A Thesis

entitled

Hydrostratigraphic Framework for the Surficial Aquifer in the Indian River Bay, Delaware Watershed

by

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Submitted to the Graduate Faculty as partial fulfillment of the requirements for

The Master of Science Degree in Geology

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December 2011
A hydrostratigraphic framework has been developed for the Indian River Bay, Delaware, watershed in support of a larger research project that will model groundwater interactions between the upland and the estuary. Four hydrostratigraphic units have been defined based on stratigraphy from high-resolution seismic surveys within Indian River Bay, supported by previously collected cores and gamma ray logs. The seismic stratigraphy is correlated with complementary marine resistivity surveys that primarily show the subsurface distribution of fresh and saline groundwater. This combined dataset is used to infer different modes of submarine groundwater discharge along the margins of Indian River Bay.

Additional geophysical surveys were conducted on land at three field sites; Holts Landing State Park, James Farm Ecological Preserve, and Fresh Pond Field Site, which are adjacent to Indian River Bay. Ground penetrating radar and electrical resistivity
transects at these sites provided the geometry of shallow stratigraphy and groundwater interactions near the estuary margins.

The hydrostratigraphic units were defined from major seismic stratigraphic surfaces and their overlying depositional units that could be traced throughout the study area. The deepest of these units is the upper Bethany Formation that is a regional confining unit and is taken as the lower boundary for the modeling effort. The next unit up, Unit II, is composed dominantly of the coarse clastic materials of the lower Beaverdam Formation; however this unit does include some beds of finer-grained sediments. Unit II has a characteristic variable signature in gamma logs, and the seismic character implies back-barrier and estuarine deposits. The base of Unit II is taken as a prominent reflecting surface found throughout the area at 15-20 m below sea level. From the data available, it is not possible to assign age to the deposits in this unit, however, they may be the uppermost Beaverdam Formation or Pleistocene deposits infilling an ancestral Indian River. Capping the entire sequence, Unit I, is composed of Holocene sediments deposited during sea level rise that fill the lowstand drainage-system valleys of Indian River and its tributaries.

Several major geologic findings were a product of the research. Evidence of multiple occupations of an ancestral Indian River valley, probably during the highstand of the middle to late Pleistocene exists within the seismic stratigraphy. Also, evidence of late Pleistocene margins of an ancestral Indian River Bay, both submerged along the flanks of the bay and beneath the land surface adjacent to the bay, are present in the seismic stratigraphy and ground penetrating radar data. There is also evidence of multiple late Pleistocene shorelines associated with the Cedar Neck and Fresh Pond ridges. These
shorelines are most likely associated with late marine isotope stage 5. The seismic stratigraphy also provided evidence of an older, inferred fluvial channel trending northwest to southeast that appears to be near the base of the Beaverdam Formation and erodes into the underlying top of the Bethany Formation.
Acknowledgements

The completion of this thesis would not have been possible without funding support from The National Science Foundation Grant EAR-0910756 and The University of Toledo, Department of Environmental Sciences.

Committee members Dr. Donald Stierman, Dr. Jamie Martin-Hayden, and Dr. Richard Becker have played a vital role in ensuring that I conduct sound quality scientific research. Without their support and mentoring it would not have been possible to complete this research.

I also would like to take this opportunity to express my gratitude towards Scott Andres of the Delaware Geological Survey. His role in providing me with existing data for this project has been a valued resource.

I would like to thank all of my friends for their help and friendship.

Dr. David Krantz cannot receive enough praise for the knowledge that he has provided while being his student. His mentoring has helped to mold me into the geologist that I am today which I am particularly proud of. I would also like to take this opportunity to thank Dr. Krantz for the opportunity to participate in his ongoing research on Assateague Island.
Table of Contents

Abstract iii

Acknowledgements vi

Table of Contents vii

List of Tables ix

List of Figures x

1 Introduction and Literature Review 1

1.1 Introduction and Objectives 1

1.2 Conceptual Models of Subsurface Discharge 8

1.3 Regional Geology 14

2 Methodology 24

2.1 Marine Chirp Seismics 24

2.2 Ground-penetrating radar 25

2.3 Electrical resistivity 26

3 Existing Data 28

3.1 Existing Marine Chirp Seismic Data 28

3.2 Existing Marine Electrical Resistivity Data 34

3.3 Existing Gamma Ray Logs 38

3.4 Existing Absolute Age Dates 39

3.5 Existing Core Data 42

3.6 Existing Ground-Penetrating Radar Data 46
# Results and Seismic Stratigraphy

4.1 Marine Chirp Seismic Results 48
4.2 Surface G 52
4.3 Surface F 55
4.4 Surface E 58
4.5 Surface D 62
4.6 Surface C 65
4.7 Surface B 68
4.8 Surface A 71
4.9 Ground-penetrating Radar Results 74
4.10 Electrical Resistivity Results 81

# Discussion

5.1 Surface G 86
5.2 Surface F 90
5.3 Surface E 96
5.4 Surface D 101
5.5 Surface C 103
5.6 Surface B 113
5.7 Surface A 115

# Hydrogeologic Units

6.1 Hydrogeologic Unit IV 117
6.2 Hydrogeologic Unit III 118
6.3 Hydrogeologic Unit II 119
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.4</td>
<td>Hydrogeologic Unit I</td>
<td>121</td>
</tr>
<tr>
<td>7</td>
<td>Paleoshorelines</td>
<td>129</td>
</tr>
<tr>
<td>8</td>
<td>Summary</td>
<td>144</td>
</tr>
<tr>
<td>9</td>
<td>Recommendations for Future Research</td>
<td>146</td>
</tr>
<tr>
<td></td>
<td>References</td>
<td>148</td>
</tr>
<tr>
<td>A</td>
<td>Gammay Ray Logs</td>
<td>159</td>
</tr>
<tr>
<td>B</td>
<td>Core Logs and Grain Size Analyses</td>
<td>176</td>
</tr>
</tbody>
</table>
List of Tables

1.1 Stratigraphic formations and groups present in Indian River Bay and Rehoboth Bay watersheds ........................................... 23

3.1 Table of wells with absolute, corrected radiocarbon ages ............ 42
List of Figures

1-1 Regional map showing location of Indian River Bay, Delaware. ............... 4
1-2 Dissolved oxygen concentration in the Inland Bays. ......................... 6
1-3 Total nitrogen concentrations in the Inland Bays. ......................... 6
1-4 Total phosphorus concentration in the Inland Bays. ......................... 7
1-5 Total nitrate + nitrite concentration in the Inland Bays. ..................... 7
1-6 Conceptual model one of groundwater-surface water interaction. ........ 8
1-7 Conceptual model two of groundwater-surface water interaction. .......... 10
1-8 Groundwater discharge modes. .................................................. 12
1-9 General stratigraphy of an infilled paleovalley. ............................ 14
1-10 General surficial geology map of Indian River and Rehoboth Bay

Watersheds. ................................................................................... 15

3-1 Seismic trackline map of Madsen & Brown 2001 data. ....................... 30
3-2 Example of Madsen & Brown 2001 seismic data. ............................. 31
3-3 Seismic trackline map of Bratton 2009 seismic data. ......................... 32
3-4 Example of Bratton 2009 seismic data. .......................................... 33
3-5 Marine resistivity trackline map of Bratton 2009 data. ...................... 35
3-6 Marine electrical resistivity, -5 m slice. ........................................ 36
3-7 Marine electrical resistivity, -10 m slice. ....................................... 37
3-8 Map of existing wells with gamma ray log data. ............................... 39
<table>
<thead>
<tr>
<th>Page</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-9</td>
<td>Map of existing boreholes with absolute age dates.</td>
</tr>
<tr>
<td>3-10</td>
<td>Map of existing core locations.</td>
</tr>
<tr>
<td>3-11</td>
<td>Map indicating the location of the Bethany Beach Core.</td>
</tr>
<tr>
<td>3-12</td>
<td>Digital elevation map with GPR transects at Fresh Pond Field Site.</td>
</tr>
<tr>
<td>4-1</td>
<td>Seismic trackline map of Krantz &amp; Banaszak 2010.</td>
</tr>
<tr>
<td>4-2</td>
<td>Example of incoherent chirp seismic data.</td>
</tr>
<tr>
<td>4-3</td>
<td>Representative example of chirp seismic data, Krantz &amp; Banaszak 2010.</td>
</tr>
<tr>
<td>4-4</td>
<td>Chirp seismic section showing Surface G.</td>
</tr>
<tr>
<td>4-5</td>
<td>Map of Krantz &amp; Banaszak 2010 seismic data with areas where Surface G has been identified.</td>
</tr>
<tr>
<td>4-6</td>
<td>Chirp seismic section showing Surface F.</td>
</tr>
<tr>
<td>4-7</td>
<td>Map of Krantz &amp; Banaszak seismic data with areas where Surface F has been identified.</td>
</tr>
<tr>
<td>4-8</td>
<td>Chirp seismic section showing Surface E.</td>
</tr>
<tr>
<td>4-9</td>
<td>Chirp seismic section showing Surface E.</td>
</tr>
<tr>
<td>4-10</td>
<td>Map of Krantz &amp; Banaszak seismic data with areas where Surface E has been identified.</td>
</tr>
<tr>
<td>4-11</td>
<td>Chirp Seismic section showing Surface D.</td>
</tr>
<tr>
<td>4-12</td>
<td>Map of Krantz &amp; Banaszak seismic data with areas where Surface D has been identified.</td>
</tr>
<tr>
<td>4-13</td>
<td>Chirp seismic section showing Surface C.</td>
</tr>
<tr>
<td>4-14</td>
<td>Map of Krantz &amp; Banaszak seismic data with areas where Surface C has been identified.</td>
</tr>
</tbody>
</table>
5-3 Gamma ray logs from wells Qh 23-03, Qh 15-06 and Qi 33-04, with interpretation of gamma increase associated with Surface G.

5-4 Map of gamma ray well log locations, area where Surface F has been identified and tracklines from Krantz & Banaszak 2010 seismic data, and the interpretation of the trend of a large fluvial channel.

5-5 Gamma ray logs from well Qi 15-03 and Qj 11-05, compared to the seismic stratigraphy of Surface F, with interpretation.

5-6 Gamma ray log from well Pi 32-03 with interpretation of the depth of Surface F.

5-7 Comparison of gamma ray logs from well Pi 32-03 and Pi 32-16 with interpretation of the gamma increase associated with Surface F.

5-8 Gamma ray logs from wells WN-1, WN-2, WN-3 and WN-4 with interpretation of gamma increase associated with Surface E.

5-9 Map of 20 m deep identified surface, with possible channel projection based on Krantz & Banaszak 2010 seismic data.

5-10 Gamma ray log from well Ph 45-03 with interpreted gamma increase associate with Surface E.

5-11 Gamma ray logs from wells Pi 53-53 and WN-2 with interpreted gamma increase associated with Surface D.

5-12 Map of Krantz & Banaszak 2010 seismic data, areas where Surface C has been identified and labels for seismic lines IRB-8b.1, IRB-8a.6, IRB-8a.5, and IRB-8a.2.

5-13 Seismic line IRB-8a.2 with interpretation.
<table>
<thead>
<tr>
<th>Page</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-14</td>
<td>Seismic line IRB-8a.5 with interpretation.</td>
</tr>
<tr>
<td>5-15</td>
<td>Seismic line IRB-8a.6 with interpretation.</td>
</tr>
<tr>
<td>5-16</td>
<td>Seismic line IRB-8b.1 with interpretation.</td>
</tr>
<tr>
<td>5-17</td>
<td>Map of GPR transects at Holts Landing State Park, with sections where flanks of a Pleistocene bay are identified.</td>
</tr>
<tr>
<td>5-18</td>
<td>GPR transect HL-05 showing possible margin of a Pleistocene bay.</td>
</tr>
<tr>
<td>5-19</td>
<td>GPR transect HL-01 showing possible margin of a Pleistocene bay.</td>
</tr>
<tr>
<td>5-20</td>
<td>Graph of sea level relative to modern sea level over the past 200,000 years.</td>
</tr>
<tr>
<td>5-21</td>
<td>Reconstruction of the ancestral Indian River paleo-drainage system.</td>
</tr>
<tr>
<td>6-1</td>
<td>Gamma ray log from well WN-1 with stratigraphic formations assigned, interpretation of hydrogeologic units and interpretation of gamma log lithologies.</td>
</tr>
<tr>
<td>6-2</td>
<td>Map showing approximate position of paleovalleys and influves at Holts Landing State Park.</td>
</tr>
<tr>
<td>6-3</td>
<td>Two individual seismic sections viewed from Holts Landing State Park.</td>
</tr>
<tr>
<td>6-4</td>
<td>Onland electrical resistivity pseudosection from Holts Landing State Park with interpretation.</td>
</tr>
<tr>
<td>6-5</td>
<td>-10 m marine electrical resistivity slice.</td>
</tr>
<tr>
<td>6-6</td>
<td>-5 m marine electrical resistivity slice.</td>
</tr>
<tr>
<td>6-7</td>
<td>Digital elevation map with Holocene paleovalleys identified, and areas of different groundwater discharge modes identified.</td>
</tr>
</tbody>
</table>
7-1 Digital elevation map with paleoshorelines, a flood tidal delta, major geomorphic boundary, and well locations of existing absolute age dates identified. .......................................................... 130

7-2 Digital elevation map of GPR transects at James Farm Ecological Preserve. .......................................................... 133

7-3a GPR transect JF-12 with interpretation. ................................. 134

7-3b GPR transect JF-12 without interpretation. ............................ 135

7-4 Model of the emplacement of a single barrier shoreline. .............. 137

7-5 Model of the emplacement of a second barrier shoreline where there is an existing barrier shoreline. .................................................. 139

7-6 Graph of sea level relative to modern sea level over the past 200,000 years. .......................................................... 141

7-7 A relative sea level surve for the time during the emplacement of barrier shorelines at James Farm Ecological Preserve and Fresh Pond Field site. 142

7-8 Cross-section view of paleoshorelines identified at James Farm and Fresh Pond Field Sites. .................................................. 143

A-1 Map of existing wells with gamma ray logs. ............................. 158

B-1 Map of existing corehole locations off White Neck. ................. 175
Chapter 1

Introduction and Literature Review

1.1 Introduction and Objectives

The Delaware Inland Bays, which include Indian River Bay, Rehoboth Bay and Little Assawoman Bay, are a treasured resource along the Delmarva (Delaware, Maryland, and Virginia) coastline. They are vital because of their influence on local economies due to their recreational worth and are considered significant because of their distinctive biologically diverse habitats. These habitats are supported through an intricate coastal hydrologic and hydrogeologic system. Persistent human development in the coastal zone has added many stressors to both the hydrologic systems and the marine ecosystems. Specifically, nutrient inputs to these systems from anthropogenic sources, mainly septic systems and agriculture, has led to the eutrophication of coastal inland bays (Howarth & Marino 2006). Eutrophication is defined as a water body acquiring an exceptionally high concentration of nutrients, predominantly phosphates and nitrates (Art 1993). This process has adverse effects on coastal marine ecosystems. With eutrophication, dissolved oxygen levels diminish consequently making it difficult for
biota such as clams and fish to survive. Eutrophication also leads to the loss of sea grass habitat. The decrease in the dissolved oxygen levels can be attributed to the ecosystem shifting from a primarily macroalgal producing system to a phytoplankton-dominated producing system (Short et al. 1996; Hauxwell et al. 2003).

