FACIES DISTRIBUTION AND HYDRAULIC CONDUCTIVITY OF LAGOONAL SEDIMENTS IN A HOLOCENE TRANSGRESSIVE BARRIER ISLAND SEQUENCE, INDIAN RIVER LAGOON, FLORIDA

By

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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACKNOWLEDGMENTS</td>
<td>iii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>vi</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>vii</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>viii</td>
</tr>
<tr>
<td>CHAPTER</td>
<td></td>
</tr>
<tr>
<td>1 INTRODUCTION</td>
<td></td>
</tr>
<tr>
<td>2 BACKGROUND</td>
<td>1</td>
</tr>
<tr>
<td>Geologic Setting</td>
<td>7</td>
</tr>
<tr>
<td>Previous Work in the Indian River Lagoon</td>
<td>8</td>
</tr>
<tr>
<td>Transgressive Barrier Island Facies Models</td>
<td>9</td>
</tr>
<tr>
<td>Grain-Size Modeled Hydraulic Conductivity</td>
<td>11</td>
</tr>
<tr>
<td>3 METHODS</td>
<td>16</td>
</tr>
<tr>
<td>Data Collection</td>
<td>16</td>
</tr>
<tr>
<td>Lithostratigraphy</td>
<td>18</td>
</tr>
<tr>
<td>Biostratigraphy</td>
<td>19</td>
</tr>
<tr>
<td>Chronostratigraphy</td>
<td>20</td>
</tr>
<tr>
<td>Grain-Size Modeled Hydraulic Conductivity</td>
<td>21</td>
</tr>
<tr>
<td>Measured Hydraulic Conductivity</td>
<td>22</td>
</tr>
<tr>
<td>4 RESULTS</td>
<td>24</td>
</tr>
<tr>
<td>Lithostratigraphy</td>
<td>24</td>
</tr>
<tr>
<td>CIRL39</td>
<td>24</td>
</tr>
<tr>
<td>BRL2</td>
<td>25</td>
</tr>
<tr>
<td>NIRL6</td>
<td>27</td>
</tr>
<tr>
<td>NIRL24</td>
<td>28</td>
</tr>
<tr>
<td>Physical Properties Summary</td>
<td>30</td>
</tr>
<tr>
<td>Biostratigraphy</td>
<td>30</td>
</tr>
<tr>
<td>Chronostratigraphy</td>
<td>31</td>
</tr>
</tbody>
</table>
Grain-size Modeled Hydraulic Conductivity..............................................................32
Measured Hydraulic Conductivity..............................................................................32

5  DISCUSSION.............................................................................................................46

Sedimentary Facies and Depositional Environments .................................................46
  Marine Facies ......................................................................................................46
  Brackish and Lacustrine Facies ...........................................................................47
  Lagoonal Facies...................................................................................................52
Transgressive Barrier Island Facies Models...............................................................53
Measured and Grain-Size Modeled Hydraulic Conductivity .....................................54
Spatial Variability in Sediment Properties over 0.04 km² ..........................................56

6  CONCLUSIONS ........................................................................................................61

  Summary ................................................................................................................61
  Future Work.............................................................................................................63

LIST OF REFERENCES ..................................................................................................65

BIOGRAPHICAL SKETCH .............................................................................................72
LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-1</td>
<td>Location and lengths of sediment cores</td>
<td>17</td>
</tr>
<tr>
<td>4-1</td>
<td>Reported radiocarbon ages and converted calendar year ages.</td>
<td>32</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>Modified site map of the Indian River Lagoon (IRL) system</td>
<td>5</td>
</tr>
<tr>
<td>1-2</td>
<td>Generalized model of a transgressive barrier complex</td>
<td>6</td>
</tr>
<tr>
<td>2-1</td>
<td>Physiographic map of east-central Florida include</td>
<td>14</td>
</tr>
<tr>
<td>2-2</td>
<td>Classification of estuaries</td>
<td>15</td>
</tr>
<tr>
<td>3-1</td>
<td>Site occupation for water chemistry and sediment analysis</td>
<td>23</td>
</tr>
<tr>
<td>4-1</td>
<td>CIRL39. (A) Physical properties of the center core, (B) Color images of all cores collected, (C) Lithostratigraphy and depositional environments</td>
<td>34</td>
</tr>
<tr>
<td>4-2</td>
<td>BRL2. (A) Physical properties of the center core, (B) Color images of all cores collected, (C) Lithostratigraphy and depositional environments</td>
<td>37</td>
</tr>
<tr>
<td>4-3</td>
<td>NIRL6. (A) Physical properties of the center core, (B) Color images of all cores collected, (C) Lithostratigraphy and depositional environments</td>
<td>40</td>
</tr>
<tr>
<td>4-4</td>
<td>NIRL24. (A) Physical properties of the center core, (B) Color images of all cores collected, (C) Lithostratigraphy and depositional environments</td>
<td>43</td>
</tr>
<tr>
<td>5-1</td>
<td>Predictions of hydraulic conductivity using the Carmen-Kozeny equation</td>
<td>58</td>
</tr>
<tr>
<td>5-2</td>
<td>Log/Log comparisons of the CK and modified CK equation</td>
<td>59</td>
</tr>
<tr>
<td>5-3</td>
<td>Chloride profiles compared to lithology and hydraulic conductivity</td>
<td>60</td>
</tr>
</tbody>
</table>
The determination of nutrient fluxes in coastal and estuarine settings is important for ecological management. However, calculations of nutrient budgets have generally ignored the potential contribution of submarine groundwater discharge (SGD) due to difficulties quantifying the volume of water discharging. Measured discharge is areally heterogeneous and often greater than the discharge calculated from water budgets and ground water flow models. Observations of mixing between the water column and pore waters to a depth of ~70 cm below sea floor suggest local variability in sediment hydraulic conductivity as a possible cause for the discrepancy. The Indian River lagoon (IRL) is a transgressive barrier island system and therefore an ideal location to test the influence of hydraulic conductivity on SGD. Existing facies models for transgressive barrier environments predict a complex spatial distribution of sediment textures that range from highly permeable, mature sands to nearly impermeable muds. Study of the facies distribution within IRL provides a comparison to existing generalized facies
models and aids in development of a depositional model for lagoonal evolution. The
variability in sediment textures also allow for comparison of methods for measurement
and modeling of hydraulic conductivity over a broad range of values.

Four sites in the northern ~45 km of IRL, previously identified as representing a
wide range of groundwater discharge rates and bottom sediment textures, were each
selected for a 200 m wide spatial vibracoring program of the upper three meters of
lagoonal sediments. Four major depositional environments were identified in the upper 3
m of Indian River Lagoon sediments: marine, brackish, lacustrine, and lagoonal.
However, the limited tidal prism of the northern Indian River Lagoon has prevented any
significant redistribution of the brackish and lagoonal deposits as is more common in
mesotidal barrier island systems. The result is a stratigraphic sequence that is not
predicted by facies models for transgressive barrier island systems.

The theoretical model of hydraulic conductivity based on sediment textural data over
predicted the measured values by up to four orders of magnitude. A modification to the well-
known Carmen-Kozeny (CK) equation was constructed by adding a “mud term”, to reflect
the down-core variability in relative percent mud (< 63 micron, 4 phi). The result was a
better fit between measured and modeled values for all of the sites tested. Over all hydraulic
conductivity values for the upper 3 m of sediments in IRL range from $10^{-2}$ - $10^{-8}$ cm/sec.
However, within the upper ~70 cmbsf, values only varied by two orders of magnitude ($10^{-2}$
- $10^{-4}$ cm/sec). Therefore, at the sites tested, the observed spatial variability in fluid
exchange depth within the surface mixing zone is not due to variation in hydraulic of the
sediments.
The Indian River Lagoon (IRL) is a transgressive, wave-dominated, siliciclastic barrier island system. It extends nearly 250 km along Florida’s central Atlantic coast (Fig. 1-1). Extensive agriculture surrounding the lagoon has led to concerns of eutrophication from surface water runoff and corresponding ecological changes in the lagoon (Sigua et al., 2000). Because of potential ecological changes, the St. Johns River Water Management District, a state agency responsible for the lagoon, has initiated a modeling effort to identify the potential sources of excess nutrients and develop a plan to reduce nutrient loading to the lagoon from surface water runoff. However, little attention has been given to quantification of nutrient fluxes associated with submarine groundwater discharge (SGD) (Zimmerman et al., 1985; Montgomery et al., 1979). The problem has been the ability to quantify the magnitude of SGD. Measured discharge is areally heterogeneous and often greater than the discharge calculated from water budgets and ground water flow models (e.g., Gallagher et al., 1996; Robinson and Gallagher, 1999; Moore, 1996; Li et al., 1999; Belanger and Walker, 1990; Pandit and El-Khazen, 1990; Martin et al., 2002; Martin et al., 2004).

One hypothesis is that discrepancies could arise from the exchange of water between the water column and pore waters of shallowly-buried sediments (Bokuniewicz, 1992; Burnett et al., 2002; Rasmussen, 1998; Martin et al., 2004). Using multi-level piezometers called “multisamplers” developed by Martin et al. (2003), Martin et al. (2004) found rapid and significant variations in pore water Cl\(^{-}\) concentrations suggesting
the presence of two flow regimes within the upper 230 cm of lagoonal sediments. At depths greater than ~70 cm below seafloor (cmbsf), groundwater flow appears to be driven upward by the higher hydraulic head of the underlying aquifer at flow rates consistent with previous estimates using finite element flow models (Pandit and El-Khazen, 1990; Moore, 1996; Robinson and Gallagher, 1999; Li et al., 1999; Martin et al., 2004). At depths less than ~70 cmbsf, active mixing between pore water and the overlying water column appears to be dominant. Therefore, it appears that SGD in the Indian River Lagoon is derived from two primary sources: fresh water, discharging from terrestrial aquifers, and marine water, circulating through surface sediments.

Driving forces for pore water mixing in the shallow (< ~70 cmbsf) sediments may include a combination of bioirrigation, wave and tidal pumping, and density-driven convection (e.g. Emerson et al., 1984; Shum, 1992). Wave pumping and convection are likely to be minor due to a small tidal range, limited fetch within the lagoon, and lack of strong density contrasts between lagoon and pore waters (Martin et al., 2006). The mixing depth of 70 cmbsf is greater than has previously been attributed to either bioirrigation or wave pumping alone, so Martin et al. (2004) suggested that a combination of bioirrigation and wave pumping coupled with highly permeable sediments may allow such deep mixing. Permeability (k) is an intrinsic physical property of sediments. When water is the permeant, the term hydraulic conductivity (K) is used, which is a measure of the rate at which water can move through a porous medium under a given driving force (Fetter, 2001). To date, no studies have been conducted on the hydraulic conductivity of IRL sediments with the resolution required to explain the observed local and regional spatial variability in SGD. It has therefore become necessary
to describe and quantify the physical properties of lagoonal sediments as well as their spatial variability to gain a better understanding of the physical controls on SGD and the potential nutrient flux into the water column.

