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Sediments of Biscayne Bay - Distribution and Depositional History

Harold R. Wanless

University of Miami

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SEDIMENTS OF BISCAYNE BAY - DISTRIBUTION AND DEPOSITIONAL HISTORY

by

Harold Rogers Wanless

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Director
Sediments of Biscayne Bay - Distribution and Depositional History.

Three shallow elongate bays, Biscayne Bay, Card Sound and Barnes Sound trend south from Miami along the southeast Florida coast. Hand probing and coring through Recent sedimentary sequences within and bordering these bays has established the general character of the underlying bedrock topography, has revealed the general features of the sediment bodies and the spatial relations of the sediment types and has given insight into the developmental history of the Recent sediment accumulations.

Biscayne Bay, Card Sound, and Barnes Sound are underlain by a shallow, north-south trending late Pleistocene bedrock basin 2 to 6 meters in depth. It is bordered to the east by a ridge formed by the Oolite member of the Miami limestone, and to the southwest by the low platform of the Everglades. The Basin was first invaded by the sea about 6,000 years ago during the post-glacial Holocene rise of sea level. Sedimentation that has taken place during the subsequent period of slowly rising sea level has been controlled by sediment supply and bedrock topography through its influence on wave energy, tidal currents and wind-driven circulation.

Six major Recent sediment regimes are recognized on the basis of sediment type, sediment body geometry and depositional controls:

(a) The influx of a quartz carbonate longshore sediment supply from the north during the past 3,500 years has been the dominant influence in the formation of the sedimentary barrier islands of Miami Beach, Virginia Key, and Key Biscayne and the associated lagoon and offshore shoals.

(b) Intrabay quartz sand accumulations fill depressions and channels in northwestern Biscayne Bay and form beaches and shoals along the mainland shoreline of Biscayne Bay and Card Sound and on bedrock rises within the Bay. The quartz is derived from the late Pleistocene Pamlico formation adjacent to the northern end of the Bay.

(c) Mud and sand carbonate tidal bars are present where tidal currents are intensified and directed by shallow thresholds of the bedrock topography. Where the bedrock threshold is entirely submerged the tidal bar belt parallels the trend of the bedrock restriction (Safety Valve and Cutter Bank). Where currents are restricted to channels through the bedrock rise the tidal bars are transverse to the bedrock restriction (Featherbed Bank and Caesar Creek Shoal).
(d) Paralic peat and fresh water peat and calcitic mud swamp deposits have developed along the transgressing shorelines since marine waters first entered the bays. Except along the more protected shorelines in Card and Barnes Sounds, these deposits have largely been eroded.

(e) The open bay contains two distinct sediment types. In areas where bedrock is less than 3 to 3.5 meters below sea level a winnowed quartz and carbonate sand forms a veneer (less than 15 cm.) over bedrock. In deeper bedrock areas lime mud has accumulated in association with turtle grass, Thalassia, which may increase bottom stability.

(f) Non-tidal mud banks in Barnes Sound appear to be actively migrating shoals which have developed in response to wind-induced circulation and wave energy in the adjacent bay in a manner comparable to that of classical cuspat.e spits.

The dominant feature of the Holocene transgression in Biscayne Bay has not been the preservation of the transgressive history in successive sheet-like deposits, but rather the erosion and redistribution of products of either present or previous deposition in patch-like accumulations.
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Dr. A. Conrad Neumann, Assistant Professor of Marine Geology at the Institute of Marine Sciences, University of Miami, has served as chairman of the advisory committee for this thesis study. His helpful guidance and criticism and assistance in equipment design have been elemental to the success of this study. The committee members, Drs. Cesare Emiliani, Leonard J. Greenfield, James I. Jones, and Donald Moore of the Institute of Marine Sciences, have collectively and individually provided thought-provoking discussions and helpful criticisms during the course of this project. I am also grateful to Dr. Mahlon M. Ball of the Institute of Marine Sciences, Dr. Keith Chave of the University of Hawaii, and Dr. Robert N. Ginsburg of The Johns Hopkins University for discussing many of the problems encountered in the interpretation of Recent carbonate sedimentary features. Dr. J. Edward Hoffmeister of the Institute of Marine Sciences, provided many helpful discussions concerning the character of the Pleistocene bedrock setting.

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*Harold R. Wanless*

Miami, Florida
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIST OF TABLE</td>
<td>x</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>xi</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>REGIONAL SETTING</td>
<td>4</td>
</tr>
<tr>
<td>BISCAYNE BAY AREA</td>
<td>5</td>
</tr>
<tr>
<td>Areal Geography</td>
<td>5</td>
</tr>
<tr>
<td>Bathymetry</td>
<td>5</td>
</tr>
<tr>
<td>Climate</td>
<td>6</td>
</tr>
<tr>
<td>Previous Study</td>
<td>7</td>
</tr>
<tr>
<td>Hydrography</td>
<td>8</td>
</tr>
<tr>
<td>Tides</td>
<td>8</td>
</tr>
<tr>
<td>Tidal Currents</td>
<td>9</td>
</tr>
<tr>
<td>Tidal Exchange</td>
<td>9</td>
</tr>
<tr>
<td>Waves</td>
<td>10</td>
</tr>
<tr>
<td>Longshore Currents</td>
<td>11</td>
</tr>
<tr>
<td>Fresh Water Influx</td>
<td>11</td>
</tr>
<tr>
<td>Salinity</td>
<td>11</td>
</tr>
<tr>
<td>Temperature</td>
<td>12</td>
</tr>
<tr>
<td>Circulation</td>
<td>13</td>
</tr>
<tr>
<td>Man's Influence</td>
<td>14</td>
</tr>
<tr>
<td>METHODS</td>
<td>16</td>
</tr>
<tr>
<td>Field Methods</td>
<td>16</td>
</tr>
<tr>
<td>Positioning</td>
<td>16</td>
</tr>
<tr>
<td>Probing</td>
<td>17</td>
</tr>
<tr>
<td>Section</td>
<td>Page</td>
</tr>
<tr>
<td>------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>Sediment Samples and Bottom Observations</td>
<td>17</td>
</tr>
<tr>
<td>Coring</td>
<td>18</td>
</tr>
<tr>
<td>Laboratory Methods</td>
<td>19</td>
</tr>
<tr>
<td>Core Preparation</td>
<td>19</td>
</tr>
<tr>
<td>Sediment Analysis</td>
<td>20</td>
</tr>
<tr>
<td>Constituent Particle Analysis</td>
<td>21</td>
</tr>
<tr>
<td>Mineralogy</td>
<td>22</td>
</tr>
<tr>
<td>Carbon-14 Dating</td>
<td>22</td>
</tr>
<tr>
<td>Data Processing</td>
<td>22</td>
</tr>
<tr>
<td>Probe Correction</td>
<td>22</td>
</tr>
<tr>
<td>Compaction of Cores</td>
<td>23</td>
</tr>
<tr>
<td>Aerial Photography</td>
<td>24</td>
</tr>
<tr>
<td><strong>BEDROCK TOPOGRAPHY</strong></td>
<td>25</td>
</tr>
<tr>
<td>General Description</td>
<td>25</td>
</tr>
<tr>
<td>Oolite Ridge</td>
<td>26</td>
</tr>
<tr>
<td>Key Largo Ridge</td>
<td>27</td>
</tr>
<tr>
<td>Sloping Platform</td>
<td>29</td>
</tr>
<tr>
<td>Open Bay Basins</td>
<td>30</td>
</tr>
<tr>
<td>Sub-Aerial Erosion</td>
<td>32</td>
</tr>
<tr>
<td>Dendritic Drainage Pattern</td>
<td>32</td>
</tr>
<tr>
<td>Solution Drainage Pattern</td>
<td>33</td>
</tr>
<tr>
<td>Local Bedrock Character</td>
<td>34</td>
</tr>
<tr>
<td>Summary of Pre-Holocene Development</td>
<td>35</td>
</tr>
<tr>
<td><strong>HOLOCENE SEDIMENTARY RECORD AND DEPOSITIONAL HISTORY: INTRODUCTION</strong></td>
<td>38</td>
</tr>
<tr>
<td>Stability of the South Florida Platform</td>
<td>38</td>
</tr>
</tbody>
</table>
# TABLE OF CONTENTS—Continued

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sea Level Rise</td>
<td>38</td>
</tr>
<tr>
<td>Climate</td>
<td>39</td>
</tr>
<tr>
<td>Depositional Controls</td>
<td>40</td>
</tr>
<tr>
<td>General Features</td>
<td>40</td>
</tr>
<tr>
<td>A. SEDIMENTARY BUILDUPS ASSOCIATED WITH LONGSHORE</td>
<td></td>
</tr>
<tr>
<td>SEDIMENT SUPPLY FROM THE NORTH</td>
<td>42</td>
</tr>
<tr>
<td>Previous Studies on Barrier Islands</td>
<td>42</td>
</tr>
<tr>
<td>General Description</td>
<td>43</td>
</tr>
<tr>
<td>Barrier Sedimentary Islands</td>
<td>44</td>
</tr>
<tr>
<td>Basal Units of Barrier Sedimentary Islands</td>
<td>46</td>
</tr>
<tr>
<td>Clastic Longshore Sediment Sequence</td>
<td>48</td>
</tr>
<tr>
<td>Beach Ridges</td>
<td>48</td>
</tr>
<tr>
<td>Fibrous Mangrove Peat</td>
<td>50</td>
</tr>
<tr>
<td>Mangrove Root Rock</td>
<td>51</td>
</tr>
<tr>
<td>Storm-Trapped Mud</td>
<td>52</td>
</tr>
<tr>
<td>Surface Environment</td>
<td>52</td>
</tr>
<tr>
<td>Barrier Island Development</td>
<td>53</td>
</tr>
<tr>
<td>Protected Lagoon Shoal</td>
<td>55</td>
</tr>
<tr>
<td>Bear Cut And Norris Cut</td>
<td>57</td>
</tr>
<tr>
<td>Southerly Offshore Trending Bank</td>
<td>59</td>
</tr>
<tr>
<td>B. INTRABAY QUARTZ SAND ACCUMULATIONS</td>
<td></td>
</tr>
<tr>
<td>General Description</td>
<td>60</td>
</tr>
<tr>
<td>Source of Quartz Sand</td>
<td>60</td>
</tr>
<tr>
<td>Methods of Concentration</td>
<td>62</td>
</tr>
<tr>
<td>Channel And Trough Filling - Remnant Sands</td>
<td>63</td>
</tr>
<tr>
<td>Quartz Sand Body In Northern Biscayne Bay</td>
<td>65</td>
</tr>
</tbody>
</table>
TABLE OF CONTENTS--Continued

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz Shoreline Shoals And Beaches</td>
<td>65</td>
</tr>
<tr>
<td>Offshore Quartz Shoals Within The Bay</td>
<td>67</td>
</tr>
<tr>
<td><strong>C. TIDAL BARS OF CALCAREOUS MUD AND SAND</strong></td>
<td>70</td>
</tr>
<tr>
<td>Featherbed Bank - Safety Valve Tidal Bar Development</td>
<td>71</td>
</tr>
<tr>
<td>General Description</td>
<td>71</td>
</tr>
<tr>
<td>Featherbed Bank - Restricted Shoal Development</td>
<td>72</td>
</tr>
<tr>
<td>Soldier Key - Transition Area</td>
<td>77</td>
</tr>
<tr>
<td>Safety Valve - Unrestricted Tidal Bar Development</td>
<td>79</td>
</tr>
<tr>
<td>Cutter Bank - Shoal Development On A Minor Slope Break Within The Bay</td>
<td>83</td>
</tr>
<tr>
<td>Caesar, Broad, And Angelfish Creek Shoals</td>
<td>84</td>
</tr>
<tr>
<td><strong>D. PARALIC AND FRESH WATER SWAMP DEPOSITS</strong></td>
<td>86</td>
</tr>
<tr>
<td>General Description</td>
<td>86</td>
</tr>
<tr>
<td>Paralic Swamps - West Of The Emergent Key Largo Ridge</td>
<td>90</td>
</tr>
<tr>
<td>Mainland Paralic Swamps - Central Biscayne Bay</td>
<td>92</td>
</tr>
<tr>
<td>Mainland Paralic And Fresh Water Swamps</td>
<td>94</td>
</tr>
<tr>
<td>Discussion</td>
<td>96</td>
</tr>
<tr>
<td><strong>E. MUD AND SAND BLANKETS OF THE OPEN BAY</strong></td>
<td>99</td>
</tr>
<tr>
<td>Sandy Areas Of Non-Accumulation</td>
<td>99</td>
</tr>
<tr>
<td>Lime Mud Accumulation</td>
<td>101</td>
</tr>
<tr>
<td>Discussion</td>
<td>104</td>
</tr>
<tr>
<td><strong>F. NON-TIDAL MUD BANKS AND KEYS</strong></td>
<td>110</td>
</tr>
<tr>
<td>General Description</td>
<td>110</td>
</tr>
<tr>
<td>Surface Environments</td>
<td>110</td>
</tr>
<tr>
<td>Mud Banks</td>
<td>110</td>
</tr>
<tr>
<td>Section</td>
<td>Page</td>
</tr>
<tr>
<td>----------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>Keys</td>
<td>110</td>
</tr>
<tr>
<td>Basal Sequences</td>
<td>111</td>
</tr>
<tr>
<td>Near Surface Sequences</td>
<td>112</td>
</tr>
<tr>
<td>Shell Beach Sand</td>
<td>112</td>
</tr>
<tr>
<td>Organic Laminated Sediments</td>
<td>113</td>
</tr>
<tr>
<td>Peat</td>
<td>114</td>
</tr>
<tr>
<td>Discussion</td>
<td>114</td>
</tr>
<tr>
<td>CONCLUSIONS</td>
<td>119</td>
</tr>
<tr>
<td>LITERATURE CITED</td>
<td>125</td>
</tr>
<tr>
<td>APPENDIX I</td>
<td>138</td>
</tr>
<tr>
<td>APPENDIX II</td>
<td>235</td>
</tr>
</tbody>
</table>
LIST OF TABLE

TABLE                      | Page
----------------------------|-----
I. Radio Carbon Dates - Sample Description, Positions in Centimeters, and Ages in Years B.P. | 234
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Regional Map</td>
<td>139</td>
</tr>
<tr>
<td>2.</td>
<td>Map of Bathymetry and Topography, Biscayne Bay Area</td>
<td>141</td>
</tr>
<tr>
<td>3.</td>
<td>Map of Pleistocene Bedrock Topography, Biscayne Bay Area</td>
<td>143</td>
</tr>
<tr>
<td>4.</td>
<td>Sketch Map of Bedrock Topography, Biscayne Bay Area</td>
<td>145</td>
</tr>
<tr>
<td>5.</td>
<td>Map of Sediment Thicknesses, Biscayne Bay Area</td>
<td>147</td>
</tr>
<tr>
<td>6.</td>
<td>Map of Probing Control and Location of Air Photos</td>
<td>149</td>
</tr>
<tr>
<td>7.</td>
<td>Aerial Photograph of Pleistocene Oolite Ridge and Channels</td>
<td>151</td>
</tr>
<tr>
<td>8.</td>
<td>Aerial Photograph of Western Central Biscayne Bay</td>
<td>153</td>
</tr>
<tr>
<td>9.</td>
<td>Aerial Photograph of Key Biscayne and Virginia Key</td>
<td>155</td>
</tr>
<tr>
<td>10.</td>
<td>Aerial Photograph and Interpretative Sketch of Featherbed Bank</td>
<td>157</td>
</tr>
<tr>
<td>11.</td>
<td>Aerial Photograph of Shoal Development in Soldier Key Area</td>
<td>159</td>
</tr>
<tr>
<td>12.</td>
<td>Aerial Photograph of Safety Valve Shoal Development</td>
<td>161</td>
</tr>
<tr>
<td>13.</td>
<td>Aerial Photograph of Southern Biscayne Bay Area</td>
<td>163</td>
</tr>
<tr>
<td>14.</td>
<td>Aerial Photograph of Swamp Development West of Card Sound</td>
<td>165</td>
</tr>
<tr>
<td>15.</td>
<td>Aerial Photograph of Mud Bank Development West of Barnes Sound</td>
<td>167</td>
</tr>
<tr>
<td>16.</td>
<td>Photographs of (a) Coral Rock Exposed on Soldier Key and (b) Soil Crust Exposed Below Sea Level</td>
<td>169</td>
</tr>
<tr>
<td>17.</td>
<td>Photographs of (a) Mangrove Rock Platform, Key Biscayne, and (b) Storm Deposited Sediment, Key Biscayne</td>
<td>171</td>
</tr>
<tr>
<td>18.</td>
<td>Photographs of (a) Quartz Beach in Card Sound and (b) Bottom Environment on Black Ledge</td>
<td>173</td>
</tr>
<tr>
<td>19.</td>
<td>Underwater Photographs of (a) higher energy surface Environment of Stringer Shoals, Featherbed Bank, and (b) Dense Thalassia beds of Safety Valve being Undercut by Channel</td>
<td>175</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
<td>-------</td>
</tr>
<tr>
<td>20</td>
<td>Underwater Photographs of Bottom Environments in Areas of Sandy Non-Accumulation within Biscayne Bay</td>
<td>177</td>
</tr>
<tr>
<td>21</td>
<td>Underwater Photograph of Bottom Environment in Area of Lime Mud Accumulation within Biscayne Bay</td>
<td>179</td>
</tr>
<tr>
<td>22</td>
<td>Unipod Drop-Weight Core Sampler used in Field Study</td>
<td>181</td>
</tr>
</tbody>
</table>
| 23     | Core Photographs from Sedimentary Barrier Islands:  
(a) Basal Lagoon Mud  
(b) Bedded Longshore Clastic Sediment  
(c) Fibrous Peat Overlying Longshore Clastic Sediment | 183   |
| 24     | Core Photographs of Quartz Sequences:  
(a) Bedded Quartz and Carbonate Beach Sand  
(b) Nearshore Quartz Bank  
(c) Black Ledge Quartz Shoal | 185   |
| 25     | Core Photographs from Tidal Bars:  
(a) Western North Featherbed Bank  
(b) Safety Valve | 187   |
| 26     | Core Photographs from Paralic and Fresh Water Swamp Deposits:  
(a) Mangrove Peat  
(b) Bedded Quartz Sand and Thalassia "Hash" Over Fibrous Peat  
(c) Calcitic Mud | 189   |
| 27     | Core Photographs:  
(a) Lime Mud Accumulation within Biscayne Bay  
(b) Shelly, Marine Mud Accumulation Beneath Main Key, Barnes Sound  
(c) Mud-Cracked, Algal-Laminated Mud from West Side of Main Key, Barnes Sound | 191   |
<p>| 28     | Sediment Photographs and Block Composition Diagrams of Longshore Clastic Sediment | 193   |
| 29     | Sediment Photographs and Block Composition Diagrams of Stringer Shoal and Tidal Bar Belt Sediments | 195   |
| 30     | Sediment Photographs and Block Composition Diagrams from Sandy Areas of Non-Accumulation within the Bay | 197   |
| 31     | Sediment Photographs and Block Composition Diagrams of Sediments from Areas of Lime Mud Accumulation within the Bay | 199   |</p>
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>32. (a)</td>
<td>Map of Aeral Distribution of the Pamlico Formation</td>
</tr>
<tr>
<td>(b) Photograph of Pamlico Quartz Sand</td>
<td></td>
</tr>
<tr>
<td>(c) Photograph of Quartz Sand from within Biscayne Bay</td>
<td>201</td>
</tr>
<tr>
<td>33. (a)</td>
<td>Generalized Profile of Depth of Transition from Sandy Non-Accumulation to Lime Mud Accumulation</td>
</tr>
<tr>
<td>(b)</td>
<td>Graph Showing the Decrease with Depth of Wave Induced Orbital Particle Velocity and its Relation to the Observed Limit of Thalassia Bed Stability in Biscayne Bay</td>
</tr>
<tr>
<td>34.</td>
<td>Sea-Level Curve</td>
</tr>
<tr>
<td>35.</td>
<td>Location Map of Cross-Sections, Cores and Sediment Samples included in this Study</td>
</tr>
<tr>
<td>36.</td>
<td>Cross Section A-A'</td>
</tr>
<tr>
<td>37.</td>
<td>Cross Section B-B'</td>
</tr>
<tr>
<td>38.</td>
<td>Cross Section C-C'</td>
</tr>
<tr>
<td>39.</td>
<td>Cross Section D-D'</td>
</tr>
<tr>
<td>40.</td>
<td>Cross Section E-E'</td>
</tr>
<tr>
<td>41.</td>
<td>Cross Section F-F'</td>
</tr>
<tr>
<td>42.</td>
<td>Cross Section G-G'</td>
</tr>
<tr>
<td>43.</td>
<td>Cross Section H-H'</td>
</tr>
<tr>
<td>44.</td>
<td>Cross Section I-I'</td>
</tr>
<tr>
<td>45.</td>
<td>Cross Section J-J'</td>
</tr>
<tr>
<td>46.</td>
<td>Cross Section K-K'</td>
</tr>
<tr>
<td>47.</td>
<td>Cross Section L-L'</td>
</tr>
</tbody>
</table>
INTRODUCTION

Recent shallow water sediments of South Florida offer an opportunity to examine many of the fundamental problems encountered in the environmental interpretation of ancient limestones. Numerous investigations, relating the character and distribution of Recent shallow water carbonate facies to the hydrographic and biologic environments, have been made in South Florida (Ginsburg, 1956; Stockman, et al., 1967; Taft and Harbaugh, 1964), the Bahamas (Cloud, 1962; Illing, 1954; Newell, et al., 1959; Purdy, 1963; Storrs, 1963), Bermuda (Chave, 1962; Neumann, 1965), Campeche (Cann, 1962; Hoskin, 1963), and British Honduras (Matthews, 1966; Pusey, 1964). The basic depositional controls responsible for the distribution of carbonate sediment bodies are, however, poorly understood. Ball (1967) has demonstrated that bottom topography, through its influence on currents and wave energy, is a primary control on shallow water sedimentation and the formation of carbonate sand bodies. Ginsburg and Lowenstam (1958) have shown that, especially in areas of carbonate deposition, certain marine communities can influence current and wave energy and can thus control sedimentation and sedimentary buildups.

Of general importance to the interpretation of shallow water derived sedimentary rocks is the sedimentary record that has been deposited during the Holocene (post-glacial) rise in sea level. This Recent transgression has offered an opportunity to examine both the sedimentary products of a well documented period of sea level rise and the role that a rising sea plays as a depositional control. Fischer (1961), for example, has
suggested that, as sea level has risen, the barrier islands of New Jersey have slowly migrated landward over the lagoon and swamp deposits producing a classical transgressive sequence. Similarly, Scholl (1964a) and Scholl and Stuiver (1967) have found that sediment accumulations associated with the Recent fresh water, paralic, and marine environments of southwest Florida have produced a classical transgressive sequence. Pusey (1964, p. 223) has found that only in the deeper areas of the platform east of British Honduras is a complete transgressive sequence of bedrock overlain by gravel, clay, peat, and carbonate mud preserved. In shallower areas, sediment sequences pass directly from bedrock to gravel to carbonate mud. Others, such as Rusnak (1960, p. 191) working on the sediments of Laguna Madre, Texas, have found that the transgressive seas have reworked the sediments before it, destroying much of the transgressive sedimentary records. Curray (1964), on the other hand, has found that in the Costa de Nayarit area, Mexico, a high rate of sediment supply can produce features characteristic of regression, even during a period of slowly rising sea level.

The following study examines the patterns and processes of sedimentation operating within the framework set by the bedrock topographic setting and the Holocene sea level rise in the Biscayne Bay area, southeastern Florida. Here, a variety of distinct carbonate, clastic, and organic sediment accumulations have developed on a shallow, irregular limestone platform during the post-glacial rise in sea level. The Recent sediment accumulations in Biscayne Bay are not arranged in simple transgressive sequences, but rather form a series of distinct patch-like developments.

An attempt has been made to understand the character and history
of Holocene sedimentation in this area in terms of distribution of living and fossil biological environments, sediment composition and source, rate of sediment supply, variation in time and space of degree of wave and current energy -- all acting within the framework set by the pre-existing bedrock topography and the specific character of the post-glacial rise in sea level.

Early field reconnaissance indicated that the complex sedimentation in the Biscayne Bay area could best be studied by (1) an examination of the pre-existing bedrock topography, (2) the areal distribution of sediment types, and (3) the general features of the sediment bodies.

This study has examined the complete and complex Holocene depositional history throughout the Biscayne Bay region. Any one feature could and should be studied in more detail. Here, however, the lure of detail has by necessity been curtailed in an effort to understand the broader problems of origin, composition, and developmental history of the several types of Holocene sedimentary bodies represented in the study area.
REGIONAL SETTING

Biscayne Bay lies on the southeast coast of the Florida Peninsula, which is the emergent portion of a much more extensive submarine plateau, the Florida Plateau (Agassiz, 1888; Vaughan, 1910a). To the west the Florida Plateau extends as much as 300 km. into the Gulf of Mexico. However, to the south and east the Florida Peninsula lies close to the edge of the Plateau and is bordered by the Straits of Florida (Figure 1). Cuba and the shallow banks of the Bahamas are separated from the Florida Plateau by the Straits of Florida which are narrow (less than 150 km.) but as much as 1,500 meters deep. The warm Florida Current flows to the north through the Straits.

Central peninsular Florida is characterized by a structural high where pre-Cretaceous rocks are within 1,000 meters of the surface. To the south the pre-Cretaceous basement slopes as about 24 meters per kilometer to a depth of at least 4,500 meters at the south end of the Florida Peninsula. The southward thickening sediment sequence overlying the basement is composed primarily of shallow water derived carbonates and evaporites and records a history of differential subsidence of the South Florida area (see Presseler, 1947; Apelin and Apelin, 1964; Puri and Vernon, 1964; and Chen, 1964).
The area of study contains three major north-south trending bays - Biscayne Bay, Card Sound, and Barnes Sound (Figure 2). Biscayne Bay is about 56 km. long and averages 8 km. in width with a maximum width of about 16 km. To the south Card Sound and Barnes Sound are each about 10 km. long and 5 to 7 km. wide. While each bay is a distinct hydrographic unit, they are connected by tidal channels and shallow banks. Biscayne Bay is bordered to the east by sedimentary barrier islands in the north, a tidal bar belt, and a discontinuous line of Pleistocene bedrock islands in the south. To the west, Biscayne Bay is bordered by a bedrock ridge in the north and mangrove swamps in the south. Card Sound and Barnes Sound are bordered to the east by a nearly continuous bedrock island barrier and to the west and south by mangrove islands and swamps. Numerous smaller bays are present to the west of Barnes Sound and southern Card Sound. The immediate shoreline throughout the area is generally mangrove.

Numerous tidal channels connect Biscayne Bay and northern Card Sound with the ocean. Biscayne Bay is separated from the outer coral reef tract and the edge of the Straits of Florida by a back reef lagoon 4 to 7 km. wide (Figure 2).

Bathymetry

The general bathymetry and topography of the Biscayne Bay area are
shown in Figure 2. Biscayne Bay, Card Sound, and Barnes Sound average less than three meters in depth. To the west of Key Biscayne the bottom is as much as five meters deep. Northern and southwestern Biscayne Bay average less than two meters in depth. The depth of the tidal channels connecting with the ocean may be as much as eight meters. Southern Biscayne Bay is partially separated from the northern areas by an east-west trending shoal development, Featherbed Bank (Figure 10).

Climate

During the summer months (May-October) gentle to moderate winds from the southeast to east prevail. The prevailing winds during the winter are from the northeast and east. Winds from frequent winter storms are generally from the north, northeast, and east and have a velocity from 20 to 30 miles per hour (see also Morrill and Olson, 1955).

Tropical storms with winds of hurricane intensity (greater than 75 miles per hour) are reported to affect Biscayne Bay about once every seven years (Weather Bureau, 1963). However, during 1964, 1965 and 1966 the eyes of three major hurricanes passed over Biscayne Bay (see also Corps of Army Engineers, 1961).

Miami Beach has a mean annual air temperature of 24.6° C. with normal extremes varying from a low of 17.8° C. (January) to a high of 31.9° C. (August). The highest and lowest recorded temperatures since 1941 are 1.7° C. and 36.7° C. (Weather Bureau, 1963).

Miami has an average annual rainfall of 142 cm. (55.8 inches), of which 73 per cent falls during the summer months (May to October) (Weather Bureau, 1963).
Previous Study

Only limited published work is available on Recent sedimentation in the Biscayne Bay area. Vaughan (1910a) has given a general description of the sediments in Biscayne Bay, and Sanford (1909, p. 229) has commented on the distribution of quartz sand along the mainland shoreline. Hoffmeister and Multer (1965) have described and dated the fossil mangrove root rock on the north end of Key Biscayne. The U.S. Army Corps of Engineers (1961) has presented a brief study on the need for beach replenishment on Key Biscayne and Virginia Key. The tidal bar belt to the south of Key Biscayne has been discussed by Ball (1967).

McNulty (1955, 1956, 1957, 1961) and McNulty, Work, and Moore (1962), in studies on pollution and the level-bottom ecology, have broadly described the distribution of the surface sediment types in Biscayne Bay. Other ecological surveys have been made by Smith, Williams, and Davis (1950) in northern Biscayne Bay, by Voss and Voss (1955) around Soldier Key, by Kohout and Kolipinski (1967) in the Cutler area, and by Thomas, Moore, and Work (1961) following Hurricane Donna. Stubbs (1939) has given cursory treatment to the Foraminifera of the Bay. Numerous logs of core borings taken by commercial and governmental agencies are available (see Morrill and Olson, 1955).

General observations on the hydrography in Biscayne Bay have been made by Vaughan (1910a), Dole (1914), Wakefield (1941), Weiss (1948), Woodmansee (1949), Smith, et al. (1950), D. Moore (1963), Kohout (1967), and Kohout and Kolipinski (1967).

Detailed hydrographic studies have been limited to northern Biscayne Bay (Minkin, 1949, Morrill and Olson, 1955; Hela et al., 1957; McNulty, 1961). Clore (1925) is reported to have studied the general circulation
of northern Biscayne Bay (see Morrill and Olson, 1955).

Recently, in association with the development of the nuclear power plant at Turkey Point there have been several general and in part contradictory reports on the circulation of southern Biscayne Bay (Division of Reactor Licensing, 1966; Florida Power and Light, 1966).

Hydrography

Biscayne Bay has been classified as a positive, shallow tidal bar-built estuary (Hela, et al., 1957). It receives warm oceanic waters of the Gulf Stream through numerous tidal channels along the eastern side of Biscayne Bay. Fresh water is introduced from small mainland rivers and creeks, ground water percolation along western Biscayne Bay, and rainfall. As Biscayne Bay is shallow throughout, vertical stratification is absent and a one layer circulation system is present (ibid., p. 50).

Tides

The tides in Biscayne Bay are semidiurnal and at the Miami Harbor entrance have a mean tidal range of 80 cm. (2.6 ft.). The maximum spring tidal range is 118 cm. and the minimum neap tidal range is 42 cm. Mean tidal ranges are much lower within Biscayne Bay (40 to 57 cm.), Card Sound (24 cm.) and Barnes Sound (less than 20 cm.) (Tide Tables, 1966).

Eastward of the tidal channels along Biscayne Bay, the semidiurnal tidal wave is essentially in phase (± 10 minutes) (Florida Power and Light, 1966). Tidal stages within Biscayne Bay, however, lag one to two hours behind that reported at the Miami Harbor entrance. In Card Sound the tidal lag is over three hours, and in Barnes Sound, it is greater than four hours and quite variable.

Winds may affect both the time and height of predicted tides
within Biscayne Bay. Morrill and Olson (1955, p. 37) state that winds greater than 20 knots may affect and even nullify tidal currents within the bay.

Hurricanes have produced storm tides over three meters above mean low water (Corps of Engineers, 1961) inundating the northern barrier islands and extending as much as five kilometers into the mainland swamps in the southern area of study.

