate.

Through this work and that of Burdette et al. (2009) we have shown that there is evidence for shoreline complexes at or near modern sea levels in both MIS-5a and 5c. However, there is also the possibility that only the Atlantic Coastal Ridge at elevations up to 8m (as at Wilson Coquina Quarry) dates to MIS-5e are the only preserved remnants of that time along the coast, and that the lower shoreline complexes were deposited after significant erosion of the previously deposited MIS-5e complexes.

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Table 3.1. Stratigraphic Units of Brevard County, Florida				
Geologic Age	Stratigraphic Unit		Approximate Thickness (m)	General Lithologic Character
Recent	Pleistocene and Recent Deposits		0-33.5	Fine to medium sand, coquina and sandy shell marl
Pleistocene				
Pliocene	Upper Miocene and Pliocene deposits		6.1 – 27.4	Gray to greenish gray sandy shell marl, green clay, fine sand, and silty shell
Miocene	Hawthorn Formation		3.0 – 91.4	Light green to greenish gray sandy marl, streaks of greenish clay, phosphatic radiolarian clay, black and brown phosphorite, thin beds of phosphatic sandy limestone
Eocene	Ocala Group	Crystal River Formation	0 – 30.5	White to cream, friable, porous coquina in a soft, chalky marine limestone
		Williston Formation	3.0 – 15.2	Light cream, soft, granular marine limestone, generally finer grained than the Inglis Formation, highly fossiliferous
		Inglis Formation	21.3+	Cream to creamy white, coarse granular limestone, contains abundant echinoid fragments
	Avon Park Limestone		86.9+	White to cream, purple tinted, soft, dense chalky limestone. Localized zones altered to light brown or ashen gray, hard, porous, crystalline dolomite.

Modified from Brown et al. (1962)

Table 3.2. Location, approximate elevation, sample depth, and U, Th, and K values of the Merritt Island samples

Sample Name	Core Location (WGS 84)	Approx Elevation relative to MSL (m)	Sample Depth (cm)	Corrected Sample Depth (cm)	U ²³⁸ (ppm) [a]	Th ²³² (ppm) [a]	K (%) [a]	Water Content (%) [b]
Tel03-03	28°28'41.6"	0.44	56	N/A	0.24	0.30	0.0055	2.72
Tel03-01	80°40'32.1"	-3.12	456	356	0.68	0.29	0.0205	7 (14.15)
Tel01-01	28°28'42.2"	-0.77	177	77	0.35	1.40	0.1076	7 (19.28)
Tel01-02	80°39'58.7"	-2.81	304	204	0.21	0.33	0.1933	7 (25.82)
Tel04-01	28°28'42.2"	-0.28	128	28	0.59	0.83	0.1645	7 (29.27)
Tel04-02	80°39'47.5"	-1.98	298	198	0.42	0.56	0.1927	7 (29.26)
Tel05-01	28°28'42.4" 80°39'22.9"	-2.98	298	198	0.74	0.62	0.3804	7 (26.83)
Tel02-03	28°28'42.1"	-1.77	177	77	0.76	2.25	0.0653	7 (24.36)
Tel02-01	80°38'46.0"	-3.36	336	236	0.40	0.71	0.5360	7 (28.18)
Tel02-02		-5.36	536	436	0.85	0.89	0.7026	7 (32.14)

[a] U, Th, and K values were determined by NAA on sub-samples derived from the OSL samples prior to chemical treatments.

[b] Water content as a fraction of dry weight determined from laboratory measurements.

Group	Sample Name	De (Gy)	σ	Associated Radar Facies / Lithofacies	Cosmic Dose Rate (μGy/a) [c]	Beta Dose Rate (μGy/a) [c]	NAA/DNC Gamma Dose (μGy/a) [d]	Total External Dose (μGy/a)	Total Internal Dose (μGy/a)	SAR-OSL Age (KA)
1	Tel03-03	5.6±0.3	23	RF1 / rS	196.18±19.6	33.9±12.2	29.0±11.0	259.1±16.4	10.5±2.3	18.9 – 22.7
2	Tel02-02	79.0±4.0	25	N/A / sS	118.47±11.9	599.3±17.9	290.5±11.9	1008.4±21.5	10.5±2.3	70.7 – 84.3
	Tel03-01	25.3±1.6	31	RF2 / sS	130.85±13.1	93.9±11.2	84.7±10.1	320.8±15.1	10.5±2.3	69.2 – 83.6
3	Tel01-01	45.0±2.0	23	RF2 / mbS	188.76±18.9	143.6±12.2	124.3±11.5	456.7±16.8	10.5±2.3	89.2 – 103.4
	Tel01-02	41.3±1.3	15	RF2 / mbS	159.14±15.9	163.8±12.7	81.2±10.9	404.2±16.8	10.5±2.3	92.3 – 106.9
	Tel02-01	80.0±5.0	29	N/A / IS	152.60±15.3	428.6±15.7	196.6±11.4	777.9±19.4	10.5±2.3	92.2 – 110.8
	Tel02-03	51.0±3.0	26	N/A / IS	188.76±18.9	180.4±12.4	196.3±12.5	565.4±17.6	10.5±2.3	81.1 – 95.9
	Tel04-01	50.4±1.3	11	RF2 / rS	221.87±22.2	199.1±12.7	137.3±11.6	558.3±17.2	10.5±2.3	83.1 – 94.1
	Tel05-01	61.0±3.0	26	N/A / IS	160.41±16.0	360.2±14.3	193.2±11.2	713.9±18.2	10.5±2.3	77.3 – 91.1
4	Tel04-02	59.0±3.0	20	RF3 / IS	160.41±16.0	192.8±12.4	113.6±10.9	466.9±16.6	10.5±2.3	113.6 – 133.6

[c] Cosmic dose rate value calculated using an overburden density of 2 g/cm³.

[d] All β and γ dose rates were calculated based on U, Th, and K concentrations of each sample accounting for moisture values of the sample.

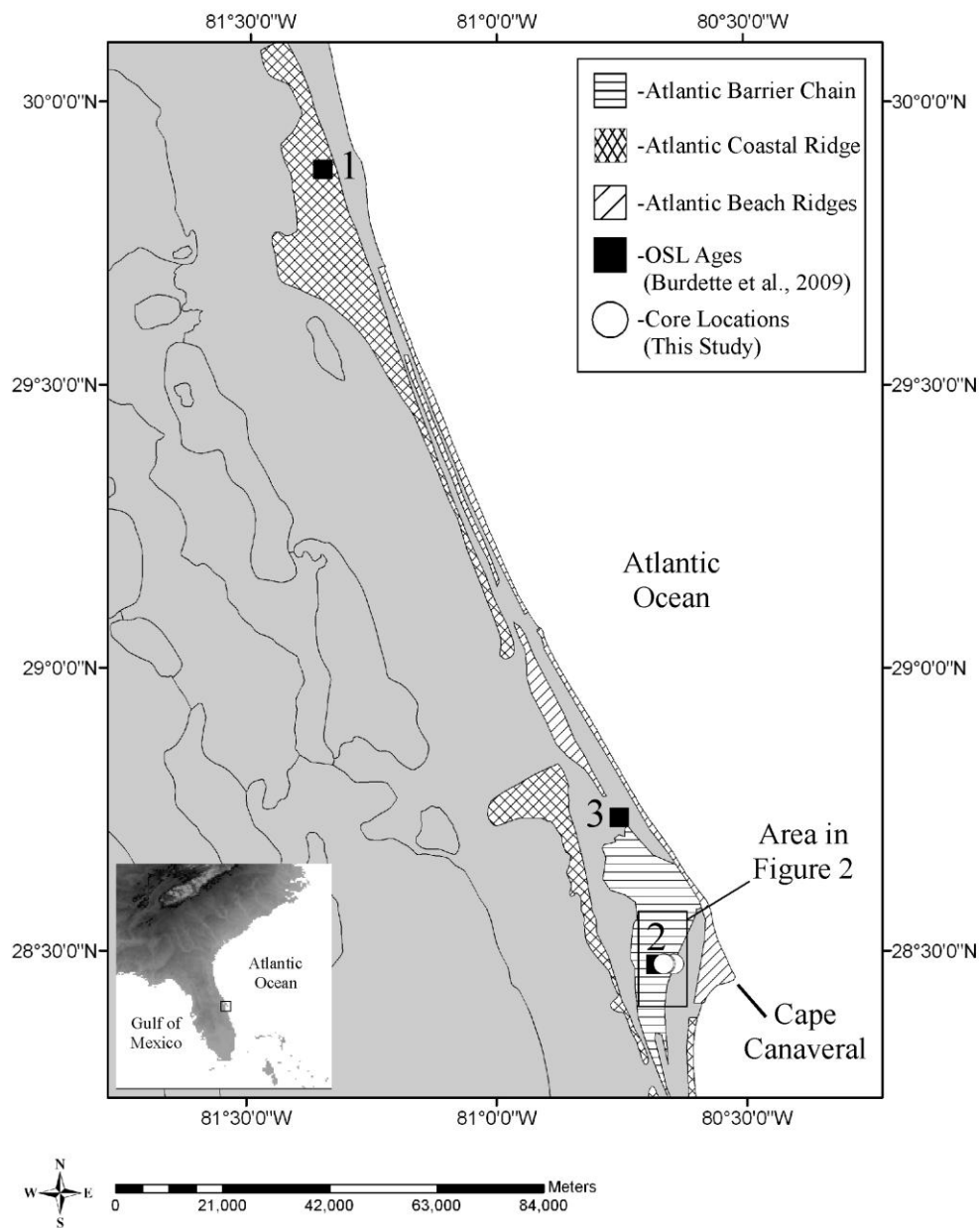


Figure 3.1. Physiographic map of eastern Florida showing the core locations from this study and sample locations from Burdette et al. (2009). Grey shaded areas are irrelevant physiographic nomenclatures. Location 1 – Wilson Coquina Quarry, Location 2 – Dalboro Road, Location 3 – Haulover Canal

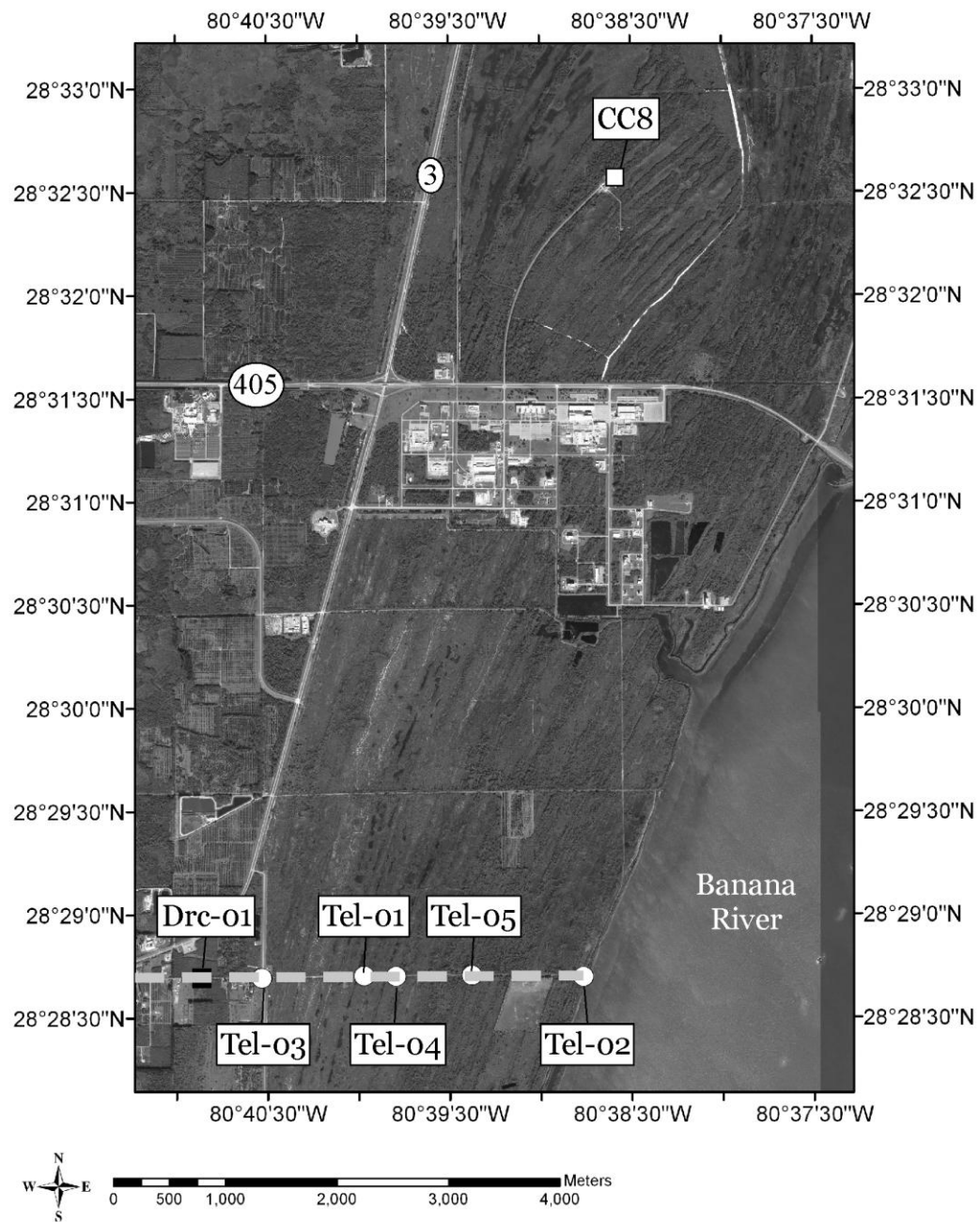


Figure 3.2. Digital Orthophoto Quarter Quad of eastern Merritt Island illustrating macrocore locations, coquina sample (Burdette et al., 2009), and OSL sample location (Forrest and Rink, 2005). Dashed grey line represents GPR transect.

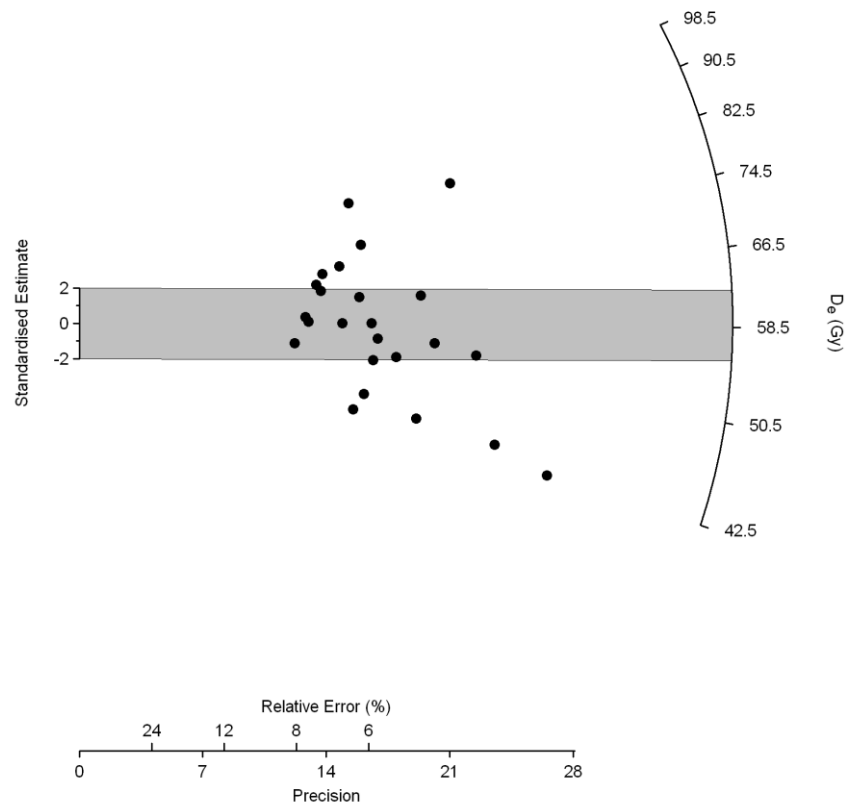
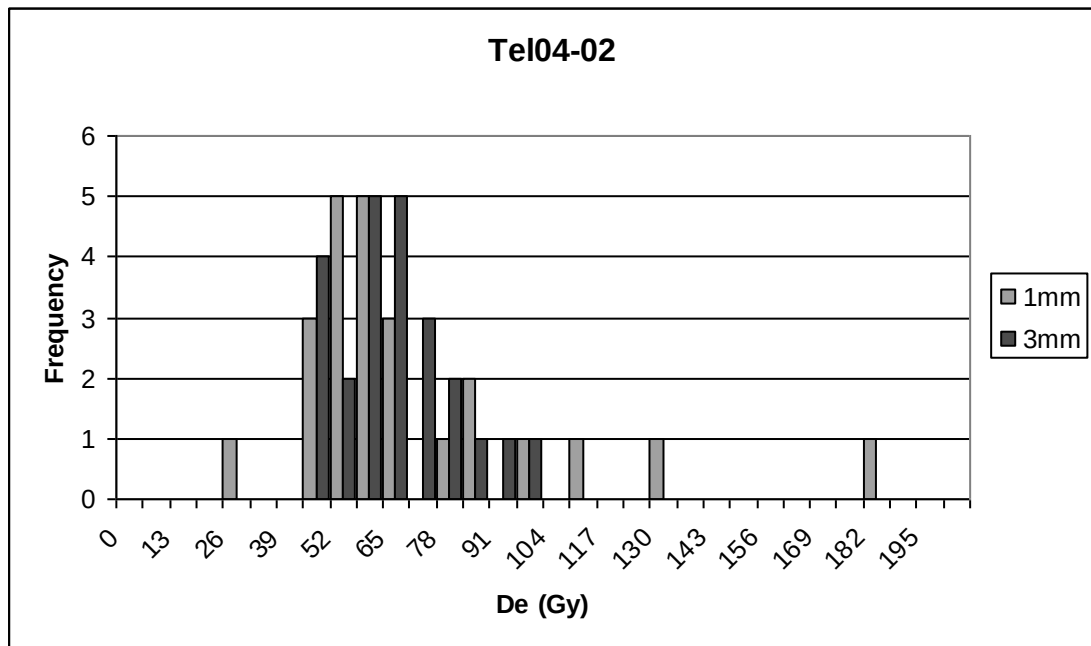


Figure 3.3. Histogram and Radial Plot of Tel04-02.

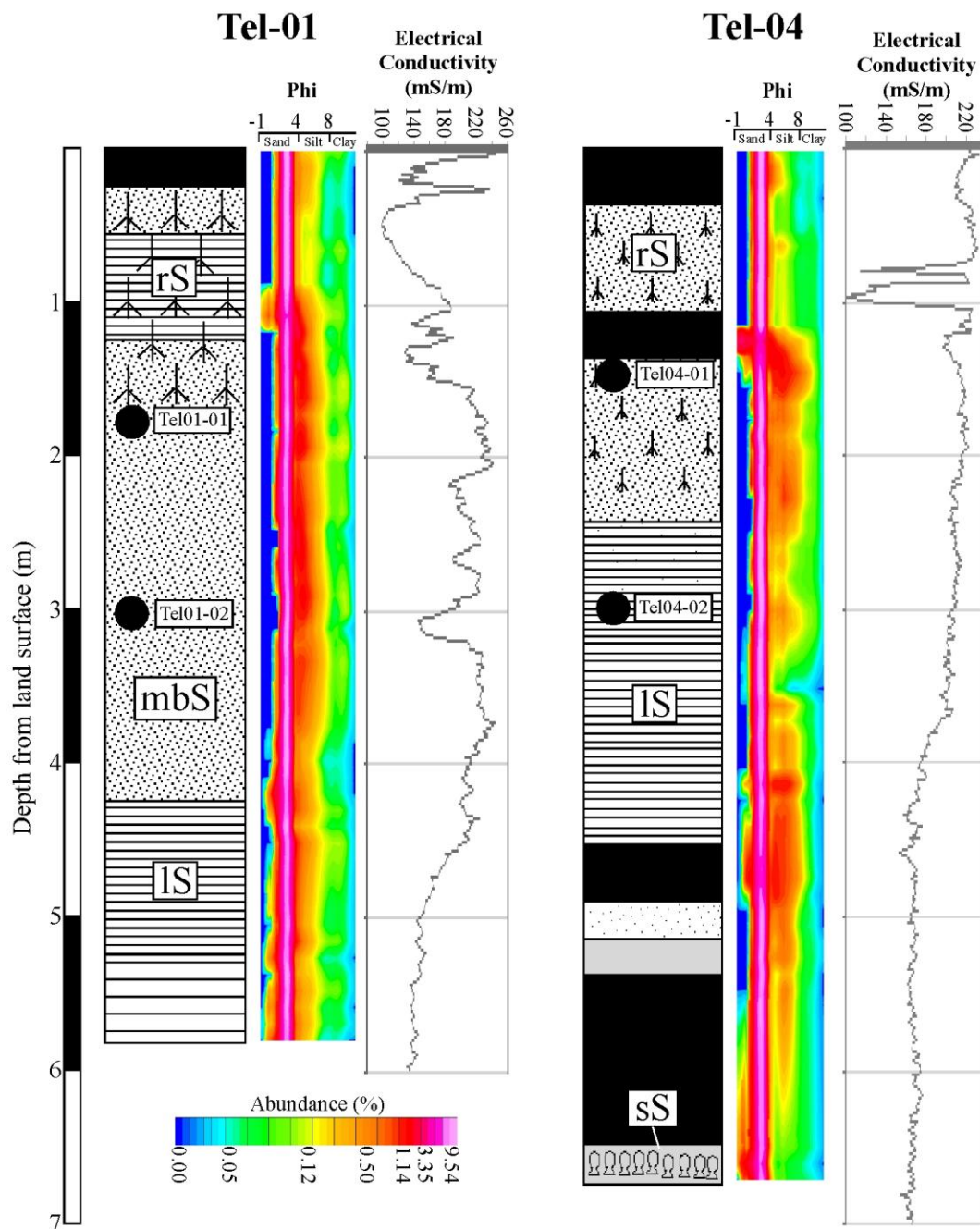


Figure 3.4. Core sedimentology log, PSD, and electrical conductivity of Tel-01 and Tel-04. Black areas represent no core recovery. Black circles represent OSL sample locations. Rooted Sand=rS, Massively Bedded Sand= mbS, Laminated Sand=IS, Shelly Sand=sS