Sediments in barrier island environments are deposited in relatively shallow and occasionally energetic waters. Common subenvironments include channel fills, mussel/oyster beds, washover fans, tidal flats and marshes. Sediment facies produced in each of these subenvironments can have textures that range from highly permeable mature sands to nearly impermeable muds (Davies et al., 1971). Previous works on local and regional scales have characterized the evolution of the southern Indian River Lagoon system in general terms as a transgressive barrier island sequence (Almasi, 1983; Bader and Parkinson, 1990; Davis et al., 1992). Figure 1-2 illustrates a generalized facies model for a transgressive barrier island system in which each of the various subenvironments migrate laterally in response to sea level rise. If this model is applicable to the Indian River Lagoon system, lateral migration of the subenvironments should be reflected in the vertical facies sequence, assuming preservation of the stratigraphic record. Spatial variability in hydraulic conductivity will depend on the relative occurrence and thickness of sediment facies produced in each of these subenvironments (Fig. 1-2).

This study examines the sediment facies distribution, textural properties, and hydraulic conductivity of 28 cores collected on both local (200 m) and regional (~45 km) scales within the northern ~45 km of the Indian River Lagoon system. There are three primary goals for this study. First, identification of the local (200 m) spatial variability of sediment facies will aid in development of a conceptual model for Holocene lagoonal
evolution on the regional (~45 km) scale. Second, comparison of field and laboratory measurements of hydraulic conductivity with mathematical models, based on sediment textural data will improve our abilities of predicting hydraulic conductivity using grain size analysis. And third, comparison of the down-core variability in measured and modeled hydraulic conductivity of the lagoonal sediments with pore water mixing depths reported by Martin et al. (2004) will allow assessment of the degree to which spatial variability in subsurface sediment facies controls the location and magnitude of SGD.

The following hypotheses were tested:

- Sediments of the Indian River Lagoon System represent the facies succession of typical transgressive barrier island systems as presented in figure 1-2;
- Mathematical models based on sediment textural data can successfully predict the hydraulic conductivity of IRL sediments;
- The observed spatial heterogeneity in SGD is controlled by variability in sediment facies and their respective hydraulic conductivities.

Results of this study impact three areas of scientific research. First, the facies distribution observed within the Indian River Lagoon system can be compared to generalized facies models for barrier island systems (e.g. fig. 1-2) to delineate common features from local irregularities. Further development of such models will aid in predictions of facies distributions in similar geologic settings, both past and present. Second, laboratory and field measurement of hydraulic conductivity is both expensive and time consuming. A more rapid and inexpensive method was discovered using grain size analysis to identify the critical sediment properties controlling the hydraulic conductivity of unconsolidated coastal sediments. And third, comparison of sediment physical properties (e.g. hydraulic conductivity) with SGD observations define the contribution of hydraulic conductivity to spatial heterogeneity in SGD.
Figure 1-1. Modified site map of the Indian River Lagoon (IRL) system with physiographic divisions from White (1970) and Cape formation ages from Brooks (1972). Original map produced by Dr. John M. Jaeger.
Figure 1-2. Generalized model illustrating the various sub-environments of a transgressive barrier complex. (From Reinson, G.E., 1992), modified to include the range of typical hydraulic conductivity value for each of the sub-environments as presented in Fetter (2001).
CHAPTER 2
BACKGROUND

Geologic Setting

The northern Indian River Lagoon system includes the Banana River Lagoon, Mosquito Lagoon, and the cuspate-forelands, False Cape and Cape Canaveral (Fig. 1-1), and is the southern most regressional component of the Georgia Bight Barrier System (Hayes, 1994). Based on the morphology of this region, it is classified as a shallow-water, wave dominated, siliciclastic, barrier island system under the influence of mild tectonic uplift (Hayes, 1994). The tectonic uplift may be an isostatic response (epeirogenic uplift) to karst development and dissolution of bedrock in the late Pliocene and Pleistocene similar to uplift observed in the Trail Ridge area (Opdyke et al., 1984) (Fig. 2-1). This tectonic regime is thought to have been in existence since late Paleocene as relict beach ridges provide physiographic evidence of similar structural trends (e.g. Ocala High “uplift”) that have influenced development of similar cuspate-foreland morphologies across east-central Florida (Colquhoun, 1983; Scott, 1997). For example, the modern Cape Canaveral is developing on the remnants of a similar Pleistocene cape (Fig. 1-1) (Osmond et al., 1970; Brooks, 1972). White (1970) identified a relict “Cape Orlando”, a near identical ridge/cuspate-foreland system formed by the mount Dora Ridge, Orlando Ridge, and Lake Wales Ridge, nearly 40 miles due west and 125 ft above current sea level (Fig. 2-1).

Holocene sediments on the east coast of Florida include a thin band of beach, dune, marsh, and lagoon deposits that have developed in response to the latest rise in sea level
Distribution of Holocene sediments in the northern Indian River Lagoon is largely controlled by the antecedent topography of the underlying Pleistocene deposits (Davis, 1997). The most notable Pleistocene sedimentary unit in this study area is the Anastasia Formation. This formation consists of interbedded quartz sands and more importantly coquina, an accumulation of shells lithified during periods of meteoric diagenesis (Scott, 1991; McNeill, 1983, 1985). These coquina deposits currently form the backbone of the modern barrier islands as well as the mainland coast of the lagoon (Atlantic Barrier Chain and Atlantic Coastal Ridge, Fig. 2-1) (Tanner, 1960; Bader and Stauble, 1987; Almasi, 1983; Davis, 1997).

Although sedimentary units of the Pleistocene are predominantly siliciclastic, erosion of the Miocene and Pliocene strata provided much of the material (Scott, 1997). Continued reworking again has provided much of the material for the Holocene units. The predominant external supply of modern sediment to the Indian River Lagoon System is through long-shore transport, which decreases by half south of Cape Canaveral (Davis, 1997).

**Previous Work in the Indian River Lagoon**

Bader and Parkinson (1990) and Almasi (1983) provided the most comprehensive work to date on the stratigraphy and evolution of the Indian River Lagoon. In a series of vibracores collected across 6 shore-normal transects from St. Lucie north to Melbourne, Almasi 1983 described a complex distribution of facies within the upper three to nine meters of bottom sediments. Based on sediment texture, fauna, 11 radiocarbon dates, and comparisons to published Holocene sea level curves of Scholl et al. (1969) and Neumann (1969), the observed facies were attributed to three depositional environments; marine, brackish, and lagoonal. Sediments of the marine environment were interpreted as shore
face and offshore bar deposits of a late Pleistocene sea level high stand. The brackish and lagoonal environments are thought to have initiated upon marine inundation about 5000-6000 Cal. BP. However, other than possible barrier dune washover processes, Almasi (1983) could not define a deposition mechanism for Holocene Lagoonal infilling.

**Transgressive Barrier Island Facies Models**

Transgressive shorelines along the Atlantic coast of North America are dominantly influenced by relative sea level rise and a low contribution of sediments from rivers and streams draining into the area (Kraft, 1978). The balance between wave energies, tidal ranges and prisms, erosion rates, and antecedent topography are the driving forces in barrier island morphology and migration (Dalrymple et al., 1992; Harris et al., 2002). Under these conditions, if sea level rise and erosion rates are balanced, barriers may migrate more or less continuously landward as sea level rises. Any back barrier lagoonal facies would likely be eroded in this process (Reinson, 1992). Alternatively, if the rate of sea level rise exceeds erosion rates, barriers may remain in place as sea level rises to the level of the top of the dunes; then the surf zone may “jump” landward to establish a new shoreline, thus drowning the barrier in place (Sanders and Kumar, 1975). In this case, an entire sequence of transgressive lagoon facies may be preserved (Reinson, 1992).

Predictive models of estuarine systems have been developed to demonstrate the sedimentologic and morphologic responses to the balance of these driving forces (Reinson, 1992) (Figs. 1-2 & 2-2). Sediments supplying the lagoon/estuary are generally considered to be either of marine origin (e.g. washover or tidal inlet) or of mainland fluvial origin. In all of the models, a zonation of facies is expected in which coarser fractions of marine and fluvial sediments fall out along their respective lagoon/estuarine margins while the finer grained sediments of fluvial and marine origin concentrate in the
center of the depositional system in a zone under the influence of a mixture of fluvial and marine depositional processes. As transgression and regression occur, facies produced within each of these zones (e.g. fluvial, mixed fluvial-marine, marine) will migrate and overlap.

The northern region of the Indian River Lagoon (IRL) barrier system, however, is rather unique when compared to the transgressive barrier systems used in the generation of facies models such as the ones presented in figures 1-2 and 2-2. The most important difference is the lack of a near by tidal inlet to allow connection to marine depositional sources and processes. Without a diurnal influx and exit of significant amounts marine water, there can be no development of tidal channels, tidal flats, marshes, and delta deposits on the flood and ebb side of inlets. While tidal currents dominate morphology in the vicinity of lagoon inlets (Sebastian, Ft. Pierce, and St. Lucie), current velocity drops off rapidly away from these regions to < 10 cm/s (Smith, 1990). Within the study area, Smith (1987) reported a semi-diurnal tidal constituent of 0-5 cm. Sediments in northern IRL will likely not therefore develop a character typically associated for lagoonal deposits such as interfingering fine sands, silts, muds, and peat deposits that may be characterized by disseminated plant remains, brackish-water invertebrates fossils, and horizontal to sub-horizontal layering (Boggs, 1995).

The IRL barrier system is also unique because much of the antecedent topography for Holocene lagoonal development is made up of Anastasia Fm coquina and thus resistant to lateral migration. Inherent to the identification of transgressive or regressive facies successions (Figs. 1-2 and 2-2) is the assumption that depositional environments will migrate and overlap in a landward or seaward (shore-normal) direction. If lateral
migration is prevented, the resulting facies succession will show a vertical change in depositional environment but the lateral change will reflect the topography of the lagoon floor rather than a progressive migration in a shore-normal orientation.