Tidal Currents

Tidal current velocities through the numerous tidal passes along the eastern side of Biscayne Bay average 25 to 100 cm/sec. (0.5 to 3.0 knots) (Hela, et al., 1957, p. 84). Within Biscayne Bay tidal currents are less than 50 cm/sec. (1 knot) and average less than 25 cm/sec. Weiss (1948, p. 156) has reported no tidal flow near the western shore of Biscayne Bay in the Coral Gables area.

Tidal Exchange

As Biscayne Bay is too shallow throughout to maintain density stratification (Hela, et al., 1957, p. 50), mixing of incoming tidal flow with water in the Bay is "confined to an interface along the perimeter of the incoming water" (Division of Reactor Licensing, Appendix C, 1966). Ball has observed in Florida Bay that "with the development of these strong (tidal) currents the interface between the relatively deeper waters of the embayment (offshore) and the shallower waters of the platform is displaced rapidly with each change of the tide. A point is reached during this displacement at which the interface becomes unstable and separates into a number of approximately equally spaced and sized (0.5 km. in length) digits" (1967, p. 164 and Figure 18). Similar
features are probably present in Biscayne Bay and, if so, would greatly increase the interface of along which mixing takes place. In addition, sedimentologic evidence (see p. 75) suggests that isolated tidal jets penetrate well into the bay in the area of the Ragged Keys. Nevertheless, it appears that overall tidal induced exchange is small and that "tidal flow" (outflow) consists mainly of water that entered the bay during the previous flood tide (Division of Reactor Licensing, Appendix C, 1966).

Weiss (1948, p. 156) notes that, even along the more open western shoreline in the Coral Gables area, no tidal currents are evident and the inshore waters do not appear to change in character during a tidal cycle. Also, Smith, et al. (1950) have found the bay to the south of Featherbed Bank to be significantly more saline than ocean water and to lack oceanic planktonic organisms generally found elsewhere in the bay. They have concluded that "this part of the bay suffers a minimum of mixing with any fresh supply of sea water or of water from the upper parts of the bay." (ibid., p. 131) Much of the Bay, thus, appears to be dependent on wind induced circulation for exchange.

Waves

Biscayne Bay, Card Sound, and Barnes Sound are completely protected from offshore swells. For winds less than 20 knots, waves within the bays are less than 0.7 meters in height. While no published data is available, general field observations indicate that wind induced waves from winter storms are fetch limited to about one meter in height. As northern and southwestern Biscayne Bay is quite shoal (less than 2 meters in depth) and as Featherbed Bank separates central and southern Biscayne
Bay, the maximum fetch in Biscayne Bay, Card Sound, and Barnes Sound is about seven kilometers. Waves within the bays appear to commonly have a wave length of about 10 to 12 meters and a period of about 2.5 seconds.

**Longshore Currents**

Along the eastern shore of the barrier islands, ocean swells and waves from the north, northeast, and to a lesser extent from the east tend to set up southerly longshore currents. This southerly drift is predominant from September through February (Corps of Engineers, 1961, p. 7). During the summer months smaller swells and waves from the south and southeast cause northerly inshore currents (see Morrill and Olson, 1955, p. 56-67).

**Fresh Water Influx**

The Miami River and three smaller rivers discharge $15 \times 10^6$ m.$^3$ ($540 \times 10^6$ ft.$^3$) (mean), during a tidal cycle into northern Biscayne Bay (Hela, et al., 1957, p. 57). To the south a number of smaller creeks carry runoff from the fresh water mainland swamps. Kohout and Kolipinski (1967) have shown that ground water discharge is also a major contributor of fresh water along the mainland shoreline in the Cutler area. The supply of water from rivers, creeks, ground water discharge fluctuates with the seasonal variation in rainfall.

**Salinity**

The water to the east of Soldier Key and Key Biscayne has a salinity of about 36.00 o/oo (Dole, 1914) similar to that of the Gulf Stream and shows small seasonal fluctuation (Smith, et al., 1950). Water within the more open part of the Bay (eastern Biscayne Bay from Key Biscayne to
Elliot Key) reflects oceanic characteristics, however, the seasonal salinity fluctuation is significantly greater within the bay than without. Smith, et al. (1950) have reported an annual salinity variation in the Soldier Key area from 33.06 o/oo (October, 1945) to 37.11 o/oo (July, 1945). They note a correlation with periods of rainfall.

Dole (1914) recognized that fresh water outflow from the small rivers in northern Biscayne Bay influenced the salinity throughout the Bay at least as far south as Key Biscayne. More recent work has recognized that fresh water runoff and artesian flow of ground water influence the salinity throughout the western areas of Biscayne Bay (Kohout, 1967; D. Moore, 1963; Weiss, 1948; Woodmansee, 1949). Woodmansee (1949) has recorded a seasonal variation (for 1948) from 10.76 o/oo to 35.12 o/oo in the Cutler area. Kohout and Kolipinski (1967, p. 492) have shown that in the Cutler area, groundwater discharge has affected the salinities as much as 5 kilometers east of the shoreline during both wet and dry seasons.

Other parts of Biscayne Bay, especially to the south of Featherbed Bank reflect their isolation by a marked increase in salinity during much of the year. To the west of Elliot Key, Smith, et al. (1950) have found a salinity variation from 34.09 o/oo (December, 1945) to 39.26 o/oo (August, 1945).

**Temperature**

On the outer reef tract Smith, et al. (1950) have found a seasonal temperature variation in surface waters from 24° C. to 29° C. (for 1945-1946). The surface temperatures within Biscayne Bay are markedly greater and correlate with seasonal variations in the air temperature.
(Weiss, 1948). The temperature near Soldier Key and to the west of Elliot Key varied from 19° C. to 32° C. in 1945 (Smith, et al., 1950). Woodmansee (1949) has recorded a seasonal fluctuation on the western side of Biscayne Bay from 15.6° C. to 32° C. for 1948. No vertical variation is reported except in protected man-made harbors and channels.

**Circulation**

Several studies have suggested that circulation in Biscayne Bay is primarily tidally driven (Hela, et al., 1957; Florida Power and Light, 1966). The tidal circulation consists of essentially oscillatory movements with very little net drift. Several nodal points of tidal current convergence are recognized within the northern part of the bay (Hela, et al., 1957). No detailed studies have been made in the central or southern parts of the bay, but as previously mentioned, western and southern Biscayne Bay appear to be quite isolated from tidal circulation. Hela, et al. (1957, p. 61) have noted that winds appear to alter the "more normal" water circulation pattern. Steady winds of 500 to 750 cm/sec. (10 to 15 miles per hour) set up surface water currents of 5 to 20 cm/sec., and winds of 1000 cm/sec. (20 miles per hour) or more are sufficient to neutralize tidal currents within the bay (Clore, 1925 - see Morrill and Olson, 1955, p. 37).

Prevailing winds from the southeast and east bring a drift of surface ocean water across the outer reef (Smith, et al., 1950, p. 121). Similar winds tend to cause a net flux of water into the bay through the more open tidal bar belt (Safety Valve). Strong northeast winds have also been observed to cause an influx of water into central Biscayne Bay. To the south, no such influx of water occurs because
Elliot Key provides a continuous rock barrier. Thus, wind-driven water within the Bay drifts to the southward across Featherbed Bank and the shallow part of the Bay to the west and appears to discharge primarily through Caesar Creek (Figure 13).

Wind-induced longshore currents, similar to those present east of the barrier islands, appear to be present along the mainland shore. The geometry of sediment bodies within Biscayne Bay appears helpful in interpreting the general circulation pattern (see pp. 75-76, 84, 115-118).

Man's Influence

Man's influence in Biscayne Bay began about 1900 when the first sewer outfalls emptied into northern Biscayne Bay. Since that time, man has dominated sedimentation in northern Biscayne Bay. In an effort to convert the mangrove shorelines into usable land, large amounts of fill have been dredged from the Bay and bulkheads and sea walls have been built. Numerous bulkhead islands were dredged within northern Biscayne Bay. Two ship channels, Baker's Haulover (1923-1924) and Government Cut (1905), were dredged through the north and south ends of Miami Beach, and a rock jetty, extending almost a mile seaward of Government Cut, was built. Six major causeways have been constructed connecting Miami Beach and Key Biscayne with the mainland, and groins have been installed along the outer shores of the barrier islands. Boat channels have been dredged across the shoal areas of the Bay.

Thus, while northern Biscayne Bay was once a shallow lagoon, open to the south and bordered to the east by a line of sedimentary barrier islands, today it resembles an estuarine complex bordered by bulkheads and spoil banks. Circulation and sedimentation patterns have been
altered. While all but two of the untreated sewer outfalls were plugged in 1954, the water and bottom environments of northern Biscayne Bay scarcely resemble those of 70 years ago.

To the south of Soldier Key, Biscayne Bay appears to have remained essentially in its natural state, however studies in progress may provide information to the contrary. Many man-made drainage canals do penetrate the swamps to the west of southern Biscayne Bay and Card Sound, and their effect on the ecology of the Bay is as yet little understood.
METHODS

During the initial part of this study, an extensive field program of manual probing was made throughout the Biscayne Bay area to establish the general relationship between Recent sedimentary buildups and Pleistocene bedrock topography. On the basis of this survey, 40 localities were selected and the sequences and structures of the Recent sedimentary accumulations were revealed by cores taken to bedrock. A selected number of samples from cores and surface samples were analyzed for grain-size distribution, composition, and fine-fraction mineralogy. In an effort to provide a time reference for some of the sedimentary sequences, carbon-14 dates were made on five samples of peat and carbonate shell and mud. Aerial photography was used extensively to extend field data and aid in interpretation.

Field Methods

Positioning

Nearshore and land probing and coring stations were located using topographic maps and hydrographic charts. Spacing of probing stations on land was achieved by using a car speedometer. On water, probing and coring stations were positioned with a sextant by triangulating on known landmarks. Probing transects were made by running from a known point on a fixed course at a constant speed for a measured period of time. The running time intervals between stations were constant for each transect. To avoid major wind or current drift, the boat was anchored
at each probing site. At every second or third station along a tran-
sect, sextant angles were taken to correct for wind and current drift.

Probing

Galvanized steel rods of 1/4" and 3/8" diameter were used in 10
and 20 foot lengths to penetrate the sediment thickness throughout the
Bay area. The probes were scored at 10 cm. intervals and numbers were
stamped on for ease in reading in the field. Except for areas that
had been filled by man and certain areas under the sedimentary barrier
islands, these hand probes worked well in all sediment types. At each
station the time was noted so that correction for the stage of the tide
could be made. The water depth was recorded, and three or more measure-
ments of the sediment thickness were made within a 3 to 5 meter (10 to
20 foot) area. Readings were made to ± 2 cm., not with the hope of
trying to correlate between stations with this accuracy, but in order
to establish the local bedrock relief at each station. While many
probing transects across special features were made at 10 to 20 meter
intervals, the 16 major transects were probed at 1/4 to 1/2 km. inter-
vals with the purpose of establishing the general bedrock trend. The
"feel" of the probe was often sufficient to distinguish general sediment
types. This information was used to fill in detail on the cross-sec-
tions in Figures 36-47.

Sediment Samples and Bottom Observations

At about 100 of the probing stations, surface sediment samples
were taken by pushing a short section of 2" core liner into the sedi-
ment and capping it before removal. The samples were sealed and placed
in a cold room within a day of sampling.
At each station, a general description of the bottom environment was made and where possible was recorded by underwater photographs.

Coring

A modified version of a unipod corer described by Ginsburg and Lloyd (1956) was used throughout the area of study for coring peat, mud, and coarse sands. The basic corer consists of 3" aluminum irrigation tubing as the coring tube, removable handles which clamp to the tube to allow pushing and twisting of the core tube into the sediment, a platform, and a pole mast to which is attached a chain leading to the piston (Figure 22). In muds, carbonate sands, and some peats, this corer worked well with up to 5 meters of penetration being easily attained.

However, in firm fibrous and woody peats and in quartz and coarse quartz-carbonate sands, several modifications were necessary. Pieces of wood or compact peat often plugged the end of the corer so that, despite the vacuum created by the piston, material would not be accepted into the tube. This problem was overcome by taking peat cores in sections. When the core would no longer penetrate easily, it was brought up and a new section put down the same hole. This cut down the amount of overall compaction. Sharpening and serrating the end of the coring tube and bending the serrated teeth alternately inward and outward also helped. It has been found that cutting the end of the tube at a sharp angle is effective in areas of very fibrous or woody peats (syringe end in Figure 22).

For most sand, hand coring methods would not work. A 105 pound cylindrical lead weight was built to fit over the coring tube so that it could be lifted and dropped on the handles (Figure 22). With the aid
of this pounder, cores of greater than 7 meters were made through coarse longshore sediments and through quartz sand bodies. Often coarse sands tend to fall out of the tube while it is being withdrawn. This was prevented by taking the core to bedrock and pounding into the rock. Depending on the nature of the bedrock surface, a rock plug will be accepted into the tube or the tube will be bent and closed. A stainless steel core head, containing a core catcher, has also been used effectively in some sands.

Initially an aluminum piston with two o-rings was used. The piston was later modified and fitted with two leather cup washers, (similar to those found on water pumps). The cup leathers provide a much better seal and maintain a much better vacuum than the o-rings.

Laboratory Methods

Core Preparation

Cores were returned to the laboratory in the aluminum coring tubes. The cores were extruded on a specially built table into plastic trays. Following extrusion, they were split lengthwise. Initial description was made immediately. One half of the core was sampled at desired intervals, sealed in a plastic container to prevent drying, and put in cold storage to minimize bacterial action.

The other half was prepared for impregnation according to the methods described by Ginsburg, et al. (1966). The core was wrapped in fiberglass cloth, put in a 3 foot aluminum tray and dried in an oven for at least two weeks. Complete drying is necessary to allow penetration of the polyester resin. Oven drying causes some shrinkage especially in the peat sections. One peat core was dried by freeze drying with very
good results; however, because only very short sections could be freeze 
dried with available equipment, this method was not generally used. When 
dry, the trays were placed in a vacuum chamber and the catalyzed poly-
ester resin poured over the core, completely covering it. The trays 
were then placed under 120 pounds pressure to drive the resin completely 
into the core section. The resin was allowed to set. If too much cat-
alyist is used, cracks may form in the impregnated core while hardening. 
The fiberglass wrapping tends to minimize cracks which may tend to form. 
A large rock saw was used to cut the hardened, impregnated cores into 
lengthwise slabs.

Sediment Analysis

A selected number of sediment samples were analyzed for composition 
and mineralogy. They were first treated with 50% "Clorox" bleach to re-
move organic material. Previous work (Neumann, personal communication) 
has indicated that if bleach solution remains in contact with an organic 
rich carbonate sediment for more than a few hours, the pH of the solution 
may drop from 11.5 to 7.0 with consequent solution of fine carbonate 
sediment. To avoid this problem, the bleach solution was removed within 
a few hours by a clay pipe candle filter and the sediment rinsed several 
times with distilled water buffered to pH 9.5 by the addition of NH₄OH.

Sieving was done wet using a vibrator shaker and buffered distilled 
water. This appears to be much gentler and more effective than dry 
sieving on a "Ro-Tap" shaker. The less-than-62-micron fraction was 
sieved first, with the washings collected in a large beaker. The volume 
of the suspension was reduced with a clay pipe filter and the fine frac-
tion was transferred to tared beakers for drying and weighing. The
coarse fraction was then wet-sieved either on the vibrator shaker or by hand shaking with tap water flowing through the column of sieves. The fractions were then rinsed with buffered distilled water before transferring to tared beakers for drying. Sieves used were 4000, 1000, 500, 250, and 62 microns.

**Constituent Particle Analysis**

In order to better interpret the sediment source and the environments of deposition of the Recent sedimentary buildups, a constituent particle analysis was made for each of the sediment size fractions greater than 62 microns (> 4000 microns, 4000-1000 microns, 1000-500 microns, 500-250 microns, 250-62 microns). A mechanical microsplitter was used to obtain a small representative fraction of each size fraction. This was sprinkled on a tray marked with a 1/20" grid. Identification under a binocular microscope was then made for at least 200 grains where possible.

Without sectioning, the identification of most skeletal fragments smaller than 250 microns is very difficult (Feray, *et al.*, 1962). The binocular microscope examination was extended to the 250-62 micron fraction only to distinguish quartz from carbonate material. Description of the characteristic features of carbonate grains applicable to this area have been made by Thorp (1936, pp. 56-63), Illing (1954, pp. 18-24), Ginsburg (1956, pp. 224-225), and Wanless (1964, pp. 29-53). The following general grain types were recognized: quartz, quartz-carbonate aggregates (mostly reworked rock fragments), sponge spicules, *Halimeda* plates, molluscs, Foraminifera, coral, *Goniolithon* (rare), ostracods, echinoid plates and spines, pelletoidal grains (rare), carbonate aggregates (mostly reworked rock fragments), pitted and blackened grains.
(mostly fragments of mollusc or Foraminifera) and unidentifiable carbonate grains. Drs. Donald Moore and Wayne Bock were helpful in identifying the characteristic molluscan and foraminiferal assemblages.

Mineralogy

The fine fractions (less than 62 microns) have been analyzed by x-ray diffraction for the pressure and general abundance of calcite, magnesian calcite (> 4 mol % MgCO₃), aragonite, and quartz.

Carbon-14 Dating

Radio-carbon analyses were made on five samples. The depth from which three samples were taken was very carefully determined in the field. The samples chosen closely overlay firm sands or bedrock so that both natural compression and compaction caused by coring would be minimized. Peat samples were taken from horizons away from present mangrove growth to avoid possible root contamination.

The two peat samples were pretreated first with hot 1% HCL to remove carbonate material, then for a period of several hours with hot 1% NaOH in order to remove humic acid contamination, and finally with a rinse of 1% HCL (Walton, et al., 1961, p. 47). Samples of shell and Halimeda sand intended for C¹⁴ analyses were washed, scrubbed, and leached with dilute HCL to remove mud and the surface contaminants. Carbon-14 samples were analyzed by Dr. Göte Ostlund at the radiocarbon laboratory of the Institute of Marine Sciences.

Data Processing

Probe Correction

All probing data was corrected to mean low water. This was necessary
as tidal range in Biscayne Bay reaches 0.75 meters. Three steps were necessary to make this correction. (1) Winds caused the actual tidal character to differ from the predicted tidal times and heights. The actual character of the tide for a given day was taken from a graphic tide recorder, located at the Institute of Marine Sciences, which monitors the tide in the center of Bear Cut. This curve was used as the basis for further interpretation. (2) The tidal lag for high and low tide at a number of points throughout Biscayne Bay was available through Hydrographic charts and the U.S. Geological Survey (Mr. J. Hartwell of the Groundwater Division, U.S.G.S., Miami, Personal Communication). Thirteen points were used to draw up a contour map of tidal times relative to Bear Cut. The tidal lag for each station was then interpolated from this map. (3) The tidal height also varies through the Bay, and it generally diminishes further into the Bay and to the south in Card Sound. The tidal variation relative to Bear Cut was established for nine points in the area (Tide Tables, 1966, 1967). Thus, knowing the time that a probing station was occupied, a fairly good correction to mean low water could be made using the above.

As far as possible, probing transects were completed within two or three hours of starting time to minimize variations of the day to day effects of winds on the tide. For stations south of Little Card Sound, no tidal correction was made as the tidal variation is less than 15 cm. and the tidal lag greater than three hours and quite variable.

Compaction of Cores

Most cores underwent very little compaction. Some of the peat and fine mud cores, however, were markedly shortened. Correction was made
in several ways. Probing adjacent to the coring location permitted accurate positioning of peat, sand, and mud horizons. The corresponding horizons in the core were then corrected for depth. Peat cores which were taken in sections were carefully measured in the field. By measuring the depth of the hole before each section was taken, the depth of the top of each section was accurately known. It is not safe to assume that the rest of the core or section represents a compressed record of the column penetrated. In several instances it is known that the core retrieved represented a relatively uncompressed record of the top few meters. The core tube then plugged up and further material was pushed aside.

Aerial Photography

Aerial photography has proven most valuable in extending field studies. The areal extent of bedrock platforms, exposed rock bottom, shoal development, surface environments, and bedrock drainage patterns has been extended far beyond field data by the use of both black and white and color aerial photography. Aerial photography has also been helpful in the northern part of the Bay to delimit the extent of man's activities. Photography has been used from 1925, 1939, 1940, 1960, and 1964 to trace dredging and fill operations.
BEDROCK TOPOGRAPHY

General Description

Biscayne Bay, Card Sound, and Barnes Sound are underlain by two shallow bedrock depressions (Figures 3 and 4). These will be called here "Biscayne Bay Basin" to the north and "Card-Barnes Sound Basin" to the south. The deep axis of both basins is 4 to 7 meters deep and extends north-south along their eastern (seaward) side. These basins are bounded to the east by a narrow elongate ridge of Pleistocene coral limestone, the Key Largo Limestone. In the southern portion, this ridge forms a nearly complete barrier of islands, but to the north it is present as a submerged feature. Along the northwestern (metropolitan) side of Biscayne Bay a Pleistocene oolite ridge rises abruptly from the Biscayne Bay Basin. To the south this oolite ridge turns inland (westward) with the result that the west flank of the Biscayne Bay Basin further south becomes a gradually sloping bedrock surface. A submerged bedrock rise extends along the west side of the Card-Barnes Sound Basin. Local ridges and troughs are superimposed on this general pattern. Subaerial erosion during the Wisconsin Glacial Stage caused two major dendritic and some poorly developed karst drainage patterns to be developed on these bedrock topographic features.

The general bedrock topography is shown in Figure 3. Letters in the following text refer to those circled in this figure. Cross sections in Appendix I (Figures 36-47) show bedrock topography in more detail.
Oolite Ridge

The oolite member of the Miami Limestone (Hoffmeister, Stockman, and Multer, 1967) forms a topographically prominent ridge bounding the western side of northern Biscayne Bay (A in Figure 3). It was first described by Sanford who named it the Miami Oolite (1909, p. 211). This oolite body, here referred to as the "Oolite Ridge", extends along Biscayne Bay south to the Cutler area (Figure 7) where it turns inland, passes under Homestead and extends west into the Everglades. It is cut by irregular, generally transverse channels or vales (Figure 7) which have been compared to the tidal channels now present in the active submarine oolite shoals of the Bahamas (Hoffmeister, et al., 1967, p. 186). These channels are now filled with a basal layer of quartz sand overlain by peat. Several of the channels cut through the eastern side of the Oolite Ridge and are presently active rivers. In the Miami area, the eastern flank of the ridge rises to 8 meters above sea level. While some erosion may have taken place, the morphology of the Oolite Ridge still appears to bear its initial depositional form as a submarine ridge or bore of unstable oolite cut by transverse tidal channels.

Throughout much of Biscayne Bay, the bedrock slopes gently eastward away from the mainland shore. However, from Coral Gables north to Miami, where the Oolite Ridge lies within 100 meters of the present shoreline, this gradual slope is not present. Here, the eastern side of the ridge drops abruptly from 4 to 8 meters above sea level to 5 to 8 meters below (Figure 38). An erosional bench or notch 3 meters above present sea level is exposed intermittently along the eastern side of the Oolite Ridge in this area. This notch represents the Silver Bluff shoreline (Parker and Cooke, 1944, pp. 22-44; Cooke, 1945), which has
been recognized in northern Florida and Georgia (MacNeil, 1950, p. 104; Hoyt and Hails, 1967). This now elevated bench or notch was cut at sea level sometime between the formation of the Oolite Ridge and the present Holocene transgression. While the age of the Silver Bluff shoreline is not certain (see p. 64), Newell (1961) has compared this shoreline with a +2.5 meter terrace of the Berry Islands, Bahamas, which has been uranium-series dated at about 80,000 years. Neumann (1968) reports three elevated shorelines in the Bahamas, the lowermost of which appears to be correlative with the Silver Bluff.

While the age of the oolite rock from the Miami area has not been determined, an oolite body forming the southern Florida Keys has been dated at 95,000 years B.P. (Broecker and Thurber, 1965, p. 59). This is believed to compare with the Oolite Ridge in the Miami area (Hoffmeister, et al., 1967, p. 187). The time of formation of the Silver Bluff notch and of the filling of the channels with quartz sand will be discussed later (see p. 64-65).

Key Largo Ridge

The Biscayne Bay Basin and the Card-Barnes Sound Basin are bounded on the east by a narrow, elongate Pleistocene coral ridge, which will be called here the "Key Largo Ridge". This arcuate feature rises above sea level along the southern part of Biscayne Bay (B in Figure 3) and extends southward forming the Florida Keys south of Key Biscayne. To the north of Soldier Key, the Key Largo Ridge is present as a less pronounced subsurface feature (C in Figure 3). It underlies the "Safety Valve" shoal area and Miami Beach and appears to lie slightly seaward of Key Biscayne and Virginia Key. Coral rock is present in this
bedrock ridge under Key Biscayne, Virginia Key, and Miami Beach (Hoffmeister, et al., 1967, p. 186).

The rock constituting the ridge is composed of typical Atlantic reef corals (Figure 16a). Sanford (1909, p. 214) named this unit the Key Largo Limestone. A more recent description of the character and extent of the Formation has been made by Hoffmeister and Multer (1962; 1968). An excellent treatment of the petrology and paleoecology of the unit has been given by Stanley (1966). Coral rock from the surface of the ridge has been dated between 95,000 and 140,000 years B.P. (Broecker and Thurber, 1965, p. 59) indicating that the development of the Key Largo Ridge was, at least in the latter (upper) part, contemporaneous with the formation of the Oolite Ridge.

General cross-sections of the Key Largo Ridge may be seen in Figures 36-47. Characteristically, there is a sloping rampart to the seaward and an abrupt rise to the ridge crest where it is exposed as an island. On the bay side the Ridge drops sharply, and in the Soldier Key area drops to 4 meters below sea level within 50 meters of the Ridge crest. Cores which penetrated bedrock bayward of the Key Largo Ridge indicate that the reef coral facies grades abruptly to the west into a calcarenite rich with mollusc fragments, suggestive of the Fort Thompson Formation (Parker, et al., 1955, pp. 93-95).

From the Ragged Keys south, the Key Largo Ridge has provided almost a complete barrier and is generally present as a single narrow feature. However, in the area of Old Rhodes Key and northern Key Largo, the Ridge becomes broader and quite complex in character (Figure 3). A number of major tidal channels cut through the rock ridge in this area (Figure 13). The irregularity of the ridge structure here
suggests that these channels were present during the formation of the ridge.

While sub-aerial erosion has smoothed and somewhat modified the reef form, the Key Largo Ridge retains much of its depositional morphology.

Sloping Platform

The western shore of Biscayne Bay south of the Oolite Ridge is characterized by a shallow, gradually sloping bedrock platform. From Cutler to Homestead, this platform intersects the eastern slope of the Oolite Ridge at or slightly above sea level. Throughout this central part of Biscayne Bay, the platform slopes eastward to the deep axis of the Bay. The bedrock surface then rises abruptly onto the Key Largo Ridge. Superimposed on this sloping platform in this area are two northwestward protruding bedrock ridges.

At the south end of Biscayne Bay, a broad shallow eastward extension of the sloping bedrock platform, lying 1 to 2 meters below sea level, all but cuts off Biscayne Bay from Card Sound to the south (D in Figure 3). This platform is called here the "Arsenicker Keys Platform." To the east, this platform drops sharply to the deep axis of the Bay. Rock at the surface is composed of a coarse calcarenite containing abundant coral (especially Porites sp.) and mollusk skeletons. This extended bedrock platform appears to be a deposition feature associated with the increased water circulation funneled through the channels cutting the Key Largo Ridge in the adjacent Old Rhodes Key area. To the south the platform drops into the Card-Barnes Sound Basin.
South of Biscayne Bay, the bedrock platform slopes gradually eastward and southward from the Homestead area. The platform is about 2 meters below sea level at the west edge of Card Sound and Barnes Sound. Here the platform drops sharply into the Card-Barnes Sound Basin (Figures 45 and 46). This submerged slope has been termed the "Everglades Rise" (E in Figure 3).

Open Bay Basins

Two distinct basins are present in the area of study - Biscayne Bay Basin (F in Figure 3) to the north and Card-Barnes Sound Basin (G) to the south. The deep axis of these basins, which might be a back-reef lagoon trough of a previous interglacial, parallels the Key Largo Ridge and lies close to it. The deep axis of the basins extends the length of the study area and joins the two basins.

Biscayne Bay Basin is an irregular basin 3 to 6 meters deep and somewhat deeper in the vicinity of Key Biscayne. From the Coral Gables area north the basin remains deep across the Bay from the Key Largo Ridge to the Oolite Ridge. To the north it narrows and gradually shoals to about 2 meters near Baker's Haulover where the Oolite Ridge and the Key Largo Ridge converge. Behind Miami Beach and Virginia Key, the basin slopes gradually eastward from two mainland to a depth of 3 to 4 meters. While probing data in this area is somewhat limited, there appears to be a low ridge, having less than 2 meters relief, running along the center of the basin from Virginia Key north.

The Biscayne Bay Basin is deepest in the vicinity of Key Biscayne and here the bedrock floor is irregular and does not show the eastward slope characteristic of the rest of the Bay (Figures 37-39).
South of Key Biscayne the Bay floor is an eastward extension of the sloping bedrock platform of the mainland. To the south, towards the Arsenicker Key Platform, the basin shoals and the deeper axis of the Bay narrows to the east.

The deep axis of the Biscayne Bay Basin deepens from Elliot Key north and from Miami Beach south to the vicinity of Key Biscayne. Bedrock in the Key Biscayne area is mantled by a thick sequence of Holocene sediments through which probing was difficult or impossible with available equipment. However, available probing data and commercial core records* indicate that there is a major channel cutting through the Key Largo Ridge in the vicinity of central Key Biscayne.

Card Sound and Barnes Sound form a nearly flat continuous basin 3 to 5 meters deep. To the north the basin rises sharply onto the shallow Arsenicker Keys Platform, except near the Key Largo Ridge where the deep axis extends north to the Biscayne Bay Basin. In the Card-Barnes Sound Basin the deep axis is much broader than to the north. It is characteristically, however, situated near the Key Largo Ridge. To the east the basin rises abruptly to the Key Largo Ridge. To the west it rises along a line, here termed the Everglades Rise (E in Figure 3), onto a submerged bedrock platform which extends into the Everglades. The basin depression continues southward under Cross Key (the route of highway U.S.1) into Buttonwood Sound.

*Over 70 commercial and government core boring records were examined from Miami Beach, Fisher Island, Virginia Key, and Key Biscayne. Wingerter Laboratories, the Public Works Department of the City of Miami Beach, Corps of Army Engineers, and Belcher Oil Company generously made these records available for study.
Sub-Aerial Erosion

The major morphology of the bedrock surface appears to be of depositional origin. During sub-aerial exposure of the Wisconsin Glacial Stage, two major types of drainage features were superimposed on the existing bedrock surface causing some topographic modification on a small scale. Solutional features predominate over other erosional features throughout most of southern Florida (Parker, et al., 1955, p. 128). In coastal areas, such as the Biscayne Bay area, however, both dendritic stream patterns and karst drainage patterns are present. Where there is little sediment cover, as in much of southern Biscayne Bay, these ancient drainage patterns are revealed by aerial photography (Figure 8 and 13).

Dendritic Drainage Pattern

There is an irregular abandoned drainage divide extending from the north end of Elliot Key to the southwest. North of this drainage divide the Bay axis deepens to more than 6 meters in the vicinity of Key Biscayne. From the north, the Bay axis behind Miami Beach also deepens to the south to the vicinity of Key Biscayne. These two ancient drainage systems appear to converge and pass seaward through the Key Largo Ridge somewhere in the vicinity of central Key Biscayne (Figure 3). Additional evidence for this is provided by a test boring made in central Key Biscayne which reached bedrock 9 meters below sea level after passing through 2 meters of quartz sand. Probings to the immediate north and south of this channel indicate rock at several meters shallower depth.