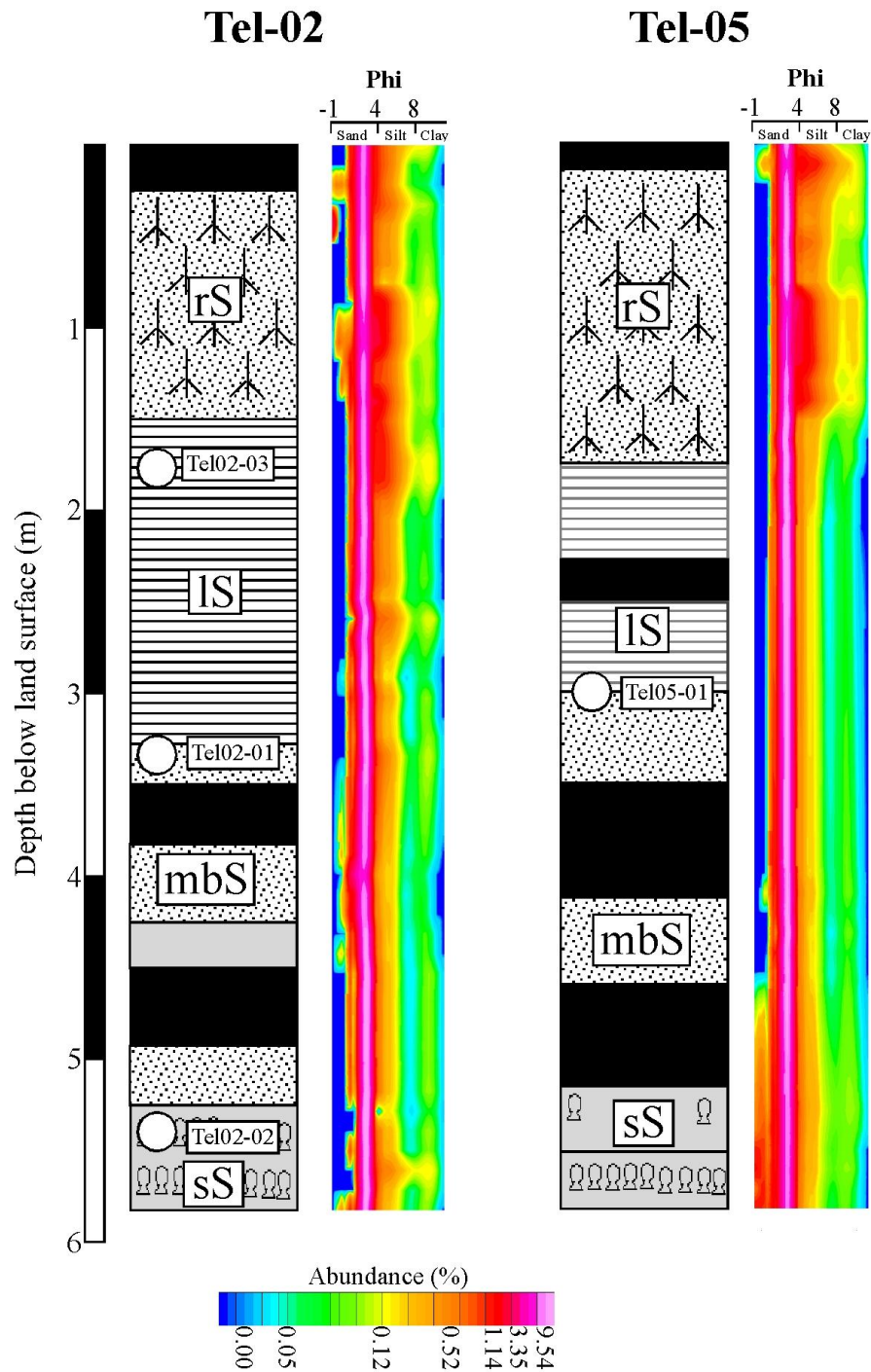


Figure 3.5. Core sedimentology log and PSD of Tel-02 and Tel-05. Black areas represent no core recovery. White circles represent OSL sample locations. Rooted Sand=rS, Massively Bedded Sand=mbS, Laminated Sand=IS, Shelly Sand=sS

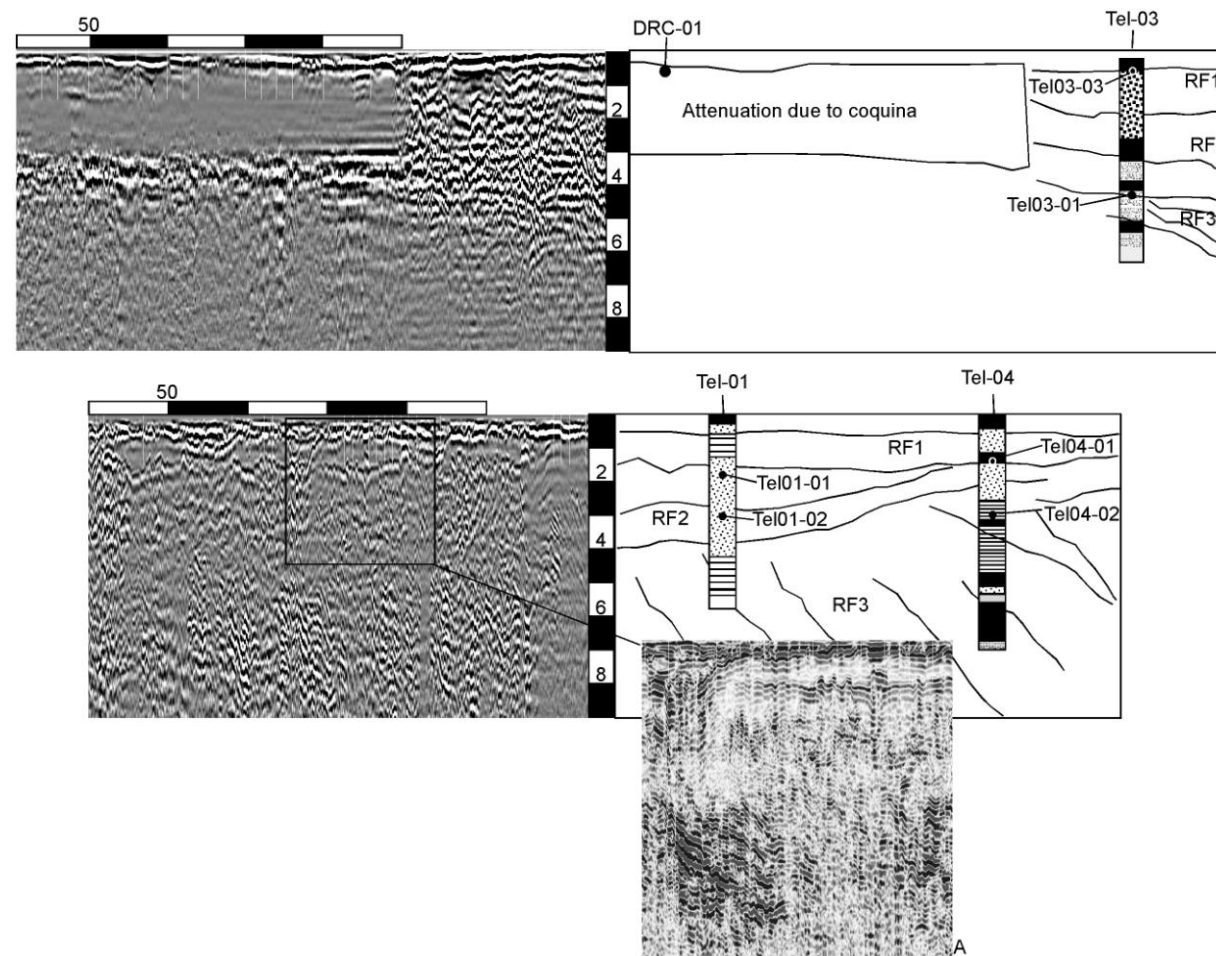


Figure 3.6. Ground penetrating radar sections (left) and interpretations with macrocore logs (right). Scale is in meters. Black area in core logs represent areas of no core recovery. Enlarged area A represents unstaked data to help visualize radar facies.

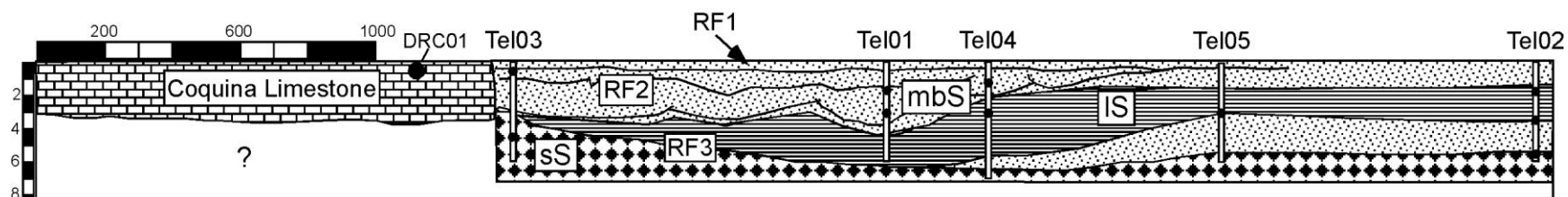


Figure 3.7. Cross section of the Merritt Island transect. Scale is in meters.

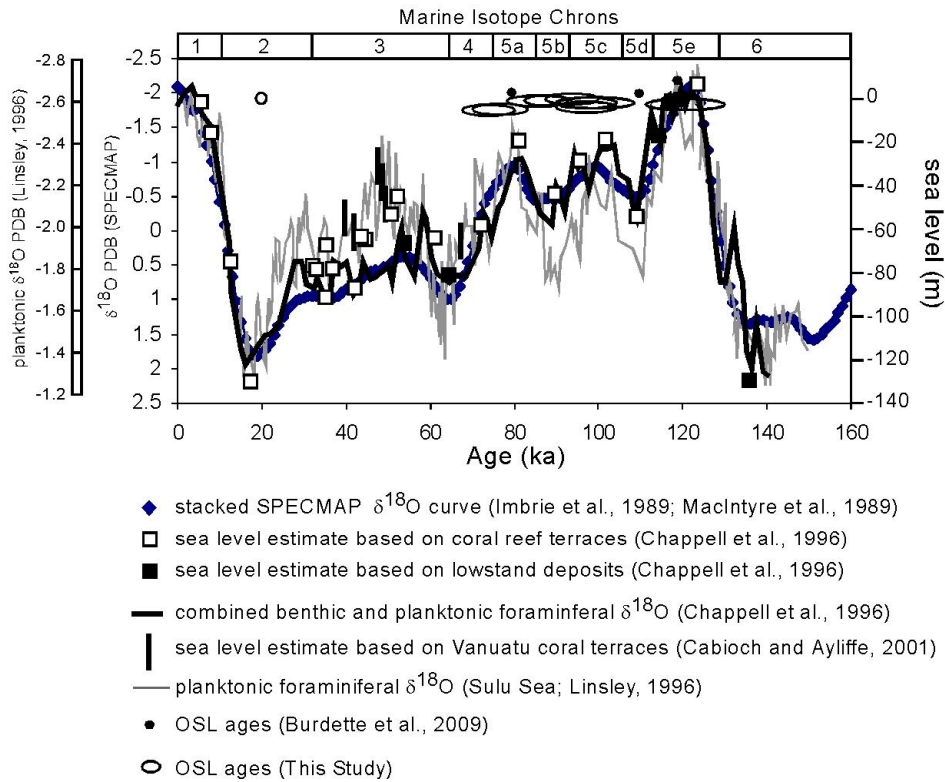


Figure 3.8. Comparison of the SPECMAP marine $\delta^{18}\text{O}$ curve (Imbrie et al., 1989; MacIntyre et al., 1989), coral reef terraces (Chappell et al., 1996; Cai and Ayliffe, 2001), foraminiferal $\delta^{18}\text{O}$ data (Chappell et al., 1996; Linsley, 1996), and OSL data (Burdette et al., 2009).

CHAPTER 4

GEOLOGIC INVESTIGATION AND OPTICAL DATING OF THE GULFPORT FORMATION NEAR APALACHICOLA, NORTHWEST FLORIDA, USA

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ABSTRACT

Ground penetrating radar (GPR) and single-aliquot regenerative-dose (SAR) optically stimulated luminescence (OSL) was used to determine the depositional environments and depositional age of the Gulfport Formation near Apalachicola, Florida. Five direct-push cores, five vibracores, and twenty-eight OSL ages were collected, as well as seven kilometers of GPR. A new model of cosmic dose rate calculation, which removes the much younger aeolian cap, was utilized to produce more consistent OSL ages. Five radar facies were identified based on reflector amplitude and orientation. The resulting data indicates that the Biloxi Formation was deposited before marine isotope stage (MIS) 6, the lower fluvial Gulfport Formation was deposited during MIS-6, and the upper beach ridge Gulfport Formation was deposited during the MIS-5e sea-level highstand.

4.1 INTRODUCTION

This paper presents new single aliquot regenerative (SAR) optically stimulated luminescence (OSL) ages of quartz grains, for several coastal siliciclastic features in the St. Joseph area of northwestern Florida. The features being dated include barrier sands (dune and overwash), alluvium sands, and marine sands associated with the Gulfport and the Biloxi Formations. Ground penetrating radar (GPR), direct-push cores (DPC), and vibracores were used to determine the geologic framework of these units. The purpose of this paper is to present and evaluate new OSL ages that constrain the depositional timeframe of these formations in western Florida.

4.2 STUDY AREA

The study area is located in Gulf County, Florida west of the town of Apalachicola. The coastline in this area is characterized by a series of Holocene barrier islands and spits separated from the mainland by estuaries and bays. The focus of this research is the mainland coastline, which is characterized by intermittent stretches of sand ridge sets of probable Pleistocene age (Schnable and Goodell, 1968).

The study area was subdivided into three smaller areas based on geomorphology (Figure 4.1). The first area is a set of east/west striking sand ridges near the township of Thirteen Mile, herein the sequence will be referred to as 13-Mile. The second is a set of north/south striking ridges south of the township of Port St. Joe, herein referred to as the Ward Ridges. The third area is between the other two ridge set and is known as Money Bayou. All three areas are located within the unit labeled Quaternary Beach Ridge and Dune (Qbd) on the Geologic Map of the State of Florida (Scott et al., 2001) (Figure 4.2 inset).

4.3 PREVIOUS REGIONAL WORK

The Biloxi Formation was defined by Otvos (1975) in coastal Louisiana and Mississippi as a fine-grained, highly fossiliferous deposit of paralic-nearshore character.

Two facies have been identified within the Biloxi Formation: a shelf facies and a nearshore/inshore brackish facies (Otvos, 1992). Dubar (1991) adds that the Biloxi Formation is typically 3- to 15-m thick along the entire northern Gulf Coast. Otvos (1995) states that they represent the earliest transgressive-regressive unit in marine isotope stage (MIS) 5e.

The Gulfport Formation, although currently not recognized by the Florida Geological Survey, is a surficial unit that is limited to a 1- to 3-km wide discontinuous barrier ridge belt that girds the Gulf mainland shore and topographically displays subdued beach ridge sets with intervening swales (DuBar, 1991). Otvos (1992) describes the formation as a 4.5 to 9 m thick, well- to moderately well-sorted, fine, rarely very fine sands, usually pale yellowish-brown or yellowish-brown in color. Parallel-laminated and current-rippled cross-stratified nearshore shallow subtidal sands with occasional cut-and-fill structures are exposed in the southeast bank of the Gulf County Canal at Port St. Joe (12 km northeast of the field area), about 2.7 m above present sea level (Otvos, 1992). It grades upward from shoreface sands that overlie nearshore facies of the Biloxi Formation, to foreshore sand and dunes whose summits reach 6 to 12 m altitude (DuBar, 1991). Schnable and Goodell (1968) concluded these beach or dune ridges were formed sometime during the Pleistocene, when the Apalachicola River emptied directly into the Gulf of Mexico. Otvos (1992) argued the wide barrier standplain complex (Gulfport Formation) prograded during the Sangamonian highstand. Otvos (2005) assumes the northwestern Gulfport barrier ridges range between 124 and 116 ka using one OSL age located in Gulf Breeze Florida, near Pensacola (approximately 200 km northeast of the field area) .

The area to the north of 13-Mile and to the east of Ward Ridges is referred to by Otvos (1992) as relict stream channels. Small, intermittent, underfit creeks (such as Depot Creek) inherited the meander remnants of the Paleo-Apalchicola River just before the Sangamonian aggradation ended. Otvos (1992) suggests these relict stream channels are Late Sangamon to Early Wisconsinan in age.

Following the last major sea level rise (~ 5,000 years ago), re-working of submerged deltaic features and sediment sorting by littoral processes constituted the main source of Apalachicola Barrier Island Complex sediments. It was estimated that the modern barrier island rim of the Apalachicola River delta formed ~ 6,000 years ago (Donoghue and Tanner, 1992; Stapor, 1973).

4.4 METHODS

4.4.1 Geophysical

Seven kilometers of GPR data were collected throughout the study area in order to define radar facies and reflectors that are indicative of depositional environments (Figure 2). Data were collected along a shore-normal (north-south) transect in the 13-mile area and a northwest-southeast transect in the Ward Ridges and Money Bayou areas.

Transect lines were chosen by accessibility along logging roads in an attempt to cross the ridge sets perpendicular to strike.

GPR data were acquired using a truck traveling between 3-5 miles per hour. A Geophysical Survey Systems Inc.® (GSSI) 200 MHz antenna was towed behind the truck while the passenger monitored the readout on the Subsurface Interface Radar (SIR) 2000 and collected notes. Data were collected at 16 bits/sample, 512 samples/scan, and 8 scans/second (approximately 6 scans/meter). Navigation data, recorded in WGS84 format, were obtained using a Garmin 76CSx Global Positioning System (GPS) unit, which the driver monitored. Waypoints were recorded simultaneously on the GPR and GPS systems.

The raw GPR data were processed using Radan software®, which included bandpass filtering (75-125 MHz), gain adjustment, and stacking (3x). Processed data were exported as bitmap files into Canvas®. The major reflectors were traced and separated from the GPR line to help visualize depositional groups and define radar facies.

4.4.2 Sample Strategy & Acquisition

Five direct-push core and five vibracore locations were chosen using the GPR data in an attempt to recover multiple lithofacies in a single core. Locations were also chosen in an attempt to determine the depositional history of the three above mentioned areas. Core locations were documented using a Garmin 76CSx GPS unit. In the lab, these positions were overlain on LiDAR data (downloaded from <http://www.csc.noaa.gov>) and ground surface elevations were determined. The LiDAR data uses the NAVD 88 vertical datum, and provides an accuracy of ± 33 cm.

After each macrocore was collected and visually logged in the field, a second hole directly beside the original was drilled for optical dating samples. An opaque core liner was used and the desired depth was sampled. The core liners were then extracted directly into a 2.5 mm black bag and taped closed. Vibracore measurements were collected in the field to determine possible compaction due to the coring process and excess core pipe was removed and the ends were sealed.

For the 13-Mile transect, TMG-01 was collected in an area that geomorphically did not appear to be part of the beach ridge sequence, while TMG-02, TMG-03, and TMG-04 were collected at the crests of the sand ridges (Figures 4.1 and 4.2). In the Ward Ridges area, Buffer Preserve Geoprobe (BPG), Jean Huffman Ridge (JHR), and Catfish Pond Ridge (CPR) were collected on the crest of sand ridges and the Conch Island (CCI) and Blacks Island (BKI) cores were collected in an attempt to sample the youngest ridges in the sequence. In Money Bayou, Oak Ridge (OR) was collected on the crest of sand ridges to determine the depositional origin and age of that sequence.

4.4.3 Lithology

In the laboratory, the clear-liner geoprobes and the archival side of the vibracores were visually logged, photographed, and sampled for lithology. Laser diffraction particle size analysis was conducted on a Beckman-Coulter LS 230 (BC LS 230) at 10 cm intervals and mathematical computations were computed for each sample using the Fraunhofer optical model (Murray, 2002). Surface plots were constructed using Geosoft Oasis[®] for all macrocores as outlined by Beierle et al. (2002). Surface plots of grain size data allow qualitative interpretation of the characteristics of the entire particle size distribution (PSD) and thus can provide important insights into depositional processes and changing environmental conditions Beierle et al. (2002).

4.4.4 Optical Dating

All optically-dated samples were processed at the School of Geography and Earth Sciences at McMaster University under UV-filtered subdued orange light. Pure quartz grains were obtained using standard OSL preparation methods which include HCl and H₂O₂ digestions to remove carbonates and organics respectively, sieving to obtain desired grain size, heavy liquid separation using Lithium Polytungstate to remove heavy minerals and feldspars, HF digestion to remove the outer alpha effected layer, a second H₂O₂ digestion to remove any remaining feldspars and any fluorides that may have formed during the HF digestion, and finally resieving to remove any grains that no longer fall in the desired size range (150 – 212 µ).

Dose rates were based on neutron activation analysis (NAA) of ²³²Th and ⁴⁰K and delayed neutron counting (DNC) analysis of ²³⁸U (conducted at the McMaster University Nuclear Reactor). Untreated subsamples of the original samples were used to determine the elemental concentrations of radioactive ²³⁸U, ²³²Th and ⁴⁰K (Table 4.2). NAA/DNC-based dose rates were calculated assuming radioactive equilibrium in the ²³⁸U and ²³²Th decay chains.

Luminescence measurements were conducted on a RISØ OSL/TL-DA-15 reader using blue light LED stimulation (470 nm) and a 7 mm-thick Hoya U-340 filter (270–400 nm). A calibrated ⁹⁰Sr beta source was used to perform laboratory irradiations. The single aliquot regeneration (SAR) protocol (Murray and Wintle, 2000) was conducted on a minimum of 24 aliquots to determine a final equivalent dose (De). Quartz grains, between 150-212 microns, were mounted with silicon spray on aluminum discs using a 3mm and a 1mm mask and were illuminated for 100 seconds at 125° C. The background (the last 4 s) of the OSL decay curve was subtracted from the “fast” component (first 0.4 s) to determine the samples luminescence signal. Only aliquots whose recycling ratios were within 10% were accepted for equivalent dose (De), also known as paleodose, determination.

Thermal transfer test and dose recovery test were performed to determine the final De preheat temperature (Madsen et al., 2005). For both tests, twelve aliquots from each sample were optically bleached by blue light illumination for 40 seconds, followed by a 10,000 second pause and another 40-second illumination. For the dose recovery test, the aliquots were given a known dose. Both tests continued with the standard SAR protocol

except the preheat temperatures varied (160, 200, 240, 280°C), with 3 aliquots from each sample receiving a different preheat temperature. For each sample the dose recovery test was used to determine which preheat temperature produced a D_e closest to the given dose. Once this preheat temperature was determined the thermal transfer test was analyzed to insure there was no induced charge transfer at that given temperature.

A feldspar contamination check, as outlined by Thompson et al. (2007), was also performed on each sample to insure purity of the quartz grain separates. An initial D_e was estimated by comparing the natural OSL signal (preheat $T = 200^\circ\text{C}$) of 3 aliquots to the regenerated OSL given by a single dose. A second identical regeneration dose was applied to the same aliquots and the IRSL signal was measured. If a ratio of IRSL to regenerated OSL signal was less than 1% for all aliquots, it is assumed there is no significant feldspar contamination (Forrest et al., 2003).

Moisture contents were measured in the lab from the recovered sediment and used for the dose rate calculations for the younger samples. If the samples were deposited before the last glacial maximum (LGM), then a moisture of 7% was used as an estimate of the moisture content throughout the samples burial history. The internal ^{238}U and ^{232}Th dose rates were calculated using the average concentration of those radioisotopes in granitic quartz (Rink and Odom, 1991), using an alpha efficiency factor of 0.04 $\pm$ 10%. Cosmic ray dose rates were calculated using the burial depth and a 2 g/cm³ of overburden density using calculations by Prescott and Hutton (1988) with the ANATOL program version 0.72B (provided by N. Mercier, CNRS, Paris). Burial depth was determined by using the instant accumulation model. The linear accumulation model assumes sedimentation was instantaneous relative to geologic time. For the instant accumulation model, the measured burial depth is used in the cosmic dose calculation.

As is typical of Florida coastal environments, the low content of U, Th, and K render the total dose rate's composition to one with a large proportion of cosmic dose rate. We found it necessary to carefully consider the average burial depth for the entire history of burial in order to properly calculate the cosmic dose rate in these circumstances. In our sites there was an aeolian layer (RF1) that was conservatively estimated to be about 1m thick in all cores. This layer was almost certainly deposited in the last 15,000 years, a relatively short period of time throughout the entire burial history. The burial depth was adjusted by employing a model that incorporated stripping off the overburden. This procedure is referred to as the aeolian cap removal model (ACRM), and was used for the first time in Burdette et al. (in review). Corrected sample depths are listed in Table 1.