**Grain-Size Modeled Hydraulic Conductivity**

The ability to predict permeability \( (k) \) and hydraulic conductivity \( (K) \) and variations in permeability (heterogeneity) of porous media such as unconsolidated sediments is of vital importance to many areas of geologic and geotechnical investigation and management. In the field of petroleum geology, reservoir characterization and development plans rely first and foremost on permeability estimates (Panda and Lake 1994). Hydraulic conductivity estimates are important for geotechnical problems (e.g. seepage losses, settlement computations, and stability analysis) as well as for the development, management, and protection of groundwater resources (Masch and Denny, 1966; Alyamani and Sen, 1993; Boadu, 2000). In the field of environmental protection, prediction of likely flow paths for petroleum leakage from underground storage tanks depends primarily estimates of the hydraulic conductivity of the surrounding soils (Cronican and Gribb, 2004). And in coastal sediments, investigation into the geochemical processes controlled by pore water circulation (e.g. remineralization of organic matter and nutrient cycling) has required the quantification of sediment hydraulic conductivity to delineate potential flow paths and make comparisons with observed flow rates (Boudreau et al., 2001; Foster et al., 2003; Martin et al., 2006).

A relationship between grain-size distribution and hydraulic conductivity has been recognized for nearly 100 years. Methods of predicting hydraulic conductivity from grain-size distribution through quantitative relations have been developed by analogy to pipe flow and flow in capillaries (Kozeny, 1927; Carmen, 1937). Besides predictive
methods, empirical relations have also been used (Hazen, 1911; Krumbein and Monk, 1942; Morrow et al., 1969; Berg, 1970; Alyamani and Sen, 1993; Koltermann and Gorelick, 1995). Equations relating grain-size distribution to hydraulic conductivity are of the form (generalized from Freeze and Cherry, 1979, p.351):

\[ K = \frac{\rho g}{\mu} c_s d^m \]

Where K = hydraulic conductivity (L/T), \( \rho \) = fluid density (M/L\(^3\)), g = gravitational acceleration (L/T\(^2\)), \( \mu \) = dynamic viscosity (M/LT), \( c_s \) = factor representing the shape and packing of grains (dimensionless), d = representative grain diameter (L), m = an exponent, often equal to 2 (dimensionless).

Furnas (1929) found that porosity and hydraulic conductivity in sediment mixtures depends on the fractional concentrations of each particle size, the diameter ratio, and particle packing. The effects of particle size, compaction, and sediment sorting can be accounted for in the Carmen-Kozeny (CK) equation presented in Bear (1972, p. 166), which takes the form:

\[ K = \left( \frac{\rho g}{\mu} \right) d^2 \phi^3 / 180(1-\phi)^2 \]

Where K = hydraulic conductivity (L/T), \( \rho \) = fluid density (M/L\(^3\)), g = gravitational acceleration (L/T\(^2\)), \( \mu \) = dynamic viscosity (M/LT), \( d \) = representative grain diameter (median) (L), \( \phi \) = total porosity, accounting for compaction (dimensionless).

The CK equation was chosen for this investigation because (1) it has gained wide spread acceptance in the literature (Panda and Lake, 1994; Boadu, 2000), (2) all of the input parameters have been measured in this study with a down-core resolution of 5 cm, and (3) results of this study can be compared to Foster et al. (2003), who found that the
CK equation overestimated measured vertical hydraulic conductivity of surface sediments (0 – 10 cm) in the southern Baltic Sea by more than a factor of 3.
Figure 2-1. Physiographic map of east-central Florida modified to include an outline of the “relict” Cape Orlando as interpreted by White 1970. Cape Orlando demonstrates the persistence of a structural high controlling the morphology of this region at least through the Pleistocene.
Figure 2-2  Classification of estuaries (based on volume of the tidal prism) illustrating morphologic, oceanographic, and sedimentological characteristics of each estuary type (Reinson 1992). Indian River Lagoon is wave dominated and microtidal so the lateral extent of sediment facies should be limited as depicted in this model (red Rectangle).
CHAPTER 3
METHODS

Data Collection

Sediments for this study were collected using a vibracoring technique described by Sanders and Imbrie (1963), Buchanan (1970), Harris (1977), and Lanesky et al. (1979). The vibracorer consisted of an 8 HP, Briggs & Stratton, air cooled, gasoline powered engine connected to a vibrating head via a 20 foot long flexible shaft. The vibrating head was clamped to the core tube that consisted of 3 inch, thin-walled aluminum irrigation pipe. Kirby (1974) confirmed that use of this technique produces little or no deformation of sediment layering. Compaction for the cores was about 14%. This was calculated by measuring the distance between the sediment water interface and the top of the sediment in the core, prior to extraction.

Vibracores for this study were collected from three sites located in the northern end of the Indian River Lagoon (NIRL6, NIRL24, and CIRL39) and one site in the southern end of the Banana Rive Lagoon (BRL2) (Fig. 1-1) (Table 3-1). These sites have been selected primarily for their ease of access, wide range of groundwater discharge rates and bottom sediment textures, and regional distribution (~45 km). At the center of each site, a multisampler and a seepage meter were installed to measure water chemistry and submarine groundwater discharge (SGD) rates, and two vibracores were collected for evaluation of the physical properties of lagoonal strata (Fig. 3-1). A multisampler is a multi-level piezometer capable of sampling pore water from discrete intervals (5-10 cm), up to 280 cmbsf. Seepage meters isolate an area of the lagoon floor and measure the flux
of water across the sediment-water interface via a collection bag attached to a port on the top of the meter. Martin et al. (2005) provides a report of multisampler and a seepage meter data. Water chemistry data used by Martin et al. (2005) to estimate pore water mixing depths was compared to measured and modeled values for hydraulic conductivity determined in this study to assess the degree to which sediment physical properties (e.g. hydraulic conductivity) influence the depth of mixing.

Table 3-1. Location and lengths of sediment cores. UTM locations are Zone 17N, WGS84 datum.

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<thead>
<tr>
<th>Site</th>
<th>Water Depth</th>
<th>Core Name</th>
<th>Latitude</th>
<th>Longitude</th>
<th>UTM - X</th>
<th>UTM - Y</th>
<th>Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>NIRL6</td>
<td>0.5 m</td>
<td>NIRL6C1</td>
<td>28.75385</td>
<td>80.8392</td>
<td>515,700</td>
<td>3,180,726</td>
<td>283 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NIRL6C2</td>
<td></td>
<td></td>
<td>515,700</td>
<td>3,180,726</td>
<td>305 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NIRL6N</td>
<td></td>
<td></td>
<td>515,700</td>
<td>3,180,826</td>
<td>280 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NIRL6S</td>
<td></td>
<td></td>
<td>515,700</td>
<td>3,180,626</td>
<td>285 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NIRL6E</td>
<td></td>
<td></td>
<td>515,800</td>
<td>3,180,726</td>
<td>292 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NIRL6W</td>
<td></td>
<td></td>
<td>515,600</td>
<td>3,180,726</td>
<td>272 cm</td>
</tr>
<tr>
<td>NIRL24</td>
<td>0.7 m</td>
<td>NIRL24C1</td>
<td>28.73529</td>
<td>80.77575</td>
<td>521,897</td>
<td>3,178,679</td>
<td>223 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NIRL24C2</td>
<td></td>
<td></td>
<td>521,897</td>
<td>3,178,679</td>
<td>302 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NIRL24N</td>
<td></td>
<td></td>
<td>521,897</td>
<td>3,178,779</td>
<td>615 cm</td>
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<tr>
<td></td>
<td></td>
<td>NIRL24E</td>
<td></td>
<td></td>
<td>521,997</td>
<td>3,178,679</td>
<td>324 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NIRL24W</td>
<td></td>
<td></td>
<td>521,797</td>
<td>3,178,679</td>
<td>320 cm</td>
</tr>
<tr>
<td>BRL2</td>
<td>1.5 m</td>
<td>BRL2C1</td>
<td>28.27500</td>
<td>80.65111</td>
<td>534,223</td>
<td>3,127,726</td>
<td>268 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BRL2C2</td>
<td></td>
<td></td>
<td>534,223</td>
<td>3,127,726</td>
<td>263 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BRL2N</td>
<td></td>
<td></td>
<td>534,223</td>
<td>3,127,826</td>
<td>238 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BRL2S</td>
<td></td>
<td></td>
<td>534,223</td>
<td>3,127,626</td>
<td>299 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BRL2E</td>
<td></td>
<td></td>
<td>534,323</td>
<td>3,127,726</td>
<td>89 cm</td>
</tr>
<tr>
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<td></td>
<td>BRL2W</td>
<td></td>
<td></td>
<td>534,123</td>
<td>3,127,726</td>
<td>248 cm</td>
</tr>
<tr>
<td>CIRL39</td>
<td>1.5 m</td>
<td>CIRL39C1</td>
<td>28.11667</td>
<td>80.61806</td>
<td>537,503</td>
<td>3,110,176</td>
<td>284 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CIRL39C2</td>
<td></td>
<td></td>
<td>537,503</td>
<td>3,110,176</td>
<td>246 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CIRL39N</td>
<td></td>
<td></td>
<td>537,503</td>
<td>3,110,276</td>
<td>200 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CIRL39S</td>
<td></td>
<td></td>
<td>537,503</td>
<td>3,110,076</td>
<td>400 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CIRL39E</td>
<td></td>
<td></td>
<td>537,603</td>
<td>3,110,176</td>
<td>249 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CIRL39W</td>
<td></td>
<td></td>
<td>537,403</td>
<td>3,110,176</td>
<td>300 cm</td>
</tr>
</tbody>
</table>

In order to characterize spatial variability in sedimentary facies surrounding each site, four additional vibracores were collected at distances of ~100 m north, south, east and west of the center location. Most vibracores were >1 m in length with some >3 m (Table 3-1). At BRL2, a semi-lithified coquina ridge at or near the lagoon floor, east of
the center cores, forced the eastern core to be only ~50 m from the central cores with only 89 cm of sediment collected. A south core was not collected at NIRL24 due to poor weather conditions and logistical difficulties returning to the site. All sediment cores were stored vertically while in the field and laid horizontally for transport to laboratory facilities at the University of Florida. Upon return to the laboratory, all cores remained horizontal and care was taken to prevent sloshing or rotation. All cores were kept in cold (4 °C) storage prior to analyses described below.