Areas of Biscayne Bay to the south of the drainage divide show a denritic pattern on the bedrock floor which trends southward to the
vicinity of Broad Creek at the south end of Old Rhodes Key (Figure 13). The axis of the Card-Barnes Sound Basin deepens to the north also towards the vicinity of Broad Creek. The bayward side of the Broad Creek area is now covered by Recent sedimentary shoals. Probing data, abandoned channels in the Recent sedimentary shoals, and the presence of a major bedrock drainage channel seaward of Broad Creek, strongly suggest that this area was a primary path for drainage of the southern part of the Bay when it was subaerially exposed during the lower sea level of the Wisconsin Glacial Stage. Probing and aerial photography show that the major and minor tributaries of these old drainage systems extend above sea level and form the present creeks and rivers (Figures 8 and 14).

Solution Drainage Pattern

The bedrock ridges, platforms, and basins of the Biscayne Bay area are spotted with numerous solution holes, a characteristic of limestone surfaces in the South Florida-Bahama region. Many of these holes are as small as 5 to 10 meters in diameter at the surface. There are, however, a number of much larger ones, all of which are filled. Air photography revealed twelve of these in Biscayne Bay and numerous others on the surrounding land. Often a minor, radial, dendritic drainage pattern is associated with these large solution holes, as shown in Figure 8. On the Bahama Platform similar large solution holes which are not filled are called, "Blue Holes", and have been described by Newell (1959). Lead line soundings in these Blue Holes have recorded depths over 75 meters, indicating that these large solution holes formed and served to drain the emergent South Florida-Bahama
carbonate platforms during the low glacial sea-level stands.

Local Bedrock Character

Throughout the South Florida and Bahamian platforms, the bedrock surface is often covered with a lithified, calcareous soil crust. Multer and Hoffmeister (1968) have classified these crusts into three types, all of which are formed during periods of sub-aerial exposure. Similar crusts are commonly seen at all depths on the Bay floor. The preservation of subaerially-formed crusts now outcropping below sea level (Figure 16b) indicates that bedrock erosion and surface reduction accompanying the Holocene transgression has been slight or negligible over much of the area that now forms the floor of the Bay. On the other hand, the east coast of Key Largo forms an exposed seaward energy barrier which may have suffered more intense erosion of the bedrock surface. Ginsburg (1953) has described the biological erosion here by rock boring and browsing organisms, and Neumann (1965) and McLean (1964) have shown that where biological erosion is active, it can proceed at a fairly rapid rate. Within the Bay area, however, most of the bedrock surface (except on the Oolite Ridge in the vicinity of Coconut Grove) does not appear to have been affected by erosion. Sub-aerial soil crusts served as an impermeable cap and protected the bedrock from solution erosion during times of lowered sea level. During Holocene flooding nearshore and swamp sediment deposits mantled the bedrock surface and protected it from biological or solutional erosion, and the seaward Key Largo Ridge protected it from mechanical erosion by waves.

Local bedrock relief is shown by vertical dots in the cross-sections in Figures 36-47. These dots represent the several probings
which were made at each station. Throughout much of the Bay, there is very little local relief. Exceptions to this are areas along the western part of Biscayne Bay from Coral Gables north, and throughout the Bay in the vicinity of Key Biscayne. These areas exhibit extreme bedrock relief; as much as 2 meters of vertical relief were measured within 1 meter of horizontal distance. The bedrock surface was also found to be more irregular along the deep axis of the Bay. It is probable that the irregular surface character of these areas of great local bedrock relief developed during the sub-aerial exposure, and are areas where the concentration of fresh water runoff in these general depressions resulted in greater solutional downcuttings.

Summary of Pre-Holocene Development

Much is still in evidence of the late Pleistocene sedimentary history of South Florida. During the Sangamon plus 7-meter stand of sea-level, the Key Largo Limestone formed as a line of patch reefs extending south from Miami Beach. The reef paralleled the shelf edge but lay several kilometers behind it. A north-south trending back reef lagoon was present in areas where the reef was continuous and well developed. These lagoons were the depressions which were to contain Biscayne Bay, Card Sound and Barnes Sound during the subsequent interval of high sea level. Where natural channels cut through the reef, sediment accumulations (such as Arsenicker Rise) developed behind the reef. Where the reef was less well developed (north of Soldier Key) stronger tidal currents extended across the back reef lagoon and controlled the formation of the submarine oolite tidal bars on which Miami, Coral Gables, and Homestead now rest. The once loose
sediment is now lithified and referred to as the Oolite member of the Miami Limestones (Hoffmeister, et al., 1967). To the north of Miami the oolite shoal graded into an elongate, north-south trending quartz shoal body, the "Pamlico Sand". This sand was a clastic influx from the north and its position was determined by the same hydrographic factors that controlled the position of the carbonate oolite body which was its southern extension. To the west of the back reef lagoon and the shallower sediment accumulations was deposited the muddier bryozoan facies of the Miami Limestone in water 3 to 10 meters deep.

After the Sangamon crest of sea level at 7 meters which Hoyt and Hails refer to as the Pamlico shoreline, sea level began dropping in response to a return to glacial conditions. Hoyt and Hails (1967), working along the southeast coast of Georgia, and others have recognized a still stand or crest of a sea level oscillation at plus 4 meters (Princess Anne). There is, as yet, no evidence of this in the South Florida area. The late Sangamon plus 2 to 3 meter stand of sea level (Silver Bluff) is well recorded in southeast Florida. The type location for the Silver Bluff shoreline is the short cliff and notch formed in the east side of the Oolite Ridge between Coral Gables and Miami. The Silver Bluff has also been recognized by Hoyt and Hails (1967) in Georgia and by Neumann (1968) and Newell (1965) in the Bahamas. In addition to notches having been formed in the now emergent Oolite Ridge body, infilling of the oolite channels with quartz sand may have taken place during this plus 2.5 meter Silver Bluff sea level stand of the late Sangamon. If these three sea levels correspond to the three lower reef terraces recently dated by Broecker et al. (1968), they would be: Pamlico, $120 \times 10^2$ yrs; Princess Anne, $100 \times 10^3$ yrs; and
Silver Bluff, 80 x 10^3 yrs. (Neumann, 1968).

During the Wisconsin Glacial Period which followed sea level was lowered well below the level of the South Florida Platform. Sub-aerial crusts formed on the exposed surface of the carbonate sediment bodies, a process which helped to preserve the depositional morphology of the carbonate sediment bodies. Vegetative cover may have helped stabilize the quartz sediment bodies. Solution and dendritic drainage patterns were superimposed on the carbonate surface causing minor, localized erosion.

About 20,000 years B.P. the Wisconsin Glacial State began to wane and sea level began to rise towards its present level. The remaining chapters describe the Holocene (post-glacial) history of sedimentation in the Biscayne Bay area.
Stability of the South Florida Platform

Through studies of elevated marine terraces and terrace deposits, it appears that the South Florida Platform has been tectonically stable throughout the Pleistocene and possibly since the Miocene (Alt and Brooks, 1965; Cooke, 1945; Davis, 1943; MacNeil, 1950; Parker and Cooke, 1944; Scholl, 1964). Thus, on the basis of available information the Holocene (post-glacial) rise of sea level in South Florida appears to have been purely eustatic.

Sea Level Rise

During the past 20,000 years, sea level has gradually (and possibly irregularly) risen from about -100 meters to its present level in response to melting of the ice masses of the Wisconsin Glacial Stage. Radio-carbon dating of sea-level-associated sediments and fossils has been used extensively to examine the character of this sea-level rise. A number of studies, however, are in major disagreement as to the sea-level trend during the past 8,000 years (Bloom and Stuiver, 1963; Fairbridge, 1961; Harrison and Lyon, 1963; Redfield, 1967; Redfield and Rubin, 1962; Scholl, 1962; Shepard, 1960b; Shepard, et al., 1967; Stuiver and Daddario, 1963; Upson, Leopold, and Rubin, 1964). Conflicting interpretation of raised terraces and reefs, the possibility of tectonic instability, compaction of peat, uncertain relation between
sample depth and sea level, and contamination of carbon-14 dated samples have been primarily responsible for this confusion. Shepard (1963b) has evaluated many of these studies and presented a general curve for sea-level rise during the past 20,000 years. More recently, Scholl and Stuiver (1967) have published a generalized curve for eustatic sea-level rise during the past 4,400 years based primarily on data from South Florida sediments (Figure 34). These studies have essentially disproven the possibility that sea level has been stable during the past 3,000 years. The elevated coral rubble terraces on islands of the Central Pacific now appear to offer no evidence for post-glacial high stands of sea level (Shepard, et al., 1967) as had earlier been suggested by Daly (1920) and Fairbridge (1961).

According to the curve of Scholl and Stuiver (1967) (Figure 34), marine waters first entered the deepest parts of the Biscayne Bay Basin (approximately 7 meters below present sea level) about 5,400 B.P. From 5,400 to 3,500 B.P., sea level rose at about 30 cm/100 years (ibid., 1967; Redfield, 1967). From 3,500 to 1,700 B.P., the average rate of sea-level rise diminished to about 6 cm/100 years, and from 1,700 B.P. to the present, the rate of eustatic sea-level rise has been only about 3 cm/100 years (Scholl and Stuiver, 1967). Thus, sea level rose rapidly to about -1.6 meters (3,500 B.P.), and has risen much more slowly since.

Climate

Paleotemperature studies based on oxygen isotope analysis of the shells of marine molluscs from human food refuse occurring in dated sedimentary layers in caves bordering the Mediterranean have shown
that marine surface temperatures have varied only within 2° C. of modern values for the past 6,500 years (Emiliani, et al., 1963). Thus, the marine sedimentary deposits present in the Biscayne Bay area should record no long term environmental changes as the result of temperature changes.

Depositional Controls

During the latter part of the Holocene (post-glacial) rise in sea level, the shallow limestone basins of the Biscayne Bay area were inundated by the sea. The sedimentary record deposited on this bedrock surface has been controlled by an interaction of bedrock topography, sediment source and supply, wave and current action, biologic environments, water hydrography, rate of sea-level rise, and post depositional chemical alteration. Bedrock topography, through its influence on currents and circulation, may be considered a primary control (Ball, 1967, p. 557). Storm and hurricane energies have left their mark but appear to be of minor importance to the overall development of sediment bodies. During the past 100 years, man's activities have caused many changes, especially in the northern part of Biscayne Bay. While man-made channels and bulkheads are not to be confused with depositional controls of the past, they will be dominant controls in the northern part of the Bay in the future.

General Features

Figure 5 shows the thickness of Recent sediments present in the Biscayne Bay area. This sediment buildup appears to represent a single rise of sea level which invaded the deeper parts of Biscayne Bay about 5,400 years ago (Figure 34). One of the most notable features is the
general lack of sheet-like sedimentation throughout the Bay area. Sediment buildups which are present form distinct patch-like accumulations controlled by a complex of several factors. Onlapping layers of progressively younger deposits, such as those described in classic transgressive sequences, are the exception more than the rule and are only locally present in the study area. This finding is considered to be significant to the overall study of stratigraphic processes in geology and constitutes one of the most significant results of this study.

Six major sediment regimes are recognized on the basis of sediment type and depositional controls. These are: (A) Sedimentary buildups associated with longshore sediment supply for the north, (B) Intrabay quartz sand accumulations, (C) Mud and sand carbonate tidal bars, (D) Paralic and fresh water swamp deposits, (E) Mud and sand blankets of the open Bay, and (F) Non-tidal mud banks in protected areas.
Within recent years, a number of different ideas have been put forward concerning the development of barrier islands and cape sands. Early workers debated the importance to barrier island formation of sediment introduced by longshore currents versus that brought by wave scouring from the platform seaward of the barrier islands (see Shepard, 1960a, p. 214). More recently the influence of a changing sea level on barrier island development has been considered. Johnson (1919) suggested that most barriers formed where shorelines were either stable or becoming emergent. Price (1954) has suggested that barrier islands may develop during the short period sea-level changes associated with storms and that overall sea-level rise or fall has little influence. Through coring in the barrier islands to the east of Laguna Madre, Texas, Rusnack (1960, p. 191) has concluded that during sea-level rise over the seaward slope the barrier island sequence transgressed landward. He also noted that in the areas where semi-arid conditions prevail, the islands are still undergoing some landward migration, but in more humid regions vegetative stabilization appears to have been responsible for the development of prograding beach ridges (ibid., p. 192). Shepard (1960), through studies on barriers throughout the coast of the Gulf of Mexico, concluded that barrier islands form during, as well as
directly following submergence (p. 215). He also points out the variation in barrier island development which may occur in response to tidal currents and heights, river outflow, and sediment supply. Fischer (1961) has described the barrier islands of New Jersey as forming a classic transgressive sequence. Hoyt (1967) has hypothesized that barrier islands initiate as a wind or water deposited ridge immediately landward of the mainland shoreline and subsequently develop into barriers by flooding of the area landward during gradual submergence. Ball (1967, p. 583) discusses the effect of longshore currents, sediment supply, and waves on the extension of cape sands and the accretion of beach ridges.

Recent studies on the Georgia coastal plain by Hoyt and Hails (1967) have shown that six major Pleistocene high stands of sea level are represented by distinct barrier island and lagoonal-marsh sedimentary developments. Colquhoun, et al., (1968) find two types of Pleistocene barrier islands bordering the Atlantic Coastal Plain: (1) those which are stratigraphically thin and discontinuous and overlie a former land surface appear to have formed during submergence; (2) those which are stratigraphically thick and continuous and overlie shelf sediments formed during sea-level stability or gradual emergence.

General Description

The northeastern part of Biscayne Bay is bordered by sedimentary barrier islands and associated shoals, channels and lagoons that have developed as the result of an influx of clastic sediment transported from the north and offshore by longshore currents. This sediment is characteristically composed of varying amounts of medium to coarse,
subrounded quartz and carbonate grains with lesser amounts of blackened and pitted shell and foraminiferal carbonate, quartz-carbonate rock fragments, and traces of heavy minerals. The carbonate fraction consists mainly of mollusc fragments, foraminiferal tests and Halimeda plates which have been infilled with carbonate material. This general sediment type is quite distinct from other sediments in the study area and will subsequently be referred to in this paper as "longshore clastic sediment". Examples of this sediment type are given in Figure 28.

The influx of longshore clastic sediment has been a dominant influence in the formation of (1) the sedimentary barrier islands of Miami Beach, Virginia Key, and Key Biscayne, (2) the protected lagoon shoal behind Miami Beach, (3) the shoals and channels of Bear Cut and Norris Cut, and (4) an offshore, southward trending bank to the south of Key Biscayne.

Barrier Sedimentary Islands

Miami Beach, Fisher Island*, Virginia Key, and Key Biscayne represent the southern-most extension of the barrier sedimentary islands along the Atlantic coast. These islands have developed to the seaward by progradation and to the south by accretion of beach and dune ridge developments onto the existing shorelines and capes. These islands are distinct from barrier islands to the north along the Atlantic coast in that they have developed in direct association with a now submerged extension of the Key Largo Ridge. The clastic sediment, constituting the body of the sedimentary barrier islands in the study area, contains

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*Fisher Island lies between Miami Beach and Virginia Key. Before dredging Government Cut in 1905, Fisher Island was connected to Miami Beach.
a higher percentage of carbonate material than is present further north.

In addition, several surface facies have undergone recent lithification, a feature not found to the north. The mangrove forests and subtropical carbonate lagoon sedimentation behind the barriers are also distinct from Spartina marshes further north.

The submerged Key Largo Ridge presently lies 3 to 5 meters below sea level under Miami Beach, Fisher Island, and Virginia Key and slight seaward of Key Biscayne.

Coring and probing data of this study indicate that to the west of the Key Largo Ridge, the basal sediments are a thin band of woody peat overlying bedrock, a sandy band, and 1 to 2 meters of carbonate lagoon mud. Longshore clastic sediment sharply overlies the lagoon mud and continues to the surface. Seaward of the Key Largo Ridge, longshore clastic sediment extends to bedrock. Mangrove peat is present only along the protected, bayward side of the islands near the surface and is absent at depth. Strand lines, representing old beach ridges depict the recent (within the past 3,500 years) southerly development of the sedimentary barrier islands. The presence of a semi-lithified, fossilized black mangrove platform (Hoffmeister and Multer, 1965) near the surface on the seaward sides of Key Biscayne and Virginia Key and the seaward truncation of strand lines show that a significant period of erosion has taken place within the past 1,000 years. This is the time interval following lithification of the black mangrove root casts which has been dated by carbon-14 to be 1,000 to 2,000 years B.P. (Hoffmeister and Multer, 1965).
Basal Units of Barrier Sedimentary Islands

A thin non-marine peat generally overlies bedrock in the deeper areas to the west of the Key Largo Ridge. This woody peat varies in thickness from 0 to 10 cm. and fills the irregularities in the bedrock surface. The peat appears similar to the basal peats found throughout much of the rest of the Bay and to those described by Spackman, Scholl and Taft (1964, p. 38). (This peat layer was not dated because of lack of sufficient sample retrieved.)

Overlying the basal peat or lying directly on bedrock is a thin band of quartz-carbonate sand. This sand is not of the longshore clastic sediment type but rather contains fine angular quartz sand, fragile tests of Foraminifera, and shell fragments. Aside from bedrock fragments, the carbonate grains are fresh and often broken but show no grain pore infillings, alteration, or solution pitting.

This band of sand grades abruptly into gray sandy-shelly carbonate mud facies 1 to 2 meters thick. Bedding is not apparent in this protected facies, but grass rootlets are abundant and extensive burrowing is evident throughout the sequence (Figure 23a). The burrows are often filled with quartz sand. Molluscs, especially Chione cancellata Linnaeus, Modulus modulus Linnaeus, and Cardita floridana Conrad, are abundant, and occasionally form complete layers. Again, no longshore clastic sediment was observed in this facies.

Paleoecologic interpretation of the molluscan and foraminiferal assemblages suggests that this mud was deposited in marine waters less than 2 meters deep in a protected area comparable with modern north-eastern Florida Bay. The micro-organisms further indicate the presence of a moderate to dense cover of marine grass which provided a site for
attachment of the organisms during growth. Sieving of the mud reveals an organic hash composed mostly of fragments of *Thalassia* blades. Within the barrier island sequence, the surface of this protected lagoon facies lies 4 to 6 meters below present sea level and is overlain sharply by longshore clastic sediment. To the east of the Key Largo Ridge, the lagoon mud facies was not observed in any of the commercial core boring records which covered the area from North Miami Beach to central Key Biscayne (see p. 31).

A Carbon-14 date was made on shells from the basal lagoon mud beneath Virginia Key. The four species of shell analyzed, *Chione cancellata* Linnaeus, *Modulus modulus* Linnaeus, *Cardita floridana* Conrad, and *Crassispira ostrearum* Stearns, are considered to be indigenous to a shallow lagoon environment (Dr. Donald Moore, of the Institute of Marine Sciences, personal communication). The sample was taken from 494 cm. below sea level (14 cm. above bedrock) and dated at 4,200 ±100 years B.P. (Figure 34). This lies 130 cm. below the sea level predicted by Scholl's curve (1967) and supports the suggestion that the lagoon mud did develop in shallow water.

The question arises, behind what seaward (eastward) protection did this lagoon mud facies develop? If sedimentary barrier islands were present to the east, one would expect to find longshore clastic sediment in the basal lagoon mud such as is present in the lagoon mud forming behind Miami Beach today (see p. 56). Longshore clastic sediment is, however, completely absent from all basal facies. At the time of formation of the basal lagoon mud facies (4,200 years B.P.) sea level was about 3.0 meters below present level (see Figure 34). The Key Largo Ridge would then form a slightly emergent bedrock barrier to the east.
This ridge appears to have provided the protection from offshore wave energy during the deposition of the basal lagoon muds. The Key Largo Ridge presently lies about 3 meters below sea level beneath the sedimentary barrier islands.

**Clastic Longshore Sediment Sequence**

Clastic longshore sediment (see p. 44) sharply overlies the basal units west of the Key Largo Ridge and lies directly on bedrock to the east. Hand probing, coring (Cores 140, 149, and 150) and examination of over 70 commercial core records show that the clastic longshore sediment facies forms the body of the sedimentary barrier islands.

Ball (1967, p. 583) has described two types of bedding developed in barrier capes extended by longshore currents. The lower unit, deposited as a submerged extension of the cape is a festoon cross-bedded marine sand. The upper sequence is composed of beach accretion beds which dip at a low angle to the seaward.

Coring into the barrier sedimentary islands has shown that all of the longshore clastic sequence is well bedded (Figure 23b). While some cross-bedding was observed lower in the sequence, no obvious distinction could be made between nearshore marine and beach deposition.

While the body of the sedimentary barrier islands is composed of an essentially uninterrupted sequence of bedded longshore clastic sediment, near the surface a number of distinctive morphologic and sedimentologic features are present which indicate that a variety of processes have been active during the more recent development of these barrier islands.

**Beach Ridges**

Strand lines, representing old beach ridges indicate the character
of growth of the sedimentary barrier islands. On Miami Beach man's influence has removed evidence of former beach ridges, but on Virginia Key and Key Biscayne, the strand lines are clearly revealed in early aerial photographs (Figure 9). Strand line development on Virginia Key is visible along the eastern shore, but less distinct to the west. Had Bear Cut, the tidal channel presently separating Virginia Key and Key Biscayne, been present during the development of the islands, strand development should trend into the Bay at the south end of Virginia Key. The beach ridges on Virginia Key, however, are truncated to the seaward and appear nearly parallel to the truncated strand developments of northern Key Biscayne. It appears that the two islands were once connected and that the present extensive sand platform to the east of Virginia Key and to the north of Key Biscayne was once a part of a more extensive barrier island development. Other evidence for supporting an earlier period of more extensive barrier island development in this area comes from the presence of protected facies of organic peat and lithified mangrove roots exposed along the eastern shore of Virginia Key and the northern shore of Key Biscayne. These deposits will be discussed in a later section.

Strand lines on Key Biscayne show that the island has developed partly by seaward progradation, but especially by southward extension of the cape by accretion of beach ridges (Ball, 1967, p. 585). Several stages of island growth are suggested by variations in the strand line development. West Point (Figure 9) developed during a period when the sediment supply and longshore currents were being strongly affected by tidal currents moving into the Bay. This relic cape is closely associated with the deep bedrock channel passing through the Key Largo Ridge in this
area (Figure 3). Storm effects, fluctuations in sediment supply and changes in longshore current patterns may have been responsible for other variations in the rate of and character of accretionary beach ridge development onto the existing barrier cape.

Many of the older strand ridges were subsequently partially eroded and are now truncated by younger beach ridges. Recent erosion has truncated older strand lines at the north end of Key Biscayne and appears to have removed considerable beach ridge development from the east of Key Biscayne and Virginia Key.

Once formed, the beach ridges are stabilized by vegetation. The older ridges are, however, much less pronounced than more recent developments. While the older beach ridges may have been somewhat flattened by storms, they appear to have formed at a slightly lower sea level.

**Fibrous Mangrove Peat**

Coarsely fibrous mangrove peat containing roots of the red mangrove, *Rhizophora mangle* is present near the surface of the barrier islands. While most red mangrove peat is free of carbonate matter, the peat of the barrier islands does contain a significant amount of longshore clastic sediment (Figure 23c). Mangrove forests are abundant on the west side of the barrier islands. However, peat accumulation is generally less than 30 cm. Peat deposits are present to a depth of about 1 meter to the west of the oldest visible beach ridge developments (Figures 37 and 38; cores 149 and 150). At several localities on the eastern shoreline of Virginia Key and at the north end of Key Biscayne where recent erosion has been extensive, this fibrous peat is exposed as an eroding bank (C in Figure 9). Scholl (1964a, p. 359), working in the coastal swamps of the Florida Everglades, has observed that red mangroves cannot become established
where water is deeper than about 70 cm. at low tide. He also states that peat accumulation normally occurs only in the upper half of the tidal cycle (ibid.). The shallow occurrence of peat deposits in the sedimentary barrier islands, thus, suggests that the emergent part of the barrier sand complex, the islands, were formed near present sea level.

Mangrove Root Rock

Hoffmeister and Multer (1965) have described an exposed sandstone platform at the north end of Key Biscayne ("A" in Figure 9 and Figure 17a). The framework of this rock, which they term a "fossil mangrove reef", is composed of lithified casts of the roots of the black mangrove, *Avicennia nitida* overlain by a compact, often case-hardened crust about 3 to 5 cm. thick. Less extensive deposits of this mangrove rock have also been found along the eastern shores of Virginia Key and Key Biscayne (localities marked "B" in Figure 9) and also along the small drainage canals penetrating northern Key Biscayne.

Significant erosion of the shoreline has taken place in the areas where the mangrove rock is present. Lineations in the extensive crustose sandstone platform are continuous with the oldest (most westerly) visible strand lines of Key Biscayne ("A" in Figure 9). Here, and in the other areas of "mangrove rock" occurrence ("B" in Figure 9), the present shoreline cuts sharply across older strand development.

It appears that 1,000 to 2,000 years ago these areas were black mangrove forests which received large amounts of longshore clastic sediment (Hoffmeister and Multer, 1965, p. 851). The buried roots of the black mangrove were subsequently replaced by carbonate "paste" (ibid.). Where the recent erosion of Key Biscayne and Virginia Key has been most
extensive, these fossilized mangrove root deposits have been exposed at the shoreline.

**Storm-Trapped Mud**

Storm-trapped layers of sediment are found near the surface on Key Biscayne and Virginia Key. These sediments form broad layers of semi-consolidated, laminated carbonate silts with plant debris concentrated along bedding planes. Mud cracks have formed at the surface of these storm deposited desiccated silts (Figure 17).

This material is deposited during the high storm tides of hurricanes when the sediment laden waters may cover much or all of the sedimentary barrier islands (Corps of Engineers, 1961, p. 7). As the turbid water recedes much of the suspended material may settle out in the protection of the vegetation. As much as 5 cm. of silt was deposited over parts of Key Biscayne during the storm tide of Hurricane Betsy in September, 1965 (see also Craighead, 1964, p. 9).

These silty storm-trapped sediments have been found only above present sea level on the sedimentary barrier islands.

**Surface Environment**

The surface of the sedimentary barrier islands is a combination of presently active depositional and erosional environments and relic features. A typical profile (right to left across line through Key Biscayne in Figure 9) would show an erosional offshore shoal (perhaps an erosional remnant of previous barrier island development), nearshore Thalassia sand flat, beach and beach ridge, dune, older slightly leveled beach ridges (the main expanse of the island surface), black mangrove forest growing near high tide level, red mangrove swamp containing small shallow bays,
and muddy back island shoal. Dune development occurs only along parts of Miami Beach and at the north end of Key Biscayne. To the east of the seaward shoal bedrock is exposed at 4 to 7 meters below sea level.

**Barrier Island Development**

The time of initiation of longshore clastic sedimentation and of barrier island formation in the northeastern Biscayne Bay area appears to have been quite recent. The carbon-14 dated shells from the basal lagoon mud (p.46) under Virginia Key were taken beneath the oldest discernable beach ridge on Key Biscayne and Virginia Key. The date obtained, 4,200 ±100 years B.P. (sample ML-481, Figure 34, Table I), represents a time previous to the presence of longshore clastic sediment in the area.

Sea-level indicators such as red mangrove peat, lithified casts of black mangrove roots, storm deposited muds, and accretionary beach ridges are present in the uppermost section of the barrier island sequence. Within the surface body of the barrier islands, however, the longshore clastic sediment sequence exhibits none of these sea-level associated features that are encountered in the upper parts of the cores. This suggests that the subsurface deposits of the present barrier islands were initially laid down as submarine sand bodies prior to island development which began some time later.

It appears that emergent barrier island development took place near present sea level. If this is the case, the strand line development on the aerial photo (Figure 9) depicts the accretionary development of this southward extending cape. This development appears comparable to the spit accretion described on the island of Bimini, Bahamas (Ball, 1967, p. 585). Longshore currents form an initial submarine extension of the
clastic sediment. Beach ridge accretion subsequently develops as wave energy moves sediment onshore. The most recent epoch of erosion of the barrier sedimentary islands appears to have been primarily the result of man's activities which have cut off the supply of sediment from the north, especially following the construction of Government Cut Jetties at the south end of Miami Beach in 1905.

While the clastic barrier island sands overlie the basal lagoon muds, it should not be considered a transgressive sequence or compared with areas where the barrier island has migrated landward. The basal lagoon mud formed behind the protection of the Pleistocene bedrock Key Largo Ridge. Longshore clastic sediment subsequently moved southward along the eastern side of and capped the Key Largo Ridge. In areas where the Key Largo Ridge is less pronounced, barrier island development extended to the west of the Ridge covering part of the basal lagoon mud facies. While this took place during a period of slowly rising sea level, no classical landward transgression of a clastic sediment wedge is implied.

When did the barrier island formation begin? Several observations suggest that it was within the past 3,000 years.

The calcareous "paste" of the fossilized black mangrove roots has been carbon-14 dated at 1,000 to 2,000 years B.P. (Hoffmeister and Multer, 1965, p. 851). The mangrove rock is present at the surface of the older beach ridge developments. The formation of these relic beach ridges must have been previous to the presence of the mangrove forest, because the root-casted sandstone most probably formed on the Bay shore side behind the protection of the beach ridges.

Possible evidence also comes from the elevation of these relic beach ridges. Presently forming beach ridges are about 2 to 2.5 meters
above mean low water. The oldest beach ridges discernable on aerial photographs are less than 1 meter above mean low water. These older beach ridges still have distinct form and are heavily vegetated. If these old beach ridges developed under similar conditions of sediment supply and wave energy as are present today, and if the relic beach ridges have not eroded significantly, then they must have developed at a slightly lower sea level (1 to 1.3 meters below present sea level). According to Scholl's curve for sea-level rise, sea level was 1 meter below present sea level about 3,000 years B.P. (Figure 34).

It appears therefore that longshore clastic sediment was introduced from the north sometime after 4,200 years B.P. and that barrier island formation began in this area about 3,000 years ago, perhaps in association with the decreasing rate of sea-level rise (Figure 34). Similar dates for the oldest surface expression of beach ridges and marsh development have been obtained by Shepard (1960a, p. 218) along the Gulf Coast and by Newman and Rusnack (1965, p. 1466) along the eastern shore of Virginia.

Protected Lagoon Shoal

Within Biscayne Bay, behind Miami Beach and Virginia Key, is an extensive shallow lagoon 1 to 2 meters deep. To the east the shelly, sandy, carbonate mud facies of this lagoon grades into the longshore clastic sediment of the barrier sedimentary islands. The western limit of this lagoon facies is a narrow, submerged bedrock rise trending north-south along the center of the Bay (Figure 3). To the west of this rise is a pure quartz sand body (Figures 36 and 37).

Bedrock lies 4 to 6 meters below sea level beneath the protected
lagoon shoal giving a sediment thickness of 2 to 4 meters.

Probing has indicated that here, as under the sedimentary barrier islands, a peat layer and band of coarse sand form the basal sequences over an irregular bedrock surface. The muddy lagoon sands overlie this. The lower part of the sequence is similar to and probably continuous with the basal lagoon deposits beneath the barrier sedimentary islands to the east. The upper part of the lagoon mud facies west of the barrier islands, however, is much sandier (Figure 36; core 160). Longshore clastic sediment becomes present and may constitute as much as 30 per cent of the sand fraction. This sand was probably introduced into the lagoon as washover deposits during storms. The upper half of the lagoon sequence is thus a gray, muddy, quartzose shelly sand in which grass rootlets are abundant. The sediment appears to have been extensively reworked by burrowing organisms, but bands of sand and layers of shell, especially Crassostrea virginica, are present.

Within northern Biscayne Bay, the lagoon muddy sand facies forms a continuous sequence above bedrock, in which longshore clastic sediment becomes present towards the top. It thus appears that there has been a protective barrier to the east throughout the development of the sequence. The lower part of the facies first formed behind the protection of the slightly emergent Key Largo Ridge, as did the basal lagoon mud beneath the barrier sedimentary islands. The longshore clastic body subsequently encroached from the north over the submerging bedrock ridge, covering a part of the lagoon sequence but providing continued protection for the accumulation of muddy lagoon sand further to the west (Figure 37).

As recently as 100 years ago, the waters in Biscayne Bay to the
north of Key Biscayne supported the environments which produced the lagoon muds. Today, as a result of man's pollution of northern Biscayne Bay and because of dredging and the development of bulkhead islands and causeways within the Bay and consequent restriction of circulation, the surface environments of northern Biscayne Bay have been altered or destroyed and the bottom is covered by a floculant organic ooze 10 to 30 cm. thick. Only in a few areas, such as part of the shoal area west of Virginia Key (Figure 9), have conditions escaped the effects of pollution (McNulty, 1961).