D_e values and their associated errors for each aliquot were calculated using an exponential plus linear function in the RISØ Luminescence Analyst program (version 3.15b). Overdispersion and D_e for each sample were calculated using the Central Age Model (written by S. Huot and provided by R. Roberts). The Central Age Model explicitly determines the extent of D_e overdispersion between aliquots, and takes this into account when estimating the mean D_e values and their precisions (Galbraith et al., 2005). Overdispersion is defined as the relative standard deviation of the D_e estimates, above

and beyond that due to photon counting statistics and curve-fitting uncertainties (Roberts and Galbraith, in press).

Histograms, comparing the 3mm mask data and the 1mm mask data, and radial plots were constructed to graphically display the De distributions (Figure 4.3). Histograms are effective at illustrating the shape of a distribution (in addition to its location and spread), however they do not take into account the precision associated with each De value (Roberts and Galbraith, in press). Therefore, in addition to histograms, radial plots were constructed. A radial plot is a graphical display for comparing estimates that have differing precision (Galbraith, 1994). It is essentially a scatter plot that plots a standardized estimate on the y-axis against the precision (defined as the reciprocal of the standard error of the estimate) on the x-axis (Roberts and Galbraith, in press).

4.5 RESULTS AND INTERPRETATIONS

4.5.1 Optical Dating

De overdispersion values of the samples range from 1-22% in all but two samples. This range of values is expected in naturally-dosed aliquots (Roberts et al., 2000; Jacobs et al., 2006; Galbraith et al., 2005). The two higher overdispersion values were found in CPR-01 (33%) and CCI-01 (40%). Both CPR-01 and CCI-01 are the upper-most samples in each core which may have been affected by undetectable factors, such as bioturbation or incomplete zeroing.

The OSL ages presented in Table 2 can be divided into six groups by depositional ages; saturated, MIS-6, MIS-5e/6, MIS -5e/5d/5c, MIS 2, and MIS-1. Saturated OSL ages indicate that they are older than datable by the SAR OSL method. Figure 3 illustrate the ages in relationship to elevation. All but four, excluding the young samples, statistically fall into MIS-5e range. TMG01-01, TMG01-02, TMG04-02, and CCI-04 clearly fall into MIS-6. CCI-02, CCI-03, and CCI-05 ages all fall into MIS-5e, since CCI-03 was collected above CCI-04 and CCI-05 was collected below CCI-04, it appears that CCI-04 is a problematic sample. The overdispersion for CCI-04 is 8.6% and is suspiciously low when the average overdispersions are ~18%.

4.5.2 Lithology

Results from the PSD graphs and physical descriptions support that the 13-mile, Wards Ridges, and Money Bayou areas are all part of the Gulfport Formation as described by Dubars et al (1991), Otvos (1992), and Otvos (2005) (Figure 4.4). The moderately sorted, fine, yellow-brown sand units at the base of the Gulfport grade upward into very well sorted, fine, yellow sands. These moderately sorted sands usually contain 1-5% muscovite, while the well sorted upper sands contain <1%. The well sorted sand units are typically laminated. Most of the cores had very dark brown to black humate sands present. These humate sands are widespread post-depositional groundwater effect caused by the downward percolation of carbon-rich humic-soil acid (Otvos, 1992).

The Biloxi Formation was captured in two cores, TMG-01 and TMG-04, at approximately 750 cm below ground surface. In TMG-04, the blue-gray shelly micaceous clayey fine sand (sS) and the very dark blue-gray micaceous clayey fine sand in TMG-01 were identified as the nearshore/inshore brackish facies as described by Otvos (1992). OSL samples TMG04-03 and TMG01-03 were collected to try to determine the depositional age of this unit. Unfortunately the luminescence signal was saturated and therefore a depositional age was unobtainable. Otvos (1992) believed the Biloxi Formation was Sangamon in age, but the depositional age of the Biloxi Formation at this location cannot be confirmed nor disputed.

4.5.3 Geophysical

Five radar facies were identified based upon reflection amplitude, continuity, and geometry. Correlation of these facies to core data allowed construction of the regional depositional and chronostratigraphic framework of the area. Only the 13-mile transect cores and the BPG-01 were collected along the GPR transect, therefore only they can be directly correlated to radar facies.

Ground penetrating radar and macrocores were used to define radar facies (RF) and lithofacies, respectively. RF1 is characterized by massively bedded sand unit and is uniformly one to two meters in thickness (Inset A, Figure 4.5). This sand unit has been recognized over most of the southeastern United States from Florida to Delaware in late Pleistocene deposits (Ivester et al., 2001; Burdette, 2005; Otvos, 2005; Mallinson et al., 2008a; Mallinson et al., 2008b; Burdette et al., in review). Mallinson et al (2008a) describes this unit in eastern North Carolina as an uppermost, remobilized aeolian sand averaging 1-2 meters in thickness. Although no OSL samples were collected in this unit, previous studies suggest this unit is deposited during late Quaternary to early Holocene cooler climates (Ivester et al., 2001; Burdette, 2005; Otvos, 2005; Mallinson et al., 2008a; Mallinson et al., 2008b; Burdette et al., in review).

RF2 is characterized by horizontal to subhorizontal clinoforms. In the 13-mile transect, TMG01-01, TMG01-02, and TMG04-02 were collected within RF2. In the Ward Ridges area, no samples were collected within RF2. All three samples date within the MIS-6 group and suggest pre-Sangamon interglacial deposition.

RF3 is characterized by continuous (>10m), low-angle landward dipping clinoforms and is interpreted as an overwash fan or an aeolian sand sheet deposit associated with beach ridges of the Gulfport Formation. No cores were collected and therefore no OSL samples were collected in RF3. Inset B of Figure 4.5 illustrates the transition from RF3 to RF4, labeled as the "Transition Point". This transition is also illustrated in Figure 4.1. RF4 is characterized by discontinuous, low to medium amplitude, seaward dipping clinoforms and is interpreted as Gulfport Formation foreshore or foreslope accretion (Inset C, Figure 4.5). RF4 correlates very well with lithofacies LS in TMG-02, TMG-03, and TMG-04. In the 13-mile transects, TMG02-01, TMG02-02, TMG03-01, TMG03-02, and TMG04-01 were collected within RF4, and all group statistically within MIS-5e, suggesting Sangamon beach ridge deposition.

RF5 is characterized by a continuous high amplitude reflector (Inset D, Figure 4.5). This very strong reflector represents the boundary between two very distinct lithologic units and sediment types. TMG01-03 and TMG04-03 (sS lithofacies) were collected below RF5, therefore it is determined that RF5 is the contact between the lower Biloxi Formation and the upper Gulfport Formation.

4.6 DISCUSSION

Although Otvos (1992) and DuBar et al. (1991) argued the nearshore/inshore brackish facies of the Biloxi Formation (RF5 and sS) is Sangamon (MIS-5) in age, saturated OSL signals from TMG01-03 and TMG04-03 suggest it was deposited before that time, possibly during MIS-7 or MIS-9. Also both samples have MIS-6 sediment deposited above them.

As sea levels began to drop during MIS-6, the Apalachicola River began to incise and meander over the study area (Figure 4.6). As the Paleo-Apalachicola River meandered, it deposited RF2, a mica-rich massively bedded sand with very gently landward dipping clinoforms. The LiDAR data (Figure 4.1) clearly shows linear north-south dunes that mimic the present day Depot Creek, suggesting the area north of the 13-Mile transect has relict fluvial ridges. TMG01-01, TMG01-02, and TMG04-02 were collected in this sediment and clearly date within MIS-6. Therefore resting atop the Biloxi Formation in the study area is a unit of MIS-6 mica rich sediments deposited by the Paleo-Apalachicola River.

During MIS-5e, sea levels rose to near present elevations (Figure 4.6). Using the 13-Mile and Ward Ridges transects, it is possible to determine the approximate maximum elevation of sea level in the study area. The elevation for the “Transition Point” on the 13-Mile Transect is 3.75m using LiDAR, and the elevation for the Ward Ridges is 3.26m using the Lidar. This suggests that MIS-5e sea levels reached an approximate maximum elevation of ~3.5m above present. As sea-level stabilized, beach ridges (13-Mile and Ward Ridges) began to form. This formation of ridges probably choked out the Depot Creek and redirected it to the northeast, but allowed some drainage through the Money Bayou area (Figure 4.1). CCI, part of a broken island chain just offshore in the St. Joseph Bay, is the remaining remnant of the youngest remaining ridges in the Ward Ridges set.

During the MIS4-2 cold periods, sea-level dropped and exposed sand began to immobilize. This sand began to deposit as a sand sheet that capped most of the southeast. OR-02 was collected in this RF1 units and dates to approximately the last glacial maximum (LGM). Sea-level did not reach near present in the study area until approximately 5000-6000 years ago, with micro-fluctuations until 3000 years ago. In St. Joseph Bay, stable sea levels around 1300 years ago caused a prominent shoreline to form at present day Blacks Island (Figure 4.2). Subsequent rise to today’s bay levels caused flooding and the shoreline is now a chain of small islands.

4.7 CONCLUSIONS

The 13-Mile and Ward Ridges transects are classic examples of MIS-5e beach ridge sets. These massively bedded sands topped with laminated sands with seaward dipping clinoforms were deposited when sea-level was approximately 3.5m above present sea level. The acquisition of LiDAR for the study area has allowed for the decimeter resolution of elevations for determining sample depth. This precision has allowed for the first time the most accurate determination of MIS-5e sea levels in the area. Sea level in this area appears to coincide almost exactly with the global sea-level curve (Figure 6).

SAR OSL ages coupled with GPR have determined the depositional history of the Gulfport Formation in the St. Joseph area in the panhandle of northeast Florida. The advancement of luminescence dating allows for the chronological controls on geologic formations described over a decade ago. OSL ages suggest the Biloxi Formation in the study area is older than previously described, dating beyond the range of OSL. This research presented here indicates the Biloxi is of probable MIS-7 or MIS-9 age. Resting atop the Biloxi Formation is a mica-rich massively bedded sand that was captured in three OSL samples and dates to MIS-6. The origin of this sand unit is probably fluvial based on the geomorphology, lithology, and GPR facies. The beach ridges of 13-Mile and Ward Ridges were deposited when MIS-5e seas eroded into the fluvial sands and sea level stabilized.

Further research is needed in the areas east of 13-Mile and north of Ward Ridges, as well as inland, to confirm the geologic determinations described here.

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Table 4.1. Sample Depths, Elevations, Grain size analyzed, U, Th, and K results, and water content of samples

Sample Name	Corrected Sample Depth (cm) [a]	Elevation of sample using LiDAR (cm)	Associated Ridge Set	Grain Size Analyzed (μm)	U ²³⁸ (ppm) [b]	Th ²³² (ppm) [b]	K (%) [b]	Water Content (%) [c]
TMG01-01	211	176	13-Mile	150-212	0.16	0.33	0.0018	11.31*
TMG01-02	537	-150	13-Mile	150-212	0.19	0.35	0.0296	26.68*
TMG01-03	811	-424	13-Mile	150-212	2.51	4.52	0.1973	20.35*
TMG02-01	69	166	13-Mile	150-212	0.17	0.49	0.0013	20.92*
TMG02-02	171	64	13-Mile	150-212	0.16	0.21	0.0017	24.20*
TMG03-01	72	132	13-Mile	150-212	0.20	1.88	0.0002	11.54*
TMG03-02	224	-20	13-Mile	150-212	0.20	0.21	0.0005	27.97*
TMG04-01	194	-51	13-Mile	150-212	0.21	0.34	0.0005	4.57
TMG04-02	575	-432	13-Mile	150-212	0.91	1.85	0.0495	26.35*
TMG04-03	809	-666	13-Mile	150-212	1.09	1.13	0.0494	26.68*
JHR-01	28	24	Ward	150-212	0.23	0.25	0.0029	22.22*
JHR-02	48	4	Ward	150-212	0.27	0.63	0.0014	20.96*
JHR-03	66	-14	Ward	150-212	0.26	0.43	0.0054	20.83*
CPR-01	18	187	Ward	150-212	0.14	0.23	0.0025	16.11*
CPR-02	77	128	Ward	90-150	0.24	0.66	0.0048	20.51*
CPR-03	124	81	Ward	150-212	0.19	0.20	0.0016	16.52*
CCI-01	60\$	-60	Ward	150-212	1.50	1.53	0.0866	21.94*
CCI-02	16	-116	Ward	150-212	0.28	0.27	0.0074	7.63
CCI-03	65	-165	Ward	150-212	0.18	0.38	0.0070	8.43
CCI-04	110	-210	Ward	150-212	0.30	0.49	0.0101	12.80*
CCI-05	154	-254	Ward	150-212	0.16	0.37	0.0120	14.50*
BPG01-01	199	-25	Ward	150-212	0.18	0.40	0.0008	26.00*
BPG01-02	441	-267	Ward	150-212	0.39	0.50	0.0192	22.10*
OR-02	118\$	186	Money Bayou	150-212	0.32	1.04	0.0176	14.00*
OR-01	113	91	Money Bayou	150-212	0.37	1.11	0.0038	16.00*
BKI-01	63\$	-33	Ward	150-212	0.44	0.30	0.0086	23.78
BKI-02	159\$	-129	Ward	150-212	0.43	0.30	0.0097	19.90
BKI-03	328\$	-298	Ward	150-212	0.48	0.35	0.0196	22.20

[a] Sample depth was calculated using the ACRM. \$-indicates samples which model was not used

[b] U, Th, and K values were determined by NAA on sub-samples derived from the OSL samples prior to chemical treatments.

[c] Water content as a fraction of dry weight determined from laboratory measurements. *-indicates 7% was used see text for explanation

Table 4.2. Luminescence dating results

Sample Name	De (Gy) [a]	σ (%) [b]	Cosmic Dose Rate ($\mu\text{Gy/a}$) [c]	Beta Dose ($\mu\text{Gy/a}$) [d]	Total Internal Dose ($\mu\text{Gy/a}$)	NAA/DNC Gamma Dose ($\mu\text{Gy/a}$) [d]	Total External Dose ($\mu\text{Gy/a}$) [d]	SAR-OSL age (KA)	Associated Marine Isotope Stage
TMG01-01	37.2 $\pm$ 1.0	13.0	157.68 $\pm$ 15.8	25.8 $\pm$ 11.3	10.5 $\pm$ 2.3	31.0 $\pm$ 10.5	237.2 $\pm$ 15.7	148.9 – 178.5	6
TMG01-02	38.0 $\pm$ 1.4	18.0	104.89 $\pm$ 10.5	49.8 $\pm$ 11.8	10.5 $\pm$ 2.3	42.6 $\pm$ 10.7	197.3 $\pm$ 16.0	163.9 – 201.7	6
TMG01-03	Saturated	N/A	76.95 $\pm$ 7.70	523.9 $\pm$ 17.8	10.5 $\pm$ 2.3	513.9 $\pm$ 17.8	1114.3 $\pm$ 22.7	N/A	N/A
TMG02-01	35.0 $\pm$ 1.0	14.0	191.43 $\pm$ 19.1	30.9 $\pm$ 11.8	10.5 $\pm$ 2.3	40.2 $\pm$ 11.8	258.2 $\pm$ 16.0	118.2 – 138.0	5e, 6
TMG02-02	29.0 $\pm$ 1.0	16.0	166.26 $\pm$ 16.6	24.3 $\pm$ 11.7	10.5 $\pm$ 2.3	26.7 $\pm$ 10.7	217.3 $\pm$ 15.9	115.6 – 138.8	5e, 6
TMG03-01	40.1 $\pm$ 1.6	19.0	190.67 $\pm$ 19.1	59.5 $\pm$ 11.5	10.5 $\pm$ 2.3	101.0 $\pm$ 11.6	358.6 $\pm$ 16.5	100.5 – 116.9	5e
TMG03-02	31.1 $\pm$ 0.8	12.0	155.01 $\pm$ 15.5	28.2 $\pm$ 11.7	10.5 $\pm$ 2.3	30.7 $\pm$ 10.7	213.9 $\pm$ 15.9	126.0 – 151.0	5e, 6
TMG04-01	29.0 $\pm$ 1.0	18.0	161.26 $\pm$ 16.1	32.9 $\pm$ 12.1	10.5 $\pm$ 2.3	38.6 $\pm$ 11.0	230.9 $\pm$ 16.4	109.5 – 130.7	5e, 6
TMG04-02	75.0 $\pm$ 2.0	13.0	100.30 $\pm$ 10.0	178.8 $\pm$ 12.1	10.5 $\pm$ 2.3	190.2 $\pm$ 12.1	469.1 $\pm$ 17.1	144.7 – 168.1	6
TMG04-03	Saturated	N/A	77.12 $\pm$ 7.71	185.3 $\pm$ 14.0	10.5 $\pm$ 2.3	177.6 $\pm$ 17.8	439.9 $\pm$ 22.7	N/A	N/A
JHR-01	40.9 $\pm$ 1.7	21.0	221.87 $\pm$ 22.2	29.9 $\pm$ 10.3	10.5 $\pm$ 2.3	32.1 $\pm$ 9.5	292.3 $\pm$ 14.0	121.3 – 145.3	5e, 6
JHR-02	36.2 $\pm$ 1.3	17.0	200.79 $\pm$ 20.1	40.4 $\pm$ 10.4	10.5 $\pm$ 2.3	51.0 $\pm$ 9.6	314.2 $\pm$ 14.2	106.7 – 123.7	5c, 5d, 5e
JHR-03	33.9 $\pm$ 1.4	19.0	199.34 $\pm$ 19.9	38.1 $\pm$ 10.4	10.5 $\pm$ 2.3	42.9 $\pm$ 9.6	290.5 $\pm$ 14.1	103.8 – 121.4	5c, 5d, 5e
CPR-01	34.0 $\pm$ 2.0	33.0	239.47 $\pm$ 23.9	21.1 $\pm$ 10.8	10.5 $\pm$ 2.3	23.8 $\pm$ 9.9	288.1 $\pm$ 14.7	104.0 – 123.6	5c, 5d, 5e
CPR-02	41.7 $\pm$ 1.8	20.0	188.76 $\pm$ 18.9	39.8 $\pm$ 10.4	10.5 $\pm$ 2.3	50.1 $\pm$ 8.6	300.5 $\pm$ 14.2	127.6 – 149.8	5e, 6
CPR-03	33.9 $\pm$ 1.5	22.0	177.07 $\pm$ 17.8	26.2 $\pm$ 11.2	10.1 $\pm$ 2.3	27.2 $\pm$ 9.9	235.1 $\pm$ 14.9	125.6 – 150.8	5e, 6
CCI-01	1.7 $\pm$ 0.1	40.0	194.43 $\pm$ 19.4	234.4 $\pm$ 10.8	10.5 $\pm$ 2.3	219.3 $\pm$ 10.4	648.2 $\pm$ 15.0	4.3 – 5.4	1
CCI-02	38.2 $\pm$ 1.5	19.0	243.69 $\pm$ 24.4	43.1 $\pm$ 11.7	10.5 $\pm$ 2.3	43.1 $\pm$ 10.6	330.7 $\pm$ 15.8	104.0 – 119.8	5c, 5d, 5e
CCI-03	34.7 $\pm$ 1.5	20.0	192.65 $\pm$ 19.3	33.4 $\pm$ 11.7	10.5 $\pm$ 2.3	37.4 $\pm$ 10.6	264.1 $\pm$ 15.8	115.8 – 136.8	5e, 6
CCI-04	46.4 $\pm$ 1.8	18.0	180.46 $\pm$ 18.0	49.5 $\pm$ 11.3	10.5 $\pm$ 2.3	53.3 $\pm$ 10.3	288.8 $\pm$ 15.3	142.8 – 167.2	6
CCI-05	29.5 $\pm$ 0.6	8.6	170.07 $\pm$ 17.0	31.2 $\pm$ 11.1	10.5 $\pm$ 2.3	33.7 $\pm$ 10.1	235.0 $\pm$ 15.0	110.5 – 129.7	5e, 6
BPG01-01	32.6 $\pm$ 1.3	19.0	160.20 $\pm$ 16.0	25.4 $\pm$ 10.0	10.5 $\pm$ 2.3	31.9 $\pm$ 9.1	227.3 $\pm$ 13.5	124.6 – 147.8	5e, 6
BPG01-02	33.3 $\pm$ 1.0	14.0	117.75 $\pm$ 11.8	60.8 $\pm$ 10.4	10.5 $\pm$ 2.3	60.4 $\pm$ 10.2	265.8 $\pm$ 14.6	114.3 – 136.3	5e, 6
OR-02	5.7 $\pm$ 0.2	17.0	194.84 $\pm$ 19.5	66.7 $\pm$ 11.2	10.5 $\pm$ 2.3	79.7 $\pm$ 10.7	341.3 $\pm$ 15.5	15.0 – 17.4	2
OR-01	47.7 $\pm$ 1.9	24.0	179.73 $\pm$ 18.0	68.9 $\pm$ 11.9	10.5 $\pm$ 2.3	89.8 $\pm$ 11.3	349.0 $\pm$ 16.4	126.2 – 147.0	5e, 6
BKI-01	0.3 $\pm$ 0.01	1.0	193.32 $\pm$ 19.3	55.1 $\pm$ 10.2	10.5 $\pm$ 2.3	54.2 $\pm$ 9.3	302.6 $\pm$ 13.8	0.94 – 1.08	1
BKI-02	0.3 $\pm$ 0.01	5.0	176.83 $\pm$ 17.7	56.5 $\pm$ 10.6	10.5 $\pm$ 2.3	55.1 $\pm$ 9.7	288.5 $\pm$ 14.3	0.93 – 1.07	1
BKI-03	0.4 $\pm$ 0.01	9.0	148.48 $\pm$ 14.8	67.6 $\pm$ 10.4	10.5 $\pm$ 2.3	63.0 $\pm$ 9.4	279.1 $\pm$ 14.0	1.20 – 1.40	1

[a] Equivalent Doses were calculated using the Central Age Model written by S. Huot.

[b] Overdispersion percentages were calculated using the Central Age Model written by S. Huot.

[c] Cosmic dose rate value calculated using an overburden density of 2 g/cm³.

[d] All β and γ dose rates were calculated based on U, Th, and K concentrations of each sample accounting for moisture values of the sample.