**Lithostratigraphy**

Each core underwent a multi-sensor core scan for determination of total porosity (φ) using a Geotek multi-sensor core logger (MSCL) prior to being split for photography, descriptions and subsampling. This device allows for automated high-resolution (0.5-1 cm) down-core measurement of bulk density. Readers are referred to Geotek web site [http://www.geotek.co.uk/mscl.html](http://www.geotek.co.uk/mscl.html) for detailed information on the specifics of the techniques. Calibration of the unit and conversion to gamma bulk density were performed using the technique of Gunn and Best (1998). Gamma bulk density is equivalent to wet, or saturated, bulk density of the sample, but the term gamma bulk density or gamma-ray attenuation (GRA) porosity is used as the device measures the attenuation of gamma rays from a $^{137}$Cs source to determine wet bulk density. The conversion to porosity assumes a mean grain density (MGD) of 2.65 g/cm$^3$ and a water density (WD) of 1.01 g/cm$^3$. The MSCL generally has an error of ≤1% when compared with porosity measurements performed on discrete sediment samples (Gunn and Best 1998).
With the exception of the replicate center cores, all cores were split in half using a circular saw. Cores were cleaned, described and then passed through the GEOSCAN® II calibrated color core imaging system on the Geotek core logger. In this process, fluorescent light reflected off the surface of the core is split into three paths to fall on red, green, and blue detectors which, when combined, reproduce a conventional color image.

Grain size measurements were made on the center core of each site at 5 cm intervals with depth. Each sample was wet sieved at < 63 micron (4 phi) for the silt and clay fraction, between 63 micron and 2 mm for the sand fraction, and > 2 mm (-1phi) for the gravel/shell fraction. The three fractions (silt and clay, sand, gravel/shell) were then dried and weighed to generate % fraction plots for each site. Grain size distributions of the sand fraction were determined using a settling column (Syvitski et al., 1991) and a Sedigraph (Coakley and Syvitski, 1991) was used on one sample from each of the four sites to determine a representative size distribution of the mud fraction. Size distribution of the gravel fraction was determined by visual separation to 1 phi intervals using a graphic sizing template. To determine the overall mean, median, sorting, and skewness of each sample, the size distribution of the sand fraction was re-normalized to include respective percentages of the representative mud fraction distribution and gravel distribution. All grain size results are expressed in phi units (\( \text{phi} = \log_2(\text{Diameter, mm}) \)).

**Biostratigraphy**

All shell material > 2 mm (-1phi) was retained in the gravel fraction and whole shells were identified to species level when possible. Identifications were determined using reference material by Abbott (1954) and Internet material produced by the Smithsonian Marine Station located in Fort Pierce, Florida (http://www.sms.si.edu/).
Attention was given to the interpretation of the living environments for each species and the presence of any zonation for the shells identified.

**Chronostratigraphy**

In order to determine rates of deposition and the timing of marine inundation, four samples were collected for radiocarbon age dating; two from site NIRL6 and two from site CIRL39. Wood fragments were collected when possible, as wood is generally considered more reliable than soft plant material (Meltzer and Mead, 1985). At site NIRL6, plant fragments were collected from between 96 and 100 cm below sea floor (cmbsf) and a 5 cm long intact wood fragment was collected from between 195 to 200 cmbsf. At site CIRL39, plant fragments were collected from between 94 and 94.5 cmbsf and wood fragments were collected from between 243 and 244 cmbsf.

Upon collection, samples were pretreated in a four step process as follows; Two 20 minute soaks in 1N HCL at 90°C, multiple 20 minute soaks in 1N NaOH at 90°C, two 20 minute soaks in 1N HCL at 90°C, multiple 10-20 soaks in distilled water. Samples were then sent to the Department of Botany at the University of Florida and combusted to obtain several mg of CO2-C. These samples were loaded along with 20mg of CuO wires in 15cm Vycor™ tubes. Both the CuO wires and the Vycor™ tubes were pre-baked in air at 900°C. The samples in the Vycor™ tubes were sealed under vacuum along with the CuO wires and combusted at 900°C for two hours. The primary standard for $^{14}$C analysis was NIST Oxalic acid II (SRM 4990C), while IAEA-C6 (ANU sucrose) was analyzed as secondary standard. Anthracite coal cleaned with a standard acid-base-acid treatment was used as a blank. All standards and blanks used for $^{14}$C measurements were combusted and purified similarly to the samples.
A portion of the sample CO2 was converted to graphite by reacting with H2 in presence of Fe catalyst (Vogel et al., 1987). The graphite samples were pressed into targets and sent for $^{14}$C analysis at the W.M. Keck Carbon Cycle Accelerator Mass Spectrometry facility at University of California, Irvine (Southon et al., 2004). All $^{14}$C results were expressed as $\Delta^{14}$C after correcting for any mass-dependent fractionation of $^{13}$C (Stuiver and Polach, 1977).

Dates were originally reported in radiocarbon years $\pm$ one standard deviation. Using the radiocarbon calibration program, CALIB REV5.0.2 (Stuiver and Reimer, 1993), all age dates were converted to calendar years before present (Cal. BP).

**Grain-Size Modeled Hydraulic Conductivity**

The initial equation used for modeling hydraulic conductivity using sediment textural data was the Carmen- Kozeny (CK) equation as presented in bear (1972, p. 166). All physical parameters were determined with a down-core resolution of 5 cm. Representative grain diameter ($d$) was taken from the grain size distribution analysis and total porosity ($\phi$) was calculated from the bulk density data, both described above in the “Lithostratigraphy” section. Fluid density ($\rho$) was calculated based on temperature and salinity data collected by martin et al. (2005).

Three standards were also prepared for modeling in the method described above and measurement in the method described below. To prepare the samples, quartz sand was first sieved in to three narrow grain size intervals using US standard sieve no.’s 18 - 25, 35-40, and 60-70 respectively. The sieved sands were then packed into 10 cm sections of vibracore collection pipe by hand tamping on the laboratory counter 30 times with light to medium force. For modeling, representative grain diameter ($d$) was assumed
to be the mid point of the sieved interval. Total porosity ($\phi$) was not measured for the prepared standards. Instead, three different porosity values were chosen that fell within the likely range for well-sorted sands (Fetter, 2001).

**Measured Hydraulic Conductivity**

The replicate center cores remained un-split and were sectioned at 10 cm intervals. All but two of the sectioned intervals were tested in a Mariotte style constant head permeameter for coarse-grained sediments, supplied by Trautwein Soil Testing Equipment. Samples remained undisturbed in the sectioned vibracore collection tube, which served as a rigid wall support for the sample. All samples and standards were then tested using up to three hydraulic gradients when possible for better statistical averaging. ASTM (2000) designation D 2434-68 was used as a guideline for general procedures.

Two samples from the base of the BRL2 center core consisted of a bedded clay layer, so the hydraulic conductivity values were judged too low for testing in the apparatus described above. These samples were tested with the “DigiFlow K” flexible wall permeameter, also supplied by Trautwein Soil Testing Equipment, using a constant head method. The equipment consists of a cell (to contain the sample and provide isostatic effective stress) and three pumps (sample top pump, sample bottom pump, and cell pump). Bladder accumulators allow for the use of deionized water in the pumps while an idealized solution of seawater (25 g NaCl and 8 g MgSO$_4$ per liter of water) permeated the sample. ASTM (1990) designation D 5084-90 was used as a guideline for general procedures.
Figure 3-1. Site occupation for water chemistry analysis (multisampler), groundwater seepage rate measurement (seepage meter), and sediment analysis (vibracore).
CHAPTER 4
RESULTS

Lithostratigraphy

The reader is referred to figures 4-1 A, B, & C thru 4-4 A, B, & C in the following discussion. In parts A, an image of the center core for each site is presented with the respective physical properties. In parts B, Images of all cores collected at each site are presented. In Parts C, identified lithofacies units and interpreted depositional environments are presented. Faunal identifications with depth for each site are presented in table format in Appendix A. The following sections are descriptions of the lithofacies units identified at each site.

CIRL39

Five cores were logged and imaged from CIRL39; a center core and four perimeter cores 100 m to the north, south, east and west of center (Fig. 4-1, A, B, & C). Unit 39A consists of lt. green well sorted fine silty quartz sand. Bioturbation is pervasive but shell fragments and whole shells are scarce. Unit 39A is thickest (~1 m) in the west and center core but thins (~40 – 50 cm) to the north and south and is not present in the east core. The contact with underlying unit 39B is gradational and median grain size shifts from fine to medium sand. Unit 39B consists of green and brown medium clayey quartz sand. Sorting values for unit 39B ranges from moderately well to poorly sorted reflecting an increased abundance of shell material and mud. Bioturbation remains pervasive. Wood and plant fragments are abundant, and a shell lag is present in all cores at depths ranging from 30 to 150 cm below sea floor (cmbsf). Unit 39B ranges in thickness from ~80 to
100 cm but thins in the west core to ~ 50 cm. The contact with underlying unit 39C is sharp in the south, east, and west cores but gradational in the north and center cores. Unit 39C consists of green and brown mottled medium silty quartz sand. Bioturbation is generally limited to the upper 10 – 20 cm in unit 39C; however, large (~1 cm diameter) burrows penetrate as much as 1 m. Abraded whole shells and shell fragments are scarce but wood and plant fragments remain abundant. Unit 39C is moderately well sorted although sections with higher mud concentration become poorly sorted. The contact with underlying unit 39D is sharp in the south and east cores but gradational in the north, west, and center cores. Units 39C and 39D are interbedded in the south and east cores but the lower contacts are all gradational. The north, west, and center cores terminate within 20 cm of the initial contact with unit 39D so interbedding with unit 39C may also be present beneath the cores from these locations. Unit 39D consists of lt. to dk. brown organic rich fine clayey quartz sand. Bioturbation, wood and plant fragments, and shell fragments are all absent, and thickness of this unit ranges from 20 - 30 cm in the south and east cores. The center core did not extend far enough into unit 39D for sorting to be assessed. Only the south and east cores reached unit 39E. and the contact was sharp in the south core but gradational in the east core. Unit 39E consists of gray fine to medium clean quartz sand with abundant whole shells and shell fragments. Sieve and grain size analyses were not performed on unit 39E.