Bear Cut And Norris Cut

Two natural tidal inlets pass through the barrier sedimentary islands.* Norris Cut passes between Fisher Island and Virginia Key. Bear Cut passes between Virginia Key and Key Biscayne. Both channels are cut to bedrock 4 to 7 meters below sea level. Seaward and bayward the channels digitate and shoals are present.

The shoals east of Norris Cut and Bear Cut form a broad shallow sand platform as much as 2 kilometers wide. Probing on these shoals reveals sand layers, impenetrable by hand probing methods, which were 4 to 6 meters below sea level. Similar deposits were encountered on Virginia Key and Key Biscayne. Peat and mangrove root rock are present along the northern and eastern shorelines of Virginia Key and at the north end of Key Biscayne indicating that the strand lines of these islands once extended further seaward. The shoal development seaward of the channels thus appears, at least in part, to be an erosional remnant

*Two man-made channels are also present through the barrier sedimentary islands. Government Cut, at the south end of Miami Beach was dredged in 1905. Baker's Haulover at the north end of Miami Beach was dredged in 1923-1924.
of previous barrier island sediment development into which the tidal channels have been cut. This seaward shoal platform is presently covered by an extremely dense cover of living Thalassia. The area is relatively unprotected from offshore storms, and thus blowouts (Hoskin, 1963, p. 27) or sand holes (Ginsburg, 1956, p. 2409), are abundant where these Thalassia beds have been ripped out forming crescentic scars along portions of the seaward shoal platform.

The eroding, intertidal peat platforms at the north end of Virginia Key, bordering Norris Cut, are capped with platforms of sabellid worm encrustations. This soft, friable deposit is formed by the colonial marine polychaete, Phragmatopoma lapidosa, whose tubes are lined almost entirely with platy, fairly well-sorted shell fragments (Multer and Milliman, 1967; Kirtley and Tanner, 1968). On the shoals seaward of Norris Cut, the sabellid worm rock is present below sea level as lobe-shaped mounds growing on a sandy bottom. Probing seaward of Norris Cut reveals that this worm rock is also present about 2 meters below the sediment surface.

The shoals west of Norris Cut are principally muddy lagoon sands which become sandier towards the tidal channel.

To the west of Bear Cut, a number of small shoal bodies have developed where the channel becomes less restricted and tidal current velocities decrease. The surface environment of these shoals is very similar to that of the tidal bar belt (see p. 80). Thalassia forms a moderate to dense cover and Halimeda and echinoids are abundant. Coring, however, has revealed the body of these shoals to be quite distinct from the algal-plate muds of the tidal bar belt. Here, the entire sequence is composed of a poorly bedded, burrowed, longshore clastic
sand (Figure 38; core 151). While Thalassia beds have helped to maintain these shoals, a comparison of aerial photography from 1940 to 1960 indicates that some migration has taken place.

Bear Cut and Norris Cut do not appear to be remnant features, but rather to have developed within the past 1,000 years or so as storms and changing longshore current patterns have eroded the newly formed sedimentary barrier islands.

Southerly Offshore Trending Bank

The longshore clastic sediment body extends to the south of the sedimentary barrier islands as a shallow sand bank lying about 1 kilometer to the east of the Key Largo Ridge. To the south this bank narrows to an irregular shoal lying about 2 meters below sea level. East of Soldier Key, this shoal terminates on a broad sand flat 6 to 8 meters below sea level. It is not certain whether wave and current action break up this longshore clastic shoal body to the south or whether this shoal body is the southernmost extension of a presently advancing longshore clastic sediment body.

The northeast end of the Safety Valve contains some longshore clastic sediment. The clastic influence is, however, surprisingly small despite the immediate proximity of the Safety Valve to the south tip of Key Biscayne (Cape Florida) and to this southerly offshore trending bank (Figure 12). The sediments of the Safety Valve are a carbonate, algal plate mud and are discussed on page 81.
B. INTRABAY QUARTZ SAND ACCUMULATIONS

General Description

Quartz sand is present in varying amounts in nearly all sediment accumulations in Biscayne Bay except those which developed behind the protection of a mangrove swamp barrier. In contrast to the frosted, well-rounded quartz characteristic of the longshore clastic sediment (Figure 28), quartz sand throughout the rest of the Bay is clear and more angular in character (Figure 32). There are several areas in the Bay where quartz sand has formed nearly pure sand bodies. (1) The deep depressions and channels of northern Biscayne Bay contain basal sequences of nearly pure unconsolidated quartz sand which may be a remnant pre-Holocene feature. (2) The northwestern part of Biscayne Bay is filled with a nearly pure quartz sand sequence. (3) Along the mainland shore from the north end of Biscayne Bay south to Card Sound, quartz shoals and beaches are developed in response to southerly longshore drift within the Bay. (4) Offshore, within Biscayne Bay, quartz sand has accumulated to form shoals associated with rises in the underlying bedrock surface.

Before examining the distribution of these quartz buildups, possible sources and methods of concentration of quartz sediment should be discussed.

Source of Quartz Sand

Longshore clastic sediment of the sedimentary barrier islands (see p.44) contains large amounts of quartz. This quartz is coarser,
more frosted and better rounded than quartz found with the Bay. The longshore clastic sediment has been an active sediment source in the northern part of Biscayne Bay only within the past 3,000 to 4,000 years. Many of the quartz sand bodies and accumulations containing quartz sand within the Bay were deposited previous to this influx (see p. 46). Longshore clastic sediment, thus, should not be considered a source for the quartz within the Bay.

Scholl (1963, p. 1598) and Spackman, Scholl, and Taft (1964, p. 44) have suggested the underlying bedrock may be a source of the quartz found in the Holocene deposits of southwestern Florida. Quartz is present in the Pleistocene bedrock underlying Biscayne Bay. It becomes especially abundant in the Miami Limestone to the north where the nuclei of many of the oolites are quartz grains. Erosion of the bedrock and dissolution of the carbonate would give some free quartz sand. The marked increase in abundance of quartz in the Miami Limestone to the north, however, indicates the presence of a larger supply of quartz nearby to the north.

Vaughan (1910a) has suggested that much of the quartz sand within Biscayne Bay may have been introduced from the Pamlico quartz sand body (Figure 32). The Pamlico sand is a gray-white to brown or black carbonaceous quartz sand which overlies bedrock in southern Florida, and along the east coast it forms the Atlantic Coastal Ridge south "to about the latitude of Miami" (Parker, et al., 1955, p. 106). This sand body formed in part as a submarine bar during the late Sangamon plus 8 meter Pamlico shoreline stand (Cooke, 1945, pp. 51-58). The proximity of the sand body to northern Biscayne Bay and the similarity in sediment type to the quartz found in the Bay strongly suggest that the Pamlico sand is a
primary source for quartz sand within Biscayne Bay (Figure 32). The time and method of introduction of the quartz sand into the Bay is discussed on p. 64-65.

Methods of Concentration

While the primary source of the quartz sand, the Pamlico sand, is quite pure, the material may become mixed with other sediment material within the Bay. There are several processes which appear to be at work within the Bay to reconcentrate the quartz into a pure sand body.

Wind, waves, and currents acting along the shoreline appear to be excellent sorting mechanisms for concentrating quartz. Much of the skeletal carbonate material within the Bay is platelike, hollow, and porous, and has a much lower excess density than the quartz grains (see Shepard, 1963a, pp. 109,110). This carbonate material will be more susceptible to transport and removed preferentially to quartz grains.

Mangrove peat appears to be responsible for the concentration of some quartz sediment. Storm tides of winter storms and hurricanes have deposited large amounts of quartz-carbonate sediment over forested mangrove platforms. The acidic environment of red mangrove peat quickly leaches all carbonate material from the sediment leaving only quartz and organic material (Goodell and Gorsline, 1961, p. 84; Craighead, 1964, p. 9). Subsequent physical breakdown and erosion of this peat would leave a pure quartz sediment, the lighter organic fraction being washed away. An excellent example of this process is found in the peat sequences to the east of Barnes Sound. Nowhere in the Sound does quartz make up more than one per cent of the beach or nearshore sediment. The top few centimeters of the peat contains storm deposited quartz-carbonate silt, but the only
non-organic sediment within the mangrove peat sequence in this area is a fine quartz sand.

Channel And Trough Filling - Remnant Sands

The deeper bedrock drainage channels of northern and southern Biscayne Bay appear to contain a basal 1 to 2 meters of quartz sand. This quartz sand also fills the channels or vales of the exposed Pleistocene Oolite Ridge (Figure 40). The presence of quartz sand bodies in these channels and depressions and the abundance of quartz sand in the basal sedimentary units throughout the Bay suggests that quartz might have been present within the Bay previous to the Holocene transgression. The basal part of the Pamlico sand which approaches the Bay at the northwest end is situated slightly above present sea level and, aside from wind transport, could not have fed sediment into Biscayne Bay during the Holocene transgression. It is thus probable that much of the quartz entered the Bay during a sea level stand higher than the present but following the period of formation of the Oolite Ridge.

Hoyt and Hails (1967), through studies of relic barrier islands along the Georgia coast, have recognized two late Sangamon high stands of the sea following the Pamlico plus 8 meter sea-level high during which the Oolite Member of the Miami Limestone formed. These are the plus 4 meter "Princess Anne" shoreline and the plus 3 meter "Silver Bluff" shoreline. Neumann (1968) has suggested that these three shorelines correspond in age to the three lower reef terraces of Barbados' dated by Broecker et al. (1968) at 120 thousand, 100 thousand and 80 thousand years B.P. respectively. The Princess Anne shoreline has not been recognized in South Florida. On the other hand, in the Miami area
is the type locality of the Silver Bluff shoreline (plus 3 meter contour in Figure 3), and this has been described by Parke and Cooke (1944), Cooke (1945), and Parker, et al. (1955). Newell (1961) has correlated the Silver Bluff shoreline found along the southeastern coast of the United States with a plus 2.5 meter terrace on the Berry Islands, Bahamas. This Bahamian terrace has been dated by uranium-series methods to be about 80,000 years old (Broecker and Thurber, 1965).

Much of the clear, angular quartz may have entered Biscayne Bay during one or both of these late Sangamon high stands of sea level, some of the sand being carried into the channels of the then lithified Oolite Ridge by wave and current action. While some of this quartz sand appears to have been preserved as basal channel units, the rest was reworked as the Holocene sea invaded Biscayne Bay.

It is also possible that some of the Pamlico quartz sand body was transported into Biscayne Bay and the channels of the oolite shoals by wind transport during the Wisconsin Glacial Stage. If reworking by wind had been extensive one would expect old coastal landforms (dunes, barrier islands and submarine bars) of the Pamlico Formation to have lost much of their original depositional topography. These developed during the plus-eight-meter late Sangamon (Pamlico) sea-level high (Cooke, 1945; Parker, et al., 1955) and have remained essentially unaltered in form until the present. Locally, beach ridge and dune deposits at altitudes higher than 8 meters have been preserved (Parker, et al., 1955, p. 106).

Furthermore, wind transport would distribute the eolian sand on the tops or sides of topographic highs rather than as flat sheets filling topographic lows which is how the quartz sand now fills the floors of the transverse vales of the Miami Oolite Ridge.
Quartz Sand Body In Northwestern Biscayne Bay

As sea level rose over the Biscayne Bay Basin, the quartz sand which was already abundant in the northern part of the Bay was moved to the west by currents and wave action. The western side of Biscayne Bay from Coral Gables north forms an irregular elongate depression 6 to 8 meters deep. Quartz in this area appears to have been deposited in bedrock basins at or near sea level. Core 152 (Figure 32), taken east of "Vizcaya", northwestern Biscayne Bay, revealed a black fibrous peat at 360 cm. depth. Above and below this peat was a sequence of wispy organic laminated quartz, commonly observed forming in the near-shore quartz shoals today (Figure 24a). The peat at 360 cm. has been carbon-14 dated as having formed 4,270 ±100 years B.P. This lies less than 10 cm. below sea level curve predicted by Scholl and Suiver (1967). It thus appears that this quartz sediment body developed in association with sea level.

To the south of Coral Gables, there is no bedrock depression on the west side of Biscayne Bay. While there was less remnant quartz in this southern part of the Bay, that which was present had no negative area in which to be deposited. Thus, much of the quartz to the south remained as a shoreline-associated sand body, migrating west as sea level rose and at the same time being carried south in response to longshore drift. In a few areas shorelines formed at a lower sea level have been preserved and quartz is seen to have been present in southern Biscayne Bay (Appendix II, core 96).

Quartz Shoreline Shoals And Beaches

Today the mainland shoreline from the north end of Biscayne Bay south to Card Sound is bordered by shallow banks and beaches of nearly
pure quartz sand (Figure 18a) (See also Sanford, 1909, p. 228). While these quartz shorelines are predominant on eastward facing shores, they are also present along other faces. The west side of Soldier Key contains a beach of nearly pure quartz sand. The mangrove islands dotting the Arsenicker Keys Platform contain quartz beaches facing to the east, south, and west.

That these shoreline accumulations are actively forming may be seen by their presence along recently formed man-made features. Along the south side of Rickenbacker Causeway (connecting Virginia Key to the mainland), quartz beaches and shoals have formed within the past 25 years. Chicken Key (southwest of Shoal Point in Figure 8), also a small man-made feature, is bordered by a broad quartz shoal and spit which have developed within the past 60 years.

As far south as Cutler, quartz forms a nearly continuous line of shoals and beaches (Figure 8). These deposits are generally 1 to 2 meters thick, capping an eroded peat platform (Core 2). In areas, such as Shoal Point (Figure 8), where littoral drift has extended the sand southward as a submarine spit, the quartz may cap bedrock.

A certain amount of quartz sediment influx is necessary to maintain a quartz shoreline because storm waves carry the sediment inland onto the presently forming mangrove peat surface. Southerly littoral drift, probably from the quartz sand body in northwestern Biscayne Bay, appears to maintain the quartz sand bodies along much of the western Biscayne Bay shoreline.

South of the Cutler area, quartz shorelines are more spotty and form a thinner cap to the peat or rock shoreline platform. In many areas quartz forms only a thin veneer (0-5 cm.) over an eroding peat bank
(Core 139). In southern Biscayne Bay and Card Sound, significant quartz beaches are only present at points or shoreline projections into the Bay (Cores 99, 100, 110). Here the beaches often form a well-bedded quartz-carbonate sequence (Figure 24a). Where quartz is being deposited with organic material, a wispy lamination often results (Figures 24a and 26b) (Cores 2 and 112). This may form both in protected intertidal areas which contain *Thalassia* and other organic hash and in areas where large amounts of quartz are being deposited in an intertidal mangrove environment behind the present quartz beach.

**Offshore Quartz Shoals Within The Bay**

Black Ledge (Figure 8) is a quartz sand shoal situated on a low, submerged, northeast-southwest trending bedrock ridge (Figure 3). Bedrock lies 2.5 meters below sea level under the shoal. A basal sequence 1 meter thick consists of a shelly carbonate mud which grades upward into a medium to fine-grained quartz sand containing occasional *Thalassia* rootlets and skeletons of *Porites furcata* (Figure 24c) (Core 163). Quartz sand presently caps the shoal and drapes all sides of it. Bedrock is exposed or nearly exposed within a short distance on all sides of the shoal. The surface of this predominantly quartz shoal lies less than 1 meter below sea level. The surface sediment is very well sorted (250 to 100 microns) quartz sand in a sparse *Thalassia* environment (Figure 18b). The axis of the shoal contains areas where *Porites furcata* is growing so densely that alcyonarians are able to attach on the firm substrate of coral rubble. Moderate tidal currents pass over the shoal, and swells from winds of less than 20 knots have been observed to agitate the bottom.

Black Ledge appears to have formed from a quartz rich sediment derived
from the deeper sandy areas nearby (see p.100). As the sediment was transported up onto the low bedrock ridge, wave and current energy increased and carbonate material was selectively removed. While quartz is of nearly the same density as calcite, the high porosity and the platy nature of most of the skeletal carbonate grains make them much more easily transported. Lower in the sediment sequence, carbonate sand and mud increase in abundance and indicate that less intensive sorting was operative earlier in the development of this shoal. Although the shoal is situated on top of the low bedrock rise, it appears to be best developed towards the west side of this rise. The initial sand accumulation, thus, may have taken place in association with decreased wave and current energies on the west (lee) side of the bedrock rise.

Field observations suggest that the surface sediment of Black Ledge is somewhat mobile and that the sand body is dependent on an influx of sediment to maintain the shoal. Southerly drift of sand from the quartz sand bodies in northwestern Biscayne Bay may provide this source.

About 1 kilometer to the southwest of Black Ledge is Black Shoal, a small, isolated shoal of carbonate mud (Figure 8). The surface environment is dense Thalassia. Thalassia rootlets are present through the core. The shoal drops on all sides to an exposed bedrock floor within 100 meters. There is no apparent bedrock relief under the shoal. The presence of this shoal is not understood, but it may lie in a current shadow in the lee of Black Ledge.

Further south in Biscayne Bay is Pelican Bank, another isolated sedimentary shoal which also has developed in association with a low, submerged, northeast-southwest trending bedrock rise. This shoal is not a pure quartz shoal as is Black Ledge. The sediment of Pelican Bank is a
muddy, quartz-rich, carbonate sand in which bedding is poorly preserved (Core 96). *Thalassia* rootlets are present throughout the sequence, and a moderate *Thalassia* cover is present at the surface. Bedrock is exposed on all sides within a short distance from the shoal.

As Pelican Bank is situated on the only other bedrock ridge in the central Biscayne Bay area, a development similar to that for Black Ledge is suggested. The different sediment character of Pelican Bank is probably the result of a different sediment source and less intense current and wave energies in this area.
C. TIDAL BARS OF CALCAREOUS MUD AND SAND

Throughout the shallow South Florida and Bahamian platforms, carbonate sand bodies have developed in response to wind and tidal currents which are controlled primarily by bottom topography. Ball (1967) has classified three types of shallow marine sand bodies - marine sand belts, belts of tidal bars and platform interior sand blankets. The former two types are found near the platform edge where currents are intensified and directed by shallow thresholds of the bedrock topography.

In Biscayne Bay there are four areas where carbonate or mixed quartz and carbonate tidal bars have developed in response to a restricting bedrock topography and the resulting tidal current patterns. These are Featherbed Bank, Safety Valve, Cutter Bank, and Caesar, Broad, Angelfish Creek shoals. Of these, the Safety Valve and Cutter Bank may be considered belts of tidal bars which developed behind the crest of a slope break.* Featherbed Bank and Caesar, Broad and Angelfish Creek shoals have developed in response to tidal currents passing through natural bedrock channels in the Key Largo Ridge.

Featherbed Bank and the Safety Valve will be considered together. Despite the distinct differences in their geometry and present setting, they appear to be genetically related.

*Slope break is a term used by Ball (1967) to describe the seaward threshold of a shallow platform beyond which the water depth increases.
Featherbed Bank - Safety Valve Tidal Bar Development

General Description

To the south of Key Biscayne is an area of shoals and channels commonly known as the "Safety Valve." This tidal bar belt extends south to the Ragged Keys where the Key Largo Ridge rises to the surface restricting tidal current flow across the bedrock ridge (Figure 3). The axis of the tidal bar belt runs north-south paralleling the submerged Key Largo Ridge, which lies along its eastern side. The tidal channels through this tidal bar belt are nearly perpendicular to the axis of the belt. These tidal channels are generally cut to bedrock across the main body of the tidal bar belt, but shoal considerably as the channels digitate seaward and bayward. Along the flanks of the tidal channels very coarse winnowed carbonate sands may be present over bedrock.

Featherbed Bank lies to the south and west of the Safety Valve and is completely separated from it. This shoal development extends from near the Ragged Keys to the west as two distinct sand bodies (Figure 10a). These will be referred to, respectively, as North and South Featherbed Bank. Both banks extend from near the Ragged Keys to the west for some distance as a narrow "stringer shoal".* Further into Biscayne Bay, each shoal trends south, broadens and then recurves to the north where it terminates. There is no major bedrock relief beneath either of these shoals (Figure 10b).

*Stringer shoal is a term here introduced to describe the geometry of these narrow elongate sand bodies which extend bayward of the restricting rock ridge and are associated with rock floored channels through the rock ridge. This is of no relation to the sand stringer of Shepard (1960a, p. 209), stringer coal of Kay (see Howell, 1957, p. 282), or the shoe-string sand of Rich (1933, p. 103).
This entire tidal bar and ridge development is quite distinct from the longshore clastic sediment body lying to the north and east. The sediments of the Safety Valve and Featherbed Bank range from very coarse coralgal-mollusc sands, through sandy algal-plate muds to fine carbonate muds. Every core taken on these shoals revealed nearly the same sediment type through the entire section to just above bedrock where the sediment generally become a quartzose carbonate sand (Cores 75, 76, 80, 81, 82, 114; Figures 40 and 41). As is common of the Bay sediments, some fine quartz sand is present throughout the sand bodies of Featherbed Bank and the Safety Valve.

The development of the Featherbed Bank-Safety Valve area has been complex. The following interpretation is made partially on hand probing and coring data and on sediment analyses of surface and core samples. However, the basis for the interpretation is mainly geomorphic - a detailed study of available aerial photography of the area. Three stages of development are recognized: (1) Featherbed Bank - restricted shoal development; (2) Soldier Key - transition area; (3) Safety Valve - unrestricted tidal bar development.

Featherbed Bank - Restricted Shoal Development

In the Ragged Keys area, the Key Largo Ridge rises to the surface forming small islands cut by tidal channels (Figure 10). The shallow rock ramparts to the east of these islands are often more restricting sills than the channels between the islands. Tidal circulation is restricted by the bedrock islands, and sand bodies have not formed immediately to the west of these islands. Sand bodies have, however, developed further to the west within the Bay and appear to be related to the
channels in the bedrock ridge.

When sea level was 1 to 2 meters below its present position most of these channels were not submerged. As sea level slowly rose, wind and tide-induced currents began to pass through those channels having deeper sills. These tidal currents began to concentrate sediment in association with the channels. Sediments transported from within Biscayne Bay and seaward of the Key Largo Ridge were deposited as well as biogenic carbonates formed in situ. Broader channels, such as those at the north end of Sands Key, developed a central elongate bar "A" in Figure 10. While these long thin bars in the center of the channels are not clearly understood, they appear to form in broad channels where a small tidal lag occurs between the left and right hand sides of the channel.

Off (1963, p. 326) has noted that in any area of constricted tidal currents, there are three factors which tend to cause a net movement of sediment. First, there is always a net movement of water due to local wind-driven currents. Second, the nature of tidal currents is such that the ebb and flood do not necessarily follow the same path. Third, the ebb and flood currents do not usually have the same maximum velocity (Off, 1963, p. 326). Morrill and Olson (1955, p. 37) state that prevailing wind-driven currents tend to cause a net flow of water into Biscayne Bay in the Ragged Keys area. This would tend to transport sediment into the Bay through channels such as those to the north of Sands Key.

With the above situation (i.e., parallel tidal channels, sufficient sediment supply, and net westward tidal transport), a narrow stringer shoal (South Featherbed Bank) began to develop and grow to the west. As the stringer shoal extended into the Bay over a deepening bedrock platform,
the sand body began to trend southward probably in response to the southerly drift of water in the Bay (B in Figure 10). When the rising bedrock slope on the west side of the Bay was approached, the shoal recurred to the north and ended giving a broader area of sediment accumulation (C in Figure 10).

North Featherbed Bank developed in a similar manner from tidal channels (D in Figure 10) in the northern Ragged Keys area somewhat later than or in part contemporaneous with South Featherbed Bank. The stringer shoal of North Featherbed Bank extends nearly due west (E) until well out into the Bay. The stringer shoal of North Featherbed Bank does not trend to the south until well into the Bay, probably because South Featherbed Bank had previously diverted the strong southerly drift in this part of the Bay. Further into the Bay, west of this restricting influence of South Featherbed Bank, the stringer shoal of North Featherbed Bank then trends south (F) until a low bedrock ridge is encountered where the shoal broadens and recurves to the west across this small rock rise. Further west, where the bedrock platform rises sharply, the broadened shoal curves to the north and ends (H).

The sediments of the narrow, elongate stringer shoals are medium to coarse-grained sands (Figure 29a) containing abundant megaskeletons of coral (Manicina areolata, Siderastrea radians, and Porites furcata) and molluscs (especially Codakia orbicularis). Quartz (30-50%), Halimeda plates, mollusc fragments, echinoid plates, and Foraminifera tests dominate the sand fraction. Quartz-carbonate aggregates, mostly bedrock fragments, compose two to four per cent of the coarser sand fraction. In addition, the surface environment contains locally dense populations of the calcareous algae, Penicillus capitatus, Udotea sp. and
Acetabularia sp. in a setting of sparse Thalassia (Figure 19a).

The broader cup-shaped area of sediment accumulation to the west of the stringer shoals shows a different sediment type and history of deposition (C and H in Figure 10). While the southern edge of these broadened shoals are somewhat sandy, the sediment accumulation to the north is a fine carbonate mud, more than 95 per cent by weight being finer than 62 microns (Figure 25a).

It appears that the stringer shoals have developed in association with moderate tidal currents which have been constricted and directed by channels through the Ragged Keys. The clastic nature of the sand body is demonstrated by the abundance of quartz and bedrock fragments (Figure 29a). While the exact process of formation is not certain, a mechanism similar to that proposed by Off (1963) for the development of rhythmic series of tidal current ridges, such as those at the south end of the Tongue of the Ocean, Bahamas, is suggested:

"Possibly a Reynolds number phenomenon is involved. This might cause the setting up of eddy currents, once a certain critical velocity was exceeded. These eddy currents would be a specific size for a particular water depth and bottom friction; all of this resulting in bands of slower current oriented parallel with the direction of tidal flow. The ridges would tend to form in these bands of slower current. Once the ridges were started in a particular area, they would be self-perpetuating because the resulting irregularity on the bottom of the sea would act as a nucleus for the additional accumulation of sediment."

(1963, pp. 333, 334)

The tidal currents discussed by Off (1963) are unrestricted laterally whereas those involved in the formation of North and South Featherbed Bank consist of only two narrow, parallel tidal currents with a single eddy feature between them.
The broadened western section of North and South Featherbed Bank appear to have developed subsequent to the stringer shoal formation as the result of distortion or dispersion of the tidal current patterns with a more restricting bedrock surface. These broad, cup-shaped western ends to the Featherbed Banks, once formed, have acted as a sediment trap to sediment drifting southward in Biscayne Bay.

Once formed, how stable are these sand bodies? A large amount of in situ carbonate skeletal formation has taken place on these shoals. Thalassia, an important agent for the entrapment of sediment and stabilization of sand bodies (Ginsburg and Lowenstam, 1958, p. 313), is sparse throughout the Featherbed Banks. The role of clastic sedimentation appears to be so important to these sand bodies that when the tidal currents responsible for their formation are cut off the shoal will not be maintained.

For example, currents to North Featherbed Bank are now cut off to the east by a small arcuate shoal body (I in Figure 10). The stringer shoal of North Featherbed Bank appears to be slowly eroding away as the result of wind and tidal currents, and it is presently not so pronounced as the stringer shoal of South Featherbed Bank (Figure 10).

The tidal jets responsible for the development of the stringer shoal of South Featherbed Bank appear to be active at the present. A breach through the shoal (B in Figure 10) formed by storm tides sometime before 1940. Observations in 1967 show that movement of sand from the east along both flanks of the shoal have nearly reconnected this breach in the stringer shoal.
Soldier Key - Transition Area

North of the Ragged Keys, the Key Largo Ridge is present as a shallow submerged feature with the crest lying generally 1 meter or less below sea level. Only at Soldier Key does the bedrock Ridge again rise to the surface. Tidal currents pass over the Ridge throughout this area except at Soldier Key. A nearly continuous sand body has developed immediately behind the shallowly submerged ridge except near Soldier Key, where water circulation is restricted by the rock barrier. Two types of shoal development appear to be present in this area: (1) a relic stringer shoal development, and (2) a presently developing tidal bar belt west of the submerged bedrock ridge.

Aerial photographs strongly suggest that this area passed through a period of stringer shoal development (X in Figure 11), probably at a slightly lower sea level when the Key Largo Ridge in this area was more restricting to tidal currents. These shoals did not, however, extend far into Biscayne Bay. Perhaps the steeper bayward slope of the bedrock and stronger southerly longshore currents, present before formation of the Safety Valve tidal bar belt, directed the stringer shoals sharply southward. Sediment supply and tidal current velocity may also have been an influence. To the southwest of Soldier Key one of these remnant stringer shoals shows the development of the characteristic western broadening and northward terminating of the shoal (lower left in Figure 11). As was the case for the Featherbed Banks, this western stringer shoal terminus is also situated across the deep bedrock axis of Biscayne Bay to the west of which bedrock shallows considerably.

As sea level encroached over the restricting bedrock barriers in the Soldier Key area, current patterns changed and these stringer shoals
began breaking up or being incorporated into subsequent tidal bar development. Where the stringer shoals are exposed to strong directed tidal flow, storm tides have breached the shoals in numerous places; where more protected from tidal flow, a general dispersion of the sand body has taken place.

With complete tidal circulation over the bedrock ridge (except behind Soldier Key), development of the tidal bar belt began. A nearly continuous sediment body has developed behind the shallow slope break provided by the submerged bedrock ridge. The tidal channels cutting this tidal bar belt initially pass through old storm tidal breaches in the stringer shoals and trend northeast-southwest probably in association with southerly nearshore water transport within the Bay. As the shoals of the tidal bar belt developed and restricted the flow of water over them, the currents in the channels intensified. The channels are presently developing more perpendicular to the axis of the tidal belt (Y in Figure 11) not by channel migration, but by new breaches through the tidal bar belt. The broad channel to the south of Soldier Key is an exception in that it represents a major break in the Key Largo Ridge.

The distribution of sediments in this area is complex. The remnant stringer shoal bodies are composed of quartz-carbonate sands containing abundant megaskeletons of shell and coral (Core 81) and are similar in composition to those of Featherbed Bank. The parts of these stringer shoals that are still exposed to strong tidal currents (though now from a different direction) have a surface environment of abundant calcareous algae, echinoids, coral, and mollusks in a setting of sparse Thalassia, similar to that described for Featherbed Bank. Similarly, the broadened terminus of the relic stringer shoal southwest of Soldier Key is composed
of fine carbonate mud (Figure 41, core 80) similar to the western sections of the Featherbed Banks.

The eastern edge of the tidal bar belt, being exposed to the greatest wave and current energy is generally a coarse calcarenite containing coral and mollusc and echinoid fragments (cores 75, 76, and 83). Along the edges of the present tidal channels and in other areas of moderate energy, a dense cover of Thalassia overlies muddy algal-plate sands (Figure 41; core 82). Well within the tidal bar belt and in abandoned tidal channels, the sediments are fine algal plate muds containing few megaskeletons.

To the north of Soldier Key (as the bedrock ridge deepens, Figure 3), the surface expression of the remnant stringer shoals fades, and the surface environments have become completely reoriented to the present wave and current energy conditions (Figure 12).

**Safety Valve - Unrestricted Tidal Bar Development**

North of Soldier Key to Key Biscayne, the Key Largo Ridge lies 2 to 3 meters below sea level. Here is the development of the tidal bar belt described by Ball (1967, p. 579). The Safety Valve forms a continuous sediment belt paralleling the axis of the shallow slope break and lying on the western side of the Ridge. This tidal bar belt is cut by quite evenly spaced channels perpendicular to the axis of the belt (Figure 12). The channels are broad and extend to bedrock (5 to 6 meters deep) across the axis of the belt. To either end, the channels generally form two major branches, a characteristic feature of tidal channels (Price, 1963). Both seaward and bayward the channels generally bend southward in response to southerly longshore currents. To the seaward (east) storm
transport of sediment has formed spillover lobes beyond the digital ends of the channels, and the tidal bar belt development has extended to the east of the now covered bedrock Ridge.