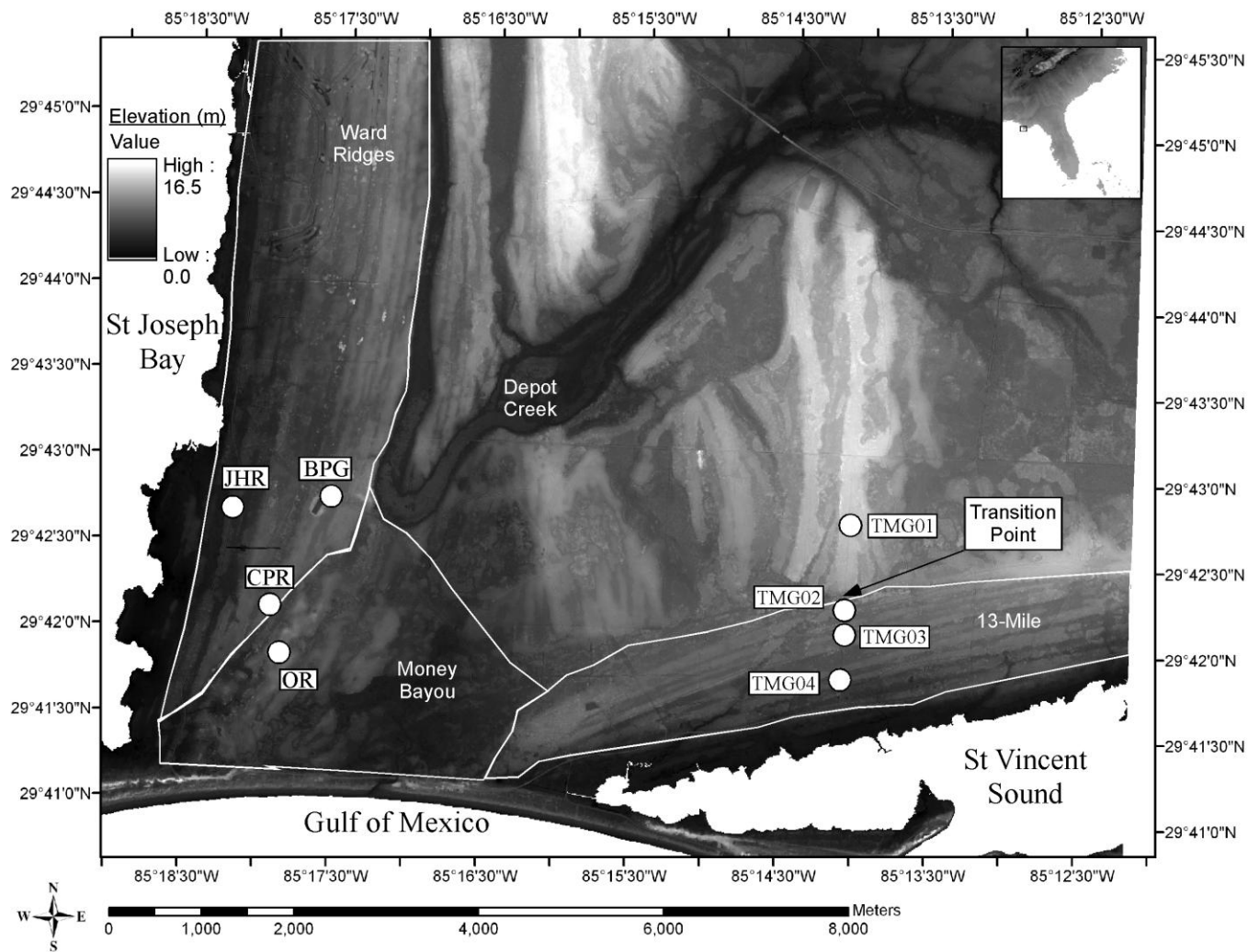


Figure 4.1. LiDAR topographic map showing the three major sample areas and core locations discussed in the manuscript.

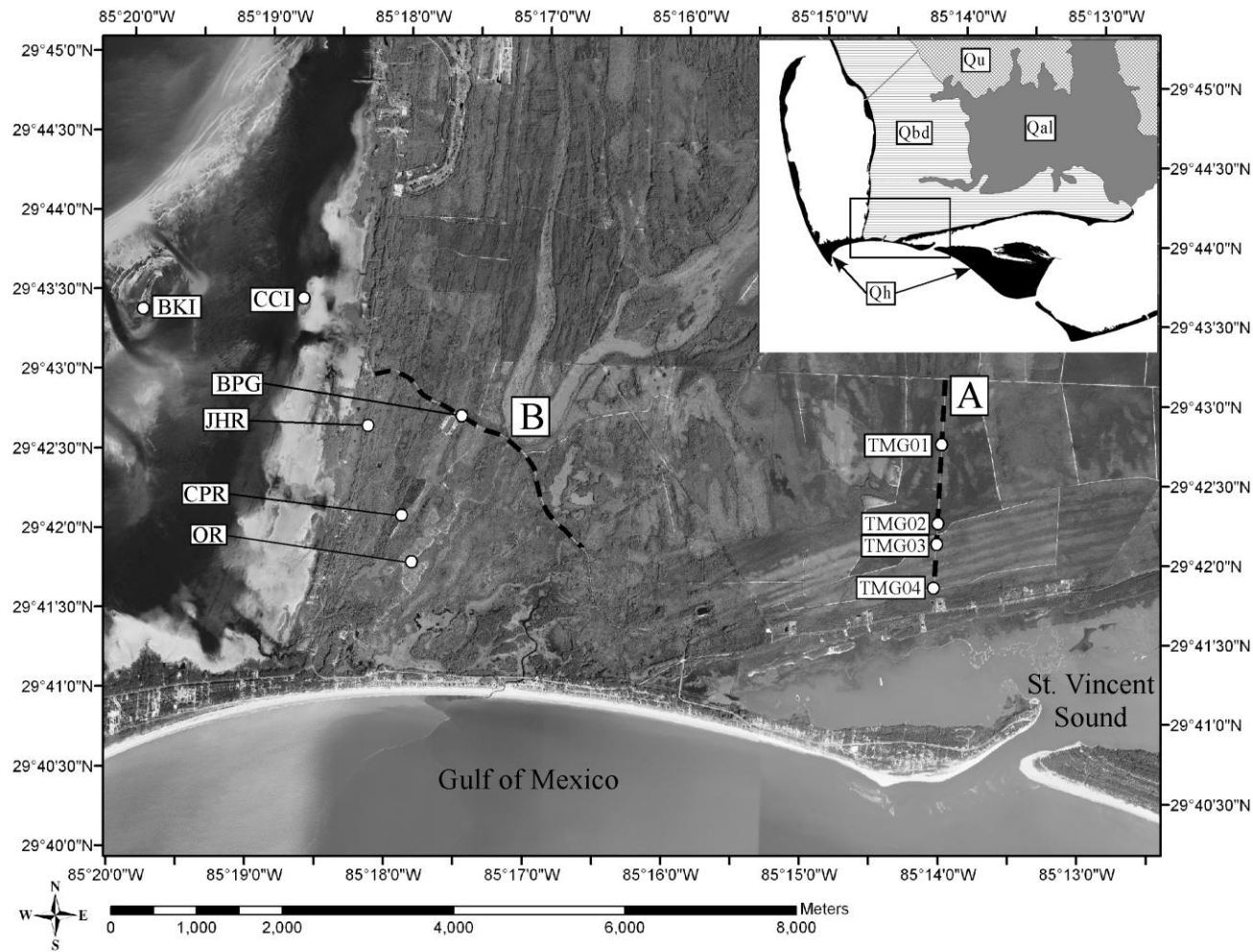


Figure 4.2. DOQQ showing location of cores. GPR transects are represented by black dashed lines. Inset – Geologic Map of the study area. Qh – Holocene Sediments, Qbd – Pleistocene/Holocene beach ridge and dune, Qal – Pleistocene/Holocene alluvium, Qu – Pleistocene/Holocene undifferentiated sediments

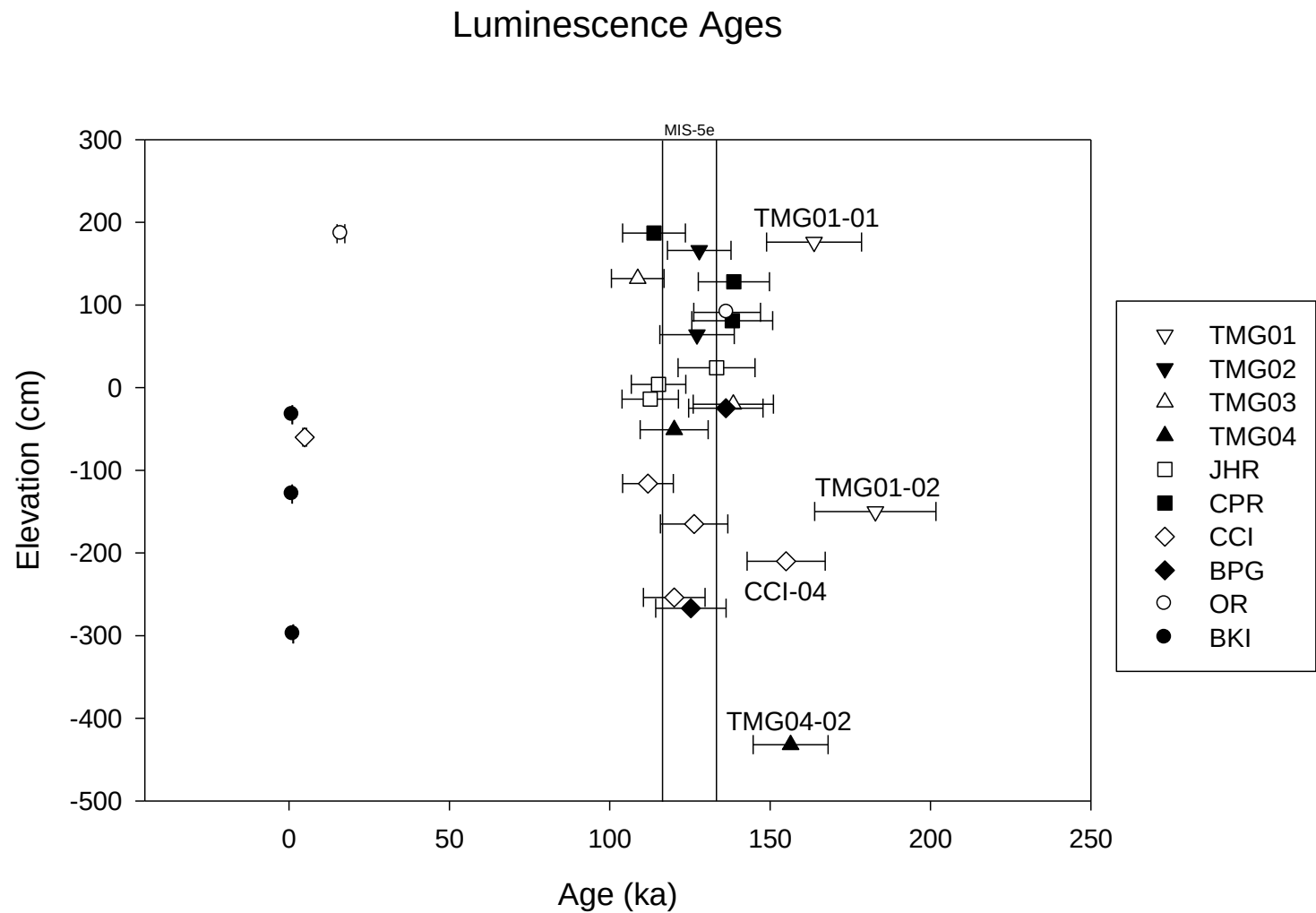


Figure 4.3. Luminescence ages with relation to elevation above mean sea level. The bars indicate the boundary of MIS-5e.

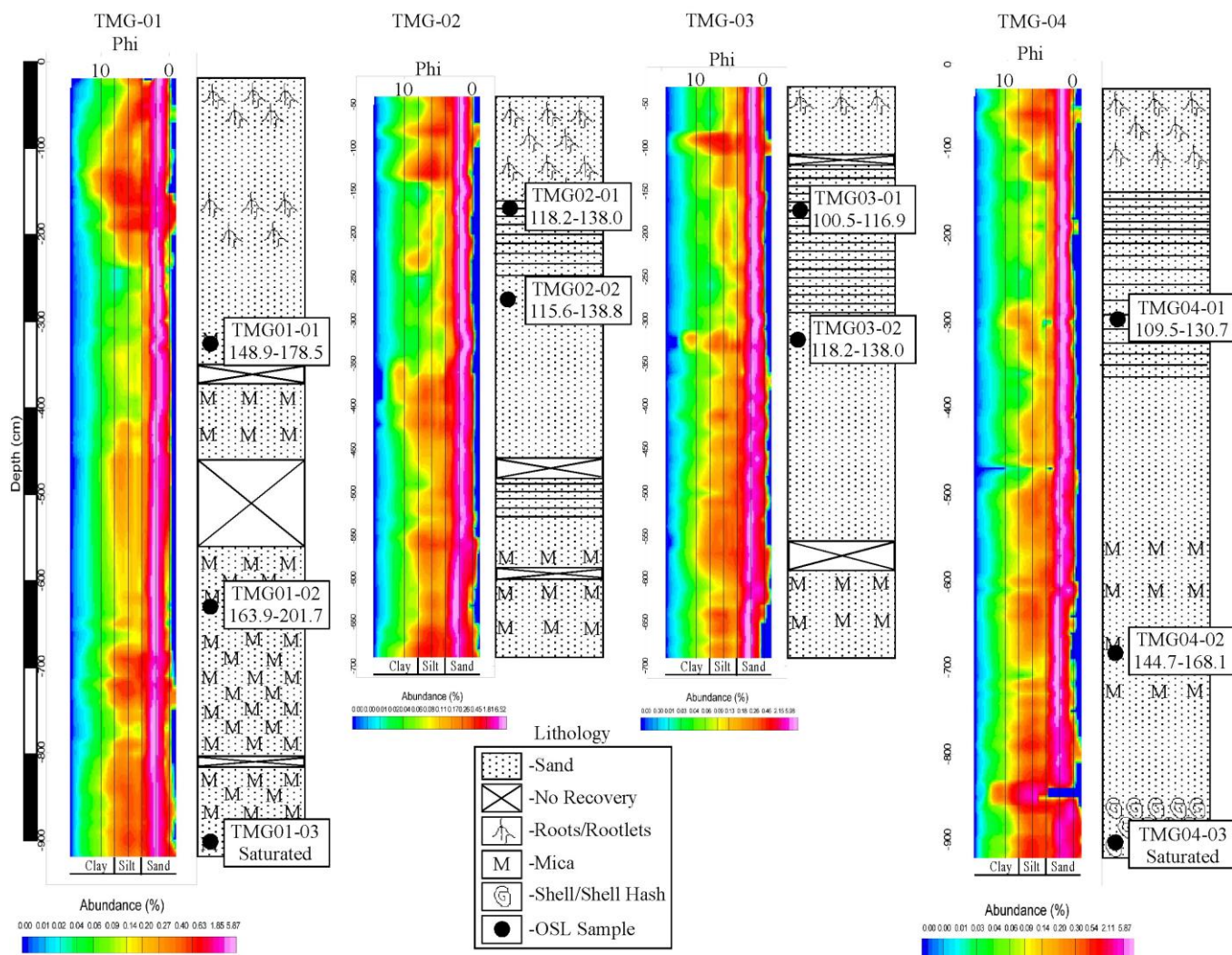


Figure 4.4. Core sedimentology log and PSD of TMG-01, TMG-02, TMG-03, and TMG-04. Ages are in ka (thousands of years before present),

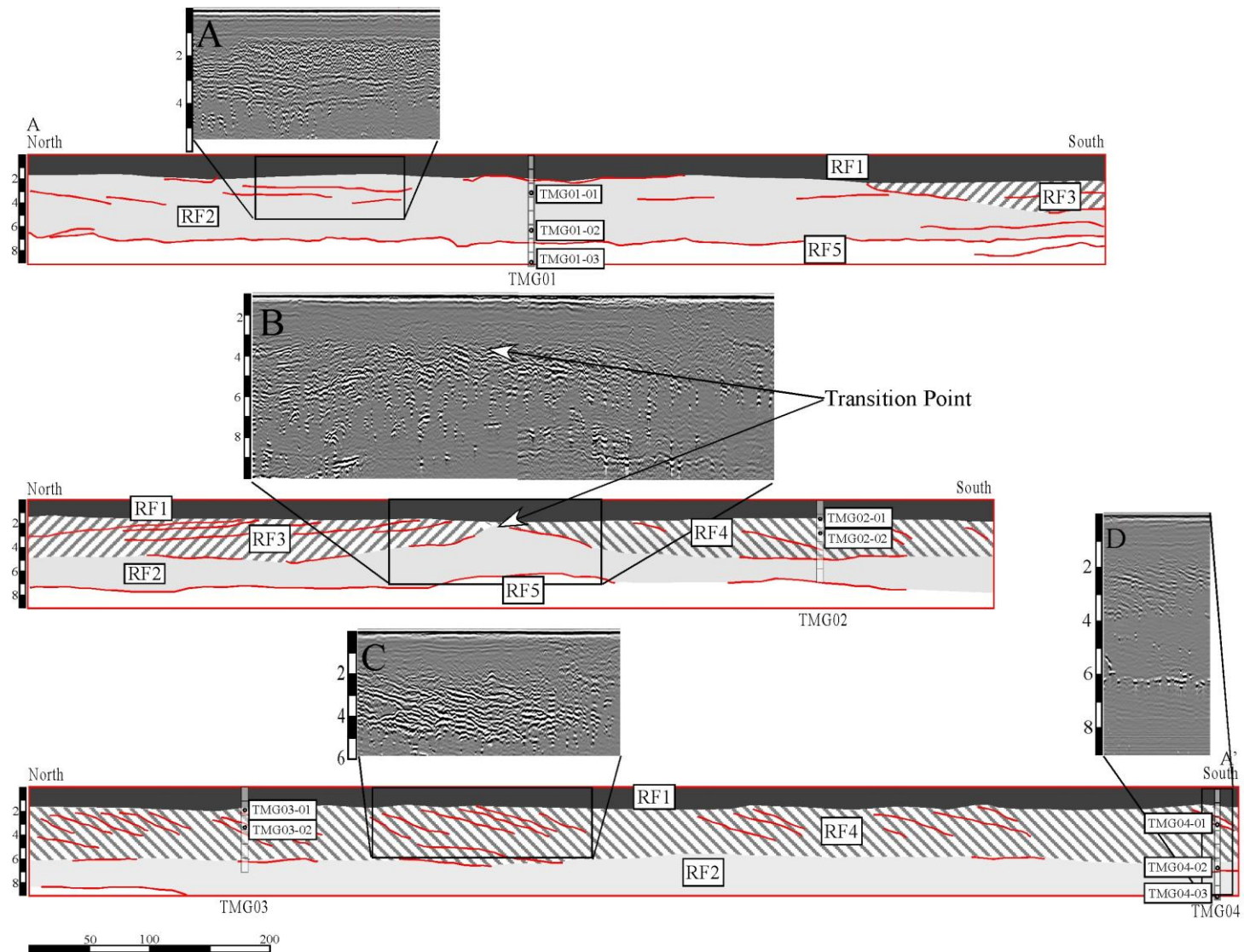


Figure 4.5. 13-mile GPR (Transect A on Figure 4.2) illustrating radar facies, interpretations, and examples.

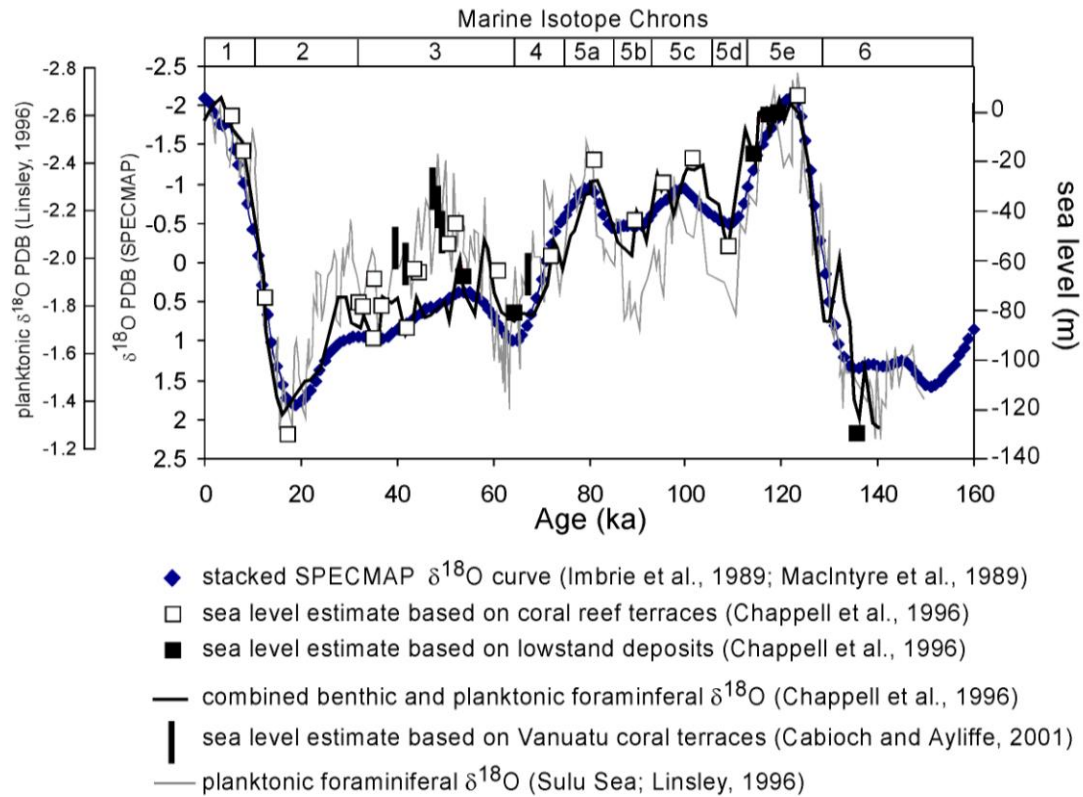


Figure 4.6. Comparison of the SPECMAP marine $\delta^{18}\text{O}$ curve (Imbrie et al., 1989; MacIntyre et al., 1989), coral reef terraces (Chappell et al., 1996; Cabioch and Ayliffe, 2001), foraminiferal $\delta^{18}\text{O}$ data (Chappell et al., 1996; Linsley, 1996).

CHAPTER 5

ELECTRON SPIN RESONANCE OPTICAL DATING OF MARINE, ESTUARINE AND AEOLIAN SEDIMENTS IN NORTHERN FLORIDA, USA

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ABSTRACT

Electron spin resonance optical dating (ESROD) of quartz sand grains was conducted on littorally transported and aeolian siliciclastic sediments in Florida for the first time. ESROD utilizes radiation-sensitive defects at silicon sites which have been replaced by aluminum and titanium atoms, to give rise to a time-dependant signal. These defects have the ability to absorb larger amounts of radiation dose, compared to optically stimulated luminescence, and therefore extend the optical dating range back into the millions of years. Our results show that the Trail Ridge sequence is a multi-depositional unit that began depositing around 2.2 Ma and continued until 6 ka. The Osceola Cape, of the Effingham Sequence, was deposited around 1.5 Ma, and the Chatham Sequence was a multi-depositional terrace with at least three events preserved.

5.1 INTRODUCTION

This paper presents new depositional ages of selected units in Florida using electron spin resonance optical dating (ESROD) of quartz sand grains. ESROD is similar to optically stimulated luminescence (OSL) such that the signal is zeroed or reduced to a residual by exposure to sunlight during transportation and the signal begins to grow once buried due to exposure to environmental radiation (Yokoyama et al., 1985; Laurent et al., 1998; Beerten et al., 2006; Rink et al., 2007). Quartz has two paramagnetic centers (aluminum and titanium) used for dose determination, these centers have slower growth to saturation rates than OSL which allows the possibility to date much older deposits (Yokoyama et al., 1985; Laurent et al., 1998; Beerten et al., 2006; Lin et al., 2006; Rink et al., 2007).