While many of the previous studies provide the general framework for understanding the geology and hydrogeology, there are many details that require further investigation. The objectives of this research are three-fold. This research seeks to provide the geometry and distribution of Holocene sediments in the bay, specifically the distribution of Holocene paleovalleys. Secondly, this research will provide more details on the stratigraphy of Pleistocene through Pliocene interglacial deposits of Indian River Bay in the context of hydrogeologic setting. The third and final objective of the study is to determine relationships between on-land geomorphology and its effect on the stratigraphy beneath Indian River Bay.

Intuitively one would think that the main pathway for nutrients into a coastal system in primarily from riverine inputs. Although this is an important contributor, it has been shown that submarine groundwater discharge of fresh water in a coastal hydrologic system is a noteworthy pathway for these nutrients (e.g., Johannes 1980; Moore 1999; Burnett et al. 2006). Previous estimates of submarine groundwater discharge have been relatively small when compared to riverine inputs. Recently though, submarine groundwater discharge has been estimated to contribute up to 40% or more of the flow in certain areas (Moore 1996). The effects of a combination of high dissolved nutrient concentrations and substantial submarine groundwater discharge (SGD) has been
witnessed worldwide and have been shown to be destructive to coastal ecosystems (e.g., Slomp and Van Cappellen, 2004; Kemp et al., 2005; Fisher et al., 2006).

The study site (Figure 1-1), Indian River Bay, Delaware, was determined to be a good candidate for further investigation on nutrient loading via SGD for several reasons. The primary reason is because it is a characteristic coastal bay on the Delmarva Peninsula. Another important aspect of the study site is that nutrient loading via submarine groundwater discharge has been identified as a primary contributor to the severe eutrophication in the bay (Roy F. Weston 1994). Previous studies conducted at Indian River Bay, Delaware indicated active submarine groundwater discharge which is controlled by geological heterogeneities that are present in the bay (Bohlke & Krantz 2003; Bratton et al. 2004; Krantz et al. 2004; Manheim et al. 2004). The final reason that Indian River Bay is a likely candidate is its commonality of anthropogenic induced nutrient loading, geology, and hydrology with other estuarine systems across the eastern United States of America.
Figure 1-1: Regional map showing location of Indian River Bay, Delaware on the Delmarva Peninsula.
Water quality monitoring in Indian River Bay has been an ongoing process with many different agencies and groups involved. In December of 1998, the Delaware Department of Natural Resources and Environmental Control (DNREC), Division of Water Resources, Watershed Assessment Section, released a report that provided details on the water quality in Indian River, Indian River Bay, and neighboring Rehoboth Bay. This report provided the most recent evaluation of the bay’s water quality. The results from the water quality assessment report were used to create total daily maximum load (TDML) standards for nutrient levels as well as target dissolved oxygen levels, as required by the U.S. Environmental Protection Agency. This report was also vital in generating a remediation plan for the afflicted waters. As indicated by the following graphs (Figures 1-2 through 1-5), nutrient over-enrichment and violation of water quality standards are prevalent in the area. The data was collected from 1995 through 1997 for the study. Summary statistics as well as water quality standards and targets are shown in these figures.
Figure 1-2: Dissolved oxygen concentrations in the Inland Bays (1995-1997).

Figure 1-3: Total nitrogen concentrations in the Inland Bays (1995-1997).
**Figure 1-4**: Total phosphorus concentrations in the Inland Bays (1995-1997).

**Figure 1-5**: Total nitrate + nitrite concentration in the Inland Bays (1995-1997).
1.2 Conceptual Models of Subsurface Discharge

Two conceptual models have been developed to illustrate the current state of SGD in Indian River Bay. Model one (Figure 1-6) presents an aquifer that possesses geologic homogeneity as well as hydraulic properties that are consistent throughout.

![Figure 1-6: Conceptual model of groundwater-surface water interaction and salinity distribution in a theoretical cross-section of a coastal aquifer with homogeneous hydraulic parameters. Process 1 is freshwater flow driven by the hydraulic gradient. Process 2 is dispersion-induced saltwater circulation. Process 3 is seasonal exchange. Process 4 is nearshore circulation due to tides and waves, and process 5 is offshore saline exchange driven by tides and waves. Theoretical cross-section with homogeneous hydraulic parameters. (Modified from Michael et al. 2009.)](image)

Process 1 in Figure 1-6 depicts fresh groundwater flow into the bay that is driven by on-shore hydraulic gradients. The hydraulic gradient can oscillate in response to changes in recharge and groundwater extraction further inland. Process 2 (Figure 1-6) depicts saltwater circulation along the interface between saltwater and freshwater. The interaction between the contrasting waters is attributed to the density gradient that is
created by the two fluids when they come in contact with one another (Cooper 1959; Kohout 1960). Diffusion and mixing between the fresh and saline waters creates a zone of brackish water that is more buoyant than the saline end member. Seasonal changes in the water table can affect the position of the freshwater-saltwater interface, moving it either seaward or landward (Michael et al. 2005). This process is depicted in process 3 (Figure 1-6). When considering tidal and wave action in the system, two modes of freshwater-saltwater exchange exist. Nearshore circulation as depicted in process 4 (Figure 1-6) is driven by run-up and infiltration on the beachface (Li and Barry 2000; Michael et al. 2005; Robinson et al. 2007a). In response to the effect of waves and tides, pressure changes in the water column offshore can create some amount of freshwater-saltwater exchange as shown in process 5 (Figure 1-6) (Reidl et al. 1972; Paulsen et al. 2004). This model can aid in the understanding of freshwater-saltwater exchange, but typically salinity distribution in a system is more complex due to geological heterogeneity and varying hydraulic properties in the hydrologic system.

Models often predict a salinity distribution like that shown in Figure 1-6, but observations from geophysical measurements both onland and offshore depict a much more complex salinity distribution. These observations indicate the occurrence of freshened groundwater underneath shallow saline groundwater. This phenomenon has been observed at several locations along the U.S. East Coast such as Waquoit Bay, Massachusetts (Belaval 2003), the Neuse River Estuary, North Carolina (Cross et al. 2006), Corsica River Estuary, Maryland (Bratton et al. 2008) and at the primary field site for this study, Indian River Bay, Delaware (Manheim et al. 2004).
The second model (Figure 1-7) presents an aquifer that possesses geologic heterogeneity with dissimilar hydraulic properties than the previous model (Figure 1-6).

Figure 1-7: Hypothetical cross-section of coastal aquifer of varying hydraulic properties and with low-permeability layer at the sea floor representing geologic heterogeneity. Diffuse and focused fresh discharge modes are depicted as processes 1a and 1b, respectively. Conceptual model of groundwater-surface water interaction and salinity distribution in coastal aquifers. Process 1 is freshwater flow driven by the hydraulic gradient. Process 2 is dispersion-induced saltwater circulation. Process 3 is seasonal exchange. Process 4 is nearshore circulation due to tides and waves and process 5 is offshore saline exchange driven by tides and waves. (Modified from Michael et al. 2009.)

One of the primary dissimilarities in the second model is the existence of an unstable density configuration that is caused by shallow saline groundwater overlying freshened groundwater. This anomaly has been identified by offshore and onshore geophysical measurements in Indian River Bay (Manheim et al. 2004). Geologic heterogeneity is responsible for this unique density configuration. Low-permeability
geologic units can create a shallow semi-confining layer that inhibits downward flow of the saltwater and allows freshwater to discharge farther offshore (Bratton, 2007). This stratigraphic package has been interpreted as a filled incised valley in many cases (Mulligan et al. 2006), and is likely responsible for the unstable “salt-fingering” phenomena (Simmons et al. 2001). The temporal, and tidal/wave considerations that are represented in model one still exist in the second model (processes 3-5, Figure 1-7). Another primary difference in the two models is the contrast between diffuse and focused discharge (processes 1a and 1b, Figure 1-7).

The more complex mixing zone and salinity distribution, and varying groundwater flow paths will consequentially make water quality more variable in the bay, particularly the nutrient species of nitrogen. Nitrate ($\text{NO}_3^-$) is a common nutrient that occurs in shallow fresh groundwater and is commonly transported to the bay. As the nitrate makes its way along the flowpath, it is likely that microbial denitrification occurs as it encounters organic substrates (Bratton et al. 2004). When the denitrification occurs, the nitrate is converted into relatively inert nitrogen gas ($\text{N}_2$). The denitrification process can also occur in the mixing zone between oxic fresh groundwater and anoxic saline groundwater. This limits the total amount of nitrate in submarine groundwater discharge (Bratton et al. 2004). Therefore to properly understand the loading of nutrients into the bay, the complexities of the saline distribution and submarine groundwater discharge must also be well understood.

Three predicted modes of groundwater discharge exist for the bay. Figure 1-8A indicates a focused discharge occurring directly along the shoreline generally within meters or a few tens of meters. Figure 1-8B represents the combination of focused and
diffuse discharge that is controlled by a low permeability surface that extends out from the shoreline into the bay. The third schematic, Figure 1-8C, depicts a focused and diffused discharge that is highly irregular. This is the groundwater discharge mode that is controlled by the spatial distribution of infilled paleovalleys. All three groundwater discharge modes appear to exist at Indian River Bay, Delaware.

**GROUNDWATER DISCHARGE MODES**

![Diagram](image)

- **A** Focused groundwater discharge directly at shoreline
- **B** Focused and Diffuse groundwater discharge, shore parallel (Shallow low permeability controlled)
- **C** Focused and Diffuse Irregular groundwater discharge (Paleochannel-controlled)

*Figure 1-8*: Diagram indicating submarine groundwater discharge modes into an idealized bay. A) Focused discharge directly along the shoreline. B) Focused nearshore discharge and diffuse offshore discharge. C) Combine discharge modes in an irregular pattern, paleochannel controlled. (Modified from Michael et al. 2009.)

Sea-level rise and fall has been a key component in determining the stratigraphy of Indian River Bay, Delaware. It has been shown through geophysical and coring studies that many of the Delmarva Peninsula’s bays are overlying ancestral river systems.
(Belknap et al. 1994; Kerhin et al. 1999). The lowstand incised valley of Indian River lies beneath Indian River Bay which many tributaries flowed into during the sea-level lowstand of the last glaciation, 18-20,000 years ago (Chrzastowski 1986). The thalweg of the ancestral Indian River is approximately 15 m deep in the center of Indian River Bay, and deepens to approximately 28 m toward the east oceanward where it passes beneath the modern day barrier island (Kraft 1971; John 1977; Chrzastowski 1986). The large tributaries of the system have incised valleys that are 5 to 8 m deep, and other tributaries to the system are approximately 2 to 3 m deep (Krantz et al. 2004). As the Holocene sea-level rise ensued, fine-grained and organic-rich sediments infilled the paleovalley (Krantz et al. 2004). The general stratigraphy of a paleovalley, Figure 1-8, is comprised of a thin bed of fluvial sand that is overlain by basal peats, which are interpreted as being swamp or tidal marsh sediments. Fine sand and silts then cap the stratigraphy (Mixon 1985; Belknap et al. 1994). This sediment package and geological environment creates a favored pathway for groundwater flow into the bay (Krantz et al. 2004).
Figure 1.9: General stratigraphy of an infilled Holocene paleovalley, consisting of a thin fluvial sand layer at the base, overlain by basal peats, overlain by fine grained sand and silts.

1.3 Regional Geology

The regional stratigraphy and hydrogeologic setting have also been primarily controlled by the rises and falls of sea level. Multiple studies conducted by the Delaware Geological Survey and other individuals have produced a general stratigraphic sequence for the Indian River Bay watershed (Jordan 1974; Johnston 1976; Hodges 1983; Andres 1986a, 1986b; Talley 1987; Benson 1990; Groot et al. 1990; Ramsey 1999; Miller et al. 2003; Ramsey 2010). Ramsey (2010) provides the most recent map of the surficial geology of Indian River Bay watershed (Figure 1-10).
Figure 1-10: General surficial geology map of Indian River and Rehoboth Bay watersheds. (Modified from Ramsey 2010.)
Modern swamp/marsh deposits are some of the youngest units in the watershed. These sediments are characterized by organic-rich silts and silty sands, and generally have a low permeability. This unit is identified in Table 1.1 by the Roman numeral I.

Active beach/barrier island sediments are also some of the youngest sediments identified on the map. These sediments are typically characterized by a variety of sands and gravels as well as overwash and backbarrier deposits. These sediments are typically highly permeable. This unit is identified in Table 1.1 by the Roman numeral II.

The next youngest unit present in the watershed is the Cypress Swamp Formation. This formation was first officially recognized by Andres and Howard (2000). The unit is thought to be late Pleistocene to Holocene in age based on its stratigraphic position. The primary characteristic of the unit is its distinct alternating beds of light colored fine sand and darker colored organic-rich silts (Andres and Howard 2000). The silts in the Cypress Swamp Formation are typically found to have plant material present in them (Andres and Howard 2000). The depositional environment for the unit ranges from fresh-water, cold-climate marsh and boreal forest, to fresh-water temperate climate and forested swamp and bog. Stratigraphically, the Cypress Swamp Formation overlies the middle Pleistocene aged Omar Formation, or where the Omar Formation is not present, it overlies the late Pliocene aged Beaverdam Formation. The Cypress Swamp Formation varies greatly in thickness but has been shown to be approximately 3 m thick in the region (Andres and Howard 2000). This unit is identified in Table 1.1 by the Roman numeral III.

The next series of formations, the Ironshire Formation, Sinepuxent Formation, and Omar Formation, are contained within the Assawoman Bay Group. The terminology
of the Assawoman Bay Group is best used when it is difficult to differentiate which formation is present at a given location. The Assawoman Bay Group was first defined by Ramsey (2010) and is identified on Table 1.1 by the Roman numeral IV. Generally the group consists of primarily well-sorted sands, silts and clays. The sediments are part of a transgressive package that was deposited on the ancestral Atlantic coast during the middle to late Pleistocene sea-level highstands (Ramsey 2010). The youngest unit of the Assawoman Bay Group is the Sinepuxent Formation.

The Sinepuxent Formation is identified in Table 1.1 by the Roman numeral V. Its age is estimated at 80,000 years B.P. or late marine-isotope stage (MIS) 5, based on amino acid age racemization dates (Ramsey 2010). The Sinepuxent Formation was first described by Owens and Denny (1979a). This unit is the most discrete of the group. Lithologically the formation consists of laminated gray, silty to very fine, quartzose sand to sandy silt. At the base of the unit a bluish-gray to dark gray clayey-silt to silty clay is typical (Ramsey 2010). The presence of shell layers has also been noted at localities in the Bethany Beach area (McDonald 1981; McLaughlin et al. 2008). The unit has also been described as lithologically distinct because of its abundance of micaceous minerals (Ramsey 2010). The thickness of the Sinepuxent Formation is highly variable but can be upwards of 12 m thick. The depositional environment of the Sinepuxent Formation is a quiet, warm-water lagoon to a near shore depositional environment (Owens and Denny 1979a; McLaughlin et al. 2008). Stratigraphically the Sinepuxent Formation can overlie the Ironshire Formation, Omar Formation, or the Beaverdam Formation, depending upon the existence of those formations in the area. The contact between these units and the
Sinepuxent Formation is easily identifiable based on the unconformity that is present and also the distinctive micaceous sands of the Sinepuxent Formation.