The surface environments here reflect only the present physical energy patterns. At the surface, coarser sediments are found along the seaward flanks of the shoals, along the edges of present channels, on channel floors (sediment veneer over bedrock), and on the spillover lobes seaward of the tidal channels. *Porites divaricata*, *Manicina oreolata*, *Cladacora arbuscua*, *Lytechinus* sp., *Halimeda iradians*, and molluscs (especially *Codakia orbicularis*, *Lucina pensylvanica*, *Chione cancellata*) are abundant in a sandy to silty sand matrix. *Thalassia* generally forms a dense cover usually having extensive root systems.

Within the tidal bar belt, mounds of *Halimeda opuntia* are abundant and the *Thalassia* cover is usually extremely dense especially to the east. The bulk of the shoal body is composed of an algal-plate (*Halimeda opuntia*) carbonate mud (see also Ball, 1967, p. 580). Bedding is generally absent as the sediment has been extremely reworked by burrowing organisms (Figure 25b).

The importance of marine grasses, especially *Thalassia testudinum*, in the development and maintenance of sand bodies has been recognized by Ginsburg and Lowenstam (1958) from their work in South Florida and by Hay (1967) from work in Bimini Lagoon, Bahamas. Strong tidal currents of 1 to 2 knots promote dense growths of *Thalassia* (Hay, 1967). The long broad blades of *Thalassia* may grow to 50 cm. in length (John Jones, personal communication) and form a baffle to currents and a layer of quiet water above the sediment surface where fine particles may settle out and where the surface will be protected from erosion. The closely
branched, meshlike root system that extends into the sediment as much as 25 cm. (Ginsburg and Lowenstam, 1958, p. 312) binds the entrapped mud and sand giving nearly complete protection to even hurricane energies (Figure 19b). Ball, Shinn, and Stockman (1963) found that during hurricane "Donna" which passed across southern Florida in 1960 the mud banks of Florida Bay showed much less destruction than the outer coral reefs. Persistent tidal currents of greater than 2 knots tend to be destructive to \textit{Thalassia} beds (Dr. William W. Hay, personal communication) causing large blocks of \textit{Thalassia} to be ripped out.

The Safety Valve tidal bar belt appears to have developed behind the submerged Key Largo Ridge in association with increased tidal currents which were favorable to the growth of \textit{Thalassia}. The \textit{Thalassia}, by entrapping and binding sediment caused the shoal body to build upwards. The upward growth of the tidal bar belt caused increased currents and provided yet more favorable conditions for \textit{Thalassia} growth and thus increased growth of the tidal bar belt. Mounds of \textit{Halimeda opuntia} have been abundant throughout the development of this shoal as their plates are abundant throughout the sequence.

The less-than-62 micron fraction of the algal plate mud of the Safety Valve is composed largely of magnesian calcite and aragonite with lesser amounts of calcite and a trace of quartz. The calcareous algae, \textit{Penicillus}, \textit{Rhipocephalus}, and \textit{Udotea}, important producers of aragonitic mud were not observed in abundance on the Safety Valve. \textit{Halimeda opuntia} is abundant, but the aragonitic skeletal material produced by this calcareous algae is primarily coarse algal plates with only minor fine material. The calcitic red algae, \textit{Melobesia}, is found on the Safety Valve covering \textit{Thalassia} blades with fragile encrustations (see also Stockman,
et al., 1967, p. 645). Upon death of the grass blades, these calcitic encrustations fall to the bottom and probably break down to supply some of the fine magnesian calcite of the Safety Valve mud. Nevertheless, the presence of quartz and the abundance of aragonite in the mud fraction suggest that much of the material has been brought onto the tidal bar belt by storm waters, probably from within the Bay where there is an abundance of sources of fine calcite, magnesian calcite, aragonite, and quartz (see especially p. 103).

It is suggested that this northern part of the Safety Valve, previous to the development of the tidal bar belt, passed through a stage of stringer shoal development (Figure 40), similar to adjacent areas to the south. As is the case with the banks in Florida Bay (Ginsburg and Lowenstam, 1958, p. 313), the marine community (dominated by Thalassia testudinum) has been a factor controlling the physical environment and has been primarily responsible for the development of the Safety Valve tidal bar belt.

The time of formation of the Safety Valve and Featherbed Bank is not certain. The presence of a basal unit of longshore clastic sediment beneath the Safety Valve (Core 114, Figure 40) suggests a relatively recent origin for the tidal bar belt. A carbon-14 dating was made of the algal-plate mud lying 490 to 400 cm. below sea level (370 to 380 cm. below the sediment surface - Core 114; Figure 40). The clean, acid-washed and acid-treated plates of Halimeda opuntia dated at 910 ±85 years B.P., and the less-than-62-micron fraction dated 2,300 ±90 years B.P. (Table I). These seemingly confusing results may be compared with carbon-14 dates made on various size fractions of a carbonate mud from Andros Island, Great Bahama Bank (Kvenvolden, 1965), in which the
less-than-62 micron fractions also gave significantly older dates than the coarser skeletal fraction. Kvenvolden has concluded that the younger age of the locally derived coarser fraction approximates the time of deposition, whereas the older fine fractions contain some detrital carbonate particles in which the carbon was fixed at a time prior to deposition. The low magnesian calcite in the fine fraction dated from the Safety Valve may in part be detrital carbonate derived from Pleistocene bedrock. If so, these particles would contain no radiocarbon and would cause a significant increase in the age of the sample (ibid.). While much more radiocarbon work is needed, it may be concluded that the time of development of at least this part of the tidal bar belt began about 900 years ago.

Cutter Bank - Shoal Development On A Minor Slope Break Within The Bay

Cutter Bank, a small east-west trending tidal bar belt has developed on the south edge of the Arsenicker Keys Platform (Figure 13). Cutter Bank is situated slightly behind the edge of this minor slope break feature within the Bay. To the north and south of Cutter Bank, bedrock is exposed. Small tidal channels are cut into the tidal bar belt. The sandy marine carbonate mud which makes up this shoal contains abundant mollusks which are often concentrated in layers (Core 134; Appendix II). Halimeda plates are not abundant. Cores indicate that the sediment has been extensively reworked by burrowing organisms. Grass rootlets are common in the cores. A moderate Thalassia cover is developed on the surface.

The origin of this small feature appears to be the same as the
Safety Valve tidal bar belt, previously discussed. To the east Cutter Bank joins the shoal associated with Broad Creek.

Caesar, Broad, And Angelfish Creek Shoals

In the Old Rhodes Key area (Figure 13), there are three major rock channels which cut through the exposed Key Largo Ridge. These are, from north to south, Caesar Creek, Broad Creek, and Angelfish Creek. Many smaller channels wander into the mangrove forest complex. All of the channels which are presently active are cut to bedrock. The major channels are 7 to 9 meters deep and have been active since marine waters first invaded the Bay. During sea-level advance, shoals have developed seaward and bayward of the channels and along its sides. These shoals have an unusual geometry owing to the restricting bedrock configuration. However, the precesses responsible for the formation of these tidal bars of carbonate skeletal debris and mud are similar to those previously described for the Safety Valve.

Sediments range from fine carbonate muds to coarse coralgal sands depending on their relation to currents and their protection from storm and wave action. Mangrove forests fringe many of the bedrock islands and provide greater protection to the shoal areas. The protected shoals in this area are high in organic content and often contain allochthonous (detrital) layers of organic debris.

Broad and Angelfish Creeks, to the south of Old Rhodes Key, show moderate shoal development to the east and the west. However, Caesar Creek, to the north exhibits extensive seaward shoal development (Figure 13). The water piling up in the southern part of Biscayne Bay appears to exit through Caesar Creek resulting in a net seaward flow of water.
and transport of sediment. The seaward accumulation of sediment is con-
centrated to the south of the channel reflecting the southerly littoral
currents present along the eastern shore of the Keys. Storm tidal cur-
rents have breached only the narrow sediment lip to the north of the
channel. The seaward shoals of Caesar, Broad, and Angelfish Creeks ap-
pear similar to Snake Creek Bank at the south end of Key Largo which has
been described by Baars (1963, p. 125).
D. PARALIC AND FRESH WATER SWAMP DEPOSITS

South Florida is underlain by a very gradually sloping bedrock platform on which marine, brackish, and fresh water swamps have developed. Extensive studies of the ecology, sedimentation, and sedimentary record in these swamps have been made in the Everglades, which extends to the west from the southern Biscayne Bay area. The following discussion summarizes the general features of these swamps, especially as they apply to the Biscayne Bay area, and then examines the three areas of swamp development in the area of study: (1) to the west of the emergent Key Largo Ridge, (2) along the western shore of central Biscayne Bay, and (3) along the western shoreline of southern Biscayne Bay, Card Sound and Barnes Sound. Finally the transgressive nature of these deposits is discussed.

General Description

Along the shorelines bordering Biscayne Bay, Card Sound, and Barnes Sound, paralic (polyhaline) and fresh water swamps have collected autochthonous \textit{(in situ)} and allochthonous \textit{(detrital)} deposits of peat and calcitic mud. The marine to brackish paralic swamps are dominated by the red mangrove, \textit{Rhizophora mangle}. In areas where a fresh water body is absent behind the mangrove swamp barrier (as to the west of Key Largo), the mangrove forests may be 3 to 4 kilometers wide. Along the mainland (western) shore of southern Biscayne Bay, Card Sound, and Barnes Sound, where fresh water flows from the west across the shallow bedrock platform of the Everglades, the coastal mangrove swamps are
restricted to a few hundred meters in width. Along the edges of tidal
and drainage creeks, however, these barrier mangrove forests may pene­
trate several kilometers inland. Landward of the paralic mangrove swamps,
fresh water swamps extend to the west over a submerged but gradually
shoaling bedrock platform.

The fresh water swamps are characterized by open marshes of sawgrass,
*Mariscus jamaicensis*, and spike rush, *Eleocharis* spp. Where saline con­
ditions are beginning to encroach, dwarf red mangrove trees will be pre­
sent and towards marine waters they may dominate the environment
(Craighead, 1964, p. 14; Schneider, 1966, p. 964; Spackman, *et al.*, 1964,
p. 23). The fresh water swamps are dotted with "hammocks" where hard­
woods and shrubs have developed in association with irregularities in
the bedrock floor (Craighead, 1964; Schneider, 1966, p. 963; Spackman,
*et al.*, 1964).

Peat deposits of the red mangrove dominate the paralic mangrove
swamps, especially to the seaward edge. Red mangrove peat is an auto­
chthonous reddish-brown fibrous peat composed primarily of rootlets
(Davis, 1940, p. 83). Where red mangrove is present as a thick sequence,
carbonate material is generally lacking. In the Biscayne Bay area, the
fibrous mangrove peats are dark and contain a fine organic hash, much of
which may be detrital material deposited during storms. The paralic man­
grove swamp deposits may also contain darker brown to black peat of the
black mangrove, *Avicennia nitida*, and the buttonwood, *Conocarpus erectus*,
and the very black, nearly homogeneous peat of the sawgrass sedge,
*Mariscus jamaicensis*. These darker peats are generally only deposited
behind the outer red mangrove belt where they have developed on top of
the red mangrove peat or other deposits which have accumulated to near
high tide level (ibid., p. 83). This is not a transgressive sequence, but rather, it is a floral succession.

The fresh water swamp environments have provided a site for accumulation of several sediment types - sawgrass peat, fresh water calcitic mud, mangrove peat, and peats associated with hammocks. Sawgrass grows only where water is quite shallow. Where this sedge has formed a dense cover over the marsh surface for a considerable period of time, a fine black autochthonous peat may be deposited. Where Mariscus is present in only moderate abundance and where Eleocharis (the spike rush, more characteristic of deeper water) forms a sparse cover over the fresh water swamp, calcitic muds have been deposited (Schneider, 1966, p. 963; Spackman, et al., 1964, p. 18).

The calcitic mud develops in apparent association with "algal mats". These mats of living periphyton are composed of "a complex mixture of filamentous and colonial algae, diatoms, and bacteria, plus entrapped organic and inorganic debris" (Spackman, et al., 1964, p. 18). The living mats have been analyzed and found to contain up to 80 per cent calcium carbonate by dry weight (Miss N. Maynard, Institute of Marine Sciences, University of Miami, personal communication). While these algal mats (largely blue-green algae) seem to be responsible for the formation of the calcitic marl, it is not yet understood whether the calcite crystals are secreted by a specific alga or bacterium (Dachnowski-Stokes and Allison, 1928) or are precipitated in a physico-chemical manner within the total micro-environment produced within the algal mat (Spackman, et al., 1964, p. 18). Aragonitic fresh water snails, Helisoma, Physa, and Planorbis, are present throughout the fresh water deposits. Fragments of these shells may account for the
small percentage or aragonite found in the fresh water calcitic muds (Spackman, et al., 1964, p. 40).

Brown to reddish-brown fibrous peat, while not abundant, is present in the fresh water swamp environments and represents isolated developments of mangrove or buttonwood peat (Cores 137 and 138; Figures 44 and 45), most of which developed in association with bedrock irregularities. The peat accumulations associated with hammocks have not been studied here. Detailed descriptions of hammocks and their development are given in Spackman, et al., (1964) and Craighead (1964).

The sawgrass peat, calcitic mud, and, to a lesser extent, mangrove peat may succeed and give way to one another both vertically and horizontally. Calcitic mud is the most abundant fresh water swamp sediment type adjacent to the paralic mangrove swamp environment (Craighead, 1964, p. 14).

In the Biscayne Bay area, where the tidal range along the shoreline is 1 meter or less, the red mangrove may grow in water 0.7 meter deep at low tide. The fibrous peat of the red mangrove generally, however, develops in the upper half of the tidal range in South Florida (Scholl, 1964a, p. 359). Where the tidal range is less than 0.3 meter, red mangrove peat may accumulate throughout the tidal range and slightly below it (ibid.). The black mangrove, Avicennia nitida, will grow only in areas which are submerged only at high tide. The formation of fibrous peat of the black mangrove is thus restricted to about the upper 0.3 meter of the tidal range.

Thus, if no compaction has taken place, the elevation or depth of a known autochthonous fibrous peat type in the sedimentary record may be regarded as an approximate indication of a previous sea level (ibid.,
p. 360). Carbon-14 dating of a red or black fibrous mangrove peat horizon has been used to obtain a general time measure of the former sea-level stand which the peat represents. Detailed studies of the significance and interpretation of carbon-14 dating of fibrous mangrove peats in South Florida have been made by Scholl (1964a), Scholl and Stuiver (1967), and Spackman and Dolsen (1962).

Paralic Swamps - West Of The Emergent Key Largo Ridge

In the southern part of the Biscayne Bay area, the emergent Key Largo Ridge has provided protection for the development of mangrove swamps. This development has been especially extensive along the eastern side of the Card-Barnes Sound Basin where paralic mangrove swamps as wide as 3 kilometers have developed. Beneath this paralic mangrove development bedrock rises sharply from a depth of 4 meters along the deep axis of the Card-Barnes Sound Basin onto the emergent Key Largo Ridge to the east.

The paralic mangrove swamps here form a nearly continuous barrier and are not interrupted or penetrated by tidal or drainage creeks. The porous coral limestone of the Key Largo Ridge supports practically no fresh water lens (Parker, et al., 1955, p. 100). The lack of a fresh water body behind the bayward barrier of the mangrove swamp and the tidal passage of some sea water through the porous Key Largo Ridge (Ginsburg, 1956, p. 2396) has allowed the formation of a broad well-developed paralic mangrove swamp. A few small bedrock channels through Key Largo have been choked by mangrove. Where the mangrove swamp is broadest, there are several isolated lakes enclosed within it.
The red mangrove is exclusively present along the bayward edge and is dominant throughout the areas behind. Locally where peat has accumulated above present sea level, black mangrove and white mangrove, 
*Laguncularia racemosa*, and some buttonwood trees are present.

This paralic mangrove swamp consists of a nearly continuous sequence of fibrous mangrove peat. Along the bayward edge red mangrove peat extends to bedrock and roots of the red mangrove penetrate cracks and holes in the bedrock (Core 126; Figure 47 and Appendix II). Behind the outer mangrove barrier, probing and coring have revealed a distinct basal sequence (Core 131; Figure 47 and Appendix II). A carbonate mud, containing fresh water gastropods and patches of black-brown peat, overlies bedrock to a thickness of 20 to 30 cm. This is overlain by a thin shell band. Fibrous mangrove peat then overlies these basal units and extends to the surface. Within the swamp, shell layers of whole and broken *Anomalocardia carinicaulis* are occasionally present near the surface where they form in small grassy openings in the mangrove swamp which are slightly above sea level and where a black allochthonous peat is also being deposited.

The acid nature of the surface environment of the red mangrove (pH 5.0 to 7.2 - Davis, 1940, p. 83) can rapidly dissolve any storm deposited carbonate material (Goodell and Gorsline, 1961, p. 81; Craighead, 1964, p. 9) and leave traces of fine quartz as the only non-organic sediment in the peat sequence. The brown-black peat found near the surface within the swamp is somewhat less acidic and contains some carbonate mud (Core 131; Figure 47 and Appendix II).

The presence of red mangrove roots penetrating the bedrock surface 310 cm. (10 ft.) below sea level (Core 126; Figure 47 and Appendix II)
indicates that mangrove forests developed when marine waters first entered the Card-Barnes Sound Basin. As sea level rose the paralic mangrove forests were maintained along this west side of the Card-Barnes Sound Basin and the nearly continuous fibrous mangrove peat sequence developed (Figures 46 and 47).

Mainland Paralic Swamps - Central Biscayne Bay

Paralic mangrove swamps border the western side of Biscayne Bay. From Black Point north to Coral Gables, bedrock rises gradually to sharply onto the Oolite Ridge, and the present mangrove swamp development is narrow ranging from 100 meters to 2 kilometers in width. South of the Coral Gables area, bedrock lies about 1 meter beneath the seaward edge of the mangrove barrier. In the Coral Gables area, bedrock lies about 2 meters below sea level at the shoreline. Throughout this area bedrock is exposed just offshore.

In the Cutler area (Figure 7), mangrove swamp development is absent, and along several kilometers of the shoreline, bedrock is exposed. Natural fresh water artesian springs are present on the shallow bedrock platform in this area (Kohout, 1967). Previous mangrove peat development may have been removed by storm erosion, but it is more likely that the presence of fresh water has restricted mangrove growth in this area.

Throughout the central Biscayne Bay area, the Oolite Ridge lies within 2 kilometers of the shoreline and has essentially isolated the paralic coastal mangrove swamp in this area from the fresh water body of the Everglades to the west. The entire swamp deposit here is thus that of a marine to brackish water paralic mangrove swamp. The mangrove barrier is broken by numerous tidal and drainage creeks. Where the
mangrove swamp is broad, these bedrock floored creeks are connected to small backswamp bays. Red mangrove forests are generally dominant along the shoreline and bordering the creeks and bays and are present throughout the paralic forest. Black mangrove, white mangrove, buttonwoods, and other trees of more restricted range often dominate within the swamp complex. In some areas, black mangrove trees are present at the shoreline suggesting that shoreward erosion of the swamp complex has removed the red mangrove belt.

Seaward of the mangrove forest bordering central Biscayne Bay, an eroding peat bank is present and is capped by a quartz shoal and beach (Figure 8). During high storm tides, wave energy may spread this quartz sand into the mangrove forest. The mud and organic hash (principally Thalassia blades) suspended in the water will also be carried into the swamp complex and deposited. Thus, at least at the surface, a mixed deposit of autochthonous (in situ) mangrove peat and allochthonous (detrital) peat is forming (Cores 112 and 164; Figure 42 and Appendix II).

Beneath these peat deposits, hand probing indicates that a basal sandy unit 10 to 20 cm. thick is generally present. This basal sand is overlain by a brown to black fibrous peat containing a moderate amount of quartz (Core 164; Figure 42 and Appendix II). While red mangrove roots are present in this peat, they are mixed with woody material and organic hash. Mangrove peat sequences present further landward within the paralic swamp complex appear to be more homogeneous as they have not been mixed with organic hash brought in by storms.

As the Oolite Ridge is approached, in many areas a surface environment of sawgrass, cat-tails, reeds, ferns, low shrubs, and weeds becomes present. While the sawgrass, cat-tails, and reeds may occur naturally,
the presence of ferns and shrubs indicates that the marsh has been drained (Davis, 1940, p. 89). Man-made drainage canals do penetrate the swamp throughout this area. The peat accumulation in these areas is a brown to black fibrous peat. Before these areas were drained, they may have formed rush marshes similar to those described by Davis (1940, p. 89).

To the north of Coral Gables, the eastern face of the Oolite Ridge drops steeply into the Bay. Mangrove peat along the shoreline, if present, is very narrow and forms only a thin cap on the quartz sand accumulation (see p. 66).

To the south of the Cutler area (Figure 7), the Oolite Ridge trends inland and paralic and fresh water mangrove swamps have developed over a gentle southwestward deepening bedrock platform.

Mainland Paralic And Fresh Water Swamps

Along the mainland side of southern Biscayne Bay, Card Sound, and Barnes Sound, fresh water swamp deposits have formed behind the paralic mangrove swamp. This fresh water swamp is the eastern segment of the extensive fresh water swamps of the Everglades.

In southern Biscayne Bay bedrock lies only about 1 meter beneath the eastern edge of the mangrove barrier. Here, the shoreline is irregular. In some areas an exposed peat platform along the eastern edge of the paralic mangrove swamp indicates erosion is taking place. In other areas the prop roots appear to be spreading over the very shallow bedrock floor. Red mangroves line the several small creeks which penetrate landward far into the fresh water swamp (top of Figure 14).

Along western Card Sound the paralic mangrove swamp lies in close association with a now submerged bedrock rise, here termed the "Everglades
Rise" ("E" in Figure 3; see also Figure 14). Here the barrier mangrove swamp is straight and nearly unbroken. Bedrock lies 2 to 3 meters beneath the eastern edge of the swamp and is exposed offshore.

In the southern part of Card Sound and in Barnes Sound, the Everglades Rise becomes less pronounced and the seaward edge of the paralic mangrove swamp becomes irregular and lies to the west of a line of mud keys (Figure 15). Numerous small brackish bays are formed by the complex shoreline as, for instance, "Manatee Bay" (Figure 15). Here bedrock lies 2 meters or less beneath the eastern edge of the mangrove peat barrier.

Within the fresh water swamp, deposits of calcitic mud dominate the sequence (Core 136, Figure 45; see also Tabb, et al., 1967). The mud contains abundant fresh water gastropods and may vary from white to quite brown depending on the amount of organic material contained (Figure 26c). Only well into the fresh water swamp does a tan to brown finely fibrous peat (sawgrass peat?) become abundant (Core 137; Figure 45). Numerous rootlets of the dwarf red mangrove penetrate several meters into the calcitic mud, and locally accumulations of fibrous mangrove peat are present throughout the fresh water swamp (Core 137; Figure 45).

In Card Sound several hand probing transects were made across the outer paralic mangrove swamps. To the east of the Everglades Rise, fibrous peat extends nearly to bedrock (Figure 45). Coring and probing at the present shoreline, however, revealed a much thinner sequence of fibrous peat beneath which calcitic muds were present (Core 135; Figure 45). Along the outer edges of the paralic mangrove swamp in southern Biscayne Bay and in Barnes Sound, fibrous peat is also underlain by calcitic mud (Cores 133 and 139; Figures 44 and 47; Appendix II). Calcitic muds
beneath the fibrous peat sequence appear very similar to the fresh water calcitic muds now forming landward of the paralic mangrove barrier. Both are characteristically low magnesium calcite containing only a trace of aragonite in the mud fraction. Fresh water gastropods are common to both.

The occurrence of calcitic mud beneath the present paralic mangrove swamp appears similar to that described for the Whitewater Bay area of the Everglades (Scholl, 1964a, p. 346). Scholl and Stuiver (1967, p. 439) have concluded that "with a rise in sea level deposition of mangrove peat spreads landward (transgressively) over fresh water deposits." The continued accumulation of calcitic muds "may have been a result of a rising water table augmented by the impounding of runoff water landward of a rising sea level and coastal wedge of paralic sediments" (Scholl, 1964a, p. 346). On the other hand, it has been suggested by Egler, (1952, p. 246) and by Craighead (1964, p. 9) that the formation of red mangrove peat deposits may take place by a process of replacement by dissolution of the carbonate muds.

Discussion

Throughout the previous discussion, the erosion of peat shorelines has been emphasized. If, at lower sea levels, paralic mangrove forests were present further into the Biscayne Bay Basin, some evidence of these peat accumulations should be present. The deep axis of the central Biscayne Bay Basin provides such evidence. Several hand-probing transects revealed the presence of buried peat deposits on the flanks of the deep bedrock trough (Figures 39 and 42). The recorded submerged peat deposits lie as deep as 5 meters below sea level. This is in one of the deepest parts of the Bay and indicates that paralic mangrove forests
bordered the marine waters when they first entered Biscayne Bay. Similarly, mangrove peat has been recorded lying almost on the axis of the Card-Barnes Sound Basin at a depth of 3 to 4 meters (Figures 20 and 27).

Why, except to a limited degree in Barnes Sound, were these deeper, older paralic swamps not maintained? Several processes may be responsible.

As sea level rose, parts of the Key Largo Ridge became submerged, and prior to the formation of the sedimentary barrier islands and the Safety Valve, the Bay could have been more open to storm-wave energy.

Once an area of peat is eroded to a depth of only a meter below low water, the mangrove forest cannot re-establish itself. Thus, during a period of rising sea level and in the presence of even occasional moderate wave energy, it appears that a mangrove shoreline can only recede, unless intertidal mud banks or shoals are developed on which the mangrove can again take root.

It is suggested that during the Recent rise of sea level in Biscayne Bay, a paralic mangrove shoreline transgressed landward over much of southern Biscayne Bay and the Card-Barnes Sound Basin depositing a fibrous peat sequence. Most of this has subsequently been eroded, and all that remains are thin patches of peat over bedrock in scattered localities.

Why has the peat and muds of the swamp deposits been so extensively eroded in some areas and not in others? Perhaps protection from wave energy is primarily responsible. Along the mainland side of southern Biscayne Bay, the eroding paralic swamp shoreline is in the form of a bench of peat with bedrock only about 1 meter below the surface.

Along the more protected shorelines bordering western Card and Barnes Sound, bedrock may lie 2 to 3 meters below sea level. On the
eastern side of Card and Barnes Sound, where the shorelines are in the lee of the prevailing winds and more protected from storm energy, the bedrock at the mangrove shoreline may be over 4 meters below sea level.

The quartz beaches and nearshore shoals found along the western shorelines of Biscayne Bay and Card Sound may also provide protection from the erosion of the peat banks (Figures 8 and 40).

The general configuration of the present shorelines of Biscayne Bay, Card Sound, and eastern Barnes Sound is thus largely the result of the underlying bedrock configuration plus differential erosion caused by differences in the intensity of the wave energy acting along the shorelines. In each area the mangrove peat shoreline has been eroded back to where bedrock is sufficiently shallow to dissipate much of the wave energy. The more extensive erosion of the western shoreline of central and southern Biscayne Bay may be the result of offshore storm waves passing into the Bay over the submerged Key Largo Ridge to the north of Soldier Key previous to the development of the Safety Valve and/or of larger waves within this part of the Bay because of a greater fetch and deeper bedrock topography.

Where a shoreline is more open to wave energy, it appears that the mangrove shoreline has been eroded back to where bedrock is sufficiently shallow to dissipate much of the energy. The quartz beaches and nearshore shoals found along the western shorelines of Biscayne Bay and Card Sound may also provide protection from erosion of the peat banks (Figures 8 and 40).
E. MUD AND SAND BLANKETS OF THE OPEN BAY

Away from the clastic, tidal bar and coastal paralic swamp sedimentary buildups, Biscayne Bay, Card Sound, and Barnes Sound form shallow semi-protected bays. The bottom sediments range from quartzose carbonate sands to sandy or silty lime muds. The most notable feature of the open Bay sedimentation is the extensive lack of sediment accumulation (Figure 5). Over 50 per cent of the Biscayne Bay Basin and the Card- Barnes Sound Basin contains less than 15 cm. (6 inches) of sediment cover over bedrock. The sediment accumulation that has occurred is confined primarily to the deep bedrock axis of Biscayne Bay and Barnes Sound. The depth of the bedrock surface, wave energy, and growth of Thalassia appear to be the primary influences on sedimentation within Biscayne Bay and the sounds to the south.

Sandy Areas Of Non-Accumulation

The areas shown in Figure 5 as having less than 15 cm. of sediment cover are here considered areas of non-accumulation of sediment. Bedrock is generally exposed in these areas with sediment filling the irregularities in the bedrock surface (Figure 20). Thalassia testudinum and other sea grasses are generally absent or occur where sand has filled isolated depressions in the bedrock.

The surface environments are typical of the semi-protected marine rock bottom communities found throughout South Florida and the Bahamas (see Ginsburg, 1956, pp. 2398, 2402; Newell, et al., 1959, pp. 19-21; Cloud, 1962, p. 33; Purdy and Imbrie, 1964, p. 21). The calcareous algae
Halimeda incrassata and Halimeda monile are present throughout the areas of non-accumulation in Biscayne Bay and Card and Barnes Sounds. The calcareous algae Penicillus spp., Rhipocephalus phoenix, Udotea spp., and Acetabularia, the alcyonarians, numerous sponges, and the corals, principally Porites furcata and Solenastrea haydes, are present only in Biscayne Bay and Card Sound away from the mainland (Figure 29). Alcyonarians are especially indicative of a rock bottom environment. Attached Sargassum and non-calcareous red and brown algae are dominant in the shallow nearshore areas of southwestern Biscayne Bay.

These areas of non-accumulation of sediment are characterized by quartzose carbonate sands. The quartz is sub-angular and medium to fine grained and is comparable to the sediment of the quartz sand bodies previously described within the Bay area (p. 60). In Biscayne Bay quartz constitutes 40 to 80 per cent of the sediment, decreasing to the south and east (Figure 30a). In Card Sound quartz composes 30 to 40 per cent of the sands. In Barnes Sound the quartz content decreases to 10 to 20 per cent (Figure 30b). While quartz is present only in size fractions less than 500 microns, quartz carbonate aggregates, mostly fragments of bedrock, are present in the coarser fractions.

The carbonate fraction from areas of non-accumulation is dominated by molluscan and foraminiferal assemblages (Figure 30). In Biscayne Bay the arenaceous Foraminifera Quinqueloculina agglutinans, Valvulina oviediana, and Triloculina carnata characterize the sandy areas of non-accumulation. In Card Sound the arenaceous forms are less abundant and Archaeas and other Soritidae dominate. In Barnes Sound Elphidium spp. and Ammonia beccarii dominate a foraminiferal assemblage also containing Sortidae and Mileolidae, suggesting that brackish conditions are present.
during a part of the year.

Distinct mollusc communities are not evident from the samples examined. The common genera observed in the sandy areas of non-accumulation are *Laevicardium*, *Nucula*, *Lucina*, *Tellina*, *Bittium*, *Chione*, *Codakia*, and *Modulus*. In Barnes Sound *Lucina* and *Caecum* dominate. More detailed studies on the distribution of molluscs in Biscayne Bay have been made by McNulty, *et al.* (1962a).

A large amount of the mollusc fragments and foraminiferal tests are blackened (Figure 30) and are suggestive of reducing conditions within the sand pockets. The occurrence of these blackened grains increases markedly to the south into Card Sound and Barnes Sound where more protected conditions prevail.

Plates of *Halimeda* are present but nowhere abundant. Ostracods are present throughout the areas of non-accumulation. Coral and echinoid fragments are present in the coarser sand fraction.

The mud fraction (less than 62 microns) constitutes less than 10 per cent of the sand facies. Low magnesium calcite forms greater than 50 per cent of the mud fraction and increases to the south. Aragonite shows a marked decrease in abundance into Card and Barnes Sound while quartz (less than 62 microns) becomes more abundant especially in these more protected areas.