BRL2

Five cores were logged and imaged from BRL2; a center core, three perimeter cores 100 m to the north, south, and west of center, and one core 50 m east of center (Fig. 4-2, A, B, & C). Unit 2A consists of tan to greenish tan well-sorted medium silty quartz sand. Bioturbation is pervasive and shell fragments are scarce with the exception of a
shell lag of fragments and whole shells in the base of the unit in the east, center, and west cores. Shell fragments and whole shells are present in the base of unit 2A in the north and south cores, however, not in significant abundance. The thickness of unit 2A is ~ 30 cm in all but the north core. In the north core, possible slumping activity has mixed unit 2A with the underlying unit 2B, making the contact highly irregular. The contact with unit 2B is sharp in the west and east cores but gradational in the center core. The south core first has a sharp contact with unit 2E before a gradation contact with unit 2B. Unit 2E consists of dk. brown medium quarts sandy clay with sparse shell fragments. Sieve and grain size analysis were not performed on unit 2E.

Unit 2B consists of lt. to dk. brown mottled well sorted medium quartz sand with abundant wood and plant fragments. Bioturbation is limited to the upper 10 -20 cm and small shell fragments are almost non-existent. Unit 2B is the dominant lithology in all but the east core with thicknesses of 1.5 – 2 m. In the east core, unit 2B has a thickness of only 20 cm and there is a sharp contact with the underlying unit 2D at ~55 cmbsf. The east core terminated on coquina at ~85 cmbsf. The south core also has a sharp contact between unit 2B and 2D but at a depth of 255 cmbsf. Although unit 2D is present in both the east and south cores, correlation between the cores is unlikely due to the wide depth range. Unit 2D consists of a bedded shell lag in a medium brown sandy clay matrix with a thickness of ~30 cm in both the South and east cores. Sieve and grain size analysis were not performed on unit 2D. Unit 2C was reached in the west, center, and south cores. In the west and center cores, the contact with overlying unit 2B is gradational at 230 and 240 cmbsf respectively. In the north core, the gradational change from unit 2B to 2C is observed suggesting the presence of unit 2C deeper in this location. In the south
core, the gradational change from unit 2B to 2C is also present but interrupted by unit 2D. Contacts with overlying unit 2B and underlying 2C are both sharp. Unit 2C consists of a massive green to lt. tan bedded clay.

**NIRL6**

Five cores were logged and imaged from NIRL6; a center core and four perimeter cores 100 m to the north, south, east and west of center (Fig. 4-3, A, B & C). Unit 6A consists of medium to dark green well sorted fine silty quartz sand. Bioturbation is pervasive. Shell fragments are mixed throughout but generally occur in more concentrated lenses 1 – 2 cm thick. Unit 6A is 60 to 70 cm thick in the north, west, and center cores but thickens to 80 cm in the south core and thins to ~40 cm in the east core. Unit 6A terminates with a rapid gradational transition to unit 6B. Unit 6B consists of organic rich black moderately well sorted fine grained sandy silt.

Unit 6B has the same general lithology as unit 6A with the addition of the organic silt fraction. Unit 6B is less than 5 cm thick in the north, west, and center cores and grades rapidly to unit 6C. However, it thickens to ~30 cm in the south core and does not appear in the east core. In the south core unit 6B is bound above and below by sharp contacts and is nearly void of shell material.

Unit 6C consists of abundant whole shells (1 to 3 cm) and shell fragments in a matrix of medium to dk. green fine grained clayey sand. This unit is very poorly sorted reflecting the increased abundance of large shell material and mud. Unit 6C is only ~10 cm thick in the south, east, and center cores; however, it thickens to 20 and 30 cm in the west and north cores respectively. The contact with underlying unit 6D is sharp in all cores.
Unit 6D consists of medium to dark green mottled fine silty quartz sand. In the south core, unit 6D is darker and more organic rich. Bioturbation in only present in the upper 10 cm but shell fragments and abraded whole shells (1-3) cm are abundant. Wood and plant fragments are abundant, some wood fragments measuring up to 5 cm in length. Unit 6F in interbedded with unit 6D at 130 and 140 cmbsf in the west and center cores respectively. Unit 6F consists of a brown massive clay lens, 2 cm thick with sharp contacts above and below. Sieve and grain size analysis were not performed on unit 6F. Sorting values for unit 6D ranges from moderately well to very poorly sorted reflecting an increased abundance of shell material and mud. Unit 6D thickens from west to east (90 to 160 cm respectively) but is consistently 130 to 140 cm thick from north to south. The contact with the underlying unit 6E is sharp in all but the west core.

Unit 6G occurs between units 6D and 6E in the west core and is bound by sharp contacts above and below. Unit 6G is ~35 cm thick and consists of a loose bedded shell lag in a fine sandy matrix. Sieve and grain size analysis were not performed on unit 6G. Unit 6E consists of abraded whole shells and shell fragment lenses interbedded with gray well sorted fine to medium grained clean quartz sand with parallel bedding of light and dark minerals is present in all cores. None of the cores reached the termination of unit 6E so its thickness is unknown.

**NIRL24**

Four cores were logged and imaged from NIRL24; a center core and three perimeter cores 100 m to the north, east and west of center (Fig. 4-4, A, B, & C). Unit 24A consists of lt. to dk. brown well to moderately well sorted fine grained quartz sand. Bioturbation is pervasive and shell fragments become more abundant at the base of the
unit. The thickness of unit 24A is consistent in all cores at ~20 to 25 cm. The contact with the underlying unit 24B is gradational in all cores.

Unit 24B consists of abundant whole shells (1 to 1.5 cm) and shell fragments in a matrix of organic rich dk. brown to black fine grained quartz sand. This unit is very poorly sorted reflecting the increased abundance of large shell material and mud. Unit 24B is 30 cm thick in the center core, but thickens to 40 cm in the north and east cores and thins to 20 cm in the west core. The contact with underlying unit 24C is sharp in all cores.

Unit 24C consists of lt. tan to dk. brown mottled fine grained quartz sand with abundant wood and plant fragments. Bioturbation is limited to the upper 10 -20 cm and small shell fragments are almost non-existent. Sorting values range from very well sorted to poorly sorted reflecting the changes in relative mud concentration. Unit 24C is the dominant lithology in this site as even the north core with a collected depth of 600 cmbsf did not reach a contact with a lower unit. Interbedded within unit 24C are units 24D at ~280 cmbsf in all cores and 24E at ~450 cmbsf in the south core.

Unit 24D consists of dk. brown poorly sorted fine grained clayey quartz sand. Small (< 3 mm) shell fragments are abundant, particularly in the west and north cores. Wood and plant fragments are not apparent. Unit 24D has a gradation upper contact in all cores but a sharp lower contact in all but the center core. Unit 24D is 15 cm thick in the center core, but thickens to 30 cm in the east core, 20 cm in the west core, and 60 cm in the north core.

Unit 24E consists of dk. brown fine grained clayey quartz sand with abundant small (1 mm) and large (~1 cm) shell fragments. Sieve and grain size analysis were not
performed on unit 24E. Unit 24E is nearly 50 cm thick with gradational upper and lower contacts. Unit 24E was only collected in the south core so the areal extent of this unit is unknown.

**Physical Properties Summary**

The mean down core porosity at all locations is relatively constant at ~ 0.45. Mud contents as high as 10% appear not to have any influence on overall porosity, whereas shell contents as high as 30 to 40% have only a modest (~0.05) effect on reducing porosity. Only when mud contents exceed 80 to 90% is porosity significantly (~0.15) altered, such as at site BRL2. There is also relative little deviation in down core porosity values amongst all sites (~0.05).

The sediments at all sites are dominantly sandy, with mean values in excess of 80% sand by weight. The amount of shelly material is less than 10% at most sites, although some intervals exceed 30 to 40% shell material by weight and a few dense shell beds were observed but not analyzed for grain size distribution. The dominant median grain sizes range from approximately 1.7 to 2.5 phi (medium to fine sand) and in general shows modest variation (~1 phi unit) down core at the sandy locations. In general, sediments at all sites are well to very poorly sorted, reflecting the broad range and grain sizes from shell to mud. Site NIRL24 has the overall best sorting. Site BRL2 is quite sandy overall, but there is a thick clay bed found near the base.

**Biostratigraphy**

The dominant bivalve of the shore face environment is the *Donax variabilis*. This species is nicknamed the “surf clam” as its common habitat is along the ocean front beach face in the intertidal to subtidal zone. The *Donax* shells were found at various depths in all cores but not within any particular lithofacies unit. At NIRL6, *Donax* was
pervasive between 40 and 200 cm. At CIRL39, *Donax* was limited to between 100 and 180 cm. At BRL2, only one *Donax* shell was found at 30 cm. At NIRM24, *Donax* was abundant but only between 30 and 55 cm.

Bivalves and gastropods of the shallow water sea grass/lagoonal environment include: *Anadara brasilina, Anomalocardia auberiana, Chione cancellata, Laevicardium laevigatum, Mulina lateralis, Gemma gemma, Macoma spp., Cerithidea scalariformis, Cerithium muscarium, Melongena carona, Nassarius vibex, Turbonilla dalli, Acteocina canaliculata*. The only notable zonation of these shells is their pervasive abundance within the dense shell lags of lithofacies units 39B, 2A, 6C, and 24B. Within these shell lags, the dominant species and shell size ranges are as follows: *C. cancellata* (1-4 cm), *M. lateralis* (1-2 cm), *D. variabilis* (1.5 cm), *C. muscarium*, (0.5-1.5 cm), and *A. canaliculata* (2-4 mm).

Freshwater hydrobiid snails, *Tryona aequicostata* and *Littoridinops monroensis*, were found in all sites corresponding to the dense shell lag of sea grass/lagoonal bivalves described above in lithofacies units 39B, 2A, 6C, and 24B.

**Chronostratigraphy**

Three of the four samples prepared for radiocarbon age-dating were within the age limits for use in the 14C system. However, the wood sample from 200 cmbsf in the NIRL6 east core was too old for calibration using the calibration program, CALIB REV5.0.2. Radiocarbon ages and converted calendar year before present (cal. BP) values are presented in Table 4-1. When these dates are used to calculate sedimentation rates, the top 100 cm of sediments (lithofacies units 6A, B, & C) at IRL6 have accumulated at a rate of 0.3 mm/y. At IRL39, sediments between 94 and 243 cmbsf (lithofacies units 39B & C) have accumulated at the same rate of 0.3 mm/y. Also at CIRL39, the top 100 cm of
sediments (top 15 cm of lithofacies unit 39B and all of unit 39A) have accumulated at a rate of 1.9 mm/y. However, the transition from unit 39B to unit 39A represents a shift in median grain size from medium to fine grained sand, which suggests a new sediment source and/or depositional process over the past ~500 ca. BP (see discussion).

Table 4-1. Reported radiocarbon ages and converted calendar year ages.

<table>
<thead>
<tr>
<th>Core</th>
<th>Interval (cmbsf)</th>
<th>Sample Description</th>
<th>Radiocarbon Age ($^{14}$C yr BP)</th>
<th>±</th>
<th>Calendar Age (cal. B.P.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRL6 Center</td>
<td>96 - 100</td>
<td>Plant Material</td>
<td>3385</td>
<td>20</td>
<td>3621</td>
</tr>
<tr>
<td>IRL6 East</td>
<td>195 - 200</td>
<td>Wood</td>
<td>48740</td>
<td>2350</td>
<td>Invalid age</td>
</tr>
<tr>
<td>IRL39 Center</td>
<td>94 – 94.5</td>
<td>Plant Material</td>
<td>440</td>
<td>20</td>
<td>499</td>
</tr>
<tr>
<td>IRL39 Center</td>
<td>243 - 244</td>
<td>Wood</td>
<td>5495</td>
<td>40</td>
<td>6289</td>
</tr>
</tbody>
</table>

**Grain-size Modeled Hydraulic Conductivity**

Application of the Carmen-Kozeny (CK) equation, using the measured values of porosity and median grain size for each central core, estimates in hydraulic conductivity values that range from ~0.5 to 4.0e$^{-2}$ cm s$^{-1}$ (Figs. 4-1 thru 4-4, parts A). The down-core variability in modeled hydraulic conductivity is only about an order of magnitude. There are three exceptions. In sites NIRL6 and NIRL24, large shells skewed the median grain-size statistic used in the CK model and produced a excessive positive shift in the modeled value that is ignored. In site BRL2, where the thick clay bed at the bottom of the core (lithofacies unit 2C) produced values that are four orders of magnitude less than the mean of the upper sections.

**Measured Hydraulic Conductivity**

Measured vertical hydraulic conductivity values using the permeameter for coarse-grained soils ranged from ~5.0e-2 to 2.0e-5 cm s$^{-1}$ (Figs. 4-1 thru 4-4, parts A).
Measured values using the DigiFlow K permeameter for the BRL2 clay bed (lithofacies unit 2C) were ~5.0e-8 (Fig. 4-2 A). Overall, measured values are lower than modeled values using the CK equation by up to 4 orders of magnitude. Measured in situ horizontal hydraulic conductivity values were also obtained by Martin et al. (2005) from recovering water level data using the Bouwer-Rice (Bouwer and Rice, 1976) and Hvorslev (Hvorslev, 1951) methods within AQTESOLV 3.0. The horizontal hydraulic conductivity values are also plotted in figures 4-1 thru 4-4, parts A. These values are generally about one order of magnitude greater than the measured vertical hydraulic conductivity values but follow the same trends.
Figure 4-1, A. Physical properties of the center core at site CIRL39. Measurements of in situ horizontal hydraulic conductivity (HC), laboratory measured vertical HC and both the Carmen-Kozeny (CK) and modified CK modeled values for HC are compared to the sediment textural parameters. Both models use median grain-size and porosity. The modified model uses an additional term, 200M, representing the relative percent mud measured down-core. Green circles signify an abundance of shelly which may have caused errors in Permeameter testing.
Figure 4-1, B. Color images of 5 cores collected at site CIRL39. Cores were spaced ~ 100 m in two transects, shore-normal and shore-parallel.
Figure 4-1, C. Lithostratigraphy and depositional environments for site CILR39. Carbon dates indicate that inundation of marine waters and initiation the lagoonal environment occurred this in this region some time after 6200 cal. BP. Also note the lobate shape of unit 39A. This unit appears to have been deposited in the last 500 years.
Figure 4-2, A. Physical properties of the center core at site BRL2. Measurements of in situ horizontal hydraulic conductivity (HC), laboratory measured vertical HC and both the Carmen-Kozeny (CK) and modified CK modeled values for HC are compared to the sediment textural parameters. Both models use median grain-size and porosity. The modified model uses an additional term, 200M, representing the relative percent mud measured down-core. Red circles signify a loss of sample mud and green circles signify an abundance of shelly material both of which may have caused errors in Permeameter testing.
Figure 4-2, B. Color images of 5 cores collected at site BRL2. Cores were spaced ~100 m in two transects, shore-normal and shore-parallel with the exception of the east core that could only be spaced at ~50 m because of a coquina deposit, adjacent to the center core.
Figure 4-2. C. Lithostratigraphy and depositional environments for site BRL2. A wide range of depositional processes have occurred from lacustrine (unit 2C) to stream channel (unit 2D). The lagoonal facies are the most poorly developed of all sites.
Figure 4-3, A. Physical properties of the center core at site N1RL6. Measurements of in situ horizontal hydraulic conductivity (HC), laboratory measured vertical HC and both the Carmen-Kozeny (CK) and modified CK modeled values for HC are compared to the sediment textural parameters. Both models use median grain-size and porosity. The modified model uses an additional term, 200M, representing the relative percent mud measured down-core. Red circles signify a loss of sample mud and green circles signify an abundance of shelly material both of which may have caused errors in Permeameter testing. This site had the worst agreement between measured and modeled HC values.
Figure 4-3, B. Color images of 5 cores collected at site NIRL6. Cores were spaced ~100 m in two transects, shore-normal and shore-parallel.
Figure 4-3, C. Lithostratigraphy and depositional environments for site NIRL6. As with site BRL2, a wide range of depositional processes have occurred from lacustrine (unit 6F) to stream channel (unit 6G). The east core also contains intraclasts of coquina with no apparent method of deposition.
Figure 4-4, A. Physical properties of the center core at site NIRL24. Measurements of in situ horizontal hydraulic conductivity (HC), laboratory measured vertical HC and both the Carmen-Kozeny (CK) and modified CK modeled values for HC are compared to the sediment textural parameters. Both models use median grain-size and porosity. The modified model uses an additional term, 200M, representing the relative percent mud measured down-core. Red circles signify a loss of sample mud and green circles signify an abundance of shelly material both of which may have caused errors in Permeameter testing. As with site NIRL6, this site showed poor agreement between measured and modeled HC values.
Figure 4-4, B. Color images of 4 cores collected at site NIRD24. Cores were spaced ~100 m in an east-west transect, but a south core was not collected.
Figure 4-4, C. Lithostratigraphy and depositional environments for site NIRL24. This site did not reach marine facies reflecting the variable antecedent topography. This site is the most consistently well-sorted of all sites cored for this study.
CHAPTER 5
DISCUSSION

Sedimentary Facies and Depositional Environments

Interpretation of ancient depositional environments depends upon identifying the combined physical, chemical and biological characteristics of the sediments that can be related to environmental parameters (Boggs, 1995). Environmental parameters operate to produce bodies of sediment (facies) that can be characterized by specific textural, structural, and compositional properties. Based on textural properties, fauna, and radiocarbon dates, four major depositional environments were identified within the upper three meters of Indian River Lagoon sediments; marine, brackish, lacustrine, and lagoonal. Graphic interpretations for the following discussion are presented in figures 4-1 thru 4-4, parts A, B, & C.

Marine Facies

Pleistocene marine facies occur above and below current sea level, surrounding and underlying the Indian River Lagoon system, and thus form the antecedent topography within which Holocene lagoonal infilling has occurred. Coquina deposits of the Pleistocene Anastasia Fm. form the “backbone” of the mainland shore (Atlantic Coastal Ridge, Fig. 2-1) and barrier island (Atlantic Barrier Chain, Fig. 2-1) and crop out at numerous locations along eastern Florida (Puri and Vernon, 1964; White, 1970; Brooks, 1972; Davis, 1997). Unlithified portions of the Anastasia Fm. also form progradational beach ridge complexes on Merritt Island (Fig. 1-1) (Brooks, 1972) and underlie Holocene strata of the interior lagoon (Almasi, 1983; Bader and Parkinson, 1990).
In this study, a lithified portion of the Anastasia Fm. (coquina) was encountered at the base of the east core at site BRL2 (Fig. 4-2 part C) and unconsolidated sandy portions of the Anastasia Fm. are present at the base of two cores from site CIRL39 (unit 39E, Fig 4-1 part C) and all cores from site NIRL6 (unit 6E, Fig 4-3 part C). Both of these sites are located just east of the present mainland lagoonal shoreline along the Atlantic Coastal Ridge (Fig. 2-1). Identification criteria for these marine facies included the presence of echinoderm fragments, arthropod fragments, and heavily abraded mollusk fragments in a matrix of fine to medium clean sand with planar bedding observed at NIRL6.

These units are likely shoreface sediments deposited seaward of a barrier island when sea level was higher in the Pleistocene. Unit 6E is topographically higher than 39E (~1 m) and appears to be from an upper shoreface environment as the sediments are fine grained, well sorted, and contain parallel bedding; all common features of an upper shoreface environment (Boggs 1995). During this time, Merritt Island would likely be taking form as conceptualized by Kofoed (1963). In this model, a convergent longshore transport system similar to today produced offshore massif deposits that emerged as migrating spit-barriers and finally developed into the progradational beach ridge complex observed today (Kofoed, 1963; Brooks, 1972). Grain size analysis was not conducted on 39E but it appears coarser grained and more poorly sorted, suggesting a lower shore face environment with the current barrier island chain as an off shore sand bar (Almasi, 1983).

**Brackish and Lacustrine Facies**

Sea level curves of Scholl et al. (1969) and Neumann (1969) and the previous work of Almasi (1983) suggest that these sediments were deposited in a restricted brackish water environment. However, fluvial depositional processes appear to have played a role in development of sedimentary facies in the brackish environment. Also identified and
included in this discussion of the brackish environment are lacustrine deposits as they are found juxtaposed and possibly syndepositional to the brackish facies. Brackish and lacustrine facies of the Indian River lagoon can vary significantly within each site (e.g. channel, fan, and lacustrine). More importantly, they appear to be genetically unrelated between sites reflecting a unique relative sediment source for each site. Discussion of the brackish depositional environment is therefore treated separately for each site. For all sites, facies of the brackish environment have a wide range of sorting values reflecting provenance and depositional process. There is generally an abundance of terrestrial wood and plant fragments and, when shell material is present, the amount of abrasion is highly variable ranging from well preserved to heavily abraded.

CIRL39 brackish facies include lithofacies units 39C & D (Fig. 4-1 A, B, & C). Unit 39C contains only limited amounts of shell fragments and whole shells (both heavily and lightly abraded) yet wood and plant fragments were very abundant. Unit 39D appears to have high organic (peat?) content although it was not measured in this study. Brackish facies for CIRL39 are moderately well to poorly sorted reflecting the variability in mud (peat?) content. The first contact between units 39C & D as well as between unit 39C and the overlying lagoonal facies show consistent lateral variability between cores. Contacts are sharp in the south and east cores but gradational in the north, west and center cores. Vertical variability in lithofacies contacts is also seen in the south and east cores between units 39C & D. Multiple interbedded contacts between units 39C & D in the south and east cores are both sharp and highly gradational indicating possible variability in both sediment character and possibly rate of deposition with time (Boggs, 1995). Immediately adjacent to this site (~ 100 m due east) are the dissected remnants of
the Pleistocene barrier island described above (Atlantic Coastal Ridge, Fig 2-1). Sands from unlithified portions of the Atlantic Coastal Ridge and muds from the back barrier lagoon (Eastern Valley, Fig. 2-1) are the likely supplies of sediment in these facies.

BRL2 brackish facies include lithofacies units 2B, C, D, & E (Fig. 4-2 A, B, & C). BRL2 is adjacent to the submerged westward dipping tail end of the Merritt Island beach ridge complex described by Brooks (1972) (Fig. 1-1). The root of the ridge is a lithified portion (coquina) of the Pleistocene Anastasia Fm. The east and west cores reached the coquina at 89 cmbsf. The west core collected coarse pebbles of lithified shell material, which are likely fragments underlying coquina, at 250 cmbsf. However, the coquina is not reached in the north, center, or south cores at depths of 2.3, 2.6, and 2.95 m respectively, demonstrating the high degree of variability in the Pleistocene antecedent topography. The center and south cores terminate in a bedded clay layer (unit 2C) that is overlain by a bedded shell lag (unit 2D) in the southern core. This suggests an erosional antecedent topography in which a low energy condition then existed, allowing for the clay deposits (e.g. lacustrine, unit 2C) to form, which were later cut by a stream channel (unit 2D) carrying abundant eroded shell material. The stream channel deposit (unit 2E) is bound by sharp contacts indicating rapid changes in depositional processes.

These basal units are overlain by up to two meters of lt. tan to dk. brown mottled well-sorted medium grained sands that are void of any sedimentary structures, shell material or mud, but contain abundant wood fragments (unit 2B). This sediment character suggests a slightly vegetated well sorted clean sand body as a sediment source. The contacts with the lower lacustrine deposit (unit 2C) are all steeply gradational indicating a moderately rapid transition of depositional processes. In the south core, Unit
2B shifts gradationally to another possible lacustrine deposit (unit 2E, ~60 cmbsf) immediately prior to marine inundation. The contacts with the overlying lagoonal facies (unit 2A) are sharp in the south, east, and west cores but slightly gradational in the north and center cores with limited burrowing (~ 40 cm) into the brackish facies in all cores.

NIRL6 brackish facies include lithofacies units 6D, F & G (Fig. 4-3 A, B, & C). The dominant brackish facies unit (6D) contains abundant whole shells and shell fragments (both heavily and lightly abraded) mixed with abundant wood fragments (up to 5 cm long) and cobble-sized limestone clasts, which are likely remnants of lithified Anastasia Fm. (coquina). All of the cores at NIRL6 reach unlithified portions of the Anastasia (unit 6E) at about 2.5 meters depth and a large river type transportation mechanism for these clasts is not evident. The clasts are only found in the east core over a nearly two-meter depth range in which shell material is absent. Since there are no coquina outcrops immediately adjacent to NIRL6, these clasts are likely intraclasts from an immediately adjacent lithified portion of the Anastasia Fm. that has been completely eroded. Sorting values for unit 6D range from very well to extremely poorly sorted reflecting a heterogeneous sediment source (e.g. sand, mud, shell, coquina clasts). Unit 6F is a massive clay lens interbedded within unit 6D in the west and center cores at 130 and 140 cmsbf respectively. This unit is only 2 cm thick, does not appear to be laterally extensive, and is bounded by sharp contacts suggesting a quiescent lacustrine or pond environment that was short lived and changed rapidly. At the base of the fluvial facies in the west core is a bedded Donax (“surf clam”) shell lag (unit 6G) suggesting the existence of a stream channel likely eroding a beach face shell hash. A variably abraded faunal assemblage, abundance of wood fragments, and a lack of variation in median grain
size across the sharp marine- brackish facies contact (Fig. 4-3 A) suggests that sediments of this brackish environment was likely supplied by eroding dunes (Atlantic Coastal Ridge, Fig. 2-1) and lagoon/marsh (Eastern Valley, Fig. 2-1) deposits of the previous barrier island lagoon system. The extremely poor sorting values and sharp lithofacies contacts observed within these fluvial facies suggest a rapid but periodic sediment delivery system with a short distance of transportation (e.g. alluvial). Finally, contacts with the overlying lagoonal facies in all cores from this site are sharp suggesting a more rapid marine inundation than the southern sites BRL2 and CIRL39.

NIRL24 brackish facies include lithofacies units 24C, D, & E (Fig. 4-4 A, B, & C). The dominant brackish facies unit (24C) contains nearly six meters of well-sorted fine grained sands that are void of any sedimentary structures or shell material but contain abundant wood fragments. Mud content remains well below 10 percent and color varies from light to dark tan suggesting variation in the presence and concentration of oxidized minerals. As with site BRL2, this sediment character suggests a slightly vegetated well sorted clean sand body as a sediment source.

Unit 24D is a dk. brown poorly sorted fine grained clayey quartz sand layer interbedded with 24C in all cores at a depth of ~280 cmbsf. Small (< 3 mm) shell fragments are abundant, particularly in the west and north cores and wood fragments are not apparent. Unit 24E is a dk. brown fine grained clayey quartz sand layer interbedded with 24C at a depth of ~450 cmbsf in the south core. Small (<3 mm) and large (~1 cm) shell fragments are abundant and wood fragments are not apparent. The other cores from NIRL24 did not reach this depth so the lateral extent of unit 24E is unknown. Both units 24D & E are bound by either sharp or steeply gradational contacts. However, both of
these units also appear to represent more of a change in sediment supply than a change in depositional process as they both maintain relatively high sand concentrations (~90%) and show no stream channel type bedding, particularly in unit 24E with its larger shell fragments. Following the model conceptualized model by Kofoed (1963) for development of the Pleistocene cape, the origin of these sediments would be reworked longshore drift deposits. However, lack of any sedimentary structure makes the method of reworking unclear. As with NIRL6, the contact with the overlying lagoonal facies is sharp and bioturbation is limited to the upper 10 cm of unit 24C, indicating a rapid transition to the lagoonal environment.

**Lagoonal Facies**

Lagoonal facies are present at all sites; units 39A & B at site CIRL39 (Fig. 4-1 C), unit 2A at site BRL2 (Fig. 4-2 C), units 6A, B, & C at site NIRL6 (Fig. 4-3 C), and units 24A & B at site NIRL24 (Fig. 4-4 C). Topographic differences between the sites cause variations in thickness from 0.2 m at BRL2 to 1.8 m at CIRL39. Transition to a lagoonal environment represents marine inundation and is identified by the presence of a coarse pebbly shell lag in an organic rich sandy matrix (units 39B, 2A, 6C, & 24B); likely a marsh environment. Topographic differences, radiocarbon ages, and sharp facies contacts in the north suggest an initially gradual inundation of marine waters in the south (later than ~ 6,200 cal. BP. at CIRL39) followed by a more rapid inundation in the north (~ 3,500 cal. BP. at NIRL6 and NIRL24).

Median grain sizes do not change through the brackish-lagoonal transitions for any of the sites suggesting persistent local sediment sources as well as similar depositional process. With the exception of the units with coarse shell lags, overall sorting values also remain consistent with the brackish facies. One exception to this is site NIRL6, unit 6A.
Above the initial lagoonal facies (unit 6C) and organic rich facies (unit 6B), sands
become well sorted. This may however represent a change in sediment source rather than
a change in depositional process. A prime example of this is more clearly demonstrated
in lithofacies unit 39A at site CIRL39 (Fig. 4-1 C). Based on a single radiocarbon age
from plant material, deposition of this unit occurred in the last 500 cal. BP. The contact
between units 39B and 39A is steeply gradation and geometry of unit 39A is that of a
lobate fan. Unit 39A is therefore likely the product an erosional breach of coquina within
the immediately adjacent (~100 m) Atlantic Coastal Ridge (Fig. 2-1) in which a new
source of well-sorted shoreface sand was released. Currently there is no immediately
adjacent “bluff“ of beach sand at NIRL6, however, unit 6A may well be the depositional
product of one that recently existed. Unit 6A thins to the east as does 39A; however, no
other lateral trend in geometry is evident in cores from NIRL6.

**Transgressive Barrier Island Facies Models**

With the exception of a muddy shell lag at their base, lagoonal facies do not appear
to have developed a sedimentologic character that is unique to the lagoonal environment
as conceptualized in the figures 1-2 & 2-2. Localized fluvial depositional processes
appear to have remained dominant throughout the transition into lagoonal facies. The
likely reason for this is the fact that the Indian River lagoon system is microtidal and has
an extremely small tidal prism, particularly in the northern region as the nearest tidal inlet
is ~20 km south. As a result, the physical mixing and redistribution processes of tidal
current shear stresses are small. Instead, the primary means of sediment redistribution is
through wave orbital shear stresses (Sun, 2001) which are minimal. Lagoonal facies
development is more characteristic in mesotidal systems with larger tidal prisms. Tidal
currents in these systems become a significant driving force in sediment transport
producing more expansive lagoonal sedimentary environments as well as characteristic sedimentary structures and textures (Reinson, 1992; Hayes, 1994; Boggs 1995).

This barrier system is also not likely to migrate in a steady manner as conceptualized in figure 1-2. The modern barrier island system is anchored by underlying coquina of the Anastasia Fm. As sea level continues to rise, it will probably submerge the current barrier islands and the Atlantic Coastal Ridge will once again become a barrier island.

**Measured and Grain-Size Modeled Hydraulic Conductivity**

Modeled hydraulic conductivity values estimated using the CK equation predicted values greater than the measured vertical and horizontal hydraulic conductivity values by up to four orders of magnitude (Figs. 4-1 thru 4-4, parts A). Down-core variability in modeled hydraulic conductivity also was not sensitive to any of the perturbations observed in the measured values. The lack of down-core variability in the modeled values is merely a reflection of the lack of variation in the median grain size and therefore demonstrates the CK model’s bias toward this parameter. However, the CK model was effective at estimating hydraulic conductivity of the prepared standards (fig. 5-1), reflecting a sound methodology in the estimation of pore throat diameters within samples of a certain grain size.

Through laboratory measurement of vertical hydraulic conductivity, it was discovered that the presence of less than five percent mud (< 63 micron, 4 phi) reduced measured hydraulic conductivity by up to an order of magnitude. As the mud content reached 10 percent, values dropped by up to three orders of magnitude. What the CK equation fails to recognize is how quickly pore throats will clog when even a small
amount of mud is added, particularly for fine-grained sands. This conclusion was also reached by Foster et al. (2003) in which the measured vertical hydraulic conductivity of surface sediments (0 – 10 cm) in the southern Baltic Sea were compare to CK modeled values in the same method as this study.

In attempts to produce better agreement between measured hydraulic conductivity values (see below) and modeled values, the CK model was empirically modified to reflect the measured down-core variability in relative percent mud (< 63 micron, 4 phi). The percent value for M was multiplied by a scaling factor of 200, which was also empirically determined in this study. Sensitivity of the modified equation to low values of percent mud (< 0.05) was only attained by placing the empirical modifier within the theoretical term for the solid phase. Further attempts will be made to find a variation of the 200M modifier that can be placed outside of the solid phase term. The modified equation takes the form:

\[ K = \left( \frac{\rho g}{\mu} \right) d^2 \phi^3 / 180(1+200M-\phi)^2 \]

Where M = relative percent mud (< 63 micron, 4 phi).

Modification of the CK equation to reflect the relative percent mud concentration in the sample resulted in a closer match between measure and modeled values (Figs. 4-1 thru 4-4, parts A and Fig. 5-2). There were notable deviations in the agreement between the measured and modeled values using the modified CK equation, however, in almost all cases, there was a problem noted during the measuring procedure. The most common problem was the loss of mud from the sample during both the de-airing and test procedures (denoted by red circles in figures 4-1 thru 4-4, parts A and Fig. 5-2). It is not clear why the mud was able to flow from these samples so easily, but not others. The
other most common deviation occurred in samples in which there was a high shell content (denoted by a green circle in figures 4-1 thru 4-4, parts A and Fig. 5-2).

Deviations in measured vs. modeled hydraulic conductivity values for these sections were likely the result of either bypass flow occurring between the shells and the rigid wall of the vibracore collection tube, or possible bedding of the shells to cause a significant decrease in the cross-sectional area available for fluid transmission.

A third cause for some deviations may be the result of a thin muddy zone or strata that was not included in the grain size analysis. Statistical values for percent mud or a shift in median grain size would therefore not be included in the hydraulic conductivity models. Additionally, samples used for permeameter analysis were 10 cm long sections from adjacent cores collected up to 1 m away from the cores used to establish grain size parameters for the models. Permeameter results for any of the 10 cm sections tested will likely only represent the portion of sediment within the section having the lowest hydraulic conductivity value. The modeled values, however, represent a 1 cm section of sediment spaced every 5 cm. Due to the observation that slight changes in the relative percent mud concentration can produce large variations in hydraulic conductivity, some deviation is to be expected. In this case, the measured hydraulic conductivity would be lower than the modeled value.

Spatial Variability in Sediment Properties over 0.04 km²

The results of the spatial coring program revealed that overall there is significant variability in sediment lithology and hydraulic conductivity. Lithology can change across a sharp contact from bedded clays to clean well sorted sands and overall values of hydraulic conductivity ranged from $10^{-2}$ to $10^{-8}$ cm/sec. The upper ~70 cmbsf is the zone of apparent rapid fluid exchange between the water column and pore waters in the
sediments. Within this zone, hydraulic conductivity values ranged from $10^{-2} - 10^{-4}$ cm/sec. Figure 5-3 presents a comparison of hydraulic conductivity data with the chloride profiles used by Martin et al. (2005) to identify the pore water mixing zone. Site CIRL39 has the highest degree of variability in hydraulic conductivity yet there is no apparent effect on the mixing depth. Spatial variations in fluid exchange depths between sampled locations in the Indian River Lagoon system are therefore not due to variation in sediment physical properties.
Figure 5-1. Predictions of hydraulic conductivity using the Carmen-Kozeny equation with well-sorted clean sand at three different phi intervals. Porosity was not measured so estimated porosity ranges are plotted. This figure demonstrates that the theoretical basis on which the CK equation estimates pore throat diameters from grain size is sound.
Figure 5-2. Log/Log comparisons of the CK and modified CK equation. None of the sites tested showed any trend in agreement with the CK equation. A) CIRL39 had the least number of problems reported during testing and has the best overall agreement with the modified CK equation. B) BRL2 had the widest range in hydraulic conductivity demonstrating the limited range for both equations. C) & D) NIRL6 and NIRL24 both had numerous problems during testing which may explain some of their disagreement with either model.
Figure 5-3. Chloride profiles compared to lithology and hydraulic conductivity. None of the sites tested showed a correlation between hydraulic conductivity, lithofacies, and pore water mixing. A) CIRL39 and D) NIRL24 both have hydraulic conductivity values that drop below $10^{-14}$, yet their mixing depths are about 20cm deeper than C) NIRL6 and 40 cm deeper than B) BRL2 where hydraulic conductivity values are an order of magnitude higher.
CHAPTER 6
CONCLUSIONS

Summary

Based on textural properties, fauna, and radiocarbon dates, four major depositional environments were identified in the upper 3 m of Indian River Lagoon sediments: marine, brackish, lacustrine, and lagoonal. Pleistocene Marine facies occur above and below current sea level, surrounding and underlying the Indian River Lagoon system, and thus form the highly variable antecedent topography within which Holocene lagoonal infilling has occurred. Brackish and lacustrine facies of the Indian River lagoon can vary significantly within each site (e.g. stream channel, fan, and lacustrine). More importantly, they appear to be genetically unrelated between sites reflecting a unique relative sediment source for each site.

The transition to a lagoonal environment represents marine inundation and is identified by the presence of a coarse pebbly shell lag in an organic rich sandy matrix, likely a marsh environment. Topographic differences, radiocarbon ages, and sharp northern facies contacts suggest an initially gradual inundation of marine waters in the southern region (later than ~ 6,200 ybp. at CIRL39), followed by a more rapid inundation in the northern region (~ 3,500 ybp. at NIRL6 and NIRL24). However, with the exception of a coarse pebbly shell lag and pervasive bioturbation, the lagoonal facies do not appear to have developed a sedimentologic character that is unique to the lagoonal environment. Instead, continued localized fluvial depositional processes appear to have remained dominant.
This facies succession represents one cycle, or sequence, of marine regression followed by subsequent transgression to the current sea level high stand. Sediments supplying these depositional environments are likely the detritus of adjacent Pleistocene barrier island (Atlantic Coastal Ridge, Fig. 2-1) and lagoonal (Eastern valley, Fig. 2-1) facies that exist in close geographic and topographic proximity. The limited tidal prism of the northern Indian River Lagoon has prevented any significant redistribution of the brackish deposits as is more common in mesotidal barrier island systems. The result is a stratigraphic sequence that is not consistent with the common facies models (Fig. 1-2 & 2-2) for transgressive barrier island systems.

In order to assess the degree to which spatial variability of subsurface sediments, and their associated hydraulic conductivities, influences the pore water mixing zone (~70 cmbsf) component of SGD in the Indian River Lagoon, hydraulic conductivity first needed to be determined. Techniques developed for determination of hydraulic conductivity abound. Those utilized in this study included field measurements of horizontal hydraulic conductivity, laboratory measurements of vertical hydraulic conductivity, and the Carmen-Kozeny (CK) model for estimating hydraulic conductivity based on sediment textural data.

Modeled hydraulic conductivity values generated using the CK equation over predicted the measure values of both vertical and horizontal hydraulic conductivity by up to four orders of magnitude. The problem appears to be the model’s dependence on median grain size as the dominant parameter. A modification to the CK equation was made by adding a “mud term” to reflect the down-core variability in relative percent mud (< 63 micron, 4 phi). The result was a better fit between measured and modeled values for all of the sites tested. Deviations between measured and modeled values were present but most commonly associated with problems in the measurement procedures. While it appears the CK
equation does successfully predict the hydraulic conductivity of a well-sorted clean sand, it fails to recognize is how quickly pore throats will clog when even a small percent (< 0.05) of mud is present, particularly in fine-grained sands.

Results of this hydraulic conductivity analysis determined that there can be significant variation in hydraulic conductivity over the upper ~70 cmbsf. At site (CIRL39) hydraulic conductivity decreases by nearly two orders of magnitude at a depth of 70 cmbsf. However, when hydraulic conductivity values are compared to the water chemistry estimates of mixing depth (Martin et al., 2005), they appear to have no controlling influence.

**Future Work**

This research has provided a detailed stratigraphic interpretation of four sites across the northern ~45 km of the Indian River Lagoon barrier island complex. Results indicate that each site has had a unique relative sediment source and that depositional processes have been highly variable, ranging from apparent rapid periods of deposition to relatively quiescent periods. However, given the complex spatial distribution of the observed sedimentary facies, better correlation between sites is needed to develop a depositional model for lagoonal infilling. First, additional sediment cores should be collected in shore normal transects across both the northern Indian River Lagoon as well as the Banana River Lagoon to gain a better understanding of depositional processes occurring on the mainland and ocean sides of the lagoons. Second, a seismic survey is needed to determine the geometries of the facies interpreted in this study and aid in selection of future coring sites.

This research has also provided a modification to the Carmen-Kozeny (CK) equation that produced more accurate estimates of hydraulic conductivity from grain-size analysis at the sites tested. However, the estimates generated in this study were made by placing an empirical modifier within the solid phase portion of the CK equation. First, further work should be done to place the modifier outside of the solid phase term. Second, this modified
CK model needs further testing on additional natural samples using different collection techniques as well as laboratory prepared samples where individual variables can be tested through sensitivity analysis.
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BIOGRAPHICAL SKETCH

Kevin Hartl grew up in Newburyport, Massachusetts. He started his academic career at Northeastern University in Boston, Massachusetts, but took time off to pursue a career as a saxophonist and develop a business as a cabinet maker. Unfulfilled in these two pursuits, Kevin returned to academics and received his B.S. (Honors) in geology from the University of Florida in 2001. While finishing his undergraduate degree, Kevin accepted the position of Senior Engineer Technician for the Department of Geological Sciences. Kevin worked in this position while doing his masters research and received his M.S. in geology from the University of Florida in 2006.