In the present study the Ti-Li signal (called the Ti signal herein) is used for equivalent dose (De) determination because the Ti-H and Ti-Na were too small or non-existent in many of our samples. Several studies have demonstrated that the Ti signal completely zeroes, but the time required to do so is still under debate. Tissoux et al. (2007) suggest the signal is completely zeroed in ~520 hours of ultra violet (UV) exposure, while Toyoda et al. (2000) concluded it was zeroed in only 72 hours. Rink et al. (2007) illustrated that the Ti signal was completely zeroed after 20 days of 12 hours of simulated sunlight per day.

Although the Al signal does not completely zero, like the Ti signal, it does reduce to a constant residual value that can in turn be removed during the De determination. The amount of time to reach this residual value is also under debate. Voinchet et al. (2007) and Laurent et al. (1998) both concluded the Al signal was maximally bleached after 6 months of natural light exposure, while Tissoux et al. (2007) argued that 2 to 3.5 months of natural exposure was sufficient and Rink et al. (2007) concluded that the equivalent of 55 days of 12 hours of sunlight per day was enough.

In this paper, we use the techniques and acceptance criteria established by Rink et al. (2007) to determine the depositional ages of shallow marine and aeolian samples in northern Florida, USA. They suggest only using ages where the De values of Al and Ti

are in statistical agreement. Although we do not have independent age controls on the samples, it is believed that ESROD is reasonably well established as a reliable geochronological tool and the best option when dating siliciclastic deposits beyond the range of OSL. Though we have not succeeded in attempts to compare ESROD and OSL on our quartz samples, we show here that our results agree closely with uplift model ages of Adams et al. (2010). Furthermore, all ages increase downcore or are statistically indistinguishable downcore (within individual cores), and ESROD ages are geomorphically consistent with a model of development of the Florida peninsula which decreases in age southward and eastward from its highland spine along the central region of the peninsula.

5.2 STUDY AREA

The Florida platform extends southward from the North American continent, separating the Atlantic Ocean from the Gulf of Mexico and is covered by a blanket of sediments ranging in age from Miocene to Holocene (DuBar, 1974; Riggs, 1984; Scott, 1988; DuBar, 1991; Randazzo, 1997; Scott, 1997; Scott et al., 2001). Elongate ridges and terraces along the Atlantic coast of Florida reflect a rich history of nearshore sediment accumulation and sea-level oscillations (Adams et al., 2010). Three sequences, the Chatham, the Effingham, and the Trail Ridge were mapped by Winker and Howard (1977), which was the foundation of this project (Figure 5.1 and Table 5.1).

5.2.1 Trail Ridge Sequence

Trail Ridge (Figure 5.1 and Figure 5.2) is a north-south trending geomorphic feature that can be traced approximately 240 kilometers from southern Georgia into northern Florida. In Florida, it occurs in parts of Baker, Duval, Bradford, and Clay Counties. Elevations range from 60 meters (m) above mean sea-level (MSL) along the crest of the ridge to 30 m above MSL near the toe. The feature is associated with a sea-level high stand and is considered to be either a relict barrier island sequence (White, 1970), a relict beach ridge (Pirkle, 1972), or a large aeolian dune (Force and Rich, 1989).

Trail Ridge is comprised of siliciclastic sediments deposited in a coastal marine environment with a large aeolian component in the upper 8 m (Pirkle and Yoho, 1970; Pirkle, 1975; Pirkle and Czel, 1983; Force and Garner, 1985; Force and Rich, 1989). These siliciclastics, which are predominately quartz sand, sit on clays and clay-rich carbonate of the Miocene Hawthorn Group (Scott, 1988). Some portions of the Trail Ridge contain heavy mineral deposits of economic value. The age of Trail Ridge has been proposed as Pliocene to Pleistocene (Pirkle, 1972; Scott et al., 2001). It is also believed to have formed in multiple episodes (Pirkle, 1972; Scott et al., 2001). Numerical modeling of uplift caused by karstification suggests the age of Trail Ridge is 1.44 Ma (Adams et al., 2010). Four areas were chosen to represent the Trail Ridge sequence: The Grandin Sand Quarry (GSQ), Marcarde Sand Pit (MCD), Jennings State Forest (JSF), and the DuPont Mine (DPM) (see Figure 5.1).

The Grandin Sand Quarry (GSQ), located in northwestern Putnam County, falls within the Northern Highlands physiographic province and just south of the southernmost tongue of the Trail Ridge sequence (White, 1970). Kane (1984) looked at the origin of what he termed the Grandin Sands in the vicinity of the Grandin Sand Quarry. He proposed that the Grandin Sands were reworked Cypresshead Formation deposited in nearshore marine environments during the Pleistocene.

The Cypresshead Formation is generally thought to be late Pliocene with a variable thickness of 20 m or more. Scott, et al. (2001) mapped the Cypresshead Formation at the surface in the vicinity of Grandin Sand Quarry. However, it is probable that some thickness of reworked, younger sediments (i.e. Grandin Sands) sit on top of the Cypresshead Formation here. Two slide-hammer sediment cores were collected to sample for ESROD.

The Marcarde Sand Pit (MCD) is a sand borrow pit with an approximately 3 m exposure of surficial Trail Ridge sands located about 2 km south of the Florida/Georgia state line. Three slide-hammer sediment cores were collected for ESROD. Jennings State Forest (JSF) is located on an eastern tongue of the Trail Ridge sequence and geomorphically resembles a dissected alluvium fan deposit caused by the erosion of Trail Ridge sediments. One direct-push core was collected for ESROD. Samples from both MCD and JSF were collected to represent surficial samples of the Trail Ridge sequence. Two slide-hammer sediment samples were collected at the DuPont Titanium Mine (DPM). Samples were collected from the Trail Ridge lower zone, which is defined locally as fine sand to silt intercalated with clay, grading to massive clay at depth, capped by a well sorted, unstained, fine to silty white-gray sand, 1-3 m in thickness with low (<1%) concentrations of heavy minerals. The unit is interpreted to be sands and detritus blown over to the leeward side of the Trail Ridge dune complex and it covers sands and clays of the undifferentiated Plio-Pleistocene sediments.

5.2.2 Effingham Sequence

The Effingham sequence (also known as the Penholoway Terrace) is characterized by broad, gently seaward-sloping strand plains that form prominent relict capes and beach ridges associated with wave-dominated cusped deltas, readily distinguished from its younger and older sequences (Winker and Howard, 1977). This sequence maps within units defined as Pleistocene/Holocene beach ridges and dune (Scott et al., 2001). Healy (1975) mapped the marine terraces and shorelines of Florida and assigned elevations from 12.8 to 21.3 m to the Penholoway terrace which was thought to have formed in the mid to late Pleistocene. Evidence for the age of the Effingham Sequence is limited to faunal assemblages in correlative deposits of the Wicomico (Colquhoun and Johnson, 1968) and Waccamaw (Dubar et al., 1974) Formations, both of which are interpreted as Pleistocene (Winker and Howard, 1977). Adams et al. (2010) suggest the Effingham Sequence is ~408 ka based on modeling uplift due to karstification of underlying carbonate rocks. Three locations were chosen to represent the Effingham Sequence: the South Rucks Quarry (SRQ) and the Osceola Cape Samples (Circle J Ranch [CJR] and Donovan Crews Road Geoprobes [DCG]).

The South Rucks Quarry (SRQ), located in northern Okeechobee County, exposes about 8 m of siliciclastics and shell material. Maddox et al. (2005) show a measured section and a detailed lithologic description from a quarry that is immediately to the north of the South Rucks Quarry which exposes the same lithologic units. The quarry operation is mining a late Pliocene coquina consisting of a quartz sandy, calcite cemented marine shell bed. Most of the section exposed consists of quartz sand with trace amounts of shell material consistent with a tidal flat/estuarine depositional environment. Scott et al. (2001) mapped the sediments in this area as Tertiary/Quaternary shell undifferentiated. Two slide-hammer sediment cores were collected in the siliciclastic sediment above the coquina for ESROD.

Sand ridges occur in the northern part of Osceola County on a broad, flat terrace called the Osceola Plain (White, 1970). Elevation ranges from 18.2 to 21.3 m above MSL. The sand ridges that formed on top of the Osceola Plain consist of quartz sand with minor amounts of clay and heavy minerals. As much as 60 m of siliciclastics and shell beds of Plio-Pleistocene age underlie the sand ridges. Scott et al. (2001) mapped the sediments in this area as Quaternary beach ridge deposits and did not assign a formational name to them. One vibracore and two direct-push cores were collected to sample for ESROD.

5.2.3 Chatham Sequence

The Chatham Sequence (also known as the Talbot Terrace) consists of beach and barrier deposits that are widely thought to represent two or more late Pleistocene eustatic sea-level cycles (Winker and Howard, 1977). Burdette et al. (2009) and Burdette et al. (in review) show that the Anastasia Formation and the beach ridges of Merritt Island were both deposited during the marine isotope stage (MIS)-5 highstands. Adams et al. (2010) argue the Talbot Terrace is ~120 ka using isostatic uplift due to karstification of underlying carbonate rocks. Three locations were chosen to represent the Chatham Sequence: Rima Ridge Geoprobe (RRG), Smokey Hunt Club (SHC), and Dickerson Sand Quarry (DSQ).

Rima Ridge is located in northern Volusia County and falls within the Eastern Valley physiographic province (White, 1970). The feature is a narrow, elongated quartz sand ridge that is parallel to the modern coastline. Scott et al., (2001) mapped these sediments as Quaternary beach ridge deposits but didn't refer to them as a formalized stratigraphic unit. Rima Ridge is a topographic high resting between the Silver Bluff Terrace to the east and the older Pamlico Terrace to the west (Knochenmus, 1968). The sands of Rima Ridge rest upon undifferentiated sands and shell beds of Plio-Pleistocene age ranging in thickness from 20 to 30 m. Two direct-push cores were collected atop Rima Ridge (RRG) and one vibracore was collected at Smokey Hunt Club (SHC) and sampled for dating. The lithology of Rima Ridge captured in the cores coupled with ground penetrating radar data suggests it is an aeolian dune with large landward dipping crossbeds.

The Dickerson Sand Quarry (DSQ), located in northern St. Lucie County, exposes approximately 15 to 20 m of siliciclastics and shell material. Eight identifiable lithologic sections have been described at this locality. Their lithology ranges from quartz sand and shell to sandy coquina. The majority of the section represents a nearshore marine depositional facies punctuated by fresh-water deposits containing terrestrial vertebrates. Fossil vertebrates recovered from this locality are middle to late Pleistocene. Fossil shell material also suggests a middle to late Pleistocene age for the deposits. Scott et al. (2001) placed the near surface sediments in this region into the Late Pleistocene Anastasia Formation. Two slide-hammer horizontal core samples were collected in the siliciclastics for ESROD.

5.3 METHODS

All samples were processed at the School of Geography and Earth Sciences at McMaster University under subdued orange light. Pure quartz grains were obtained using standard preparation methods which include Hydrochloric Acid (HCl) and Hydrogen Peroxide (H_2O_2) digestions to remove carbonates and organics respectively, sieving to obtain proper grain size, heavy liquid separation using Lithium Polytungstate to remove heavy minerals and feldspars, Hydrofluoric acid (HF) digestion to remove the outer alpha effected layer, and finally resieving to remove any grains that no longer fall in the desired size range.

Dose rates were based on elemental concentrations of radioactive ^{238}U , ^{232}Th and ^{40}K in untreated subsamples of the original samples using neutron activation analysis (NAA) for ^{232}Th and ^{40}K and delayed neutron counting (DNC) analysis for ^{238}U (conducted at the McMaster University Nuclear Reactor) (Table 2). NAA-based dose rates were calculated assuming radioactive equilibrium in the ^{238}U and ^{232}Th decay chains. Moisture contents were measured in the lab from the recovered unprocessed sediment and used for the dose rate calculation. Cosmic ray dose rates were calculated using the burial depth (assuming an instant sedimentation rate of the overburden) and a 2 g/cm^3 of overburden density using calculations by Prescott and Hutton (1988) with the ANATOL program version 0.72B (provided by N. Mercier, National Center for Scientific Research, Paris). The internal ^{238}U and ^{232}Th dose rates were calculated using the average concentration of those radioisotopes in granitic quartz (Rink and Odom, 1991), using an alpha efficiency factor of $0.04 \pm 10\%$. All measurements were conducted on a JEOL FA-100 X-band spectrometer in a Dewar cooled to 77K with liquid nitrogen, using microwave power of 5 mW and modulation amplitude 0.16 mT. An example of the spectrum of a natural quartz sample (Figure 5.3) shows the existence of the $[\text{AlO}_4]^-$ and $[\text{TiO}_4/\text{Li}]^0$ peaks (henceforth referred to as the Al and Ti signals).

For all samples, equivalent doses ($\text{De}'\text{s}$) were determined after irradiating at the McMaster University Nuclear Reactor, 100 mg aliquots in optically shielded glass tubes with a ^{60}Co γ ray source. The maximum dose given to each sample was 5000 Gray (Gy). The dose response data were fitted with single saturating exponential (SSE) functions using the VFIT program of E. Bulur (Figure 5.4). No weighting functions were used to fit

the SSE. Equivalent dose error determinations were made using the method of Brumby (1992).

Optical exposure experiments were conducted using a Hönle SOL2 solar simulator, equipped with filtration to produce exposure similar to solar radiation, with its UV contribution. Quartz aliquots were exposed for a maximum of 130 hours (equivalent to 910 hours of natural sunlight) and measured at regular intervals. These experiments were to verify that the Ti signal bleaches completely and to determine the Al's constant residual value after light exposure.

5.3.1 Proof of Concept

It is well documented that aeolian, lacustrine, and fluvial transport of sand grains sufficiently bleaches the Al and Ti signals (Yokoyama et al., 1985; Laurent et al., 1998; Toyoda et al., 2000; Rink et al., 2007; Tissoux et al., 2007; Voinchet et al., 2007)). Our study assumes that longshore littoral transport of sand grains also sufficiently bleaches the Al and Ti signals. To test this assumption, 3 samples were collected on the St. Joseph Peninsula (SJP), Florida, located on the Gulf of Mexico. The first sample was collected on the crest of an active dune, the second sample was collected in the swash zone, and the third sample was collected in one meter of water. The two littoral samples were collected on the western shore of SJP.

The littoral samples were collected to test the idea that sand being transported and reworked by long shore drift receives enough sunlight to optically zero the Al and Ti signals. The natural signal of all three samples was measured and then a 72 hour bleaching experiment of all three samples was performed using the same method as described above. If the samples were sufficiently naturally bleached there should be no difference in the signal intensity of the natural and the 72 hour bleach. Results indicate that the Ti signal was completely bleached and the Al signal was bleached to a background signal. The same is true for the aeolian samples.

5.3.2 Optically Stimulated Luminescence

An “initial De” test was conducted on all samples to determine if the OSL signal was saturated. The quartz grains were prepared the same way as for ESROD. Quartz grains were mounted with silicon spray on aluminum discs using an 8mm mask and were illuminated for 100 seconds at 125° C on a RISØ OSL/TL-DA-15 reader using blue light LED stimulation (470 nm) and a 7 mm-thick Hoya U-340 filter (270–400 nm). A calibrated ⁹⁰Sr beta source was used to perform laboratory irradiations. The single aliquot regeneration (SAR) protocol (Murray and Wintle, 2000) was conducted on 3 aliquots to determine an initial De. The background (the last 4 seconds) of the OSL decay curve was subtracted from the “fast” component (first 0.4 seconds) to determine the samples’ luminescence signal.

5.4 RESULTS AND DISCUSSIONS

The ESROD analytical data are listed in Table 5.2 and the ESROD ages and dose rate data are given in Table 3 and illustrated in Figure 5.5. We used Rink et al.'s (2007) criterion that the Al and Ti De's must be statistically indistinguishable in order to accept derived ages. All but three samples (DCG-02, DCG-04, and GSQ-01) produced acceptable ages. For ease of discussion the Ti and Al ages were averaged. Although the percent error on individual Al and Ti ages of five samples is greater than 25%, most samples' errors range between 15 to 25%, which agrees with the finding of Rink et al. (2007).

5.4.1 Independent Age Control Test with OSL

In an attempt to have independent age controls on the siliciclastic sediments, an OSL initial De test was conducted on all samples. Every sample's (see Table 5.2) OSL signal was found to be saturated, indicating that the samples were beyond the dating capacity of OSL. The dose saturation capacity of Florida sands has not been systematically studied. However, doses of 75-85 Gy have been determined on the west and east coasts, respectively. If we conservatively assume 100 Gy as a typical saturation dose and 0.4 Gy/ka as a typical dose rate for Florida sands, we can estimate roughly that a saturated OSL signal probably represents a minimal age of 250 ka assuming that the sample was fully zeroed at burial.

5.4.2 North Area: Macarde Sand Pit (MCD), DuPont Mine (DPM), Jennings State Forest (JSF), and Grandin Sand Quarry (GSQ)

5.4.2.1 Macarde Sand Pit (MCD)

The MCD samples were collected along the axis of the Trail Ridge Sequence, geographically similar to DPM, but the MCD samples came from much shallower depths (< 2 m). MCD-03 was collected 1.9 m below ground surface and had an age of 1.17-1.67 Ma. MCD-03 may represent continuing deposition or simply reworking of pre-existing Trail Ridge sediment. MCD-02 was collected 70 cm above MCD-03, but had an age estimate of 0.63-0.82 Ma.

5.4.2.2 DuPont Mine (DPM)

The DPM samples were collected in an attempt to determine the age of the Trail Ridge earliest deposition onto the Hawthorn Group. DPM-02 was collected at the very base of the Trail Ridge Sequence and had an age estimate of 1.78-5.08 Ma. Despite the large error, the age range is consistent with the overlying sample. DPM-01 was collected only 0.5 m above DPM-02 and had an age estimate of 1.83-2.59 Ma. We use this age to benchmark initial deposition of Trail Ridge.

5.4.2.3 Jennings State Forest (JSF)

The JSF sample ages cluster very closely together and suggest the sequence captured in the direct-push core is a single unit. JSF-01 had an age estimate of 0.64-0.96

Ma and JSF-02 had an age estimate of 0.68-0.96 Ma. The small percentage of error on both samples, along with their similarity in age gives us very high confidence in these samples.

5.4.2.4 Grandin Sand Quarry (GSQ)

The Al and Ti De's of GSQ-01 did not statistically overlap; therefore the sample was unusable according to Rink et al.'s (2007) criteria. The age estimate of GSQ-02 was 0.89-2.29 Ma. The percent error on this sample is very large, so our confidence in the sample is weak.

5.4.3 East Area: Rima Ridge Geoprobe (RRG) and Smokey Hunt Club (SHC)

5.4.3.1 Rima Ridge Geoprobe (RRG)

The RRG samples' ages cluster very closely and suggest that Rima Ridge was a single deposition dune. RRG-01 had an age estimate of 0.41-0.61 Ma and RRG-02 had an age estimate of 0.44-0.58 Ma.

5.4.3.2 Smokey Hunt Club (SHC)

The SHC vibracore was collected slightly south of Rima Ridge in an attempt to place an age on the sediment underlying Rima Ridge. SHC-03 had an age estimate of 0.86-1.22 Ma and SHC-02 had an age estimate of 0.71-1.09 Ma.

5.4.4 South Area: South Rucks Quarry (SRQ), Dickerson Sand Quarry (DSQ), Circle J Ranch (CJR), and Donovan Crews Geoprobe (DCG)

5.4.4.1 South Rucks Quarry (SRQ)

The SRQ samples cluster very closely and probably represent a single depositional event. SRQ-03, the lower sample, dates to 0.38-0.64 Ma, and SRQ-02, the upper sample, dates to 0.42-0.78 Ma.

5.4.4.2 Dickerson Sand Quarry (DSQ)

The DSQ samples were two of the deepest samples collected. DSQ-01, collected 14 m below ground surface, had an age of 0.61-1.37 Ma. DSQ-02 was collected 11.5 m below ground surface and had an age of 0.43-0.73 Ma.

5.4.4.3 Circle J Ranch (CJR)

The lower sample at CJR (CJR-02) dated to 1.18-1.72 Ma, while the upper sample (CJR-01) dated to 0.33-0.49 Ma. Although the samples are only vertically separated by 1.3 m, two depositional units were captured.

5.4.4.4 Donovan Crews Geoprobe (DCG)

The Al and Ti De's of DCG-02 and DCG-04 did not statistically overlap; therefore the samples were unusable according to Rink et al.'s (2007) criteria. DCG-01, located on the east side of the sand ridge sequence dated to 1.01-1.55 Ma, and DCG-03, located on the western side of the sand ridge sequence, dated to 1.43-2.21 Ma.

5.4.5 Trail Ridge Sequence

It is well documented that Trail Ridge is a multi-depositional coastal feature. Our results support this hypothesis. From bottom to top, the ages range from 2.59 Ma to 0.006 Ma (unpublished OSL data), with the sands of Jennings State Forest (JSF) grouping around 0.80 Ma. Around marine isotope stage (MIS) 75 (using the mean age for ease of discussion), sea level reached one of its highest levels in the last 2.5 Ma, well above present assuming no uplift has occurred (Tiedemann et al., 1994) (Figure 5.2). Statistically this deposition ranges from MIS-65 to ~MIS-102. This high stand would have been sufficient enough to inundate much of the Florida Platform and would have facilitated initial deposition of Trail Ridge (DPM-01). Although the base of the Trail Ridge Sequence is ~40 m above MSL, it is not believed that sea level reached that high. Adams et al. (2010) suggest Trail Ridge, as well as the Effingham Sequence and the Chatham Sequence have been significantly uplifted due to karstification of underlying carbonate rocks.

5.4.6 Effingham Sequence

The two usable samples from the Donovan Crew Geoprobe transect (DCG-01 and DCG-03) and the lower sample from CJR (CJR-02) has mean ESROD ages that range from 1.28 to 1.82 Ma. All three samples were collected less than 3 meters below the ground surface therefore it is believed this is the age range of the sand ridges that compose the Osceola Cape. Around MIS-45, sea-level rose to higher than present levels, stabilized, and began depositing beach ridges very similar to that of Merritt Island (Tiedemann et al., 1994) (Figure 6). Although the orientation of the ridges is different, their similarity geomorphically allows for the deduction that Osceola Cape's depositional history is similar to the ridge formation history of Merritt Island as described by Burdette et al. (in review). The upper CJR sample (CJR-01) dates much younger (~0.41 Ma) and represents a redepositional aeolian event. The samples from the South Rucks Quarry represent a tidal flat or estuarine area based on the fossil assemblage and was deposited around 0.5 Ma. These samples are much younger than the Osceola sand ridges, but correlate with the age of deposits of the Chatham sequence.

5.4.7 Chatham Sequence

The Chatham Sequence is the youngest of the three sequences and is believed to represent late Pleistocene highstands (Winker and Howard, 1977). Burdette et al. (2009) and Burdette et al. (in review) have confirmed this for the Atlantic Coastal Ridge (Anastasia Formation) and the Atlantic Barrier Chain (Merritt Island). Data presented

here suggest the Chatham Sequence preserves at least 2 other depositional events on the same terrace.

Around MIS-25 (approximately 1 Ma), sea-level rose to above present level and deposited the lower near shore marine sands of DSQ (DSQ-01 in our south sequence) as well as the sands of the SHC (SHC-03 and SHC-02 in our east area). These latter sands are also the Plio-Pleistocene undifferentiated sands and shell beds that Rima Ridge rest upon. Also around this time in our North Area, the alluvial sands of JSF (JSF-01 and JSF-02) and the reworked sands of MCD (MCD-03) and probably GSQ (GSQ-02) were being deposited.