A maximum sediment thickness of 15 cm. was chosen as the limit for areas of non-accumulation for two reasons. First, the bedrock surface is highly irregular and throughout the Biscayne Bay area has a local relief of at least 10 to 15 cm. and often much greater (see p. 35). Thus, even where persistent currents or wave energies are present, sediment will be present in the protection of depressions in the irregular
bedrock surface. Second, *Thalassia* does not appear to establish extensive grass beds unless a sediment thickness of at least 20 to 30 cm. is present. Where *Thalassia* beds are present, the sediment sequence is thicker and more muddy.

Lime Mud Accumulation

In the eastern part of Biscayne Bay north of Featherbed Bank and along the deep bedrock axis in Southern Biscayne Bay and Barnes Sound, sandy to silty lime muds have accumulated, generally to a thickness of less than 2 meters. Here the bedrock surface lies between 3 to 6 meters below sea level. The sediment surface lies between 3 to 5 meters below sea level.

The surface environments in areas of lime mud accumulation in Biscayne Bay are characterized by a moderate to dense cover of *Thalassia*. During much of the year the blades are covered with growths of epiphytes which aid in the entrapment of suspended particles (Ginsburg and Lowenstam, 1958, p. 313). In addition numerous calcareous microorganisms grow attached to the *Thalassia* blades. In these deeper waters, the meshlike root system of *Thalassia* does not form so dense a network as is found on the Safety Valve. The *Thalassia* beds do, however, appear to bind and protect the sediment from severe erosion during storms. Aside from the winnowing of a few centimeters of the surface sediment, the areas of lime mud accumulation in Biscayne Bay appeared virtually unaffected by the passage of Hurricane "Inez" in October of 1966.

Calcareous green algae are present in the bottom lime mud communities and locally form dense populations (Figure 21a). *Halimeda incrassata*, *Halimeda monile*, *Penicillus* spp., and *Udotea* spp. are abundant throughout
central and southern Biscayne Bay. With the exception of Halimeda, the calcareous algae are absent from the sandy lime mud communities in Barnes Sound.

A conspicuous feature of the bottom communities in the areas of lime mud accumulations are the presence of holes and mounds on the sediment surface (Figure 21b). These have also been observed throughout the deeper lime mud grass flats of South Florida and the Bahamas. Shrimp (Cloud, 1962, p. 33) and, possibly, small burrowing fish, worms, and molluscs are responsible for their formation. They indicate intense burrowing.

Hand probing and limited coring (Figure 42; cores 107 and 162) was carried out in the areas of lime mud accumulation. A basal unit of coarse sand, 10 to 20 cm. thick overlies bedrock and is similar in composition to the sands presently found in adjacent areas of non-accumulation. Upwards, this sand grades into a sandy to silty lime mud (Figures 27c and 31).

To the north of Featherbed Bank, where 90 to 95 per cent of the sediment is finer than 62 microns, the sediment may be classified as a sandy carbonate mud. Here, the mud fraction is composed of nearly equal amounts of magnesian calcite and aragonite. Calcite is a minor constituent and quartz is present only in trace amounts. The sharp decrease in low Mg-calcite as compared with the adjacent areas of non-accumulation reflects the absence of bedrock as an immediate sediment source in the areas of lime-mud accumulation. The sand fraction is composed primarily of plates of Halimeda incrassata, molluscs, Foraminifera (principally miliolids) and ostracods. Quartz constitutes only about 3 per cent of the sediment.
Along the deep axis of Biscayne Bay south of Featherbed Bank and in Barnes Sound, less than 100 cm. of sediment accumulation has taken place (Figure 5). Here, the sediment is much sandier with only about 50 percent being finer than 62 microns (Figure 31b). The mud fraction is similar to the adjacent area of non-accumulation, except quartz is absent. The fine fraction is dominated by calcite which may be derived either from erosion (by boring or browsing) of the bedrock or from calcitic mud of the fresh water swamps which has been washed into the Bay during storms. Magnesian calcite and aragonite are both present.

In areas of lime-mud accumulation in Barnes Sound, shell material dominates the sand fraction as it does also in the adjacent areas of non-accumulation (Figure 31b). Similarly, Ammonia and Elphidium dominate the foraminiferal assemblage, indicating brackish conditions. No blackened molluscs or Foraminifera were observed in areas of sandy mud accumulation suggesting aerobic conditions in the sediment.

The cores taken in the lime mud to the north of Featherbed Bank indicate that extensive burrowing and reworking of the sediment has taken place (Figure 27a). Grass rootlets are present in section, but not to the extent found in the tidal bar belt. Sandier sediment is present filling some burrows and occasionally forms thin layers. The sandier nature of the surface sediment may reflect winnowing associated with the abnormal number of hurricanes (four) that have affected the Bay in the past three years (1964 to 1966).

Discussion

Why has no sediment accumulated throughout large areas of Biscayne Bay? These areas have been subjected to marine conditions for 2,000 to
4,000 years and presumably, during much or all of this time communities of sediment producing organisms similar to those of today have prevailed. By comparing Figure 3 with Figure 5 it may be seen that the lower limit of non-accumulation (15 cm.) coincides closely with the 3 to 3.5 meter bedrock depth contour. In other words, where bedrock is shallower than 3 to 3.5 meters, open Bay lime mud and/or sand accumulation has not taken place. (Exceptions to this general rule are some of the localized build-ups of certain bars and shoals discussed in previous sections).

From consideration of the following factors, and in the absence of the necessary further quantitative data, it is proposed that the 3 to 3.5 meter upper limit of open Bay lime mud accumulation represents the upper limit of the stability of the *Thalassia* rhizome "sod" system which protects the sediment beneath from winnowing and transport by wind and wave induced water movements. Listed below are the observations and arguments that have led to the working hypothesis proposed above.

(1) This general situation of open Bay lime mud accumulation being restricted to areas deeper than 3 to 3.5 meters prevails in Barnes Sound as well as in Biscayne Bay. Tidal currents in Barnes Sound are very weak. Thus, tidal currents appear not to be a major controlling factor in the distribution of lime mud.

(2) The sediments in the shallow areas of non-accumulation appear to have been extensively winnowed. For example, there is a paucity of aragonite in the mud fraction, despite the local abundance of calcareous algae, an important producer of fine aragonite needles (Lowenstam, 1955; Lowenstam and Epstein, 1957; Studer, 1963; and Stockman, Ginsburg, and Shinn, 1967).

(3) It is suggested that an "effective wave base" is present at
about 3 to 3.5 meters in the Biscayne Bay area. Throughout Biscayne Bay and Barnes Sound, the maximum fetch is 8 to 10 kilometers and less than in Card Sound. Wind-induced waves are limited by this fetch to about 1 meter in height.*

(4) Wave-induced orbital particle velocity was calculated as a function of depth** for a wave height of 1 meter (Figure 33). A wave length of 10-13 meters and a period of 2.5 seconds was assumed. Bottom friction was not taken into account. For a wave height of 1 meter, maximum particle velocity at a depth of 3 meters would be between 40 to 60 cm/sec. (0.8-1.2 knots). This velocity is well above that necessary to erode and transport fine sand according to the theoretical consideration of Hjulstrom (1939, p. 10), and thus purely orbital wave energy does not appear to explain why lime muds have accumulated to about 3 meters depth within Biscayne Bay. For a wave height of 1 meter, purely physical winnowing would be erosive to lime mud to a depth of over 5 meters, accordingly to Hjulstrom's curves (ibid.).

In addition to the physical energy due to pure orbital motions of passing waves, turbulent water movements occur to an underfined amount, and, added to the orbital motion, may provide an important source of

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*This was calculated from a generally applicable empirical formula $H=1/3 F$ where $H$ is the maximum wave height (m.) and $F$ is the fetch (km.) (Sverdrup, et al., 1942, p. 533). The result of $H=1$ meter for Biscayne Bay, Card Sound, and Barnes Sound is an agreement with general field observations made during winter storms.

**This was calculated using the formula $v=2\pi a/T)\left(e^{2\pi z/\lambda}\right)$, where $v=$ maximum orbital particle velocity, $a=$wave height, $\lambda=$wave length, $z=$depth, and $T=$period. While this formula is designed for deep water where the wave length is small relative to the depth of water (Sverdrup, et al., 1942, p. 528), Dr. Russel Snyder of the Institute of Marine Sciences (personal communication) suggested that it might best describe conditions in Biscayne Bay.
From theoretical considerations of physical energy, we may conclude that winnowing should extend well below the 3 to 3.5 meter depth of transition observed. The lime mud facies thus appears to be present as the result of some stabilizing bottom influence. One notable environmental difference between the shallower sandy areas and the deeper lime mud environments is the abundance of *Thalassia* in the latter.

(5) Perhaps, then, the distribution of lime mud is related to wave energy as it affects the physical limits of *Thalassia* bed stability. Studies in Bimini Lagoon, Bahamas, suggest that a steady tidal current of about 100 cm/sec. begins to erode grass beds and, thus, would appear to be the upper limit for the stability of the dense *Thalassia* beds there (see p. 81; W. Hay, personal communication; ibid., 1967). This velocity is well above the calculated maximum oscillatory wave-induced current velocity at the observed upper limit (3 to 3.5 m.) for the occurrence of *Thalassia* beds in Biscayne Bay. It could be alternately supposed that an oscillatory, wave-induced current is a more effective erosional or winnowing agent than a steady current, so that an orbital velocity of only 40-60 cm/sec. is sufficient to determine the upper limit to the stability of *Thalassia* beds and, thus, the areas of lime mud accumulation in Biscayne Bay. Another factor to be considered in this respect is that of the observed greater density of the *Thalassia* beds present on tidal banks such as the Safety Valve and Bimini Lagoon compared to the more sparse *Thalassia* growth in the deeper areas of lime mud accumulation in Biscayne Bay. One would expect that less energy would be necessary to destroy these beds than the more dense growths in areas of tidal currents. Furthermore, steady (tidal) currents might bend over the *Thalassia*
blades so that a blanket of protection is formed over the sediment, while the oscillatory (wave-induced) currents wash the blades back and forth and this action allows some energy to penetrate to the base of the grass and thus provide less protection to the sediment surface and also to the binding rhizome and root system.

Where *Thalassia* beds do become established in the deeper regions, the blades then act as a baffle and tend to protect the sediment surface from further winnowing due to wave-induced water motions. Away from *Thalassia* beds, the waves of winter storms are free to act unhampered upon sediment or rock surfaces. All but the coarsest material and the material in the protection of depressions in the bedrock could then be put into suspension by the unbaﬄed orbital currents.

(6) On the basis of taxonomic studies it has been reported that the rhizome root system of *Thalassia* might be capable of rapid horizontal and vertical spreading (Tomilson and Vargo, 1967). Field observations in Biscayne Bay indicate that this is not the case. A trench (70 cm. in width) dug in the heavy *Thalassia* beds seaward of Bear Cut north of Key Biscayne has remained virtually free from encroachment of *Thalassia* for two years (John Jones, Institute of Marine Sciences, personal communication). Also, in shoal areas, the "trails" formed where the propellers of motorboats have cut up the bottom, destroying the *Thalassia*, appear to remain for at least several years.

Thus, *Thalassia* appears to be very slow in spreading horizontally. Major winter storms having a frequency of three to four per year and wave heights of about 1 meter could be sufficient to prevent the establishment of *Thalassia* beds and subsequent accumulation of mud in areas of Biscayne Bay where bedrock is shallower than 3 to 3.5 meters. In as
much as the height of waves is fetch-limited to about 1 meter in Biscayne Bay, wave induced oscillatory currents strong enough to be destructive to *Thalassia* beds appear to be active only to a depth of 3 to 3.5 meters. *Thalassia* beds and associated sediment accumulation may build up to but not beyond this level (Figure 33).

(7) The accumulation of lime muds in the deeper areas of Biscayne Bay and Barnes Sound is probably quite recent. As sea level approached its present position, the limit for the stability of *Thalassia* beds did not extend to the rock floor. *Thalassia* beds developed and, as sediment was entrapped in the *Thalassia* baffle, accumulation began. (The greater sediment accumulation in central Biscayne Bay appears to be the result of the damming effect produced by Featherbed Bank to southerly drift of sediments in the Bay.

(8) Similar areas of non-accumulation are observed in Florida Bay where bedrock lies shallower than the stability limit for *Thalassia* beds. The "lakes" separating the mud banks in eastern Florida Bay have an exposed rock floor (Gorsline, 1963, p. 139; Stockman, et al., 1967, p. 643). To the west in Florida Bay, an exposed rock platform has been observed to a water depth of 4 meters.

In summary, the open Bay contains two distinct sediment types. A winnowed quartz and carbonate sand forms a veneer (less than 15 cm.) over bedrock in areas where bedrock is less than about 3 meters in depth. In the areas deeper than 3 to 3.5 meters, lime mud has accumulated in association with *Thalassia* bed development. The distribution of the two facies could be related to wave energy as it effects the physical limits of *Thalassia* bed stability.
F. NON-TIDAL MUD BANKS AND KEYS

General Description

Southern Card Sound and Barnes Sound are bordered on the south and west by narrow mud banks, many of which are capped by chains of mangrove islands. These mud banks are not underlain by anomalous bedrock and are not associated with bedrock channels through the Key Largo Ridge. On either side of these mud banks, bedrock is exposed or nearly exposed. The body of these grass-topped mud banks is a shelly carbonate mud sequence. The hydrographic environment is slightly brackish. Where these mud banks have developed above sea level, mangrove forests, shell beaches, and algal mats may be present. The shell beach deposits are present only above sea level and the fibrous peat and laminated algal mat deposits normally extend less than 1 meter below sea level.

Surface Environments

Mud Banks

In Card Sound and Barnes Sound, the submerged mud banks are covered by a sparse to moderate cover of Thalassia and other marine grasses. Echinoids and the calcareous algae, Penicillus spp., are common on the banks. The surface sediment is predominantly a muddy sand, but in areas where tidal currents are stronger, the sediment may be quite sandy.

Keys

The mud banks present further south in Florida Bay contain only isolated emergent islands called keys. Craighead (1964, pp. 11-13) has
given an excellent description of the surface environments of the keys in Florida Bay in various stages of vegetative stabilization.

In eastern Florida Bay and in the Barnes Sound area, the mud banks are capped by nearly continuous elongate, chains of mangrove keys. Along the west side of southern Card Sound and Barnes Sound, the keys are characteristically bordered to the east by shell beaches. These are in sharp contrast to the quartz beaches present further to the north. Locally, where beach deposits have built up areas well above sea level, hardwoods may develop. Behind the beach ridge or at the shoreline, red mangrove swamps are present and may extend across the island. In a number of areas behind the beach, there is an intertidal swamp containing grasses, mangroves and marine algal mats. To the west of the mud banks and keys are numerous protected sub-circular bays, themselves bordered by mud banks or keys (Figure 15).

The mangrove peninsular separation across the Card-Barnes Sound Basin is somewhat of an exception (see Figure 2) in that it is composed largely of a mangrove peat surface environment. Red mangroves border the shoreline as well as the tidal creeks cutting through this peninsular key. Behind the red mangrove barrier, however, the surface appears to be mostly above sea level and a dense forest of black mangrove, white mangrove, and buttonwood is present.

Basal Sequences

Seven probing transects were made across the mud banks and keys and a coring profile was made at the north end of Main Key (Cores 132 a, b, c; Figures 15 and 47). Probing revealed a basal sand 5 to 15 cm. thick overlying bedrock. Coring did not penetrate this basal sand, but it may
compare with that of the sandy area of non-accumulation (see p. 100).

Coring revealed that the body of the mud banks and keys is a dark, shelly carbonate mud containing grass roots and evidence of burrowing (Figure 27b). The variety of molluscs (including Bittium, Cerithium, Chione, Brachidontes, Anomalocardia, and Modulus) and the predominance of Ammonia and Elphidium in the foraminiferal assemblage suggest that the surface environment during deposition was slightly brackish and contained moderate Thalassia cover.

This shelly mud facies is present beneath the seaward mud bank of Main Key, beneath the shell beach, and beneath the mangrove-algal mat environment on the west side of Main Key. The feel of the probe across other keys bordering the west side of the sounds and bordering the south end of Barnes Sound indicated a similar muddy sequence.

The elongate mangrove peninsula dividing Card Sound and Barnes Sound may be an exception. The few probings made here suggested that peat may compose most of the sequence to bedrock (3 to 4 meters below sea level). However, additional probing and coring is necessary.

Near Surface Sequences

Shell Beach Sand

Along the eastern sides of the Keys' shell beaches are sometimes present. These beaches are quite distinct from the quartz sand beaches present along the mainland shoreline further to the north (see p. 65). These beaches are composed of bedded shells and shell fragments similar to those found in the mud bank sediments (Core 132b; Figure 47 and Appendix II). Following Hurricane Inez in October, 1966, concentrations of Truncatella were present along the beaches. These land snails had evidently been blown
and washed into the sounds during the storm and then floated ashore.

As these beaches and beach ridges are narrow, hurricanes and winter storms form spillover lobes where the shelly sand is carried onto the back island environments.

Shelly beach sands extend only to about low tide level and are underlain by the dark shelly carbonate mud facies.

Organic Laminated Sediments

Marine algal mats cover much of the intertidal mud flats along the protected sides of the keys. Ginsburg, et al. (1954) have described laminated algal sediments and the variations in sediment structure which algal mats form on the mud keys in Florida Bay. Coring on the west side of Main Key reveals comparable organic laminated sediments beneath the algal mat surface (Core 132c, see Figures 27c and 47). These muds consist of alternate light and dark bands reflecting alternation between storm-deposited muds and algal mat growth. The laminated sediments extend as much as 1 meter below the sediment surface and overlie the dark shelly muds of the mud bank.

While the algal mat sedimentation is often horizontally laminated, Ginsburg (1954, p. 5) has described a wide variety of forms of lamina-
tion. Desiccation features are common in the sequences of Main Key (Figure 27c) and are present as much as 50 cm. below sea level.

The abundance of aragonite, calcite, and magnesium calcite and the presence of quartz in the muddy laminated sediments beneath the algal mats suggests that much of the sediment may settle out from the turbid waters of hurricanes and winter storms. Following Hurricane Inez (1966), for example, the low grassy and algal mat environments of Main Key were covered
with a layer of storm-deposited mud. Precipitation of some calcium carbonate by the algal mat community in intertidal and supratidal has been suggested and cannot be discounted (Black, 1933; Ginsburg, et al., 1954; Greenfield, 1963). *Batillaria minima* dominates the molluscan assemblage throughout the organic laminated deposits and suggests that the sequences were deposited in very shallow or intertidal waters.

**Peat**

Some deposits of fibrous mangrove peat are present on the keys capping the mud banks, but peat development is irregular. In many areas where there are dense mangrove forests at the surface, there is little or no associated peat accumulation. Peat has not been observed to extend more than 1 meter below sea level on the keys. Again, the possible exception to this is the mangrove peninsular key dividing Card Sound from Barnes Sound.

**Discussion**

Two problems stand out. First, when did these mud banks develop? Second, in the absence of direct tidal current and bedrock control, what has determined the morphology and position of the mud banks and what process has been responsible for their development?

Gorsline (1964, p. 137) and Scholl (1966, p. 284) have suggested that the mud banks to the south in Florida Bay developed in association with the rise of sea level over the bedrock platform. Craighead (1964, p. 9), Taft and Harbaugh (1964, p. 37), and Spackman, et al. (1964, pp. 36, 38) have shown that peat is present overlying bedrock beneath some of these mud banks. These basal peats have dated at about 4,000 years (Taft and Harbaugh, 1964, p. 37). Fleece (1962) has found that where
carbonate sediment overlies bedrock beneath the mud banks, it is about 4,000 years old and contains much more calcite than aragonite or magnesium calcite.

The mud banks bordering the west side of Card Sound and Barnes Sound are underlain by a basal sand which overlies bedrock. This indicates that before the development of the mud banks the area was a sandy marine environment of non-accumulation (see p. 99). If this is so, then radiocarbon dates of basal sand and peats would predate and have little relation to the time of formation of the mud banks. Previous workers appear to have used dates from such basal sediments to suggest the time of formation of mud keys in Florida Bay (Taft and Harbaugh, 1964, p. 37).

Since shelly beach sands, peat, and laminated algal sediments are present only near the surface, it appears that the development of the islands has been quite recent. However, as mud-cracks are present in the laminated sediment as much as 50 cm. below low water level, island growth may have originated when sea level was slightly below present level.

The islands are presently undergoing some erosion on the eastern side. Following Hurricane Inez, a government bench mark, which had been placed on the beach ridge on Main Key, was found eroded on the beach. If significant erosion and migration of the mud bank keys has taken place, evidence of earlier island formation would probably be removed. However, if the islands are actively migrating to the west, laminated algal sediments should be present beneath the eastern edge of the islands. Core 132a (Appendix II), taken about 20 meters east of the Main Key shoreline, does indeed reveal a laminated mud sequence nearly identical to that presently forming today on the west side of the island. This sequence extends about 1 meter below sea level and is underlain by shelly marine
carbonate mud. Thus, the mud banks along the western side of Barnes Sound do appear to be undergoing active migration to the west or erosion on the east.

The mud banks and keys from Card Sound south into Florida Bay are somewhat irregular, but generally are arcuate features enclosing oval to sub-circular bays called "lakes". Figure 2 and Figure 15 show the generally circular pattern of the mud banks, keys, and bays in and adjacent to the area of study (see also Ginsburg, 1956, Figure 5). Utilizing the work of Fleece (1962) in Florida Bay, Gorsline (1964, pp. 134, 139) has suggested that slow, counter-clockwise "gyral" circulation patterns may be responsible for the formation of the "lakes" and banks in Florida Bay. No data is available on circulation patterns in Card Sound, Barnes Sound or the smaller adjacent bays. A comparison with cuspate spits* may shed some light on the character and distribution of these mud banks, keys, and bays.

Cuspate spits are most often developed in protected elongate bays and lagoons in areas of small tidal range and where strong lagoon currents are absent (Shepard, 1960a, p. 203; 1963a, pp. 194, 195). It has also been noted that such lagoons may become segmented into a series of oval to sub-circular bays by the joining of cuspate spits from the two sides of the Bay (Zenkovitch, 1959). Similarly, isolated irregular bays and lakes have been observed to have developed into circular or oval features (ibid.; Johnson, 1919). Zenkovitch has noted that these features develop by a combination of accretion and erosion of the shoreline (1959). Price, (1964) has pointed out that the size and interval of cuspate spits are

*Cuspate spits are "prominent points or horns found extending into bays and lagoons inside of barrier islands" (Howell, 1957).
determined partly by the original plan (dimensions) and water depth of the lagoon.

The processes responsible for the formation of cuspate spits and the development of oval and circular bays have been a subject of controversy since their existence was first recognized. Standing tidal waves, sieches, pre-existing irregularities in the shoreline, shoreline changes resulting from storm breaches in barrier islands, efficiency of clastic sediment transport, tidal currents, wave action, wave and tide-induced circulation, current eddies, and sea-level changes have all been suggested as important to the development of cuspate spits and circular bays and lakes (Johnson, 1925; Fisher, 1955; Price and Wilson, 1956; Zenkovitch, 1959; Shepard, 1960a and 1963a; Price, 1964).

There is a striking similarity between the configuration of the cuspate spits and sub-circular bays and the mud banks and bays in the southern area of study. Further, the bays in the areas of mud bank formation have a small tidal range and are not subjected to strong currents. However, the mud banks and bays in the area of study are distinct in several ways from the classical cuspate spits and circular bays: no sandy clastic sediment body or sedimentary barrier island is present; tidal currents are negligible; the mud banks, unlike clastic sands, are stabilized by marine grasses and mangrove keys.

Despite these differences, it is suggested that the mud banks bordering and projecting into Card Sound, Barnes Sound, and adjacent bays have developed from processes similar to those responsible for the formation of cuspate spits and circular bays. Wind-induced circulation and wave energy have probably been the primary influences (see Zenkovitch, 1959).
If this is the case, the mud banks developed well after marine waters had covered the bedrock platform. Deeper areas, such as the elongate Card-Barnes Sound Basin may have been segmented into separate circulation basins somewhat earlier, as suggested by the peat sequence indicated by probing which divides Card Sound from Barnes Sound.

The shape and size of the bays which form appear to be in part determined by the pre-existing shape of the basin and the bedrock depth. There is observed a direct relation between bedrock depth and size. Card Sound and Barnes Sound are deepest and largest. The bays adjacent to the paralic mangrove shoreline are shallowest and smallest.

In summary, the non-tidal mud banks in the southern part of the area of study appear to be actively migrating shoals which have developed in response to wind-induced circulation and wave energy in the adjacent bay in a manner comparable to that of classical cuspate spits. The configuration of the circulation pattern (cells) and thus of the mud banks is generally determined by the pre-existing topography and depth.
CONCLUSIONS

One of the objectives proposed at the beginning of this study was to examine the transgressive character of the Holocene sedimentary record in Biscayne Bay and to compare, if possible, these sedimentary sequences with the classical Holocene transgressive records, such as those found by Fischer (1961) along the Atlantic coast of New Jersey and by Scholl and Stuiver (1967) along the southwestern coast of Florida. Having examined the sedimentary accumulations in Biscayne Bay, these conclusions may be made.

1. There are several sedimentary sequences in Biscayne Bay which have preserved the transgression in a classical manner.

   For example, the continuous, four-meter thick sequence of fibrous mangrove peat along the west side of Barnes Sound could only have been deposited during a period of rising sea level (Figure 47). On the west side of Card Sound and Barnes Sound, fresh-water calcitic muds overly bedrock and are themselves overlain by paralic swamp peats and marine muds (Figure 46). This is directly comparable with the transgressive sequence described by Scholl and Stuiver (1967, p. 441).

2. There are numerous sequences which do preserve evidence of transgression, but not in a manner that would be easily recognizable in the geologic record.

   For example, the areas which have undergone and are undergoing transition from restricted stringer shoal
development (as Featherbed Bank) to the tidal bar
belt development (as the Safety Valve) record a peri-
od in which sea level encroached and then overrode
an offshore energy barrier, in this case a bedrock
ridge.

The presence of fossilized roots of the black
mangrove within the upper sands of older beach ridges
is a definite, if not obvious, expression of rising
sea level.

3. The dominant feature of Holocene transgression in Biscayne Bay
has not been the preservation of the transgressive history in suc-
cessive sheet-like deposits, but rather the erosion and redistribu-
tion of products of either present or previous deposition.

For example, the presence of buried fibrous peats along
the flanks of the deep axis of Biscayne Bay as well as
in isolated depressions, and also peat sequences exten-
ding to and penetrating bedrock irregularities beneath
the present paralic swamps west of the Key Largo Ridge,
indicate that sedimentation associated with sea level
did take place throughout the transgressive history of
Biscayne Bay. However, as sea level rose, the bedrock
setting became less restrictive to water movements into
and within the Bay. Increased wave and current energy
eroded most of these early, initially low energy, sea-
level-associated sequences leaving little more than a
thin layer of winnowed quartz-carbonate sand as evidence
of transgression.
4. Many of the sedimentary accumulations now present in Biscayne Bay have been deposited within the past 3,000 years (when sea level was within 1 meter of present sea level), and their development shows little apparent relation to sea-level rise.

For example, Featherbed Bank, the Safety Valve, the mud banks and keys bordering the sounds to the south, and the open bay lime mud accumulation all appear to have been deposited relatively recently. These sedimentary bodies developed in response to increased wave energies and new tidal current energies and circulation patterns once the Bay became deeper and more open. If preserved they would show a thin basal sand overlain by a marine carbonate sediment body as the record of transgression.

5. While the longshore clastic sediment of the sedimentary barrier islands overlies a lagoon mud facies, this does not appear to represent the landward transgression of the barrier islands in the same manner as that described by Fischer (1961) for the barrier island sequences further to the north. Rather, the barrier island sequence of northern Biscayne Bay represents the southern transport of longshore clastic sediment and the development and extension of a cape by spit accretion when sea level was near its present level.

6. If the Recent sedimentary sequences were to be preserved as they are today, the Holocene transgression over most of the Biscayne Bay area would be recorded only as a thin band (less than 15 cm.) of quartz-carbonate sand overlying and filling irregularities in the Pleistocene bedrock surface. The bulk of the sediment is piled up in a relatively small area as shoals, bars and beaches of various types.
The other basic question put forth at the beginning of this study was to examine the sedimentary accumulations in the Biscayne Bay area in terms of the depositional controls responsible for their development. The following conclusions may be made.

1. The pre-existing Pleistocene bedrock topography has been the primary control upon sedimentation in Biscayne Bay throughout the Holocene rise in sea level. Through influence on wave energy, tidal currents and wind-driven circulation, the bedrock topography has exerted the major control on the location and type of most of the sediment accumulation in the Bay.

For example, tidal bar development has taken place where bedrock topography has constricted tidal current flow. Black ledge, a quartz sand body within the Bay, has developed on a small bedrock rise probably as the result of increased sorting of sediment from higher wave energy on the shallow ledge.

The mud banks and keys of Card Sound and Barnes Sound appear to have resulted from circulation patterns determined by the configuration of the Card-Barnes Sound Basin.

2. As sea level rose in Biscayne Bay, the influence of bedrock topography on waves and currents continually changed. The resulting changes in wave energy and tidal current patterns brought about changes in patterns of sedimentation.

For example, as the Key Largo Ridge submerged and became less restrictive to tidal currents in the Soldier Key area, sedimentation changed from stringer shoal type development to the formation of a tidal bar belt.
3. Biologic communities are present which alter the surface environment of deposition as suggested by Ginsburg and Lowenstam (1958). For example, in an environment of moderate current energy, the baffle of *Thalassia* blades may provide a layer of quiet water near the sediment surface where fine particles may settle out and be protected from subsequent winnowing and transport. The extensive root and rhizome network of *Thalassia* beds may then bind and protect the sediment accumulation from erosion during storms.

4. Biologic communities have been responsible for the development and maintenance of several sedimentary accumulations in Biscayne Bay. The influence of the biologic communities may act only within certain limits of the wave and current energy spectrum. For example, in the absence of other causitive factors the *Thalassia* beds of both the tidal bar belt and areas of lime mud accumulation appear to have been responsible for the formation of these sediment bodies by entrapment and upward growth. However, where maximum oscillatory wave-induced currents are greater than 40-60 cm/sec., or where tidal currents are frequently greater than 100 cm/sec., *Thalassia* beds will be destroyed. At the other extreme, where currents are lacking, *Thalassia* will not flourish.

Paralic mangrove swamps have provided a seaward barrier to wave energy and permitted the development of marine and fresh water swamp sedimentation behind the barrier. As sea level rose over the bedrock basins, the
paralic swamp shorelines have been eroded in response to increased wave energy.

5. Once formed, the Recent sedimentary accumulations, themselves, become important controls on local deposition through the influence they exert on wave and current energies.

For example, the greater accumulation of open bay lime mud in central Biscayne Bay appears to be in part the result of ponding of the southerly drift of sediments by the restricting barrier of Featherbed Bank.

Where the Key Largo Ridge once provided protection for lagoon mud sedimentation in northern Biscayne Bay, the sedimentary barrier islands now serve a similar function.

6. In areas of high sediment influx, as the areas of longshore clastic sedimentation, the direct influence of bedrock topography on the formation of sediment bodies is less apparent. Nevertheless, as the barrier sedimentary islands cap the submerged Key Largo Ridge, the bedrock topography was probably an important early influence in determining the original trend of longshore currents and thus of clastic sedimentation.