The medial unit of the Assawoman Bay Group is the Ironshire Formation. The Ironshire Formation is identified in Table 1.1 by the Roman numeral VI. Based upon the stratigraphic position of the unit, it is hypothesized that the unit was deposited approximately 120,000 years B.P. or early marine isotope stage (MIS) 5 (Ramsey 2010). This unit consists primarily of beach, near shore, and lagoonal deposits. Owens and Denny (1979) originally described the Ironshire Formation as pale-yellow to white, well-sorted medium sand. The unit also is characterized by long, low-angle, inclined beds with laminae of black minerals. In the upper portions of the unit, trough cross-stratification of well-sorted sand with some granules and pebbles is present. Stratigraphically the Ironshire Formation unconformably overlies the Omar Formation, or the Beaverdam Formation in areas where the Omar Formation is not present. This can cause some confusion among geologists because the contact between the Ironshire Formation and the Omar Formation is not always clear but it has been noted by Ramsey (2010) that a coarse sand or pebbly layer may mark the boundary between the two, but it is not always present. The contact between the Ironshire Formation and the Beaverdam Formation is much clearer and is easily identifiable by the contrast between the well-sorted sands of the Ironshire Formation and the silty sands of the Beaverdam Formation. The Ironshire Formation varies greatly in thickness but rarely exceeds 6 m thick.

The oldest formation of the Assawoman Bay Group is the middle Pleistocene Omar Formation, ranging from 400,000 to 325,000 years B.P. based on amino acid age racemization dates (Ramsey 2010) and is identified in Table 1.1 by the Roman numeral
VII. This unit was first described by Jordan (1962). This unit consists of swamp and near shore deposits that fill and overtop a west to east trending paleovalley that is south of the primary field site for this investigation (Owens and Denny 1979a). The lithology of the Omar Formation is primarily interbedded gray to dark gray quartz sands and silts. There are also lenses of coarse sand and gravel interspersed throughout the unit. Organic-rich horizons with stumps and logs of cypress trees are also found within the Omar Formation (Ramsey 2010). The lower unconformable contact between the Omar Formation and Pliocene Beaverdam Formation is recognized by the relatively cleaner sands and gravels of the Omar Formation overlying the clayey gray silts of the Beaverdam Formation. The thickness of the Omar Formation is highly variable and can be upwards of 25 m thick in areas of infilled paleovalleys (Ramsey 2010).

The Delaware Bay Group consisting of the Scotts Corner Formation and Lynch Heights Formation was first recognized by Ramsey (1997). The Delaware Bay Group is identified by the Roman numeral VIII in Table 1.1. This group ranges in age from middle to late Pleistocene (400,000-800,000 years B.P.) (Ramsey 2010). This package of sediments is interpreted as being transgressive deposits that were laid down along the margins of the ancestral Delaware Bay estuaries. Typical depositional environments present in the Delaware Bay Group are stream, swamp, marsh, estuarine, barrier and beach, tidal flat, lagoonal and shallow offshore estuarine environments (Ramsey 1997).

The youngest formation in the Delaware Bay Group is the Scotts Corner Formation. The Scotts Corner Formation is identified in Table 1.1 by the Roman numeral IX. The age of the Scotts Corner Formation is interpreted to be late Pleistocene (120,000 – 80,000 years B.P. or MIS 5) based on its stratigraphic position (Ramsey 2010). This
The Lynch Heights Formation is the oldest unit of Delaware Bay Group. This unit is identified in Table 1.1 by the Roman numeral X. It is presumed to be middle Pleistocene (400,000 to 330,000 years B.P., probable MIS 9 equivalent) based upon its stratigraphic position. The unit was first described by Ramsey (1997). This formation consists of two primary sea-level highstand deposits that are referred to as the older and younger Lynch Heights Formation (Ramsey 1997). Lithologically the unit is described as consisting of light-yellowish and light reddish-brown to gray, medium quartz sand. Discontinuous beds of fine to very fine silty sand, clayey silt and organic rich silt are also present (Ramsey 2010). These deposits indicate depositional environments of stream, marsh, estuarine barrier and beach, tidal flat, lagoonal and shallow offshore estuarine (Ramsey 1997). In southern Delaware, the Lynch Heights Formation unconformably overlies the Beaverdam Formation. This boundary is distinguishable by the bed of pebbly
sand or gravel at the base of the Lynch Heights Formation (Ramsey 2010). The maximum thickness of the Lynch Heights Formation is approximately 15 m (Ramsey 2007).

The late Pliocene aged Beaverdam Formation is the oldest unit present in the surficial geology of Indian River Bay Watershed (Groot et al. 1990) and is identified in Table 1.1 by the Roman numeral XI. This unit was first described as early as 1955 by Rasmussen and Slaughter, but was not officially accepted as a geological formation in Delaware until 1962 (Jordan 1962). The lithology of the Beaverdam Formation is heterogeneous, ranging from very coarse feldspathic sands with pebbles to silty clay. Laminations of this consistency are common throughout the unit (Jordan 1962, 1974; Andres and Ramsey 1995, 1996; Ramsey 2001, 2005, 2010; Andres and Klinbeil 2006). The sands of the Beaverdam Formation have a white silty-clay matrix. A fining upward pattern is also typical of the formation, which is indicative of a transitional depositional environment from fluvial lower delta plain to more estuarine (Owens and Denny 1979a; Ramsey 1992, 2007; Millet et al. 2003). The Beaverdam Formation overlies the late Miocene to early Pliocene Bethany Formation in the field area. The Beaverdam Formation can be overlain by any of the before-mentioned Pleistocene interglacial deposits. The contact between the Beaverdam Formation and the Bethany Formation is easily identifiable by the distinct erosional surface and coarse clastic sediments at the contact. The thickness of the Beaverdam Formation is highly variable, but in the field area it is approximately 23 to 25 m thick (Miller et al. 2003).

The subsurface stratigraphy of Indian River Bay watershed can continue from the discussion of the surficial geology. The oldest unit present at the surface in Indian River
Bay Watershed is the Pliocene aged Beaverdam Formation. Underlying the Beaverdam Formation is the late Miocene to early Pliocene aged Bethany Formation (Owens and Denny 1979a; Benson 1990; Miller et al. 2003). This unit is identified in Table 1.1 by the Roman numeral XII. Andres (1986b) originally described the Bethany Formation but it was not formalized as an acceptable unit in Delaware until 2004 (Andres 2004) with supporting work from Miller et al. (2003). This unit creates the first regional confining layer in the field area. The Bethany Formation consists of marine silts at the top of the unit with some discontinuous lenses of sand interspersed within the unit, creating confined aquifers (Krantz et al. 2004). It has been shown that there is little or no geochemical interaction between the groundwater within the Bethany Formation and the overlying Beaverdam Formation (Hodges 1983; Denver 1986). For this reason, the top of the Bethany Formation is considered the lower boundary for this hydrostratigraphic study.

The surficial unconfined aquifer in much of Delaware is the Columbia Aquifer. In the field area, this aquifer consists of the Pliocene aged Beaverdam Formation up through the stratigraphic sequence to the Holocene/modern sediments. Beneath the Columbia Aquifer is the first confined aquifer, the Pocomoke Aquifer. This hydrologic unit consists only of the Bethany Formation. This unit will be identified in the study but is beyond the scope of the hydrostratigraphic aspect of the study.
Table 1.1: Table of stratigraphic formations and groups present in Indian River Bay and Rehoboth Bay Watersheds, with their assigned ages and aquifer designation (Ramsey 2010).

<table>
<thead>
<tr>
<th>ID</th>
<th>Unit</th>
<th>Age</th>
<th>Aquifer</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Marsh Holocene</td>
<td></td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>Active Beach/Barrier Island</td>
<td>Holocene</td>
<td>Columbia</td>
</tr>
<tr>
<td>III</td>
<td>Cypress Swamp Formation (Qcs)</td>
<td>Holocene – Late Pleistocene</td>
<td>Aquifer</td>
</tr>
<tr>
<td>IV</td>
<td>Assawoman Bay Group</td>
<td>Middle – Late Pleistocene</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>Sinepuxent Formation (Qsi)</td>
<td>Late Pleistocene</td>
<td></td>
</tr>
<tr>
<td>VI</td>
<td>Ironshire Formation (Qi)</td>
<td>Late Pleistocene</td>
<td></td>
</tr>
<tr>
<td>VII</td>
<td>Omar Formation (Qo)</td>
<td>Middle – Late Pleistocene</td>
<td></td>
</tr>
<tr>
<td>VIII</td>
<td>Delaware Bay Group</td>
<td>Middle – Late Pleistocene</td>
<td></td>
</tr>
<tr>
<td>IX</td>
<td>Scotts Corner Formation (Qsc)</td>
<td>Late Pleistocene</td>
<td></td>
</tr>
<tr>
<td>X</td>
<td>Lynch Heights Formation (Qlh)</td>
<td>Middle Pleistocene</td>
<td></td>
</tr>
<tr>
<td>XI</td>
<td>Beaverdam Formation</td>
<td>Early Pleistocene – Late Pliocene</td>
<td></td>
</tr>
<tr>
<td>XII</td>
<td>Bethany Formation</td>
<td>Late Miocene – Early Pliocene</td>
<td>Pocomoke</td>
</tr>
</tbody>
</table>

Columbia Aquifer

Pocomoke Aquifer
Chapter 2

Methodology

To obtain information on the subsurface stratigraphy and groundwater flow multiple geophysical techniques were employed. These techniques included; marine chirp seismics, ground-penetrating radar, and electrical resistivity. In addition to the newly collected data, multiple existing data sets from previous studies were available for use. These data sets included existing marine chirp seismic data, marine electrical resistivity data, gamma ray logs, absolute age dates, cores and ground-penetrating radar data.

2.1 Marine Chirp Seismics

Approximately 50 kilometers of seismic reflection data was collected throughout Indian River Bay, Delaware during the summer of 2010. An EdgeTech 512i sub-bottom profiler in conjunction with an X-STAR topside data acquisition system was utilized for the survey. A swept-frequency pulse ranging from 500 Hz to 4.5 kHz with a 50 millisecond pulse length was used for most lines in the survey. The towfish was suspended from a raft with inflatable pontoons to make it possible to survey in shallow areas of the bay. Navigation data was collected using a Lowrance LMS-334 iGPS in real
time and integrated with the seismic data. The maximum speed while surveying was approximately 2.5 knots. This relatively low speed was necessary because of the effects on the seismic signal of a thin water column between the towfish and bottom.

Data collection focused on areas of the bay that would allow for good quality seismic profiles. Areas that would produce methane gas and wipe out the signal were avoided. Also, weather and water depth at the time of the survey were controlling factors in determining what areas could be surveyed.

Processing of the seismic data was done using the Discover software. Individual seismic profiles were exported as JPG files. All files were exported with a maximum depth of 45 m. A standard velocity of 1500 m/s for water-saturated, unconsolidated sediments was used to convert two-way travel time to depth (in m). The JPG images were then used to print out individual sections and interpreted. Notable surfaces were identified in the seismic data set and were used as upper and lower boundaries of seismic stratigraphic units. The notable surfaces were also correlated with lithologic boundaries in four cores that were collected previously in Indian River Bay by other scientists (Krantz et al. 2004). To expand the area of the seismic boundaries to areas where cores were not collected and seismic data was not collected, a correlation based upon borehole geophysics, mainly natural gamma, was used.

2.2 Ground-penetrating radar

Ground penetrating radar (GPR) and electrical resistivity were the two geophysical methods that were utilized on land during this investigation. A Sensors & Software Pulse EKKO 100 with a 100 MHz transmitter in conjunction with the Pulse
EKKO 100 data acquisition software was used at two field sites, Holts Landing Field Site and James Farm Field Site to collect a total of 3000 m of GPR data. Two antenna frequencies were chosen, 50 MHz and 100 MHz. Most data was collected using the 100 MHz antennas due to their overall ability to penetrate to approximately 8 m while still providing good vertical resolution and detail of sedimentary structures and stratigraphy. GPR survey areas were chosen based on two factors. Areas that have salt water and fine grained material at the surface were avoided because GPR cannot penetrate those two media (Jol et al. 1995). Another factor that was considered when choosing targets was the importance of the stratigraphy at a target to understand the geomorphic history of the field site. In the lab, the computer program EKKO View was used to create JPG image files of the 2-D GPR sections. The JPG files were imported into CorelDraw and cropped to manageable lengths and edited to make depths and time more legible.

2.3 Electrical Resistivity

Electrical resistivity data was collected using an Advanced Geosciences, Incorporated (AGI), SuperSting R1/IP with the Swift Dual Mode Automatic 28-electrode cable and automatic switchbox. Two arrays were used when collecting data, the dipole-dipole method and automatic Schlumberger method. Three electrode spacings were used, three meters, five meters, and ten meters. A smaller electrode spacing, for instance three meters, allows for data to be acquired to a depth of approximately 16 m. As the electrode spacing is increased, the depth of penetration increases but detail of subsurface changes is sacrificed. Ten meter electrode spacing yields a penetration depth of over 50 m but relatively poor vertical resolution. The automatic Schlumberger method was found to be the array which yielded the most consistently acceptable results. In areas that had an
excessive amount of dry sand at the surface, the standard 45 c stainless steel electrode was not used because of the lack of conductance between dry sand and the electrode. To achieve better electrical connection between the sediment and the electrode, 122 cm long pieces of reinforcement bar were used in place of the standard electrode. Holes were either drilled using a soil auger or dug to a depth of approximately, a meter then the reinforcement bar was pounded into the ground. This was done to reach a depth where moist/damp sand existed. The non-standard electrode was connected to the multi-electrode cable using single strand 14 gauge electricians wire. This non-traditional method of electrical resistivity surveying did not compromise the results.

Electrical resistivity surveys were conducted at two field sites, Holts Landing Field Site and James Farm Field Site, collecting a total of 1500 m of electrical resistivity data. In the lab, the electrical resistivity data files were read from the SuperSting R1/IP using the Advanced Geosciences, Inc. SuperSting Administrator Version 1.3.2.160. The files were imported into AGI EarthImager 2D inversion and modeling software. Standard settings were used when running the iterations. A maximum of six iterations was allowed during data processing. To ensure that only quality data was interpreted, a maximum root mean square (RMS) error of 20% and an L2 value of less than 10 were the minimum requirements to be considered valid data. In areas where the geologic setting was relatively consistent, a color to ohm-meter template was created based on the resultant resistivity and used for all pseudosections to maintain a standard color to ohm-m scale. Upon completion of data processing in EarthImager 2D, the images of the inverted pseudosections were exported as JPG image files at the highest quality available.
Chapter 3

Existing Data

Multiple data sets were available from previous studies that were conducted on Indian River Bay, Delaware and the surrounding area. The data sets included marine chirp seismic data, marine electrical resistivity data, gamma ray logs, absolute age dates, cores, and ground-penetrating radar.

3.1 Existing Marine Chirp Seismic Data

Two chirp seismic data sets were collected previously in Indian River Bay. The earliest data set was collected in 2001 by Dr. John Madsen and Lyndon Brown, from the University of Delaware, in support of Ph.D. student Lyndon Brown’s dissertation research (Brown 2006). The seismic data covered approximately 14 km (Figure 3-1). The system used was an EdgeTech 216 sub-bottom profiler with a pulse bandwidth of 4-12 KHz and a 2 ms pulse. A typical seismic section from the data set has maximum depth of penetration 15 m, but many of the coherent reflections were within the upper 10 m (Figure 3-2). The general quality of the data was low, with methane gas wipe out
dominating much of the dataset, and was consulted only to confirm existing interpretations.