During MIS-15 (approximately 0.6 Ma) and MIS-11 (approximately 0.4 Ma), sea-level rose above present level and the upper nearshore marine sands of DSQ (DSQ-02) (South Area) and the tidal flat/estuarine sands of SRQ (SRQ-03 and SRQ-02) (South Area) were deposited. During this same time in the East Area, a large dune, Rima Ridge (RRG-01 and RRG-02) was deposited, as well as an aeolian cap on the Osceola Cape ridges (CJR-01) (South Area) and Trail Ridge (MCD-02) (North Area).

5.5 CONCLUSIONS

ESROD of littorally transported quartz sands show encouraging results for marine and aeolian deposits in northern Florida. Proof of concept experiments using modern Florida beach sediments show that initial conditions of deposition nearshore and onshore along beaches were most likely sufficient for the proper resetting of ESROD signal in our Florida samples before burial. Using the criteria suggested by Rink et al. (2007), we were able to achieve usable ages, except for three samples, up to ~2.5 Ma and determine the depositional age of several previously unknown sequences. An attempt to cross-check our ESROD results against OSL in all samples was partially successful because the OSL signals had reached saturation at an earlier time in their burial history, proving the samples are older than the dating capacity of OSL, approximately 250 ka.

For the first time, we have radiometric dating evidence for the timing of deposition of siliciclastic sediments in the interior of the Florida Peninsula which predate the penultimate interglacial (MIS-5). Our data suggest that deposition of the Trail Ridge Sequence began around 2.2 Ma (~MIS-75) and aeolian deposition continued until ~6 ka. The Osceola Cape structure, in the Effingham Sequence, was deposited between 1.43 Ma and 1.55 Ma (MIS-47 to MIS-53) with an aeolian cap being deposited around 0.4 Ma (MIS-11). Previous research suggested the Chatham Sequence was deposited during MIS-5 (Winker and Howard, 1977; Adams et al., 2010), but our data suggests that only the Atlantic Coastal Ridge and the Atlantic Barrier Chain were deposited during this time (Burdette et al., 2009, Burdette et al, in review). The majority of the Chatham Sequence was deposited between 0.86 Ma and 1.09 Ma (MIS-21 to MIS-31), with surficial aeolian features such as Rima Ridge being deposited between 0.41 Ma and 0.61 Ma (MIS-11 to MIS-15). The DSQ faunal age estimates of middle to late Pleistocene (0.78 to 0.01 Ma) are consistent with the ESROD age estimate of 1.37 to 0.61 Ma and 0.75 to 0.45 Ma.

This study advances the geologic knowledge of Florida in several ways. The first is the ability to begin to understand relative sea-level fluctuations and cyclicity, compared to the eustatic sea-levels, and its effects on the Florida Platform over the last 2.5 Ma. Recent developments in modeling uplift due to karstification for the area may benefit by having ages of terraces used in models (Adams et al., 2010). Lastly, the ability to place depositional ages on geologic units may allow for the refinement of geologic mapping in Florida. Further experiments should include comparisons with cosmogenic $^{26}\text{Al}/^{10}\text{Be}$ dating on splits of our archival samples.

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Table 5.1. Location/ Core Name, Coordinates, Associated Sequences and Terraces				
Location / Core Name	Latitude	Longitude	Associated Sequence (Winker & Howard, 1977)	Associated Terrace (Healey, 1975)
NORTH AREA				
MCD	30° 20' 43.8"	82° 05' 51.6"	Trail Ridge	100'-170'
DPM	30° 09' 40.6"	82° 02' 25.2"	Trail Ridge	170'-215' (Coharie)
JSF	30° 08' 07.5"	81° 57' 12.7"	Trail Ridge	100'-170'
GSQ	29° 43' 05.3"	81° 56' 24.6"	Trail Ridge	70'-100' (Wicomico)
EAST AREA				
RRG-01	29° 13' 59.7"	81° 10' 23.1"	Chatham	25'-42' (Talbot)
RRG-02	29° 13' 45.9"	81° 11' 02.6"	Chatham	25'-42' (Talbot)
SHC	29° 07' 32.8"	81° 07' 29.3"	Chatham	25'-42' (Talbot)
SOUTH AREA				
SRQ	27° 30' 44.4"	80° 45' 03.2"	Effingham	25'-45' (Talbot)
DSQ	27° 31' 31.6"	80° 28' 12.2"	Chatham	8'-25' (Pamlico)
CJR	28° 02' 38.6"	81° 02' 35.4"	Effingham	42'-70' (Penholoway)
DCG-01	28° 03' 19.5"	80° 59' 32.2"	Effingham	42'-70' (Penholoway)
DCG-02	28° 03' 21.0"	81° 01' 18.1"	Effingham	42'-70' (Penholoway)
DCG-03	28° 03' 21.8"	81° 02' 42.5"	Effingham	42'-70' (Penholoway)

Locations were collected using a handheld Garmin GPS and reported in NAD 83 Coordinate System.

Table 5.2 Elevation, Burial Depth, Associated Sequence, Grain Size Analyzed, E, Th, and K results, Water Content, and Cosmic Dose Rates

Sample Name	Elevation (m) above MSL	Sample Burial Depth(m)	Associated Sequence	Grain Size Analyzed	U ²³⁸ (ppm) [a]	Th ²³² (ppm) [a]	K (%) [a]	Water Content (%) [b]	Cosmic Dose Rate (μGy/a)
NORTH AREA									
MCD-02	40.8	1.25	Trail Ridge	150-212	0.30	0.39	0.0034	3.28	176.83
MCD-03	40.1	1.90	Trail Ridge	150-212	0.33	0.40	0.0000	2.89	162.11
DPM-01	44.0	8.96	Trail Ridge	90-150	0.98	5.2	0.0250	20.7	70.33
DPM-02	43.5	9.50	Trail Ridge	90-150	0.53	1.2	0.0003	16.3	66.52
JSF-01	28.9	2.07	Trail Ridge	150-212	1.80	4.41	0.0074	3.83	158.51
JSF-02	24.0	7.00	Trail Ridge	150-212	2.25	3.05	0.0157	28.4	86.93
GSQ-02	21.5	8.54	Trail Ridge	150-212	0.77	1.16	0.0075	2.63	73.50
GSQ-01	18.3	11.74	Trail Ridge	150-212	0.52	2.45	0.0130	3.41	53.47
EAST AREA									
RRG-01	8.8	3.19	Chatham	150-212	1.22	3.40	0.1487	21.4	137.12
RRG-02	12.9	2.09	Chatham	150-212	1.34	7.10	0.0074	9.96	158.10
SHC-02	9.8	1.17	Chatham	150-212	0.23	0.27	0.0015	7.77	178.76
SHC-03	9.0	2.03	Chatham	150-212	1.48	5.04	0.0038	17.9	159.35
SOUTH AREA									
SRQ-02	8.0	4.00	Effingham	150-212	2.21	5.80	0.3095	11.4	123.85
SRQ-03	1.0	11.00	Effingham	150-212	2.47	3.97	0.7380	21.7	57.34
DSQ-02	-4.5	11.50	Chatham	150-212	2.09	1.04	0.1540	4.34	43.77
DSQ-01	-7.0	14.00	Chatham	90-150	2.50	4.88	0.9749	15.1	54.68
CJR-01	20.0	1.05	Effingham	150-212	0.79	2.64	0.0612	13.7	181.69
CJR-02	18.7	2.30	Effingham	150-212	0.47	1.30	0.0101	18.8	153.80
DCG-01	15.0	3.00	Effingham	150-212	0.25	0.6	0.0154	16.5	140.48
DCG-02	12.6	5.45	Effingham	150-212	1.28	1.1	0.2811	26.7	103.90
DCG-03	19.1	1.87	Effingham	150-212	0.63	2.5	0.0397	20.6	162.76
DCG-04	15.4	5.63	Effingham	150-212	1.15	2.1	0.1115	21.8	101.72

Table 5.3. ESROD Equivalent Doses, Dose Rates, and Age Data

Core	Sample Name	Al Center De (Gy)	Ti Center De (Gy)	Al and Ti Agreement	Annual Dose (μ Gy/a)	Al Center ESROD Age (Ma)	Ti Center ESROD Age (Ma)	Average Age Range if in agreement(Ma)	Mean ESROD Age (Ma)	% Error
NORTH AREA										
N/a	MCD-02	190.5 $\pm$ 20.0	214.5 $\pm$ 25.9	Yes	283.1 $\pm$ 16.1	0.67 $\pm$ 0.08	0.76 $\pm$ 0.10	0.71 – 0.53	0.62 $\pm$ 0.09	15
N/a	MCD-03	376.7 $\pm$ 60.0	398.6 $\pm$ 68.8	Yes	272.6 $\pm$ 16.1	1.38 $\pm$ 0.24	1.46 $\pm$ 0.27	1.58 – 1.08	1.33 $\pm$ 0.25	19
N/a	DPM-01	915.1 $\pm$ 111.5	824.8 $\pm$ 154.3	Yes	393.5 $\pm$ 18.5	2.33 $\pm$ 0.34	2.10 $\pm$ 0.42	2.59 – 1.83	2.21 $\pm$ 0.38	17
N/a	DPM-02	711.7 $\pm$ 249.5	895.7 $\pm$ 537.4	Yes	234.2 $\pm$ 17.5	3.04 $\pm$ 1.07	3.82 $\pm$ 2.24	5.18 – 1.68	3.43 $\pm$ 1.75	51
JSF-01	JSF-01	799.9 $\pm$ 150.0	593.0 $\pm$ 116.5	Yes	866.8 $\pm$ 21.4	0.93 $\pm$ 0.18	0.68 $\pm$ 0.14	0.93 – 0.67	0.80 $\pm$ 0.13	16
JSF-01	JSF-02	671.8 $\pm$ 119.9	667.6 $\pm$ 94.8	Yes	814.8 $\pm$ 19.0	0.82 $\pm$ 0.16	0.82 $\pm$ 0.13	0.96 – 0.68	0.82 $\pm$ 0.14	17
N/a	GSQ-02	478.5 $\pm$ 289.7	602.8 $\pm$ 177.4	Yes	339.0 $\pm$ 16.5	1.41 $\pm$ 0.84	1.78 $\pm$ 0.53	2.29 – 0.89	1.59 $\pm$ 0.70	44
N/a	GSQ-01	1713.1 $\pm$ 615.0	599.4 $\pm$ 146.4	No	352.3 $\pm$ 17.8	4.86 $\pm$ 1.75	1.70 $\pm$ 4.30	N/A	N/A	N/A
EAST AREA										
RRG-01	RRG-01	344.8 $\pm$ 62.0	446.9 $\pm$ 80.6	Yes	778.6 $\pm$ 19.1	0.44 $\pm$ 0.08	0.57 $\pm$ 0.11	0.61 – 0.41	0.51 $\pm$ 0.10	19
RRG-02	RRG-02	536.1 $\pm$ 80.4	427.5 $\pm$ 33.6	Yes	939.0 $\pm$ 29.3	0.57 $\pm$ 0.09	0.46 $\pm$ 0.05	0.58 – 0.44	0.51 $\pm$ 0.07	15
SHC-01	SHC-02	244.6 $\pm$ 55.9	225.2 $\pm$ 38.9	Yes	259.8 $\pm$ 16.0	0.94 $\pm$ 0.22	0.87 $\pm$ 0.16	1.09 – 0.71	0.90 $\pm$ 0.19	21
SHC-01	SHC-03	994.6 $\pm$ 131.3	741.7 $\pm$ 145.0	Yes	833.8 $\pm$ 23.1	1.19 $\pm$ 0.18	0.89 $\pm$ 0.18	1.22 – 0.86	1.04 $\pm$ 0.18	17
SOUTH AREA										
N/a	SRQ-02	742.8 $\pm$ 295.2	804.4 $\pm$ 140.5	Yes	1290 $\pm$ 25.0	0.58 $\pm$ 0.23	0.62 $\pm$ 0.12	0.78 – 0.42	0.60 $\pm$ 0.18	30
N/a	SRQ-03	649.9 $\pm$ 249.4	936.8 $\pm$ 100.6	Yes	1554 $\pm$ 24.9	0.42 $\pm$ 0.16	0.60 $\pm$ 0.08	0.64 – 0.38	0.51 $\pm$ 0.13	25
N/a	DSQ-02	598.2 $\pm$ 94.0	778.7 $\pm$ 254.7	Yes	1196.7 $\pm$ 25.7	0.50 $\pm$ 0.08	0.65 $\pm$ 0.22	0.75 – 0.41	0.99 $\pm$ 0.38	29
N/a	DSQ-01	766.4 $\pm$ 356.2	701.2 $\pm$ 175.2	Yes	741.8 $\pm$ 17.1	1.03 $\pm$ 0.48	0.95 $\pm$ 0.24	1.37 – 0.61	0.58 $\pm$ 0.17	38
CJR-01	CJR-01	281.3 $\pm$ 55.8	208.0 $\pm$ 35.4	Yes	597.4 $\pm$ 18.4	0.47 $\pm$ 0.10	0.35 $\pm$ 0.06	0.49 – 0.33	0.41 $\pm$ 0.08	20
CJR-01	CJR-02	475.9 $\pm$ 92.9	580.8 $\pm$ 91.5	Yes	363.7 $\pm$ 16.6	1.31 $\pm$ 0.27	1.60 $\pm$ 0.27	1.72 – 1.18	1.45 $\pm$ 0.27	18
DCG-01	DCG-01	391.9 $\pm$ 83.1	274.3 $\pm$ 43.6	Yes	260.2 $\pm$ 16.7	1.51 $\pm$ 0.33	1.05 $\pm$ 0.18	1.55 – 1.01	1.28 $\pm$ 0.27	21
DCG-01	DCG-02	N/A	245.8 $\pm$ 98.1	No	729.6 $\pm$ 17.7	N/A	0.34 $\pm$ 0.13	N/A	N/A	N/A
DCG-03	DCG-03	902.4 $\pm$ 111.5	969.0 $\pm$ 251.2	Yes	513.8 $\pm$ 18.8	1.76 $\pm$ 0.24	1.89 $\pm$ 0.50	2.21 – 1.43	1.82 $\pm$ 0.39	21
DCG-03	DCG-04	145.6 $\pm$ 22.1	357.9 $\pm$ 63.6	No	608.7 $\pm$ 19.0	0.24 $\pm$ 0.04	0.59 $\pm$ 0.11	N/A	N/A	N/A

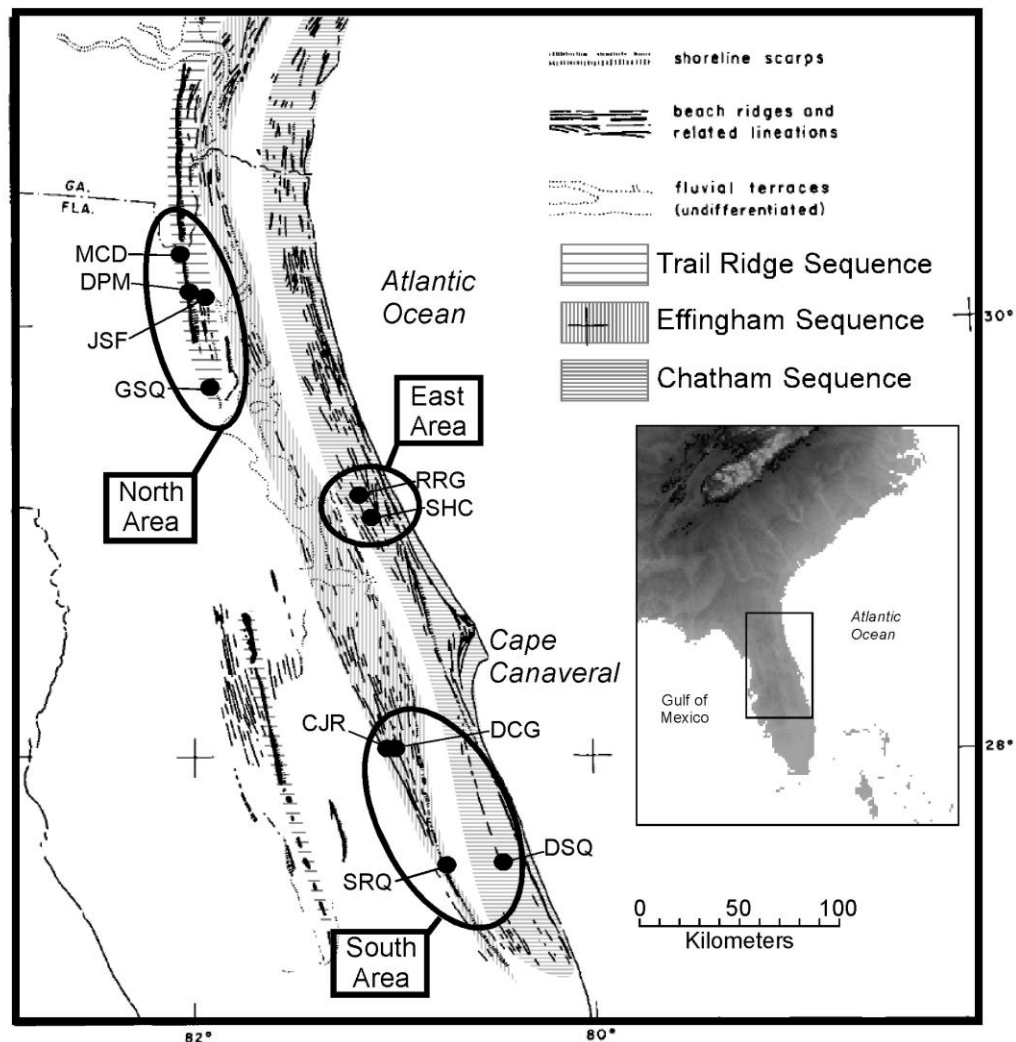


Figure 5.1. Map illustrating the Plio-Pleistocene shoreline sequences in Florida as defined by Winker and Howard (1977) and core locations (modified from Winker and Howard, 1977).

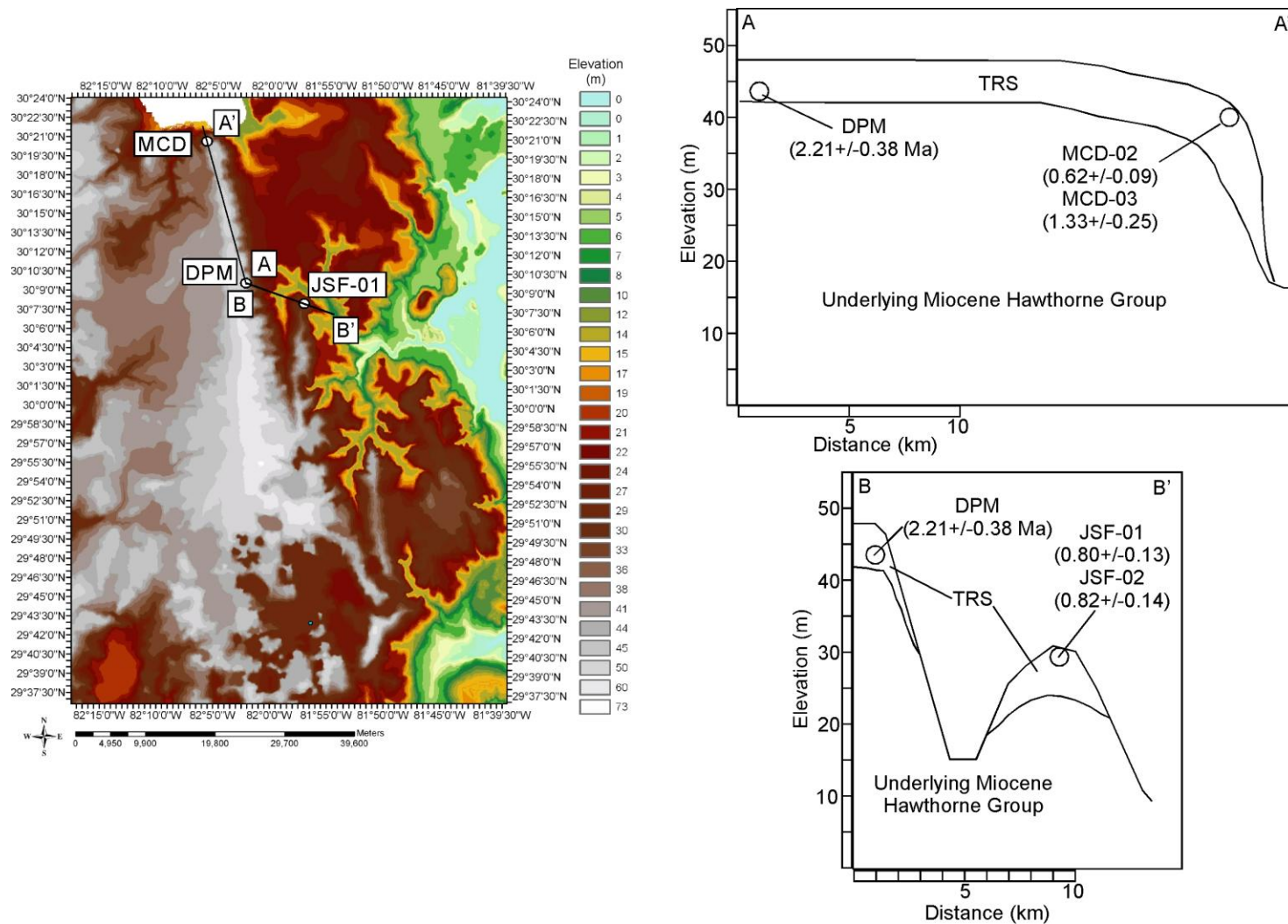


Figure 5.2. DEM of the Trail Ridge Sequence showing transect lines and core locations. TRS – Trail Ridge Sequence.