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APPENDIX I

FIGURES
Figure 1. Regional map of South Florida and the Bahamas showing Biscayne Bay area of study.
Figure 2. Map of bathymetry and topography of the Biscayne Bay area. Lighter contour is present shoreline (mean low water). Dots show probing locations. Contours are generalized from hydrographic charts and topographic maps.
BATHYMETRY AND TOPOGRAPHY
BISCAYNE BAY AREA

SCALE

KILOMETERS

Contours in meters relative to mean low water

H. Monies, 1967
Figure 3. Map of Pleistocene bedrock topography of the Biscayne Bay area as determined by hand probing and topographic maps. Probing locations shown by dots. Lighter contour is present shoreline. Letters refer to text. Twenty meter depth contour is shown to right.
Figure 4. Sketch map of the bedrock topography in the Biscayne Bay area. The heavy contour is the intersection of present sealevel with the bedrock surface.
SKETCH MAP OF BEDROCK TOPOGRAPHY BISCAYNE BAY AREA

scale

5 km

LARGE VERTICAL EXAGGERATION

INTERSECTION WITH PRESENT SEA LEVEL
Figure 5. Map of sediment thicknesses in Biscayne Bay as determined by hand probing. Contours in centimeters. Probing locations shown by dots. Lighter contour is present shoreline. Twenty meter depth contour is shown to right.
Figure 6. Map of probing control and locations of aerial photograph illustrations. Dotted line to right is 20-meter depth contour.
Figure 7. Aerial photography (1940) of Pleistocene Oolite Ridge and channels in the Cutler area adjacent to the western shoreline of Biscayne Bay. Scale in miles. See Figure 6 for location.
Figure 8. Aerial photograph (1940) of western central Biscayne Bay in the Cutler area. Only a veneer of sediment covers bedrock over much of this area, so that the dendritic and solution drainage patterns of the bedrock surface are visible. Quartz banks along the mainland shoreline cover some dendritic channels (dotted lines). Isolated quartz shoal (Black Ledge) is surrounded by sandy areas of non-accumulation. See Figure 6 for location.
Figure 9. Aerial photograph of Key Biscayne and Virginia Key in 1940 before the development of the islands and the construction of Rickenbacker Causeway. Strand lines of old beach ridges are visible depicting growth of the islands. Letters and line are referred to in text. See Figure 6 for location.
Figure 10. (a) Aerial photograph (1960) of North and South Featherbed Bank. Narrow stringer shoals extends west from channels between the Pleistocene bedrock islands. Further west the shoals broaden and terminate. Lime mud accumulation to north; sandy area of non-accumulation to south and west. (b) Sketch of (a) showing bedrock depth contours in meters. Letters refer to text. See Figure 6 for location.
Figure 11. Aerial photograph (1960) of shoal development in Soldier Key area. To the south relic stringer shoals are present (X). To the north their presence is being obscured by the development of tidal bar belt and channels. See Figure 6 for location.
Figure 12. Aerial photograph (1960) of tidal bar belt (Safety Valve) development to the south of Key Biscayne. Tidal channels are cut to bedrock across axis of shoal. See Figure 6 for location.
Figure 13. Aerial photograph (1965) of Old Rhodes Key area. Cutter Bank separates Biscayne Bay and Card Sound. Bedrock channels dissecting the Key Largo Ridge are Caesar Creek (north of Old Rhodes Key) and Broad and Angelfish Creeks (to the south). Note Extensive shoal development seaward of Broad Creek. Scale in miles. See Figure 6 for location.
Figure 14. Aerial photograph (1940) of paralic and fresh water swamp development west of Card Sound. Bedrock depth contours are shown in meters. The darker spots west of the mangrove barrier are isolated hammocks. See Figure 6 for location.
Figure 15. Aerial photograph (1940) of area to west of Barnes Sound. Mangrove-capped mud banks (as Main Key) border Barnes Sound. Irregular paralic mangrove swamp shoreline lies to the west of the mud banks and smaller bays. Note the arcuate and cuspate character of shorelines. See Figure 6 for location.
Figure 16. (a) Pleistocene coral rock of the Key Largo Limestone outcropping on Soldier Key. (b) Under water exposure of subaerially-formed soil crust on bedrock surface. Water depth two meters. Location, west of East Arsenicker Key, southern Biscayne Bay.
Figure 17. (a) Hardened, fossilized casts of black mangrove roots forming framework of intertidal rock platform at north end of Key Biscayne. Scale in one-foot sections. (b) Semi-lithified, mud-cracked sediment on southern Key Biscayne. Sediment was deposited by storm tides of hurricanes which can cover much of the island with sediment-laden waters. Scale, one foot.
Figure 18. (a) Quartz sand beach capping mangrove platform on west side of Card Sound. (b) Underwater photograph of Black Ledge, a quartz sand body in central Biscayne Bay. Fine, well-sorted quartz sand has formed ripples perpendicular to tidal currents. Sparse Thalassia. Depth, about one meter.
Figure 19. (a) Surface environment of stringer shoal, south Featherbed Bank. Bottom covered with coarse rubble of coral and shell. *Siderastrea radians* (center) and sea urchins (left, covered with shells) are growing in a sparse *Thalassia* environment. Depth less than one meter. (b) Underwater photograph at edge of tidal channel on Safety Valve. Dense *Thalassia* bed of shoal being undercut by currents. Note extensive mesh of rhizomes and roots. Depth at edge of shoal less than one meter.
Figure 20. Underwater photographs in areas of non-accumulation of sediment (less than 15 cm. of Recent sediment cover over bedrock). Basket sponges (a) and alcyonarians (b) are characteristic of rock bottom communities. Calcareous algae are abundant; Thalassia sparse, sandy bottom. Mounds of burrowing organisms present (b). Frame 25 cm. long. Depth 2.5 meters.
Figure 21. Underwater photograph of bottom environment in area of lime mud accumulation in central Biscayne Bay. Moderate to dense growth of Thalassia, the blades of which are covered with epiphytes which aid in the entrapment of particulate matter from water. Mounds of burrowing organisms are present; calcareous algae sparse. Depth 3.3 meters.
Figure 22. Sketch of drop-weight coring sampler used, showing adaptation for various sediment types. Pounding weight was developed to aid in penetration of coarse clastic sands.
UNIPOD MAST

UNIPOD STAND

SYRINGE END FOR MUD, PEAT, ETC. WHERE POUNDING USED MORE THAN TWISTING

- CHAIN TO PISTON
- 3" ALUMINIUM IRRIGATION TUBING AS CORING TUBE
- 100 LB. LEAD WEIGHT (CUTAWAY TO SHOW SUPPORT) FITS OVER CORE TUBE AND DROPS ON HANDLES
- REMOVABLE HANDLES FOR PUSHING AND TWISTING CORE TUBE INTO SEDIMENT
- CUTAWAY SHOWING PISTON HELD IN POSITION BY CHAIN
- STAKES TO HOLD UNIPOD UPRIGHT
- PISTON AT GROUND LEVEL
- END OF TUBE SHARPENED AND SERRATED FOR PEAT
- CORE BIT AND CATCHER FOR SAND
Figure 23. Impregnated core sections from the sedimentary barrier islands:

(a) Basal lagoon mud facies beneath longshore clastic sediment. Sandy shelly carbonate mud. Core 149, 387 - 400 cm.

(b) Bedded longshore clastic sediment containing bands of shell material. Core 149, 120 - 141 cm.

(c) Contact between near surface peat and longshore clastic sediment on Virginia Key. Fibrous red mangrove peat contains some sand. Longshore clastic sediment is poorly bedded. Core 149, 25 - 46 cm.
Figure 24. Impregnated core sections from areas of quartz accumulation:

(a) Well-bedded quartz beach on the southeast side of East Arsenicker Key. Alternating bands of pure quartz peat (dark). Core 100, 5-23 cm.

(b) Nearshore quartz bank along the mainland shoreline north of Shoal Point, Biscayne Bay. Pure quartz sand with irregular organic bands; no bedding. Core 2, 24-45 cm.

(c) Wispy, quartz - organic bedding in Black Ledge, central Biscayne Bay. Nearly pure quartz sand; occasional Porites (37 cm.) Core 163, 12-39 cm.
Figure 25. (a) Impregnated core section from the western part of North Featherbed Bank. Carbonate mud contains abundant Thalassia rootlets and shows no distinct bedding. Some of the section appears to be reworked by burrowing (26 cm.). Core 106, 24-40 cm.

(b) Representative impregnated core section of the algal-plate mud of the Safety Valve tidal bar belt. The sediment has been extensively reworked by burrowing. The algal plates (Halimeda opuntia) have mostly been deposited in burrows. Note lack of grain orientation. Transverse sections through two burrows (68-69 cm.) show tangential pattern of algal-plates lining burrows. Cracks in core caused by drying. Core 114, 55-74 cm.
Figure 26. Impregnated core sections of paralic and fresh water swamp deposits:

(a) Shell bed of Anomalocardia cunimeris overlying fibrous red mangrove peat. Paralic swamp, east side of Barnes Sound. Core 131, 20-38 cm.

(b) Shoreline sequence on west side of West Arsenicker Key. Thalassia hash (0-2 cm.) overlies bedded quartz-carbonate sand beach. Sand caps an eroding fibrous mangrove peat. Quartz sand present in peat. Core 112, 0-23 cm.

(c) Fresh water calcitic mud and bands and patches of black peat; west of Barnes Sound. Fresh water shells (Helisoma) are abundant. Rootlets from scrub mangrove trees and sedges penetrate sequence. Break in core at 11 cm. is due to shrinkage on drying. Core 133, 0-23 cm.
Figure 27. Impregnated core sections:

(a) Lime mud accumulation in central Biscayne Bay. *Thalassia* rootlets, *Halimeda* plates, and shells are present but not abundant. Horizontal bands of sandy sediment occur, but no distinct bedding is present. Cracks are from shrinkage during drying. Core 162, 23-40 cm.

(b) Dark, shelly carbonate mud beneath Main Key, Barnes Sound. This is typical of the marine mud banks in Barnes Sound and southern Card Sound. Core 132a, 166-181 cm.

(c) Algal laminated mud sequence on west side of Main Key, Barnes Sound. Evidence of mud cracks at 55 cm. Core 132c, 44-61 cm.
Figure 28. Sediment photographs and block composition diagrams of longshore clastic sediment.

(a) Sample of bedded sand beneath Virginia Key. Core 149, 125 cm. Worn, well-rounded grains of carbonate, quartz, and quartz-carbonate aggregates (mostly reworked fragments of bedrock). Note infilling of grains with carbonate material. Many mollusk and Foraminifera grains are blackened. Few fresh carbonate grains.

(b) Longshore clastic sediment from platform east of Key Biscayne. Shell and foraminiferal grains are mostly blackened, worn and pitted. Some fresh shell in coarse fraction.

Block composition diagram below photographs. - The width of the horizontal bars equals the weight per cent within the size fraction indicated by the numbers on the lines. The finest fraction is less than 62 microns (lower bar); the coarsest fraction is greater than 4000 microns (upper bar, when present). Compositional elements within each size fraction are vertical bars, the width of which equals the volume per cent of each compositional element (see key). The area devoted to each compositional element is proportional to its abundance in the total sample. Blackened grains are mostly mollusk and Foraminifera.

KEY TO BLOCK COMPOSITION DIAGRAMS

- QUARTZ
- QUARTZ - CARBONATE AGGREGATE
- HALIMEDA
- MOLLUSK
- FORAMINIFERA
- OSTRACODS
- BLACKENED CARBONATE
- UNIDENTIFIABLE CARBONATE
Figure 29. Sediment photographs and block composition diagrams of samples from Featherbed Bank and the Safety Valve. See Figure 28 for key to composition diagrams.

(a) South Featherbed Bank, stringer shoal (surface sample 95-AA). Halimeda plates and mollusks dominate the coarser sand fractions. Bedrock fragments are present. Foraminifera are abundant in the 250 µ fractions. Angular, fine quartz sand composes 29 per cent of the total sample. No blackened grains. See also Figure 19a.

(b) Algal-plate mud of the Safety Valve tidal bar belt (Core 114, 40 cm.). Fresh and broken plates of Halimeda opuntia dominate the 62 µ fractions. Quartz is present only as a trace in fine sand fraction. See also Figure 25b.
Figure 30. Sediment photographs and block compositions diagrams of samples from sandy areas of non-accumulation. See Figure 28 for key to composition diagrams.

(a) West central Biscayne Bay (surface sample 89-I). Mollusks and Foraminifera dominate the coarse fractions. Quartz-carbonate aggregates (bedrock fragments) are present. Angular quartz dominates the $<500 \mu \text{m}$ fraction and composes thirty-nine per cent of the total sample. Blackened and pitted fragments of Foraminifera and mollusks are present throughout.

(b) Barnes Sound (surface sample 125-G). Coarse fraction is dominated by mollusks. Blackened mollusks and Foraminifera are very abundant throughout. Angular quartz sand is abundant in the $<500 \mu \text{m}$ fraction and composes 19 per cent of the total sample.
Figure 31. Sediment photographs and block composition diagrams of samples from areas of lime mud accumulation. See Figure 28 for key to composition diagrams.

(a) Central Biscayne Bay (Core 162, 35 cm.). Halimeda incrassata and mollusks dominate the >250 µ fractions. Fine, angular quartz composes less than one per cent of the total sample. Carbonate grains are fresh to broken, and no blackened grains are present.

(b) Barnes Sound (surface sample 125-G). Mollusks dominate the coarser fractions. Fine, angular quartz composes eight per cent of the total sample. In sharp contrast to the adjacent areas of non-accumulation (see Figure 30b), no blackened, pitted carbonate grains are present. The sandier character of the sediment in Barnes Sound may indicate that some winnowing is taking place in the narrow belt of sediment accumulation.
Figure 32. (a) Map on left shows the generalized distribution of the Pamlico Formation in southeastern Florida (from Parker and Cooke, 1944). This quartz sand body developed as an elongate submarine bar during the plus eight meter (Pamlico) stand of the sea during the Sangamon Interglacial. It is suggested that most of the quartz sand within Biscayne Bay was derived from this adjacent remnant sand body.

(b) Sediment photo of angular quartz sand from the Pamlico Formation (5 km. north of Miami). (x10).

(c) Sediment photo of quartz sand from Black Ledge, a Recent quartz sand body within Biscayne Bay (Core 163, 30 cm.). Note the similarity in angularity and texture to the sand of the Pamlico Formation. (x10).
Figure 33. (a) Generalized profile of depth of transition from sandy areas of non-accumulation (less than 15 cm. of sediment cover over bedrock) to lime mud accumulation within Biscayne Bay and Barnes Sound. Areas of lime mud accumulation are characterized by a surface environment of moderate to dense Thalassia, an important agent in the entrapment and binding of particulate matter.

(b) Graph showing decrease in maximum orbital wave velocity with depth for a wave height 1.0 meter, assuming a wave length of 10-13 m., and a period of 2.5 sec. Waves appear to be fetch-limited to about 1.0 meter in height in Biscayne Bay. At the observed depth of transition from sandy non-accumulation to lime-mud accumulation, the maximum orbital wave velocity (for wave height of 1.0 m.) is between 40 and 60 cm/sec. (bottom friction excluded). It is suggested that the limit for the stability of Thalassia beds occurs at about three meters in Biscayne Bay and Barnes Sound and is partially responsible for the distribution of lime mud accumulation. In areas of greater wave energy, this depth would be greater. See p.104 for discussion.
GENERALIZED PROFILE OF
DEPTH OF TRANSITION FROM
SANDY NON-ACCUMULATION TO
LIME MUD ACCUMULATION

DECREASE IN MAXIMUM ORBITAL
WAVE VELOCITY WITH DEPTH.
FOR WAVE HEIGHT = 1.0 m.,
PERIOD = 2.5 sec., WAVE
LENGTH = 10 TO 13 METERS

BED STABILITY LIMIT *

*Observed upper limit of stability of
Thalassia beds in areas of lime mud
accumulation in Biscayne Bay. Above
this level, normal storm waves produce
orbital currents greater than 40-60
cm./sec., which are destructive to
Thalassia beds.
Figure 34. General curve of sea level rise for South Florida according to Scholl and Stuiver (1967). Radio-carbon ages of samples dated in Biscayne Bay are plotted against depth of sample. Arrow above vertical error line indicates depth of formation of marine carbonate mud as inferred from sediment composition. Double arrow indicates that sea level was well above sediment surface at time of deposition. See Table I for description of samples.
YEARS BEFORE PRESENT

DEPTH IN METERS BELOW MODERN SEA LEVEL

ML-469
FIBROUS PEAT,
PELICAN BANK

ML-472
FIBROUS
PEAT,
EAST OF
VIZCAYA

ML-462
FORMED ABOUT 1.5
METERS BELOW SEA
LEVEL

ML-481
SHELLS FROM LAGOON
MUD BENEATH VA. KEY,
SEDIMENT FROM
SAFETY VALVE

ML-463
CARBONATE
MUD <62 µ
CROSS SECTIONS OF RECENT SEDIMENTARY ACCUMULATIONS

The following 12 cross sections give a generalized description and interpretation of the Holocene sedimentary record preserved in the Biscayne Bay area. The topography of the bedrock surface and the Recent sediment thicknesses are based on probing traverses and cores. All probing data was corrected to mean low water (see p. 22). Aerial photography, hydrographic charts, and topographic maps were used to extend interpretation of field data.

Figures 36 to 39 have a vertical exaggeration of 500. Figures 40 to 47 have a vertical exaggeration of 1000.

Mean low water (MLW) is shown on the cross sections by the lighter horizontal line.

The lower heavy irregular line is the Pleistocene bedrock surface. Dots (.) interrupting the bedrock surface line are individual probing stations. Variations found in the bedrock depth at each probing station are shown by vertical range of dots. The shallowest bedrock depth recorded at a station was taken to be the bedrock surface.

The upper heavy line shows the Recent sediment surface. The sediment accumulations are patterned according to general sediment type. Where the bedrock surface and sediment surface coincide, bedrock is exposed, but sediment may fill the irregularities in the bedrock surface. Cores taken along a cross section are numbered above it.

Locations of the cross sections are given in Figure 35. Locations of all cores taken and of samples illustrated in the figures are also shown.
Figure 35. Locations of cross-sections shown in Figures 36-47, cores taken, and sediment samples illustrated. Dots represent core locations. Sediment samples are shown by an "x".
LOCATIONS OF CROSS-SECTIONS, CORE AND SEDIMENT SAMPLES ILLUSTRATED IN PLATES
SCALE

H. Wankel, 1967
Figure 36. Cross-section A-A' of Recent sediment accumulation, northern Biscayne Bay. Bottom line is pre-existing bedrock surface. Dots interrupting line are probing stations. Variations in bedrock depth at each station shown by vertical dots. Numbers refer to core localities. All data relative to mean low water. See Figure 35 for location. Vertical exaggeration x500.
Figure 37. Cross-section B-B' of Recent sediment accumulation in northern Biscayne Bay. East-west profile from Miami area through Virginia Key. Bottom line is pre-existing bedrock surface. Dots interrupting line are probing stations. Variations in bedrock depth at each station are shown by vertical dots. Numbers refer to core localities. All data relative to mean low water. See Figure 35 for location. Vertical exaggeration x500.
Figure 38. Cross-section C-C' of Recent sediment accumulation in northern Biscayne Bay. East-west profile from Miami area through Key Biscayne. Bottom line is pre-existing bedrock surface. Dots interrupting line are probing stations. Variations in bedrock depth at each station are shown by vertical dots. Numbers refer to core localities. All data relative to mean low water. See Figure 35 for location. Vertical exaggeration x500. See Figure 37 for key to sediment types.
Figure 39. Cross-section D-D' of Recent sediment accumulation in northern Biscayne Bay. East-west profile from Coconut Grove to West Point, Key Biscayne. Bottom line is pre-existing bedrock surface. Dots interrupting line are probing stations. Variations in bedrock depth at each station are shown by vertical dots. Numbers refer to core localities. All data relative to mean low water. See Figure 35 for location. Vertical exaggeration x500.
Figure 40. Cross-section E-E' of Recent sediment accumulation in central Biscayne Bay. East-west profile from Cutler through the Safety Valve tidal bar belt. Relic stringer shoal is suggested in Safety Valve. Bottom line is pre-existing bedrock surface. Dots interrupting bedrock line are probing stations. Variations in bedrock depth at each station are shown by vertical dots. Numbers refer to core localities. All data relative to mean low water. See Figure 35 for location. Vertical exaggeration x1000.
Figure 41. Cross-section F-F' of Recent sediment accumulation in central Biscayne Bay. East-west profile from mainland through southern portion of Safety Valve and relic stringer shoals. Bottom line is pre-existing bedrock surface. Dots interrupting line are probing stations. Variations in bedrock depth at each station are shown by vertical dots. Numbers refer to core localities. All data relative to mean low water. See Figure 35 for location. Vertical exaggeration x1000.
Figure 42. Cross-section G-G' of Recent sediment accumulation in central Biscayne Bay. East-west profile from mainland, across Featherbed Bank, through Sand Key. Bottom line is pre-existing bedrock surface. Dots interrupting line are probing stations. Variations in bedrock depth at each station are shown by vertical dots. Numbers refer to core localities. All data relative to mean low water. See Figure 35 for location. Vertical exaggeration x1000.
Figure 43. Cross-section H-H' of Recent sediment accumulation in southern Biscayne Bay. East-west profile from Homestead Bayfront Park through Elliot Key. Bottom line is pre-existing bedrock surface. Dots interrupting line are probing stations. Variations in bedrock depth at each station are shown by vertical dots. Numbers refer to core localities. All data relative to mean low water. See Figure 35 for location. Vertical exaggeration x1000.
Figure 44. Cross-section I-I' of Recent sediment accumulation in southern Biscayne Bay. East-west profile from mainland through Key Largo Ridge in the Old Rhodes Key area. Bottom line is pre-existing bedrock surface. Dots interrupting line are probing stations. Variations in bedrock depth at each station are shown by vertical dots. Numbers refer to core localities. All data relative to mean low water. See Figure 35 for location. Vertical exaggeration x1000.
Figure 45. Cross-section J-J' of Recent sediment accumulation in Card Sound and adjacent swamps. East-west profile from mainland through Pumpkin Key and northern Key Largo. Bottom line is pre-existing bedrock surface. Dots interrupting line are probing stations. Variations in bedrock depth at each station are shown by vertical dots. Numbers refer to core localities. All data relative to mean low water. See Figure 35 for location. Vertical exaggeration x1000.
Figure 46. Cross-section K-K' of Recent sediment accumulation in southern Card Sound and adjacent swamps. East-west profile from mainland, across Card Bank, through Key Largo. Note marine transgressive sequence developing over swamp deposits to west. Bottom line is pre-existing bedrock surface. Dots interrupting line are probing stations. Variations in bedrock depth at each station are shown by vertical dots. All data relative to mean low water. See Figure 35 for location. Vertical exaggeration x1000.
Figure 47. Cross-section L-L' of Recent sediment accumulation in Barnes Sound and adjacent swamps. East-west profile from Everglades, across mud bank keys, through Key Largo. Bottom line is pre-existing bedrock surface. Dots interrupting line are probing stations. Variations in bedrock depth at each station are shown by vertical dots. Numbers refer to core localities. All data relative to mean low water. See Figure 35 for location. Vertical exaggeration x1000.
### TABLE I

**RADIO CARBON DATES - SAMPLE DESCRIPTIONS, POSITIONS IN CENTIMETERS, AND AGES IN YEARS B.P.**

<table>
<thead>
<tr>
<th>Marine Lab. Sample No.</th>
<th>Core No.</th>
<th>Location</th>
<th>Material Dated</th>
<th>Midpoint of dated interval below sediment surface</th>
<th>Sediment surface elevation above (+) or depth below (-) mean sea level</th>
<th>Midpoint of dated interval below mean sea level</th>
<th>Estimated position of mean sea level relative to elevation of midpoint when deposited</th>
<th>Depth of former sea level relative to present stand when dated interval midpoint was deposited</th>
<th>Age of interval midpoint in C-14 years B.P. (1950)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ML-462</td>
<td>114</td>
<td>Safety Valve, tidal bar belt, west side</td>
<td>Halimeda plates &gt;250µ</td>
<td>365 ± 8</td>
<td>-147 ± 10</td>
<td>512 ± 18</td>
<td>Above</td>
<td>?</td>
<td>910 ± 85</td>
</tr>
<tr>
<td>ML-463</td>
<td>114</td>
<td>Safety Valve, tidal bar belt, west side</td>
<td>Carbonate mud &lt;62µ</td>
<td>365 ± 8</td>
<td>-147 ± 10</td>
<td>512 ± 18</td>
<td>Above</td>
<td>?</td>
<td>2,300 ± 90</td>
</tr>
<tr>
<td>ML-469</td>
<td>96</td>
<td>Pelican Bank, southwest Biscayne Bay</td>
<td>Fibrous mangrove peat</td>
<td>165 ± 8</td>
<td>-35 ± 10</td>
<td>200 ± 18</td>
<td>0 ± 30</td>
<td>-200 ± 48</td>
<td>3,540 ± 100</td>
</tr>
<tr>
<td>ML-472</td>
<td>152</td>
<td>Spoil island, 0.5 km. west of Vizcaya, northwest Biscayne Bay</td>
<td>Fibrous mangrove peat</td>
<td>360 ± 5</td>
<td>-20 ± 10</td>
<td>380 ± 15</td>
<td>0 ± 30</td>
<td>-380 ± 45</td>
<td>4,270 ± 100</td>
</tr>
<tr>
<td>ML-481</td>
<td>149</td>
<td>North end of Virginia Key, beneath oldest visible beach ridge</td>
<td>Shells</td>
<td>495 ± 8</td>
<td>+5 ± 5</td>
<td>490 ± 13</td>
<td>150 ± 40</td>
<td>-340 ± 53</td>
<td>4,200 ± 100</td>
</tr>
</tbody>
</table>

*Correction from mean low water according to tidal ranges given in Tide Tables (1966).*
APPENDIX II

DESCRIPTION OF CORES
CORE: 2

DATE: 6-24-66

LOCATION: * Quartz shoal, 70 meters east of mainland shoreline, 3 km. north of Shoal Point.

WATER DEPTH: 40 cm.

SEDIMENT THICKNESS: 127 cm.

CORE PENETRATION/LENGTH: 61 cm/61 cm.

DESCRIPTION:

0 - 2 cm. Dark gray quartz sand, grass roots.
2 - 20 cm. Gray quartz sand, some shell.
20 - 55 cm. Gray to light gray quartz sand, wispy organic laminated bedding.
55 - 56 cm. Black quartz-organic sand.
56 - 61 cm. Gray quartz sand, wispy bedding.

CORE: 75

DATE: 8-22-66

LOCATION: One kilometer south of Soldier Key, 60 meters west of axis of Key Largo Ridge.

WATER DEPTH: 0 cm.

SEDIMENT THICKNESS: 183 cm.

CORE PENETRATION/LENGTH: 130 cm/116 cm.

DESCRIPTION:

0 - 10 cm. Calcareous sand with Thalassia rhizomes, Halimeda plates abundant.
10 - 116 cm. Calcareous sand with Thalassia roots to 35 cm., abundant Halimeda, some shell and Porites.

*The general locations of cores are given in Figure 9. Location names and places given in the following core descriptions may be found on U.S. Coast and Geodetic Survey charts for the Biscayne Bay area (C. & G.S. 847, 848, and 849).
CORE: 76

DATE: 8-22-66

LOCATION:
15 meters south of channel to south of Soldier Key, in line with keys.

WATER DEPTH:
0 cm.

SEDIMENT THICKNESS:
137 cm.

CORE PENETRATION/LENGTH:
122 cm/80 cm.

DESCRIPTION:

0 - 26 cm.
Carbonate sand with coarse Halimeda plates and shell fragments; abundant Thalassia rhizomes and rootlets.

26 - 52 cm.
Same, but no rhizomes.

52 - 75 cm.
Coarse carbonate sand with abundant mega-skeletons of Porites and shell.

75 - 78 cm.
Large burrow filled with carbonate sand.

78 - 80 cm.
Coarse, Halimeda plate, carbonate sand with Porites.

CORE: 80

DATE: 8-24-66

LOCATION:
On isolated shoal 5 km. S.W. of Soldier Key.

WATER DEPTH:
64 cm.

SEDIMENT THICKNESS:
457 cm.

CORE PENETRATION/LENGTH:
270 cm/209 cm.

DESCRIPTION:

0 - 8 cm.
Muddy carbonate sand, with Halimeda plates, shell and friable pellets, some grass roots.

8 - 17 cm.
Less sandy.

17 - 117 cm.
Carbonate mud with traces of grass roots and shell band at 40 cm.

117 - 137 cm.
Muddy carbonate sand.

137 - 145 cm.
Carbonate mud.

145 - 209 cm.
Muddy carbonate sand with bands of coarse carbonate sand.
CORE: 81
DATE: 8-24-66
LOCATION: On remnant stringer shoal 4 km. SSW of Soldier Key.
WATER DEPTH: 48 cm.
SEDIMENT THICKNESS: > 290 cm.
CORE PENETRATION/LENGTH: 290 cm/283 cm.
DESCRIPTION:
0 - 14 cm. Muddy, *Halimeda* plate, carbonate sand.
14 - 107 cm. Muddy, coarse carbonate sand (*Halimeda*) with very abundant megaskeletons of *Porites* and shell.
107 - 283 cm. Muddy *Halimeda* plate sand with occasional shell and *Porites*; extensively burrowed.

CORE: 82
DATE: 8-24-66
LOCATION: 3 km. south of Soldier Key, in line with keys, north edge of channel.
WATER DEPTH: 91 cm.
SEDIMENT THICKNESS: 183 cm.
CORE PENETRATION/LENGTH: 138 cm/136 cm.
DESCRIPTION:
0 - 22 cm. Gray muddy carbonate sand with *Thalassia* rhizomes and roots.
22 - 76 cm. Same, but no rhizomes.
76 - 136 cm. Lighter, less muddy, coarse carbonate sand (*Halimeda* plates) with megaskeletons of *Porites*, *Manicina* (not in growth position) and shells; burrowed.
<table>
<thead>
<tr>
<th>CORE: 83</th>
<th>DATE: 8-24-66</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOCATION: 40 meters south of Soldier Key.</td>
<td>WATER DEPTH: 28 cm.</td>
</tr>
<tr>
<td>SEDIMENT THICKNESS: 213 cm.</td>
<td>CORE PENETRATION/LENGTH: 196 cm/141 cm.</td>
</tr>
<tr>
<td>DESCRIPTION:</td>
<td></td>
</tr>
<tr>
<td>0 - 16 cm.</td>
<td>Off white carbonate sand with coarse shells and <em>Halimeda</em> plates; <em>Thalassia</em> rhizomes.</td>
</tr>
<tr>
<td>16 - 28 cm.</td>
<td>Carbonate sand with abundant pieces of Porites.</td>
</tr>
<tr>
<td>28 - 55 cm.</td>
<td>Shelly, <em>Halimeda</em> plate carbonate sand with some fine quartz.</td>
</tr>
<tr>
<td>55 - 80 cm.</td>
<td>Quartzose carbonate sand with very abundant megaskeletons of Porites and shell.</td>
</tr>
<tr>
<td>80 - 103 cm.</td>
<td>Quartzose, <em>Halimeda</em> plate, carbonate sand with fragments of Porites and shell.</td>
</tr>
<tr>
<td>103 - 141 cm.</td>
<td>Quartzose, shelly, <em>Halimeda</em> plate, carbonate sand.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CORE: 85s</th>
<th>DATE: 8-29-66</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOCATION: West side of Elliot Key, north side of Billy's point, 3 meters from shore.</td>
<td>WATER DEPTH: 107 cm.</td>
</tr>
<tr>
<td>SEDIMENT THICKNESS: 76 cm.</td>
<td>CORE PENETRATION/LENGTH: 71 cm/69 cm.</td>
</tr>
<tr>
<td>DESCRIPTION:</td>
<td></td>
</tr>
<tr>
<td>0 - 2 cm.</td>
<td>Brown quartz sand containing shell and <em>Halimeda</em> material.</td>
</tr>
<tr>
<td>2 - 9 cm.</td>
<td>Brown peat with thin bands of shell and quartz.</td>
</tr>
<tr>
<td>9 - 24 cm.</td>
<td>Reddish-brown peat.</td>
</tr>
<tr>
<td>24 - 27 cm.</td>
<td>Irregular band of shell and quartz sand.</td>
</tr>
<tr>
<td>27 - 58 cm.</td>
<td>Peat.</td>
</tr>
<tr>
<td>58 - 69 cm.</td>
<td>Shelly, quartzose, carbonate mud, red mangrove root.</td>
</tr>
</tbody>
</table>
CORE: 86a

LOCATION: Shoal north of Broad Creek, 3 meters west of Swan Key shoreline.

WATER DEPTH: 76 cm.

SEDIMENT THICKNESS: 117 cm.