The second seismic data set was collected in the fall of 2009 by Dr. John Bratton, United States Geological Survey. The seismic data covered approximately 33 km (Figure 3-3). The system used was an EdgeTech 424 chirp sub-bottom profiler with a pulse bandwidth of 4-24 kHz and a 2 ms pulse. A typical seismic section from the data set has maximum depth of penetration of 5 m (Figure 3-4). The quality of the data was generally low with methane gas wipe out dominating over 50% of the data. This data was used to aid in interpretation of the western part of the field area where no new data was collected.
Figure 3-1: Seismic trackline map of Madsen & Brown 2001 chirp seismic data.
Figure 3-2: Example of Madsen & Brown 2001 chirp seismic data showing coherent reflections to a depth of approximately 10 m
Figure 3-3: Seismic trackline map of Bratton 2009 chirp seismic data.
Figure 3-4: Example of Bratton 2009 chirp seismic data showing coherent reflections to a depth of approximately 5 m.
3.2 Existing Marine Electrical Resistivity Data

One hundred and fifty-four kilometers of marine electrical resistivity data was available to aid in interpretation for this project. The data was collected in fall of 2009 by Dr. John Bratton, United States Geological Survey. The tracklines covered most of the bay, with dense coverage in the area offshore of Holts Landing State Park (Figure 3-5). The system used was an Advanced Geosciences, Inc. SuperSting Marine R8/I with a 50 m streamer and 5 m spacing of electrodes. The maximum depth of penetration is unknown. During processing two map view layers were created at -5 m BMSL and -10 m BMSL. The overall quality of the data is very good.

The -5 m BMSL layer (Figure 3-6) indicates high resistivity, 7-9 ohm-m, values directly offshore at Holts Landing State Park. There is a transition into lower resistivity values towards the north. The eastern side of the image indicates relatively low resistivity, 1-3 ohm-m, values directly offshore. There is an area of higher resistivity, 7-9 ohm-m, values farther out in the bay than all of the rest.

The -10 m BMSL layer, Figure 3-7, indicates higher resistivity values, 7-9 ohm-m, directly offshore at Holts Landing State Park. There is a transition into lower resistivity values towards the north. The eastern side of the image indicates relatively low resistivity values, 1-3 ohm-m, directly offshore. There is an area of higher resistivity values, 7-9 ohm-m, farther out in the bay than to the east.
Figure 3-5: Marine resistivity trackline map of Bratton 2009 resistivity data.
Figure 3-6: Marine electrical resistivity, -5 m slice, indicating higher resistivity values offshore at Holts Landing State Park, transitioning into lower resistivity values (Bratton 2009).
Figure 3-7: Marine electrical resistivity, -10 m slice, indicating higher resistivity values offshore at Holts Landing State Park, transitioning into lower resistivity values (Bratton 2009).
3.3 Existing Gamma Ray Logs

The forty-four existing gamma ray logs used in this study were provided by the Delaware Geological Survey (Figure 3-8) (Appendix A). The gamma ray logs have been collected from wells throughout the history of the Delaware Geological Survey. The total depth of the wells ranged from approximately -10 m BMSL to greater than -50 m BMSL. A maximum depth of -50 m BMSL was chosen for the boundary of the gamma log data. The scale used for the gamma logs was from 0 to 120 counts per second (cps). Some of the gamma ray logs do exceed the scale but still were able to be used for interpretation. The gamma log data was of good quality overall.
3.4 Existing Absolute Age Dates

Several resources for absolute age dates of the stratigraphy were available for this project. Most of them were compiled into Delaware Geological Survey Report of Investigations Number 54: Radiocarbon Dates from Delaware: A Compilation, by Kelvin W. Ramsey and Stefanie J. Baxter (1996). Dates from within the field area were selected from this report and were used to aid in interpretation. Most of the dates occur in the eastern part of the study area from cores along the barrier island (Figure 3-9). Since the
report is a compilation of dates from different publications as well as unpublished data, appropriate credit will be given to the original authors of the dates. Table 3.1 shows the depths at which the dated material was collected as well as the numerical radiocarbon age. In addition to this report, there were also dates available from the Bethany Beach borehole which was an onshore site of the Coastal Plain Drilling Project. These dates have been included in the figures which illustrate the spatial distribution of dates as well as their depths and ages.
Figure 3-9: Map of existing boreholes with absolute age dates (Ramsey & Baxter 1996, Miller et al. 2003).
Table 3.1: Table of wells with absolute, corrected radiocarbon age dates, date in years B.P., depth in feet and meters at which the sample was taken, and references to original authors (Ramsey & Baxter 1996, Miller et al. 2003).

<table>
<thead>
<tr>
<th>Well Label</th>
<th>Date in years B.P</th>
<th>Depth feet</th>
<th>Depth meters</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bethany Beach Core</td>
<td>48000</td>
<td>-40.9</td>
<td>-12.4</td>
<td>Miller et al. 2003</td>
</tr>
<tr>
<td>Bethany Beach Core</td>
<td>47100</td>
<td>-50.4</td>
<td>-15.3</td>
<td>Miller et al. 2003</td>
</tr>
<tr>
<td>Pj42-11 3736</td>
<td></td>
<td>-35.3</td>
<td>-10.7</td>
<td>Kraft 1976a Belknap 1975</td>
</tr>
<tr>
<td>Pj42-11 12561</td>
<td></td>
<td>-84.3</td>
<td>-25.6</td>
<td>Kraft 1976a Belknap 1975</td>
</tr>
<tr>
<td>Qj22-06 45000</td>
<td></td>
<td>-24.6</td>
<td>-7.4</td>
<td>McDonald 1982</td>
</tr>
<tr>
<td>Qj22-08 39900</td>
<td></td>
<td>-25</td>
<td>-7.6</td>
<td>Kraft 1976a Belknap 1975 Kraft &amp; John 1976</td>
</tr>
<tr>
<td>Qj42-09 31750</td>
<td></td>
<td>-37.7</td>
<td>-11.4</td>
<td>McDonald 1982</td>
</tr>
<tr>
<td>Qj42-07 45000</td>
<td></td>
<td>-32.8</td>
<td>-10.0</td>
<td>McDonald 1982</td>
</tr>
</tbody>
</table>

3.5 Existing Core Data

Three cores were available from a previous study conducted by Drs. David Krantz, John Bratton and Frank Manheim (Bratton et al. 2004, Krantz et al. 2004, Manheim et al. 2004). The locations of the cores were offshore of White Neck at Holts Landing State Park (Figure 3-10).
Core site WN-1 was cored to a depth of 14.75 m BMSL with a recovery rate of 57%. The total depth drilled at site WN-1 was 27.43 m BMSL and gamma ray logging was done the entire length. The lithology of core WN-1 is fairly homogeneous. Most of the core consists of fine to medium sands with occasional packages of quartz pebbles and coarse sands. There are also some clay lenses present throughout the entire core. The only significant lithologic change occurs at a depth of approximately 8.07 m where a lens of
mica and heavy mineral grains become present. The lens is approximately 15 cm thick, and the lithology then changes back to medium sands.

Core site WN-2 was cored to a depth of 15.48 m BMSL with a recovery rate of 62%. The total depth drilled at site WN-2 was 24.32 m BMSL and gamma ray logging was done the entire length. The lithology of core WN-2 begins with a layer of coarse to medium fine sands which continues to a depth of approximately 25 cm. The lithology then changes to a peat layer which has fragments of wood and roots throughout. This layer continues to a depth of approximately 2.14 m. At this depth, a transition occurs to fine sands with little clay content. The lithology increases in clay content with depth until a depth of approximately 3 m. Occasional fine gravel and clean medium sand are interspersed through the unit. At 3 m the lithology becomes entirely light gray medium sands with little clay content and has occasional quartz pebbles. This continues to a depth of approximately 5 m where a 30-cm thick layer of coarse gravels with black chert is present. At 5.3 m the coarse gravel layer discontinues and medium sands again become the predominant lithology. At a depth of 6.5 m the lithology changes to silty sands which continue to a depth of approximately 7.1 m where medium sands again become the predominant lithology. At a depth of approximately 7.6 m the lithology changes to fine gravels which contain high amounts of bluish gray clay. This lithology discontinues at 8.0 m where the lithology transitions to medium sands with occasional quartz pebbles, clay lens and heavy minerals. This lithology remains consistent for the rest of the core to a depth of 15.4 m.

Core site WN-3 was cored to a depth of 8.44 m BMSL with a 72% recovery. The total depth drilled at site WN-3 was 28.83 m BMSL and gamma ray logging was done the
The lithology of core WN-3 ranged from clay-rich fine sands to quartz pebbles. The upper 1.5 m of the core is predominately fine sands with little clay content. At a depth of approximately 1.5 m the lithology transition into greenish gray clay-rich fine sands. At a depth of 2.4 m wood fragments begin to appear and are consistent to a depth of approximately 3 m. At this contact the organic matter discontinues but the clay-rich sand remains persistent to a depth of approximately 4.8 m. This contact marks a transition into silty-clay and medium light gray sands with occasional pocks of quartz pebbles. This is the predominant lithology until approximately 6.25 m, where there is a 30-cm thick layer of coarse sands rich in angular to sub-angular chert pebbles. The remainder of the core has a consistent lithology of clay-rich silty sands to a maximum depth of 8.44 m.

At site WN-4 no core was taken, but a well was drilled to a depth of 23.19 m BMSL and a gamma ray log was taken the entire length of the well. All gamma ray logs from this study were processed using a maximum depth of 50 m BMSL and the scale from 0-120 counts per second. The cores were analyzed for grain size and described, and lithologic logs were made of them (Appendix B).

Detailed core data was also available from the Bethany Beach borehole which was an onshore site of the Coastal Plain Drilling Project (Figure 3-11). This core was taken during May and June of 2000. The core was collected to a depth of 61 m BMSL with a mean recovery of 80%. Drilling continued to a depth of 486.06 m BMSL. The entire length of the borehole was gamma ray logged.
Figure 3-11: Map indicating the location of the Bethany Beach Core (Miller et al. 2003).

### 3.6 Existing Ground Penetrating Radar Data

One existing ground-penetrating radar data set was available for use in this project. The data set was collected during the years 1999 and 2003 by Dr. David Krantz and Maria Honeycutt, in support of Maria Honeycutt’s doctoral dissertation, *Spatial variability in shoreline change along the Atlantic coast of Delaware: Influence of the geologic framework*, (2003) and the subsequent publication; *Influence of the geologic framework on spatial variability in long-term shoreline change, Cape Henlopen to Rehoboth Beach, Delaware* (Honeycutt & Krantz 2003). There are approximately 4.23
km of data covering mostly the eastern part of the field area at the Fresh Pond State Park Field Site (Figure 3-12). The data was generally of good quality with a maximum penetration of 8 m below surface level. The system used was a Sensors and Software Pulse EKKO 100 with a 1000 volt transmitter in conjunction with the Pulse EKKO 100 data acquisition software. Antenna frequency used was 50 MHz.

**Figure 3-12:** Digital elevation map with GPR transects at Fresh Pond Field Site from Honeycutt & Krantz (1999 & 2003).
Chapter 4

Results and Seismic Stratigraphy

4.1 Marine Chirp Seismic Results

Sixty-five kilometers of chirp seismic data were collected during summer 2010 in Indian River Bay in support of this project (Figure 4-1). Overall the quality of the data was very good, but some areas did produce poor seismic data. Areas with extremely poor data are attributed to having methane gas in the surficial sediments. The methane gas bubbles attenuate the seismic signal and obscure any coherent reflections (Figure 4-2). An ideal seismic section had coherent reflections as deep as approximately 30 m and also was able to be used for interpretation of shallower strata (Figure 4-3). In conjunction with previously collected seismic data (Madsen, Brown, Bratton), seismic sections were used to define seven different seismic stratigraphic surfaces. The surfaces are labeled in alphabetical order with the shallowest surface being assigned the letter “A” and the deepest being assigned the letter “G”. The surfaces were described for their reflection characteristics, distribution, and the depth to the reflecting surface.
Figure 4-1: Seismic trackline map of Krantz & Banaszak 2010 chirp seismic data.
Figure 4-2: Example of incoherent chirp seismic data due to methane gas in the surficial sediments, from Krantz & Banaszak 2010 chirp seismic data.
Figure 4-3: Representative example of chirp seismic, from Krantz & Banaszak 2010 chirp seismic data.
4.2 Surface G

Surface G is the deepest surface identified in the seismic stratigraphy. The depth to the surface varies between 29 m and 35 m. The character of the reflection is not always consistent. It generally appears as a fuzzy, dark gray, reflection and at other times is weak and less obvious to the viewer (Figure 4-4). The characteristic of the seismic reflection and the depth to the surface are the defining character of this surface. The distribution of this surface is fairly consistent throughout the entire field area (Figure 4-5).
Figure 4-4: Chirp seismic section taken from Krantz & Banaszak 2010 seismic data showing representative Surface G, Surface F, Surface E, Surface D, and Surface A reflections, interpreted and uninterpreted.
Figure 4-5: Map of Krantz & Banaszak 2010 seismic data with areas indicated in green where Surface G has been identified.
4.3 Surface F

Surface F is the sixth deepest coherent reflection identified in the seismic stratigraphy. The surface varies in depth between 20 and 35 m. It typically appears as a fuzzy, dark reflection that is not always completely obvious to the viewer. Where this surface is expressed most clearly, it produces a sigmoidal shape that drops in elevation by 10-15 m over a distance of 200-300 m. This appears to be a channel margin that cuts down into the underlying strata and truncates lower reflecting surfaces such as regional Surface G. However in none of the seismic lines does an opposite, paired sigmoidal surface appear. Instead, these deeper reflections are typically lost toward the depper parts of the Indian River valley. It many cases, the deeper hole produced by Surface F has additional overlying, sub-parallel sigmoidal surface, as shown in Figure 4-6 as an example. It is mostly identified in the south-central part of the field area, with only one seismic line in the north-central part of the field area showing similar dipping clinoforms (Figure 4-7).
Figure 4-6: Chirp seismic section taken from Krantz & Banaszak 2010 seismic data showing representative Surface F, Surface E, and Surface A reflections, interpreted and uninterpreted.
Figure 4-7: Map of Krantz & Banaszak 2010 seismic data with areas indicated in red where Surface F has been identified.
4.4 Surface E

Surface E is the fifth deepest surface identified in the seismic stratigraphy. The depth to this surface varies between 14 m and 21 m. The variation in depth is attributed to dipping clinoforms that are present within the unit. Where the clinoforms exist, the surface begins at 14 m and deepens to 21 m (Figure 4-8). The character of the reflection is fairly consistent and it typically is a strong, dark, black sharp reflection, although on occasion though it does appear somewhat of a weaker gray (Figure 4-9). The defining characteristics of this surface are its strong reflection characteristics in the depth range that it has been identified. This surface has been identified through most of the field area (Figure 4-10).
Figure 4-8: Chirp seismic section taken from Krantz & Banaszak 2010 seismic data showing representative, Surface E, Surface D, Surface C and Surface A reflections, interpreted and uninterpreted.
Figure 4-9: Chirp seismic section taken from Krantz & Banaszak 2010 seismic data showing representative Surface E, Surface D, and Surface A reflections, interpreted and uninterpreted.
Figure 4-10: Map of Krantz & Banaszak 2010 seismic data with areas indicated in orange where Surface E has been identified.
4.5 Surface D

Surface D is the fourth deepest surface identified in the seismic stratigraphy. The depth to this surface is approximately 11 m. There are no extreme dipping sections of this surface, indicating that it is fairly flat lying. Its reflection characteristics are that it appears as a weak dark gray reflection on the seismic profile (Figure 4-11). On occasion this surface is eroded into by overlying seismic surfaces. It is identifiable throughout most of the study area (Figure 4-12).
Figure 4-11: Chirp seismic section taken from Krantz & Banaszak 2010 seismic data showing representative Surface G, Surface E, and Surface D reflections, interpreted and uninterpreted.
Figure 4-12: Map of Krantz & Banaszak 2010 seismic data with areas indicated in yellow where Surface D has been identified.
4.6 Surface C