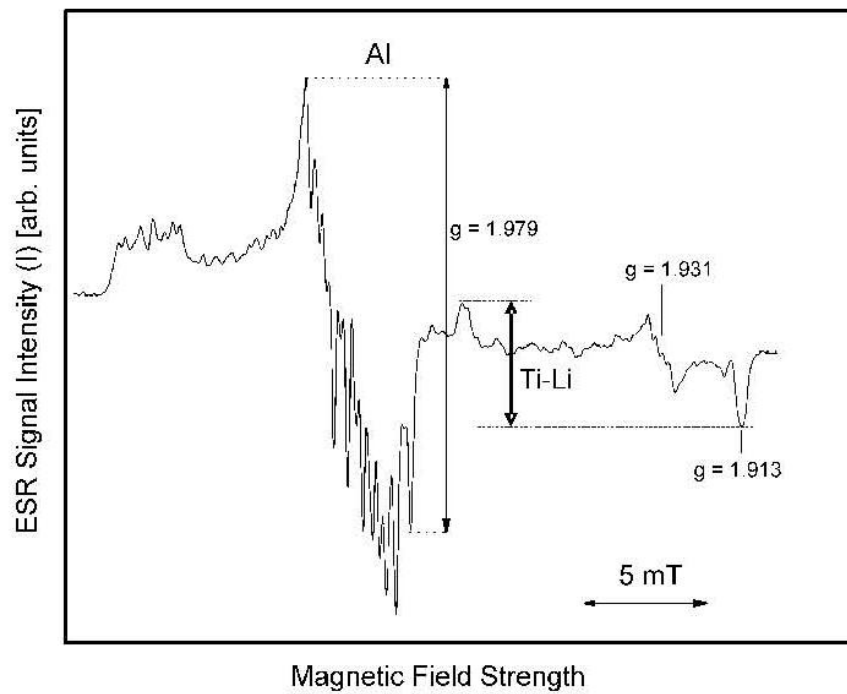


Figure 5.3. ESR spectrum showing the method used to determine the intensity of the $[\text{AlO}_4]^{0-}$ and $[\text{TiO}_4/\text{Li}]^{0-}$.
Modified from Rink et al. (2007)

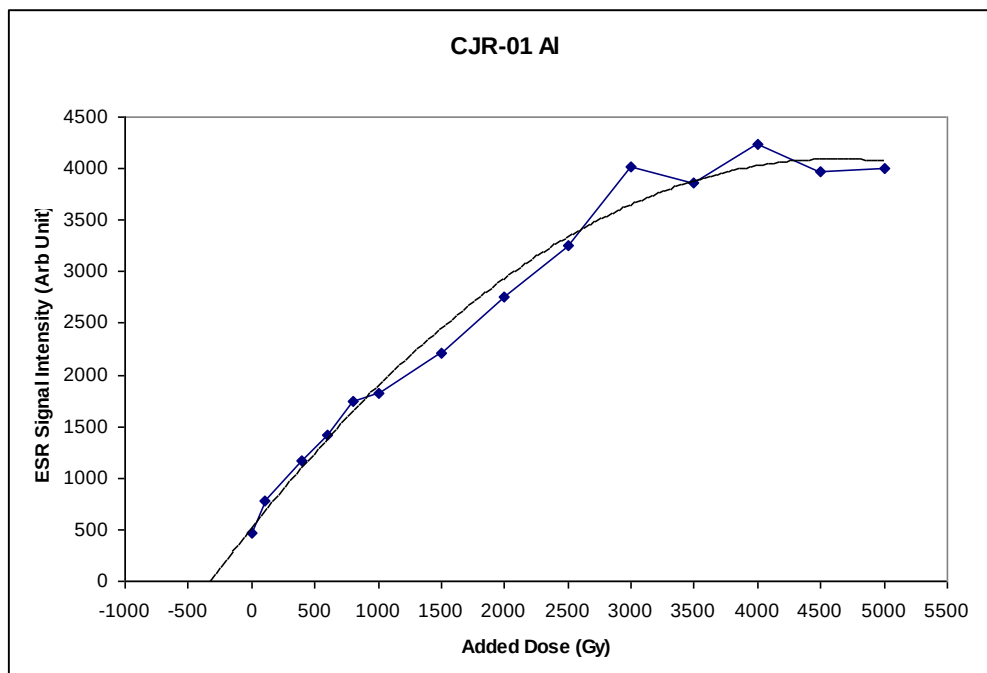


Figure 5.4. Dose response curves for the Al signal of CJR-01 using all added dose points

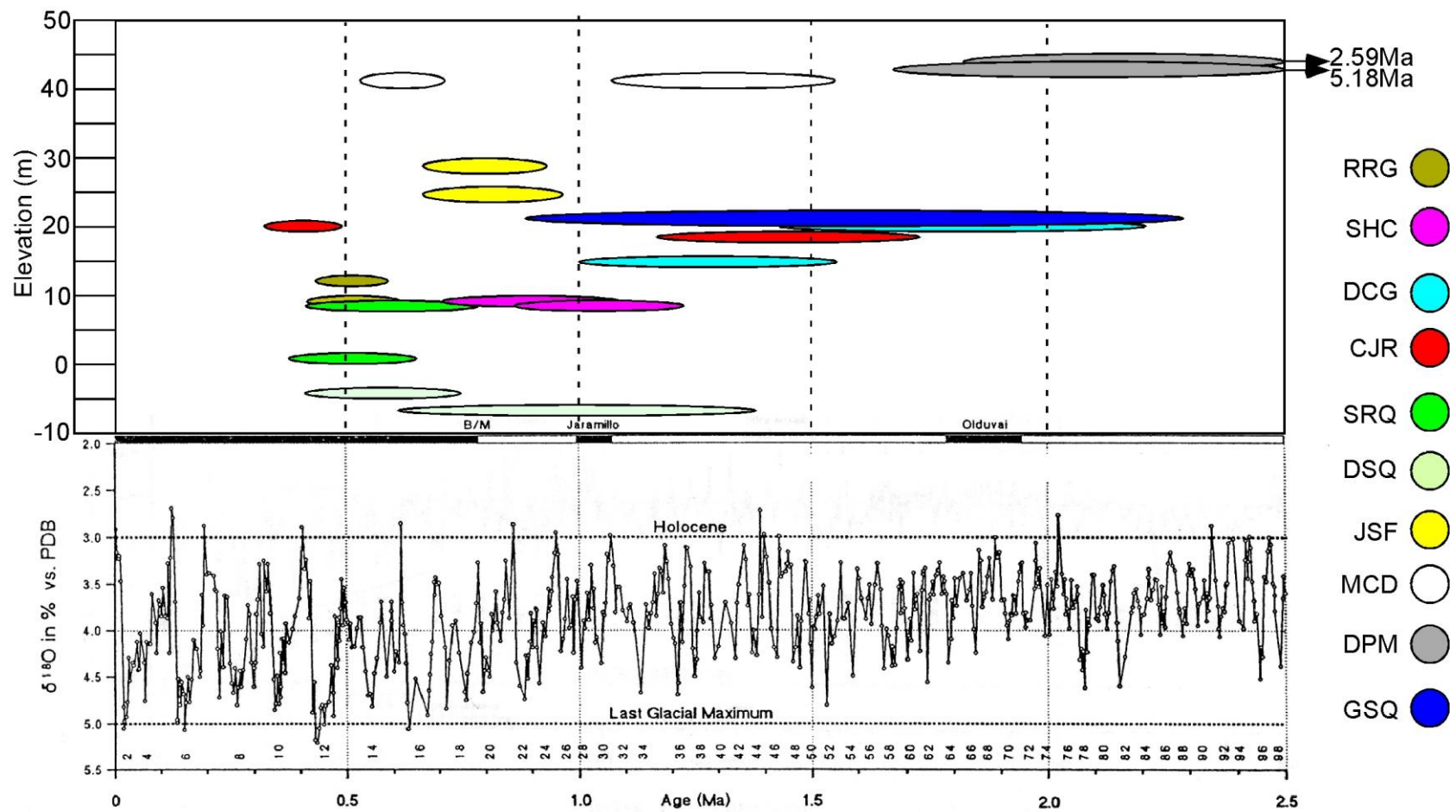


Figure 5.5. ESROD depositional age ranges, elevations relative to mean sea level, and $\delta^{18}\text{O}$ in ‰ vs. PDB record modified from Tiedemann et al. (1994).

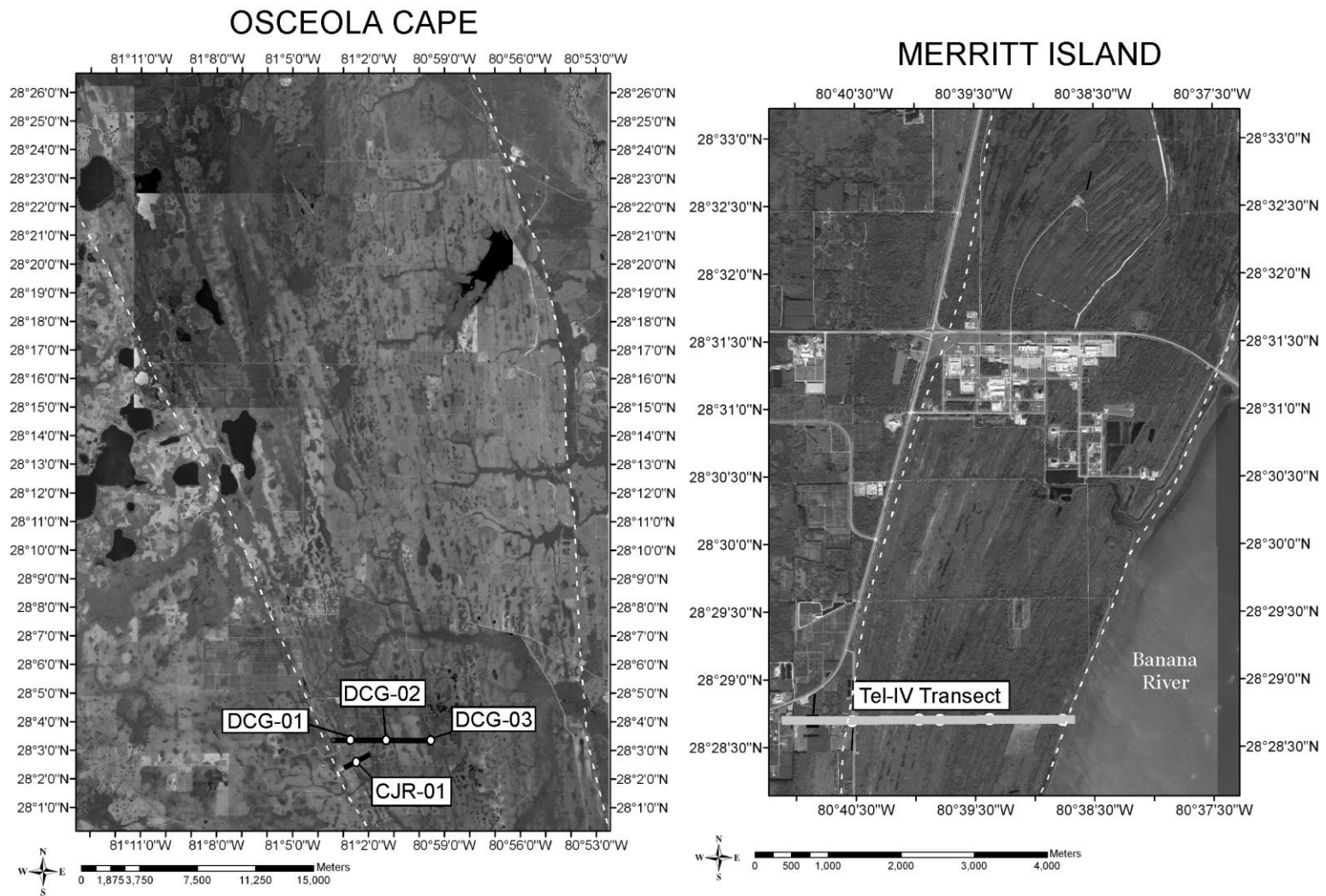


Figure 5.6. Comparison of the beach ridge sequence of the Osceola Cape and Merritt Island as described by Burdette et al. (*in review*). Dashed lines indicate extent of sand ridges.

CHAPTER 6

SUMMARY & CONCLUSIONS

This dissertation was designed from the onset to be a pilot project. A broad scoped investigation of numerous locations, numerous depositional environments, and numerous techniques used to accomplish the single goal of better understanding the late Quaternary sea levels and their effects on Florida. As the project developed it became clear the magnitude of the project and the direct impact it will have. This project was the first for many things in Florida; first time Anastasia and coquina was dated using OSL, first time ESROD was conducted in Florida, and the first time the Trail Ridge was successfully dated. But its greatest contribution is the use of multiple tools (OSL, ESROD, GPR, etc) to develop an understanding of late Quaternary sea level in Florida.

OSL is now well established as a very useful geochronological tool for coastal geoscientists. It fills a niche that coastal geoscientists were looking for when trying to place absolute ages on deposits older than radiocarbon or in environments where radiometric datable material was absent. This project not only used OSL successfully but advanced it in several ways. One way was the use of OSL on coquina rock. Before this project it had only been done a handful of times and never conducted in Florida. Our results were very conclusive and proved OSL dating of coquina rock not only works but gives the research the depositional age of a very important sea level indicator. Another way was using OSL in unfavorable depositional environments. OSL has been well demonstrated in aeolian and even fluvial deposits to be well behaved and easily datable. But researchers have stayed away from marine deposits. The dating of shallow marine deposits was essential for this project. We successfully dated several shallow marine deposits in Florida. During this project we came across many hurdles that needed to be overcome. One such hurdle saw the development of the ACRM. This model is the first to remove a natural overburden caused by aeolian deposition much later than the original deposition. The development of the ACRM allowed for more accurate dating of the target material.

Two types of geophysics were used for this project. GPR is not a new technology; geoscientists have been using it for years to determine depositional environments. At Merritt Island, GPR allowed for the interpretation of the sand ridge sequence. Although the signal was attenuated as we approached the river, enough data was collected to allow us to determine the ridges were in fact beach ridges. At 13-Mile, the GPR transect allowed us to determine the exact location of the transition point. This point is described as the maximum point sea level rose during that sea-level high stand. This location coupled with high resolution LiDAR allowed us to get the precise elevation of sea level. Direct-push electrical conductivity was tested at Merritt Island. This instrument gives a very quick down core readout of variations in soil type. This technology can and should be utilized in later projects where large scale stratigraphic correlations are necessary.

The most exciting part of this project, personally, is the use of ESROD. This is a new technique that is only performed by a handful of researchers around the world. There are two major firsts this project accomplished with regards to ESROD. The first is this project marks the first time ESROD has been used in Florida and the second is that ESROD has never been performed on marine and estuarine sediments. The use of ESROD in Florida allows researchers to determine the age of siliclastic units previously thought too old to date. The Florida Geologic Map may benefit the most. Many of the units defined by the Florida Geologic Survey are very broad and very vague. A single unit may cover several geologic times. ESROD will help them narrow the ages of some of Florida's most important units, such as Trail Ridge.

Until now, ESROD was only used on fluvial and aeolian deposits; due to the certainty the samples would be sufficiently bleached. This study shows ESROD can be used on estuarine and shallow marine units and that the quartz grains receive enough sunlight to zero the signal. The ability to use ESROD on marine and estuarine deposits allows researchers around the world to obtain absolute ages on materials too old to use OSL. This advancement with ESROD is, I feel, the projects greatest accomplishment.

The following summarizes first by chapter and then in general the major findings of this research.

Chapter 2: Mainland Anastasia Formation hard rock coquina from the Wilson Quarry west of St. Augustine yielded depositional age range of 107-129 ka (MIS5c – MIS5e), which was interpreted as evidence of a paleoshoreline at 8m $\pm$ 3m AMSL. Lower lying and non-mainland Anastasia Formation coquinas presently at 2m AMSL at Haulover Canal and Dalboro Road in the Merritt Island area further south yielded 77-92 ka (MIS-5a) and 100-119 ka (MIS5c-MIS5e) ages respectively. All three OSL ages on coquina agree with the previous MIS-5 age estimates of Osmond et al. (1970), and with Brooks' (1972) idea that the Anastasia was formed during several depositional events. Concerns that dissolution of shell and reprecipitation might have resulted in dose rate changes through time were probably not a problem. Evidence for this is a comparison of the average gamma dose rates in the sands studied on Merritt Island (144.4 μ Gy/a) and suggests that the main radioactivity in the coquina is carried by the non-carbonate fraction.

Chapter 3: Studies along a transect across a relict coastal sand ridge sequence in southeastern Merritt Island yielded core lithologies and GPR images that were used to establish the geometry of a classic beach ridge sequence which abuts coquina to the west and the Banana River to the east. An overlying aeolian sand caps these units.

OSL was used to establish that the beach ridge sequence was deposited during MIS-5c, which indicated based on present day elevations of these deposits, that sea level was near its present day levels between 95-105 ka. This is in contrast to general beliefs that sea levels in the peak warm time of MIS-5c were lower than modern levels.

The aeolian sand cap dated to about 18 ka, some 80,000 years younger than the underlying sands. It was realized that the aeolian overburden should be removed from the amount of overburden used to calculate the cosmic dose rates to the underlying sands because this would better approximate the true overburden over the duration of the burial time. This new approach was named the aeolian cap removal model (ACRM) and was found because the ages were more sensible from geologic standpoint.

Chapter 4: Combined GPR and coring along transects yielded a detailed stratigraphy of the beach ridge set between Apalachicola and Port St. Joe on the Gulf of Mexico, called here for the first time the 13-Mile Ridges. The Biloxi Formation at the base of the sequence was dated to >170 ka, while the overlying Gulfport Formation included MIS-6 age deposits of mica-rich sand thought to be fluvial sands of the meandering paleo-Apalachicola River, and a classic beach ridge sequence deposited in MIS-5e (about 115-130 ka). As at Merritt Island, a thick aeolian sand cap was present, which when removed using the ACRM (Chapter 3), yielded a clear MIS-5e age pattern for the beach ridge sands.

The nearby relict sand ridge set just northwest of 13-Mile, called here for the first time the Ward Ridges, and the intervening alluvial areas were also cored and yielded similar age results of MIS-5e and MIS-6.

Finally at 13-Mile, the subsurface GPR, core lithologies, and surface geomorphology were combined to define a “transition point” that corresponds to where sea level reached its highest elevation before beginning to recede and deposit a beach ridge sequence as it regressed. This highest sea level position corresponds to approximately 3.5 m AMSL. Combining the OSL ages, the subsurface data, and the maps of the landforms in the area, the local geological evolution of the area over the last 200,000 years has now been defined at the basic level.

Chapter 5: Using criteria that the aluminum and titanium ESR signal equivalent doses must match, ESR optical dating was applied to 22 samples over a large region of Florida that hosts dune and relict coastal deposits. Nineteen of the 22 samples (86%) showed the match, yielding ages ranging from 2.21 ± 0.38 to 0.41 ± 0.08 Ma. OSL tests on the same 22 samples showed dose saturation of the natural signal indicating they were all beyond the theoretical OSL dating range of ~250 ka for Florida sand environments, supporting their attribution to middle and lower Pleistocene time frames. Tests of sediment from modern Florida beach systems clearly showed fully zeroed signals and non-decaying aluminum signals during extended optical exposure. These tests confirm the likelihood that coastal optical exposure should be useful in ESROD studies.

Based on ESROD deposition of the Trail Ridge Sequence samples began at around 2 Ma, probably resulting from a very high sea level during MIS-75. This is somewhat older than an age of 1.44 Ma based on isostatic uplift modeling by Adams et

al. (2010). Multi-time domain and depositional regimes in the Trail Ridge sequence were also identified. Alluvial sequences at Jennings State Forest, Grandin, and Macarde were dated to about 1 Ma, and an aeolian cap only ~6,000 years old at Macarde was also found.

Within the Effingham Sequence, the mean ESROD age from Donovan Crews and Circle J Ranch ranged from 1.28 to 1.82 Ma. It is believed that the sand ridge sequence here (Osceola Cape Sequence) may have formed after sea levels stabilized during MIS-45. An aeolian cap of 0.4 ± 0.08 Ma was also found here. At South Rucks Quarry, the tidal flat/estuarine sands were deposited in a similar time frame of 0.51 ± 0.13 , in statistical agreement with the aeolian cap to the north at Circle J Ranch.

Chatham Sequence deposition began about MIS-25 (1 Ma) with the formation of nearshore sands exposed at Dickerson Sand Quarry. Much later at Dickerson, another depositional event occurred with another set of nearshore sands at about MIS-15 (0.6 Ma). Much further north, at Smokey Hunt Club, sands of ~1 Ma were found, some 200 km north of Dickerson, indicating that a long stretch of coastline was experiencing deposition at the same time. An aeolian cap at Rima Ridge, just north of Smokey Hunt Club was deposited at ~0.4 Ma.

General Conclusions: The results in Chapter's 2,3,4 show that mainland coastal segments of the Anastasia and Gulfport Formations, fronting the Atlantic Ocean and Gulf of Mexico respectively, are of late Pleistocene age and can be attributed to MIS-5a – MIS-5e on the Atlantic Side, but only to MIS-5e on the Gulf side. Pre-MIS-5e sandy deposits underlie Gulfport sands. These lie inboard of Holocene barrier island complexes.

Dating conducted further inland using ESROD revealed that all three of the classic sequences: Trail Ridge, Effingham, and Chatham are composed of multiple depositional events of different mode, which exhibit age differences that could be resolved with ESROD. The Chatham Sequence' most outboard member (Anastasia Formation) was late Pleistocene (80 – 130 ka), while further inland we found nearshore marine sands of ~1 Ma in two locations capped either by tidal flat/estuarine sand of ~0.4 Ma in one locality (DSQ) and by 0.4 Ma aeolian sands at the SHC/Rima Ridge complex. Even further inland, the Effingham Sequence exhibited a similar pattern, with a sand ridge sequence probably forming about 1.4 Ma capped by ~0.4 aeolian sand, while further south at South Rucks, estuarine/tidal flat sands at about 0.4 – 0.6 Ma. Finally on Trail Ridge Sequence areas, ~2.2 Ma sands occur in the central portion flanked by lower lying alluvial cap at Macarde dating to only 6 ka was found.

The regional scale study with ESROD in Chapter 5, combined with the OSL studies in Chapters 2 and 3 clearly show that simple model of terraces each individually occupied by relatively recent high sea level stands must be abandoned. The complexity of depositional modes and timing identified using GPR, coring, OSL, and ESROD has significantly modified the views of how the Winker and Howard (1977) sequences

formed and attest to the efficacy of the OSL and ESROD methods in a wide range of coastal environments.

For the first time, we are beginning to piece together the Quaternary sea level history in Florida. Before this project many researchers speculated on the timing of sea levels during the early, middle, and late Quaternary and the deposits associated with each. We have begun to put absolute depositional ages on several key units throughout Florida. With a total of 66 ages compiled, we are beginning to understand the effects of global and regional sea level effects on Florida. Revisions of the Geologic Map of the State of Florida can now be made using our results, focused mainly on divisions that separate lower, middle, and upper Pleistocene deposits from one another. We are just beginning this research and I feel privileged to be the first researcher to contribute. As ESROD advances, the error on several of my ages will become smaller and we will be able to determine exactly when the Trail Ridge, Effingham, and Chatham sequences were formed.

This project succeeded in achieving its goals. The groundwork has been laid for future project to continue the work started here. Researchers will be able to revisit the areas studied in this pilot project and focus on certain aspects. Small things that may not have worked can be solved as technology and knowledge increases. This is only the beginning for the advancement of late Quaternary sea level research in Florida.

APPENDIX I

LIST OF CORES COLLECTED

There were four types of cores collected for this research: vibracores, direct push cores, horizontal slide hammer cores, diamond tipped cores.

Vibracoring induces high frequency vibrations onto a 3-inch diameter aluminum irrigation pipe, which allows the pipe to penetrate into the ground. A custom made coupling, which clamps onto the pipe, is mounted to head of a gas-powered flex-shaft concrete vibrator. Typical cores measure 4 to 6 meters below the ground surface. Precise measurement of core penetration depth, recovered core length, and sediment lost were recorded in the field. Vibracore locations were documented using a Garmin GPSMAP 76CSx handheld GPS unit and are reported in NAD 1983 degrees, minutes, and seconds. Elevation is based on LiDAR data downloaded from <http://www.csc.noaa.gov>.

Vibracores

- Catfish Pond Ridge (CPR)
- Jean Huffman Ridge (JHR)
- Blacks Island (BKI)
- Conch Island (CCI)
- Buffer Preserve Core (BPC)
- Smokey Hunt Club (SHC)
- Circle J Ranch (CJR)

Name	Date Collected	Latitude	Longitude	Elevation (ft)
CPR-01	11/30/2006	29°42'08.8"	85°17'56.7"	9.77
JHR-01	12/1/2006	29°42'42.1"	85°18'12.7"	4.73
CJR-01	12/6/2006	28°02'38.6"	81°02'35.4"	N/A
CCI-01	8/12/2007	29°43'29.4"	85°18'42.7"	N/A
BKI-01	8/14/2007	29°43'23.2"	85°19'52.1"	N/A
SHC-01	8/16/2007	29°07'32.8"	81°07'29.3"	N/A
SHC-02	8/16/2007	29°07'32.9"	81°07'28.9"	N/A
SHC-03	8/16/2007	29°03'51.0"	81°06'32.6"	N/A

Direct push cores (also known as macrocores or geoprobes) were collected in the more accessible areas. The truck-mounted Geoprobe coring rig uses a hydraulically driven hammer with a percussion rate of 30 Hz to obtain a 5 cm diameter core in 1.2 m sections.