CORE PENETRATION/LENGTH: 90 cm/88 cm.

DESCRIPTION:

0 - 1 cm. Coarse carbonate sand.
1 - 79 cm. Carbonate mud with coarse shell and Hali­meda plates, Thalassia roots, no quartz.
79 - 88 cm. Darker organic-carbonate mud, mangrove root.

DATE: 8-29-66

CORE: 89a

LOCATION: Shoreline, west side of Card Sound, 30 meters north of Canal.

WATER DEPTH: 0 cm.

SEDIMENT THICKNESS: 244 cm.

CORE PENETRATION/LENGTH: 299 cm/198 cm.

DESCRIPTION:

0 - 5 cm. Quartz sand.
5 - 198 cm. Reddish brown to dark brown fibrous peat.

DATE: 8-30-66
CORE: 96*

LOCATION
Center of Pelican Bank (east of Turkey Point).

WATER DEPTH: 28 cm.

SEDIMENT THICKNESS: 338 cm.

CORE PENETRATION/LENGTH: 290 cm/234 cm.

DESCRIPTION:

0 - 50 cm. Quartzose carbonate sand.
50 - 150 cm. Gray sandy carbonate mud with bands of quartz carbonate sand and shell.
150 - 159 cm. Tan organic-carbonate mud.
159 - 177 cm. Dark brown fibrous peat containing some burrows filled with coarse sand.
177 - 178 cm. Shell layer.
178 - 184 cm. Gray sandy (quartz) carbonate mud with mangrove roots.
184 - 185 cm. Shell layer.
185 - 240 cm. Gray sandy (quartz) carbonate mud, sandier towards bottom.

*Note: Core was taken in narrow bedrock depression (bedrock depth as much as 366 cm.); adjacent bedrock depth is about 225 cm.
<table>
<thead>
<tr>
<th>CORE: 99a</th>
<th>DATE: 9-1-66</th>
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<tbody>
<tr>
<td>LOCATION:</td>
<td>South tip of Long Arsenicker Key, on Shoreline.</td>
</tr>
<tr>
<td>WATER DEPTH:</td>
<td>0 cm.</td>
</tr>
<tr>
<td>SEDIMENT THICKNESS:</td>
<td>198 cm.</td>
</tr>
<tr>
<td>CORE PENETRATION/LENGTH:</td>
<td>43 cm/42 cm.</td>
</tr>
<tr>
<td>DESCRIPTION:</td>
<td></td>
</tr>
<tr>
<td>0 - 23 cm.</td>
<td>Clean quartz sand grading downward to gray quartz sand.</td>
</tr>
<tr>
<td>23 - 33 cm.</td>
<td>Brown quartz sand with organic hash and some shell.</td>
</tr>
<tr>
<td>33 - 37 cm.</td>
<td>Gray quartz sand.</td>
</tr>
<tr>
<td>37 - 38 cm.</td>
<td>Brown quartz sand with organic hash and shell.</td>
</tr>
<tr>
<td>38 - 40 cm.</td>
<td>Gray quartz sand.</td>
</tr>
<tr>
<td>40 - 41 cm.</td>
<td>Brown quartz sand.</td>
</tr>
<tr>
<td>41 - 42 cm.</td>
<td>Gray quartz sand.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CORE: 100</th>
<th>DATE: 9-2-66</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOCATION:</td>
<td>At shoreline, southeast side of Arsenicker Key.</td>
</tr>
<tr>
<td>WATER DEPTH:</td>
<td>0 cm.</td>
</tr>
<tr>
<td>SEDIMENT THICKNESS:</td>
<td>191 cm.</td>
</tr>
<tr>
<td>CORE PENETRATION/LENGTH:</td>
<td>30 cm/27 cm.</td>
</tr>
<tr>
<td>DESCRIPTION:</td>
<td></td>
</tr>
<tr>
<td>0 - 6.5 cm.</td>
<td>Clean to light gray quartz sand.</td>
</tr>
<tr>
<td>6.5 - 7 cm.</td>
<td>Detrital peat and shell.</td>
</tr>
<tr>
<td>7 - 9.5 cm.</td>
<td>Bedded shelly quartz sand.</td>
</tr>
<tr>
<td>9.5 - 17.5 cm.</td>
<td>Bedded quartz sand.</td>
</tr>
<tr>
<td>17.5 - 18 cm.</td>
<td>Shelly quartz sand.</td>
</tr>
<tr>
<td>18 - 19 cm.</td>
<td>Gray quartz sand.</td>
</tr>
<tr>
<td>19 cm.</td>
<td>Detrital peat and shell.</td>
</tr>
<tr>
<td>19 - 22 cm.</td>
<td>Gray to dark gray shelly quartz sand.</td>
</tr>
<tr>
<td>22 - 23 cm.</td>
<td>Black shelly quartz sand and organic material.</td>
</tr>
<tr>
<td>23 - 25 cm.</td>
<td>Bedded gray quartz sand and shell.</td>
</tr>
<tr>
<td>25 - 25.5 cm.</td>
<td>Coarse shell hash.</td>
</tr>
<tr>
<td>25.5 - 27 cm.</td>
<td>Bedded shelly quartz sand.</td>
</tr>
<tr>
<td>CORE: 105</td>
<td>DATE: 9-3-66</td>
</tr>
<tr>
<td>-----------</td>
<td>--------------</td>
</tr>
<tr>
<td>LOCATION: South of North Featherbed Bank, 300 meters S.E. of Marker #5.</td>
<td></td>
</tr>
<tr>
<td>WATER DEPTH: 305 cm.</td>
<td></td>
</tr>
<tr>
<td>SEDIMENT THICKNESS: 61 cm.</td>
<td></td>
</tr>
<tr>
<td>CORE PENETRATION/LENGTH: 20 cm/14 cm.</td>
<td></td>
</tr>
<tr>
<td>DESCRIPTION:</td>
<td></td>
</tr>
<tr>
<td>0 - 8 cm. Sandy, shelly carbonate mud, Thalassia rhizomes.</td>
<td></td>
</tr>
<tr>
<td>8 - 14 cm. Sandy, shelly carbonate mud with Porites and Thalassia roots.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CORE: 106</th>
<th>DATE: 9-3-66</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOCATION: Western broadening of North Featherbed Bank, 100 meters east of Featherbed Channel.</td>
<td></td>
</tr>
<tr>
<td>WATER DEPTH: 99 cm.</td>
<td></td>
</tr>
<tr>
<td>SEDIMENT THICKNESS: 302 cm.</td>
<td></td>
</tr>
<tr>
<td>CORE PENETRATION/LENGTH: 165 cm/157 cm.</td>
<td></td>
</tr>
<tr>
<td>DESCRIPTION:</td>
<td></td>
</tr>
<tr>
<td>0 - 2 cm. Sandy carbonate mud with Halimeda plates and Porites.</td>
<td></td>
</tr>
<tr>
<td>2 - 10 cm. Sandy carbonate mud with Thalassia rhizomes.</td>
<td></td>
</tr>
<tr>
<td>10 - 157 cm. Silty carbonate mud with Thalassia rootlets and occasional shells and Halimeda; reworked by burrowing.</td>
<td></td>
</tr>
</tbody>
</table>
CORE: 107  
DATE: 9-3-66

LOCATION: Deeper water 0.5 km. north of North Featherbed Bank.

WATER DEPTH: 295 cm.

SEDIMENT THICKNESS: 150 cm.

CORE PENETRATION/LENGTH: 135 cm/110 cm.

DESCRIPTION:

0 - 110 cm. Sandy carbonate mud with whole shells, \textit{Halimeda} plates, \textit{Thalassia} roots, \textit{Porites} at 98 cm.

CORE: 109  
DATE: 9-3-66

LOCATION: West shoreline of Rubicon Key.

WATER DEPTH: 81 cm.

SEDIMENT THICKNESS: 236 cm.

CORE LENGTH: 48 cm.

DESCRIPTION:

0 - 72 cm. Gray, sandy carbonate mud with \textit{Thalassia} roots and moderate shell and \textit{Halimeda.}

72 - 79 cm. Brown, sandy, organic-carbonate mud with \textit{Thalassia} roots and \textit{Halimeda.}

79 - 82 cm. Tan sandy mud.

82 - 148 cm. Very dark, fibrous peat which has been extensively burrowed. Burrows are filled with tan, sandy carbonate mud with \textit{Halimeda} plates.
CORE: 110  
LOCATION: East Arsenicker Key shoreline.  
ELEVATION: 5 cm.  
SEDIMENT THICKNESS: 173 cm.  
CORE PENETRATION/LENGTH: 175 cm/141 cm.  
DESCRIPTION:  
0 - 10 cm.  Clean quartz sand.  
10 - 15 cm.  Dark quartz sand with organic hash.  
15 - 21 cm.  Shelly quartz sand with root material.  
21 - 34 cm.  Tan carbonate mud with roots.  
34 - 39 cm.  Dark brown organic-carbonate mud.  
66 - 81 cm.  Dark brown organic-carbonate mud.  
81 - 82 cm.  Shell hash.  
82 - 139 cm.  Shelly, sandy, carbonate mud.  
139 - 141 cm.  Bedrock.  

CORE: 112  
LOCATION: Northeast shore of West Arsenicker Key, 5 meters from mangrove shoreline.  
WATER DEPTH: 48 cm.  
SEDIMENT THICKNESS: 43 cm.  
CORE PENETRATION/LENGTH: 40 cm/23 cm.  
DESCRIPTION:  
0 - 2 cm.  Thalassia hash.  
2 - 7 cm.  Bedded quartz sand with bands of shell hash.  
7 - 23 cm.  Dark brown peat with irregular patches of quartz sand.
<table>
<thead>
<tr>
<th>CORE: 114</th>
<th>DATE: 9-20-66</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOCATION:</td>
<td>West side of Safety Valve.</td>
</tr>
<tr>
<td>WATER DEPTH:</td>
<td>122 cm.</td>
</tr>
<tr>
<td>SEDIMENT THICKNESS:</td>
<td>488 cm.</td>
</tr>
<tr>
<td>CORE PENETRATION/LENGTH:</td>
<td>457 cm/432 cm.</td>
</tr>
<tr>
<td>DESCRIPTION:</td>
<td></td>
</tr>
<tr>
<td>0 - 2 cm.</td>
<td>Carbonate sand, Halimeda plates and shell abundant.</td>
</tr>
<tr>
<td>2 - 390 cm.</td>
<td>Sandy algal-plate (Halimeda) carbonate mud, Thalassia roots, some shell; Halimeda especially abundant filling burrows; no bedding.</td>
</tr>
<tr>
<td>390 - 432 cm.</td>
<td>Shelly quartzose carbonate sand, no Halimeda plates or Thalassia roots.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CORE: 119a</th>
<th>DATE: 10-14-66</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOCATION:</td>
<td>South Main Key Beach, Barnes Sound, low water line.</td>
</tr>
<tr>
<td>WATER DEPTH:</td>
<td>0 cm.</td>
</tr>
<tr>
<td>CORE LENGTH:</td>
<td>41 cm.</td>
</tr>
<tr>
<td>DESCRIPTION:</td>
<td></td>
</tr>
<tr>
<td>0 - 15 cm.</td>
<td>Bedded shell hash sand.</td>
</tr>
<tr>
<td>15 - 17 cm.</td>
<td>Peat band.</td>
</tr>
<tr>
<td>17 - 20 cm.</td>
<td>Bedded shell hash sand.</td>
</tr>
<tr>
<td>20 - 22 cm.</td>
<td>Muddy shell hash sand.</td>
</tr>
<tr>
<td>22 - 27 cm.</td>
<td>Bedded coarse shell hash sand.</td>
</tr>
<tr>
<td>27 - 39 cm.</td>
<td>Muddy quartzose shell hash.</td>
</tr>
<tr>
<td>39 - 40 cm.</td>
<td>Peat band.</td>
</tr>
<tr>
<td>40 - 41 cm.</td>
<td>Coarse shell hash.</td>
</tr>
<tr>
<td>CORE:</td>
<td>120</td>
</tr>
<tr>
<td>-----------</td>
<td>-----------------------------------------</td>
</tr>
<tr>
<td>LOCATION:</td>
<td>Small bay west of South Main Key.</td>
</tr>
<tr>
<td>WATER DEPTH:</td>
<td>120 cm.</td>
</tr>
<tr>
<td>CORE LENGTH:</td>
<td>43 cm.</td>
</tr>
<tr>
<td>DESCRIPTION:</td>
<td>Dark gray organic-carbonate mud, Soritidae abundant, floculant.</td>
</tr>
<tr>
<td></td>
<td>17 - 30 cm.</td>
</tr>
<tr>
<td></td>
<td>30 - 43 cm.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CORE:</th>
<th>126*</th>
<th>DATE:</th>
<th>12-4-66</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOCATION:</td>
<td>Mangrove swamp, east side of Barnes Sound, 100 meters east of shoreline.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WATER DEPTH:</td>
<td>0 cm.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SEDIMENT THICKNESS:</td>
<td>308 cm.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CORE PENETRATION/LENGTH:</td>
<td>325 cm/246 cm.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DESCRIPTION (corrected for compaction):</td>
<td>Muddy carbonate sand and peat.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5 - 301 cm.</td>
<td>Reddish-brown fibrous mangrove peat.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>301 - 308 cm.</td>
<td>Fibrous peat and bedrock.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>308 - 325 cm.</td>
<td>Bedrock.</td>
<td></td>
</tr>
</tbody>
</table>

*Note: Core taken in three sections.
CORE: 131*                              DATE: 11-29-66
LOCATION: About one kilometer east of mangrove
waterline, Barnes Sound.
WATER DEPTH: 0 cm.
SEDIMENT THICKNESS: 211 cm.
CORE PENETRATION/LENGTH: 211 cm/145 cm.
DESCRIPTION:

0 - 24 cm. Black peat with bands of shell
(Anomalocardia).
24 - 30 cm. Shelly black peat grades into fibrous
reddish brown peat.
30 - 43 cm. Fibrous peat with shell hash in a burrow.
43 - 123 cm. Fibrous peat.
123 - 130 cm. Shell hash.
130 - 145 cm. Tan organic-carbonate mud with bands and
patches of dark peat.

CORE: 132a                              DATE: 11-29-66
LOCATION: Shoal, 20 meters east of shell beach, North
Main Key, Barnes Sound.
WATER DEPTH: 36 cm.
SEDIMENT THICKNESS: 208 cm.
CORE PENETRATION/LENGTH: 196 cm/186 cm.
DESCRIPTION:

0 - 18 cm. Tan, shelly, muddy carbonate sand.
18 - 32 cm. Organic laminated sandy carbonate mud.
Alternating dark and light bands. Several burrows are filled with shelly sand.
32 - 95 cm. Gray sandy carbonate mud reworked by bur-
rowing. Marine shells present in irregular bands.
95 - 186 cm. Dark shelly carbonate mud with some grass
roots. No bedding.

*Note: Core taken in two sections.
CORE: 132b
LOCATION: Shoreline, North Main Key Beach, Barnes Sound.
WATER DEPTH: 0 cm.
SEDIMENT THICKNESS: 224 cm.
CORE LENGTH: 20 cm.
DESCRIPTION:
0 - 17 cm. Coarse shell hash.
17 - 20 cm. Dark shelly carbonate mud with grass roots.

CORE: 132c
LOCATION: Intertidal algal mat environment west of North Main Key Beach, Barnes Sound.
WATER DEPTH: 0 cm.
SEDIMENT THICKNESS: 274 cm.
CORE LENGTH: 104 cm.
DESCRIPTION:
0 - 1 cm. Finely laminated algal mat containing carbonate mud.
1 - 2 cm. Bedded, muddy shell hash.
2 - 31 cm. Gray, organic-carbonate mud with fine rootlets and a few shells, finely laminated.
31 - 51 cm. Organic-carbonate mud with rootlets; very distinct bedding cut by burrows.
51 - 57 cm. Lighter and darker gray organic-carbonate mud bands; evidence of mud cracks.
57 - 91 cm. Dark gray carbonate mud with rootlets and a few shells; not so distinctly bedded.
91 - 92 cm. Shelly band.
92 - 104 cm. Gray sandy carbonate mud, few shells, no rootlets.
<table>
<thead>
<tr>
<th>CORE: 133</th>
<th>DATE: 11-29-66</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOCATION:</td>
<td>At shoreline, east side of spit north of Flat Point, Manatee Bay, Barnes Sound.</td>
</tr>
<tr>
<td>WATER DEPTH:</td>
<td>0 cm.</td>
</tr>
<tr>
<td>CORE LENGTH:</td>
<td>157 cm.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CORE: 134</th>
<th>DATE: 12-2-66</th>
</tr>
</thead>
<tbody>
<tr>
<td>WATER DEPTH:</td>
<td>122 cm.</td>
</tr>
<tr>
<td>SEDIMENT THICKNESS:</td>
<td>147 cm.</td>
</tr>
<tr>
<td>CORE PENETRATION/LENGTH:</td>
<td>~ 120 cm/98 cm.</td>
</tr>
<tr>
<td>DESCRIPTION:</td>
<td>0 - 2 cm. Muddy shell hash with Thalassia roots. 2 - 14 cm. Gray muddy sand. 14 - 98 cm. Gray muddy sand with frequent bands of shell.</td>
</tr>
<tr>
<td>CORE: 135</td>
<td>DATE: 12-2-66</td>
</tr>
<tr>
<td>-----------</td>
<td>--------------</td>
</tr>
<tr>
<td>LOCATION:</td>
<td>Fresh water swamp west of Card Sound, 0.5 km. west of mangrove shoreline.</td>
</tr>
<tr>
<td>WATER DEPTH:</td>
<td>10 cm.</td>
</tr>
<tr>
<td>SEDIMENT THICKNESS:</td>
<td>226 cm.</td>
</tr>
<tr>
<td>CORE PENETRATION/LENGTH:</td>
<td>246 cm/177 cm.</td>
</tr>
<tr>
<td>DESCRIPTION:</td>
<td></td>
</tr>
<tr>
<td>0 - 42 cm.</td>
<td>Brown fibrous mangrove peat.</td>
</tr>
<tr>
<td>42 - 138 cm.</td>
<td>Light gray carbonate mud with mangrove roots.</td>
</tr>
<tr>
<td>138 - 146 cm.</td>
<td>Bedrock.</td>
</tr>
<tr>
<td>146 - 160 cm.</td>
<td>Fibrous peat and bedrock.</td>
</tr>
<tr>
<td>160 - 177 cm.</td>
<td>Bedrock.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CORE: 136*</th>
<th>DATE: 12-1-66</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOCATION:</td>
<td>Fresh water swamp west of Card Sound, 0.8 km. west of mangrove shoreline.</td>
</tr>
<tr>
<td>WATER DEPTH:</td>
<td>0 cm.</td>
</tr>
<tr>
<td>SEDIMENT THICKNESS:</td>
<td>61 cm.</td>
</tr>
<tr>
<td>CORE PENETRATION/LENGTH:</td>
<td>61 cm/61 cm.</td>
</tr>
<tr>
<td>DESCRIPTION:</td>
<td></td>
</tr>
<tr>
<td>0 - 20 cm.</td>
<td>Brown organic-carbonate mud containing fresh water snails and roots, patch of light fine carbonate mud.</td>
</tr>
<tr>
<td>20 - 61 cm.</td>
<td>Dark brown organic-carbonate mud containing rootlets.</td>
</tr>
<tr>
<td>61 cm.</td>
<td>Rock fragments.</td>
</tr>
</tbody>
</table>

*Note: Core taken in two sections.*
CORE: 137  DATE: 12-1-66

LOCATION: Fresh water swamp west of Card Sound,  
           1.4 km. west of mangrove shoreline.

WATER DEPTH: 0 cm.

SEDIMENT THICKNESS: 97 cm.

CORE PENETRATION/LENGTH: 95 cm/87 cm.

DESCRIPTION:

0 - 1 cm. Tan sandy carbonate mud.
1 - 10 cm. White carbonate mud with some rootlets.
10 - 16 cm. Tan carbonate mud.
16 - 20 cm. Dark peat.
20 - 31 cm. Peaty carbonate mud with fresh water snails.
31 - 41 cm. Tan carbonate mud with fresh water snails.
41 - 66 cm. Peaty carbonate mud with fresh water snails and root material.
66 - 87 cm. Dark peat with some carbonate mud.

CORE: 138  DATE: 12-4-66

LOCATION: One kilometer west of mangrove shoreline  
           of Turtle Point, southwest Biscayne Bay.

WATER DEPTH: 15 cm.

SEDIMENT THICKNESS: 109 cm.

CORE PENETRATION/LENGTH: 106 cm/92 cm.

DESCRIPTION:

0 - 1 cm. Sandy carbonate mud.
1 - 12 cm. Dark peat.
12 - 49 cm. Carbonate mud with mangrove roots and patches of peat.
49 - 92 cm. Dark to reddish brown fibrous peat.
CORE: 139*  

DATE: 12-6-66

LOCATION: At shoreline 100 m. south of Turtle Point.

WATER DEPTH: 10 cm.

SEDIMENT THICKNESS: 130 cm.

CORE PENETRATION/LENGTH: 130 cm/119 cm.

DESCRIPTION:

0 - 1 cm. Quartzose shelly sand.
1 - 95 cm. Reddish brown fibrous peat.
95 - 103 cm. Brown peat with carbonate mud.
103 - 119 cm. Bedrock, carbonate mud and mangrove roots.

*Note: Core taken in two sections.
CORE: 149  
DATE: 2-7-67  

LOCATION: Northwest tip of Virginia Key at shoreline on eroding peat bank.  

ELEVATION: 30 cm.  
SEDIMENT THICKNESS: 508 cm.  
CORE PENETRATION/LENGTH: 510 cm.  

DESCRIPTION (corrected for compaction):  

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 1</td>
<td>Coarse quartz-carbonate sand.</td>
</tr>
<tr>
<td>1 - 30</td>
<td>Reddish brown fibrous mangrove peat containing some sand.</td>
</tr>
<tr>
<td>30 - 33</td>
<td>Sandy quartz rich band.</td>
</tr>
<tr>
<td>33 - 34</td>
<td>Peat.</td>
</tr>
<tr>
<td>34 - 40</td>
<td>Coarse sand with reddish brown peat.</td>
</tr>
<tr>
<td>40 - 90</td>
<td>Bedded gray quartz-carbonate sand with mangrove roots and abundant shell material.</td>
</tr>
<tr>
<td>90 - 315</td>
<td>Bedded tan to gray quartz-carbonate sand, with numerous bands and layers of shell material, occasional cross-bedding.</td>
</tr>
<tr>
<td>315 - 335</td>
<td>Gray to dark gray bedded sand with some plant material.</td>
</tr>
<tr>
<td>335 - 355</td>
<td>Gray muddy quartz-carbonate sand with plant material.</td>
</tr>
<tr>
<td>355 - 435</td>
<td>Tan sandy carbonate mud with shells and plant material.</td>
</tr>
<tr>
<td>435 - 460</td>
<td>Tan sandy carbonate mud.</td>
</tr>
<tr>
<td>460 - 484</td>
<td>Gray sandy carbonate mud.</td>
</tr>
<tr>
<td>484 - 497</td>
<td>Gray shelly carbonate mud.</td>
</tr>
<tr>
<td>494 - 501</td>
<td>Shell layer.*</td>
</tr>
<tr>
<td>497 - 501</td>
<td>Gray muddy sand.</td>
</tr>
<tr>
<td>501 - 508</td>
<td>Peat and bedrock.</td>
</tr>
</tbody>
</table>

*Note: Core taken in three sections; part of clastic sequence lost on withdrawal. Shell layer dated at 4,200 years B.P.
CORE: 150
DATE: 2-7-67

LOCATION: At mangrove shoreline west side of Key Biscayne, west of oldest visible beach ridge.

WATER DEPTH: 20 cm.

SEDIMENT THICKNESS: ~ 690 cm.

CORE PENETRATION/LENGTH: 550 cm/368 cm.*

DESCRIPTION (corrected for compaction and loss):

0 - 1 cm. Dark brown organic-carbonate mud.
1 - 22 cm. Muddy quartz-carbonate sand with dark organic bands.
22 - 50 cm. Dark reddish brown peat with roots, burrows containing sand.
50 - 102 cm. Sandy peat with bands of quartz-carbonate sand; mangrove roots towards bottom.
102 - 115 cm. Bedded quartz carbonate sand.
115 - 507 cm. Tan bedded quartz-carbonate sand alternating with gray quartz rich sand, occasional detrital peat lenses.
507 - 550 cm. Tan sand grading to coarse quartz sand with detrital peat and root material.

*Note: Core taken in two sections, some loss on each withdrawal. Probing indicated that sand extended to 610 cm. below which a sandy mud extended to 670 cm. followed by some gravel.
<table>
<thead>
<tr>
<th>Core Penetration/Length</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 10 cm.</td>
<td>Bedded quartz-carbonate sand.</td>
</tr>
<tr>
<td>10 - 34 cm.</td>
<td>Tan, muddy carbonate sand with shells.</td>
</tr>
<tr>
<td>34 - 70 cm.</td>
<td>Sandier with no shells.</td>
</tr>
<tr>
<td>70 - 144 cm.</td>
<td>Bedded coarse, gray quartz rich sand with occasional shell and organic bands.</td>
</tr>
<tr>
<td>144 - 200 cm.</td>
<td>Light gray to tan muddy quartz carbonate sand.</td>
</tr>
<tr>
<td>200 - 223 cm.</td>
<td>Gray quartz rich sand.</td>
</tr>
<tr>
<td>223 - 246 cm.</td>
<td>Light gray to tan, muddy quartz-carbonate sand.</td>
</tr>
</tbody>
</table>

*Note: Extensive loss on withdrawal.*
CORE: 152

LOCATION: Western spoil island of the Deering Estate (Vizcaya) Channel.

ELEVATION: 0 cm.

SEDIMENT THICKNESS: 537 cm.

CORE PENETRATION: 537 cm.

DESCRIPTION (corrected for compaction):

<table>
<thead>
<tr>
<th>Layer</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 210 cm.</td>
<td>Spoil, clean quartz sand and pieces of bedrock.</td>
</tr>
<tr>
<td>210 - 240 cm.</td>
<td>Bedded tan quartz sand with organics.</td>
</tr>
<tr>
<td>240 - 260 cm.</td>
<td>Dark gray organic-rich quartz sand.</td>
</tr>
<tr>
<td>260 - 330 cm.</td>
<td>Alternating irregular bands (less than 50 mm. wide) of clean quartz sand and dark brown detrital peat.</td>
</tr>
<tr>
<td>330 - 380 cm.</td>
<td>Dark brown peat* with some quartz.</td>
</tr>
<tr>
<td>380 - 410 cm.</td>
<td>Alternating irregular bands of clean quartz sand and dark brown detrital peat.</td>
</tr>
<tr>
<td>410 - 480 cm.</td>
<td>Bedded tan to gray quartz sand with dark organic bands.</td>
</tr>
<tr>
<td>480 - 510 cm.</td>
<td>Clear quartz sand.</td>
</tr>
<tr>
<td>510 - 530 cm.</td>
<td>Tan quartz sand.</td>
</tr>
<tr>
<td>530 - 537 cm.</td>
<td>Bedrock, quartz and muddy quartz sand.</td>
</tr>
</tbody>
</table>

*Note: Core taken in three sections. Only general correction for compaction could be made throughout much of the core. However, section two ended and section three began in the middle of the peat bed (360 cm.) allowing exact positioning of it. The peat dated at 4,267 ± 100 years B.P.
CORE: 160  
DATE:  2-18-67

LOCATION:  Lagoon behind Miami Beach, 0.5 km. west of Mt. Sinai Hospital.

WATER DEPTH:  122 cm.

SEDIMENT THICKNESS:  ~ 396 cm.

CORE PENETRATION/LENGTH:  152 cm/126 cm.

DESCRIPTION:

0 - 9 cm.  Dark gray stinky sandy muck.
9 - 12 cm.  Dark gray shell hash.
12 - 95 cm.  Tan, shelly, muddy quartz-carbonate sand.
95 - 105 cm.  Shell layer (Crassotrea virginica).
105 - 110 cm.  Gray, muddy quartz-carbonate sand.
110 - 126 cm.  Gray, shelly, muddy sand.

CORE: 162  
DATE:  2-19-67

LOCATION:  Open bay, three kilometers due west of Soldier Key.

WATER DEPTH:  340 cm.

SEDIMENT THICKNESS:  262 cm.

LENGTH:  55 cm.

DESCRIPTION:

0 - 1 cm.  Off white, muddy carbonate sand with shells and Halimeda plates.
1 - 5 cm.  Light gray, muddy, carbonate sand with Thalassia roots.
5 - 10 cm.  Light gray sandy carbonate mud.
10 - 55 cm.  Off white sandy carbonate mud with gray carbonate mud filling burrows, no bedding.
CORE: 163  
DATE: 2-19-67

LOCATION: Center of Black Ledge on line with marker "2" and Soldier Key.

WATER DEPTH: 78 cm.

SEDIMENT THICKNESS: 244 cm.

CORE PENETRATION/LENGTH: 244 cm/220 cm.

DESCRIPTION:

<table>
<thead>
<tr>
<th>Interval</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 3 cm.</td>
<td>Clean quartz sand with Porites.</td>
</tr>
<tr>
<td>3 - 73 cm.</td>
<td>Clean quartz sand with Thalassia roots, occasional Porites and wispy bedding.</td>
</tr>
<tr>
<td>73 - 90 cm.</td>
<td>Muddy quartz sand.</td>
</tr>
<tr>
<td>90 - 100 cm.</td>
<td>Clean quartz sand.</td>
</tr>
<tr>
<td>100 - 164 cm.</td>
<td>Quartz sand grading to muddy sand with shells.</td>
</tr>
<tr>
<td>164 - 168 cm.</td>
<td>Muddy sand containing Porites and shells.</td>
</tr>
<tr>
<td>168 - 183 cm.</td>
<td>Sandy carbonate mud.</td>
</tr>
<tr>
<td>183 - 216 cm.</td>
<td>Shelly carbonate mud with grass roots.</td>
</tr>
<tr>
<td>216 - 220 cm.</td>
<td>Bedrock and muddy quartzose sand.</td>
</tr>
</tbody>
</table>

CORE: 164  
DATE: 2-19-67

LOCATION: Mainland shoreline 200 m. north of Black Point.

ELEVATION: 23 cm.

SEDIMENT THICKNESS: 122 cm.

CORE PENETRATION/LENGTH: 120 cm/75 cm.

DESCRIPTION:

<table>
<thead>
<tr>
<th>Interval</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 17 cm.</td>
<td>Black fibrous peat and muddy quartz-carbonate sand.</td>
</tr>
<tr>
<td>17 - 75 cm.</td>
<td>Dark fibrous peat with roots and sticks.</td>
</tr>
<tr>
<td>75 cm.</td>
<td>Sandy sediment, pieces of bedrock.</td>
</tr>
</tbody>
</table>
CORE: 165a

LOCATION: Small filled solution hole in shallow basin west of Old Rhodes Key; surrounding area contains only sediment veneer over bedrock.

WATER DEPTH: 43 cm.

SEDIMENT THICKNESS: 153 cm.

CORE PENETRATION/LENGTH: 140 cm/101 cm.

DESCRIPTION:

0 - 11 cm. Coarse, shelly, muddy, sand with Thalassia rhizomes.
11 - 16 cm. Dark tan fibrous peat.
16 - 19 cm. Shell layer.
19 - 21 cm. Peat.
21 - 27 cm. Shelly sand with roots.
27 - 48 cm. Dark reddish brown fibrous peat and woody material.
48 - 86 cm. Fibrous peat with increasing carbonate mud towards bottom, shell hash in burrow.
86 - 101 cm. Dark gray carbonate mud with roots and bedrock.

CORE: 165b

LOCATION: Intertidal bedrock platform on west side of Old Rhodes Key. Core taken in small depression where black mangrove trees were present.

ELEVATION: - 30 cm.

SEDIMENT THICKNESS: 61 cm.

CORE PENETRATION/LENGTH: 15 cm/15 cm.

DESCRIPTION:

0 - 15 cm. Tan fibrous peat with a small amount of carbonate mud.