Surface C is the third deepest surface identified in the seismic stratigraphy. The depth to this surface varies between 4 m and 9 m. This surface appears as a very strong, high-amplitude, dark reflector where it has been identified (Figure 4-13). No major dipping sections have been identified on this surface. It is defined by its reflection characteristics and its range of depth. This surface has only been identified on the North and South flanks of Indian River Bay (Figure 4-14).
Figure 4-13: Chirp seismic section taken from Krantz & Banaszak 2010 seismic data showing representative Surface G, Surface E, Surface D, and Surface C reflections, interpreted and uninterpreted.
**Figure 4-14:** Map of Krantz & Banaszak 2010 seismic data with areas indicated in brown where Surface C has been identified.
4.7 Surface B

Surface B is the second deepest surface identified in the seismic stratigraphy. It occurs between 4 m and 5 m. Its reflection characteristics are a strong black/gray reflector. This surface has a shallow dip towards the east (Figure 4-15). It is defined by both its seismic reflection characteristics and its shallow dip. This unit was only identified east of Cedar Neck (Figure 4-16).
Figure 4-15: Chirp seismic section taken from Krantz & Banaszak 2010 seismic data showing representative Surface F, Surface E, Surface D, and Surface B reflections, interpreted and uninterpreted.
Figure 4-16: Map of Krantz & Banaszak 2010 seismic data with areas indicated in pink where Surface B has been identified.
4.8 Surface A

The shallowest surface in the seismic stratigraphy is Surface A. This surface varies in depth from 8 m to <1 m. This surface is highly irregular with channel-shaped features within it. The depth to the surface increases towards the center of the bay. This surface is defined by its solid bold black reflection and its variability in depth (Figure 4-17). This surface occurs throughout most of the bay (Figure 4-18).
Figure 4-17: Chirp seismic section taken from Krantz & Banaszak 2010 seismic data showing representative Surface E, Surface D, and Surface A reflections, interpreted and uninterpreted.
Figure 4-18: Map of Krantz & Banaszak 2010 seismic data with areas indicated in blue where Surface A has been identified.
4.9 Ground-penetrating Radar Results

Ground-penetrating radar data was examined for three primary field sites within the study area (Figure 4-19). During the summer of 2010, approximately three kilometers of GPR data was collected at two field sites in the study area, 1.5 km at James Farm Ecological Preserve (Figure 4-20), and 1.5 km at Holts Landing State Park (Figure 4-21). The overall quality of the data was very good with penetration over 5 m in many cases. A third field site, Fresh Pond, was surveyed previously by David Krantz and Maria Honeycutt. Collectively, there are 4.5 km of GPR data in the study area. All three field sites produced good, interpretable results.
Figure 4-19: Map of Indian River Bay field area with the three primary onland field sites, Holts Landing State Park, James Farm Ecological Preserve, and Fresh Pond Field Site, identified.
Figure 4-20: Map of GPR transects at James Farm Ecological Preserve.
James Farm Ecological Preserve and Fresh Pond, both showed two distinct GPR stratigraphies. Each site showed an underlying reflection that varied between approximately 3 m at Fresh Pond, and 5 m at James Farm Ecological Preserve (Figure 4-22). The second ground-penetrating radar facies present at both field sites is one that shows eastward dipping beds (Figure 4-22).
Figure 4-22: Representative GPR section from Fresh Pond Field Site, showing underlying surface and steeply dipping clinoforms.
Holts Landing State Park ground-penetrating radar data yielded two ground-penetrating radar facies as well but of a different fashion than the other two field sites. At Holts Landing State Park the GPR stratigraphy shows an underlying surface which dips from approximately 4 m to 7 m towards the west and north with relatively flat lying stratigraphy lying above it from approximately 4 m to the surface (Figure 4-23).
Figure 4-23: Representative GPR section from Holts Landing State Park, showing beds dipping to the west with relatively flat lying beds above.
4.10 Electrical Resistivity Results

1.5 kilometers of electrical resistivity data was collected at two primary onland field sites, approximately 900 meters at Holts Landing State Park (Figure 4-24) and approximately 600 meters at James Farm Ecological Preserve (Figure 4-25) Electrode spacing was 5 m at Holts Landing State Park, allowing the maximum depth of viewing to be 54 m. Electrode spacing at James Farm was 3 m, allowing the maximum depth of viewing to be 16 m. The two field sites yielded different results.

Figure 4-24: Map of electrical resistivity transects at Holts Landing State Park.
Holts Landing State Park resistivity values range from 1 ohm-m to 36.1 ohm-m. The resistivity data shows low-resistance material, 1-2 ohm-m, from the surface down to approximately 6 m. From 6 m to approximately 9 m, there is a zone of medium resistance material, 3-7 ohm-m. Beneath the medium resistivity zone, a relatively high resistivity, 7-36 ohm-m, zone exists (Figure 4-26).
Figure 4-26: Representative electrical resistivity pseudosection from Holts Landing State Park.
James Farm Ecological Preserve yielded very different results than Holts Landing State Park. The resistivity values at James Farm Ecological Preserve were much higher, ranging from a low of 32.4 ohm-m to a high of 680 ohm-m. The general trend of the resistivity data at James Farm Ecological Preserve shows low-resistivity, 32.4-69 ohm-m material at the surface, along with high resistivity, 318-680 ohm-m, material. The lower resistivity material only extends to a depth of approximately 3.5 m. The high resistivity material dips towards the east and extends underneath the low resistivity materials, reaching a maximum depth of approximately 8 m. Underlying the highly resistive material there is a medium resistivity, 70-250 ohm-m, section, with an upper surface that also dips to the east, originating at approximately 4 m and reaching a maximum depth of 8 m to the east (Figure 4-27).
Figure 4-27: Representative electrical resistivity pseudosection from James Farm Ecological Preserve
Chapter 5

Discussion

5.1 Surface G

Surface G is interpreted to be the contact between the late Miocene Bethany Formation and the overlying Pliocene Beaverdam Formation. This is determined based on the projected depth from Andres (2006) (Figure 5-1). The variance in the depth to the contact within the seismic profiles and gamma logs can be explained by the regional dip of the surface and also by overlying surfaces eroding into the contact. When gamma logs from wells within the bay (Figure 5-2) are compared to the seismic stratigraphy for surface G, it is apparent that the gamma increase occurs slightly shallower than the surface is imaged in the seismic data. It cannot be determined from the wells in the bay if a relatively larger gamma increase exists exactly at the contact because they did not penetrate deep enough. When gamma logs from outside the bay are examined, a consistent gamma increase is observed at depths which are consistent with the seismic data (Figure 5-3). In a hydrostratigraphic sense, this surface is also the boundary between the Pocomoke aquifer and the overlying unconfined Columbia aquifer. The
lithology of this surface has not been confirmed, but based on the interpretation that it is the contact between the Beaverdam and Bethany Formation, it is expected to be primarily sands with a silty clay matrix lying above marine silts.

**Figure 5-1:** Structure-contour map of the elevation of the top of the Bethany Formation (Andres 2006).
Figure 5-2: Gamma ray logs from wells WN-1, WN-2 and WN-3 compared to seismic stratigraphy.
Figure 5-3: Gamma ray logs from wells Qh 23-03, Qh 15-06 and Qi 33-04, with interpretation of gamma increase associated with Surface G.
5.2 Surface F

Surface F is only identifiable in a few parts of the study area. The character of its reflections, primarily its dipping beds, leads to the interpretation that this is possibly a large fluvial channel. The age of this surface cannot be very well constrained. The surface which the channel is cutting into, Surface G, is presumed to be the contact between the late Miocene Bethany Formation and the overlying Pliocene Beaverdam Formation. This would therefore put the channel into the Pliocene Beaverdam Formation, based on stratigraphic position. But there are no absolute age dates available to prove this definitively. The only overlying surface within the area of Surface G that is confidently dated is Surface A, which is presumed to be the base of the Holocene aged sediments. Based on the given evidence, the age of the channel can only be constrained to the time period between the late Miocene and Late Pleistocene. However, considering the number of overlying seismic stratigraphic units, a late Miocene to Pliocene age is reasonable for surface F.

Gamma logs within the area of the channel were examined to determine the spatial orientation of the channel. Four wells with gamma logs fell within the projection of the channel, wells Qi 15-03, Qi 11-05, Pi32-16, and Pi32-03 (Figure 5-4). When the gamma logs from wells Qi 15-03 and Qi 11-05 are compared to the seismic stratigraphy, there is a consistent signal at the depth equivalent to Surface F exists (Figure 5-5). Well Qi 11-05 exhibits a gamma increase at a depth slightly deeper, ~37 meters, than where surface F has been identified in the nearest seismic profile.
This would be expected because of the slope of the channel from the northwest to the southeast. With the given data, a general slope of 1.17 m/km was calculated. This slope can then be used to estimate the depth at which a gamma increase should be present in wells Pi32-03 and Pi 32-16. This calculation produces an estimated depth of approximately 29 meters for the gamma increase that indicates the base of Surface F. Well Pi32-03 displays a gamma kick at the expected depth of ~29 m (Figure 5-6). Well Pi 32-16 has gamma kicks present at depths both slightly shallower ~28 m and slightly deeper ~31.5 m (Figure 5-7). It cannot be determined by just the gamma signature which of the gamma increases represents the base of Surface F. Both gamma increases are probable because the range is not outside of the typical relief expected in a river channel system. But when compared to the gamma log of well Pi32-03, it can be seen that the gamma increase at 29 m is followed by gamma increase at a depth of approximately 32.5 m which can be related to the deeper gamma increase in well Pi32-16 (Figure 5-7). Therefore making the shallower, ~28 m, of the two gamma increases in well Pi32-16 the likely base of surface F. This also indicates that that Surface F is may no longer be eroding into the now underlying Surface G. The lithology of this surface is not known, but the gamma values within the infill sequence of the channel are consistently low, indicating probable sands and gravels. Based on the interpretation that it is a fluvial channel, it is expected that it is predominantly sand with some silts and gravels, which fits the lithologic description for the Beaverdam Formation.
Figure 5-4: Map of gamma ray well log locations, area where Surface F has been identified and tracklines from Krantz & Banaszak 2010 seismic data, and the interpretation of the trend of a large fluvial channel.
Figure 5-5: Gamma ray logs from wells Qi15-03 and Qj11-05, compared to the seismic stratigraphy of Surface F, with interpretation.
Figure 5-6: Gamma ray log from well Pi32-03 with interpretation of the depth of Surface F.
Figure 5-7: Comparison of gamma ray logs from wells Pi 32-03 and Pi 32-16 with interpretation of the gamma increase associated with Surface F.
5.3 Surface E

Surface E is identified throughout most of the field area. This surface occurs at two different depths; approximately 20 m and 15 m with dipping clinoforms marking the transition between the two depths. Three of the four gamma logs from within the bay, WN-1, WN-2, and WN-3, are from areas where the 15 m surface exists and do show a consistent gamma increase at that boundary (Figure 5-8). WN-4 is presumed to be in an area where the surface should be approximately 15 m, but when the gamma log is compared to the stratigraphy, it appears to have an increase at a depth of ~20 meters. WN-4 though is in an area where ancestral river systems have been eroding and infilling for several sea-level cycles. Therefore the gamma increase at 15 m may not be present because the associated silty unit has been removed by erosion. When the area which is consistently around 20 m deep is mapped out, two distinct areas are identified. An area to the north of the bay is estimated to be about 1 km wide and trends parallel to the axis of Indian River Bay, and an area to the south is identified to be approximately 500 meters wide and does not follow any particular orientation (Figure 5-9). These two areas are both interpreted as channels. Their paths run from west to east, and then at some point they may have converged farther offshore (Figure 5-9). The 20 m deep surface is only slightly traceable onland using a single gamma log from well Ph45-03 (Figure 5-10). There may not be any evidence of the channels east of Cedar Neck because of emplacement of barrier island systems and shoreface erosional activity.

The age of Surface E cannot be well constrained based purely on its stratigraphic position. It may be part of the Pliocene aged Beaverdam Formation, or it may be younger, having been produced during an early to middle Pleistocene sea-level highstand, although
all of the dates from the eastern part of the field area, excluding Pj42-11 and Pj42-02,
indicate that all of the material above a depth of 15 meters is at the very oldest
Pleistocene in age, these dates do not correlate directly to Surface E west of Cedar Neck.
These dates are likely to be associated with the material which lies above the shoreface
ravinement surface, Surface B, which is located at and east of Cedar Neck. The lithology
of the unit overlying this surface is confirmed only in the shallowest portions of where is
exists. It is likely though that this surface is part of the Beaverdam Formation and
matches the lithologic description.
Figure 5-8: Gamma ray logs from wells WN-1, WN-2, WN-3 and WN-4 with interpretation of gamma increase associated with Surface E.
Figure 5-9: Map of 20 m deep identified surface, with possible channel projection based on Krantz & Banaszak 2010 seismic data.
Figure 5-10: Gamma ray log from well Ph45-03 with interpreted gamma increase associated with Surface E.
5.4 Surface D

Surface D is identified throughout most of the field area and has a consistent depth of ~10-11 meters. This surface is interpreted as an erosional surface from a prior sea-level lowstand followed by transgressive erosion in a moderate-energy estuarine setting, similar to modern Indian River Bay, during the subsequent sea-level rise. The spatial extent of the surface is difficult to trace outside of the bay. This surface appears on the gamma logs from wells within the bay as a gamma increase and is consistent with the seismic stratigraphy (Figure 5-11). When compared with onland gamma ray logs, the surface seems to be continuous but the signal is not strong enough to allow for a confident interpretation. The age of this surface also cannot be determined other than that it is older than the Holocene and younger than the late Miocene. Although, because of its stratigraphic position, it is likely that this surface is Pliocene and part of the Beaverdam Formation. The lithology overlying this surface primarily consists of medium sands with some clay lenses present as well as occasional fine gravels and quartz pebbles.

An alternative interpretation is that this surface represents the base of the Pleistocene. This is based on the characteristic of the seismic reflection. In most profiles Surface D is an extremely sharp surface which is interpreted to be an erosional surface. This indicates that it is most likely to be relatively young, otherwise the reflection would appear blurred due to weathering and formation of a soil horizon. Also, Surface D, is usually overlain by a unit that has a specific seismic character. The overlying unit tends to have lots of relatively thin beds, mottled reflections which are sometimes bright and sometimes subdued, which is interpreted to be a relatively young back-barrier facies.
Figure 5-11: Gamma ray log from wells Pi53-53 and WN-2 with interpreted gamma increase associated with Surface D.
5.5 Surface C

Surface C is identified on the flanks of modern day Indian River Bay and also in the western part of the field area. This surface varies some in depth but is consistently found to be 5-9 meters deep. This surface is interpreted as a sea-level low stand erosional surface. The lack of this surface in the areas where it was not identified is most likely due to the erosion of it by the subsequent sea-level events that produced the overlying surfaces. This surface does not produce a consistent gamma log signal on any of the gamma logs from within the bay, thus making it very difficult to trace on land. The age of this surface can only be constrained to be after the late Miocene and before the Holocene, but based on its stratigraphic position is likely to be part of the Pleistocene Omar Formation or possibly the Pliocene Beaverdam Formation.

There are several pieces of evidence which support the interpretation that this surface and the overlying unit may be associated with a Pleistocene aged embayment. Several seismic transects, IRB-8a.2, IRB-8a.5, IRB-8a.6, and IRB-8b.1, indicate a flank of a bay which is mimicked by the Holocene embayment (Figures 5-12 through 16). It would be extremely coincidental for a Pliocene estuary to match the configuration of the Holocene bay. It is much more likely that the Pleistocene bay acts as an antecedent control on the position of the Holocene bay. Again, the dates that are east of Cedar Neck cannot be used because there is not a direct correlation between the major stratigraphic surfaces. Therefore it is hypothesized that this surface is Pleistocene in age. The lithology of this unit consists of medium sands with occasional packages of silty-sands, coarse sands, and pebbles. It is noted also that there are occasionally lenses of mica-rich sands in the sediments directly above this surface. An abundance of mica in the fine sand
fraction is a key characteristic that distinguishes the late Pleistocene aged Sinepuxent Formation from older units in the region (Ramsey 2010).

Figure 5-12: Map showing Krantz & Banaszak 2010 seismic data, areas where Surface C has been identified, and labels for seismic lines IRB-8b.1, IRB-8a.6, IRB-8a.5, and IRB-8a.2.
**Figure 5-13:** Seismic line IRB-8a.2 with interpretation of a Holocene bay and an underlying Pleistocene bay.
Figure 5-14: Seismic line IRB-8a.5 with interpretation of a Pleistocene bay and a Holocene surface. Note, the lack of the Holocene bay.
Figure 5-15: Seismic line IRB-8a.6 with interpretation of a Pleistocene bay overlain by the Holocene bay.
Figure 5-16: Seismic line IRB-8b.1 with interpretation of a Pleistocene bay overlain by a Holocene bay.
In addition to the seismic transects with possible flanks of a Pleistocene embayment, GPR transects from Holts Landing Field Site indicated similar stratigraphic evidence for a Pleistocene embayment (Figure 5-17). Three ground-penetrating radar transects trending west to east and three south to north crossing lines, show beds which dip to the west and north approximately 3 m over 60-80 m (Figure 5-18). The beds range in elevation from approximately 1 m to 6 m below mean sea level. This unit is interpreted as the flank of a Pleistocene embayment, but based on the limited areas that it was identified may not be a true representation of the margin of the Pleistocene bay but rather a smaller cove. A single GPR transect with similar dip was identified but with the direction of the dip being to the north, and also a well imaged infilling sequence (Figure 5-19). Again, this is interpreted as being the margin of a Pleistocene bay or cove. These beds are interpreted to be associated with surface C.
Figure 5-17: Map of GPR transects at Holts Landing, with sections where flanks of a Pleistocene bay are identified.
Figure 5-18: GPR transect HL-05 showing possible margin of Pleistocene bay, with and without an interpretation.
Figure 5-19: GPR transect HL-01 showing possible margin of Pleistocene bay and infilling sequence, with and without an interpretation.
5.6 Surface B

Surface B exists only at and to the east of Cedar Neck. Its primary identifying characteristic is its dip which is approximately 50 centimeters per 100 meters. Another characteristic of this surface is the eastward dipping clinoforms which overlie it. This surface is interpreted to be a shoreface ravinement surface associated with the emplacement of Cedar Neck as a barrier island during the sea level high of MIS 5a (Figure 5-20). This surface does not appear on any of the gamma ray logs from the area. This surface is likely to be Pleistocene in age and part of the Sinepuxent Formation based on its stratigraphic position. The dates from coreholes to the east are not valid because of the geomorphic relationship between the stratigraphy which surface B is part of and the stratigraphy that the dates correspond to. This will be discussed further in the paleoshorelines chapter.
Figure 5-20: Graph of sea level relative to modern sea level over the past 200,000 years (Modified from Krantz? I need the citation for the book).
5.7 Surface A

Surface A is identified throughout most of the field area. It varies in depth from less than 1 m to approximately 10 m deep. This surface is interpreted to be the base of the ancestral Indian River drainage system which was created during the last sea level lowstand, MIS 2 (Figure 5-20). The channel-shaped features that are present within the unit are interpreted to be paleovalleys which have been infilled during the Holocene sea-level rise since the last glacial maximum (LGM) at 20,000 years B.P. The overall configuration of the surface indicates that all of the tributary paleovalleys flowed into the central paleovalley of the ancestral Indian River (Figure 5-21). Although not imaged in the seismic profiles because of gas wipeout, it is presumed that within the main paleovalley, the thalweg of the ancestral Indian River cuts down deeper than 10 meters. This is based on the known depth of the ancestral river system’s thalweg at the modern day Indian River inlet of 30 m (Kraft 1971; John 1977; Chrzastowski 1986; Ramsey 1999). The age of this unit is determined to be Holocene. This is based on dates from corehole Pj42-11 which were 3,736 years B.P. at a depth of 10.75 m and 12,561 years B.P. at a depth of 25.70 m below sea level.
Figure 5-21: Reconstruction of the ancestral Indian River paleo-drainage system.
Chapter 6

Hydrogeologic Units

Based on the seven separated surfaces that were identified in the seismic stratigraphy four primary hydrogeologic units were identified. The deepest unit is identified as unit IV and the shallowest as unit I. These units are described and interpreted primarily for their lithologic and hydrogeologic properties.

6.1 Hydrogeologic Unit IV

Unit IV is the deepest hydrogeologic unit in the stratigraphy. It’s upper boundary is Surface G, which is the contact between the overlying Beaverdam Formation and the underlying Bethany Formation. This contact is also the boundary between the underlying confined Pocomoke aquifer, and the overlying unconfined Columbia aquifer. The lower boundary of this unit is undefined because the contact between the Beaverdam Formation and the Bethany Formation is the lower boundary for the scope of the hydrogeologic portion of the study. This unit consists of primarily marine silts and silty sand, which is what, gives it its low porosity and permeability. It has been shown that there is little
geochemical interaction at the boundary between the Bethany Formation and Beaverdam Formation (Hodges 1983; Denver 1986). The upper boundary of this unit is easily identified on gamma logs WN-1, WN-2, and WN-3, as a significant gamma increase at ~27 m (Figure 6-1).

6.2 Hydrogeologic Unit III

Unit III is the third deepest hydrogeologic unit in the stratigraphy. The upper boundary of unit III is defined by slight decrease in gamma followed by an increase at approximately 15 m in the gamma logs (Figure 6-1). This contact is likely to also be associated with Surface E in the seismic stratigraphy. The lower boundary of this unit is defined as the top of the Bethany Formation. Therefore unit II varies approximately 10-15 m in thickness. Based on its stratigraphic position this unit is part of the Beaverdam Formation. No cores from within the bay penetrate this layer, but based on lithologic description of the Beaverdam Formation it can be concluded that this unit consists of very coarse feldspathic sands with pebbles, silty clay and medium sands with a white silty-clay matrix (Jordan 1962; 1974; Andres and Ramsey 1995, 1996; Ramsey 2001, 2005, 2010; Andres and Klinbeil 2006). A fining upward pattern is also typical of the formation (Owens and Denny 1979a; Ramsey 1992, 2007; Millet et al. 2003). Gamma ray logs from boreholes WN-1, WN-2 and WN-3 show a pattern that is consistent with the description of the Beaverdam Formation. The gamma ray log from corehole WN-1 shows a gamma increase at approximately 29 m which is interpreted to be the top of the Bethany Formation. Above the gamma increase at 29 m is another large gamma increase that is approximately 2.5 m thick. This is interpreted to be silty sands from within the Beaverdam formation. From ~25 m to the upper boundary of the unit at ~15 m there is a
consistent fining upward pattern with some packages of finer grained material creating some larger gamma increase (Figure 6-1). This pattern also exists in coreholes WN-2 and WN-3 (figure yada).

### 6.3 Hydrogeologic Unit II

Unit II is the next hydrogeologic unit encountered in the stratigraphy. The depth of the upper boundary of this unit varies. The upper boundary of this unit is very difficult to distinguish based on lithology or gamma ray logs, but has been identified in the seismic stratigraphy as Surface A. This unit can be overlain by Unit I, or in areas where hydrogeologic Unit I is not present, unit II can outcrop at the surface, or have a small amount of modern sediments overlying it. The lower boundary of Unit II is defined as the upper boundary of Unit III. This unit ranges in thickness from 5-20 m thick. It is assumed that there is hydrogeologic interaction between Unit II and Unit III. This unit is defined by a saw-tooth pattern in the gamma logs. This pattern is likely due to alternating medium to coarse sands with a silty-clay matrix and some finer grained materials. This unit is lithologically different from Unit III based on Unit II’s relatively siltier nature. Core material from WN-1 supports the interpretation of the gamma ray log from the borehole. A maximum depth of 14.75 m was cored at site WN-1. The general trend of the core was consistently medium to coarse sand with clay matrix with occasional lenses of coarser grained material. Grain size analysis was performed on the material which yielded results which support the interpretation (Appendix B). The results showed that the primary lithology was approximately 70% coarse to medium sand with a matrix of finer material; 5% clays, 10 % silts, 5 % very fine sands and 10% fine sands. The packages of gravels or pebbles that were found in the cores were typically thin and never
exceeded 15 cm in thickness. Cores WN-2 and WN-3 show a lithology that is consistent with core WN-1.

**Figure 6-1**: Gamma ray log from well WN-1 with stratigraphic formations assigned, interpretation of hydrologic units and interpretation of gamma log lithologies.
6.4 Hydrogeologic Unit I

Hydrogeologic unit I is the primary unit that is controlling submarine groundwater discharge into Indian River Bay. The upper boundary of the unit is the modern Indian River Bay seafloor. The boundary lower boundary of Unit I is identified as Surface A in the seismic stratigraphy. The upper boundary of the unit is the modern Indian River Bay seafloor. This unit ranges in thickness from <1 m to ~ 10 m. During the last sea level transgression the paleovalleys of the ancestral Indian River system were infilled producing a stratigraphic sequence of thin fluvial sands at the base of the paleovalley overlain by basal peat and then capped by fine grained silts and sands (Krantz 2004). Core WN-2 from directly offshore at Holts Landing State Park was taken at the approximate center of a paleovalley. The upper 25 cm of this core consists of medium coarse sands and clay-rich fine sands. The core then transitions into basal peat which is the semi-confining unit which controls the SGD into the bay. The basal peat is continuous to a depth of ~ 2 m where the lithology changes medium sands and clay rich fine sands. The base of the paleovalley itself is indistinguishable from the top of unit II because the lithologies are very similar. This is an important concept because the base of the paleovalley has little control on the groundwater interaction between unit I and II. This stratigraphic packaged as discussed before allows for submarine groundwater discharge out into the bay. At the Holts Landing State Park Field Site two paleovalleys separated by an interfluence which converge offshore into one paleovalley were identified in the seismic stratigraphy (Figure 6-2 and 6-3). The onland resistivity results indicated two plumes of fresh groundwater underlying the paleovalleys which reached depths of over 54 meters deep which is indicated by high resistivity values, 11-36.1 ohm-m (Figure
Although the results from the marine electrical resistivity indicate much lower resistivity, the relative high and low resistivity values indicate the presence of fresh or freshened groundwater. The -10 m marine electrical resistivity slice results indicates that the plume of fresh groundwater extends at least 420 meters out into Indian River Bay, indicated by relatively high resistivity values, 7-9 Ohm-m (Figure 6-5). The -5 m marine electrical resistivity slice shows a very similar trend but the plume has only reach approximately 300 m out into the bay (Figure 6-6). This is due in part to the basal peat of the infilling sequence capping off the paleovalley and creating a preferential groundwater flow path out into the bay rather that direct discharge at the surface.

In addition to the low-permeability cap submarine groundwater discharge mode, two other primary modes of groundwater discharge are associated with Unit I. These are the focused groundwater discharge directly at the shoreline mode and the focused/diffuse groundwater discharge mode which is controlled by a shallow low-permeability layer. The focused groundwater discharge mode directly at the shoreline is typical of areas where paleovalleys do not exist and also large headlands which are indicated by relatively higher elevations (Figure 6-7). The focused/diffuse groundwater discharge mode is associated mostly with areas low-permeability sediments extend out into the bay, but are not associated with the infilling of a paleovalley (Figure 6-7). This mode is primarily in areas where marshes and lowlands exist.
Figure 6-2: Map showing approximate position of paleovalleys and interfluves at Holts Landing State Park Field Site.
Figure 6-3: Two individual seismic sections viewed from Holts Landing State Park Field Site looking out into Indian River Bay, showing two individual paleovalleys which converge to one paleovalley offshore.
Figure 6-4: Onland electrical resistivity pseudosection from Holts Landing State Park, showing two plumes of fresh groundwater underneath two paleovalleys.
Figure 6-5: -10 m marine electrical resistivity map indicating freshwater offshore at Holts Landing State Park Field Site.
Figure 6-6: -5 m marine electrical resistivity map indicating freshwater offshore at Holts Landing State Park Field Site.
Figure 6-7: Digital elevation model with Holocene paleovalleys identified, with areas of different groundwater discharge modes identified.
Chapter 7

Paleoshorelines

Multiple sets of paleoshorelines were identified in the field area. There are three shorelines at James Farm Field Site and three at the Fresh Pond Field Site. There are also several younger shorelines identified further to the east. The geomorphic relationship between the emplacement of the paleoshorelines and the stratigraphy of Indian River Bay is controlled by the rise and fall of sea level. The shorelines at James Farm Field Site are labeled I-III, from west to east, also with a flood tidal delta (FTD) being present on the western side of Cedar Neck/James Farm Ecological Preserve (Figure 7-1). The paleoshorelines that are identified at the Fresh Pond Field Site are labeled IV-VI and the younger sets of paleoshorelines to the east are labeled VII (Figure 7-1). It is assumed that the age of the paleoshorelines, at James Farm and Fresh Pond Field Sites, are chronologically younger from west to east, although there are no absolute age dates from the shorelines themselves.
Figure 7-1: Digital elevation map with paleoshorelines, a flood tidal delta, major geometric boundary, and well locations of existing absolute age dates identified.
The process of the emplacement of the paleoshorelines must be understood to
determine the relationship between the geomorphology and the stratigraphy. Ground-
penetrating radar results from the James Farm Field Site show evidence of the
emplacement of a single paleoshoreline, shoreline I, from a sea level highstand, then
subsequent sea level regression, and the emplacement of another shoreline, shoreline II,
at the same location as a result of another transgression (Figure 7-2). The initial
emplacement of a barrier shoreline, shoreline I, at Cedar Neck is recorded in the GPR as
a seaward dipping bed with a relief of 3 m over a distance of approximately 130 m, which
is interpreted as a transgressive ravinement surface (TR1) that is eroding into back-barrier
silts (BBS), overlying a major sequence boundary (SB) (Figure 7-3a, b). The major
sequence boundary identified in the GPR at approximately 10 m is likely to be Surface D
which is identified in the seismic stratigraphy. It is hypothesized that Surface B,
identified in the seismic stratigraphy is the same transgressive ravinement. Landward of
the transgressive ravinement surface are landward dipping beds which have a dip of 2 m
over a distance of 210 m. These beds (OW1) are interpreted to be overwash deposits
from shoreline I. Overlying the transgressive ravinement surface are the main barrier
island deposits (BID1) which form the body of the barrier island (Figure 7-3a, b).
Associated with the GPR stratigraphy of shoreline I is a potential inlet (INL1) (Figure 7-
3a, b). The occurrence of this inlet is not unexpected because where it has been identified
is directly seaward of where the FTD deposits are located. The inlet and FTD are only
present in the GPR stratigraphy associated with shoreline I. The regression of sea level
following the emplacement of shoreline I was not preserved in the stratigraphy. It is
likely though that there was a regressional ravinement associated with shoreline I.
In the GPR stratigraphy the next surface encountered above the main body of the barrier island is a surface which dips seaward approximately 6 m over a distance of 70 m. This surface is interpreted to be the transgressive ravinement surface associated with the emplacement of shoreline II (TR2). Landward of the transgressive ravinement surface are landward dipping beds which have a dip of only 2 m over a distance of 210 m. These beds are interpreted to be overwash deposits associated with shoreline II (OW2). Overlying the transgressive ravinement surface are the main barrier island deposits which form the body of the barrier island (BID2) (Figure 7-3a, b). Above the main island body sediments is a surface that dips seaward 4 m over a distance of approximately 80 m. This surface is interpreted as the regressive ravinement surface associated with seaward progradation of the beachface during the relative fall of sea level (RR2). Overlying the regressive ravinement surface is a body of material which is associated with the accretion of prograding beach face (PB1). Capping the entire the sequence is the lower boundary of the eolian sediments (ES).
Figure 7-2: Digital elevation map of GPR transects at James Farm Ecological Preserve.
Figure 7-3a: GPR transect JF-12 from James Farm Field Site with interpretation.
Figure 7-3b: GPR transect JF-12 from James Farm Field Site without interpretation.
This stratigraphic sequence of sediments allowed for the development of a model depicting the emplacement of a shoreline, the subsequent regression, and the emplacement of another barrier shoreline at the same approximately location (Figure 7-4). The lowermost layer of the sequence would be a layer of back-barrier silts. The uppermost boundary of the back barrier silts is marked by the tidal ravinement surface which is the base of the FTD. Above the flood tidal delta sediments are intertidal deposits including reworked overwash deposits. The surface overlying the intertidal deposits in the sequence is the transgressive ravinement surface. There is then a package of sediments which is the main body of the barrier shoreline and overwash deposits. As sea level falls, there is a regressive ravinement which marks the sea level falling. Overlying the regressive ravinement surface is a body of material which is the seaward progradation of the accreting beachface as sea level drops slowly.
Figure 7-4: Model of the emplacement of a single shoreline with major sequence boundaries identified.
The second portion of the model depicts the emplacement of a second barrier shoreline in the same location as the previous barrier shoreline (Figure 7-5). The stratigraphy remains similar to the first portion of the model up to the first transgressive ravinement. Overlying the first transgressive ravinement may now be either transgressive ravinement II or the same sediments as before. It is also likely that transgressive ravinement II has eroded away transgressive ravinement I and there is only some fragmentary evidence left of it. Overlying transgressive ravinement I and the sediments from barrier shoreline I is transgressive ravinement II. This surface marks the boundary of the underlying barrier shoreline I and the overlying barrier shoreline II. Overlying the transgressive ravinement surface II are sediments which are the main body of barrier shoreline II and its overwash deposits. Again, as sea level falls slowly there is a regressive ravinement. Overlying the regressive ravinement surface is a body of material which is the seaward progradation of the accreting beachface as sea level drops slowly.

The first standard model can be applied to emplacement of single barrier shorelines. The second model can be applied to multiple barrier shorelines which were emplaced in close proximity to one another.
**Figure 7-5:** Model of the emplacement of a second barrier shoreline where there is an existing barrier island with major sequence boundaries identified.
The barrier shorelines at James Farm Field Site and Fresh Pond Field Site are likely to be associated with MIS 5a based on their stratigraphic position (Figure 7-6). It is assumed that the paleoshorelines are older in the west, at the James Farm Field Site, and younger in the east, at the Fresh Pond Field Site. Several sea level rises and falls during MIS 5a can account for the geographic distribution of the paleoshorelines (Figure 7-7). Following the sea level highstand of MIS 5a was the lowstand of MIS 4 and then the relative highstand of early MIS 3. The paleoshorelines probably emplaced during MIS 3 are located to the east of Fresh Pond Field Site. It is likely that there is a geomorphic boundary which separates the two highstand events (Figure 7-8). Dates taken from several coreholes in the eastern part of the field area support this interpretation (map of data). Corehole Qj22-06 has a date of 45,000 years B.P. from a depth of 7.49 m (McDonald 1982) and corehole Qj22-08 has a date of 39,900 years B.P. from a depth of 7.62 m (Belknap 1975, Kraft 1976a, Kraft and John 1976) and the Bethany Beach Core has dates of 48,000 years B.P. from a depth of 12.3 m and 47,100 years B.P. from a depth of 15.3 m (Miller et al. 2003) (Figure 7-1). Dates from coreholes further to the south, Qj42-07 and Qj42-09 also support a Pleistocene age but were not used. Coreholes Pj 42-02 and Pj 42-11 cannot be used to date the geomorphic boundary between the two sea level highstand because of they are positioned in the thalweg of the ancestral Indian River, thus are not related stratigraphically to either of the sea level highstands. Based on the depths at which a Pleistocene, MIS 3, age dates were taken from the three coreholes a probable depth for the geomorphic boundary at the modern shoreline is approximately 15 m.
Figure 7-6: Graph of sea level relative to modern sea level over the past 200,000 years

(Modified from Krantz? I need the citation for the book).
Figure 7-7: A relative sea level curve for the time during the emplacement of barrier shorelines at James Farm Field Site and Fresh Pond Field Site.
Figure 7-8: Cross-section view of paleoshorelines identified at James Farm and Fresh Pond Field Sites with interpretation of the placement of a major geomorphic boundary between late MIS 5 (5a) and MIS 3.
Chapter 8

Summary

Based on the marine chip seismic data which was collected for this project several key conclusions have been made about the stratigraphy and geologic history of Indian River Bay, Delaware. It is apparent that the Indian River drainage system has been in place for several sea-level cycles and as shown by the existence of previous bays in the stratigraphy, particularly Surface E. Another contribution is the existence of a large fluvial channel cutting into the contact between the Bethany and Beaverdam Formation, Surface F. The seismic data provides information on the contact between the Beaverdam and Bethany Formation from beneath the bay. The marine seismic data provides evidence for Pleistocene material underlying the modern bay, through the existence of paleo-bay flanks which are mimicked by the Holocene Bay. The new seismic data also allowed for the distribution of the Holocene paleo-drainage system to be better constrained.

In the context of submarine groundwater discharge into Indian River, this project has provided supporting evidence for this process through the onland electrical resistivity survey at Holts Landing Field Site and also the coupling of the marine seismic data and
the marine electrical resistivity data. The analyses of previously collected core data provides the basis for the definition of four individual hydrogeologic units which are present beneath the bay; the lower two units are interpreted to be regional and to extend beneath the upland areas of the watershed. This project has also provided significant details on the paleoshorelines along the eastern edge of the Indian River Bay watershed. Ground-penetrating radar data from both the James Farm Field Site and Fresh Pond Field Site supports the existence of multiple sets of paleoshorelines. The development of the geomorphic model for the emplacement of multiple barrier shorelines in close proximity can now be used as a foundation for further studies looking to delineate other paleoshorelines. One of the most important conclusions related to the paleoshorelines is the identification of the geomorphic and stratigraphic boundary between probable MIS 5 and MIS 3 deposits.
Chapter 9

Recommendations for Future Research

The results and interpretations from this study provide an excellent foundation for future investigations on the stratigraphy, geomorphology, and groundwater flow in Indian River Bay watershed. Much of the future research on the stratigraphy of the IRB watershed will revolve around filling in areas where there are gaps in the seismic data sets. Deeper seismic reflections such as Surface F must be focused on so that the spatial orientation of the surface can be better constrained. Shallower reflections such as Surface E also require more attention for the same reason. More seismic data in the areas where possible Pleistocene bay margins are thought to be is essential to support the interpretation of Pleistocene aged material being present in the stratigraphy underneath IRB. Although, it is seemingly impossible to obtain a seismic image of the ancestral Indian River thalweg, due to methane gas wipe out, it is recommended that multiple techniques are tried in hopes of obtaining a clearer image of the base of the valley. Offshore seismic data in the Atlantic Ocean would be beneficial to see the relationship between ancestral Indian River System and other ancestral river systems, such as
ancestral Delaware River. In addition to more seismic data, it is also recommended that all seismic surfaces that were identified be confirmed with cores and absolute age dates to constrain the ages of the deposits. In addition to absolute age dating it is vital that all of the identified paleoshorelines are also absolute age dated. The paleoshorelines in the field area should be cored to obtain information on their lithologies. The potential flood tidal delta west of Cedar Neck also should be cored, and have more ground-penetrating radar collected across it.

In the context of submarine groundwater discharge into Indian River Bay, there are many future projects which could be completed. The Holts Landing Field Site was the focus site for this study and primarily focused on two paleovalleys at that site. The scope of the research should be broadened to include a variety of sizes and geometries of paleovalleys. In addition to including different field sites, more marine electrical resistivity surveys should be completed, particularly during seasonal extremes, i.e., dry summers and wet springs, to see if that effects the spatial distribution of the submarine groundwater discharge.
References


Watershed Assessment Section, Division of Water Resources, Delaware Department of Natural Resources and Environmental Control. Total Maximum Daily Load (TDML) Analysis for Indian River, Indian River Bay and Rehoboth Bay, Delaware. Dover, Delaware. 1998.
Appendix A

Gamma Ray Logs

Figure A-1: Map of existing wells with gamma ray log data; well logs provided by Delaware Geological Survey.
Appendix B

Core Logs and Grain Size Analyses

Figure A-2: Map of existing corehole locations off White Neck at Holts Landing State Park (Bratton et al. 2004, Krantz et al. 2004, Manheim et al. 2004).
Indicates where a sample has been taken for a grain size analyses and its identifying number
White Neck - 1 (WN-1) Core Log

Project: USGS - Indian River Bay
Site Name: White Neck - 1
Lat / Lon: 38°35'34.10" / 76°07'39.10"
Land-Surface Elevation: -5' BMSL
Total Depth: 48.4'
Other: All grains rounded to subrounded

Date Drilled: Oct. 23, 2001
Date Described: Oct. 25, 2001
Described by: P. Haywood

- 0.0' to 8.0' medium to lower coarse sand that is very dark grey to black, a few minor coarse grains and shell fragments
- 7.5' to 10.0' coarse sand and pebbles
- 10.0' very thin tapering lense of greenish blue clay

- 10.2' to 18' medium light gray sand with green and gray clay clasts
- 18.1' to 42.2' begins mottled medium to lower coarse sands, light brown, yellow-orange, very dark gray, gray (light)
- *Note* - presence of burrows infilled with very dark gray sand

- 42' to 60' missing due to sloughing of core

Drilling Rod #: Rod 1A
White Neck - 1 (WN-1) Core Log

Project: USGS - Indian River Bay  Date drilled: Oct. 23, 2001
Site Name: White Neck - 1  Date described: Oct. 25, 2001
Lat / Lon: 38°35'34.10" / 75°07'39.10"  Described by: P. Haywood
Land-Surface Elevation: -5' BMSL  This section, FROM 0' TO 5'
Total Depth: 148.4'  Drilling Rod#: 1B
Other: All grains rounded to subrounded

- Coarse asnd, light brown with some gray color. Very few lithics, occasional feldspar grains
- 7" to 12.5" iron staining is heavy, yellow/orange, some small gravels visible 1/8" in width, some clay around grains
- Orange/yellow iron stained coarse sands and very small gravel
- Transition where iron stain gives way to yellowish to light brown coarse sands with some gravel, again 1/8" in width
- Starting at 13.5" it is purely light brown coarse sand with rounded to well rounded grains
White Neck - 1 (WN-1) Core Log

- 0” to 15” coarse sand with occasional pebbles 1/4” to 1/8” in size
- 0” to 1.5’ homogeneous light brown to light gray color
- 15” to 22.5” coarse sand and higher concentration of 1/4” to 1/8” pebbles
- 23” to 24” sand mixed with clay yellowish brown to beige in color
- At 2’ returns to medium to lower coarse sand with heavy mineral lenses at 25” to 25.5”, 26”, 27”, 27.5”, 29”, 30”, 31.5” to 32
- 39” grain size drops to finer grain size, lower medium/upper fine sand and continues until 49”
- 48.5” heavy mineral layer
- 49.5 grains coarsen to medium sand
- Bottom of core is darker with grey “blobs” of heavy minerals
White Neck - 1 (WN-1) Core Log

Project: USGS - Indian River Bay  Date drilled: Oct. 23, 2001
Site Name: White Neck - 1  Date described: Oct. 25, 2001
Lat / Lon: 38°35'34.10" / 76°07'39.10"  Described by: D. Soyinka
Land-Surface Elevation: -5' BMSL  This section, FROM 10' TO 15'
Total Depth: 48.4'  Drilling Rod#: Rod 3
Other: All grains rounded to subrounded

- Homogeneous light brown to grey medium to upper fine sands
- Streaks of heavy minerals present between 3" to 4.5" and 7" to 8"
- Sediments grade into coarser grain size sands with large sized pebbles with an average size 1/2"
- 11" to 1.2" homogenous white lower medium grained sands
- 1/2" to 1/11" medium to coarse sands predominate, yellow/brown iron stains noticeable between 1/2" and 1/3"
- 1'11" to 2'9" fine sands predominate with streaks of heavy minerals between 2'8" and 2'9"
- 2'9" to 5' predominately light brown to gray coarse sands
- 4'3" to 4'6" dark gray streaks of heavy mineral concentrations
White Neck - 1 (WN-1) Core Log

Project: USGS - Indian River Bay
Site Name: White Neck - 1
Lat / Lon: 38°35'34.10" / 75°07'39.10"
Land-Surface Elevation: -6' BMSL
Total Depth: 48.4'
Other: All grains rounded to subrounded

Date drilled: Oct. 23, 2001
Date described: Oct. 25, 2001
Described by: D. Soyinka

This section, FROM 15' TO 20'
Drilling Rod#: Rod 4

0m - 0.0'
- Homogeneous light brown to grey medium to lower coarse sands

0.5m
- Dark gray streaks of heavy mineral concentration from 1/3" to 1/6" and 2' to 2'3"

1m
- Sediments grade into coarse sands from 2.5' to 3'10"
- 2.5' to 2'8" pebbles of average size 1/2" present

- 2'10" to 3'3" yellowish/brown iron stains

1.5m
- Sediments grade into light brown to grey lower coarse sands

27
28
29
30
31
32
33
34
35
36
37
38

2.0'
2.5'
3.0'
3.5'
4.0'
4.5'
5.0'
White Neck - 1 (WN-1) Core Log

Project: USGS - Indian River Bay
Site Name: White Neck - 1
Lat / Lon: 38°35'34.10" / 75°07'39.10"
Land-Surface Elevation: -5' BMSL
Total Depth: 48.4'

Date drilled: Oct. 23, 2001
Date described: Oct. 25, 2001
Described by: D. Soyinka
This section, FROM 20' TO 25'
Drilling Rod#: Rod 5

Other: All grains rounded to subrounded

0m - 0.0'
- 0" to 5" light brown to gray lower coarse sands predominate

39m - 0.5'
- 5" to 8" light brown to gray medium coarse are present with small pebbles of 1/8" average size

40m - 1.0'
- 8" to 1'9" light brown to gray lower coarse medium sands present

41m - 1.5'
- 1'9" sediments grade into lower coarse sands up to 3'9.5"

42m - 2.0'
- Light yellow brown stains present between 2'11.5" and 3'5"

43m - 3.0'

44m - 4.0'
- Light brown to gray lower coarse to medium sands
- Dark gray streaks of heavy mineral concentration present at 4'8"

45m - 5.0'
1.5m --
White Neck - 1 (WN-1) Core Log

Project: USGS - Indian River Bay
Site Name: White Neck - 1
Lat / Lon: 38°35'34.10" / 75°07'39.10"
Land-Surface Elevation: -5' BMSL
Total Depth: 48.4'
Other: All grains rounded to subrounded

Date drilled: Oct. 23, 2001
Date described: Oct. 25, 2001
Described by: P. Haywood
Drilling Rod#: Rod 6

0m - 0.0'
- 0" to 7.5" medium light gray sand with occasional quartz pebbles 1/8" to 1/4". Occasional chert fragments sands begin to coarsen downward

1m - 1.0'
- 8.5" iron staining of coarse sands (yellow/orange)
- 9" to 16" very coarse sand light brownish gray with large fragments of chert and quartz pebbles, some heavy minerals present

1.5m - 1.5'
- 16" concentration of heavy minerals
- 16.5" concentration of heavy minerals

2.0m - 2.0'
- 17" to 20.8" coarse to medium light gray/brown sand

2.5m - 2.5'
- 20.8" to 21" lense of micas and heavy minerals, sands are medium to fine surrounding these lenses
- 21.5 second mica layer, at 23" another mica layer surrounded by light gray/brown medium to fine sand

3.0m - 3.0'
- 23" to 44" gray medium to fine sand

4.0m - 4.0'
- 44" to 54" very coarse sands, gravels, and 1/4" rip up clasts of clay, coarse pebbles range from 1/4" to 1" in diameter

4.5m - 4.5'
- 54" to 60" missing core due to slough

5.0m - 5.0'
- No Data
White Neck - 2 (WN-2) Core Log

<table>
<thead>
<tr>
<th>Depth</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0'</td>
<td>- 0.0” to 4” mixture of medium and coarse sands, light gray</td>
</tr>
<tr>
<td>0.5'</td>
<td>- 4” to 8” dark gray mottled with very dark gray fine clayey sands</td>
</tr>
<tr>
<td>1.0'</td>
<td>- 10.0” very thin tapering lense of greenish blue clay</td>
</tr>
<tr>
<td>1.5'</td>
<td>- 8” a transition from the sands to an all inclusive layer of peat that is very dark, moldable with fingers and visible fragments of wood/roots</td>
</tr>
<tr>
<td>4.0'</td>
<td>- 42” to 60” missing due to sloughing of core</td>
</tr>
</tbody>
</table>

- **Project**: USGS - Indian River Bay
- **Site Name**: White Neck - 2
- **Lat / Lon**: 38°35’33.72” / 75°07’50.15”
- **Land-Surface Elevation**: -3’7” BMSL
- **Total Depth**: 50.8’
- **Other**: All grains rounded to subrounded

**Date drilled**: Oct. 26, 2001
**Date described**: Oct. 28, 2001
**Described by**: P. Haywood

This section, FROM 0’ TO 15’

**Drilling Rod#**: Rod 1 Run 1
White Neck - 2 (WN-2) Core Log

Project: USGS - Indian River Bay
Date drilled: Oct. 26, 2001
Site Name: White Neck - 2
Date described: Oct. 28, 2001
Lat / Lon: 38°35'33.72" / 75°07'50.15"
Described by: P. Haywood
Land-Surface Elevation: -3'7" BMSL
This section, FROM 0' TO 1.5'
Total Depth: 50.8'
Drilling Rod#: Rod 1 Run 2
Other: All grains rounded to subrounded

- 0” to 8.5” lower medium to upper fine sands, olive gray in color, some organic material within it (green sea lettuce)
- 8.5” to 2’, peat, really muck to quote Dan Phalon
White Neck - 2 (WN-2) Core Log

- **0m - 0.0’**: 0” to 1’11.5” dark gray to black easily molded peat with roots and wood fragments
- **0.5m**: 2’2” transition zone from peat to a fine sand with some clay, easily molded. Olive gray in color
- **56m**: 3’0’ begin to see occasional coarse sand grains
- **57m**: 4’0’ - 45” the fine light gray sands contain much more clay, they are very hard to push on with the finger, also retain the shape of the probe used top push on them

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**Project**: USGS - Indian River Bay  
**Date drilled**: Oct. 26, 2001  
**Site Name**: White Neck - 2  
**Date described**: Oct. 28, 2001  
**Lat / Lon**: 38°35’33.72” / 75°07’50.15”  
**Land-Surface Elevation**: -8’7” BMSL  
**Total Depth**: 50.8’  
**Described by**: P. Haywood  
**This section, FROM 5’ TO 10’**:  
**Drilling Rod#: Rod 2 Run 1**  
**Other**: All grains rounded to subrounded
White Neck - 2 (WN-2) Core Log

Project: USGS - Indian River Bay  Date drilled: Oct. 26, 2001
Site Name: White Neck - 2  Date described: Oct. 28, 2001
Lat / Lon: 38°35'33.72" / 75°07'50.15"  Described by: D. Soyinka
Land-Surface Elevation: -8'7" BMSL  This section, FROM 5' TO 10'
Total Depth: 50.8'  Drilling Rod# Rod 2 Run 2

Other: All grains rounded to subrounded

- 0 to 0.5" light gray fine sands

- 0.5" to 11.5", homogeneous peat layer, grading into a muddle of peat and light gray fine sands from 11.5" to 1'2"

- 1'2" to 1'5", a 1.5" thick section of fine sands, bounded by a muddle of peat and fine sands

- 1'5" to 3', light gray fine sands are predominant, fine gravels (0.70"-.15") are present between 1'6" to 1'8"

- 3' to 4' light gray medium sands are predominant, fine gravels are present from 4'1" to 4'4"
White Neck - 2 (WN-2) Core Log

Project: USGS - Indian River Bay
Site Name: White Neck - 2
Lat / Lon: 38°35'33.72" / 75°07'50.15"
Land-Surface Elevation: -3'7" BMSL
Total Depth: 50.8'

Date drilled: Oct. 26, 2001
Date described: Oct. 28, 2001
Described by: D. Soyinka
This section, FROM .10' TO .15'
Drilling Rod#: Rod 3 Run 2

Other: All grains rounded to subrounded

- Entire core light gray sand with occasional quartz pebbles (0.5")
**White Neck - 2 (WN-2) Core Log**

- **Project**: USGS - Indian River Bay
- **Site Name**: White Neck - 2
- **Lat / Lon**: 38°35'33.72" / 75°07'50.15"
- **Land-Surface Elevation**: -3'7" BMSL
- **Total Depth**: 50.8'
- **Date drilled**: Oct. 26. 2001
- **Date described**: Oct. 28. 2001
- **Described by**: D. Soyinka
- **This section, FROM 15' TO 20'**: Drilling Rod# Rod 4 Run 2
- **Other**: All grains rounded to subrounded

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<th>Depth</th>
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<td>1.5' to 2' fine to coarse gravels predominate, black chert pebbles are also present within the gravels</td>
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<td>2.5'</td>
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White Neck - 2 (WN-2) Core Log

Project: USGS - Indian River Bay
Site Name: White Neck - 2
Lat / Lon: 38°35'33.72" / 75°07'50.15"
Land-Surface Elevation: -3'7" BML
Total Depth: 50.8"
Other: All grains rounded to subrounded

Date drilled: Oct. 26, 2001
Date described: Oct. 28, 2001
Described by: D. Soyinka
Drilling Rod#: Rod 5 Run 2

- Homogeneous medium sands, light gray

- Angular to sub-angular quartz and chert pebbles are irregularly dispersed within the sand, ranging in size from 0.2" to 0.4"

- Shape of steel core barrel is retained throughout the core

- 1.5" to 3.4" high percentage of silt and sands are more compacted
White Neck - 2 (WN-2) Core Log

Project: USGS - Indian River Bay
Site Name: White Neck - 2
Lat / Lon: 38°35'33.72" / 75°07'50.15"
Land-Surface Elevation: -8'7" BMSL
Total Depth: 50.8'
Other: All grains rounded to subrounded

Date Drilled: Oct. 26, 2001
Date Described: Oct. 28, 2001
Described by: D. Soyinka
Drilling Rod#: Rod 6 Run 3

0.0'
- 0" to 1'3" light gray fine gravels predominate, containing high amounts of bluish gray clay

0.5'

1.0'
- 1'3" to 5' light gray medium sands with occasional quartz pebbles (0.5") present variable amounts of bluish gray clay

1.5'

2.0'

2.5'

3.0'
- 0.5" to 1" thick clay clasts are present at 1'3" and 3'3.5"

3.5'

4.0'

4.5'

5.0'
**White Neck - 2 (WN-2) Core Log**

**Project:** USGS - Indian River Bay  
**Site Name:** White Neck - 2  
**Lat / Lon:** 38°36'33.72" / 75°07'50.15"  
**Land-Surface Elevation:** -8'7" BMSL  
**Total Depth:** 50.8"  
**Date drilled:** Oct. 26, 2001  
**Date described:** Oct. 28, 2001  
**Described by:** D. Soyinka  
**Drilling Rod#** Rod 7 Run 3  

- **0m - 0.0’**  
  - Section contains homogeneous light gray medium to fine sands

- **0.5’**  
  - Angular to sub-angular quartz pebbles of sizes 0.30” to 0.65” are dispersed within the section, concentration of pebbles in a particular part of the section is absent

- **1.0’**  
  - Chert pebbles are also present with no preferred concentration

- **1.5’**

- **2.0’**

- **2.5’**

- **3.0’**

- **3.5’**

- **4.0’**

- **4.5’**

- **5.0’**
White Neck - 2 (WN-2) Core Log

- 0.0” to 1’1” light gray medium sand with some of what appears to be minor amounts of clay (smooth powder when fingers rubbed together

- 1’1”. 2’1” color change to mottled light gray and light brown medium to lower coarse sand with occasional 0.5” to 1” pebbles, large pebble of sandstone (quartz arenite)

- Note large pebble, 1” diameter at 1’4”

- 2’1” to 3’ more of the light gray medium to lower coarse grained sands with some clay powder residue, also occasional quartz pebbles

- 3’ there is a color change from light gray to yellow orange, some iron stain mottling

- 3’8” to 3’9” higher occurrence of quartz pebbles

- 3’10” transition to fine sand with no pebbles, yellow in color with lenses of heavy minerals

- Heavy mineral lenses at 4’1.5”, 4’2”, 4’3”, 4’7.5”

- F. Manheim removed soil at 4’7” to 4’8” in oblong shape
White Neck - 3 (WN-3) Core Log

Project: USGS - Indian River Bay
Site Name: White Neck - 3
Lat / Lon: 38°35'40.62" / 75°07'53.46"
Land-Surface Elevation: -5'4" BML
Total Depth: 27.7
Other: All grains rounded to subrounded

- 0.0' to 1'5" uniform fine grain sand of dark gray color, some clay detected with the sand grains, again smooth when fingers rubbed together
- 1' to 1'2" clam is present
- 1.5' core is mottled with greenish gray and black sand, grain size coarsens to medium sand
- 1.90' to 1.96' uniform medium greenish gray sand

This section, FROM 0' TO 5'
Drilling Rod # Rod 1 Run 1

Date drilled: Oct. 29, 2001
Date described: Oct. 29, 2001
Described by: P. Haywood
White Neck - 3 (WN-3) Core Log

Project: USGS - Indian River Bay  Date drilled: Oct. 29, 2001
Site Name: White Neck - 3  Date described: Oct. 29, 2001
Lat / Lon: 38°36'40.62" / 75°07'53.46"
Land-Surface Elevation: -5'4" BMSL
Total Depth: 27.7'  Described by: D. Soyinka
Other: All grains rounded to subrounded  This section, FROM 5' TO 10'
Drilling Rod#: Rod 2 Run 1

0m - 0.0' - 0.0" to 0.5' a zone of mixture between greenish gray fine sands and dark greenish gray fine sands, the dark greenish gray sands are sticky to touch and easily molded, containing a high percentage of clay.

105.0' - 0.5' - 0.5" to 4'9" a thin layer of dark greenish gray clay rich fine sands it trapped between layer of the greenish gray fine sands.

106.0' - 1.0' - 2'5" a single quartz pebble (0.8" x 0.5"

107.0' - 2.0' - 2'10" to 4'9" wood fragments of varying shape are embedded in the clay-rich fine sands. The clay rich sands are also very rich in dead organic matter.

108.0' - 3.0' - The bottom 3" of the core was not recovered

109.0' - 4.0'

1.5m - 5.0'
White Neck - 3 (WN-3) Core Log

Project: USGS - Indian River Bay
Site Name: White Neck - 3
Lat / Lon: 38°35'40.62" / 75°07'53.46"
Land-Surface Elevation: -6.4" BML
Total Depth: 27.7'
Drilling Rod#: Rod 3 Run 1

- 0.0" to 3" dark greenish gray fine sands, rich in clay and wood fragments present
- 3" to 3'1" the clay rich sands grade in dark greenish gray medium sands.

Other: All grains rounded to subrounded
White Neck - 3 (WN-3) Core Log

Project: USGS - Indian River Bay
Site Name: White Neck - 3
Lat / Lon: 38°35’40.62” / 75°07’53.46”
Land-Surface Elevation: -5’4” BM
Total Depth: 27.7’
Other: All grains rounded to subrounded

Date drilled: Oct. 29, 2001
Date described: Oct. 29, 2001
Described by: P. Haywood

- 0” to 1’1.5” dark gray fine sand

- 1’1.5” transition into silt clay with organic material present, darker gray in color (black organics)
  - 1’1.5” to 1’3” dark gray clay
  - 1’3” sharp contact between dark gray clay and medium light gray sands with occasional quartz pebbles present

- 3.9’ begins a mottled appearance in the medium sand and a color change to olive yellow
White Neck - 3 (WN-3) Core Log

Project: USGS - Indian River Bay
Site Name: White Neck - 3
Lat / Lon: 38°35'40.62" / 75°07'53.46"
Land-Surface Elevation: -64" BM SL
Total Depth: 27.7'
Other: All grains rounded to subrounded

Date Drilled: Oct. 29, 2001
Date Described: Oct. 29, 2001
Described by: D. Soyinka
This section, FROM 20' TO 25'
Drilling Rod# Rod 5 Run 2

- 0" to 8", medium sands with yellowish brown iron staining, between 0" to 3" iron staining is more distinct, iron staining lighten s from 3" to 6.5"
- 6.5", yellowish brown medium sands grade into light gray coarse sands rich in angular to sub-angular quartz and chert pebbles
- 1'4", medium sands present
- 1'6" to 1'9" there is a zone of mixing between the medium sands and light gray clay. This zone of mixing has distinct olive yellow iron stains which extends into the clay horizon
- 2'2" to 3'4" there is a continuous length of silty sand
- 2'2" to 2'11" the silty sands are yellow, streaks of heavy mineral concentration are present within the silty sands (2'3", 2'5", 2'9", 3'1")
- 3'4" to 3'7" the silty sands become dry, compacted and have gray to black colors. It also becomes rich in quartz pebbles
- 3'7" olive yellow iron stained coarse sands present they grade into olive yellow medium sands at 4.5"
### B.1 Grain Size Analyses Results

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<th>Sample Identification Number</th>
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<th>3.90µm-7.80µm</th>
<th>7.80µm-15.60µm</th>
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