Direct push core locations were documented using a Garmin GPSMAP 76CSx handheld GPS unit and are reported in NAD 1983 degrees, minutes, and seconds. Elevation is based on LiDAR data downloaded from <http://www.csc.noaa.gov>.

Direct Push Cores

- Jennings State Forest (JSF)
- Thirteen Mile Geoprobe (TMG)
- Donovan Crew Geoprobe (DCG)
- Rima Ridge Geoprobe (RRG)
- Buffer Preserve Geoprobe (BPG)

Name	Date Collected	Latitude	Longitude	Elevation
JSF-01	8/1/2007	30°08'07.5"	81°57'12.7"	N/A
Tel-01	8/2/2007	28°28'42.2"	80°39'58.4"	N/A
Tel-02	8/2/2007	28°28'41.9"	80°38'46.1"	N/A
Tel-03	8/2/2007	28°28'41.6"	80°40'32.1"	N/A
Tel-04	8/3/2007	28°28'42.0"	80°39'47.8"	N/A
Tel-05	8/3/2007	28°28'42.4"	80°39'22.9"	N/A
TMG-01	5/1/2008	29°42'42.9"	85°14'03.9"	16.19
TMG-02	5/1/2008	29°42'12.9"	85°14'04.7"	10.96
TMG-03	5/2/2008	29°42'05.2"	85°14'04.8"	10.23
TMG-04	5/2/2008	29°41'48.7"	85°14'05.4"	8.34
BPG-01	5/3/2008	29°42'46.9"	85°17'32.3"	9.41
DCG-01	5/6/2008	28°03'19.5"	80°59'32.2"	N/A
DCG-02	5/7/2008	28°03'21.0"	81°01'18.1"	N/A
DCG-03	5/7/2008	28°03'21.8"	81°02'42.5"	N/A
RRG-01	5/9/2008	29°13'59.7"	81°10'23.1"	N/A
RRG-02	5/9/2008	29°13'45.9"	81°11'02.6"	N/A
RRG-03	5/9/2008	29°12'37.3"	81°11'29.6"	N/A

An AMS soil sampler with a 7.68 lb slide hammer was used to take horizontal cores in outcrop exposures. The sampler is fitted with stainless steel liner that is inserted in the sampler before drilling. After drilling, the liner and sediment was removed, capped, and labeled. Locations were documented using a Garmin GPSMAP 76CSx handheld GPS unit and are reported in NAD 1983 degrees, minutes, and seconds.

Horizontal Slide Hammer Cores

- DuPont Mine (DPM)
- Grandin Sand Quarry (GSQ)
- Dickerson Sand Quarry (DSQ)
- South Rucks Quarry (SRQ)
- Macarde Sand Pit (MCD)
- Pine Island (PI)

Name	Date Collected	Latitude	Longitude
MCD	11/29/2006	30°20'43.8"	82°05'51.6"
DSQ	12/5/2006	27°31'31.6"	80°28'12.2"
SRQ	12/5/2006	27°30'44.4"	80°45'03.2"
PI	12/11/2006	28°29'25.1"	80°43'56.7"
GSQ	12/13/2006	29°43'05.3"	81°56'24.6"
DPM	5/14/2008	30°09'40.6"	82°02'25.2"

A Hilti DD130 electric 3-speed core drill fitted with a 3-inch diamond tipped hollow core bit was used to collect samples in lithified sediments (i.e. coquina). The core was then extracted directly into a _mm opaque bag, taped, and labeled. Locations were documented using a Garmin GPSMAP 76CSx handheld GPS unit and are reported in NAD 1983 degrees, minutes, and seconds.

Diamond Tipped Corer

- Haulover Canal (HCC)
- Wilson Coquina Quarry (WCQ)

Name	Date Collected	Latitude	Longitude
HCC	5/12/2008	28°44'09.2"	80°45'17.2"
WCQ	5/13/2008	29°52'53.4"	81°21'08.8"

APPENDIX II

SAMPLE SELECTION, COLLECTION GUIDELINES, AND LABORATORY PROCEDURES

Sample Selection and Collection

VERTICAL CORES

Sampling for OSL samples in vertical cores such as vibracores or macrocores must be done in dark room conditions. There are two main criteria the AGE Laboratory tries to uphold when sampling. The first criterion is 15 cm of lithologically homogenous sediment above and below the targeted area. This reduced the influence of radioisotopic variations that can be encountered between two lithologically different sediments. The second criterion is samples should not be collected above 50 cm from the top of the core. The soft cosmic radiation is attenuated around 50 cm.

Once a target area is selected, approximately 2 cm of sediment is removed and placed in a pre-weighed dry beaker. The sediment directly against the core wall should not be sampled. This sediment could have been dragged down the core from above during coring.

HORIZONTAL CORES

Sampling for OSL samples in horizontal cores must be done in dark room conditions. Since the cores are collected horizontally, lithologic homogeneity is not a factor. The main factor when sampling from horizontal cores is exposed sediment during the coring process at the end of the cores. Therefore the outer couple inches of sediment are discarded and the remaining sediment is used as the OSL sample.

Laboratory Procedures

The follow table summarizes the step-by-step procedure the AGE laboratory uses to obtain quart grains, suitable for OSL or ESR measurements, from bulk sand samples. All samples are prepared in darkroom conditions using subdued orange light. All chemical treatments are performed in a fume hood. A very detailed record of sample weights is maintained through out this process. The sample is weighed after each step and the weight is recorded.

Step	Procedure	Approximate Duration
1	Remove sediment from collection tube being sure to avoid contact with edges (possible contamination)	
2	Weigh Wet Sediment	
3	Dry Sediment in <60°C Oven	~24 hours
4	Weigh Dry Sediment	
5	Calculate Percent Moisture of Sediment	
6	Remove ~2g of Sediment for NAA determination	
7	If Large Enough Split into “Working” & “Archive” (Store Archive Half)	
8	Digest Working Sample in 10% HCl	Until reaction stops (~24 hours)
9	Digest in 50%HCl if 10% HCl reacts for longer than 24 hours	Until reaction stops
10	Digest Working Sample in 30% H ₂ O ₂	Until reaction stops (~24 hours)
11	Digest in NaOH if 30% H ₂ O ₂ reacts for longer than 24 hours	Until reaction stops
12	Dry Sediment in <60°C Oven	~24 hours
13	Dry Sieve using ___ sieves and disposable nylon meshes: <90 µm, 150 µm, 212 µm, 250 µm, >250 µm	15 minutes
14	Retain either the 90-150 µm or the 150-212 µm fraction. Archive the remaining fractions	
15	Mineral separation using Lithium Polytungstate. Separate into Heavy Minerals, Feldspars, & Quartz	
16	Archive the Heavy Mineral and Feldspars Fractions	
17	Digest Quartz Fraction in 40% HF	40 minutes
18	Digest Quartz Fraction in 10% HCl	40 minutes
19	Dry Sediment in <60°C Oven	~24 hours
20	Store in glass vial until ready for measurement	

APPENDIX III

INSTRUCTIONS FOR USING CD-ROM

A CD-Rom was created to archive the raw data that was not published in this dissertation and is available from Dr. Jack Rink. Readers using the CD-Rom to locate raw data or files used in this dissertation should follow these steps:

- 1) Insert CD and Open it. This CD does not contain an .exe file that automatically opens the contents of the disk. Therefore is not prompted by the computer to open the disk, the reader should do so manually.
- 2) Once the CD is open the reader will find 4 folders labeled: Cores, ESROD, NAA, and OSL. The contents of each folder will now be discussed.
- 3) The first folder is labeled Cores. This folder is subdivided into two subfolders: Core Photos and Grain Size. The photographs of each archived core are located in the folder with its core name. The Grain Size folder contains 3 subfolders: Oasis, TMG, and Tel-IV. TMG and Tel-IV contain the raw data retrieved from the laser diffraction particle size analyzer located in Dr. Reinhardt's laboratory. The Oasis folder contains all the data used to create the particle size distributions (PSD) in this dissertation divided by cores.
- 4) The ESROD folder is subdivided into 4 subfolders and one spreadsheet. The spreadsheet is a quick reference when determining what processes were conducted on what samples. The ESROD Spectra subfolder contains every scan performed on the samples. These files can only be opened in the Jeol ESR software. The Irradiation Measurements subfolder is a series of spreadsheets that illustrate what procedures were done to each sample, with respect to irradiating the samples. The Sol Experiment is also a series of spreadsheets that illustrate what illumination times were performed on each sample. The VFit subfolder contains files that can only be opened using the VFit program located in the AGE laboratory.
- 5) The third folder is the NAA results. There are 5 subfolders that contain the PDF files received from the McMaster Nuclear Reactor with the results of the NAA tests conducted on our samples. An easy to read spreadsheet is available for quick determination of U, Th, and K of each sample.
- 6) The last folder is the OSL folder. There are 8 subfolders and one spreadsheet. This spreadsheet contains a quick log of all the samples processed during the duration of this project. Individual worksheets separate the samples by state or by project. The Anatol subfolder contains every file (.age format) used for the calculation of an age. The ASCII subfolder contains every file (ASC format) retrieved from Analyst. These files are to be opened in Excel or any other spreadsheet style program and are used to determine De and De errors. The Bin subfolder contains every file (.bin format) retrieved from the Riso machine and used in Analyst to create the ASCII file. The Huots Spreadsheets subfolder contains De determination models graciously given to K. Burdette during his

research. These spreadsheets can be used to determine the Central Age Model De and the Minimal Age Model De. The Sequence Files subfolder contains the files (.seq format) that are inputted into the Riso to conduct an OSL run. The Sites subfolder contains folders of every sample run for this dissertation. It contains several spreadsheets per site depending on the tests run, the mask size run, etc.

APPENDIX IV

RESULTS OF SAMPLES NOT PUBLISHED

ESROD & OSL Cross Comparison

Initial De tests were run on the following samples to determine if they could be used in a cross check with ESROD. Following each sample name is the Sequence File number and Bin File number (which are the same number). The Bin Files can be opened in Analyst to illustrate these samples were saturated and not datable by OSL.

- CJR-01 – KB07047 (aliquots 13-15)
- CJR-02 – KB07020 (aliquots 1-3)
- DCG-01 – KB09035 (aliquots 4-6)
- DCG-02 – KB09035 (aliquots 7-9)
- DCG-03 – KB09035 (aliquots 10-12)
- DCG-04 – KB09035 (aliquots 12-14)
- DPM-01 – KB09035 (aliquots 22-24)
- DPM-02 – KB09035 (aliquots 25-27)
- DSQ-01 – KB08079 (aliquot 1)
- DSQ-02 – KB09079 (aliquot 2)
- GSQ-01 – KB07046 (aliquots 10-12)
- GSQ-02 – KB07047 (aliquots 7-9)
- JSF-01 – KB09053 (aliquots 1-3)
- JSF-02 – KB09053 (aliquots 4-6)
- MCD-02 – KB08081 (aliquot 2)
- MCD-03 – KB08081 (aliquot 3)
- RRG-01 – KB09035 (aliquots 16-18)
- RRG-02 – KB09035 (aliquots 19-21)
- SHC-02 – KB09053 (aliquots 10-12)
- SHC-03 – KB09053 (aliquots 13-15)
- SRQ-02 – KB07046 (aliquots 1-3)
- SRQ-03 – KB07047 (aliquots 19-21)

OSL Sample Not Included In Thesis

Five OSL samples were processed and an age was calculated, but not put in this dissertation. They are PI-01, BRD-01, BRD-02, MCD-01, and SHC-01. As per request the following is a summary sheet of the parameters used in Anatol to calculate and age and a screen capture of each sample in the Anatol Program. These samples were not included in any text because they did not further the research.

Sample	De	Regeneration Curve Fit	Number of aliquots	Mask Size	Cosmic Dose Model	Preheat Temp
PI-01	1.02±0.1	Linear	12	8mm	Instant	240
BRD-01	7.4±0.3	Linear	24	3mm	Instant	200
BRD-02	0.7±0.01	Linear	24	3mm	Instant	200
MCD-01	2.76±0.17	Linear	24	3mm	Instant	180
SHC-01	1.21±0.1	Linear	24	3mm	Instant	240

Age calculation - PI-01_IA.age

File Calculation Parameters Transfer in ... ?

Grain size: 150 - 212 μm

Etching: ☒ Yes Error: 2 %

Sample: PI-01

☒ Quartz ☐ Feldspars

AGE (ans) 2.680 $\pm$ 316 Total error 272 Stat. error

Paleodose (Gy) 1.02 $\pm$ 0.1 0 %

Annual dose ($\mu\text{Gy/a}$) 380.5 $\pm$ 13

Doses (%)

	Internal (2.7)	External (97.2)
Alpha	8.6 $\pm$ 2.2	0 $\pm$ 0
Beta	1.9 $\pm$ 0.4	81.1 $\pm$ 9.4
Gamma		81.5 $\pm$ 8.7
Cosmic		207.3
Total $\pm$ stat.	10.5 $\pm$ 2.3	370 $\pm$ 12.8

Grains:

	U (ppm)	Th (ppm)	K (%)
0.0665	$\pm$ 0.0219	0.55 $\pm$ 0.1	
0.1135	$\pm$ 0.0424	0.89 $\pm$ 0.09	
0	$\pm$ 0	0.0371 $\pm$ 0.0058	

Global Systematic Error: 10 %

Water Saturation level (w): 0.43 Fraction (F): 0.8 $\pm$ 0.2

Internal:

Alpha ☐ None ☒ U, Th contents Value: 0.04 $\pm$ 10 % 0 %

Beta ☐ None ☒ U, Th, K contents ☐ by Beta counting or dosimetry Beta - absorbed fractions: U 0.137 Th 0.195 K 0.063 Dose: 0 $\pm$ 0 0 %

External:

Alpha ☒ None ☐ U, Th contents ☐ by Alpha counting Alpha - attenuation factors: U 0 Th 0 Nb. alpha / ksec: 0 $\pm$ 0 0 %

Beta ☐ None ☒ U, Th, K contents ☐ by Beta counting or dosimetry ☐ by Alpha counting Dose: 0 $\pm$ 0 0 %

Gamma ☒ U, Th, K contents ☐ In-situ dosimetry Dose: 0 $\pm$ 0 0 %

Cosmic Dose: 207.32 $\pm$ 10 Estimated water content (w/F) during measurement: 0

Age calculation - BRD-01_IA_age

File Calculation Parameters Transfer in ... ?

☒ Quartz
 ☐ Feldspars

Sample : BRD-01

Grain size: 150 - 212 μm

Etching: ☒ Yes Error: 2 %

AGE (ans) Total error: 1,529
20,022 +/- Stat. error: 1,227

Paleodose (Gy) 7.4 +/- 0.3
 0 +/- 0 %

Annual dose ($\mu\text{Gy/a}$) 369.5 +/- 17.2

Doses (%) Internal (2.8) External (97.1)

Alpha	8.6 +/- 2.2	0 +/- 0
Beta	1.9 +/- 0.4	83.2 +/- 12.4
Gamma		104.8 +/- 11.7
Cosmic		170.9
Total +/- stat.	10.5 +/- 2.3	359 +/- 17.1

Grains:

U (ppm)	0.0665 +/- 0.0219	0.43 +/- 0.1
Th (ppm)	0.1135 +/- 0.0424	1.19 +/- 0.08
K (%)	0 +/- 0	0.0062 +/- 0.0008

Global Systematic Error: 10 %

Water Saturation level (w): 0.02 Fraction (F): 0.8 +/- 0.2

Internal:

Alpha
☐ None
☒ U, Th contents
 Value: 0.04 +/- 10 %

Beta
☐ None
☒ U, Th, K contents
☐ by Beta counting or dosimetry
 Beta - absorbed fractions: U 0.137 Th 0.195 K 0.063
 Dose: 0 +/- 0 %

External:

Alpha
☐ None
☐ U, Th contents
☐ by Alpha counting
 Alpha - attenuation factors: U 0 Th 0
 Nb. alpha / ksec: 0 +/- 0 %

Beta
☐ None
☒ U, Th, K contents
☐ by Beta counting or dosimetry
☐ by Alpha counting
 Dose: 0 +/- 0 %
 Dose: 0 +/- 0 %

Gamma
☒ U, Th, K contents
☐ In-situ dosimetry
 Dose: 0 +/- 0 %

Cosmic
☐ None
☒ U, Th, K contents
☐ by Beta counting or dosimetry
☐ by Alpha counting
 Dose: 170.99 +/- 10
 Estimated water content (w.F) during measurement: 0

Age calculation - BRD-02_IA.age

File Calculation Parameters Transfer in ... ?

Grain size: 150 - 212 μm

Etching: ☒ Yes Error: 2 %

Sample: ☐ Quartz ☒ Feldspars

BRD-02

AGE (ans) 1.651 $\pm$ 101 $\pm$ 71

Paleodose (Gy) 0.7 $\pm$ 0.01 $\pm$ 0 %

Annual dose ($\mu\text{Gy/a}$) 423.7 $\pm$ 17.4

Doses (%)

	Internal (2.4)	External (97.5)
Alpha	8.6 $\pm$ 2.2	0 $\pm$ 0
Beta	1.9 $\pm$ 0.4	92.8 $\pm$ 12.4
Gamma		120.9 $\pm$ 11.9
Cosmic		199.4
Total $\pm$ stat.	10.5 $\pm$ 2.3	413.2 $\pm$ 17.3

Grains:

	Grains	Environment
U (ppm)	0.0665 $\pm$ 0.0219	0.45 $\pm$ 0.1
Th (ppm)	0.1135 $\pm$ 0.0424	1.49 $\pm$ 0.1
K (%)	0 $\pm$ 0	0.0078 $\pm$ 0.0008

Global Systematic Error: 10 %

Water Saturation level (w): 0.025 Fraction (F): 0.8 $\pm$ 0.2

Internal:

Alpha

☐ None ☒ U, Th contents

Value: 0.04 $\pm$ 10 %

Beta

☐ None ☒ U, Th, K contents ☐ by Beta counting or dosimetry

Beta - absorbed fractions: U 0.137 Th 0.195 K 0.063

Dose: 0 $\pm$ 0 %

External:

Alpha

☐ None ☒ U, Th contents ☐ by Alpha counting

Alpha - attenuation factors: U 0 Th 0

Nb alpha / ksec: 0 $\pm$ 0 %

Beta

☐ None ☒ U, Th, K contents ☐ by Beta counting or dosimetry ☐ by Alpha counting

Dose: 0 $\pm$ 0 %

Dose: 0 $\pm$ 0 %

Gamma

☒ U, Th, K contents ☐ In-situ dosimetry

Dose: 0 $\pm$ 0 %

Cosmic

Dose: 199.47 $\pm$ 10

Estimated water content (w/F) during measurement: 0

MCD-01

Age calculation - MCD-01_IA.AGE

File Calculation Parameters Transfer in ... ?

Grain size: 150 - 212 μm

Etching: ☒ Yes Error: 2

Systematic error:

Sample: MCD-01

☒ Quartz ☐ Feldspars

Water Saturation level (w): 0.033 Fraction (F): 0.8 +/- 0.2

☐ S-a system ☒ a-value

Value: 0.04 +/- 10 %

Internal:

Alpha

☐ None ☒ U, Th contents

Beta - absorbed fractions: U [0.137] Th [0.195] K [0.063]

Dose: 0 +/- 0 %

Beta

☐ None ☒ U, Th, K contents by Beta counting or dosimetry

External:

Alpha

☐ None ☒ U, Th contents by Alpha counting

Alpha - attenuation factors: U 0 Th 0

Nb. alpha / ksec: 0 +/- 0 %

Beta

☐ None ☒ U, Th, K contents by Beta counting or dosimetry

Dose: 0 +/- 0 %

Gamma

☐ None ☒ U, Th, K contents by Alpha counting

Dose: 0 +/- 0 %

Cosmic

☒ U, Th, K contents In-situ dosimetry

Dose: 0 +/- 0 %

Estimated water content (w/F) during measurement: 0

Paleodose (Gy)

AGE (ans) Total error 661 +/- Stat error 579

2.76 +/- 0.17 %

Annual dose ($\mu\text{Gy/a}$)

362 +/- 16.8

Doses (%)

Internal (2.9) External (97)

Alpha 8.6 +/- 2.2 0 +/- 0

Beta 1.9 +/- 0.4 74.3 +/- 12.2

Gamma 82.7 +/- 11.3

Cosmic 194.4

Total +/- stat. 10.5 +/- 2.3 351.5 +/- 16.6

Grains:

U (ppm) 0.0665 +/- 0.0219 0.46 +/- 0.1

Th (ppm) 0.1135 +/- 0.0424 0.67 +/- 0.06

K (%) 0 +/- 0 0.0056 +/- 0.0007

Environment:

Global Systematic Error: 10 %

Dose: 194.43 +/- 10

SHC-01

Age calculation - SHC-01_IA.AGE

File Calculation Parameters Transfer in ... ?

Grain size: 150 - 212 μm

Etching: ☒ Yes Error: 2 %

Sample: SHC-01

☒ Quartz ☐ Feldspars

AGE (ans) 4.383 $\pm$ Total error 471 Stat. error 439

Paleodose (Gy) 1.21 $\pm$ 0.1 $\pm$ 0 %

Annual dose ($\mu\text{Gy/a}$) 276 $\pm$ 16.6

Doses (%)

	Internal (3.8)	External (96.1)
Alpha	8.6 $\pm$ 2.2	0 $\pm$ 0
Beta	1.9 $\pm$ 0.4	26.8 $\pm$ 12.3
Gamma		28.2 $\pm$ 10.9
Cosmic		210.3
Total $\pm$ stat.	10.5 $\pm$ 2.3	265.4 $\pm$ 16.4

Grains:

	Grains	Environment
U (ppm)	0.0665 $\pm$ 0.0219	0.18 $\pm$ 0.1
Th (ppm)	0.1135 $\pm$ 0.0424	0.18 $\pm$ 0.02
K (%)	0 $\pm$ 0	0.0017 $\pm$ 0.003

Global Systematic Error: 10 %

Internal:

Water Saturation level (w): 0.04 Fraction (F): 0.8 $\pm$ 0.2

☐ S-a system ☒ a-value

Alpha

☐ None ☒ U, Th contents

Value: 0.04 $\pm$ 10 % 0 %

Beta

☐ None ☒ U, Th, K contents ☐ by Beta counting or dosimetry

Beta - absorbed fractions: U 0.137 Th 0.195 K 0.063

Dose: 0 $\pm$ 0 0 %

External:

Alpha

☐ None ☒ U, Th contents ☐ by Alpha counting

Alpha - attenuation factors: U 0 Th 0

Nb. alpha / ksec: 0 $\pm$ 0 0 %

Beta

☐ None ☒ U, Th, K contents ☐ by Beta counting or dosimetry ☐ by Alpha counting

Dose: 0 $\pm$ 0 0 %

Dose: 0 $\pm$ 0 0 %

Gamma

☒ U, Th, K contents ☐ In-situ dosimetry

Dose: 0 $\pm$ 0 0 %

Cosmic Dose: 210.38 $\pm$ 10

Estimated water content (w/F) 0

during measurement:

