

Best, Kelly M., QUATERNARY GEOLOGIC EVOLUTION OF THE CROATAN BEACH RIDGE COMPLEX, BOGUE SOUND, AND BOGUE BANKS CARTERET COUNTY, NC. (Under the direction of Drs. David J. Mallinson and Stephen J. Culver) Department of Geological Sciences, January 19, 2010.

Foraminiferal, lithologic, chronostratigraphic, and geophysical data were utilized to describe the Quaternary geologic evolution of the Croatan Beach Ridge Complex, Bogue Sound, and Bogue Banks. The Croatan Beach Ridge Complex is a beach ridge feature located on the mainland of Carteret County, NC. It is separated from the adjacent barrier island, Bogue Banks, by Bogue Sound. Seventeen geoprobe and vibracores were collected along four shore-normal and shore-parallel transects from within the beach ridge complex, on the sound side of Bogue Banks, and in Bogue Sound. Seven depositional facies representing various coastal paleoenvironments were identified using sedimentological data and a cluster analysis of foraminiferal samples taken from core material. Three of these depositional facies were determined to be of normal marine salinity (high energy normal marine salinity, low energy normal marine salinity, and shallow inner shelf) and comprise the basal units of the Croatan Beach Ridge Complex, Bogue Banks, and Bogue Sound. The high energy normal marine salinity depositional facies is characterized by *Buccella inusitata*, *Cibicides lobatulus*, *Elphidium galvestonense*, *Eponides repandus*, *Hanzawaia strattoni*, *Nonionella atlantica*, *Quinqueloculina* spp., and *Textularia* cf. *T. gramen*. The low energy normal marine salinity depositional facies is characterized by *Bolivina lowmani*, *Bolivina paula*, *Eponides repandus*, *Gavelinopsis praegeri*, *Quinqueloculina seminula*, and *Rosalina floridana*. The shallow inner shelf depositional facies is characterized by *Bolivina*

lowmani, *Buliminella elegantissima*, and *Quinqueloculina bosciana*. The flood tide delta depositional facies contains a diverse foraminiferal assemblage with abundant *Elphidium excavatum*, *Ammonia parkinsoniana*, and *Elphidium mexicanum* and is found in the older sediments underlying Bogue Sound. The high salinity estuary depositional facies, restricted to basal units of Bogue Sound and Bogue Banks, is characterized by *Ammonia tepida*, *Elphidium poeyanum*, *Haynesina germanica*, and *Trochammina* sp. The high energy back-barrier lagoon depositional facies comprises the modern sediment of Bogue Sound and contains the shelf taxa typical of assemblages South of Cape Hatteras (such as *Ammonia* cf. *A. beccarii* and *Elphidium gunteri*) as well as agglutinated species (*Ammotium salsum*).

Chronostratigraphic data combined with foraminiferal, sedimentological, and geophysical data suggest that the Croatan Beach Ridge Complex formed and prograded south during MIS 5a (~80-95 ka), producing a cape structure at the southern end of the Suffolk Scarp. Similar data suggest aeolian reactivation of the upper segments of the Croatan Beach Ridge Complex during MIS 2 (~18 ka). OSL and radiocarbon age estimates and the occurrence of flood tide delta deposits indicate the formation of Bogue Banks approximately 6 ka. Seaward and westward spit progradation of Bogue Banks began in the Pine Knoll Shores area ca. 1.7 ka and continued to the eastern tip of Salter Path until ca. 1.3 ka. This corresponds to a spit progradation rate of ~16 m/yr, a rate similar to those found at Oregon Inlet. Normal marine salinity conditions were present in Bogue Sound ca. 1.1 ka, suggesting removal of at least the narrowest parts of Bogue

Banks, coincident with the collapse of segments of the barrier islands along the Outer Banks.

Quaternary Geologic Evolution of the Croatan Beach Ridge Complex, Bogue Sound, and
Bogue Banks, Carteret County, NC.

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QUATERNARY GEOLOGIC EVOLUTION OF THE CROATAN BEACH RIDGE
COMPLEX, BOGUE SOUND, AND BOGUE BANKS, CARTERET COUNTY, NC

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TABLE OF CONTENTS

LIST OF TABLES.....	xiii
LIST OF FIGURES.....	xiv
CHAPTER ONE: INTRODUCTION.....	1
PURPOSE OF STUDY.....	1
OBJECTIVES.....	5
CHAPTER TWO: PREVIOUS WORK.....	6
REGIONAL GEOLOGIC FRAMEWORK.....	6
The Suffolk Scarp.....	8
Croatan Beach Ridges.....	9
Bogue Banks.....	12
Geomorphology of Beach Ridges.....	24
FORAMINIFERA.....	26
Foraminifera as Paleoenvironmental Indicators.....	26
Modern United States Atlantic Coast Foraminiferal Assemblages.....	27
<i>Estuaries, Sounds, and Lagoons</i>	29
<i>Overwash and Inlets</i>	34
<i>Salt Marshes</i>	36
Modern United States Atlantic Continental Shelf Foraminiferal Assemblages.....	38
<i>Murray (1969)</i>	39
<i>Schnitker (1971)</i>	41

<i>Workman (1981)</i>	42
CHRONOSTRATIGRAPHY.....	45
Optically Stimulated Luminescence.....	45
Radiocarbon Dating.....	48
GEOPHYSICAL DATA.....	50
SEA LEVEL CURVES FOR NORTH CAROLINA.....	55
CHAPTER THREE: METHODOLOGY.....	62
GEOPROBE CORING.....	62
VIBRACORING.....	64
LITHOLOGY AND SEDIMENTOLOGY.....	64
FORAMINIFERAL ANALYSES.....	65
CLUSTER ANALYSIS.....	67
OPTICALLY STIMULATED LUMINESCENCE (OSL) CORE COLLECTION.....	67
RADIOCARBON DATING SAMPLE COLLECTION AND PROCESSING.....	69
GEOPHYSICAL DATA ACQUISITION.....	69
Ground Penetrating Radar.....	69
Seismic Surveys.....	69
CHAPTER FOUR: RESULTS AND INTERPRETATION.....	71
LITHOFACIES DESCRIPTIONS.....	71
Sand (S).....	71
Organic-rich Sand (orgS).....	76
Muddy Sand (mS).....	76

Shelly, Muddy Sand (shmS).....	76
Shelly Sand (shS).....	78
Gravelly Sand (gS).....	78
Mud (M).....	78
Sandy Mud (sM).....	78
Shelly Mud (shM).....	81
Shelly, Sandy Mud (shsM).....	81
Interbedded Mud and Sand (I).....	81
Interbedded Mud and Sand with Shells (shI).....	84
Large Shells (Sh).....	84
BIOFACIES DESCRIPTIONS.....	86
Biofacies A.....	91
Biofacies B.....	91
Biofacies C.....	92
Biofacies D.....	93
Biofacies E.....	94
Biofacies F.....	94
DEPOSITIONAL FACIES DESCRIPTIONS.....	96
Depositional Facies I: Shallow Inner Shelf.....	96
Depositional Facies II: Low Energy Normal Marine Salinity.....	97
Depositional Facies III: High Energy Normal Marine Salinity.....	97
Depositional Facies IV: Flood Tide Delta.....	98

Depositional Facies V: High Salinity Estuary.....	100
Depositional Facies VI: High Energy Back Barrier Lagoon.....	101
Depositional Facies VII: Aeolian Sand.....	102
CHRONOSTRATIGRAPHY.....	103
OSL Age Estimates.....	103
<i>Croatan Beach Ridge Complex</i>	103
<i>Bogue Sound</i>	104
<i>Bogue Banks</i>	106
AMS ¹⁴ C Estimates.....	107
GEOPHYSICAL DATA INTERPRETATION.....	109
Ground Penetrating Radar.....	109
Seismic.....	122
PALEOENVIRONMENTAL RECONSTRUCTION.....	135
Transect A.....	135
Transect B.....	144
Transect C.....	148
Transect D.....	150
CHAPTER FIVE: DISCUSSION.....	154
LATE QUATERNARY DEPOSITS RELATED TO SEA-LEVEL CHANGE.....	154
MIS 6 to MIS 5e (150-120 ka).....	156
MIS 5c to 5a (110-70 ka).....	156
MIS 3 (60-40 ka).....	160

MIS 2 to 1 (30 ka to present).....	162
CHAPTER SIX: SUMMARY.....	172
REFERENCES.....	174
PLATES.....	197
APPENDIX A: Geoprobe and Vibracore Location, Elevation, and Length.....	201
APPENDIX B: Core Logs Including Foraminiferal and Grain Size, OSL, and AMS ¹⁴ C	
Sample Locations.....	203
APPENDIX C: GRADISTAT Statistics of Geoprobe Cores and Vibracores.....	222
APPENDIX D: Mud/Sand/Gravel Percentages for Foraminiferal Samples.....	226
APPENDIX E: Raw Census Data of Foraminiferal Assemblages.....	229
APPENDIX F: Relative Abundance Data of Foraminiferal Assemblages.....	233
APPENDIX G: Transformed Abundance Data of Foraminiferal Assemblages.....	236
APPENDIX H: Alphabetical List of Foraminiferal Taxa Identified to the Species Level	
with Original References.....	240
APPENDIX I: OSL and AMS ¹⁴ C Sample Information.....	245

LIST OF TABLES

Table 1: Dominant/Characteristic Foraminiferal Taxa Found in Murray (1969), Schnitker (1971), and Workman (1981).....	44
Table 2: Composition and sedimentological characteristics of thirteen lithofacies identified in the seventeen cores collected. G/S/M/ ratios refer to the percentage of gravel, sand, and mud present in each lithofacies.....	72
Table 3: Summary of grain size data of lithofacies using the Folk and Ward Method (all data given in Φ).....	74
Table 4: Occurency (O), Constancy (C), and Biofacies Fidelity (BF) values of foraminiferal biofacies as defined by cluster analysis. C and BF values boxed where both are ≥ 3 for a taxon.....	88
Table 5: Characteristic and subsidiary species of each biofacies (as defined by Constancy and Biofacies Fidelity), including their interpreted paleoenvironment.....	89
Table 6: Average relative abundance calculations of each taxon in each biofacies. The three most abundant taxa in each biofacies are shown in bold.....	90
Table 7: OSL age estimates and equivalent dose data of samples from the Croatan Beach Ridge Complex, Bogue Banks, and Bogue Sound, NC.....	105
Table 8: AMS ^{14}C age estimates of samples from Bogue Sound, NC. Depositional facies abbreviations: HSE = high salinity estuary; LEOS = low energy normal marine salinity; FTD = flood tide delta. Dates were calculated using MARINE04 database and calibrated with INTCAL04 radiocarbon age calibration, with no local reservoir correction applied.....	108
Table 9. Summary of geologic evolution of the Croatan Beach Ridge Complex, Bogue Sound, and Bogue Banks and pertinent histories of the Suffolk Shoreline and Outer Banks over the past 150 ka.....	157

LIST OF FIGURES

Figure 1: LiDAR map of eastern North Carolina. The Suffolk Scarp extends from Norfolk, VA to Morehead City, NC. Geographic location of map is shown in black box (inset). Study area is indicated by blue box on the LiDAR map. Map source: www.ncfloodmaps.com .	3
Figure 2: LiDAR elevation map of southern Carteret County, North Carolina. Note the large-scale beach ridge complex (shown in red). Unit 1 is the prograding beach ridge complex, Unit 2 is the younger, mainland shoreline ridge, and Unit 3 is the present Holocene barrier island (Bogue Banks). Study area shown in black box. Map source: www.ncfloodmaps.com .	4
Figure 3: Map of the coastal plain of North Carolina showing the two distinct geologic provinces (from Riggs and Ames, 2003).	7
Figure 4: Map of the Croatan Beach Ridge Complex showing the beach ridge system. The larger area map is shown in the inset. The Suffolk Scarp is depicted, with the approximate southern terminus in the study area dashed. Adapted from Fisher (1967), where this beach ridge system was named the Newport Group.	11
Figure 5: Map of Bogue Banks (adapted from Steele, 1980).	13
Figure 6: Depositional history of Bogue Banks illustrating relict beach ridges and sequence boundaries. Letter correlate to the development of the island outlined by Fisher (1967), shown in Figure 7. Adapted from Fisher (1967).	14
Figure 7: The development of Bogue Banks as proposed by Fisher (1967).	16
Figure 8: Map of transects illustrated by Steele (1980) along Bogue Banks.	19
Figure 9: Cross section from the mainland, through Bogue Sound, to Emerald Isle (on Bogue Banks). Note the shoreface sediments only present on the ocean side and back barrier present only on the sound side (taken from Steele, 1980).	20
Figure 10: Longitudinal section of Bogue Banks running along the dunes along the center of the island. The final point in the east represents a core (Sh-5) on Shackleford Banks, N.C. (taken from Steele, 1980).	21
Figure 11: Cross section along eastern Bogue Banks, in Pine Knoll Shores. Note the large area of inlet fill, confirming inlet activity in the marsh areas of this part of the island (from Steele, 1980).	22
Figure 12: Major genera of foraminiferal assemblages found in marginal marine environments (from Scott et al., 2001).	28

Figure 13: Distribution of samples and biofacies from Grossman and Benson (1967). Taken from Pruitt (2008), modified from Grossman and Benson (1967).....	30
Figure 14: Abundant species found in surface samples taken in Core Sound, organized by biofacies (taken from Pruitt, 2008).....	33
Figure 15: GPR facies and interpretations in mid- to high-latitude coastal environments (taken from van Heteren et al., 1998).....	52
Figure 16: Sea level curves of Onslow Bay from data collected from Susman (1975), Moslow (1977), Herbert (1978), Berelson (1979), and Steele (1980) (adapted from Steele, 1980). Dashed line represents data from the Cape Lookout area (curve modified from Berelson, 1979). Solid line drawn using rates of sea-level rise proposed by Hine et al. (1979).....	56
Figure 17: Relative sea-level index points and limiting data for North Carolina with error bars. Sea-level index points are shown as black crosses, minimum (freshwater) limiting data shown in green, and maximum (marine) limiting data shown in red. Taken from Horton et al. (2009).....	57
Figure 18: Sea-level reconstructions of Sand Point and Tump Point marshes in North Carolina since AD 1500. Two tidal-gauge records along the Atlantic margin are also shown. Inset: Tump Point sea-level reconstruction compared to 20 th century tide-gauge records (taken from Kemp et al., 2009b).....	60
Figure 19: Relative sea-level index points with superimposed local tide-gauge records as comparison (Nova Scotia: Halifax; Connecticut: New London [red] and New York City [blue]; North Carolina: Charleston, SC [red] and NC average [blue]). Global tide gauge records from Church and White (2006; red) and Jevrejeva et al. (2008; blue) are shown along bottom. Taken from Kemp et al. (2009b).....	61
Figure 20: Map of study area showing core locations and GPR/seismic lines. Inset shows LiDAR data of Croatan Beach Ridge Complex and the location of cores and geophysical lines with respect to the ridges. Red in the LiDAR data represents the highest elevation, pale blue the lowest elevation. LiDAR data taken from www.ncfloodmaps.com	63
Figure 21: Photographs of BS-08-02 and Croatan-08-GP2 illustrating the sand and organic-rich sand lithofacies, respectively.....	75
Figure 22: Photographs of BS-08-03 illustrating the muddy sand and shelly, muddy sand lithofacies, respectively.....	77
Figure 23: Photographs of BS-08-01 and Croatan-08-GP2 illustrating the shelly sand and gravelly sand lithofacies, respectively.....	79
Figure 24: Photographs of BS-08-03 illustrating the mud and sandy mud lithofacies, respectively.....	80

- Figure 25:** Photographs of BS-08-02 and BS-08-01 illustrating the shelly mud and shelly sandy mud lithofacies, respectively.....82
- Figure 26:** Photographs of BS-08-01 and BS-08-05 illustrating the interbedded mud and sand and interbedded mud and sand with shells lithofacies, respectively.....83
- Figure 27:** Photographs of BS-08-06 and BS-08-04 illustrating the large shells lithofacies.....85
- Figure 28:** Dendrogram resulting from cluster analysis (Ward's Linkage, Euclidean distances) of foraminiferal data, indicating biofacies, assemblage data, and resulting interpreted paleoenvironments.....87
- Figure 29:** Depositional history of Bogue Banks showing the position of BB08-GP1 and BB08-GP2. BB08-GP1 is located on an older segment of the western- and seaward-moving spit complex that comprises the island. The aeolian sand depositional facies of BB08-GP1 yielded an age estimate of 1.58-1.86 ka; the age estimate for BB08-GP2, in the same depositional facies, is 1.2-1.5 ka. The division between Salter Path and Pine Knoll Shores is dashed.....107
- Figure 30:** Filtered and interpreted GPR data from Line 1838. Inset: All GPR lines collected in the Croatan Beach Ridge Complex shown in black; location of Line 1838 in the study area is shown in yellow.....110
- Figure 31:** Filtered and interpreted GPR data from Line 1839. Inset: All GPR lines collected in the Croatan Beach Ridge Complex shown in black; location of Line 1838 in the study area is shown in yellow.111
- Figure 32:** Filtered and interpreted GPR data from Line 1840. Inset: All GPR lines collected in the Croatan Beach Ridge Complex shown in black; location of Line 1840 in the study area is shown in yellow.113
- Figure 33:** Filtered and interpreted GPR data from Line 1845. Inset: All GPR lines collected in the Croatan Beach Ridge Complex shown in black; location of Line 1845 in the study area is shown in yellow.115
- Figure 34:** Filtered and interpreted GPR data from Line 69. Inset: All GPR lines collected in the Croatan Beach Ridge Complex shown in black; location of Line 69 in the study area is shown in yellow.116
- Figure 35:** Filtered and interpreted GPR data from Line 80. Inset: All GPR lines collected in the Croatan Beach Ridge Complex shown in black; location of Line 80 in the study area is shown in yellow.118
- Figure 36:** Filtered and interpreted GPR data from Line 35. Inset: All GPR lines collected on Bogue Banks shown in black; location of Line 35 in the study area is shown in yellow..119

- Figure 37:** Filtered and interpreted GPR data from Line 41. Inset: All GPR lines collected on Bogue Banks shown in black; location of Line 41 in the study area is shown in yellow..121
- Figure 38:** Filtered and interpreted seismic line L6f2 from Bogue Sound. Core BS-08-03 is shown in red. Inset: Black lines represent all seismic data collected, L6f2 is shown in yellow.....123
- Figure 39:** Filtered and interpreted seismic line L9f4 from Bogue Sound. Inset: Black lines represent all seismic data collected, L9f4 is shown in yellow.....125
- Figure 40:** Filtered and interpreted seismic line L6f1 from Bogue Sound. Inset: Black lines represent all seismic data collected, L6f1 is shown in yellow. Black lines on Bogue Banks indicate GPR data.....126
- Figure 41:** Filtered and interpreted seismic line L5f1 from Bogue Sound. Inset: Black lines represent all seismic data collected, L5f1 is shown in yellow. Black lines on Bogue Banks indicate GPR data.....128
- Figure 42:** Filtered and interpreted seismic line L8f1 from Bogue Sound. Inset: Black lines represent all seismic data collected, L8f1 is shown in yellow. Black lines on Bogue Banks indicate GPR data.....130
- Figure 43:** Map of seismic data collected from Bogue Sound indicating the depth to the Holocene/Pleistocene boundary. Pink stars indicate core locations. Where no color is indicated, a lack of seismic data of seismic data occurred, most likely due to attenuation. Note the depth of the Pleistocene ranges from ~8-14 m below MSL.....131
- Figure 44:** Filtered and interpreted seismic line L1f2 from Bogue Sound. Inset: Black lines represent all seismic data collected, L1f2 is shown in yellow. Black lines on Bogue Banks indicate GPR data.....133
- Figure 45:** Filtered and interpreted seismic line L5f3 from Bogue Sound. Inset: Black lines represent all seismic data collected, L5f3 is shown in yellow. Black lines on Bogue Banks indicate GPR data.....134
- Figure 46:** Map of study area showing core locations and transects. Transect A shown in green, Transect B shown in dark blue, Transect C shown in light blue, and Transect D shown in red.....136
- Figure 47:** Cross section of depositional facies along Transect A.....137
- Figure 48:** GRADISTAT plot of grain size data for Croatan-08-GP5. Note the change from less-negatively skewed to more-negatively skewed which occurs at ~3.4 m (~11 ft; shown in triangles).....139

- Figure 49:** Lithologic core log and depositional facies log from BS-08-04 superimposed on seismic line L6f1. Yellow line illustrates boundary between seismic unit 1 (above) and seismic unit 2 (below).....142
- Figure 50:** Lithologic core log and depositional facies log from BS-08-03 superimposed on seismic line L6f2. Yellow lines show seismic reflections interpreted at approximate lithologic changes within the core.....143
- Figure 51:** Cross section of depositional facies along Transect B.....145
- Figure 52:** Cross section of depositional facies along Transect C.....149
- Figure 53:** Cross section of depositional facies along Transect D.....151
- Figure 54:** Lithologic core log and depositional facies log from BS-08-01 superimposed on seismic line L651. Yellow line indicates a seismic reflection interpreted at approximate lithologic change within the core.....153
- Figure 55:** Oxygen isotope curve derived from Chappell and Shackleton (1986), modified by Lucchi et al. (2004). This curve serves as a graphical representation of global glacial/interglacial events and a proxy for sea level over the past 240,000 years. Note the Marine Isotope Stage nomenclature for each glacial/interglacial is depicted above its corresponding trough/peak.....155
- Figure 56:** Shoreline model of sea-level during late MIS 5a. OSL dates taken from Cronin et al. (1981), Mixon et al. (1982), Szabo (1985), Wehmiller et al. (2004), Scott et al. (2006), Mallinson et al. (2008b), and Parham (2009). From Parham (2009).....158
- Figure 57:** Map of shoreline associated with MIS 5a. The Suffolk Shoreline is hatched, and its location determined from LiDAR data. The development of the Croatan Beach Ridge Complex through this period is shaded. The eastern-extent of the ridges (past the Suffolk Scarp) forming proto-Cape Lookout (Figure 56) taken from Parham (2009). The modern shoreline is shown for the purpose of orientation.....159
- Figure 58:** Lithologic core log of Croatan-08-GP3. Note the extent of muddy deposits within the aeolian sand depositional facies from 0.3-5 m (represented as dashes). Litho-biofacies Code abbreviations: As = aeolian sand depositional facies (equivalent to DF VII); heos = high energy open shelf (equivalent to DF III); sis = shallow inner shelf (equivalent to DF I).....161
- Figure 59:** Spit development of Bogue Banks. Letter A illustrates the beginning of a westward and seaward-progradation of the barrier island (continuing to G). OSL age estimates are labeled at their collection sites. Progradation is shown to occur over ca. 400 years. Inset: Bogue Banks, with the area of spit development shaded.....165

Figure 60: Evolution of Bogue Banks as described by Fisher (1967), including new proposed time slices (A-E). (A) Initial formation of the island; (B-C) Seaward and westward spit progradation; (D) Normal marine salinity conditions persist in Bogue Sound; (E) Eventual closing of the island through spit progradation; present configuration of the island. Depositional facies of Bogue Sound cores are shown at each time slice. Inset: Map of Bogue Banks, with each community of the island labeled.....169

CHAPTER ONE: INTRODUCTION

Purpose of Study

The North Carolina Coastal Geology Cooperative (NCCGC), a research initiative composed of investigators from East Carolina University, North Carolina Geological Survey, United States Geological Survey, Virginia Institute of Marine Sciences, University of Pennsylvania, and University of Delaware, aims to better understand the Quaternary geology of the Outer Banks and the Albemarle-Pamlico Estuarine System (APES) by defining the geologic framework of the area and describing how modern processes are affecting the coastal system. The NCCGC supports many studies with objectives directed towards understanding past climatic and environmental changes that have influenced the Quaternary development and morphology of North Carolina's coastal system. This study was supported by the NCCGC and aims to characterize Pleistocene and Holocene deposits in southern Carteret County, North Carolina.

Recently acquired Light Detection and Ranging (LiDAR) elevation data of eastern North Carolina indicate northeast-southwest trending ridges located on the mainland of Carteret County, which are hypothesized to be relict beach ridges (herein referred to as the Croatan Beach Ridge Complex within the Croatan National Forest). These beach ridges are located adjacent and to the southwest of the Suffolk Scarp (also known as the Suffolk Shoreline, Mallinson et al., 2008a), a paleoshoreline complex which runs from Norfolk, Virginia to Morehead City, North Carolina (Figure 1). Based on the geomorphology, it is hypothesized that the Croatan ridge complex is the landward-most component of at least three shoreline units; a prograding beach ridge feature, a

younger paleoshoreline occurring at the mainland shoreline adjacent to Bogue Sound, and the present Holocene barrier islands (Figure 2). The goal of this study is to discern the evolutionary history of this area, the relationship of the ridges to the Suffolk Scarp and Holocene barrier islands, and to place constraints on late Pleistocene and Holocene sea level. This will be accomplished by utilizing several geologic tools and an interdisciplinary approach to understand the evolution of this area, by comparing data from the present barrier island (Bogue Banks), the back-barrier sound (Bogue Sound), and the relict ridges.

This study will further the knowledge of the controlling factors which influence the position of late Pleistocene and Holocene shorelines, as well as contribute to the understanding of how barrier island systems form and evolve through time. Numerous studies suggest that sea-level change and storm events are responsible for the destruction and subsequent rebuilding of successive barrier island systems in North Carolina during the late Quaternary (Sager, 1996; Sager and Riggs, 1998; Riggs et al., 2000; Smith, 2004; Mallinson et al., 2005; Ricardo, 2005; Grand Pre, 2006; Rosenberger, 2006; Smith, 2006; Twamley, 2006; Culver et al., 2007, 2008; Hale, 2008; Pruitt, 2008; Metger, 2009; Parham, 2009). Therefore, a greater understanding of the geologic framework is necessary to predict future barrier island evolution. This study will also contribute to knowledge of late Pleistocene and Holocene relative sea-level fluctuations along the North Carolina margin. A more complete knowledge of how these systems change in response to sea-level change and associated processes is essential for responsible management of coastal environments.

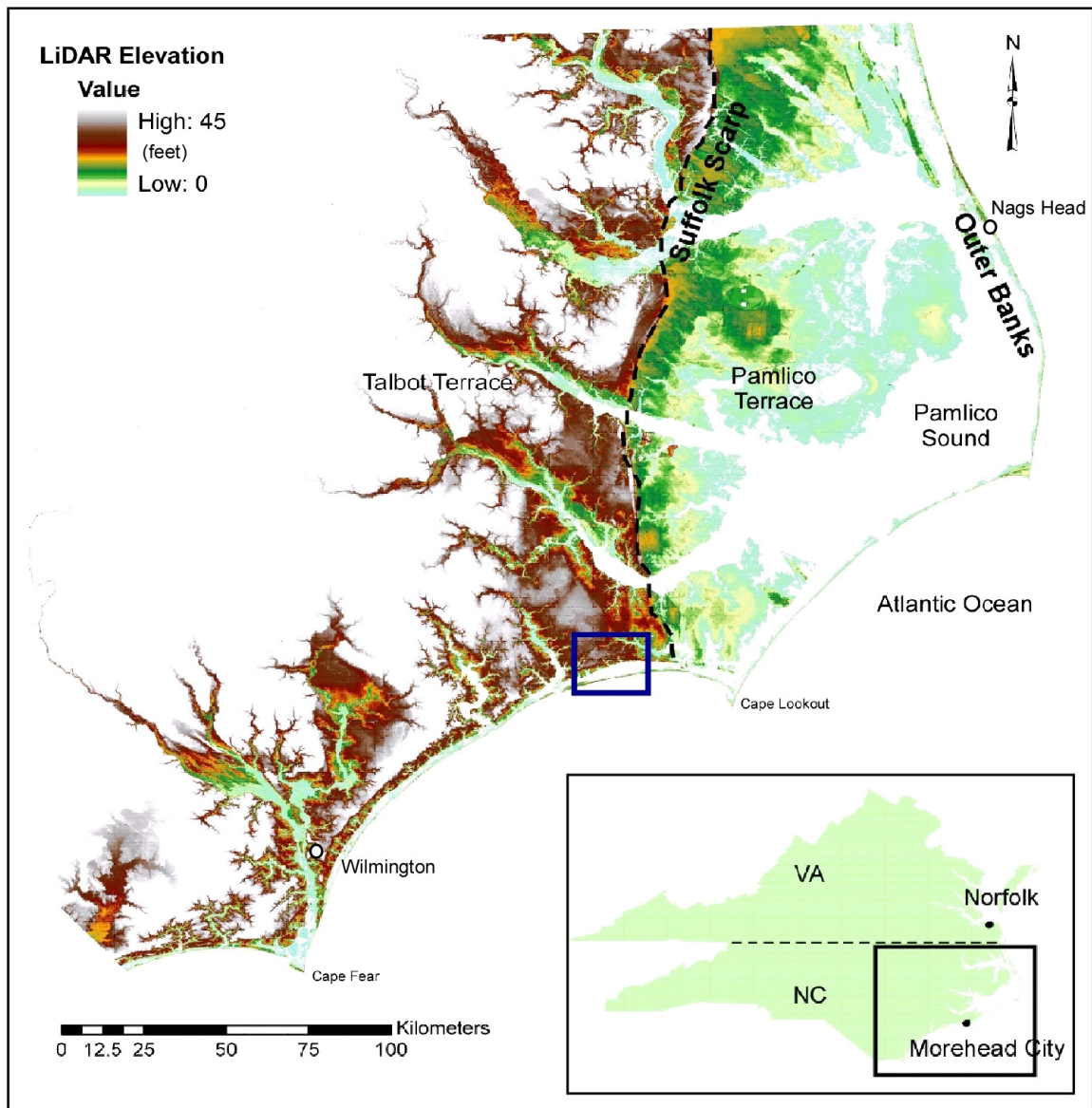


Figure 1. LiDAR map of eastern North Carolina. The Suffolk Scarp extends from Norfolk, VA to Morehead City, NC. Geographic location of map is shown in black box (inset). Study area is indicated by blue box on the LiDAR map. Map source: www.ncfloodmaps.com

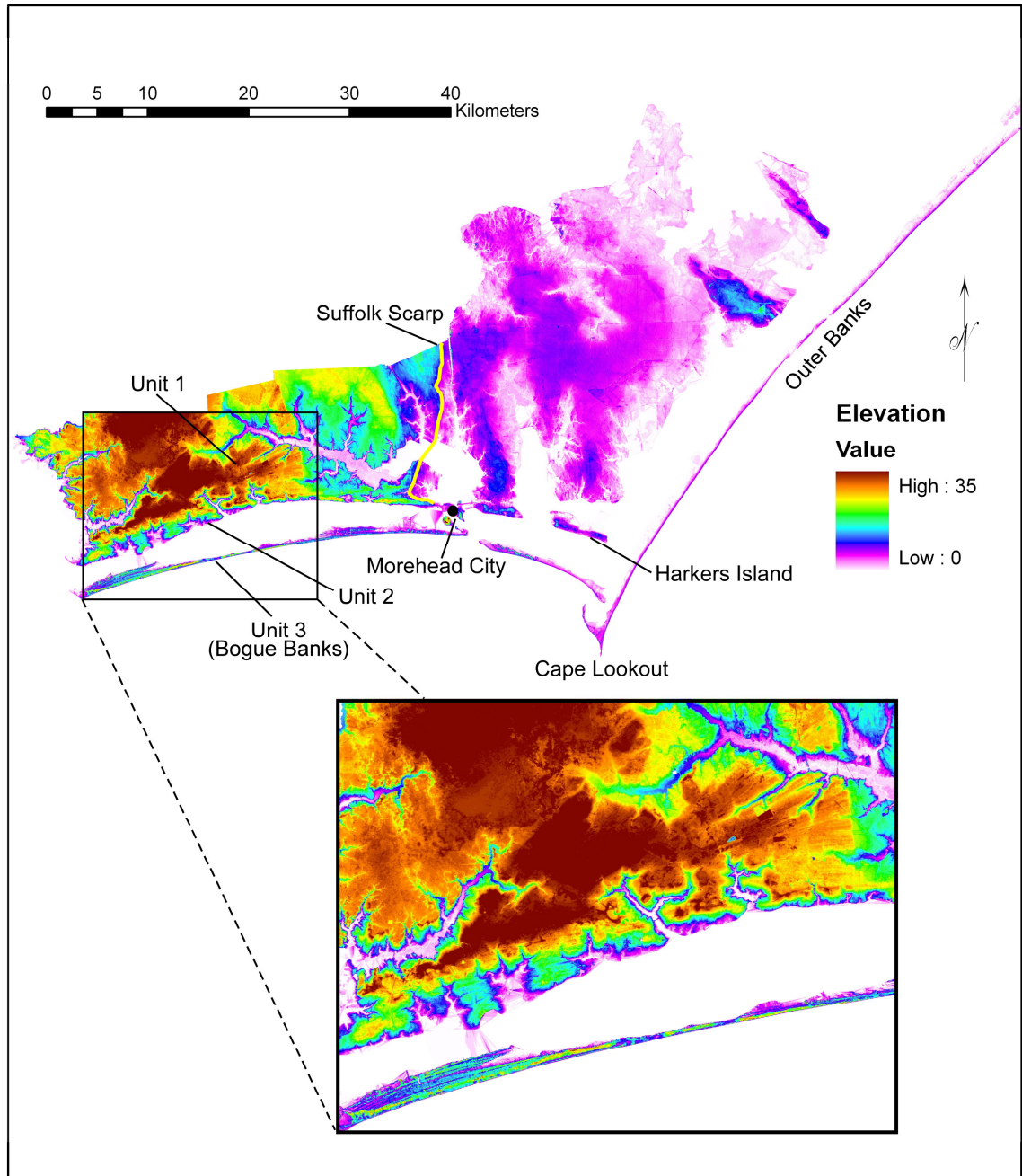


Figure 2. LiDAR elevation map of southern Carteret County, North Carolina. Note the large-scale beach ridge complex (shown in red). Unit 1 is the prograding beach ridge complex, Unit 2 is the younger, mainland shoreline ridge, and Unit 3 is the present Holocene barrier island (Bogue Banks). Study area shown in black box. Map source: www.ncfloodmaps.com

Objectives

This study combines geophysical data, sedimentological and foraminiferal analysis of core materials, and chronostratigraphic data to describe the evolution of a section of Pleistocene and Holocene coastal deposits in Carteret County, North Carolina. The following objectives are addressed to formulate an understanding of the evolution of the beach ridges:

- 1) Define and characterize the separate depositional sequences (Units 1-3; Figure 2) contained within the study area.
- 2) Define distinct depositional environments and understand the geologic evolution of the area by lithofacies and biofacies analysis.
- 3) Use OSL and radiocarbon dating techniques to place the evolution and development of the system in a temporal framework.

PREVIOUS WORK

Regional Geologic Framework

The underlying geologic framework of eastern North Carolina comprises a seaward-thickening wedge of rock and sediment approximately 2 km thick, ranging in age from Mesozoic to Holocene (Riggs et al., 1992). These sediments and rocks are deposited upon Paleozoic crystalline basement rocks which control the distribution of structural basins and highs underlying the United States Atlantic margin (Ward et al., 1991). The coastal plain of North Carolina is divided into two geologically distinct provinces which are related to antecedent basins and highs and influence its coastal system (Riggs et al., 1995; Sager and Riggs, 1998; Riggs, 2002; Parham, 2003; Mallinson et al., 2005; Parham et al., 2007) (Figure 3).

The northern coastal province lies in northeastern North Carolina and southeastern Virginia and occurs within the Albemarle Embayment. The Albemarle embayment is a geologic basin containing Mesozoic and Cenozoic sediments that lie unconformably upon a Paleozoic crystalline basement. The northern coastal province is composed of gently sloping (0.004 m/km) unconsolidated to weakly consolidated sediment that overlies the Mesozoic rock comprising the basement of the southern province (Riggs, 2002; Riggs and Ames, 2003). Sea-level fluctuations that have taken place since the Pliocene have affected the coastal development in the Albemarle Embayment, creating long, thin barrier islands, few inlets, and estuaries with limited marine water input (Riggs, 2002; Riggs and Ames, 2003).

The Outer Banks, located in the northern coastal province, is a wave-dominated barrier island system with microtidal influence which protects Pamlico Sound from the Atlantic Ocean by approximately 300 kilometers of sandy barrier islands (Mallinson et al., 2008a). These barriers are cut by few inlets (currently four), the only means by which Pamlico Sound interacts with the Atlantic Ocean. These inlets are dynamic and storm events have a tendency to close inlets and open new ones (Robinson and McBride, 2006).

The southern coastal province runs from northern South Carolina to just south of the Neuse River estuary (just north of the study area) and comprises the Cape Fear Arch.

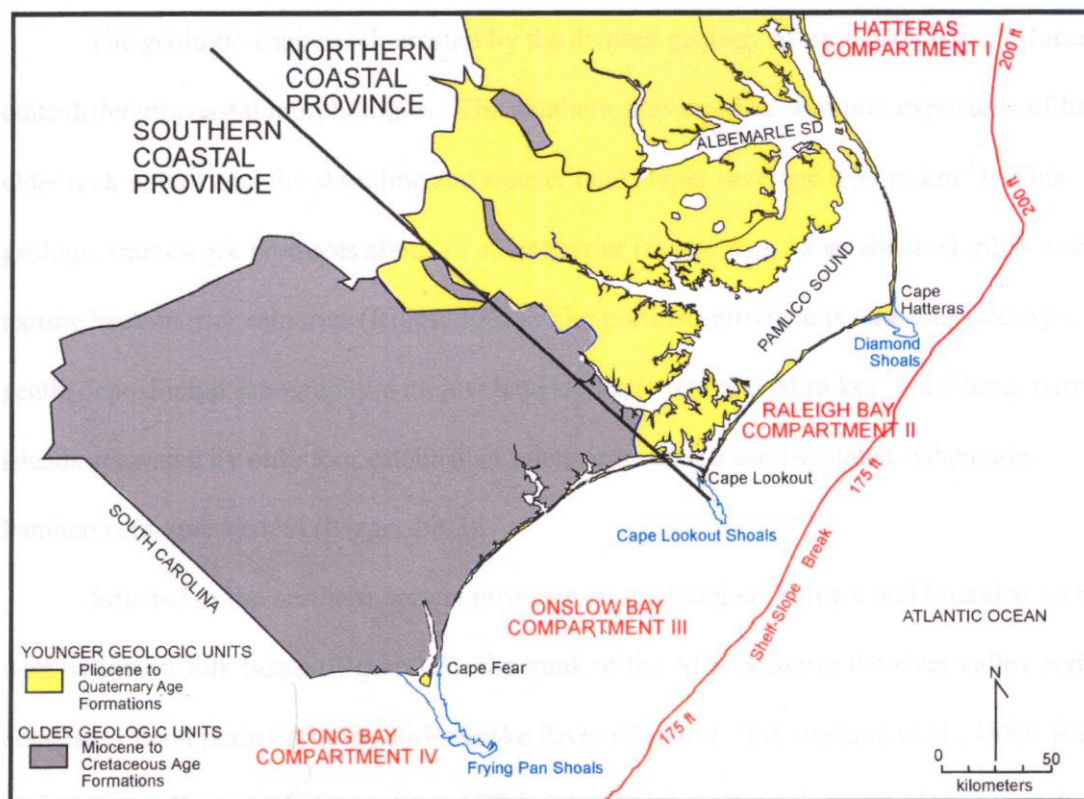


Figure 3. Map of the coastal plain of North Carolina showing the two distinct geologic provinces (from Riggs and Ames, 2003).

This geologic structure is a topographic high composed of Mesozoic to Miocene rock, causing a steeper slope in the province (0.568 m/km) and creating a different coastal geomorphology than found in the northern province (Riggs, 2002; Riggs and Ames, 2003). Coastal features of the southern province include narrow back-barrier estuaries and short barrier islands truncated by many inlets. The narrow estuaries of this province are typically of high salinity and are more tidally-influenced than those of the northern province due to the numerous inlets separating the barrier islands (Riggs and Ames, 2003).

The Suffolk Scarp

The study area is located southwest of the Outer Banks, adjacent to and near the southern terminus of the Suffolk Scarp, a 300+ km feature marking a physiographic break between ca. 4 m and 15 m above sea level (Graves, 2001), and has been dated to approximately 80 ka (Mallinson et al., 2008a). The Suffolk Scarp is a paleoshoreline which developed during multiple late Quaternary sea-level highstands, primarily during Marine Isotope Stage (MIS) 5a (Mallinson et al., 2008a; Parham, 2009). The scarp lies between two terraces, the Talbot Terrace to the west and the Pamlico Terrace to the east (Oaks and Dubar, 1974). The Pamlico Terrace and associated paleoshoreline ridges in northeast North Carolina represent the second most recent sea-level highstand, formed during MIS 3 (Burdette, 2005; Mallinson et al., 2008a; Parham, 2009).

Sediments of the Shirely Formation comprise the Talbot Terrace, while sediments of the Sedgefield Member of the upper Pleistocene Tabb Formation comprise the Pamlico

Terrace (stratigraphic units described by Johnson, 1976). The Sedgefield Member, the eastern (younger) terrace, has been dated using OSL and U-Th techniques to have an approximate age of 70 ka (MIS 5a), as determined by Cronin (1981), Mixon et al. (1982), Szabo (1985), Muhs (1992), Wehmiller et al. (2004), and Mallinson et al. (2008a).

Brill (1996) also studied the Suffolk Scarp and identified three periods of sea-level highstand. Two of these highstands were believed to have been associated with MIS 5e; however, Mallinson et al. (2008) presented OSL data suggesting that these highstands occurred as recently as MIS 5a (80-69 ka). Fournet (1990) utilized coring to identify sea-level highstand deposits on the Tar River flood plain. These deposits were located in drainage basins upstream of the Suffolk Scarp and were identified as flooded estuaries during the highstands of MIS 5.

Croatan Beach Ridges

The stratigraphy and geologic development of the mainland ridge complex in the study area have yet to be studied in detail. Two previous studies have looked at the subsurface within the study area, but both studies concentrated on archaeological objectives (Mathis, 1993; Mallinson et al., 2008b). The geomorphology of the beach ridges on the mainland and on Bogue Banks were briefly described by Fisher (1967), but no mechanisms of geologic development were addressed. The evolution and geologic history of Bogue Sound and/or Bogue Banks have been investigated (e.g., Steele, 1980; Heron et al., 1984; Sproat, 1999), but no study has yet tied together the evolutionary history of past (late Pleistocene) and present barrier island systems at this location.

Fisher (1967) described the geomorphic development of all relict beach ridges identified on the Outer Banks. While Bogue Banks and the mainland ridges are not generally referred to as being part of the Outer Banks, they were included in his study. Fisher referred to the mainland relict beach ridges in the study as being located north of Bogue Sound, running parallel to the coastline for 24 km and extending inland 8 km (Figure 4). However, the regional pattern of the ridge complex does show that they converge toward the southwest. These ridges have the highest elevation of all the mainland beach ridges in Fisher's study. Fisher explained that while the ridges are 9-11 meters above sea level, the ridges themselves are located on a coastal plain that rises 7.5 meters out of the water at the shoreline. It was also postulated (Fisher, 1967) that these ridges formed on the mainland (rather than as a barrier island welded to the mainland during high sea level) due to their 8 km width.

The origin, mechanism of formation, and age of the beach ridges comprising the Croatan Beach Ridge Complex is still undetermined. Fisher (1967) promoted the hypothesis that it is a mainland attached complex cusate foreland. This beach ridge complex is morphologically very similar to the beach ridges present in the Cape Hatteras cusate foreland, suggesting it is a previous cape complex. Fisher suggested its development would have occurred at the southern extent of the Suffolk Scarp (the oceanic shoreline) in a similar manner to the development of Cape Hatteras today. Winds from the north would drive longshore transport from the Croatan Beach Ridge Complex (and possibly the Neuse River) south, building out a cape south of the Suffolk

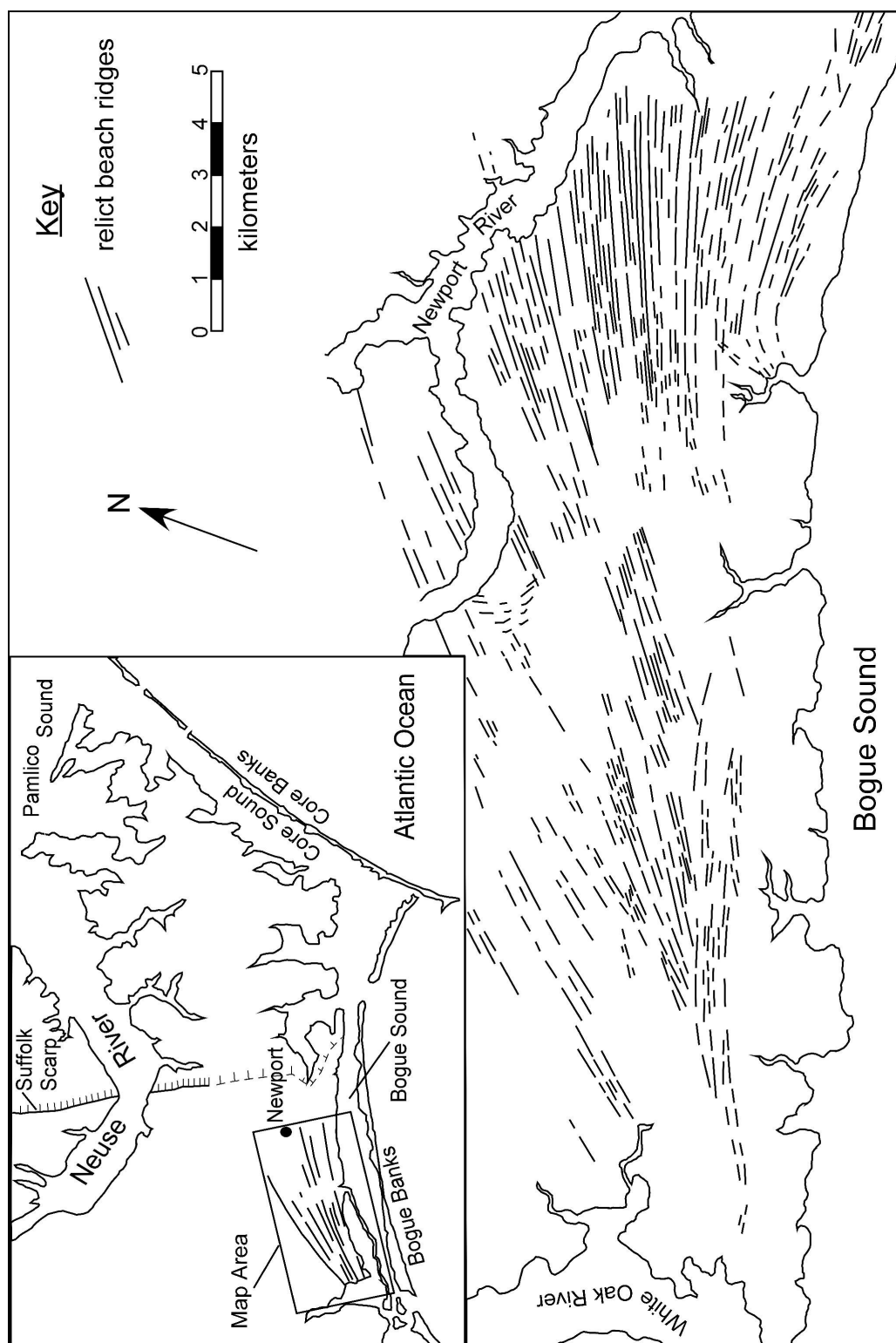


Figure 4. Map of the Croatan Beach Ridge Complex showing the beach ridge system. The larger area map is shown in the inset. The Suffolk Scarp is depicted, with the approximate southern terminus in the study area dashed. Adapted from Fisher (1967), where this beach ridge system was named the Newport Group.

Scarp. The entire ridge and swale system (eolian, dune, and swale components) comprise the Croatan Beach Ridge Complex.

The stratigraphy of the Pleistocene units underlying the Croatan Beach Ridge Complex was described from cores taken by Steele (1980), who defined three units. The lowest unit (with a thickness of 0.45-1 m, from -14 meters to -15 m maximum depth below surface) is leached of shell and bears organic staining, suggesting it was a subaerial erosional surface/paleosol. The middle unit (from -2 meters to -14 m depth below surface) consists of a shelly, muddy sand with thin mud lenses and is dominated by *Mercenaria lateralis*. The upper unit (approximately 6.5 m thick) lies unconformably above the middle unit and is composed of leached fine to fine-medium quartz sand.

Bogue Banks

Bogue Banks is a barrier island formed ~4,000 years BP (Hine and Snyder, 1985) and comprising approximately 40 km of an arcuate barrier island chain extending from Cape Fear to Cape Lookout (Figure 5) (Cleary and Hosier, 1979; Steele, 1980; Hine and Snyder, 1985). This island terminated by Beaufort Inlet on the east and Bogue Inlet on the west, is dominated by elongate linear relict beach ridges oriented parallel to the strike of the island (Steele, 1980). Relict recurved spit ridges are also present, and maritime forest dominates the sound side of the island.

Fisher (1967) developed an interpretation of the depositional and erosional history of the island (Figure 6). Using old maps, photographs, and the present geomorphology, Fisher was able to locate historic inlets on Bogue Banks. Seven major sequences of

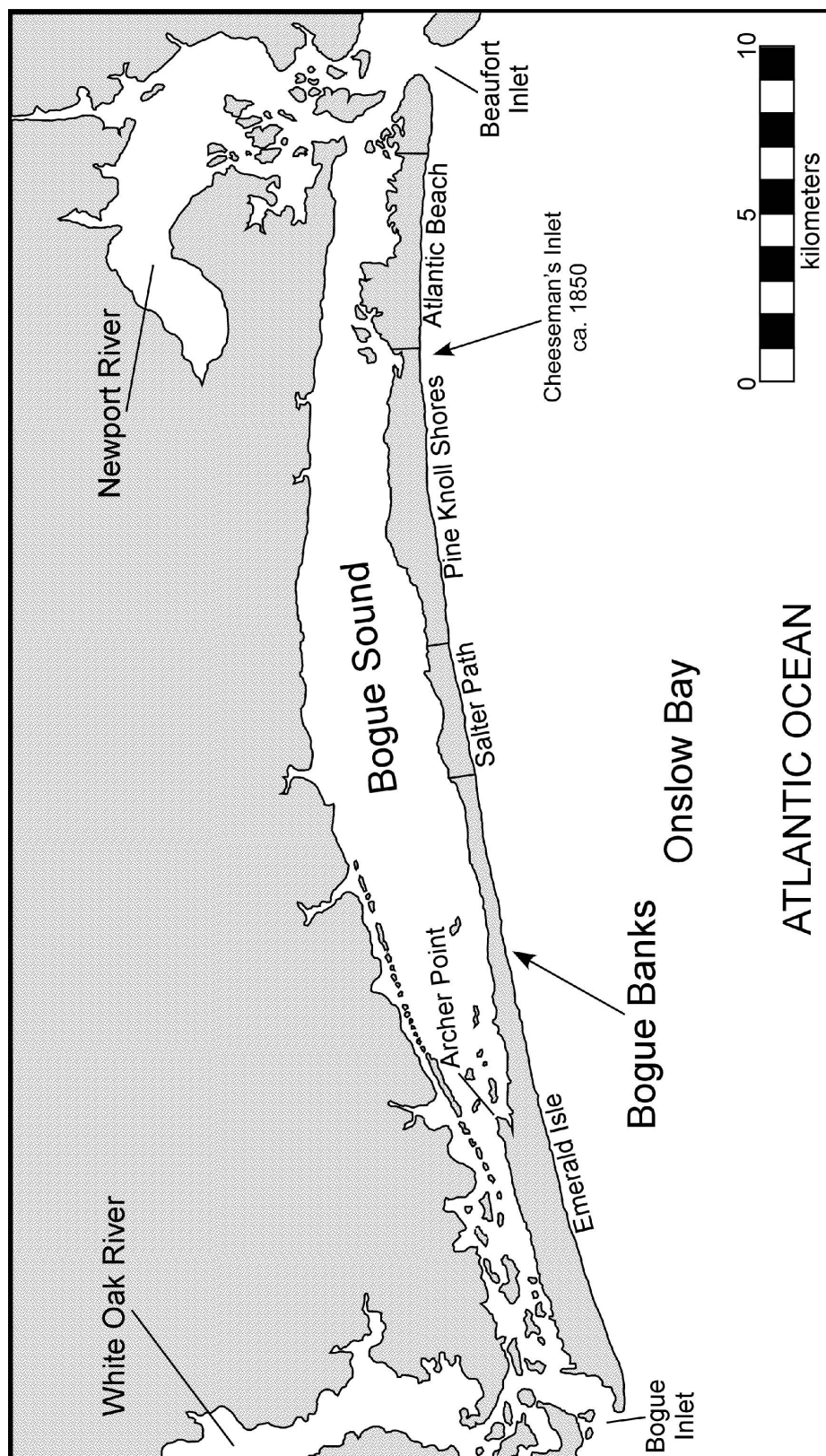


Figure 5. Map of Bogue Banks (adapted from Steele, 1980).

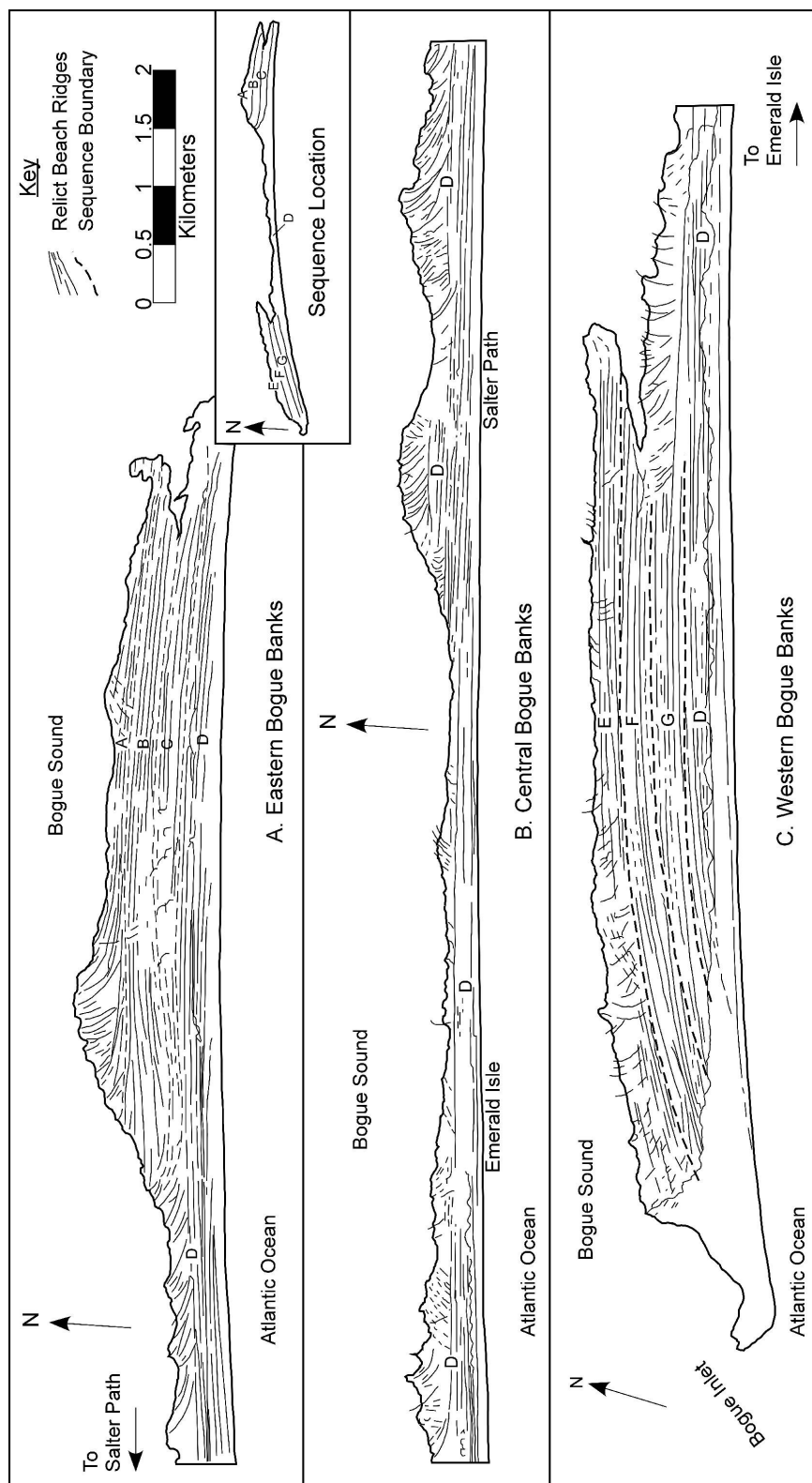


Figure 6. Depositional history of Bogue Banks illustrating relict beach ridges and sequence boundaries. Letters correlate to the development of the island outlined by Fisher (1967), shown in Figure 7. Adapted from Fisher (1967).

beach ridges were identified, with the oldest located on the sound side of the island and the youngest on the ocean side. Six of the seven sequences were organized into three couplets; each pair of ridges in a couplet was interpreted to have formed simultaneously. The remaining beach ridge complex is contiguous throughout the island. Fisher concluded the three couplets and the contiguous beach ridge set represented four aggradational events on the islands, each separated by an erosional event (Figure 7).

The eastern part of the island (specifically the easternmost 8 km) is distinctly different from the rest of Bogue Banks. Fisher (1967) described the three large lobate marshes present on the sound side of the island as relict flood tidal deltas. Development has altered the morphology in this area drastically (Atlantic Beach is located directly on top of the largest of the marshes), but older aerial photographs show an intact marsh morphology (Fisher, 1962).

The narrowest part of the island occurs between Archer Point and Salter Path (Figure 5). Elevations in this location rarely exceed 5 m, leaving this part of the island vulnerable to overwash, inlet opening, and flood tidal delta development following hurricane activity (Steele, 1980).

The stratigraphy underlying Bogue Banks consists of three main units: older sediments from the lower Miocene to Pliocene, the Pleistocene Diamond City Clay, and the Holocene sediments that comprise the island itself (Steele, 1980). The Diamond City Clay (Susman and Heron, 1979) underneath Bogue Banks is lithologically similar to its type locality on neighboring Shackleford Banks (Susman, 1979), coarsening to the west. However, this unit under Bogue Banks is more poorly sorted than its equivalents beneath

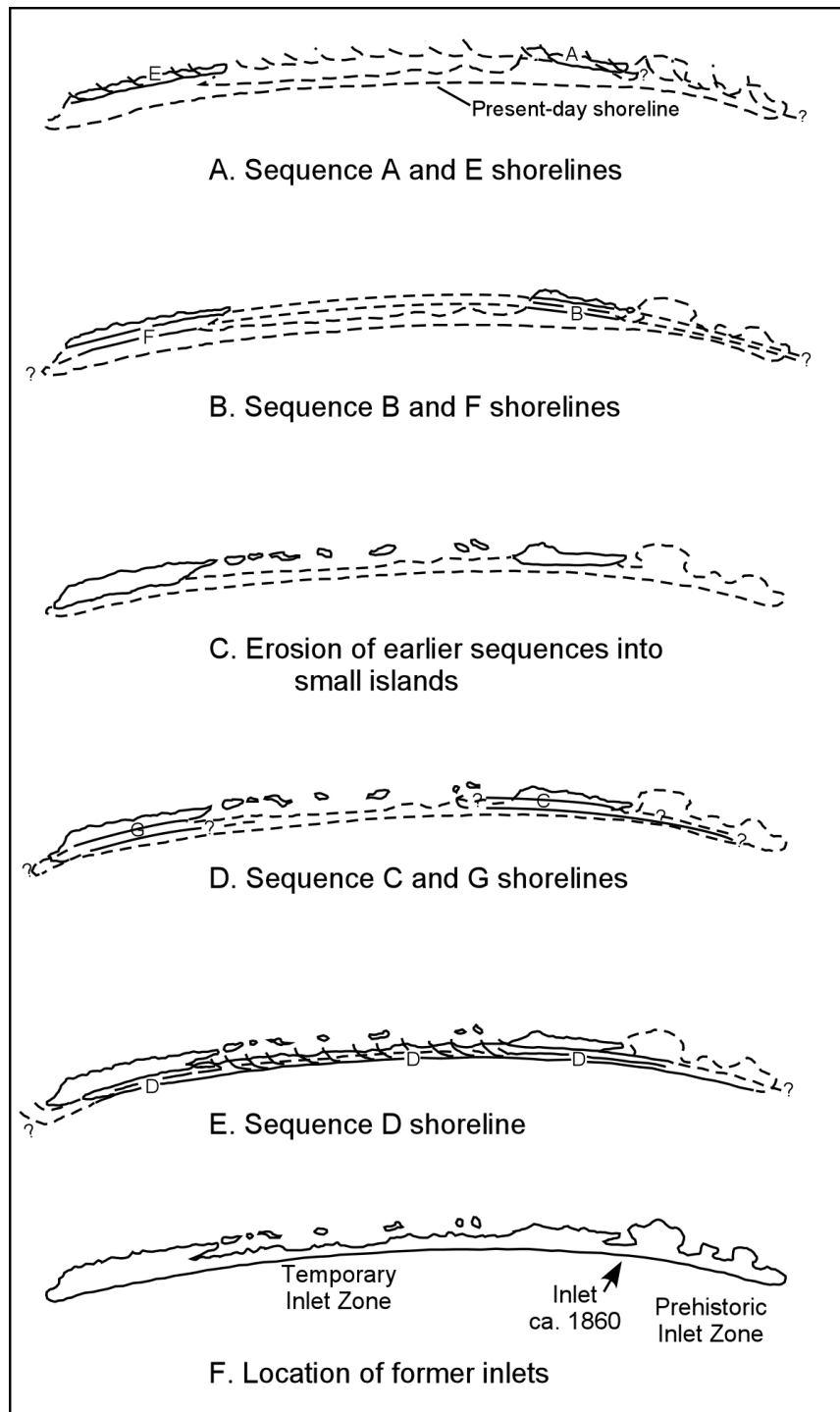


Figure 7. The development of Bogue Banks as proposed by Fisher (1967).

Shackleford and Core Banks, with significant amounts of medium and coarse grained sand. This shelly sandy clay suggests a higher energy backbarrier subenvironment for the Bogue Banks region, one that contributed more sand to the system than the lower energy backbarrier lagoonal environment described by Susman (1975) and Moslow (1977) for the Shackleford and Core Banks regions (Steele, 1980). The Diamond City Clay has been recorded from -12 m to -20.2 m below MSL. Susman and Heron (1979) used radiocarbon dating to constrain the age of this unit under Bogue Banks to 24,000 – 30,000 years BP. Steele (1980) confirmed these dates using radiocarbon in a shell deposit (25,535 ^{14}C years BP) and salt water peat deposit (26,440 ^{14}C years BP). These dates, however, are not believed to be reliable; radiocarbon dating on possibly reworked shell material does not yield accurate results and sea level is known to have been lower than -120 m MSL ca. 20,000 years ago (Fairbanks, 1989). The Diamond City Clay in this location was interpreted as having a backbarrier origin (Steele, 1980).

The contact between the Holocene and Pleistocene units is distinct. The Diamond City Clay is composed of poorly sorted clay to coarse sand and up to 50% shell material. The immediately overlying Holocene material is well sorted silty fine sand or clay with a low percentage of shell material. The macrofauna of the Pleistocene is dominated by *Mulinia lateralis*, while *Mercenaria mercenaria* and *Crassostrea virginica* dominate the Holocene unit. The shells of the Pleistocene are also bleached (whereas those of the Holocene are not), indicating they were deposited in an oxidizing environment (Steele, 1980).

The Holocene unit on Bogue Banks is composed of sediments from four different depositional environments: back-barrier, inlet, shoreface/offshore, and subaerial dune/overwash (Figure 8-11). The back-barrier deposits are generally the oldest deposits in this unit (with a few exceptions). These deposits are poorly sorted but generally fine grained and usually absent of shell material (except for the occasional oyster bed). Inlet deposits are present in Pine Knoll Shores and on the west end of the island (Steele, 1980). Inlet channel-fill deposits typically display large-scale fining upward sequences in other areas (i.e., Shackleford and Core Banks [Moslow and Heron, 1978; Susman and Heron, 1979]), but this was not readily apparent in this location (Steele, 1980). Generally inlet facies contain a coarse shell fragment lag deposit (which varies in thickness depending upon the location in the inlet deposit) and have low macrofaunal diversity (Moslow and Heron, 1978). Shoreface and offshore deposits are thick (~11 m) on the ocean side of the island and nonexistent on the sound side (Steele, 1980). The shoreface/offshore facies generally coarsens upward; sediment on the shoreface is composed of fine to coarse-grained sand while further offshore sediment is fine to muddy-fine sand (Steele, 1980). Highly abraded coarse to pebble-sized shell material is also found on the shoreface. Dune/overwash deposits comprise the subaerial material on Bogue Banks today. Cleary and Hosier (1979) observed that overwash rarely occurs on Bogue Banks due to the relatively high elevation of the island. Therefore, much of the modern change to the dune facies is wind-influenced dune development rather than storm-induced overwash.

The current mainland shoreline (Unit 2 in Figure 2) has not been studied in detail. The cross-sections of Steele (1980) suggest the shoreline is composed of Pleistocene mud

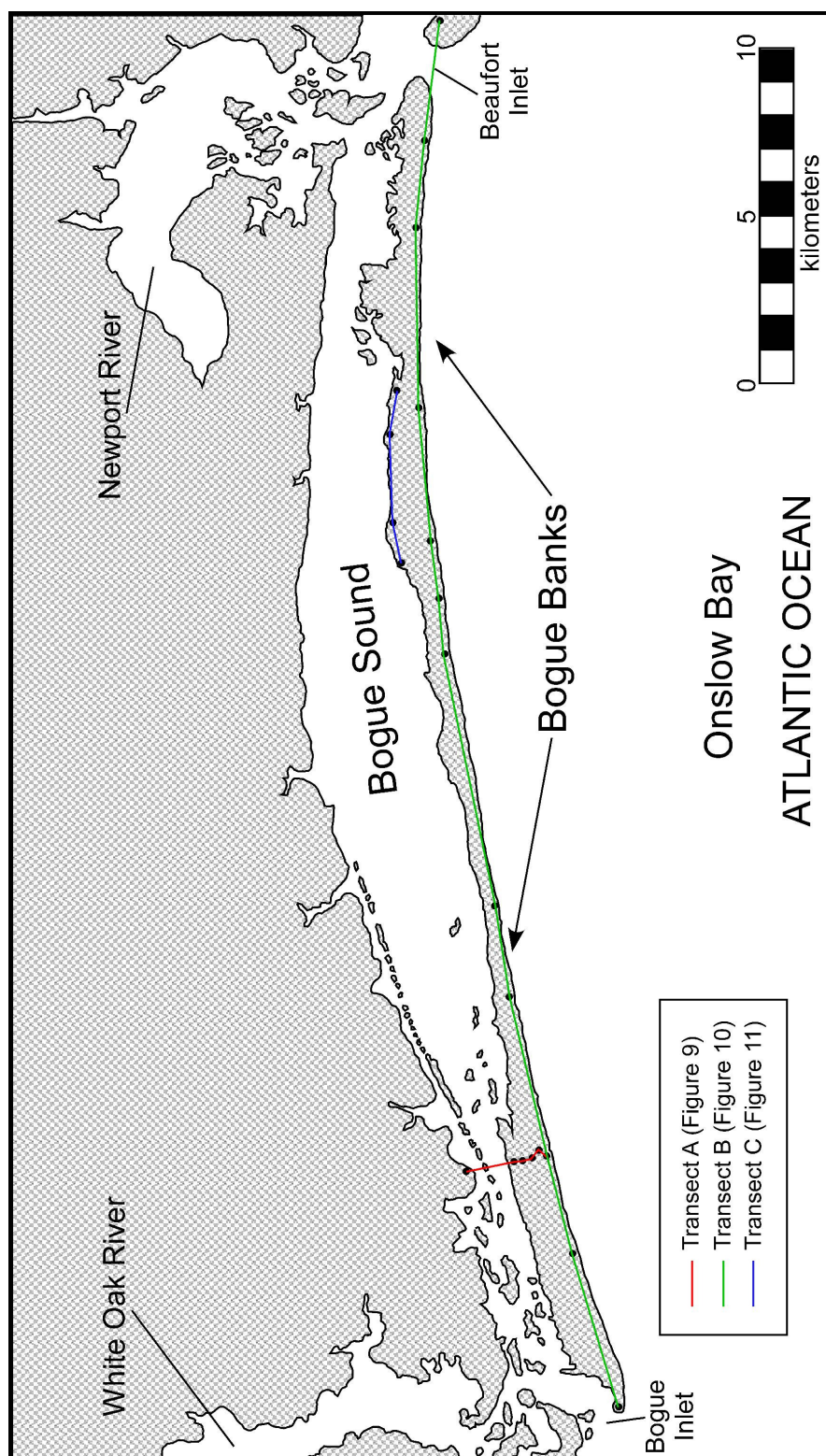


Figure 8. Map of transects illustrated by Steele (1980) along Bogue Banks.

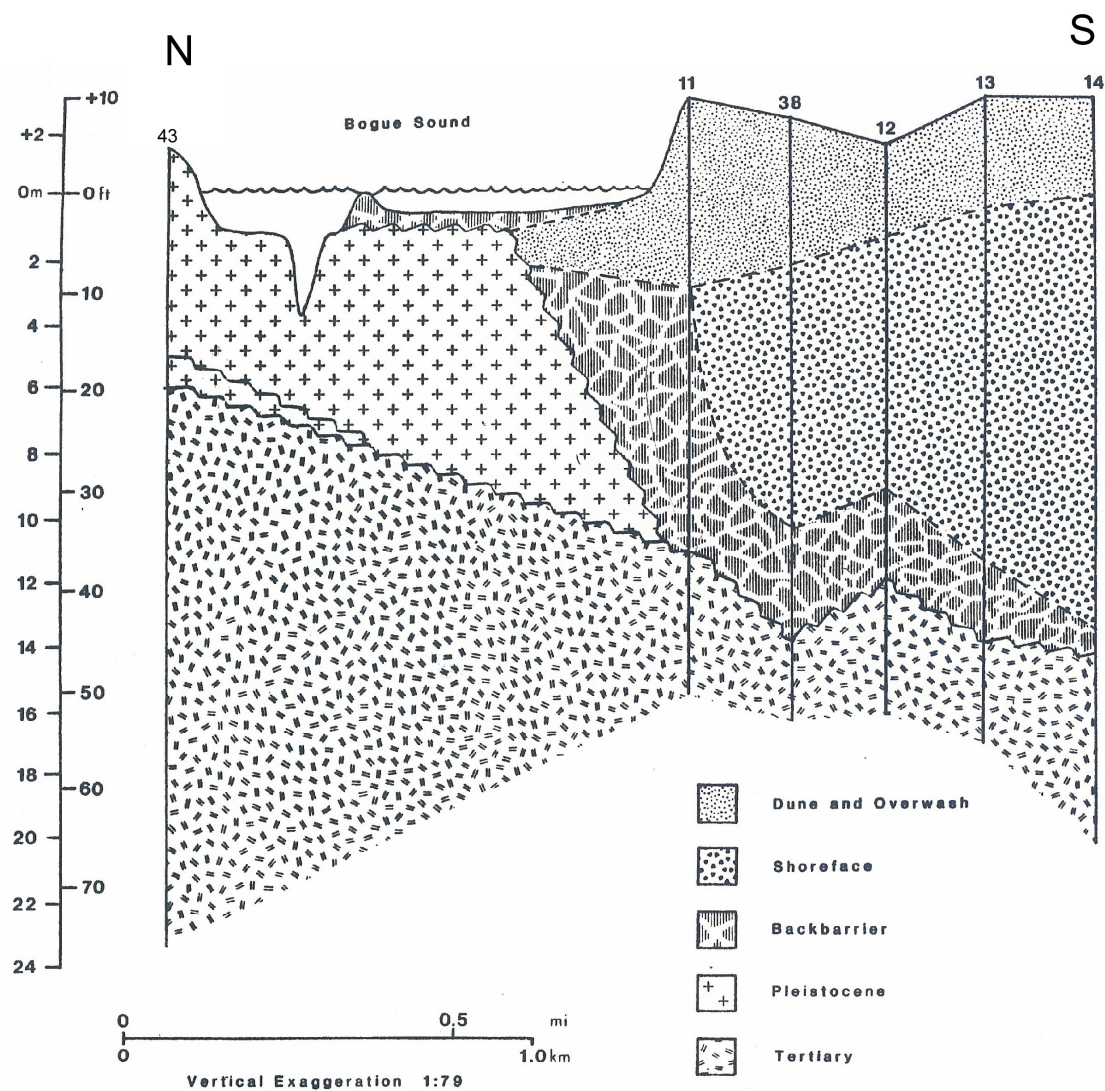


Figure 9. Cross section from the mainland, through Bogue Sound, to Emerald Isle (on Bogue Banks). Note the shoreface sediments only present on the ocean side and back barrier present only on the sound side (taken from Steele, 1980).

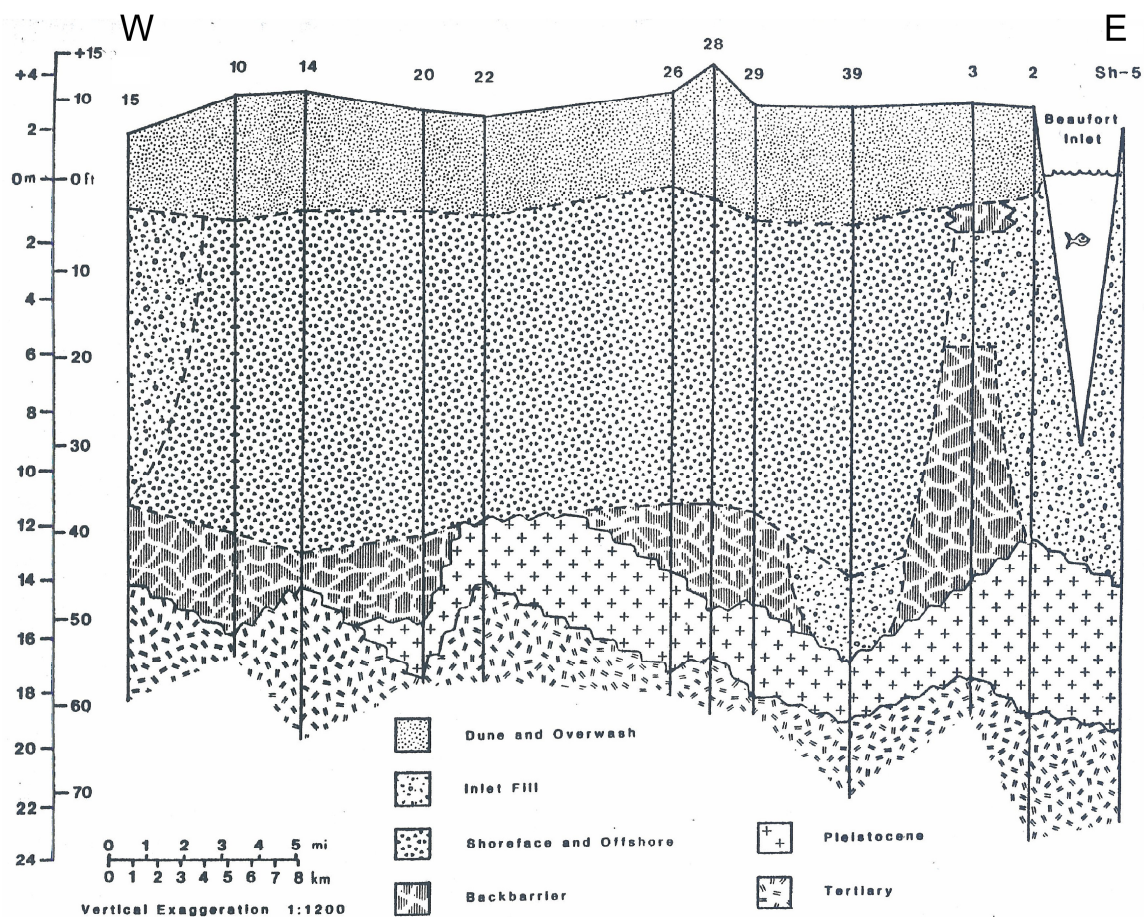


Figure 10. Longitudinal section of Bogue Banks running along the dunes along the center of the island. The final point in the east represents a core (Sh-5) on Shackleford Banks, N.C. (taken from Steele, 1980).

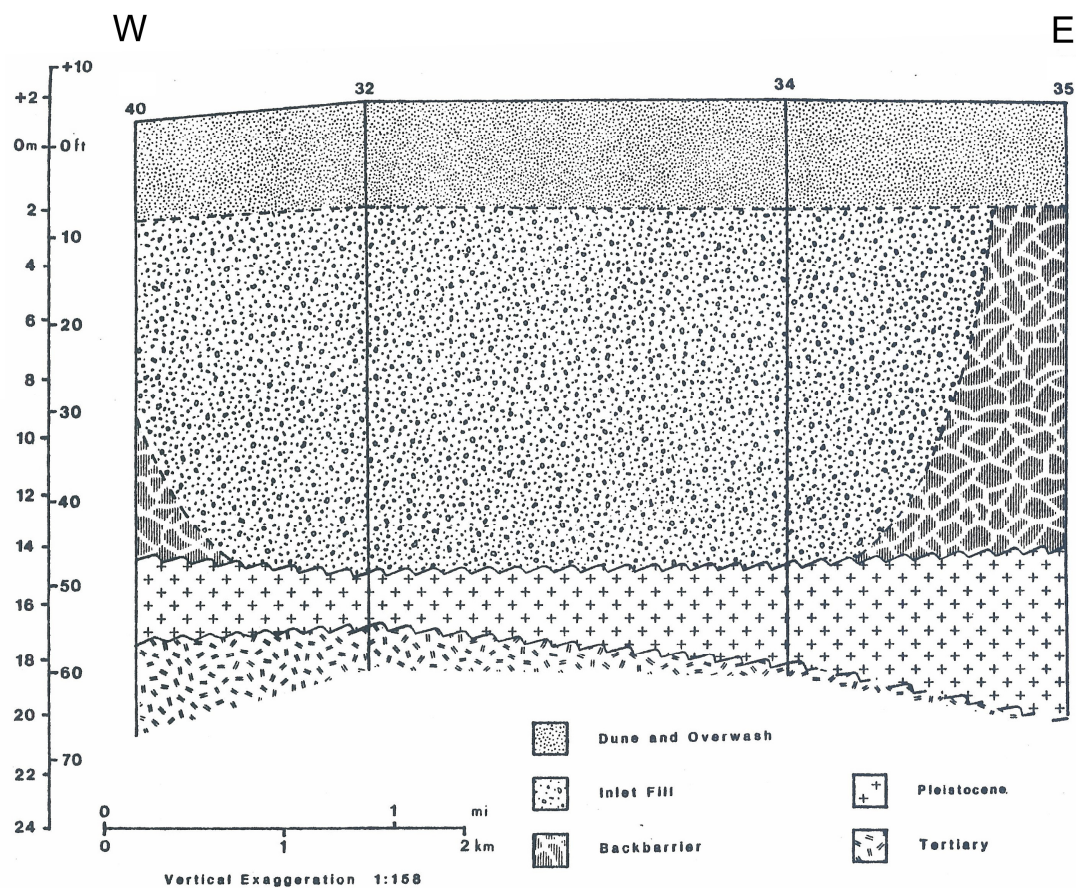


Figure 11. Cross section along eastern Bogue Banks, in Pine Knoll Shores. Note the large area of inlet fill, confirming inlet activity in the marsh areas of this part of the island (from Steele, 1980).

deposits underlying an eolian cap. The shoreline age is constrained by the creation of Bogue Banks, the newer shoreline, developing ca. 4 ka (Hine and Snyder, 1985) and the Suffolk Scarp developing 69-80 ka (Mallinson et al., 2008). It is hypothesized this shoreline began to form during MIS 3, as its formation is constrained by OSL dates of the Suffolk Shoreline and other paleoshorelines further north (Burdette, 2005; Mallinson et al., 2008; Parham, 2009) and by the younger Bogue Banks to the south. This study seeks to expand upon the origin and composition of this shoreline.

Geomorphology of Beach Ridges

Otvos (2000), in an attempt to standardize the definition of a beach ridge, recommended that all relict ridges of eolian or wash/swash-built origin be termed beach ridges. Any active shoreline sand feature should not be designated as a beach ridge. Otvos (2000) and van Heteren et al. (2000) suggested there may be a distinct boundary between the foreshore/backshore and overlying eolian deposits. This suggests that sedimentological characteristics likely change across this interface on a specific ridge, and can be used as indicators to represent the upper limit of the mean high water (MHW) and run-up factor (Fraser and Hester, 1977; Thompson, 1992; van Heteran et al., 2000). However, this boundary is not always clear. In many cases, there is not a sufficient difference in grain size characteristics between swash deposits and eolian deposits (Otvos, 1999). Therefore, it is important to consider other factors (such as biofacies and geometry, as determined from ground-penetrating radar [GPR] data) in conjunction with lithologic analysis when determining past sea-level positions.

Swash-built beach ridges are hypothesized as resulting from minor-scale sea-level changes (± 1 -2 meters, Tanner, 1995). As a shoreline progrades, it leaves relict ridges behind, with a younger beach ridge set truncating the older set (Fisher, 1967). In this way, a history of the geologic evolution of a shoreline/barrier island system is preserved. The highest wave-built beach berms are natural coastal blockades on a barrier island (Komar, 1998; Masselink and Hughes, 2003) protecting the back-barrier from storm surge. These berms are usually transient and frequent erosion and storm damage

typically determines their shape (Baldock et al., 2008). When these berms become inactive along prograding coastlines, they become beach ridges (Otvos, 2000).

Beach ridges are also an important sediment source to the beach and nearshore environment. Sediment from the beach berms can move to the back-barrier dune complexes via eolian transport and overwash. It has also been shown that the erosion of beach ridges during storm events and its subsequent re-deposition on the beach is an important step of natural post-storm beach recovery (Elfrink and Baldock, 2002) and an important factor to consider when developing a beach nourishment project (Dean, 2002).

Overwash is the flow of water and sediment over the beach berm that does not directly return to the original body of water (Donnelly et al. 2006). It is an important component of beach ridge development, and can be a precursor to barrier island breaching. Overwash causes beach-face erosion, transport of beach sediment into the back-bay, and lowering of the overall berm elevation; making the barrier more susceptible to overwash in the future (Kraus, Militello, and Todoroff, 2002; Kraus and Wamsley, 2003). However, limiting overwash in developed areas generally leads to the transport of sediment offshore, causing the beaches to disappear and the island to narrow.

Foraminifera

Foraminifera are protists with a test of one or more chambers composed of calcium carbonate or agglutinated sand particles. Foraminifera are abundant, species are morphologically distinctive, they are resistant to degradation, and easily collectable; these characteristics make them a useful indicator of depositional environments (Scott et al., 2001). Foraminifera are affected by salinity, temperature, depth, substrate material, pH, turbidity, dissolved oxygen, currents, tides, and latitude, causing assemblages to differ both spatially and temporally (Ellison and Nichols, 1970; Ellison and Nichols, 1976; Culver, 1987). Examples of foraminifera found in coastal marine environments are shown in Figure 12.

Foraminifera as Paleoenvironmental Indicators

Foraminifera reflect environmental conditions (temperature, depth, salinity, etc.) and respond when these conditions change. Therefore, a foraminiferal assemblage represents a snapshot of specific environmental conditions. Once modern assemblages of a specific location (and therefore, environmental conditions) are established, they can be used to infer paleoenvironments. Foraminifera have been used extensively to reconstruct marine environments downcore (Collins, 1996; Brewster-Wingard and Ishman, 1999; Goldstein and Watkins, 1999; Hippensteel and Martin, 1999; Polyak et al., 2002; Cronin et al., 2003; Edwards et al., 2004; Culver and Horton, 2005; Abbene et al., 2006; Culver et al., 2006; Foley, 2006; Grand Pre, 2006; Robinson and McBride, 2006; Rosenberger, 2006; Smith, 2006; Twamley, 2006; Vance et al., 2006; Hale, 2008; Stanton, 2008).

Analysis of foraminifera downcore provides unique information on sea-level change (Scott and Medioli, 1978, 1986; Gehrels, 1999; Patterson et al., 1999, 2000; Horton et al., 2007), storm events (Goodbred and Hine, 1995; Collins et al., 1999; Scott et al., 2003; Williams, 2009; Mamo et al., in press), anthropogenic change (Cronin et al., 2000; Tsujimoto et al., 2006; Pruitt, 2008), and climate change (Varekamp et al., 1992; Karlsen et al., 2000; Leorri et al., 2006).

Foraminiferal assemblages and distributions have been shown to be excellent indicators of coastal paleoenvironments. More specifically, they have been shown to be reliable in barrier island environments such as the Outer Banks (Culver and Horton, 2005; Ricardo, 2005; Smith, 2006; Twamley, 2006; Rosenberger, 2006; Culver et al., 2007; Hale, 2008; Pruitt, 2008).

Modern United States Atlantic Coast Foraminiferal Assemblages

Foraminifera exist in every benthic marine community, and their identification can yield information about their environment. Many studies have been done in North Carolina and similar Atlantic margin locations to document the foraminiferal assemblages of distinct shallow marine environments such as salt marshes (Culver and Horton, 2005; Horton and Culver, 2008; Kemp et al., 2009), estuaries (Grossman and Benson, 1967; Nichols and Norton, 1969; Ellison and Nichols, 1970; Akers, 1971; Ellison and Nichols, 1976; Lefurgey, 1976; Abbene et al., 2006; Vance et al., 2006; Pruitt, 2008), back-barrier lagoons (Culver et al., 1996; Woo et al., 1997), as well as the

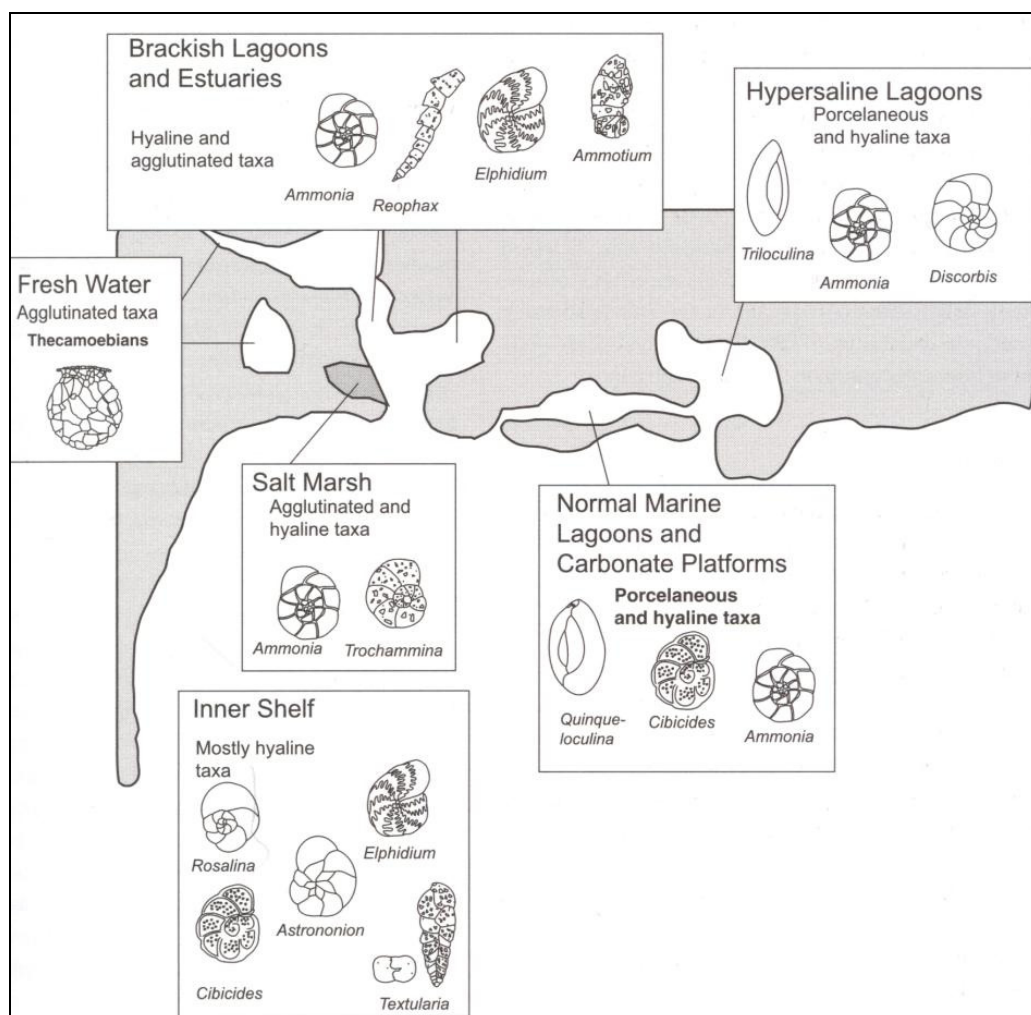


Figure 12. Major genera of foraminiferal assemblages found in marginal marine environments (from Scott et al., 2001).

continental shelf (Wilcoxon, 1964; Murray, 1969; Schnitker, 1971; Culver and Buzas, 1980, Workman, 1981).

Estuaries, Sounds, and Lagoons

Grossman and Benson (1967) studied 215 samples from Pamlico Sound and identified five foraminiferal biofacies associated with different depositional environments: lagoon, estuarine, open-sound, flood tide delta, and salt marsh (Figure 13). The lagoonal and flood tide delta biofacies were similar, both dominated by *Elphidium tumidum* (*E. excavatum* in this study) and *E. gunteri*. The biofacies were distinguished by the presence of *Quinqueloculina* spp. in the flood tide delta biofacies. The estuarine biofacies was dominated by *Ammobaculites*, which was also present concurrently with *Elphidium* in the open-sound biofacies. Agglutinated species *Arenoparrella mexicana*, *Trochammina* spp., and *Haplophragmoides wilberti* comprised the majority of the marsh biofacies. Grossman and Benson (1967) postulated that pH, salinity, currents, and turbidity controlled the distribution of foraminifera.

Vance et al. (2006) investigated the efficacy of using modern foraminiferal assemblages to make paleoenvironmental interpretations in the Albemarle Estuarine System (AES) using both living and dead foraminifera. Five biofacies were identified: Nearshore Marine and Inlet, Estuarine Shoal, Estuary, Inner Estuary, and Marsh. The Nearshore Marine and Inlet biofacies was dominated by calcareous species and dominated by *Elphidium excavatum*. The remaining four biofacies were dominated by

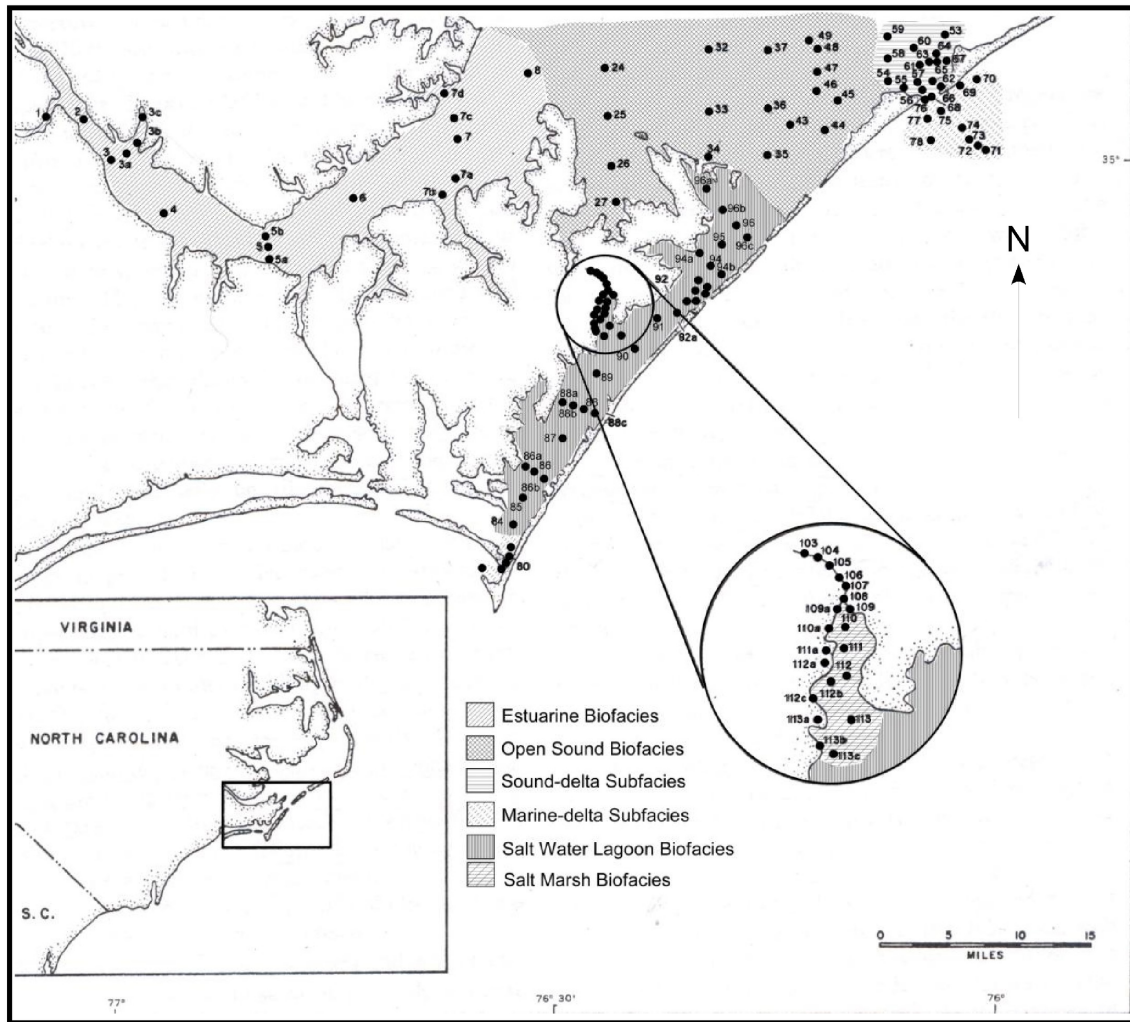


Figure 13. Distribution of samples and biofacies from Grossman and Benson (1967). Taken from Pruitt (2008), modified from Grossman and Benson (1967).

agglutinated taxa *Ammobaculites crassus* (Estuarine shoal), *Ammotium salsum* (Estuary), *Ammobaculites subcatenulatus* (Inner Estuary), and *Miliammina fusca* (Marsh). Vance et al. (2006) found that the modern foraminifera (living) and down-core (dead) assemblages display similar distribution patterns, and concluded that the modern assemblages represent a good proxy for down-core paleoenvironmental interpretations in the AES.

Abbene et al. (2006) investigated the distribution of foraminifera in Pamlico Sound to discern environmental change on a centennial scale. Four biofacies were identified: Marsh, Estuarine A, Estuarine B, and Marine. The dominant modern foraminifera in each biofacies were *Ammonia parkinsoniana*, *Ammotium salsum*, *Elphidium excavatum*, and *E. excavatum*, respectively. While *Ammonia parkinsoniana* dominated the marsh biofacies, many agglutinated species were also present that were completely absent in the other biofacies. These include *Trochammina inflata* and *Haplophragmoides wilberti*. Downcore samples confirm that approximately 120 years BP (dated using ^{210}Pb activity), Pamlico Sound was a brackish lagoon composed of estuarine biofacies A. Forty years ago, the same area was dominated by estuarine biofacies B, a higher salinity condition.

Pruitt (2008) collected 76 foraminiferal samples from Core Sound, North Carolina. Core Sound is a narrow, high salinity estuary located adjacent to Bogue Sound. Bogue Sound is more similar in size and salinity to Core Sound than Pamlico Sound. These modern samples were compared to samples from 1959 to deduce environmental change over the past fifty years. Five biofacies were identified in 1959: Estuarine, Open Sound, Salt Water Lagoon, Tidal Delta, and Salt Marsh. Four biofacies were identified in

2004: Marsh, Estuarine High Salinity A, Estuarine High Salinity B, Estuarine Low Salinity. Both studies identified a Salt Marsh biofacies with abundant species *Trochammina inflata*, *Haplophragmoides wilberti*, *Jadammina macrescens*, and *Arenoparrella mexicana*. Biofacies Estuarine High Salinity A was correlated to the Tidal Delta biofacies of 1959 due to the presence of *Quinqueloculina* species. Other abundant species in Estuarine High Salinity A included *Ammonia parkinsoniana*, *Elphidium mexicanum*, *Elphidium galvestonense*, *Elphidium excavatum*, and *Elphidium gunteri*. Estuarine High Salinity B was correlated to the Salt-Water Lagoon biofacies of 1959, with both biofacies containing a large percentage of calcareous species. Abundant species in Estuarine High Salinity B included *Ammonia parkinsoniana*, *Elphidium excavatum*, *Elphidium galvestonense*, *Elphidium mexicanum*, and *Elphidium gunteri* (Pruitt, 2008). The Estuarine Low Salinity biofacies of 2004 correlated to the Open Sound biofacies of 1959, with both biofacies containing coarsely agglutinated and calcareous species. Abundant species included *Ammotium salsum*, *Ammonia parkinsoniana*, *Elphidium gunteri*, and *Elphidium excavatum*. Two noteworthy changes were observed: the dominant species in the Estuarine High Salinity A changed from *Elphidium* spp. in 1959 to *Ammonia parkinsoniana* in the modern samples, and *Quinqueloculina* spp. became more extensive throughout Core Sound over time (Figure 14).

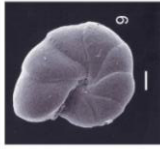
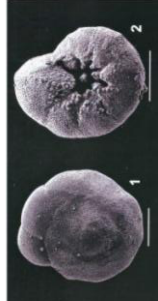
Biofacies	Abundant species				Biofacies Interpretation
4 	 <i>Trochammina inflata</i> (54.2%)	 <i>Haplophragmoides wilberti</i> (27.5%)	 <i>Jadammina macrescens</i> (4.88%)	 <i>Arenoparrella mexicana</i> (4.53%)	Marsh
3 	 <i>Ammonia parkinsoniana</i> (23.5%)	 <i>Elphidium mexicanum</i> (21.9%)	 <i>Elphidium galvestonense</i> (14.4%)	 <i>Elphidium excavatum</i> (9.82%)  <i>Quinqueloculina impressa</i> (8.75%)  <i>Elphidium gunteri</i> (8.41%)	Estuarine High Salinity A
2 	 <i>Ammonia parkinsoniana</i> (53.0%)	 <i>Elphidium excavatum</i> (25.6%)	 <i>Elphidium galvestonense</i> (4.51%)	 <i>Elphidium mexicanum</i> (4.51%)  <i>Elphidium gunteri</i> (4.26%)	Estuarine High Salinity B
1 	 <i>Ammonium salsum</i> (33.8%)	 <i>Ammonia parkinsoniana</i> (28.5%)	 <i>Elphidium gunteri</i> (9.36%)	 <i>Elphidium excavatum</i> (4.57%)	Estuarine Low Salinity

Figure 14. Abundant species found in surface samples taken in Core Sound, organized by biofacies (taken from Pruitt, 2008).

Overwash and Inlets

Overwash deposits usually represent the drowning or overtopping of a barrier island berm or marsh. Created during storm events, this deposit transports coarse material overtop of the barrier island in the high energy conditions. When storms cause overwash to occur, it can be deposited on the back barrier marsh. Hippensteel and Martin (1999) identified overwash deposits on Folly Island, South Carolina. These deposits were identified as interbedded sand and marsh deposits. The foraminifera from the sands of these deposits were used to identify “impulses”, suggesting overtopping of the island had occurred. Marshes are reliable indicators of local sea level, making the intervals of washover/marsh deposits indicative of changes in sea level. When washover deposits are found above a marsh deposit, Hippensteel and Martin (1999) suggested that the barrier island was catching up to sea-level rise. When marsh deposits are located above washover deposits, they suggested that sea level was rising too quickly for the barrier island to catch up, causing a back barrier marsh to cover the overwash deposit.

Culver et al. (2006) studied inlet and overwash deposits at Pea Island National Wildlife Refuge near Rodanthe, North Carolina. Foraminiferal, sedimentological, geophysical, and geochemical data were used to identify these deposits in this portion of the Outer Banks historically containing numerous inlets. Foraminiferal data show four depositional events comprised of overwash sand fining upwards to an estuarine/salt-marsh sandy mud/peat unit. The basal sequence identified, sequence 4, was barren of foraminifera. Sequence 3 was composed of normal marine salinity species, including *Elphidium excavatum* and *Buccella inusitata*, and interpreted to be part of an overwash

deposit. Above this, another (muddier) unit contained a mixed assemblage of estuarine and marsh foraminifera typical of a back-barrier estuarine, marsh-influenced environment, with *Ammobaculites* sp., *Trochammina inflata*, and *Jadammina macrescens*. The second sequence also contained foraminifera typical of normal marine salinity conditions (*Elphidium excavatum*, *E. subarcticum*, *E. mexicanum*, *E. galvestonense*, *Hanzawaia strattoni*, *Ammonia parkinsoniana*, *Buccella inusitata*) underlying a deposit barren of foraminifera, and was therefore interpreted to have originated from an overwash deposit underlying an inlet-shoal deposit. The fining-upward nature of sequence 2 was interpreted as part of salt marsh deposition, and contained rare marsh foraminifera species (i.e., *Polysaccammina ipohalina*) as well as *Trochammina inflata*, *Milammina fusca*, and *Jadammina macrescens*. No foraminifera were found in the upper-most sequence (sequence 1). Culver et al. (2006) concluded that these sequences were the result of episodic overwash and inlet deposits occurring over at least a millenium.

Robinson and McBride (2006) utilized benthic foraminifera from a relict flood tidal delta to identify a succession of depositional environments associated with the opening of Old Currituck Inlet and subsequent marsh development above the delta. These depositional sequences occurred at each of six vibracore locations and represented the estuary, flood tidal delta, medium salinity marsh, and low salinity marsh environments. Both the estuary and flood tidal delta environments clustered together and were dominated by *Elphidium excavatum*. An estuarine subgroup was distinguished from a flood tidal subgroup by the lack of continental shelf species. The medium salinity

marsh assemblages was dominated by *Trochammina inflata*, and contained *Arenoparrella mexicana*, *Tiphotrocha comprimata*, and *Jadammina macrescens*. The low salinity marsh assemblage contained the characteristic species *Jadammina macrescens* and *Miliammina petila*.

Smith et al. (2009) compared sedimentological and foraminiferal data collected from a known inlet and flood tidal-delta deposit (New Inlet) to two additional barrier island segments where historic inlet (and subsequent flood tidal-delta) activity had not been recorded to try and identify their presence in the past. Five biofacies were identified – two dominated by marine/estuarine species and three dominated by agglutinated marsh species. The flood-tidal delta biofacies contained a small amount of normal marine salinity foraminifera (*Elphidium excavatum*, *Buccella inusitata*, *Ammonia parkinsoniana*, and *Hanzawaia strattoni*) and occasional agglutinated marsh species. Similar assemblages to this biofacies have been reported by Schnitker (1971) and Workman (1981) along the Atlantic continental shelf and by Culver et al. (2006) in overwash deposits along the Outer Banks. The investigators were able to identify an undocumented inlet and relict flood-tidal delta in the Pea Island area that opened between 962-662 cal. yr BP.

Salt Marshes

Culver and Horton (2005) described the distribution and abundance of living and dead foraminifera in a fringing marsh of the Outer Banks in three locations of varying salinities at both the surface and subsurface (> 1 cm) in the low and high marsh.

Arenoparrella mexicana, *Haplophragmoides wilberti*, *Jadammina macrescens*, and *Trochammina inflata* were found to be the most resistant to degradation and post-mortem disintegration. *Miliammina fusca* is delicate and was found to be very susceptible to degradation. When compared to other marsh studies (Goldstein and Harben, 1993; Goldstein et al., 1995; Saffert and Thomas, 1998), North Carolina marsh foraminifera occur and are concentrated at much shallower depths (generally in the first 10 centimeters) than other marshes in the eastern United States. The researchers also found only one calcareous species (*Helenina anderseni*) living in North Carolina salt marshes, in contrast to other marshes where at least two taxa are present (Larchmont Harbor, NY – Steineck and Bergstein, 1979; St. Catherines Island – Goldstein et al., 1995). Foraminifera assemblages of the first centimeter of most cores did not differ from assemblages downcore, confirming that they can be used to make accurate paleoenvironmental inferences and reconstructions (Culver and Horton, 2005).

Horton and Culver (2008) were the first to study modern salt marsh foraminifera in a back-barrier environment affected by wind-driven tides. Three study sites were chosen with different salinity regimes. Two regions existed in the intertidal zone; a vegetated marsh dominated by *Ammobaculites crassus*, *Ammobaculites subcatenulatus*, *Arenoparrella mexicana*, *Jadammina macrescens*, *Miliammina fusca*, and *Trochammina inflata*, and a mudflat/sandflat dominated by *Ammonia parkinsoniana*, *Elphidium excavatum*, and *Haynesina germanica*. This study corroborated others (Scott and Medioli, 1978, 1980; Horton et al., 1999a, 1999b; Horton et al., 2003; Scott and Leckie, 1990) that suggest a vertical zonation of assemblages occurs as a function of elevation.

However, site-specific assemblages were also found, suggesting that some distributions are localized and cannot be used to correlate to another assemblage from a different salinity. Horton and Culver (2008) concluded that all environmental factors they investigated (vegetative cover, clay fraction, loss on ignition, salinity, elevation and pH) affect foraminiferal assemblages, with the exception of pH.

Kemp et al. (2009a) described foraminiferal distributions in elevation-dependent biozones within the Albemarle-Pamlico estuarine system of North Carolina. Sub-tidal calcareous foraminifera were associated with high salinity estuarine paleoenvironments. High marshes were dominated by *Haplophragmoides wilberti*, *Trochammina inflata*, and *Arenoparrella mexicana*, while low marsh assemblages were primarily composed of *Miliammina fusca*. Low salinity marsh environments were dominated by *Ammobaculites* spp., *Miliammina fusca*, and *Jadammina macrescens*. The zonation of foraminifera in this study allowed for the construction of a sea-level curve of the past 400 years.

Modern United States Atlantic Shelf Foraminiferal Assemblages

Numerous researchers have described both the taxonomy and distribution patterns of foraminifera on the Atlantic shelf. Cushman (1947) and Wilcoxon (1964) (among others) have documented the continental shelf fauna from the southern tip of Florida to Cape Hatteras. Hadley (1936) discussed modern foraminifera from the Beaufort, N.C. area (a coastal area adjacent to the study area). Culver and Buzas (1980) mapped occurrences and geographical distribution of benthic foraminifera along the Atlantic coast.

Bumpus and Pierce (1955) described a major faunal boundary on the continental shelf at Cape Hatteras. While some species demonstrate a very distinct boundary (Abbott, 1954), foraminifera in this area tend to demonstrate a gradational change from southern fauna to northern fauna (Schnitker, 1971). Murray (1969) and Schnitker (1971) observed this faunal boundary and described the assemblages in detail. Workman (1981) observed the northern faunal assemblage off Nags Head (north of Cape Hatteras) and Wilmington (south of Cape Hatteras), N.C. A summary of foraminifera found in each study is given in Table 1.

Murray (1969)

Murray (1969) compared the living and dead foraminifera on the continental shelf off of Vineyard Sound (MA), Long Island (NY), and Capes Hatteras and Lookout (NC). The purpose of this study was to compare foraminifera in a large regional area (the Atlantic seaboard) and sample from distinct environments to determine if there was a notable difference in foraminiferal assemblages.

Vineyard Sound, a high-energy system with strong tidal currents, was dominated by clinging species. The living assemblage was dominated by *Eggerella advena*. Living *Cyclogyra involvens*, *Patellina corrugata*, *Rosalina* spp., *Spirillina vivipara*, *Trochammina ochracea*, and *Wiesnerella auriculata* were also present, and represent fauna that cling to coarse substrate (pebbles, shell debris, etc.) along the bottom. The dead assemblage varied considerably from the living, dominated by *Elphidium clavatum*

(= *E. excavatum* of this study) and *E. subarcticum* with the clinging species *Rosalina* spp. and *Trochammina ochracea* still present.

The shelf off Long Island was characterized by cold-water fauna. Murray (1969) described a continuum of dominant foraminifera on the shelf, where Rotaliina were more abundant seaward, the Textulariina dominated landward, and the clinging species were less abundant. The living assemblage contained *Cribrostomoides crassimargo* and *Elphidium clavatum* consistently across the shelf. *Eggerella advena*, *Reophax scottii*, *Saccammina atlantica*, *Quinqueloculina* spp., and *Miliolinella* spp. dominated landward while *Fursenkoina fusiformis*, *Globobulimina auriculata*, and *Nonionella* cf. *N. turgida* dominated seaward. The dead assemblage was dominated uniformly throughout the area by *Eggerella advena* and *Saccammina atlantica*. *Cribrostomoides crassimargo* was more abundant seaward. Murray concluded the cold temperatures and low salinities of this area contributed to the high abundance of agglutinated foraminifera near shore.

Diamond Shoals, located off Cape Hatteras, represent a lateral boundary between the warm water of the Florida current south of Cape Hatteras and the cooler water from Virginian coastal currents to the north (Sverdrup et al., 1946). The Virginian Coastal water and Carolinian Coastal water rarely mixes, doing so only when the water masses are mixed by a nor'easter (Bumpus and Pierce, 1955). Latitudinal faunal changes occur over a short distance in this area, causing a large number of species to be present. In the living assemblage, *Ammonia beccarii* and *Buliminella elegantissima* were abundant in a few samples but became less important in the remaining samples. The northern Virginian water contained *Brizalina* sp., *Cibicides concentricus*, *Eggerella advena*, *Rosalina* spp.,

and *Stetsonia minuta* while the southern water contained these same species as well as *Cibicides pseudoungerianus*, *Florilus grateloupi*, *Miliolinella circularis*, *Quinqueloculina* spp., and *Trifarina angulosa*. The species in the dead assemblage were similar to those found in the living assemblage with some species showing increased abundance and some showing decreased abundance. *Elphidium clavatum*, *E. poeyanum*, and *Peneroplis carinatus* were scarce or absent in the living assemblage but were abundant in the dead assemblage. North of Cape Hatteras, Rotaliina were abundant and Textulariina and Miliolina were less abundant. South of Cape Hatteras, Rotaliina were still highly abundant, Miliolina were moderate to highly abundant, and Textulariina were again rare. Murray (1969) concluded that transport and mixing of foraminifera must be occurring off the coast of Cape Hatteras.

Schnitker (1971)

Schnitker studied the foraminiferal faunal boundary that exists at Cape Hatteras (described above). Eighty-six samples were taken from the continental shelf of North Carolina to inventory the foraminiferal populations and distribution. Schnitker found diverse assemblages, most probably due to the mixing of a Pleistocene fossil fauna with the modern fauna. Diversity south of Cape Hatteras was notably greater than diversity further north. Virginian Coastal water north of Cape Hatteras varies greatly in temperature and salinity, creating a lower diversity (Schnitker, 1971). The more stable water influenced by the steady Gulf Stream currents south of Cape Hatteras enable more diverse assemblages to exist.

Schnitker (1971) divided the study area into two large areas, the Virginian and Carolinian. The near-shore environment only contained species in the Virginian division, and was composed of 50% *Elphidium clavatum* (*E. excavatum* of this study). The dominant species of the central shelf of the Virginian coastal waters were *Elphidium clavatum*, *Hanzawaia concentrica*, and *Reophax atlantica*. The dominant species of the central shelf in the Carolinian waters were *Hanzawaia concentrica*, *Peneroplis proteus*, *Placopsilina confusa*, *Quinqueloculina seminula*, *Reophax atlantica*, and *Asterigerina carinata*. The shelf edge in Virginian water was characterized by *Islandiella subglobosa*, *Bulimina marginata*, *Trifarina angulosa*, and *Cibicides bradyi*. The shelf edge in Carolinian coastal waters consisted of *Amphistegina lessonii* and *Cibicides pseudoungerianus*.

Schnitker (1971) also observed an increase in abundance with distance from shore. This trend occurred both north and south of Cape Hatteras. Similar findings were reported in the Gulf of Mexico (Bandy, 1954, 1956), attributed to high sedimentation rates in the nearshore environment, and the west coast (Walton, 1955; Uchio, 1960), attributed to very low outer-continental shelf sedimentation.

Workman (1981)

Workman identified and compared foraminiferal assemblages (both distributions and abundances) in surface sediments at Nags Head and Wilmington, N.C. This study was similar to both Murray (1969) and Schnitker (1971) as it also investigated the faunal boundary that exists at Cape Hatteras. In addition, a comparison of living versus dead

foraminifera was conducted to determine differences in the modern versus relict assemblages, as well as the influence of transport on post-mortem test deposition.

In surface samples, Workman found that north of Cape Hatteras (the Hatteras Embayment), foraminiferal assemblages generally had a lower specimen density, fewer species, and a lower diversity index than assemblages south of Cape Hatteras (Onslow Bay). The Hatteras Embayment assemblages were dominated by *Elphidium excavatum*, with important subsidiary species *Eggerella advena*, *Elphidium gunteri*, and *Ammonia beccarii* forma *tepida* (in this study, *A. tepida*). The Onslow Bay assemblages were dominated by *Quinqueloculina lamarckiana*, *Elphidium limatulum*, *E. excavatum*, *Ammonia beccarii* forma *tepida*, with important occurrences of *E. gunteri*, *Q. jugosa*, and *Q. seminula*.

Workman (1981) concluded that any foraminifera transport caused by human activities (dredging, beach nourishment, etc.) was strictly localized, strengthening the argument that using them as paleoenvironmental indicators was a valid technique. While minor local transport can possibly occur, Workman confirmed that cool water *Elphidium excavatum* dominated Hatteras Embayment and warm water species (*Quinqueloculina lamarckiana*, *Elphidium limatulum*) dominated Onslow Bay, further documenting the nature of the Cape Hatteras faunal boundary.

Table 1. Dominant/characteristic foraminiferal taxa found in Murray (1969), Schnitker (1971), and Workman (1981).

	North of Cape Hatteras	South of Cape Hatteras
Murray (1969)	<i>Brizalina</i> sp. <i>Cibicides concentricus</i> <i>Eggerella advena</i> <i>Rosalina</i> spp. <i>Stetsonia minuta</i>	<i>Brizalina</i> sp. <i>Cibicides concentricus</i> <i>Eggerella advena</i> <i>Rosalina</i> spp. <i>Stetsonia minuta</i> <i>Cibicides pseudoungerianus</i> <i>Florilus grateloupi</i> <i>Miliolinella circularis</i> <i>Quinqueloculina</i> spp. <i>Trifarina angulosa</i>
Schnitker (1971)	<i>Elphidium clavatum</i> <i>Hanzawaia concentrica</i> <i>Reophax atlantica</i> <i>Islandiella subglobosa</i> <i>Bulimina marginata</i> <i>Trifarina angulosa</i> <i>Cibicides bradyi</i>	<i>Hanzawaia concentrica</i> <i>Peneroplis proteus</i> <i>Placopsilina confusa</i> <i>Quinqueloculina seminula</i> <i>Reophax atlantica</i> <i>Asterigerina carinata</i> <i>Amphistegina lessonii</i> <i>Cibicides pseudoungerianus</i>
Workman (1981)	<i>Elphidium excavatum</i> <i>Eggerella advena</i> , <i>Elphidium gunteri</i> <i>Ammonia beccarii</i> forma <i>tepida</i>	<i>Quinqueloculina lamarckiana</i> <i>Elphidium limatulum</i> <i>Elphidium excavatum</i> <i>Ammonia beccarii</i> forma <i>tepida</i> <i>Elphidium gunteri</i> <i>Quinqueloculina jugosa</i> <i>Quinqueloculina seminula</i>

Chronostratigraphy

Optically Stimulated Luminescence

Optically stimulated luminescence (OSL) is a relatively new technique which can be used to date coastal sediment deposition (Carter et al., 1989; Devoy et al., 1996; Berger et al., 2003, Havholm et al., 2004). OSL is typically applied to quartz and/or feldspar, allowing the dating of sediments to be independent of organic material (a requirement for ^{14}C dating). OSL also allows for the dating of a wider age range than ^{14}C ; sediments can be dated back several hundred thousand years (van Heteren, 2000; Murray and Olley, 2002). Dating of OSL dune sand has yielded approximately the same results as using ^{14}C dating, suggesting it is equally as precise (Ollerhead et al., 1994).

OSL measures the amount of time since the sediment was last exposed to sunlight. Electrons energized by ionizing radiation in the sediment (thorium, uranium, potassium-40, rubidium-87) collect in “traps” or imperfections in the crystal lattice of a buried quartz grain (Aitken, 1998). When that quartz grain is exposed to light (“bleached”), the electrons are knocked out of traps and release their energy in the form of photons (i.e., it luminesces). When the grain is buried, photons begin to fill the traps once more. OSL measures the amount of electrons remaining in these traps and compares them to the background radiation of the sample. This comparison reveals the last time the quartz grain was exposed to light (and thereby reveals the “age” of deposition).

The age is calculated using the (simplified) equation:

$$\text{Age} = \frac{\text{Paleodose}}{\text{Dose-rate}}$$

The paleodose is the amount of laboratory radiation necessary to replicate the measured luminescence. The dose-rate is the rate at which radiation is absorbed from the sediments.

OSL provides the ability to date sediments back to approximately 250,000 years (Murray and Olley, 2002). The 250 ka threshold represents the age at which the traps in the quartz grains become full (saturated). When the traps can no longer gain electrons, it is impossible to calculate whether the sample is 250 ka or 250 Ma, as the amount of electrons contained in the traps would be the same.

OSL dating procedures can involve single- or multiple-aliquots. The single-aliquot method, used in this study, assigns an age for each aliquot (~100 quartz grains) by matching a lab-generated signal to the natural signal in the sample. The multiple-aliquot method uses ostensibly identical single aliquots, subjecting some aliquots to the test dose and some to the laboratory dose (Aitken, 1998). The regenerative-dose method, used with a single aliquot, initially zeroes the signal (similar to the natural bleaching event) and then incrementally adds radiation doses to construct a growth curve of luminescence versus dose. The natural OSL signal is then overlain with the growth curve to determine the paleodose (Aitken, 1998).

OSL data are an additional tool to understanding sea-level fluctuations and burial along barrier islands (van Heteren, 2000). Numerous studies have utilized OSL on the coast of North Carolina to determine age of deposition of Quaternary sediments (Berger

et al., 2003, Havholm et al., 2004, Burdette, 2005; Smith, 2006; Parham, 2007, 2009; Mallinson et al., 2008a, 2008b; Hale, 2008).

Radiocarbon Dating

Radiocarbon dating measures the radioactive isotope ^{14}C in organic material. The technique provides the ability to date organic material or carbonates contained in sediments to approximately 40,000 years BP (Shackleton et al., 2004). Many studies in coastal North Carolina have utilized radiocarbon dating of Holocene coastal sediments to acquire a depositional age (e.g., Havholm, 2004; Mallinson et al., 2005; Smith, 2006; Culver et al., 2006; Rosenberger, 2006; Foley, 2007; Hale, 2008; Metger, 2008).

^{14}C in live organic tissue is in equilibrium with the (local) atmospheric concentration. Once respiration of the tissue ceases, ^{14}C begins to break down via β -decay. The decay of ^{14}C follows an exponential curve and has a half-life ($t_{1/2}$) of 5,370 years; half of the ^{14}C in a sample decays every $\sim 5,300$ years into stable ^{14}N (Bradley, 1999).

Radiocarbon dating has become more versatile and accurate since the development of Accelerator Mass Spectrometry (AMS). Previously, ^{14}C was measured in an experimental setup which allowed it to decay over time and then be measured by a beta counter. AMS directly counts the number of ^{14}C atoms, requiring a much smaller sample size (milligrams instead of grams) and allowing testing to be performed on a broader range of sample types (Bradley, 1999).

Calibration is required of recovered ^{14}C ages to account for variations in atmospheric ^{14}C concentrations (Stuiver and Reimer, 1993). Atmospheric bomb testing in the middle of the 20th century caused localized increases in ^{14}C concentrations; these spikes were particularly evident in the northern hemisphere. Atmospheric ^{14}C has also

been diluted by old carbon with no ^{14}C (i.e. radiocarbon “dead”) since the onset of the Industrial Revolution, through the burning of fossil fuels. Other natural oscillations in ^{14}C worldwide require a calibration curve to accurately determine a radiocarbon age (Stuiver et al., 2008).

Geophysical Data

Geophysical data analysis is an essential tool for describing the geologic framework of the subsurface. Ground-penetrating radar (GPR) utilizes an electromagnetic signal to penetrate the subsurface. The signal is reflected off boundaries which represent changes in dielectrical properties (which generally occur along lithologic contacts) received by an antenna, and recorded as two-way travel time. GPR data can be gathered in terrestrial environments; however the signal is attenuated if salt water or clay occurs in the subsurface, making data acquisition in some coastal environments difficult (Jol et al., 2006).

It has been shown that GPR is a successful tool for interpreting the geologic framework of barrier island systems (Gawthorpe et al., 1993; Schenk et al., 1993; van Heteran et al., 2000; Smith, 2006; Culver et al., 2006). GPR can yield high resolution, shallow subsurface data using electromagnetic radiation in appropriate conditions (Bridge et al., 1995). These data can be correlated with cores to create a more complete picture of the geologic framework.

Fitzgerald et al. (1992) utilized GPR data along with coring to describe Horseneck Beach, a beach-ridge barrier island fronting Buzzards Bay, Massachusetts. Their data demonstrated prograding accretionary wedges at the eastern end of Horseneck Beach, with each additional wedge indicating a change in sediment type (sand to gravel or gravel to sand). GPR data indicated progradation and increased barrier island elevation (shown by horizontal to slightly seaward dipping reflections) during times of high sediment (sand) supply. With lower sand inputs to the system, the shoreface eroded and steepened,

with gravel as the primary sediment source on the beach (shown in the GPR data by dark, sharp reflections).

Van Heteran et al. (1998) identified eight reflection trends in a data base of GPR profiles along paraglacial barrier islands in New England which typify reflections in the mid- to high-latitude coastal environment (Figure 15). Van Heteren et al. (2000) utilized GPR data of Sandy Neck, Massachusetts to identify units in the subsurface. The investigators identified the basal eolian sand, a smooth plane in the GPR data, located between dune sand and beach sand/gravel, as a sea-level marker (van Heteren and van de Plassche, 1997). This boundary allowed the investigators to determine depths from which OSL samples were taken. By identifying and dating this basal eolian sand, relative sea-level was determined at this location.

Many studies have collected data which document inlet clinoform propagation and inlet fill (Smith, 2004; Ricardo, 2005; Smith, 2006; Twamley, 2006; Culver et al., 2006; Culver et al., 2007; Smith et al., 2009). GPR data have also been used to establish a chronology in beach ridge complexes in North Carolina (Havholm et al., 2004; Burdette, 2005; Mallinson et al., 2008b). Havholm et al. (2004) used GPR to study back-barrier dune development along the northern North Carolina/southern Virginia border. GPR revealed five phases in dune development of Jockeys Ridge and Run Hill, the largest and oldest of the dune systems. From these data, Havholm was able to attribute

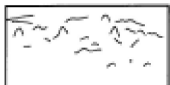
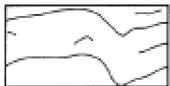
CHAOTIC		HIGH-FREQUENCY	COLLAPSED OUTWASH SAND AND GRAVEL, SAPROLITE, TILL (BARRIER ANCHOR POINTS, SOURCES OF BARRIER SEDIMENT)
		LOW-FREQUENCY	ARTIFICIAL FILL, BURIED UTILITY PIPES AND CABLES
PARALLEL		EVEN	DRAPED GLACIOMARINE MUD, OUTWASH-DELTA SILT AND SAND (SOURCE OF BARRIER SEDIMENT), BEACH SAND AND GRAVEL, TIDAL-INLET SAND AND GRAVEL
		WAVY	DRAPED GLACIOMARINE MUD
OBLIQUE		TANGENTIAL	OUTWASH-DELTA SILT AND SAND (SOURCE OF BARRIER SEDIMENT), WASHOVER SAND AND GRAVEL
		SIGMOIDAL	PROGRADATIONAL OR ACCRETIONARY BEACH SAND AND GRAVEL
		COMPLEX SIGMOIDAL	PROGRADATIONAL AND AGGRADATIONAL BEACH SAND AND GRAVEL
		HUMMOCKY	ACCRETIONARY SPIT-BEACH SAND AND GRAVEL
		BOUNDING SURFACE	DUNE SAND (INCLUDING PALAEOSOLS)
		REFLECTION-FREE	SIGNAL ATTENUATION BY SALTY GROUNDWATER OR PEAT LENSES, HOMOGENEOUS DUNE SAND
		BASIN-FILL	BACK-BARRIER MUD AND PEAT

Figure 15. GPR facies and interpretations in mid- to high-latitude coastal environments (taken from van Heteren et al., 1998).

the growth of these large dune complexes to increased storminess, drought, and slow sea level rise.

Mallinson et al. (2008a) utilized GPR data to discern the geology of shoreline features in the Kitty Hawk beach ridges of North Carolina. GPR revealed a transgressive system located on the sound side of Currituck Sound (The Land of Promise and Powell's Point Ridges) and a Holocene-age prograding beach ridge complex (Kitty Hawk Woods) from the last relative sea-level rise located on the barrier island. Mallinson et al. (2008b) conducted GPR surveys and collected OSL samples at the Broad Reach archaeological site near Swansboro, N.C. The GPR data supported the hypothesis of an eolian sandsheet that developed at ca. 10-12 ka on Pleistocene beach ridges.

Seismic data collection may be employed in a marine or terrestrial environment and utilizes acoustic energy to image the subsurface. In this study a chirp subbottom profiler was used. This system utilizes a tuned transducer with a frequency of 2-16 kHz as the acoustic source. Energy is reflected from subsurface boundaries where a change in density and velocity (acoustic impedance) occurs. The reflections are recorded and displayed as a two-dimensional image.

Thieler et al. (2001) utilized sidescan sonar and seismic reflection techniques (along with 200 vibracores) to map the shoreface and inner continental shelf in Onslow Bay, directly east of Wrightsville, North Carolina. Shore-oblique rippled scour depressions dominate the shoreface landscape and contain coarse shell hash and shell gravel. Sidescan and seismic data suggested that these scours lie unconformably on antecedent topography – either paleofluvial channel or tidal inlet lithosomes. Semi-

annual sidescan and seismic sonar data showed little change in seafloor morphology, which suggested the subbottom in this area is stable or had the ability to return to a similar morphological state after storm-induced change. The investigators also concluded that the surficial morphology and geologic framework are important to beach and inner shelf sedimentation.

Mallinson et al. (2005) conducted seismic surveys and collected cores to determine the geologic framework of eastern Albemarle Sound. A thick bay-mouth sand deposit indicated that a continuous barrier island was not present in this area throughout most of the Holocene. The identification of a valley-fill deposit composed of organic-rich mud suggested deposition during a significantly decreased wave and tidal regime (i.e., the establishment of a barrier island). This valley-fill was linked to similar depositional sequences discovered by Boss et al. (2002) and seismic sequences described by Riggs et al. (1992), as well as similar amino-acid racemization dates.

Sea Level Curves for North Carolina

GPR combined with sedimentological data can be used to resolve sea-level index points in the subsurface (van Heteren, 2000). Sedimentary structures such as deepest dry eolian scour and range of low-angle nearshore bars (Roep and Beets, 1988), when identified using GPR, can indicate a facies boundary and provide a relative sea-level marker (van Heteren and van de Plassche, 1997; van Heteren, 2000). These boundaries can then be sampled and tested using OSL to acquire approximate ages of these past sea-level indicators. McDowell (2009) showed that this technique works well in the beach ridges associated with Cape Hatteras, NC.

Steele (1980) combined his radiocarbon data with data from Susman (1975), Moslow (1977), Herbert (1978) and Berelson (1979) to create a sea-level curve of the Cape Lookout area (Figure 16). The solid curve is taken from Neumann (unpublished data) and represents an average of the rates of sea level change in the atectonic area of the Bahamas. The dashed curve is a line of best fit drawn to mimic the first curve but to take into account the data points plotted. However, Steele (1980) admitted that the data points were not taken with regard to shoreface or marsh deposits, and do not necessarily reflect the true rate of sea-level change.

Horton et al. (2009) created a database of 53 sea-level index points and 37 additional minimum/maximum sea-level data points which illustrated rapid relative sea-level rise during the Holocene (Figure 17). This study placed emphasis on calibrating all new and existing data points uniformly to properly take into account the relationship

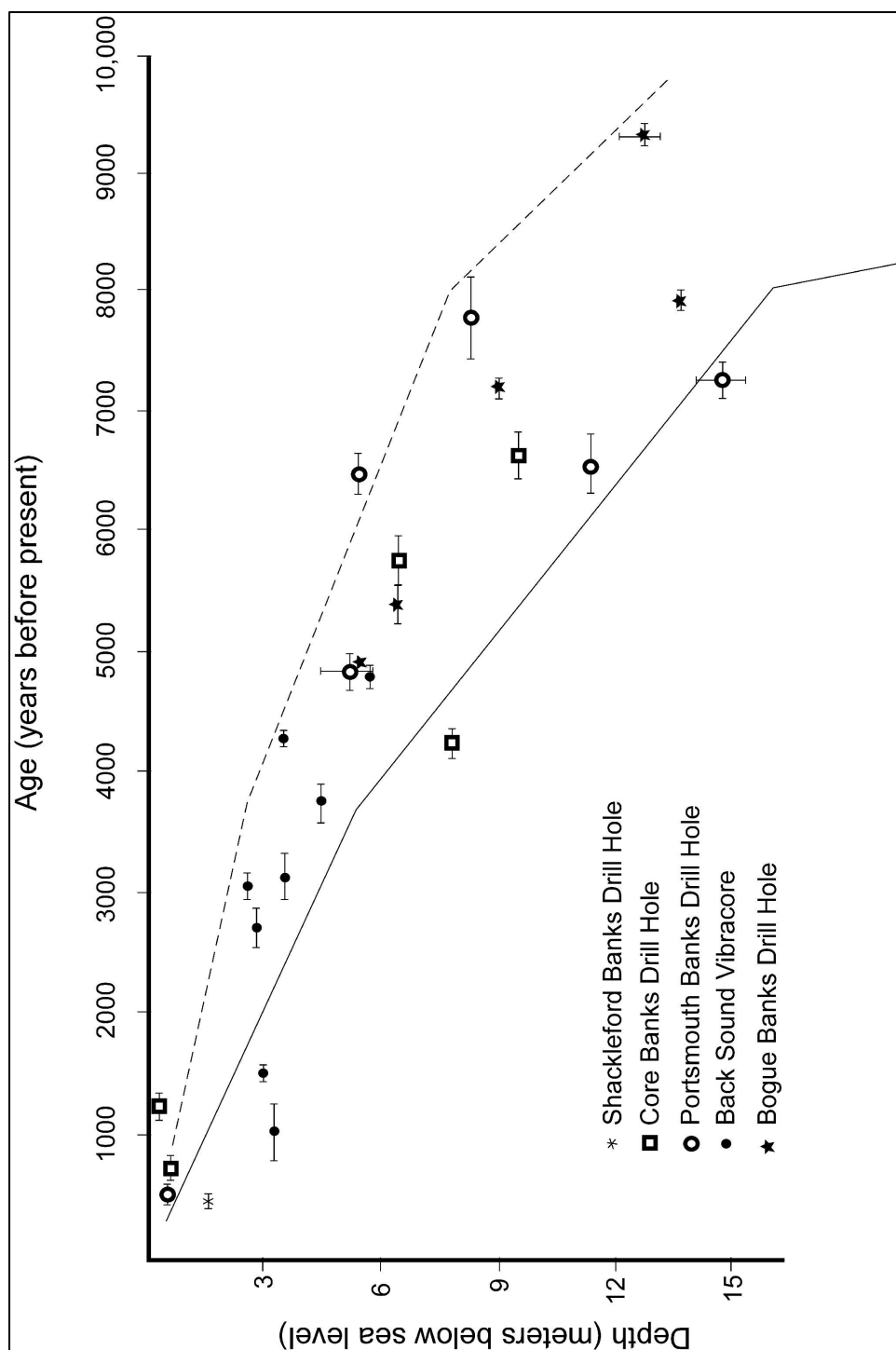


Figure 16. Sea level curves of Onslow Bay from data collected from Susman (1975), Moslow (1977), Herbert (1978), Berelson (1979), and Steele (1980) (adapted from Steele, 1980). Dashed line represents data from the Cape Lookout area (curve modified from Berelson, 1979). Solid line drawn using rates of sea-level rise proposed by Hine et al. (1979).

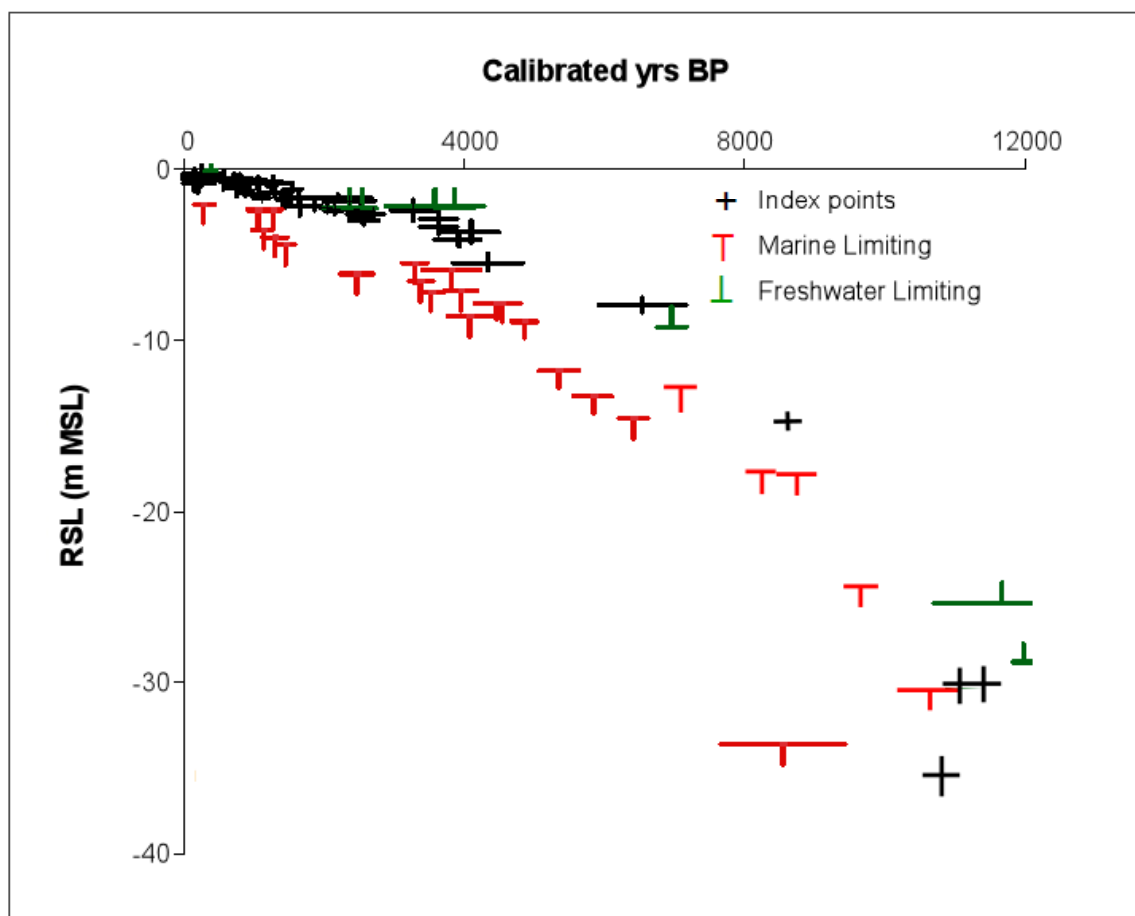


Figure 17. Relative sea-level index points and limiting data for North Carolina with error bars. Sea-level index points are shown as black crosses, minimum (freshwater) limiting data shown in green, and maximum (marine) limiting data shown in red. Taken from Horton et al. (2009).

between sea-level indicators and sea level. Numerous studies (Emery et al., 1967; Redfield, 1967; Sears, 1973; Field et al., 1979; Cinquemani et al., 1982; Riggs et al., 1992; Moslow and Heron, 1994) have created North Carolina relative sea-level curves for the Holocene, but most did not take into account all the factors contributing to the indicative meaning (the relationship between the environment of deposition and a specific water level during a tidal cycle; Horton et al., 2004). Horton et al. (2009) did not overlook these key problems with elevation data, which include the incorrect usage of mean high water and mean sea level, unreported elevation errors, and the use of different calibrations for radiocarbon dates. Horton et al. (2009) divided North Carolina into two regions; the northern region comprised Albemarle, Currituck, Roanoke, Croatan, and northern Pamlico sounds, and the southern region comprised Core, Bogue, and southern Pamlico sounds and south to Wilmington. Index points from the northern region indicated that from 2849-2543 cal years BP to present, relative sea-level rose from -2.62 ± 0.19 m MSL at 1.02 ± 0.04 mmyr⁻¹. Data from the southern region indicated that from 3905-3389 cal years BP to present, relative sea-level rose from -3.39 ± 0.44 m MSL at 0.92 ± 0.05 mmyr⁻¹ (Figure 17). Tide gauges and satellite altimetry data also suggest an additional rate of sea-level rise of >2 mmyr⁻¹ during the 20th century (Douglas, 1995, 1997, 2001; Peltier and Jiang, 1997; Church et al., 2004; Church and White, 2006; Cabanes et al., 2001; Cazenave and Nerem, 2004; Leuliette et al., 2004).

Kemp et al. (2009b) reconstructed sea-level rise since AD 1500 using foraminifera from two salt marshes in North Carolina. These were compared against 20th century tide-gauge records to determine site-specific sea-level rise at both marshes.

Kemp et al. (2009b) identified 73 relative sea-level points from both marshes (calculated by subtracting the estimated paleommarsh elevation from the current elevation) and plotted their age versus relative sea-level (with the help of an age model) to create a sea-level reconstruction (Figure 18). They were then able to describe a eustatic sea-level rise of 2.2 mm/year above the background rate of sea-level rise during the 20th century, a finding corroborated by similar rates in Nova Scotia (1.6 mm/yr; Gehrels et al., 2005) and Connecticut (Donnelly et al., 2004) (Figure 19). This, and previous studies (Douglas, 1991; Peltier, 2001; Wake et al., 2006), suggested that the rate of sea-level change varies latitudinally, with a larger magnitude of sea-level rise occurring with decreasing latitude.

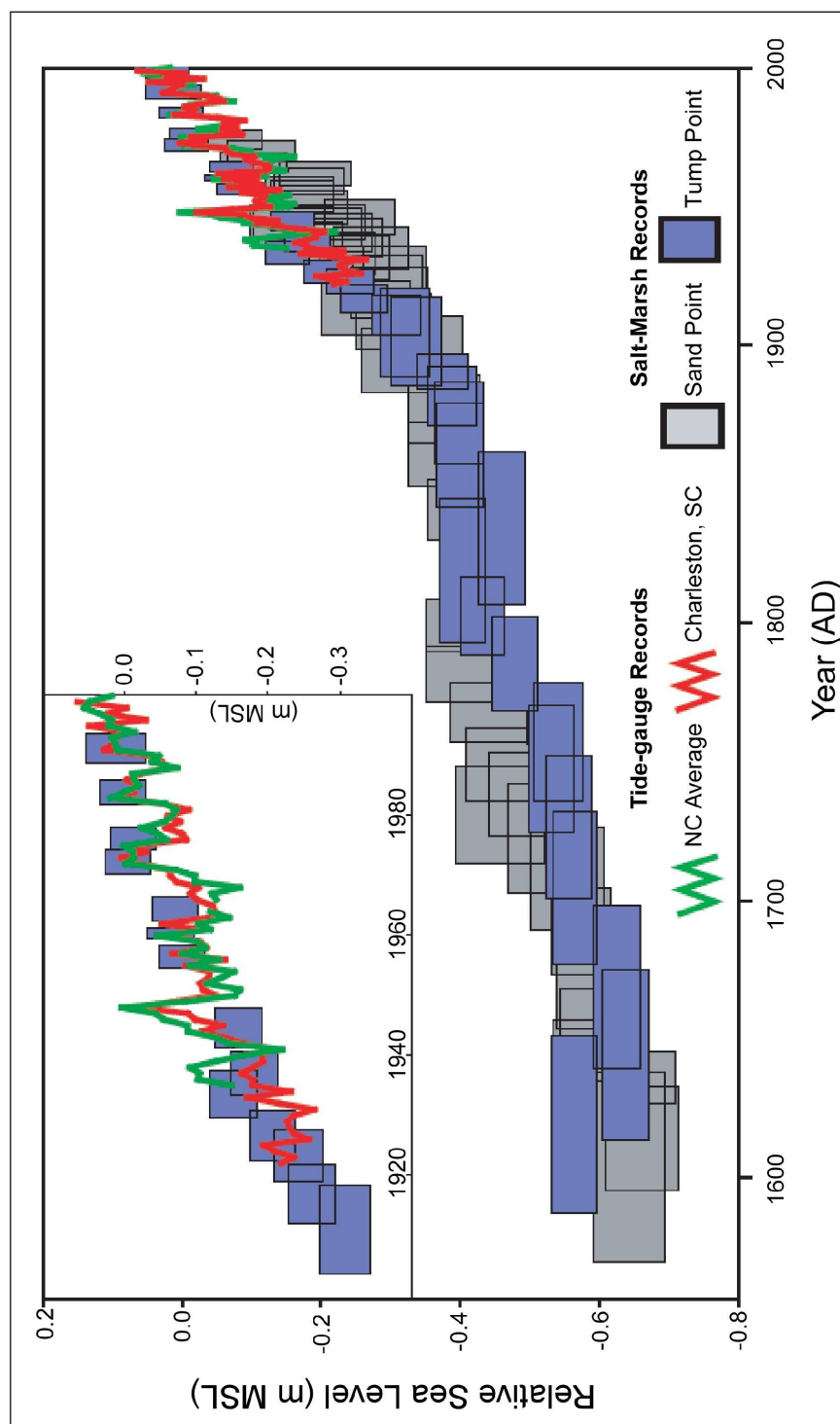


Figure 18. Sea-level reconstructions of Sand Point and Tump Point marshes in North Carolina since AD 1500. Two tidal-gauge records along the Atlantic margin are also shown. Inset: Tump Point sea-level reconstruction compared to 20th century tide-gauge records (taken from Kemp et al., 2009b).

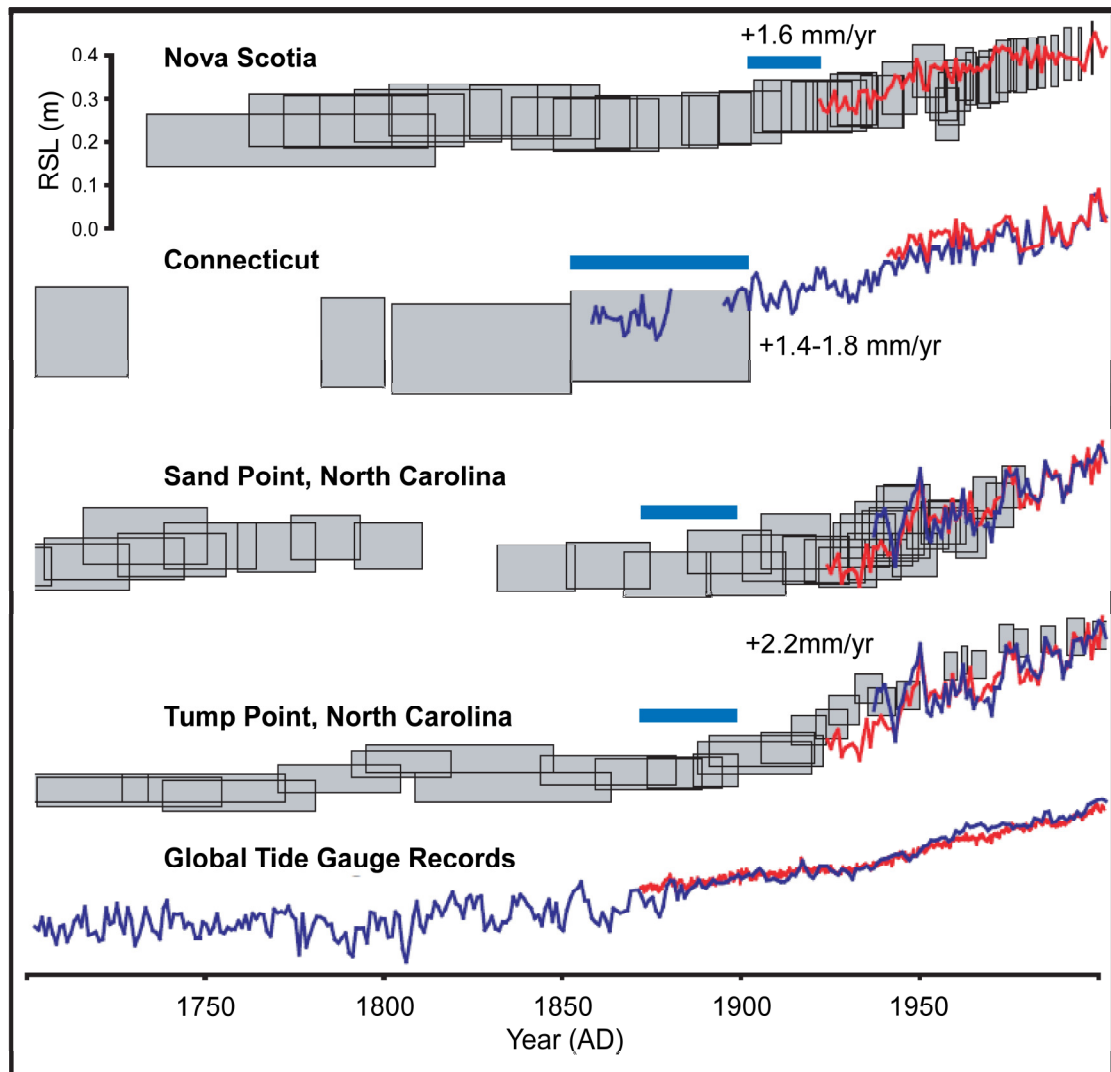


Figure 19. Relative sea-level index points with superimposed local tide-gauge records as comparison (Nova Scotia: Halifax; Connecticut: New London [red] and New York City [blue]; North Carolina: Charleston, SC [red] and NC average [blue]). Global tide gauge records from Church and White (2006; red) and Jevrejeva et al. (2008; blue) are shown along bottom. Taken from Kemp et al. (2009b).

METHODOLOGY

Geoprobe Coring

Eleven Geoprobe cores were taken on the mainland of Carteret County (8) and Bogue Banks (3), North Carolina from January to October of 2008 (Figure 20). Geomorphology of the area was examined using LiDAR elevation data (www.ncfloodmaps.com), and core locations were positioned in three north-south transects, approximately perpendicular to the mainland beach ridge features. When coring on the beach ridge complex, an attempt was made to core on the southern side of the ridge and swale complex to potentially recover plunge points (indicators of sea-level). The precise geographic location of each core was recorded using a Trimble Global Positioning System (GPS). The elevation of each core with respect to MSL was determined using LiDAR elevation data, which has a reported accuracy of ± 0.25 m (www.ncfloodmaps.com).

Geoprobe cores were taken using a truck-mounted Geoprobe pneumatic/hydraulic drill. A two-inch diameter, four-foot long plastic tube was inserted into the approximately four-foot long core barrel and pneumatically pressed into the ground. After the core barrel was inserted completely into the subsurface, it was extracted, the plastic tube containing the sediment sample was removed, and another core barrel was attached to the apparatus to drill deeper. Sediment samples were collected at four-foot intervals until no progress was made upon further penetration. After removal from the core barrel, the sediment sample tube was then capped, sealed with duct tape, and labeled with core name and core depth interval.

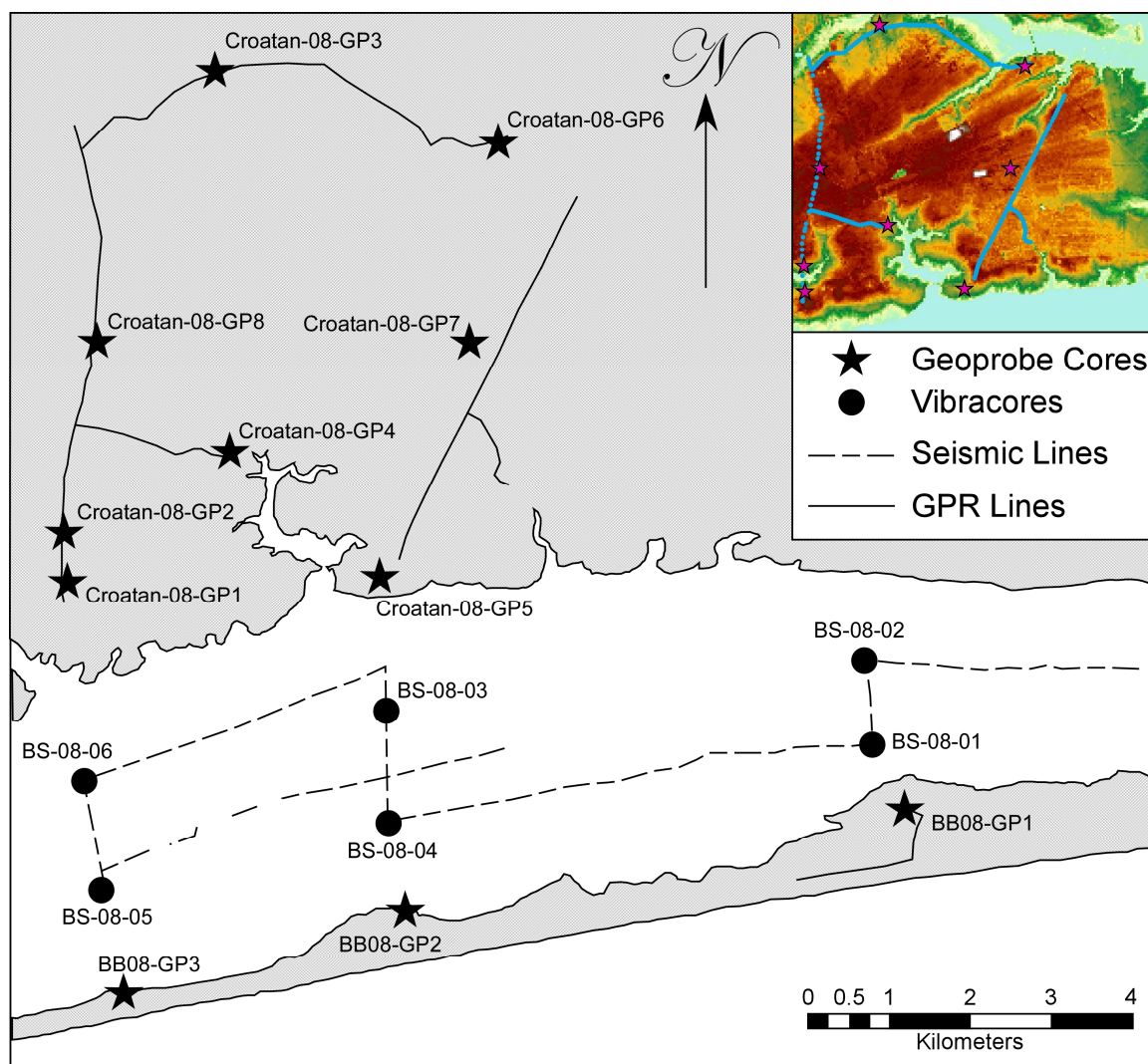


Figure 20. Map of study area showing core locations and GPR/seismic lines. Inset shows LiDAR data of Croatan Beach Ridge Complex and the location of cores and geophysical lines with respect to the ridges. Red in the LiDAR data represents the highest elevation, pale blue the lowest elevation. LiDAR data taken from www.ncfloodmaps.com

Vibracoring

Six vibracores were collected in Bogue Sound in November of 2008 (Figure 20). Vibracore locations were selected to extend the three established Geoprobe core transects, providing information between the barrier island Bogue Banks cores and the mainland beach ridge cores. The location of each core was collected using the Trimble GPS. Water depth was recorded using a tape measure.

Core collection was conducted from a barge. Upon arrival to our core location, three anchors were set to minimize drift. A 3-inch diameter pipe was attached to a concrete vibrating head powered by a gas generator. After vibration into the sediment the pipe was removed from the seafloor and capped by a diver to prevent sediment loss. On deck, the pipe was cut into 1.5 meter sections, capped, sealed with tape, and labeled. Measurements of core penetration, core recovery, and core loss were recorded.

Lithology and Sedimentology

Vibracores were cut lengthwise; one half was photographed and archived and the other used to construct lithologic logs and sample for grain size and foraminifera. The top quarter of each plastic Geoprobe core was sliced off to reveal the sediment collected. The Geoprobe core was then photographed, logged, and sampled for grain size and foraminifera before being archived.

All cores were logged using methods outlined by Folk (1980) to estimate grain size, color, rounding, sorting, mineral composition, percent shell material, heavy minerals, and organics, bioturbation, approximate gravel/sand/mud ratios,

sedimentological contacts, and additional sedimentary features where present. These logs were then drawn using Canvas X (Appendix B) and correlated to identify different and distinct lithofacies.

Grain size samples were taken in each core, downcore, where a lithofacies change occurred. Each sample (approximately 40 grams) was placed into a metal weigh boat and dried overnight in a 60°C oven. Sieve stacks were created at half phi (ϕ) intervals from 4ϕ to -1.5ϕ . Each sample was removed from the oven, weighed, and placed on the mesh of the coarsest sieve (-1.5ϕ), on the top of the stack. The sieve stack was then placed in a Ro-tap, vibrated for 20 minutes and the sediment in each sieve was weighed to determine weight percent of each sieve fraction. These weight percents were then combined into an Excel spreadsheet and input into GRADISTAT (Blott and Pye, 2001) to create graphs of grain size, sorting, skewness, and kurtosis over an entire core (Appendix C).

Foraminiferal Analyses

At each vibracore location, a foraminifera surface sample was collected using a ponar sediment sampler. A 40 ml sediment sample was scraped off the top 1 cm of the collected sediment. The sediment sample was placed into a plastic bottle and preserved in alcohol. Surface salinity at each location was measured using a refractometer.

Foraminiferal samples were processed using methods outlined by Culver et al. (1996) and Woo et al. (1997). Each sample was dried overnight in a 60°C oven, weighed, and placed in a beaker with tap water, sodium metaphosphate (to disperse

sediment), and sodium hydroxide (to dissolve organic material) and left overnight. Each sample was washed over 710 μm (gravel-sized) and 63 μm (sand-sized) nested sieves to separate the coarse and fine-grained material and wash away the clay and silt particles. Each fraction was placed in separate weigh boats, dried overnight at 60°C, and weighed. Dry weights of the gravel and sand fractions were used to calculate gravel/sand/mud ratios (Appendix D). The foraminifera in the 63 μm (sand) fraction were separated from the sediment using the sodium polytungstate floatation method established by Munsterman and Kerstholt (1996). Sodium polytungstate is a high density liquid which allows sediment to sink and foraminifera to float. Once separated, the sink and float were washed and dried overnight at 60°C.

When dry, the float was equally distributed over a 45-square picking tray. If the sample was too large to easily sift through, it was split into smaller fractions using a microsplitter. Approximately 200 foraminifera were picked from each sample, unless fewer specimens were present. Once picked, foraminifera were organized into squares on a slide and identified to the species level. Total number of specimens picked, squares picked, and fraction picked were recorded. Identifications were confirmed using type specimens located in the Cushman Collection at the Smithsonian Institution, Washington, D.C. Scanning electron micrographs were taken of taxa included in the cluster analysis for which a well-preserved specimen existed (Plates 1, 2).

Cluster Analysis

Foraminiferal assemblages were determined using Q-mode cluster analysis data (Euclidean distances, Ward's linkage) calculated using Systat 12 (Mello and Buzas, 1968). Only those species which represent $\geq 2\%$ of the assemblage of any one sample were included. The average relative abundance was then calculated for each taxon in a biofacies.

Occurrence (O), constancy (C), and biofacies fidelity (BF) were calculated to identify the species which were faithful to their biofacies (Hazel, 1977). Occurrence expresses the number of samples in a biofacies which contain a specific species. Constancy expresses the percentage of samples in a biofacies which contain a specific species ($C = O / \# \text{ of samples in biofacies}$). Biofacies fidelity is a measure of how faithful a species is to a biofacies, and is calculated using the equation:

$$BF = P_i / \sum_{i=1}^p P_i \times 10$$

where $P = \% \text{ of occurrences (constancy)}$.

Optically Stimulated Luminescence (OSL) Core Collection

OSL samples cannot be exposed to light, thus requiring four-foot geoprobe core intervals to be pre-selected for OSL sample collection. When these intervals were brought to the surface, they were removed directly from the core barrel to an industrial black garbage bag to prevent bleaching of the grains. Caps were placed on either end and the bag taped up and labeled. No special requirements were necessary for the collection

of OSL samples from vibracores as they are brought to the surface sealed in aluminum pipes.

Geoprobe cores from which OSL samples were to be taken were opened in a dark room. Vibracores were cut in the core cutting room and moved into the dark room to be opened using piano wire. The sample depth was chosen and 100 g of sediment was removed from the center of the core to prevent contamination of grains on the core wall that could have been exposed to light during collection. Approximately 500 grams of sediment from above and below the sample were placed into a separate whirlpack and used for dose rate analysis.

OSL samples were processed in a dark lab under safe light conditions at the USGS Optically Stimulated Luminescence Lab in Denver, Colorado. Samples underwent a 4 N HCl and 35% H₂O₂ bath to dissolve carbonates and organics and then washed with deionized water. Samples were then wet-sieved to collect the 180-250 μm fraction and dried overnight. Once dry, the samples underwent heavy liquid separation using a centrifuge to isolate the quartz grains. Once washed and dried, the quartz grains were etched with HF. The isolated quartz grains in each sample underwent the blue-light and infra-red OSL method and single-aliquot regeneration-dose technique (SAR) (Wintle and Murray, 1999). The dose rate of the surrounding sediment was determined by the activity of ^{40}K , ^{238}U , and ^{234}Th .

Radiocarbon Dating Sample Collection and Processing

Accelerator mass spectrometry (AMS) ^{14}C was used to date three samples: two disarticulated bivalves (*Ensis directus* and *Crassostrea* sp.) and 2000 specimens of *Elphidium excavatum*. Each bivalve sample was placed in a beaker of distilled water with sodium metaphosphate and placed in a sonic vibrator. After one hour, the samples were removed, rinsed in distilled water, and placed in a drying oven. Two thousand well preserved specimens of *Elphidium excavatum* in different sizes were picked, washed, and dried. The foraminifera were placed in a glass vial for transport to Beta Analytic, Inc. (Miami, Florida).

Geophysical Data Acquisition

Ground Penetrating Radar (GPR)

GPR data were collected along roadways on the mainland of Carteret County and Bogue Banks using the Geophysical Survey Systems, Inc. (GSSI) SIR-2000 & 3000 GPR unit equipped with a 200 MHz antennae. The data were collected at an approximate speed of 5-6 km/h at a rate of 32 scans/second. Geographic positions of these data were recorded on a Trimble GPS unit and linked to the data by waypoint and scan numbers. GPR data were filtered, gain adjusted, and stacked using Radan software. The processed files were imported into Canvas to be digitized.

Seismic Surveys

Seismic data were collected in Bogue Sound using an Edgetech 216 (chirp) system. Transects were created that passed over the vibracore sites in Bogue Sound,

along established core transects that run south through Carteret County, through Bogue Sound, and onto Bogue Banks. These data were linked to differential GPS to record their specific geographic locations. Seismic data were processed, filtered, and digitized using Seismic Micro-Technology (SMT), Inc., Kingdom Suite software.

RESULTS AND INTERPRETATION

Lithofacies Descriptions

Thirteen lithofacies were identified in eleven Geoprobe cores and six vibracores (Table 2). The sediments comprising the lithofacies were described using the Folk Method (1980). Grain size, rounding, and approximate percentages of constituents were observed both macro- and microscopically. Organic material refers to wood or plant debris (roots, rootlets, bark, woody material, etc.). Shell material described as “shell hash” varies in size from microscopic to gravel-sized unless otherwise specified. Grain size data for each lithofacies are given in Table 3.

Sand (S)

The sand lithofacies ranges in color but typically lies between a medium gray (10YR 5/1) to yellowish gray (5Y 8/1) (Figure 21). The sand is moderately to well-sorted, subrounded to rounded, and fine to coarse-grained. This lithofacies is composed of primarily sand-sized grains (98-99%), heavies (<1-10%), some organics (<1-5%) and mud (1%). It is primarily massively-bedded, but also contains thin (0.5 cm) to thick (2 cm) heavy mineral laminations, and can also be bioturbated. Roots are present in shallow sections of some cores. Minor organic laminations can also occur, generally at shallow depths (<1 meter).

Table 2. Composition and sedimentological characteristics of thirteen lithofacies identified in the seventeen cores collected. G/S/M/ ratios refer to the percentage of gravel, sand, and mud present in each lithofacies.

Lithofacies Name	Color	Description	Sedimentary Features	G/S/M Ratio (%)	Organics (%)	Shell Hash (%)
Sand (S)	Medium gray (10YR 5/1) to yellowish gray (5Y 8/1)	Moderately to well sorted, subrounded to rounded, fine to coarse-grained, primarily quartz sand	Minor to large heavy mineral laminations; massively bedded; minor organic laminations; bioturbation	<1/98-99/1	<1-5	<1
Organic-Rich Sand (orgS)	Very dark brown (7.5YR 2.5/2)	Moderately to well sorted, subrounded to rounded, fine-grained sand with organic mud	Bioturbated; common roots, wood chips and plant debris; organic particulates and mud	<1/80-95/5-20	20-60	<1
Muddy Sand (mS)	Yellowish brown (10YR 5/4) to dark gray (2.5Y 4/1)	Moderately sorted, subrounded to subangular, fine-grained sand with mud	Rare organic concretions	<1/70-85/15-30	1-3	<1
Shelly, Muddy Sand (shmS)	Gray (10YR 5/1) to very dark gray (2.5Y 4/1)	Poorly to well sorted, subrounded to subangular, fine-grained sand with mud, marine shells	Usually interbedded with shelly, sandy mud; burrows	<1/70-85/15-30	<1	1-30
Shelly Sand (shS)	Gray (10YR 5/1)	Moderately to well sorted, subrounded to subangular, fine to medium-grained sand with shells	Rare mud-filled burrows; massively bedded	<1/90-98/<1	<1	5-15
Gravelly Sand (gS)	Gray (GLEY 1 5/5G)	Poorly sorted, subrounded to subangular, fine to very coarse sand	Gravel lag deposits	10-45/60-80/<1	<1-3	<1

Table 2 (continued).

Lithofacies Name	Color	Description	Sedimentary Features	G/S/M Ratio (%)	Organics (%)	Shell Hash (%)
Mud (M)	Dark gray (2.5Y 4/1)	Clay and silt-size particles	Massive	<1/<1/95-100	<1	<1
Sandy Mud (sM)	Light gray (10YR 7/2) to dark gray (2.5Y 4/1)	Moderately well sorted, subrounded to subangular, primarily quartz sand with mud	Occasionally burrowed	<1/5-20/80-95	<1-3	<1
Shelly Mud (shM)	Dark gray (2.5Y 4/1)	clay and silt-size particles with marine shell fragments and whole shells	Massive	<1/1-3/95-99	<1	5-25
Shelly, Sandy Mud (shsM)	Light gray (10YR 7/2) to dark gray (2.5Y 4/1)	Mud with moderately to well-sorted medium to fine sand with marine shell fragments	Usually massive, sometimes found in layered horizons	<1/15-30/70-85	<1	1-30
Interbedded Mud and Sand (I)	Light gray (10 YR 6/1) to dark gray (2.5Y 4/1)	Interbedded mud and moderately well-sorted, moderately well-rounded fine sand	Interbedded layers typically 10 – 40cm thick	<1/40-60/40-60	<1-3	<1
Interbedded Mud and Sand with Shells (shI)	Light gray (10 YR 6/1) to (GEY 3/5GY) dark greenish gray	Interbedded mud and moderately well-sorted, subangular to subrounded fine sand with shells	Interbedded layers typically 5 – 50cm thick	<1/40-60/40-60	<1	5-50
Large Shell (Sh)	Light yellowish brown (2.5Y 6/3) to dark gray (2.5Y 4/1)	Dominated by large marine shell beds with minor amounts of moderately well-sorted to poorly-sorted fine to coarse sand and mud	Oyster beds <i>in situ</i>	1-5/60-80/<1-35	<1	50-95

Table 3. Summary of grain size data of lithofacies using the Folk and Ward Method (all data given in Φ)

Lithofacies	Mean Grain Size	Median Grain Size	Mean Sorting	Mean Skewness	Mean Kurtosis
Sand (S)	2.601	2.612	0.439	-0.126	1.058
Organic-rich Sand (orgS)	2.580	2.338	0.828	0.121	1.084
Muddy Sand (mS)	1.985	2.388	0.974	0.237	1.384
Shelly, Muddy Sand (shmS)	2.830	2.604	2.716	0.115	0.983
Shelly Sand (shS)	2.779	2.676	0.559	-0.253	2.460
Gravelly Sand (gS)	2.471	1.742	1.405	-0.025	0.769
Mud (M)	3.730	4.241	1.544	0.098	1.068
Sandy Mud (sM)	1.523	1.884	1.164	-0.052	1.223
Shelly Mud (shM)	3.224	4.411	1.535	-0.119	1.298
Shelly, Sandy Mud (shsM)	4.493	2.680	2.102	0.112	0.865
Interbedded Mud and Sand (I)	3.227	2.725	0.779	0.110	1.248
Interbedded Mud and Sand with Shells (mI)	2.815	2.744	1.322	-0.235	1.431
Large Shell (Sh)	2.393	2.361	0.563	-0.249	1.674

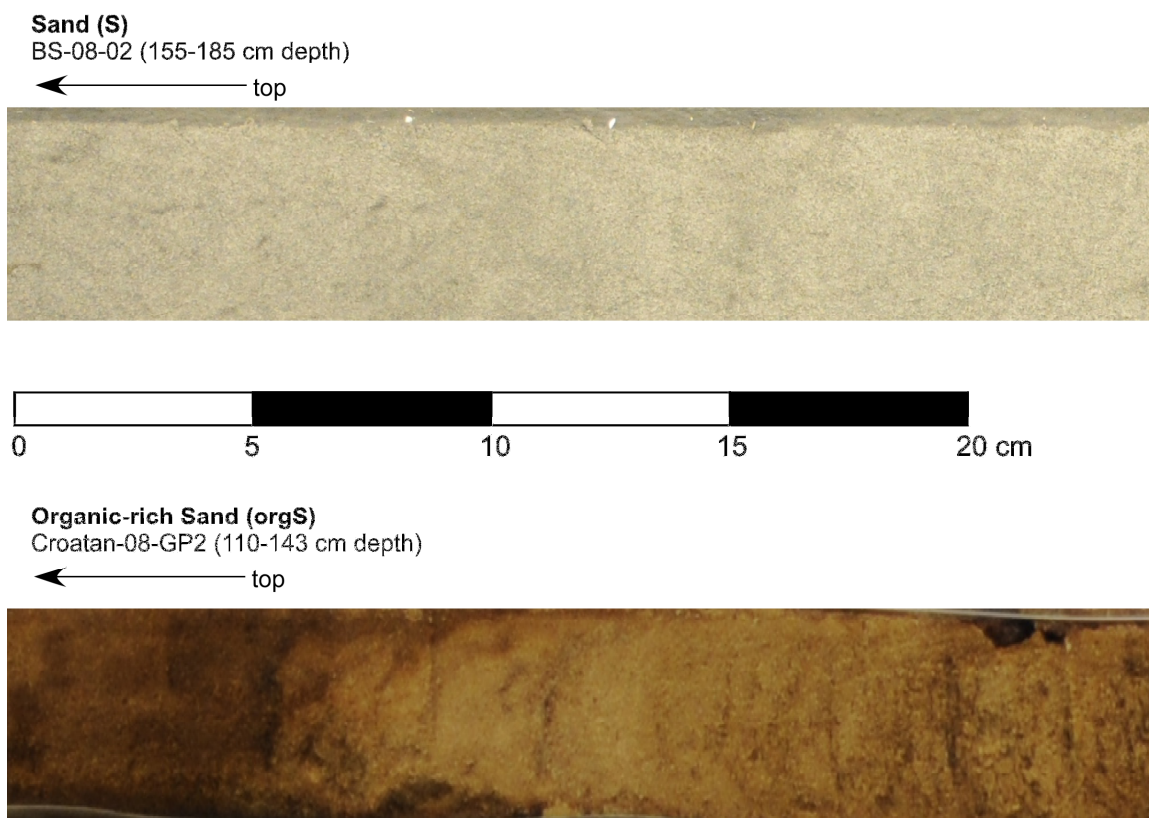


Figure 21. Photographs of BS-08-02 and Croatan-08-GP2 illustrating the sand and organic-rich sand lithofacies, respectively.

Organic-rich Sand (orgS)

The organic-rich sand lithofacies is very dark brown (7.5YR 2.5/2), moderately to well-sorted, subrounded to rounded fine-grained sand with organic mud (Figure 21). This lithofacies is commonly bioturbated and contains roots, wood chips, and plant debris. The organic material present in this lithofacies is either organic particulates or organic mud. It is composed of sand (80-95%), organic matter (20-60%), heavies (<1-5%) and mud (5-20%). This lithofacies is distinguished from the sand (S) lithofacies by the greater percentage of organic material. It is generally found no more than 2 m deep on the Croatan Beach Ridge Complex.

Muddy Sand (mS)

The muddy sand lithofacies is yellowish brown (10YR 5/4) to dark gray (2.5Y 4/1), moderately well-sorted, subrounded to subangular fine sand with mud (Figure 22). This lithofacies is composed of sand-sized particles (70-85%), mud (15-30%), heavies (<1-3%), and organic material (1-3%). Organic concretions, approximately 1 cm in diameter, occur (rarely) in this lithofacies. This lithofacies is generally located near the sandy mud (sM) lithofacies.

Shelly, Muddy Sand (shmS)

The shelly, muddy sand lithofacies is gray (10YR 5/1) to very dark gray (2.5Y 4/1), poorly to well-sorted, subrounded to subangular fine-grained sand with mud and marine shells (Figure 22). This lithofacies is composed of sand-sized particles (70-85%), mud (15-30%), heavies (<1-3%), and shell fragments (1-30%), and is usually found

Muddy Sand (mS)
BS-08-03 (117-138 cm depth)

← top



Shelly, Muddy Sand (shmS)
BS-08-03 (158-175 cm depth)

← top



Figure 22. Photographs of BS-08-03 illustrating the muddy sand and shelly, muddy sand lithofacies, respectively.

interbedded with shelly, sandy mud (shsM). Shell fragments vary in size from very coarse to cobble size. Mud-filled burrows are common in this lithofacies.

Shelly Sand (shS)

The shelly sand lithofacies is gray (10YR 5/1), moderately to well-sorted, subrounded to subangular, fine to medium-grained sand with marine shells (Figure 23). The lithofacies is composed of sand-sized particles (90-98%), whole shells, and shell fragments (5-15%). It is generally massively bedded, and contains rare mud-filled burrows. Heavies constitute <1-5%.

Gravelly Sand (gS)

The gravelly sand lithofacies is a gray (GLEY 1 5/5G), poorly sorted, subrounded to subangular, fine to very coarse quartz sand (Figure 23). This lithofacies is composed of gravel (10-45%) and sand-sized particles (60-80%), occasionally containing organics (<1-3%) and heavies (<1-3%). Marine shell material does not occur with this lithofacies.

Mud (M)

The mud lithofacies is composed of dark gray (2.5Y 4/1) clay and silt-size particles (95-100%) (Figure 24). Very minor amounts of fine sand (<1%) occur in some of the deposits, but this lithofacies is generally massively-bedded mud.

Sandy Mud (sM)

The sandy mud lithofacies is light gray (10YR 7/2) to dark gray (2.5Y 4/1) clay and silt-size particles with moderately well-sorted, subrounded to subangular fine quartz sand (Figure 24). This lithofacies is composed of mud (80-95%) and sand-size particles (5-20%), with small amounts of organics (<1-3%). Organics are not common, but when

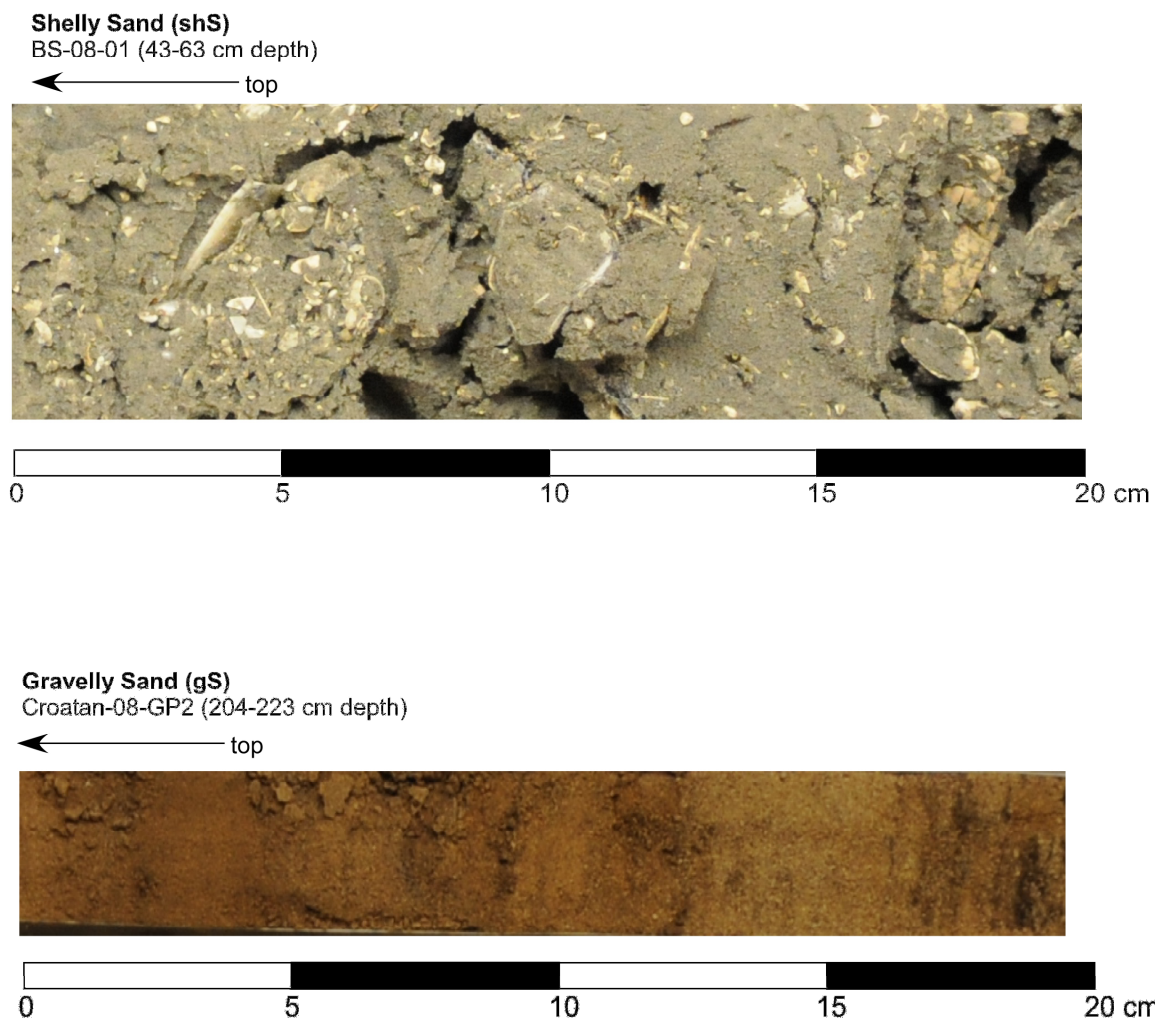
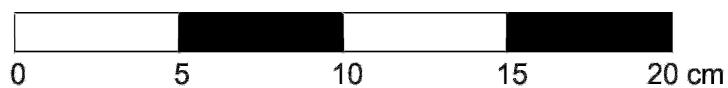
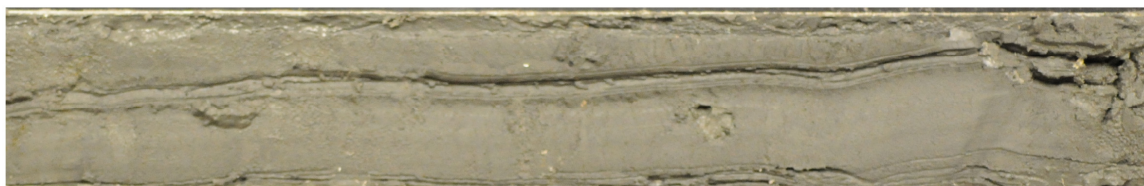


Figure 23. Photographs of BS-08-01 and Croatan-08-GP2 illustrating the shelly sand and gravelly sand lithofacies, respectively.

Mud (M)

BS-08-03 (461-496 cm depth)

← top

**Sandy Mud (sM)**

BS-08-03 (71-106 cm depth)

← top



Figure 24. Photographs of BS-08-03 illustrating the mud and sandy mud lithofacies, respectively.

present they are generally found in thin organic laminations. Sand-filled burrows are also present but occur infrequently.

Shelly Mud (shM)

The shelly mud lithofacies is composed of dark gray (2.5Y 4/1) clay and silt-size particles with whole *Mercenaria mercenaria*, *Crassostrea virginica*, various other marine shells and shell fragments (Figure 25). This lithofacies is composed of clay and silt-size particles (95-99%), a small amount of sand-size particles (1-3%), and shell material (5-25%). Shell material is dispersed throughout the lithofacies rather than found in horizons. The shelly mud lithofacies is very similar to the mud lithofacies except with the inclusion of shell material.

Shelly, Sandy Mud (shsM)

The shelly, sandy mud lithofacies is light gray (10YR 7/2) to dark gray (2.5Y 4/1) clay and silt-size particles with moderately to well-sorted, subangular to subrounded, medium to fine quartz sand with marine shells (Figure 25). This lithofacies is dominated by mud (70-85%), with small amounts of sand-sized particles (15-30%), and whole shells (*Mercenaria mercenaria*, *Crassostrea virginica*) and shell fragments (1-30%). The shell material in this lithofacies is generally broken, disarticulated bivalves and gastropods, occasionally found in layered horizons. This lithofacies is very similar to the sandy mud lithofacies except with the inclusion of shell material.

Interbedded Mud and Sand (I)

The interbedded mud and sand lithofacies is light gray (10YR 6/1) to dark gray (2.5Y 4/1) and composed of interlayered mud and sand units (Figure 26). The mud

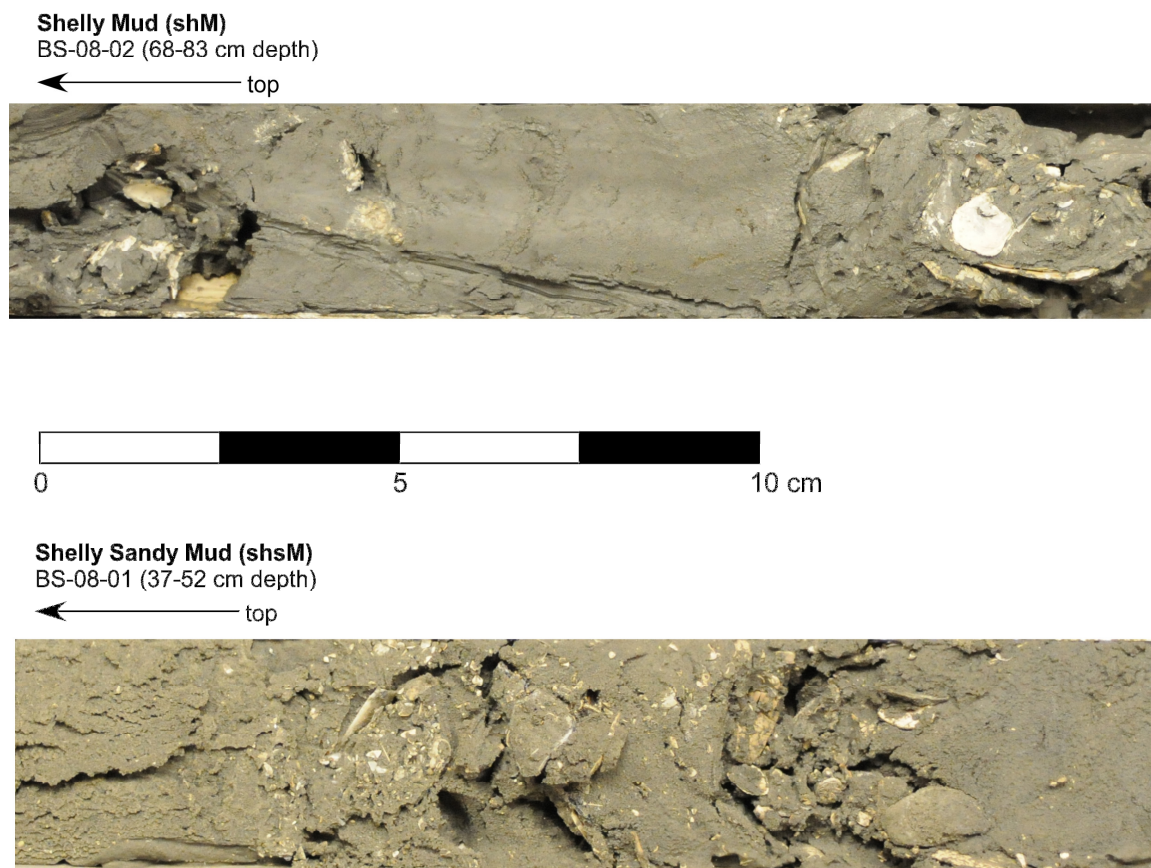
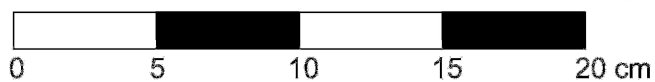


Figure 25. Photographs of BS-08-02 and BS-08-01 illustrating the shelly mud and shelly sandy mud lithofacies, respectively.

Interbedded Mud and Sand (I)

BS-08-01 (342-383 cm depth)

← top

**Interbedded Mud and Sand with Shells (shl)**

BS-08-05 (26-61 cm depth)

← top

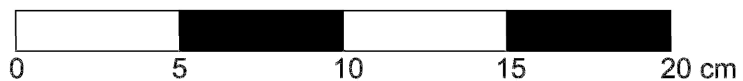


Figure 26. Photographs of BS-08-01 and BS-08-05 illustrating the interbedded mud and sand and interbedded mud and sand with shells lithofacies, respectively.

interlayers are primarily clay and silt-size particles. The sand interlayers are composed of moderately well-sorted, moderately well-rounded fine quartz sand. Overall, the lithofacies is composed of mud (40-60%) and sand-size particles (40-60%) with minor amounts of organics (<1-3%). The interbedded layers vary in thickness from 10-40 cm.

Interbedded Mud and Sand with Shells (shI)

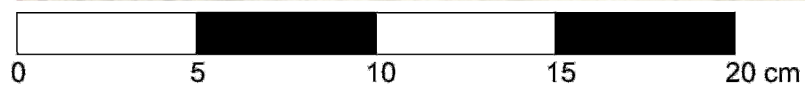
The interbedded mud and sand lithofacies with shells lithofacies is light gray (10 YR 6/1) to (GLEY 3/5GY) dark greenish gray and composed of interlayered mud and sand units with marine shell material (Figure 26). The mud interlayers are primarily clay and silt-size particles. The sand interlayers are composed of moderately well-sorted, moderately well-rounded fine quartz sand. Overall, the lithofacies is composed of mud (40-60%) and sand-size particles (40-60%) with whole shells and shell fragments (5-50%). Each interbedded unit ranges in thickness from 5-50 cm.

Large Shell (Sh)

The large shell lithofacies is light yellowish brown (2.5Y 6/3) to dark gray (2.5Y 4/1) and dominated by large marine shell beds with minor amounts of moderately well-sorted to poorly-sorted, fine to coarse sand and mud (Figure 27). This lithofacies contains gravel (1-5%), sand-sized (60-80%), mud (<1-35%), and large shell material (50-95%). Shells include *Mercenaria mercenaria* (hard clam), *Mulinia* sp., *Ensis directus* (razor clam), and *Crassostrea* sp. (oyster). *Crassostrea* sp. in this unit can be articulated as well as broken and disarticulated. The shells in this lithofacies reach 12cm in width.

Large Shell (Sh)
BS-08-06 (203-226 cm depth)

← top



Large Shell (Sh)
BS-08-04 (22-44 cm depth)

← top

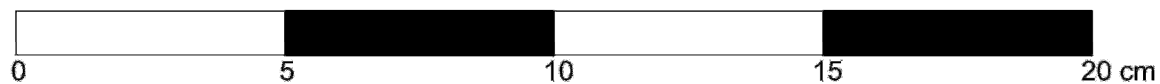
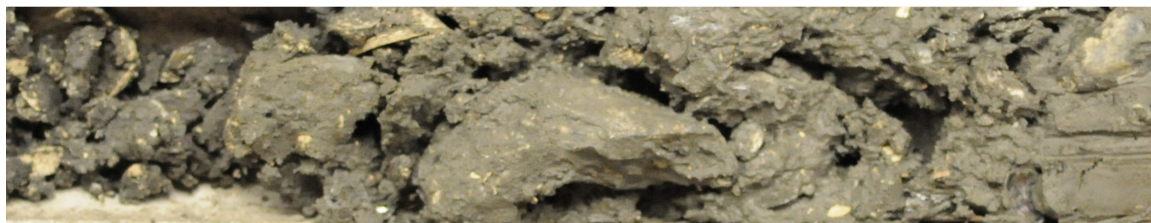


Figure 27. Photographs of BS-08-06 and BS-08-04 illustrating the large shells lithofacies.

Biofacies Descriptions

Seventy-eight foraminifera samples were obtained from eleven Geoprobe and six vibracores on the mainland, in Bogue Sound, and on Bogue Banks. Fifty-nine samples contained foraminifera and nineteen were barren. Eighty-seven taxa were identified to the generic level, and sixty-five were identified to the species level.

Foraminiferal taxa were reduced for cluster analysis; any taxon which did not comprise $\geq 2\%$ of any assemblage was eliminated from the analysis (Appendix G). The relative abundances were transformed for input into Systat using the following equation:

$$2\arcsin\sqrt{p}$$

where p = abundance.

The cluster analysis identified six distinct groups from the fifty-nine samples and thirty-two taxa input into Systat (Ward's linkage, Euclidean distances) (Figure 28). Occurrence (O), constancy (C), and biofacies fidelity (BF) were calculated for each biofacies using the thirty-two taxa representing $\geq 2\%$ of the assemblage in any one sample (Table 4). In this study, taxa with both a constancy and biofacies fidelity value ≥ 3 were deemed characteristic. Any taxa which is present in a biofacies but is not characteristic is named subsidiary (Table 5). Average relative abundances of each taxon in a biofacies is also given in Table 6.

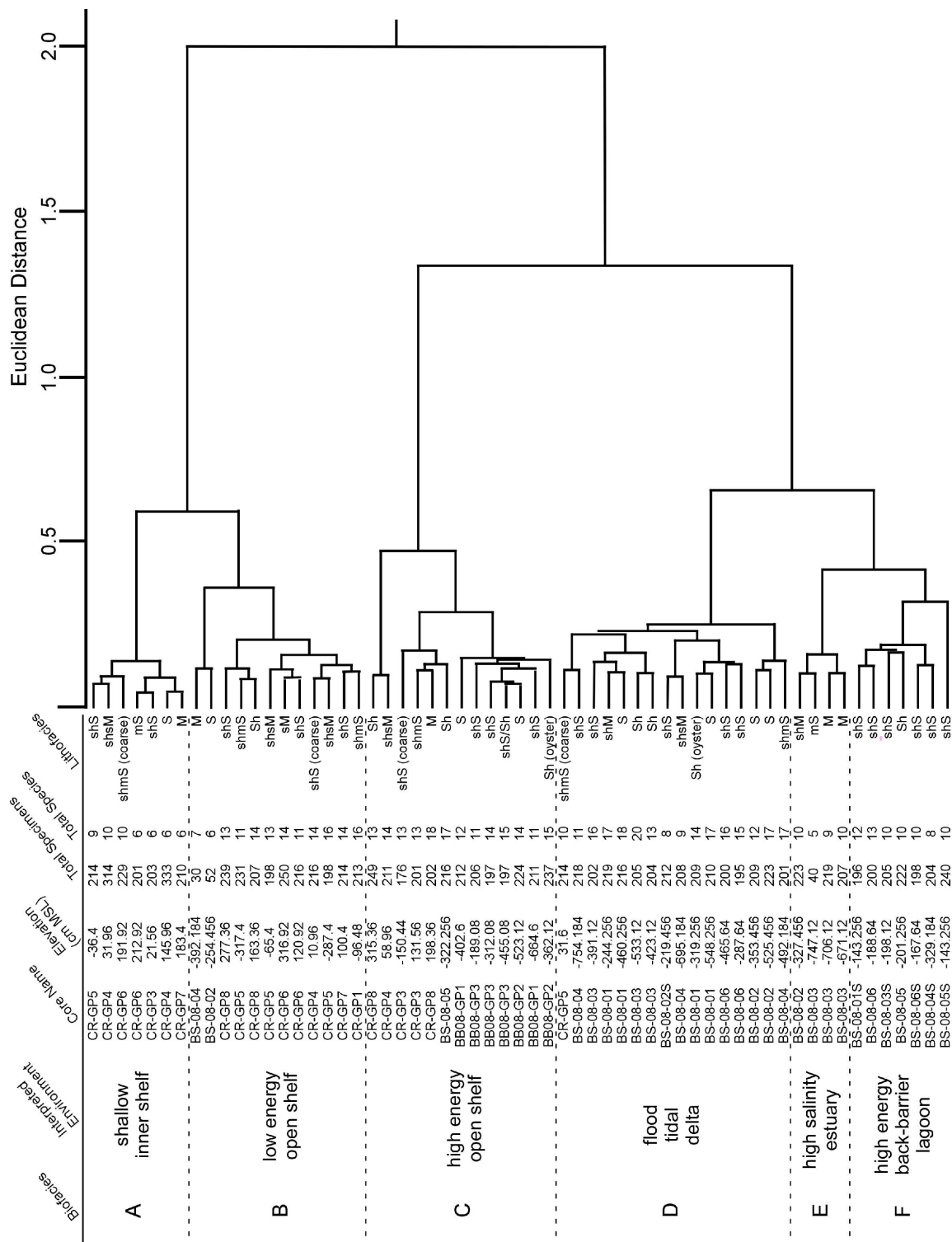


Figure 28. Dendrogram resulting from cluster analysis (Ward's Linkage, Euclidean distances) of foraminiferal data, indicating biofacies, assemblage data, and resulting interpreted paleoenvironments.

Table 4. Occurrence (O), Constancy (C), and Biofacies Fidelity (BF) values of foraminiferal biofacies as defined by cluster analysis. C and BF values boxed where both are ≥ 3 for a taxon.

Species List	A			B			C			D			E			F		
	O	C	BF	O	C	BF	O	C	BF	O	C	BF	O	C	BF	O	C	BF
<i>Ammonia</i> cf. <i>A. beccarii</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	3	10
<i>Ammonia parkinsoniana</i>	7	10	2	11	10	1	13	10	1	16	10	2	4	10	2	8	10	2
<i>Ammonia tepida</i>	1	1	2	0	0	0	0	0	0	5	3	3	2	5	5	0	0	0
<i>Ammotium salsum</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	5	10
<i>Bolivina lowmani</i>	5	7	3	7	6	3	3	2	1	3	2	1	1	3	1	1	1	1
<i>Bolivina paula</i>	1	1	1	6	5	4	2	2	1	4	3	2	0	0	0	3	4	2
<i>Buccella inusitata</i>	1	1	1	5	5	1	10	8	3	12	8	3	1	3	1	2	3	1
<i>Buliminella elegantissima</i>	5	7	3	5	5	2	0	0	0	6	4	1	2	5	2	3	4	2
<i>Cibicides lobatulus</i>	0	0	0	2	2	1	11	8	3	14	9	3	1	3	1	3	4	2
<i>Cibicides</i> sp.	0	0	0	0	0	0	2	2	7	1	1	3	0	0	0	0	0	0
<i>Elphidium excavatum</i>	7	10	2	11	10	2	13	10	2	16	10	2	4	10	1	8	10	1
<i>Elphidium galvestonense</i>	0	0	0	2	2	1	9	7	3	6	4	1	1	3	1	8	10	4
<i>Elphidium gunteri</i>	2	3	1	3	3	1	6	5	1	13	8	2	4	10	2	8	10	3
<i>Elphidium mexicanum</i>	4	6	1	10	9	1	12	9	2	16	10	2	4	10	2	8	10	2
<i>Elphidium poeyanum</i>	0	0	0	0	0	0	2	2	1	2	1	1	2	5	5	3	4	3
<i>Elphidium translucens</i>	5	7	1	8	7	2	11	8	2	12	8	2	3	8	2	4	5	1
<i>Eponides repandus</i>	0	0	0	7	6	4	11	8	5	4	3	1	0	0	0	0	0	0
<i>Gavelinopsis praegeri</i>	5	7	2	9	8	3	3	2	1	10	6	2	1	3	1	2	3	1
<i>Hanzawaia strattoni</i>	2	3	1	8	7	2	13	10	3	12	8	2	2	5	1	2	3	1
<i>Haynesina germanica</i>	0	0	0	3	3	1	3	2	1	10	6	3	4	10	4	3	4	1
<i>Nonionella atlantica</i>	1	1	0	7	6	2	11	8	3	13	8	3	1	3	1	2	3	1
<i>Quinqueloculina bosciana</i>	2	3	3	1	1	1	2	2	1	0	0	0	0	0	0	4	5	5
<i>Quinqueloculina jugosa</i>	0	0	0	1	1	1	10	8	5	5	3	2	1	3	1	2	3	1
<i>Quinqueloculina lamarckiana</i>	0	0	0	2	2	1	12	9	7	3	2	2	0	0	0	0	0	0
<i>Quinqueloculina seminula</i>	1	1	1	9	8	3	13	10	4	6	4	1	0	0	0	2	3	1
<i>Rosalina floridana</i>	2	3	2	9	8	4	2	2	1	10	6	3	0	0	0	0	0	0
<i>Textularia</i> cf. <i>T. gramen</i>	0	0	0	1	1	1	6	5	5	6	4	4	0	0	0	0	0	0
<i>Trifarina angulosa</i>	1	1	1	3	3	2	1	1	1	11	7	6	0	0	0	0	0	0
<i>Trochammina inflata</i>	0	0	0	1	1	10	0	0	0	0	0	0	0	0	0	0	0	0
<i>Trochammina</i> sp.	0	0	0	2	2	3	0	0	0	0	0	0	2	5	7	0	0	0
Fossil <i>Cibicides</i>	0	0	0	0	0	0	0	0	0	7	4	8	0	0	0	1	1	2
Fossil benthics	1	1	2	0	0	0	0	0	0	5	3	4	1	3	4	0	0	0
No. Species	18			24			23			27			19			22		

Table 5. Characteristic and subsidiary species of each biofacies (as defined by Constancy and Biofacies Fidelity), including their interpreted paleoenvironment.

Biofacies	Characteristic Species	Subsidiary Species	Interpreted Environment
A	<i>Bolivina lowmani</i> , <i>Buliminella elegantissima</i> , <i>Quinqueloculina bosciana</i>	<i>Ammonia parkinsoniana</i> , <i>Elphidium excavatum</i> , <i>Ammonia tepida</i> , <i>Gavelinopsis praegri</i> , <i>Rosalina floridana</i> , Fossil Benthics, <i>Elphidium translucens</i> , <i>Elphidium mexicanum</i> , <i>Elphidium gunteri</i> , <i>Hanzawaia strattoni</i> , <i>Bolivina paula</i> , <i>Buccella inusitata</i> , <i>Quinqueloculina seminula</i> , <i>Trifarina angulosa</i> , <i>Nonionella atlantica</i>	shallow inner shelf
B	<i>Bolivina lowmani</i> , <i>Bolivina paula</i> , <i>Eponides repandus</i> , <i>Gavelinopsis praegeri</i> , <i>Quinqueloculina seminula</i> , <i>Rosalina floridana</i>	<i>Ammonia parkinsoniana</i> , <i>Buccella inusitata</i> , <i>Buliminella elegantissima</i> , <i>Cibicides lobatulus</i> , <i>Elphidium excavatum</i> , <i>Elphidium galvestonense</i> , <i>Elphidium gunteri</i> , <i>Elphidium mexicanum</i> , <i>Elphidium translucens</i> , <i>Hanzawaia strattoni</i> , <i>Haynesina germanica</i> , <i>Nonionella atlantica</i> , <i>Quinqueloculina bosciana</i> , <i>Quinqueloculina jugosa</i> , <i>Quinqueloculina lamarckiana</i> , <i>Textularia</i> cf. <i>T. gramen</i> , <i>Trifarina angulosa</i> , <i>Trochammina inflata</i> , <i>Trochammina</i> sp.	low energy open shelf
C	<i>Buccella inusitata</i> , <i>Cibicides lobatulus</i> , <i>Elphidium galvestonense</i> , <i>Eponides repandus</i> , <i>Hanzawaia strattoni</i> , <i>Nonionella atlantica</i> , <i>Quinqueloculina jugosa</i> , <i>Quinqueloculina lamarckiana</i> , <i>Quinqueloculina seminula</i> , <i>Textularia</i> cf. <i>T. gramen</i>	<i>Ammonia parkinsoniana</i> , <i>Bolivina lowmani</i> , <i>Bolivina paula</i> , <i>Cibicides</i> sp., <i>Elphidium excavatum</i> , <i>Elphidium gunteri</i> , <i>Elphidium mexicanum</i> , <i>Elphidium poeyanum</i> , <i>Elphidium translucens</i> , <i>Gavelinopsis praegeri</i> , <i>Haynesina germanica</i> , <i>Quinqueloculina bosciana</i> , <i>Rosalina floridana</i> , <i>Trifarina angulosa</i>	high energy open shelf
D	<i>Ammonia tepida</i> , <i>Buccella inusitata</i> , <i>Cibicides lobatulus</i> , <i>Haynesina germanica</i> , <i>Nonionella atlantica</i> , <i>Rosalina floridana</i> , <i>Textularia</i> cf. <i>T. gramen</i> , <i>Trifarina angulosa</i> , fossil <i>Cibicides</i>	<i>Ammonia parkinsoniana</i> , <i>Bolivina lowmani</i> , <i>Bolivina paula</i> , <i>Buliminella elegantissima</i> , <i>Cibicides</i> sp., <i>Elphidium excavatum</i> , <i>Elphidium galvestonense</i> , <i>Elphidium gunteri</i> , <i>Elphidium mexicanum</i> , <i>Elphidium poeyanum</i> , <i>Elphidium translucens</i> , <i>Eponides repandus</i> , <i>Gavelinopsis praegri</i> , <i>Hanzawaia strattoni</i> , <i>Quinqueloculina jugosa</i> , <i>Quinqueloculina lamarckiana</i> , <i>Quinqueloculina seminula</i> , fossil benthics	flood tidal delta
E	<i>Ammonia tepida</i> , <i>Elphidium poeyanum</i> , <i>Haynesina germanica</i> , <i>Trochammina</i> sp., fossil benthics	<i>Ammonia parkinsoniana</i> , <i>Bolivina lowmani</i> , <i>Buccella inusitata</i> , <i>Buliminella elegantissima</i> , <i>Cibicides lobatulus</i> , <i>Elphidium excavatum</i> , <i>Elphidium galvestonense</i> , <i>Elphidium gunteri</i> , <i>Elphidium mexicanum</i> , <i>Elphidium translucens</i> , <i>Gavelinopsis praegri</i> , <i>Hanzawaia strattoni</i> , <i>Nonionella atlantica</i> , <i>Quinqueloculina jugosa</i>	high salinity estuary
F	<i>Ammonia</i> cf. <i>A. beccarii</i> , <i>Ammotium salsum</i> , <i>Bolivina paula</i> , <i>Elphidium galvestonense</i> , <i>Elphidium gunteri</i> , <i>Elphidium poeyanum</i> , <i>Quinqueloculina bosciana</i>	<i>Ammonia parkinsoniana</i> , <i>Bolivina lowmani</i> , <i>Buccella inusitata</i> , <i>Buliminella elegantissima</i> , <i>Cibicides lobatulus</i> , <i>Elphidium excavatum</i> , <i>Elphidium mexicanum</i> , <i>Elphidium translucens</i> , <i>Gavelinopsis praegeri</i> , <i>Hanzawaia strattoni</i> , <i>Haynesina germanica</i> , <i>Nonionella atlantica</i> , <i>Quinqueloculina jugosa</i> , <i>Quinqueloculina seminula</i> , fossil <i>Cibicides</i>	high energy back-barrier lagoon

Table 6. Average relative abundance calculations of each taxon in each biofacies. The three most abundant taxa in each biofacies are shown in bold.

	Biofacies					
	A	B	C	D	E	F
<i>Ammonia</i> cf. <i>A. beccarii</i>	0.00	0.00	0.00	0.00	0.00	0.38
<i>Ammonia parkinsoniana</i>	1.89	6.30	10.89	20.87	36.18	23.45
<i>Ammonia tepida</i>	0.06	0.00	0.00	0.50	0.61	0.00
<i>Ammotium salsum</i>	0.00	0.00	0.00	0.00	0.00	4.94
<i>Bolivina lowmani</i>	0.66	1.08	0.19	0.24	0.25	0.06
<i>Bolivina paula</i>	0.12	0.87	0.11	0.18	0.00	0.17
<i>Buccella inusitata</i>	0.07	0.38	0.71	0.84	0.37	0.32
<i>Buliminella elegantissima</i>	0.41	0.34	0.00	0.63	0.35	0.62
<i>Cibicides lobatulus</i>	0.00	0.13	1.34	1.66	0.12	0.18
<i>Cibicides</i> sp.	0.00	0.00	0.33	0.09	0.00	0.00
<i>Elphidium excavatum</i>	93.93	76.61	54.71	54.40	39.15	41.26
<i>Elphidium galvestonense</i>	0.00	0.83	0.54	0.30	0.46	6.81
<i>Elphidium gunteri</i>	0.13	0.30	0.51	1.28	3.83	4.05
<i>Elphidium mexicanum</i>	0.73	1.99	1.46	7.51	7.96	13.88
<i>Elphidium poeyanum</i>	0.00	0.00	0.07	0.06	0.57	0.66
<i>Elphidium translucens</i>	0.42	1.11	1.13	1.78	1.35	0.75
<i>Eponides repandus</i>	0.00	0.42	2.50	0.28	0.00	0.00
<i>Gavelinopsis praegeri</i>	0.56	1.84	0.29	0.66	0.12	0.18
<i>Hanzawaia strattoni</i>	0.11	1.23	6.15	2.84	0.49	0.19
<i>Haynesina germanica</i>	0.00	0.21	0.11	0.44	6.95	1.05
<i>Nonionella atlantica</i>	0.07	0.71	1.54	1.26	0.12	0.13
<i>Quinqueloculina bosciana</i>	0.27	0.08	0.07	0.00	0.00	0.56
<i>Quinqueloculina jugosa</i>	0.00	0.04	1.45	0.32	0.12	0.12
<i>Quinqueloculina lamarckiana</i>	0.00	0.13	2.37	0.14	0.00	0.00
<i>Quinqueloculina seminula</i>	0.14	2.58	12.75	0.50	0.00	0.18
<i>Rosalina floridana</i>	0.29	1.54	0.11	1.07	0.00	0.00
<i>Textularia</i> cf. <i>T. gramen</i>	0.00	0.08	0.63	0.23	0.00	0.00
<i>Trifarina angulosa</i>	0.07	0.13	0.04	0.69	0.00	0.00
<i>Trochammina inflata</i>	0.00	0.30	0.00	0.00	0.00	0.00
<i>Trochammina</i> sp.	0.00	0.78	0.00	0.00	0.24	0.00
Fossil <i>Cibicides</i>	0.00	0.00	0.00	0.74	0.00	0.06
Fossil benthics	0.07	0.00	0.00	0.48	0.75	0.00

Biofacies A

Seven samples from the Croatan beach complex comprise Biofacies A. All samples (except one) are located above modern sea level (ranging from 2.12 m to 0.21 m above MSL). The only sample which is not above sea level is located 0.36 m below MSL (in Croatan-08-GP5). Biofacies A contains 18 species, and is dominated by *Elphidium excavatum* (93.9%); *Ammonia parkinsoniana* comprises 1.9% (Table 6). Characteristic species of Biofacies A include *Bolivina lowmani*, *Buliminella elegantissima*, and *Quinqueloculina bosciana* (Tables 4, 5). Subsidiary species include *Ammonia parkinsoniana*, *Elphidium excavatum*, *Ammonia tepida*, *Gavelinopsis praegeri*, *Rosalina floridana*, Fossil Benthics, *Elphidium translucens*, *Elphidium mexicanum*, *Elphidium gunteri*, *Hanzawaia strattoni*, *Bolivina paula*, *Buccella inusitata*, *Quinqueloculina seminula*, *Trifarina angulosa*, and *Nonionella atlantica* (Tables 4, 5). This biofacies contains the fewest number of species (18) and is found in primarily shelly sand/mud units.

Biofacies B

Twelve samples comprise Biofacies B. Ten of the twelve samples are from the Croatan beach complex; the remaining two were taken between -2.5 meters and -4.0 meters elevation in Bogue Sound. The samples originating from the Croatan beach complex come from six cores and vary greatly in elevation, from 3.16 meters above to 3.92 m below MSL. Biofacies B contains 24 species, and is dominated by *Elphidium excavatum* (76.6%) and *Ammonia parkinsoniana* (6.3%) (Table 6). Characteristic species include *Bolivina lowmani*, *Bolivina paula*, *Eponides repandus*, *Gavelinopsis praegeri*,

Quinqueloculina seminula, and *Rosalina floridana* (Tables 4, 5). Subsidiary species include *Ammonia parkinsoniana*, *Buccella inusitata*, *Buliminella elegantissima*, *Cibicides lobatulus*, *Elphidium excavatum*, *Elphidium galvestonense*, *Elphidium gunteri*, *Elphidium mexicanum*, *Elphidium translucens*, *Hanzawaia strattoni*, *Haynesina germanica*, *Nonionella atlantica*, *Quinqueloculina bosciana*, *Quinqueloculina jugosa*, *Quinqueloculina lamarckiana*, *Textularia* cf. *T. gramen*, *Trifarina angulosa*, *Trochammina inflata*, and *Trochammina* sp. (Tables 4, 5). This biofacies contains all but four of the modern species included in the cluster analysis. Samples from this biofacies are usually found in the shelly sandy mud and shelly muddy sand lithofacies, with single samples appearing in the mud, sand, shelly sand, large shell, and sandy mud lithofacies.

Biofacies C

Thirteen samples comprise Biofacies C. Seven of these samples are from Bogue Banks (1.89 to 6.64 m below MSL), five samples are from the Croatan beach complex (3.15 m above to 1.5 m below MSL), and one sample from Bogue Sound (3.22 m below MSL). Biofacies C contains 23 species and is dominated by *Elphidium excavatum* (54.7%), *Ammonia parkinsoniana* (10.9%), *Quinqueloculina seminula* (12.8%), and *Hanzawaia strattoni* (6.2%) (Table 6). Characteristic species include *Buccella inusitata*, *Cibicides lobatulus*, *Elphidium galvestonense*, *Eponides repandus*, *Hanzawaia strattoni*, *Nonionella atlantica*, *Quinqueloculina jugosa*, *Quinqueloculina lamarckiana*, *Quinqueloculina seminula*, *Textularia* cf. *T. gramen* (Tables 4, 5). Subsidiary species include *Ammonia parkinsoniana*, *Bolivina lowmani*, *Bolivina paula*, *Cibicides* sp., *Elphidium excavatum*, *Elphidium gunteri*, *Elphidium mexicanum*,

Elphidium poeyanum, *Elphidium translucens*, *Gavelinopsis praegeri*, *Haynesina germanica*, *Quinqueloculina bosciana*, *Rosalina floridana*, and *Trifarina angulosa* (Tables 4, 5).

Biofacies D

Sixteen samples almost exclusively from Bogue Sound comprise Biofacies D. Fourteen samples were collected from cores in Bogue Sound (2.44 to 7.54 m below MSL); the remaining two samples come from the sediment surface of Bogue Sound (< 10 cm depth; 2.19 m below MSL) and the Croatan beach complex (0.32 m above MSL), respectively. Biofacies D contains 27 species. This biofacies contains more specimens and species than any other biofacies, and is dominated by *Elphidium excavatum* (54.4%), *Ammonia parkinsoniana* (20.9%), *Elphidium mexicanum* (7.5%), and *Hanzawaia strattoni* (2.8%) (Table 6). Characteristic species include *Ammonia tepida*, *Buccella inusitata*, *Cibicides lobatulus*, *Haynesina germanica*, *Nonionella atlantica*, *Rosalina floridana*, *Textularia* cf. *T. gramen*, *Trifarina angulosa*, and fossil *Cibicides* (Tables 4, 5). Subsidiary species include *Ammonia parkinsoniana*, *Bolivina lowmani*, *Bolivina paula*, *Buliminella elegantissima*, *Cibicides* sp., *Elphidium excavatum*, *Elphidium galvestonense*, *Elphidium gunteri*, *Elphidium mexicanum*, *Elphidium poeyanum*, *Elphidium translucens*, *Eponides repandus*, *Gavelinopsis praegri*, *Hanzawaia strattoni*, *Quinqueloculina jugosa*, *Quinqueloculina lamarckiana*, *Quinqueloculina seminula*, and fossil benthics (Tables 4, 5). More planktonics and fossil foraminifera occur in more samples in this biofacies than in any other biofacies.

Biofacies E

Four samples from Bogue Sound comprise Biofacies E. These four samples were collected downcore in two vibracores, and range in elevation from 3.27 to 7.47 m below MSL. Biofacies E contains 19 species and is dominated by *Elphidium excavatum* (39.1%), *Ammonia parkinsoniana* (36.2%), *Elphidium mexicanum* (8.0%), and *Haynesina germanica* (7.0%) (Table 6). Characteristic species include *Ammonia tepida*, *Elphidium poeyanum*, *Haynesina germanica*, *Trochammina* sp., and fossil benthics (Tables 4, 5). Subsidiary species include *Ammonia parkinsoniana*, *Bolivina lowmani*, *Buccella inusitata*, *Buliminella elegantissima*, *Cibicides lobatulus*, *Elphidium excavatum*, *Elphidium galvestonense*, *Elphidium gunteri*, *Elphidium mexicanum*, *Elphidium translucens*, *Gavelinopsis praegri*, *Hanzawaia strattoni*, *Nonionella atlantica*, and *Quinqueloculina jugosa* (Tables 4, 5). This biofacies contains the least amount of species and specimens than any other biofacies.

Biofacies F

Seven samples from Bogue Sound comprise Biofacies F. Five of these are sediment surface samples (<10 cm depth in core). The two samples that are not surface samples occur at approximately 2 m below MSL – the approximate average elevation of each surface sample in this biofacies. Biofacies F contains 22 species and is dominated by *Elphidium excavatum* (41.3%), *Ammonia parkinsoniana* (23.4%), and *Elphidium mexicanum* (13.9%) (Table 6). Characteristic species include *Ammonia* cf. *A. beccarii*, *Ammotium salsum*, *Bolivina paula*, *Elphidium galvestonense*, *Elphidium gunteri*,

Elphidium poeyanum, and *Quinqueloculina bosciana* (Tables 4, 5). Subsidiary species include *Ammonia parkinsoniana*, *Bolivina lowmani*, *Buccella inusitata*, *Buliminella elegantissima*, *Cibicides lobatulus*, *Elphidium excavatum*, *Elphidium mexicanum*, *Elphidium translucens*, *Gavelinopsis praegeri*, *Hanzawaia strattoni*, *Haynesina germanica*, *Nonionella atlantica*, *Quinqueloculina jugosa*, *Quinqueloculina seminula*, and fossil *Cibicides* (Tables 4, 5).

Depositional Facies Descriptions

Lithologic and biofacies data were analyzed and correlated to interpret depositional facies in the Croatan Beach Ridge Complex, Bogue Sound, and Bogue Banks study areas. Seven depositional facies were identified based on comparisons with others studies of the modern marginal marine environments of North Carolina, and are described below.

Depositional Facies I: Shallow Inner Shelf

Depositional Facies I, interpreted to have been deposited in an inner shelf environment, is recognized in samples from the central and eastern-most cores in the Croatan Beach Ridge Complex. Samples range in elevation from 2.13 m above MSL to 0.36 m below MSL and occur in the shelly sand (shS), shelly sandy mud (shsM), shelly muddy sand (shmS), muddy sand (mS), sand (S), and mud (M) lithofacies. This depositional facies is characterized by Biofacies A.

The dominance of *Elphidium excavatum* in this facies (93.9%) as well as the presence of *Ammonia parkinsoniana* (1.9%) compares with shoreface and shallow-water assemblages documented by Workman (1981). While eighteen species are present in this biofacies, *Elphidium excavatum* and *Ammonia parkinsoniana* make up > 95% of the relative abundance in this biofacies (Table 6). This suggests that the more delicate tests of inner shelf species may have been destroyed post-mortem (Murray and Alve, 1999; Smith, 2004; Ricardo, 2005; Culver et al., 2006). The more robust tests (e.g., *Elphidium gunteri*, *Quinqueloculina seminula*) are able to preferentially survive destruction.

Buliminella elegantissima and *Quinqueloculina bosciana* are found in many normal salinity coastal environments (including south of Cape Hatteras) usually at a depth of less than 200 meters (Culver and Buzas, 1980), as are most of the subsidiary species.

Depositional Facies II: Low Energy Normal Marine Salinity

Depositional Facies II is primarily found in the Croatan Beach Ridge Complex, with only two samples located in Bogue Sound. Samples range from 3.17 m above MSL to 3.92 m below MSL and primarily occur in shelly muddy sand (shmS) and shelly sandy mud (shsM) lithofacies, with only a few samples in the mud (M), sand (S), shelly sand (shS), large shell (Sh), and sandy mud (sM) lithofacies. This depositional facies is characterized by Biofacies B.

Depositional Facies II is interpreted to have been deposited in a low energy normal marine salinity environment. Most samples in this depositional facies contain mud, suggesting relative quiescence. The foraminiferal assemblages of Depositional Facies I and II are very similar. Depositional Facies II, however, contains more species than Depositional Facies I and generally a higher percentage of each species is also present in Depositional Facies I (with the exception of *Elphidium excavatum*). The highest relative abundance of *Bolivina lowmani* occurs in this biofacies and this taxon, along with *Trifarina angulosa*, represent typical muddy substrate Atlantic continental mid-shelf species (Murray, 1969; Schnitker, 1971).

Depositional Facies III: High Energy Normal Marine Salinity

Depositional Facies III contains samples from Bogue Banks, the Croatan Beach Ridge Complex and one sample in Bogue Sound. Samples range from 3.15 m above

MSL to 1.50 m below MSL in the Croatan Beach Ridge Complex and one occurs at 3.22 m below MSL in Bogue Sound. Depositional Facies III contains all the foraminiferal samples from Bogue Banks, ranging from 1.89 to 6.65 m below MSL. Ten of the 13 samples were collected from a shelly unit (shelly sandy mud (shsM), shelly sand (shS), shelly muddy sand (shmS), and large shells (Sh) lithofacies); the remaining three samples were each found in either the sand (2) or mud (1) lithofacies. This depositional facies is characterized by Biofacies C.

Depositional Facies III is interpreted to be a high energy normal marine salinity environment. Most samples in this depositional facies were taken in coarse shell fragment deposits, suggesting a high energy environment. The presence of robust species (*Quinqueloculina lamarckiana*, *Quinqueloculina seminula*, *Elphidium galvestonense*) indicate an assemblage typical of the inner continental shelf of North Carolina (Murray, 1969; Schnitker, 1971; Workman, 1981).

Depositional Facies IV: Flood Tide Delta

Depositional Facies IV contains samples from underneath Bogue Sound, with the exception of one surface sample from Bogue Sound and one sample from the Croatan Beach Ridge Complex. In Bogue Sound, samples range from 2.44-7.54 m below MSL; the sample in the Croatan has an elevation of 0.32 m above MSL and the Bogue Sound surface sample was located on the sediment surface, 2.20 m below MSL. Twelve of the sixteen samples were located in a shelly lithofacies (shelly muddy sand [shmS], shelly sand [shS], shelly mud [shM], large shells [Sh], and shelly sandy mud [shsM]), with the remaining four samples located in the sand (S) lithofacies. Depositional Facies IV is

characterized by Biofacies D.

Depositional Facies IV is interpreted to represent a flood tidal delta environment. The samples in this biofacies are coarser grained than any of the other biofacies. These samples were taken downcore in Bogue Sound, an environment that can be somewhat protected from high energy depending on its location relative to an inlet. Distance from the inlet explains the three samples in the biofacies which contain mud. Coarse shell lag deposits, similar to those of this biofacies, are typical of an inlet/flood tide delta deposit (Moslow and Heron, 1978).

Robinson and McBride (2006) found a similar flood tide delta foraminiferal assemblage, dominated by *Elphidium excavatum*, at Old Currituck Inlet. This assemblage was distinguished from the estuarine assemblage by the occurrence of continental shelf species. The foraminifera of this depositional facies are also similar to flood tide delta assemblages described by Smith et al. (2009) at New Inlet. They found normal marine salinity foraminifera as well as saltmarsh agglutinated species in this flood tide delta deposit. While this depositional facies lacks agglutinated species, this could be the result of preferential preservation of the calcareous, non-agglutinated species or distance from saltmarsh environments.

The stratigraphy of Bogue Banks adjacent to these sample locations indicate a large section of inlet-fill occurring on the barrier island (Figure 10), which could have created these inlet/flood tide delta deposits in Bogue Sound. BS-08-01 is the closest vibracore to the inlet fill on Bogue Banks, and all four non-barren foraminifera samples from this core are found in this depositional facies. Additionally, vibracore BS-08-02, located

approximately 1 km north of BS-08-01 and the next closest to the inlet fill structure, yields half its samples (the deepest two [of four] – 3.53 and 5.25 m below MSL) in Depositional Facies IV. The Pine Knoll Shores area of Bogue Banks is interpreted as a flood-tide delta overtopped by a marsh (Steele, 1980), which also explains the coarse shell deposits in Bogue Sound. Three of four foraminifera samples in vibracore BS-08-04, just west of BS-08-01 and adjacent to the Pine Knoll Shores flood-tide delta, are contained within Depositional Facies IV. The relatively high percentage of *Ammonia parkinsoniana* (20.9%) within this facies compared to Depositional Facies I, II, and III (shallow inner shelf and open shelf environments, respectively) also suggests greater estuarine influence.

Depositional Facies V: High Salinity Estuary

Depositional Facies V contains four foraminiferal samples from Bogue Sound. The samples range in depth from 3.28 – 7.47 m below MSL. All of the samples were found in a muddy lithofacies (shelly mud [shM], muddy sand [mS], and mud [M]). This depositional facies is characterized by Biofacies E.

Depositional Facies V is interpreted to be a high salinity estuary, similar to the modern high salinity back-barrier lagoon (discussed below). The overwhelming presence of mud in these samples suggests the most quiescent environment found in any of the biofacies of this study. This depositional facies is similar to the High Salinity Estuary B Biofacies described by Pruitt (2008). Both Pruitt's Estuary B biofacies and this depositional facies contain similar percentages of *Ammonia parkinsoniana* (53% in Pruitt compared to 36.2%) and *Elphidium excavatum* (26% in Pruitt compared to 36.2%).

Pruitt's High Salinity Estuary B was also generally located on the eastern margin of Core Sound, adjacent to the barrier island, which is a similar setting to the location of the samples comprising Depositional Facies V of this study. The dominance of calcareous species in high salinity estuarine environments has been previously documented (Abbene et al., 2006; Pruitt, 2008).

Depositional Facies VI: High Energy Back Barrier Lagoon

Depositional Facies VI is recognized in surface sediment foraminiferal samples from Bogue Sound, and two downcore samples from BS-08-05 and BS-08-06. The surface samples range in depth from 1.43-3.30 m below MSL. The downcore sample from BS-08-05 was collected at 2.01 m below MSL and from BS-08-06 at 1.89 m below MSL. Every sample, with the exception of one, was characterized by the shelly sand (shS) lithofacies. The downcore BS-08-05 sample was located in the large shell (Sh) lithofacies. This depositional facies is characterized by Biofacies F.

Depositional Facies VI, dominated by *Elphidium excavatum* and *Ammonia parkinsoniana*, is interpreted to be a modern high energy, back-barrier lagoonal environment. The agglutinated *Ammotium salsum* (representing an average 4.9% in the assemblages) in the surface samples of this biofacies is also found (although with a greater percentage – 34%) in the Estuarine Low Salinity Biofacies of adjacent Core Sound as described by Pruitt (2008). *Ammotium salsum* is also found in the Low to Mid-Brackish Estuary of Grand Pre (2006), who distinguished this biofacies from her High Brackish Estuary Biofacies by the presence of agglutinated species (Grossman and Benson, 1967; Ellison and Nichols, 1970; Vance and others, 2006). Foley (2007)

described her Biofacies C, composed of 100% *Ammotium salsum*, as representing a low salinity estuary. Biofacies A of Metger (2009) contained a similar relative abundance of *Ammotium salsum* as this study and was interpreted as a low brackish estuary. Grand Pre (2006), Foley (2007), and Metger (2009) described foraminifera in Pamlico Sound, a system with far less oceanic influence than Bogue Sound. Depositional Facies VI is termed a back-barrier lagoon, not an estuary, because of its known location, its relatively small abundance of *Ammotium salsum* and its high salinity (≥ 35). This biofacies also contains numerous calcareous species indicative of an open shelf environment, suggesting much greater transport of ocean water into the lagoon.

Depositional Facies VII: Aeolian Sand

Depositional Facies VII occurs in the cores on the Croatan Beach Ridge Complex and on Bogue Banks. These samples are generally barren of foraminifera, and were not included in the cluster analysis. Most of these samples were found in the sand (S) and organic-rich sand (orgS) lithofacies, but they are also present in the interbedded mud and sand (I) and gravelly sand (gS) lithofacies. This depositional facies caps cores located in the Croatan Beach Ridge Complex and Bogue Banks. Hale's (2008) Litho/biofacies I is similar to this depositional facies, and was interpreted as a barrier island sand/overwash sand and back-barrier sand flats. However, the draping of this depositional facies over older coastal features in the Croatan Beach Ridge Complex suggest it represents an aeolian sand accumulation.

Chronostratigraphy

Chronostratigraphic data were collected from core sediments in the Croatan Beach Ridge Complex, Bogue Sound, and Bogue Banks. Eleven OSL samples were collected, five from the Croatan Beach Ridge Complex, four from Bogue Sound and two from Bogue Banks. Three AMS ^{14}C age estimates were obtained from shell material and foraminifera in cores from Bogue Sound.

OSL Age Estimates

Croatan Beach Ridge Complex

Five OSL samples were obtained from the northern (Croatan-08-GP3), central (Croatan-08-GP4), and southern (Croatan-08-GP1, Croatan-08-GP5) regions of the Croatan Beach Ridge Complex (Table 7, Figure 20). The northern-most sample obtained from Croatan-08-GP3 was collected from Unit 1 at an elevation of 3.95-4.06 m above MSL from a fine sand unit (sand [S] lithofacies) interpreted to be part of the aeolian sand depositional facies. This sample yielded an age estimate of 71.9-89.8 ka. The sample collected from Croatan-08-GP4 was taken from Unit 1 at an elevation of 7.14-7.19 m above MSL in a medium to medium-fine sand unit (sand [S] lithofacies) also interpreted to be part of the aeolian sand depositional facies. This sample yielded an age estimate of 86.0-104.5 ka. Croatan-08-GP1 and Croatan-08-GP5 were taken from Unit 2, a sand ridge that runs along the coastline to Morehead City and Harkers Island (Figure 2). Two OSL samples were taken from Croatan-08-GP1; the shallowest taken from 3.80-3.87 m

above MSL and the deepest from 1.30-1.38 m above MSL. The shallowest sample was collected from a fine sand unit (sand [S] lithofacies) interpreted to be part of the aeolian sand depositional facies. This sample yielded an age estimate of 16.7-19.9 ka. The deeper sample was collected from a fine sand unit (sand [S] lithofacies) and interpreted to be part of the low energy normal marine salinity depositional facies. This sample yielded a significantly older age estimate of 46.6-54.2 ka, suggesting it was deposited during a different stage of beach ridge development. The sample from Croatan-08-GP5 was taken at an elevation of 4.45-4.53 m above MSL in medium to medium-fine sand (sand [S] lithofacies) and interpreted to be part of the aeolian sand depositional facies and yielded an age estimate of 83.4 ± 8.92 ka.

Bogue Sound

Four OSL samples were obtained from eastern (BS-08-01), central (BS-08-03, BS-08-04), and western (BS-08-05) Bogue Sound (Table 7, Figure 20). The eastern-most sample, collected from BS-08-01 at a depth of 5.67-5.77 m below MSL, was taken from a fine sand unit (sand [S] lithofacies) interpreted to be part of the flood tide delta depositional facies. This sample yielded an age estimate of 2.24-2.74 ka.

One of the central Bogue Sound samples was taken from BS-08-03 at a depth of 7.96-8.06 m below MSL in an interbedded mud and sand unit (I) in the high salinity estuary depositional facies. This sample yielded an age estimate of 41.0 ± 3.78 ka. An adjacent sample was collected in a shelly sand unit of BS-08-04 at a depth of 7.61-7.71 m. However, this sample was collected in the flood tide delta depositional facies, and gave an age estimate of 5.18 ± 0.53 ka.

Table 7. OSL age estimates and equivalent dose data of samples from the Croatan Beach Ridge Complex, Bogue Banks, and Bogue Sound, NC.

Core	Sample Depth above MSL (m)	% Water content ^a	K (%) ^b	Th (ppm) ^b	U (ppm) ^b	Cosmic dose ^c additions (Gy/ka)	Total Dose Rate (Gy/ka)	Equivalent Dose (Gy)	n ^d	Age (ka) ^f	Depositional Facies
<i>CR-08-GP1a</i>	3.80-3.87	23 (34)	0.47 ± 0.05	0.91 ± 0.12	0.36 ± 0.07	0.14 ± 0.01	0.60 ± 0.04	11.0 ± 0.61	20 (25)	18.3 ± 1.60 ^e	AS
<i>CR-08-GP1b</i>	1.30-1.38	29 (36)	0.78 ± 0.03	1.66 ± 0.18	0.74 ± 0.08	0.10 ± 0.01	0.89 ± 0.05	44.9 ± 2.45	23 (25)	50.4 ± 3.80 ^e	LENMS
<i>CR-08-GP3</i>	3.95-4.06	5 (42)	0.52 ± 0.02	1.62 ± 0.13	0.85 ± 0.09	0.19 ± 0.01	0.77 ± 0.06	62.2 ± 4.91	20 (21)	80.8 ± 9.00	AS
<i>CR-08-GP4</i>	7.19-7.14	6 (40)	0.23 ± 0.01	1.66 ± 0.24	0.57 ± 0.11	0.17 ± 0.09	0.52 ± 0.05	49.5 ± 3.86	25 (25)	95.2 ± 9.25	AS
<i>CR-08-GP5</i>	4.45-4.53	15 (41)	0.33 ± 0.02	2.47 ± 0.32	1.06 ± 0.18	0.16 ± 0.01	0.70 ± 0.06	58.8 ± 5.23	24 (25)	83.4 ± 8.92	AS
below MSL (m)											
<i>BB08-GP1</i>	0.15-0.25	21 (31)	0.56 ± 0.02	4.90 ± 0.43	2.66 ± 0.26	0.19 ± 0.01	1.38 ± 0.07	2.37 ± 0.15	19 (20)	1.72 ± 0.14	AS
<i>BB08-GP2</i>	0.80-0.89	22 (31)	0.54 ± 0.02	1.01 ± 0.19	0.69 ± 0.11	0.18 ± 0.09	0.77 ± 0.08	1.04 ± 0.05	21 (22)	1.35 ± 0.15	AS
<i>BS-08-01</i>	5.67-5.77	23 (35)	0.71 ± 0.03	1.51 ± 0.25	1.02 ± 0.15	0.18 ± 0.09	0.96 ± 0.08	2.40 ± 0.14	26 (28)	2.49 ± 0.25	FTD
<i>BS-08-03</i>	7.96-8.06	24 (39)	0.61 ± 0.01	2.00 ± 0.19	1.67 ± 0.10	0.16 ± 0.01	0.99 ± 0.06	40.6 ± 2.31	19 (20)	41.0 ± 3.78	HSE
<i>BS-08-04</i>	7.61-7.71	20 (44)	0.69 ± 0.03	1.67 ± 0.24	0.88 ± 0.19	0.18 ± 0.01	0.88 ± 0.07	4.56 ± 0.26	28 (28)	5.18 ± 0.53	FTD
<i>BS-08-05</i>	3.30-3.40	22 (27)	0.40 ± 0.01	0.93 ± 0.20	0.72 ± 0.11	0.19 ± 0.01	0.69 ± 0.08	0.81 ± 0.06	17 (20)	1.18 ± 0.17	HENMS

^aField moisture, with figures in parentheses indicating the complete sample saturation %. Ages calculated using 90% of saturation values (below water table).

^bAnalyses obtained using laboratory Gamma Spectrometry (low resolution NaI detector).

^cCosmic doses and attenuation with depth were calculated using the methods of Prescott and Hutton (1994). See text for details.

^dNumber of replicated equivalent dose (De) estimates used to calculate the mean. Figures in parentheses indicate total number of measurements made including failed runs with unusable data.

^eDose rate and age for fine-grained 250-180 µm quartz sand. Linear + exponential fit used on age, errors to one sigma.

^fDose rate and age for fine-grained 150-90 µm quartz sand. Linear + exponential fit used on age (only linear for De <1 Gy), errors to one sigma.

The western-most sample was collected from BS-08-05 at a depth of 3.30-3.40 m below MSL. This sample was taken from medium-fine to fine sand and large shell units (sand [S] and large shell [Sh] lithofacies) and interpreted to be part of the high energy normal marine salinity depositional facies. The sample yielded an age estimate of 1.01-1.35 ka.

Bogue Banks

Two OSL samples were taken from cores on Bogue Banks (Table 7; Figure 20). One sample, from BB08-GP1, was obtained from a depth of 0.15-0.25 m below MSL in a fine sand unit (sand [S] lithofacies) interpreted to be part of the aeolian sand depositional facies. This sample yielded an age estimate of 1.58-1.86 ka. The second sample from Bogue Banks was collected from BB08-GP2 at a depth of 0.80-0.89 m below MSL in a medium-fine sand unit (sand [S] lithofacies) interpreted to be part of the aeolian sand depositional facies. This sample yielded a younger age estimate, 1.2-1.5 ka, from a deeper sample when compared to the other age estimate on Bogue Banks, discussed above. This is because BB08-GP1 is located on the eastern-side of a westward-prograding spit complex which comprises this eastern segment of Bogue Banks (Figure 29). BB08-GP2 lies to the west of BB08-GP1, and was, therefore, deposited more recently.

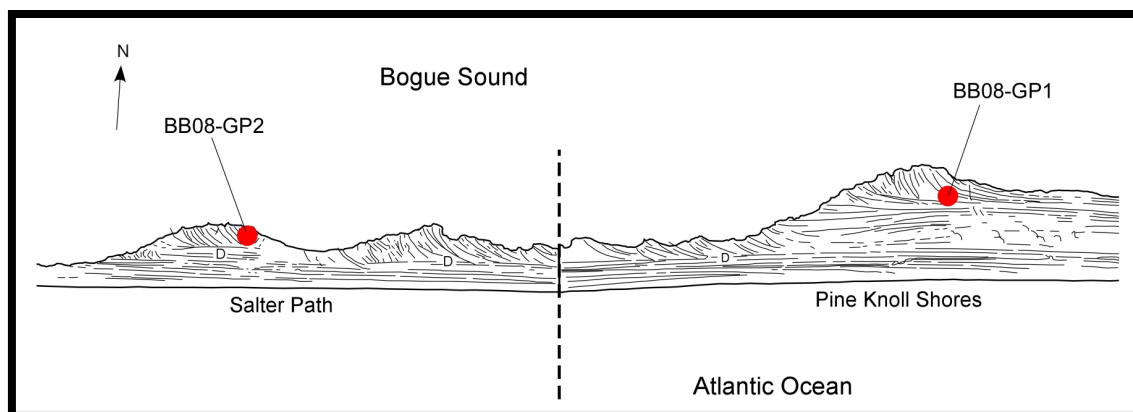


Figure 29. Depositional history of Bogue Banks showing the position of BB08-GP1 and BB08-GP2. BB08-GP1 is located on an older segment of the western- and seaward-moving spit complex that comprises the island. The aeolian sand depositional facies of BB08-GP1 yielded an age estimate of 1.58-1.86 ka; the age estimate for BB08-GP2, in the same depositional facies, is 1.2-1.5 ka. The division between Salter Path and Pine Knoll Shores is dashed.

AMS ^{14}C Age Estimates

Three radiocarbon dates were obtained from *in situ* carbonate within Bogue Sound (Table 8). An exquisitely-preserved, delicate, articulated *Cyrtopleura costata* (angel wing clam) was collected from BS-08-03, taken at a depth of 4.59 m below MSL, within the sandy mud lithofacies (sM). This sample was taken from the LENMS depositional facies and yielded an age estimate of 3.82-4.02 cal ka. An articulated oyster preserved *in situ* was collected from BS-08-02, taken at a depth of 3.24 m below MSL. This sample was taken from within the high salinity estuary depositional facies and yielded an age estimate of 3.32-3.46 cal ka. A third sample of 2,000 specimens of *Elphidium excavatum* was collected from BS-08-03. These foraminifera were taken from foraminifera sample #4, at a depth of 7.06-7.09 m below MSL. This sample is located within the flood tide delta depositional facies and yielded an age estimate of 5.92-6.18 cal ka.

Table 8. AMS ^{14}C age estimates of samples from Bogue Sound, NC. Depositional facies abbreviations: HSE = high salinity estuary; LENMS = low energy normal marine salinity; FTD = flood tide delta. Dates were calculated using MARINE04 database (Hughen et al., 2004) and calibrated with INTCAL04 radiocarbon age calibration (Reimer et al., 2004), with no local reservoir correction applied.

Core	Lab Sample #	Sample Depth (m below MSL)	Material	Conventional Radiocarbon Age	$\delta^{13}\text{C}$ Ratio	2 σ Calibration	Depositional Facies
BS-08-02	261208	3.24	oyster	3500 +/- 40 BP	0	3.32-3.46 ka	HSE
BS-08-03	261209	4.59	angel wing clam	3930 +/- 40 BP	1.9	3.82-4.02 ka	LENMS
BS-08-03	261210	7.06-7.09	foraminifera	5650 +/- 50 BP	-5.1	5.92-6.18 ka	FTD

Geophysical Data Interpretations

Ground Penetrating Radar

Line 1838:

Line 1838 was collected perpendicular to the beach ridge complex and approximately along Transect B (Figure 30). The shallowest horizontal reflection located at 0.5 m depth represents the water table in this area. Below the water table, the highest amplitude set of reflections is present at a depth of 1 to 2.5 m comprised of numerous short, steep seaward- and landward-dipping clinoforms present between scans 7000-12000. These clinoforms are present in sets (ie., four seaward-dipping clinoforms followed by four landward-dipping clinoforms), and represent a migrating dune complex. This is supported by the shape of the reflections and the sedimentology of nearby cores. Immediately below these clinoforms lies a set of horizontal to subhorizontal reflections from 3-3.5 m depth. These reflections are especially visible between scans 7000-12000, and absent further north. A deep, high-amplitude reflection dips southward from scan 1000, eventually flattening out at scan 5000, and is present throughout the majority of the line. This reflection runs from 3 m depth in the north to a maximum depth of approximately 7 m to the south and most probably represents the ravinement surface marking the base of the beach ridge complex.

Line 1839:

Line 1839 was collected perpendicular to the beach ridge complex and approximately along Transect B (Figure 31). The shallow horizontal to subhorizontal reflection located between 0.5 and 1 m depth represents the water table in this area. A set

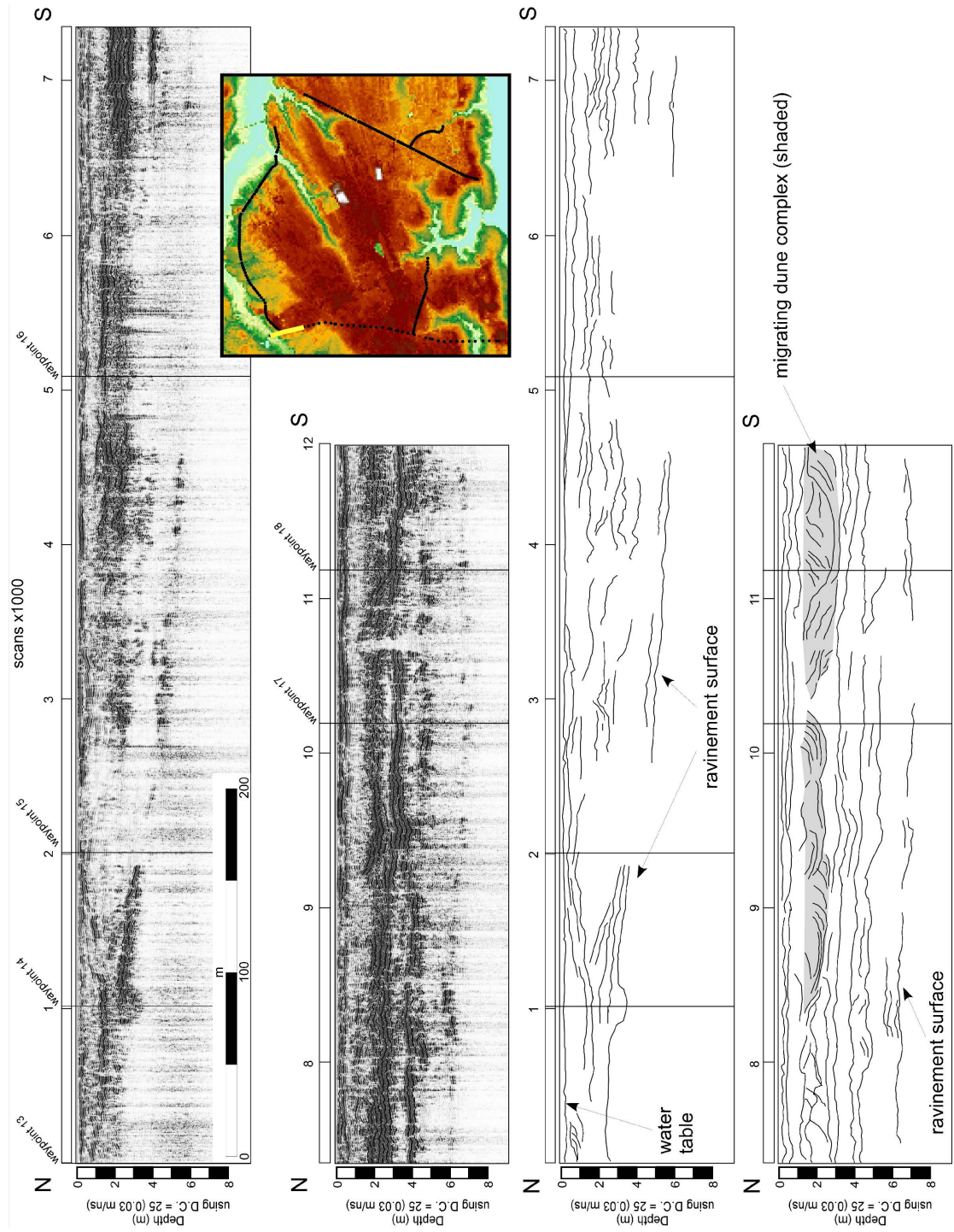


Figure 30. Filtered and interpreted GPR data from Line 1838. Inset: All GPR lines collected in the Croatan Beach Ridge Complex shown in black; location of Line 1838 in the study area is shown in yellow.

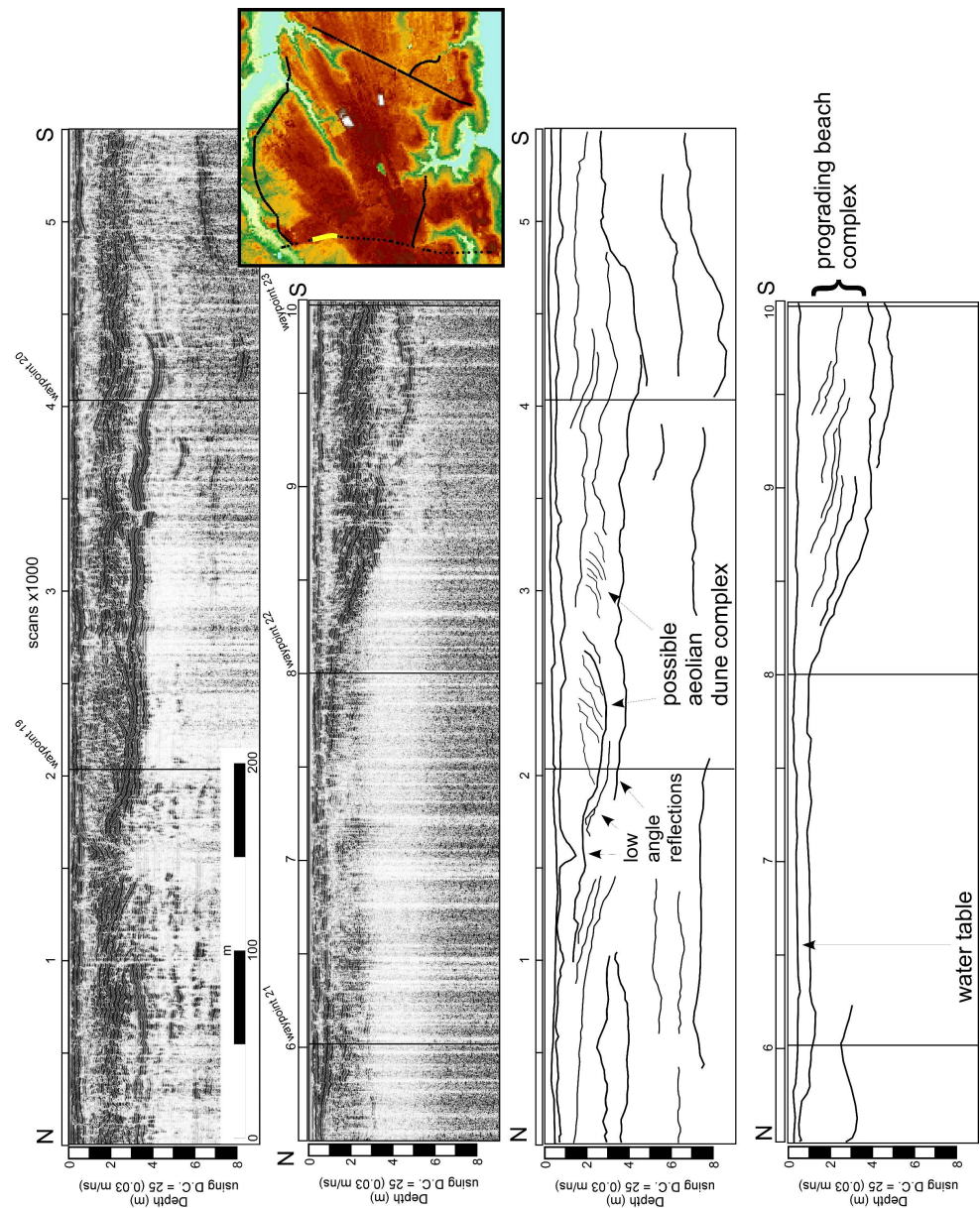


Figure 31. Filtered and interpreted GPR data from Line 1839. Inset: All GPR lines collected in the Croatan Beach Ridge Complex shown in black; location of Line 1838 in the study area is shown in yellow.

of low amplitude sinusoidal reflections are present throughout the majority of Line 1839, underlying a large, subsurface beach ridge feature ranging in depth from 1.5 m (crests) to 5 m (troughs). A set of south-dipping, moderately steep clinoforms lie to the south of the larger beach ridge feature (between scan 8,250 and 10,000). These clinoforms represent a prograding beach ridge complex. An additional set of high-angle reflections (located between scan 2,000 and 3,500) is present between 1.5 and 3 m. These clinoforms dip to the north and are located in a trough of the larger beach ridge feature. The high angle of these reflections could represent the slipface of a migrating aeolian dune.

Line 1840:

Line 1840 was collected perpendicular to the beach ridge complex and approximately along Transect B (Figure 32). Three high amplitude reflections are present in this line. The shallowest reflection represents the water table in the area, and is located at approximately 0.5 m depth. The highest amplitude reflection is located between 1 and 4 m depth. This reflection is composed of numerous south-dipping reflections. One of these reflections is especially high amplitude between scans 3375-10000, and most probably represents an erosional surface. The deepest high amplitude reflection is horizontal to subhorizontal and is located between 5 and 6.5 m depth. This reflection is also present in adjacent Line 1839 and Line 1838.

Sedimentological data taken from near this line do not readily suggest a transition from an aeolian to shoreface facies (Croatan-08-GP8, Croatan-08-GP3; Appendix C). However, this could be the result of incomplete sedimentological data, so the depositional

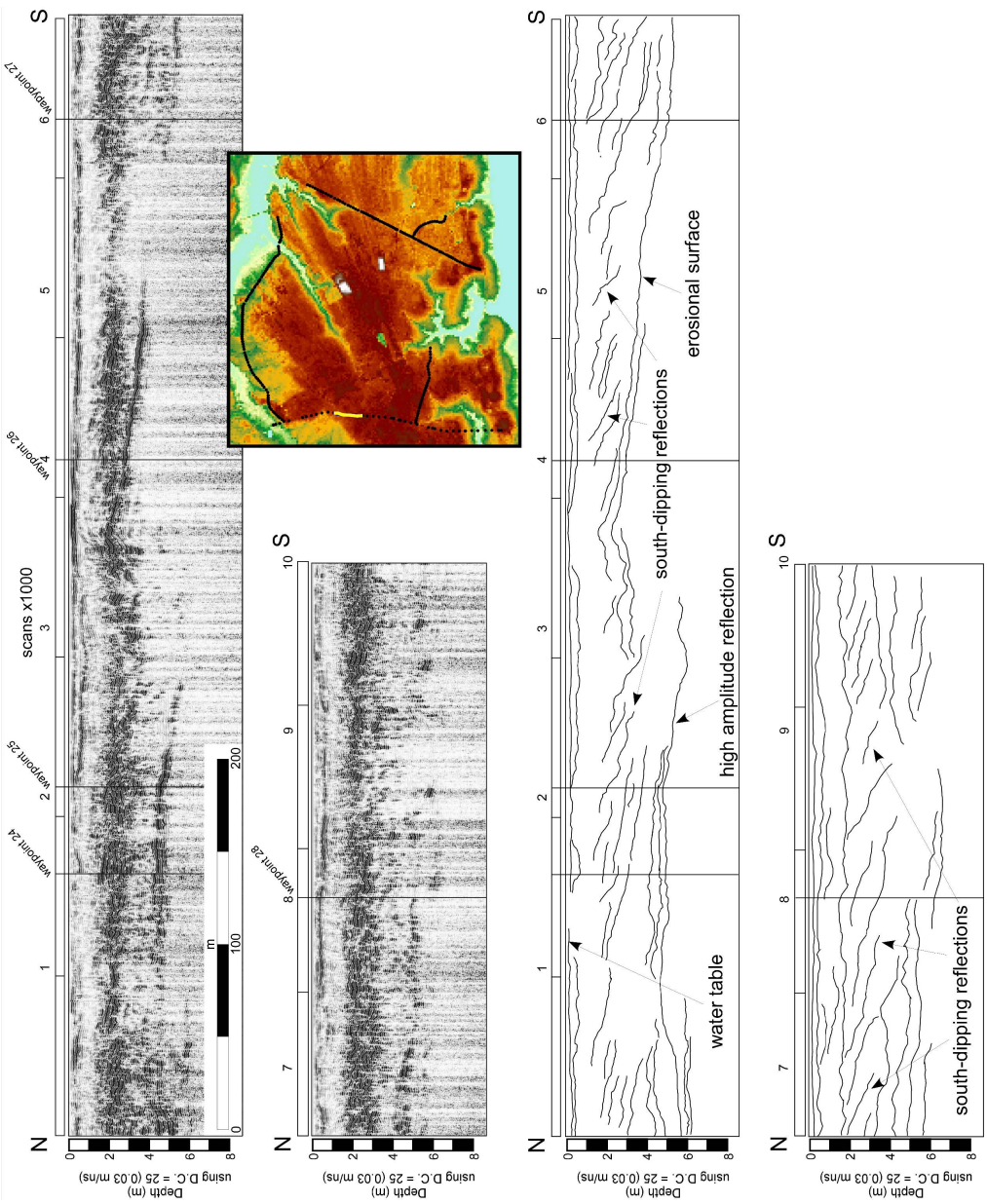


Figure 32. Filtered and interpreted GPR data from Line 1840. Inset: All GPR lines collected in the Croatan Beach Ridge Complex shown in black; location of Line 1840 in the study area is shown in yellow.

history of the south-dipping reflections can not be unequivocally determined.

Line 1845:

Line 1845 is located perpendicular to the beach ridge complex, approximately along Transect B (Figure 33). This is the southern-most line in the Croatan Beach Ridge Complex. Approximately three sets of reflections are present in this line. The shallowest reflection represents the water table in the area, and is located at ~0.25 m. Below the water table, a set of seaward-dipping clinoforms are present at 1.5-4.5 m depth. These reflections are similar to those found in Line 1840, though further south, and probably represent migrating beach dunes. Core data from Croatan-08-GP1 and Croatan-08-GP2 indicate these clinoforms are composed of fine to medium-fine well-sorted quartz sand, suggesting they are aeolian in origin. Below these sets of clinoforms is a higher amplitude, seaward-dipping reflection. This reflection is at a lower angle and greater amplitude than the sets of clinoforms located above it. The reflection is located at a greater depth (maximum depth of 7.5 m) than the deepest reflections in the lines further north, and most probably represents the shoreface of an older berm.

Line 69:

Line 69 is located perpendicular to the beach ridge complex, near Transect C, and east of the previous GPR lines (Figure 34). Three distinct sets of reflections are present. The shallowest reflection, present between 0.25-1 m, represents the water table in this area. Between scans ~2600-3300 a depression is present, extending downwards from the water table reflection. The second set of reflections is located between 1-4 m depth, ranging from 1.5 to 4 m thick. It is composed of numerous low-angle, seaward dipping

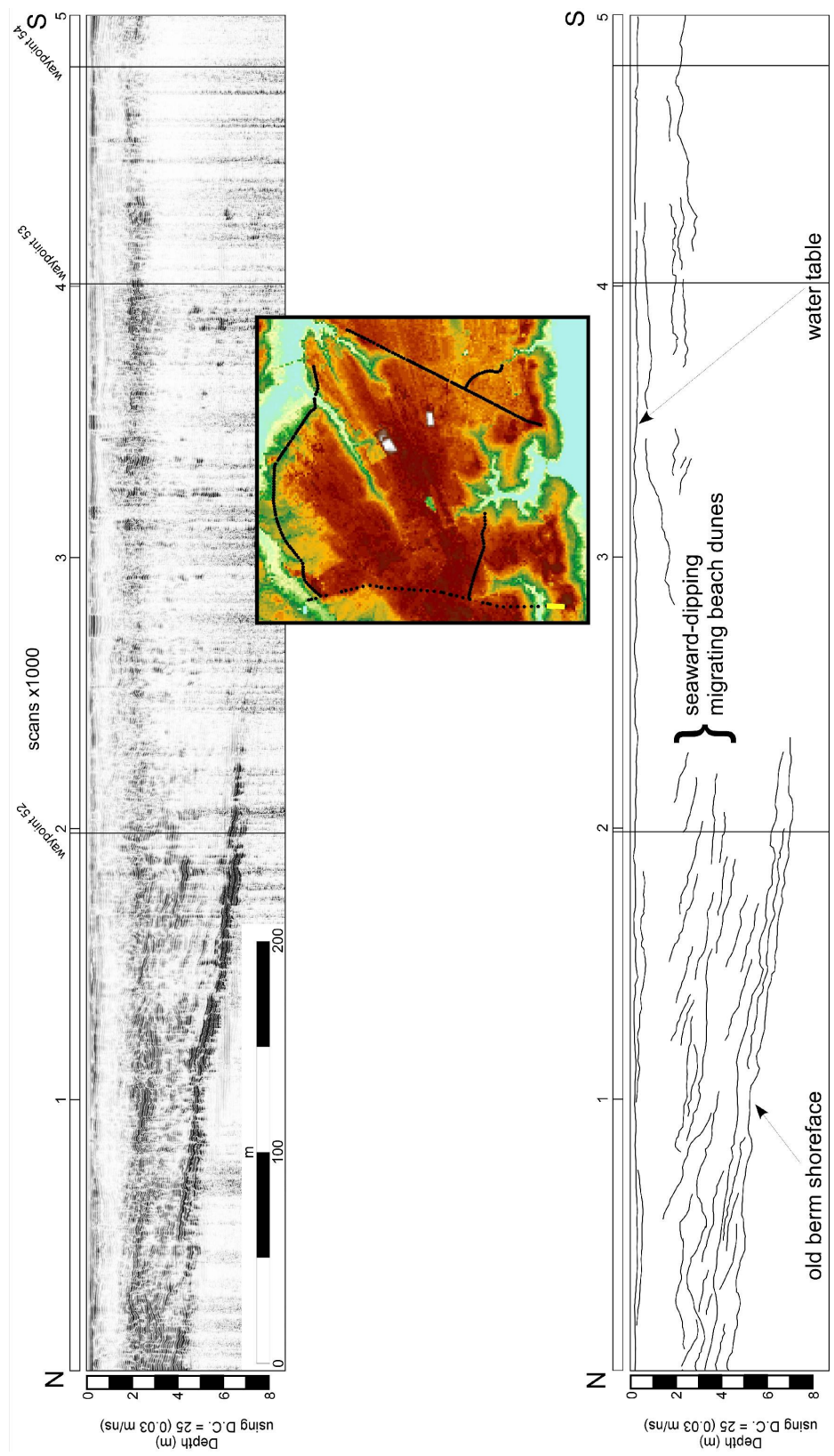


Figure 33. Filtered and interpreted GPR data from Line 1845. Inset: All GPR lines collected in the Croatan Beach Ridge Complex shown in black; location of Line 1845 in the study area is shown in yellow.

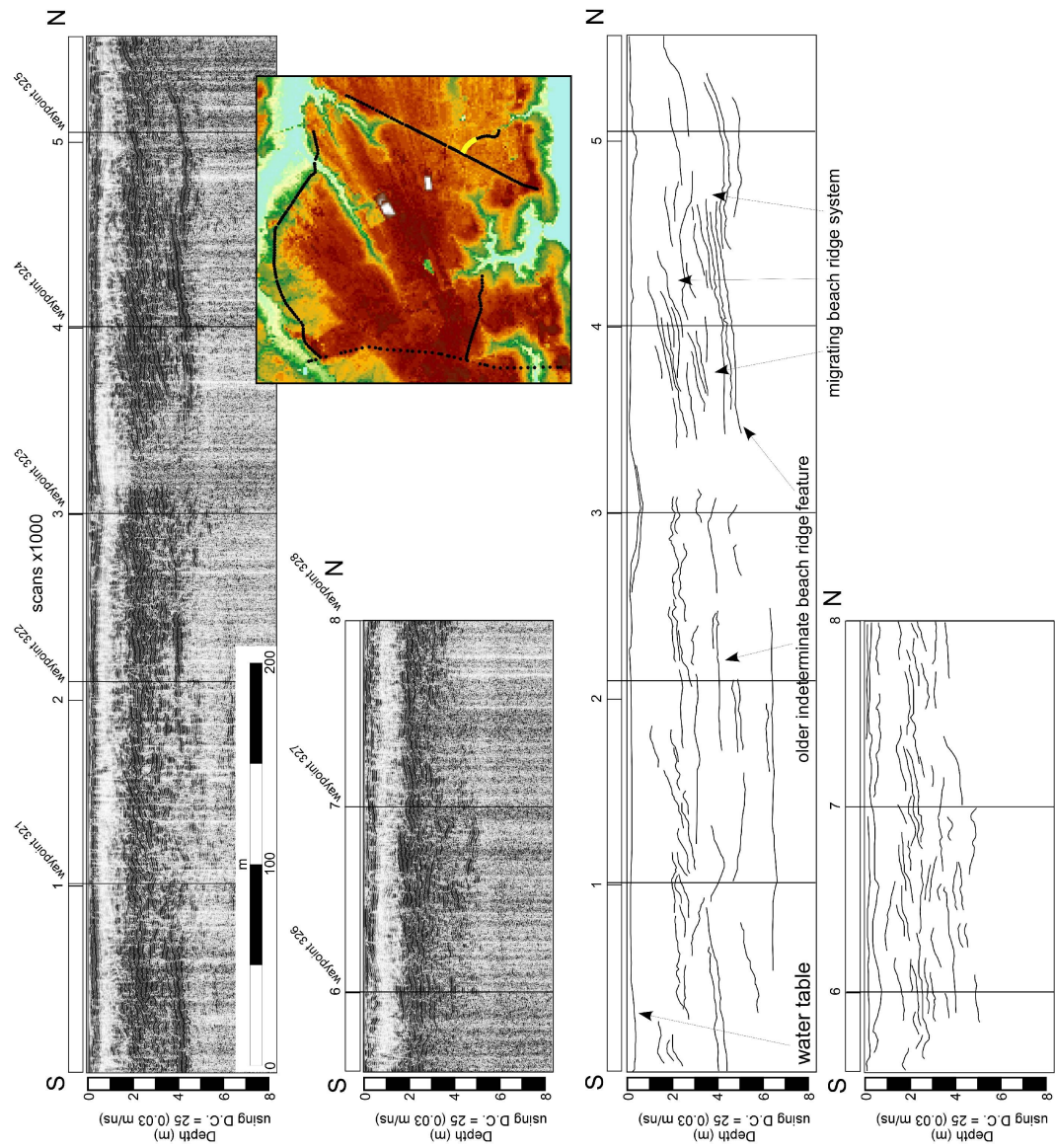


Figure 34. Filtered and interpreted GPR data from Line 69. Inset: All GPR lines collected in the Croatan Beach Ridge Complex shown in black; location of Line 69 in the study area is shown in yellow.

reflections. These clinoforms probably represent an older migrating beach ridge system. The third set of reflections is located at approximately 4-5 m depth. The set of reflections is considerably thinner (~1 m) and lacks the regressive stacking pattern displayed by the more shallow set of clinoforms. This suggests that while they represent an older beach feature, any distinct morphology was eroded, weathered, or unable to be detected by the GPR receiver.

Line 80:

Line 80 is located approximately parallel to the beach ridge complex, in the north of the study area near a relict tributary of the Newport River (Figure 35). As with the other GPR lines discussed above, three primary sets of reflections are present. The shallowest reflection is located from 0-0.5 m depth and represents the water table in this area. A second set of reflections is located at 1.5-4 m depth and is 2-4 m thick – similar to corresponding units in other sections of GPR in the study area. However, the reflections in this line do not display shallow, seaward dipping clinoforms as they do in the other GPR lines. Instead, this set of reflections displays chaotic bedding – reflections that are approximately horizontal but undulate throughout their entirety. This signature would be expected when observing reflections parallel to a beach ridge complex (along strike). The deepest reflection is located between 3.5-5.5 m and is subhorizontal, dipping slightly to the east. This reflection is also present in other GPR lines in the area.

Line 35:

Line 35 is located in the Pine Knoll Shores region of Bogue Banks (Figure 36). The first half of this line runs west to east, and then turns to run north-south.

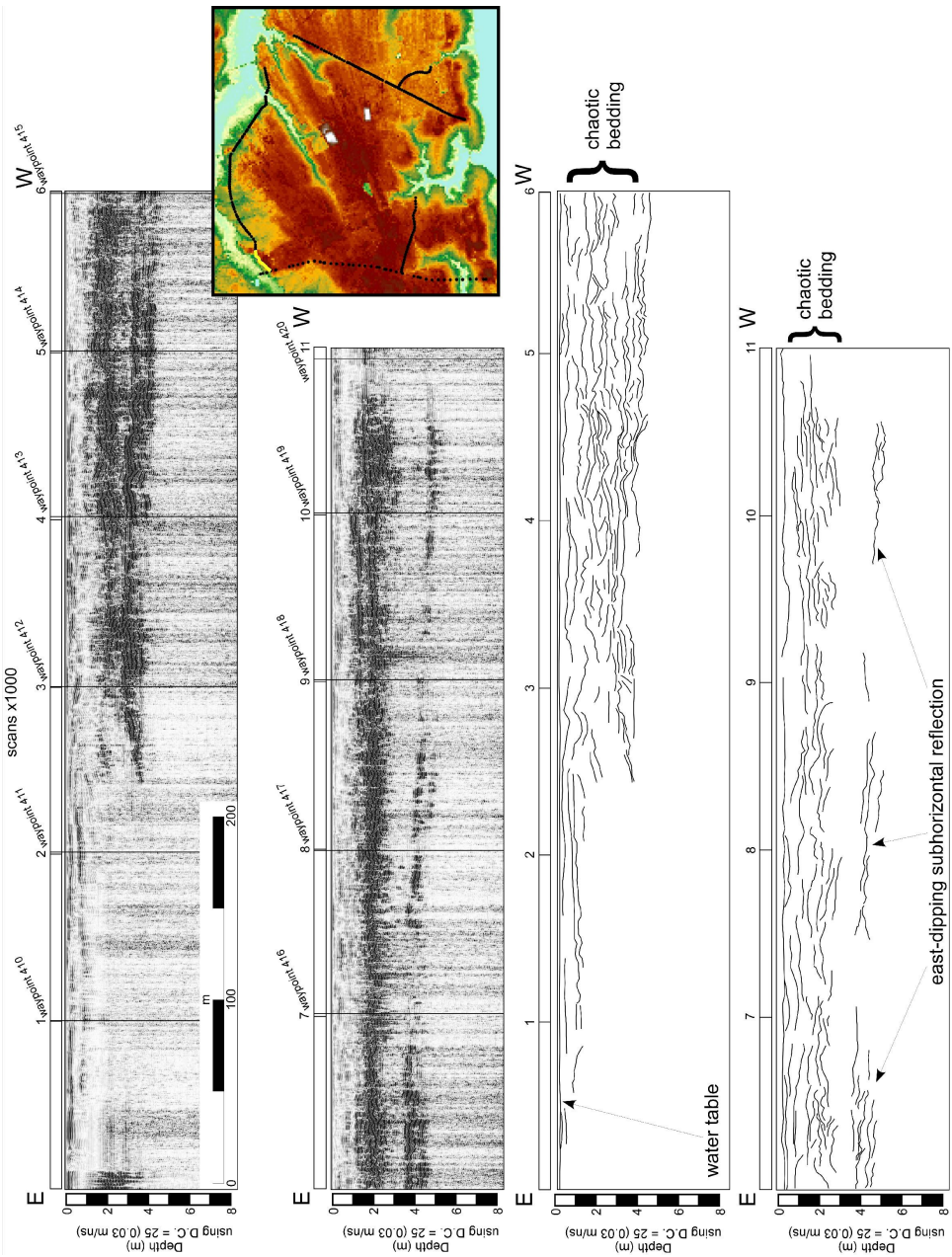


Figure 35. Filtered and interpreted GPR data from Line 80. Inset: All GPR lines collected in the Croatan Beach Ridge Complex shown in black; location of Line 80 in the study area is shown in yellow.

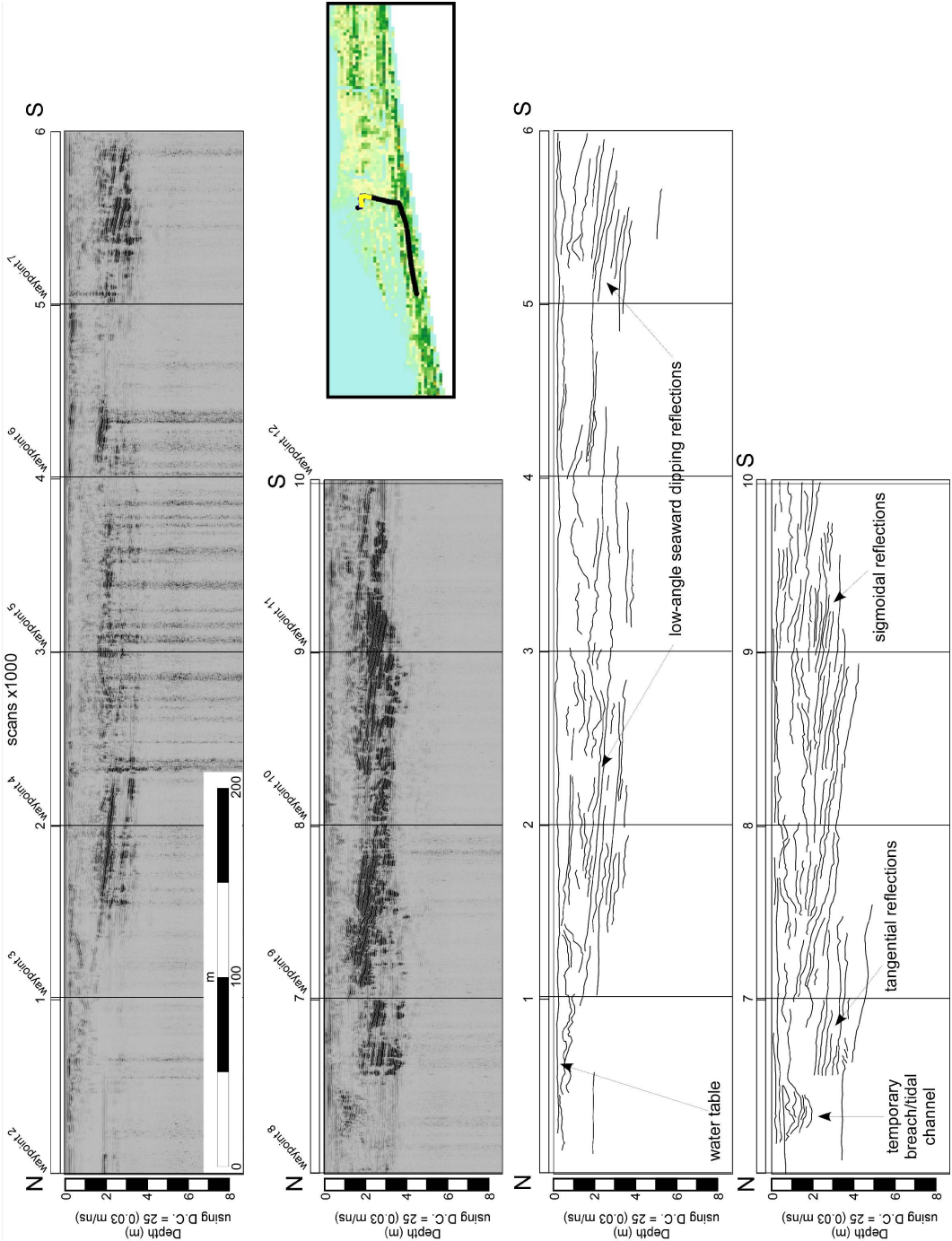


Figure 36. Filtered and interpreted GPR data from Line 35. Inset: All GPR lines collected on Bogue Banks shown in black; location of Line 35 in the study area is shown in yellow.

Approximately two sets of reflections dominate this data set. The shallowest reflection is located at ~0.25 m depth and represents the water table. This reflection cross-cuts other reflections. The largest depression is located between scans 6300-6600 and reaches a depth of 2 m. These depressions could represent inlet activity, but due to their small scale, probably represent minor and temporary breaching of the island during a storm event or a tidal channel occupying a swale. Low-angle seaward dipping tangential reflections dominate the section of the line which runs perpendicular to the strike of the island (scans 6500-10000). These reflections are located at a depth between 1.5-5 m. The second set of reflections display primarily oblique tangential reflections, which could represent washover barrier sands, as well as several oblique sigmoidal reflections, which can represent progradational/accretionary beach sand and gravel (van Heteren et al., 1998).

Line 41:

Line 41 runs east to west along western Pine Knoll Shores, on Bogue Banks, parallel to the shoreline (Figure 37). Two primary sets of reflections are observed in the GPR line: a shallow water table reflection with minor perturbations/depressions, and larger-scale subhorizontal reflections. The shallow reflection, representing the water table, is located from the surface to a maximum depth 0.5 m. Several small-scale perturbations are cross-cut by the shallow reflection throughout the line. The largest is a depression located between scans ~3800-5010 to a depth of 1.75 m. This depression could represent a breach of the island during storm conditions, which was later infilled, or a tidal creek. However, this reflection is very low amplitude, suggesting it was not

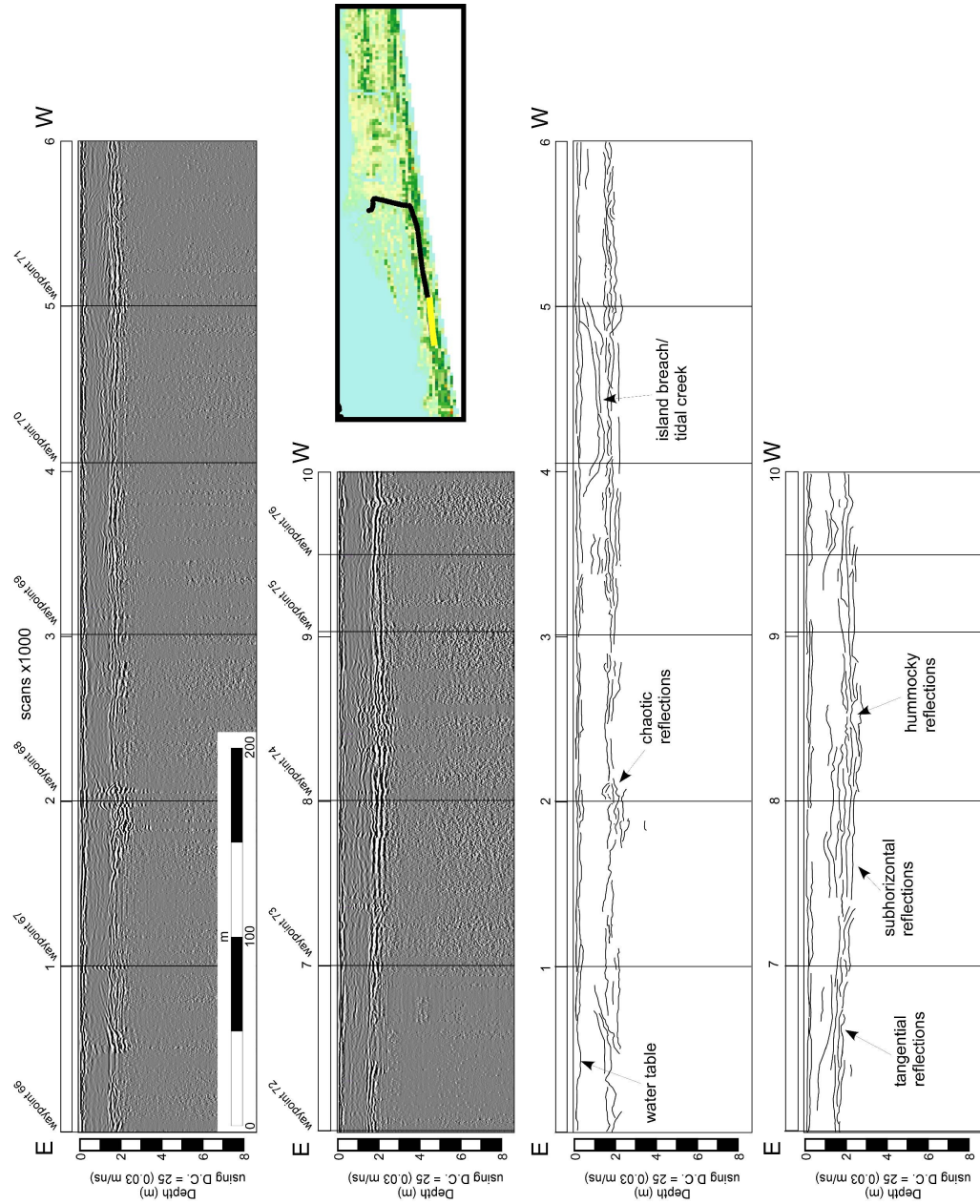


Figure 37. Filtered and interpreted GPR data from Line 41. Inset: All GPR lines collected on Bogue Banks shown in black; location of Line 41 in the study area is shown in yellow.

infilled with coarse-grained material. The larger, high amplitude set of reflections is dominated by subhorizontal reflections with occasional oblique tangential, chaotic, and hummocky reflections. Generally, these reflections are subhorizontal, which is expected of GPR data collected parallel to the shoreline and any beach ridge complexes located on the island. The hummocky reflections (located at scans ~2000 and 8500) are typical of accretionary spit-beach sand and gravel (van Heteren et al., 1998), which is typical on Bogue Banks.

Seismic Surveys

Line L6f2:

Line L6f2 was collected along a north-south transect on Bogue Sound (Figure 38). Vibracore BS-08-03 is located along this transect, ~250 m from the southern terminus of the line, and penetrating to a maximum depth of 10 m below sea level. The shallowest seismic unit is bounded by the sediment/water interface (Figure 38) and a discontinuous horizontal reflection, and is composed of estuarine shoal sand (supported by vibracore data). Below this unit lies a seismic unit representing open marine sand, which is also supported by vibracore data. This unit contains a large paleochannel, approximately 300 m wide, at a depth ranging from 5-12 m. Southward-dipping reflections inside the channel may represent a flood tide delta channel. The Pleistocene boundary is located below the seismic unit containing the paleochannel, at a depth of ~14 m below sea level (Figure 38). The Pleistocene reflection is horizontal to subhorizontal and is the highest amplitude reflection in the data set. The Pleistocene seismic package is bounded on the

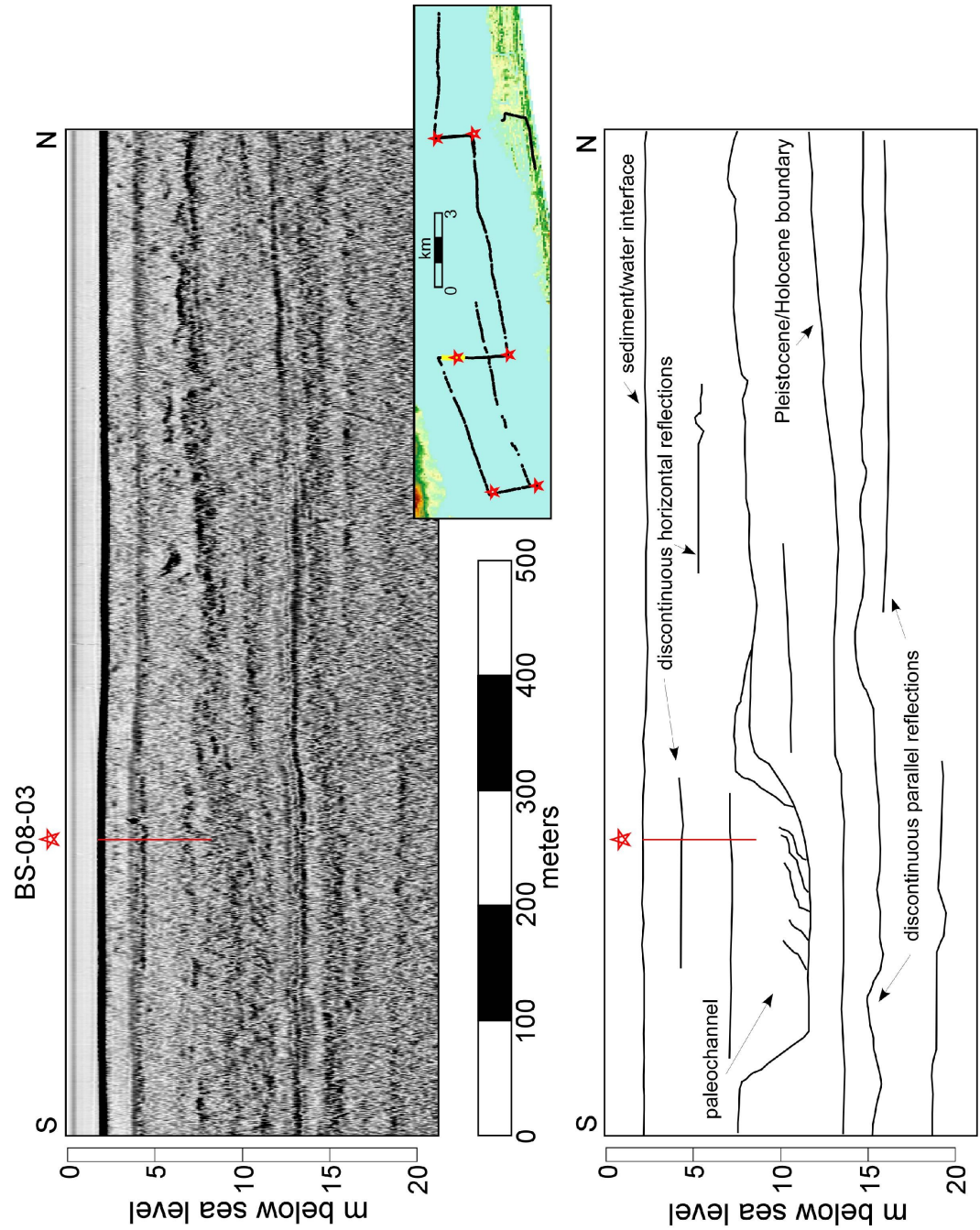


Figure 38. Filtered and interpreted seismic line L6f2 from Bogue Sound. Core BS-08-03 is indicated by the star and shown in red. Inset: Black lines represent all seismic data collected, L6f2 is shown in yellow. Black lines on Bogue Banks indicate GPR data.

top by the subhorizontal/horizontal reflection representing the Pleistocene/Holocene boundary. Below the high amplitude reflection are several discontinuous, parallel, reflections at approximately 15 m below sea level which compose the Pleistocene deposits.

Line L9f4:

Line L9f4 was collected along an east-west transect on Bogue Sound (Figure 39). The shallowest seismic unit (seismic unit 1) is located between the sediment/water interface and a discontinuous reflection located at approximately 4 m below sea level. Below this seismic unit lie several discontinuous, horizontal, low amplitude reflections which continue to a maximum depth of 13 m below sea level. Seismic unit 2 is cross-cut by a large paleochannel, 600 m wide, with the top of the channel located at 5 m below sea level and incising down to 11 m below sea level. This seismic unit is bounded on the bottom by the Holocene/Pleistocene boundary (Figure 39). The boundary reflection is continuous, horizontal, and located at 13 m below sea level. Below this reflection lies seismic unit 3 (Figure 39), which contains a continuous reflection comprised of a low frequency sinusoidal pattern.

Line L6f1

Line L6f1 was collected along a north-south transect on Bogue Sound (Figure 40). The shallowest seismic unit is (seismic unit 1) is located between the sediment/water interface and a discontinuous, horizontal reflection located at ~8 m below MSL. A lower-amplitude, horizontal reflection within seismic unit 1 at approximately ~4 m below MSL correlates with a transition between a shelly mud (low energy normal marine

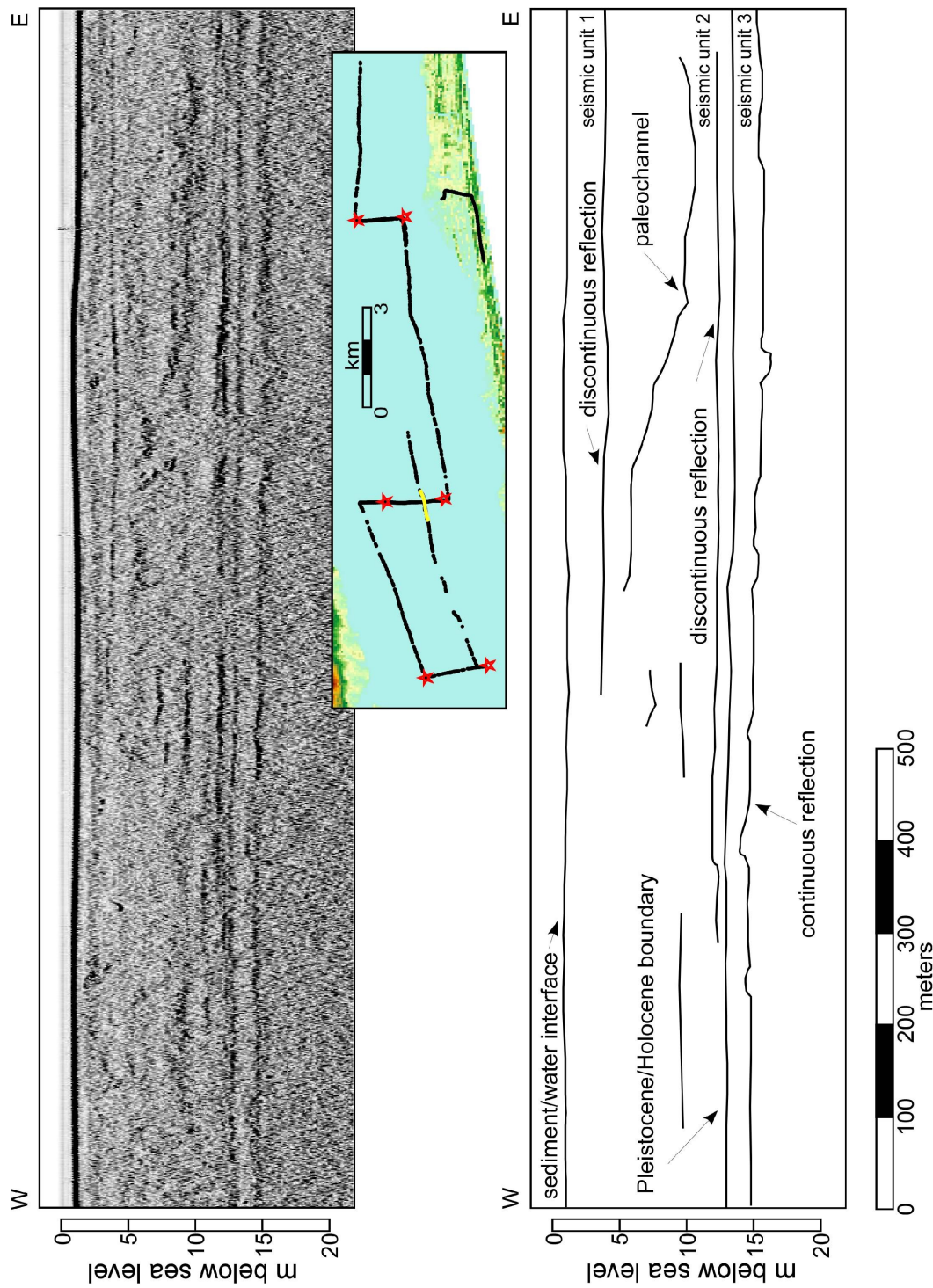


Figure 39. Filtered and interpreted seismic line L9f4 from Bogue Sound. Inset: Black lines represent all seismic data collected, L9f4 is shown in yellow. Black lines on Bogue Banks indicate GPR data.

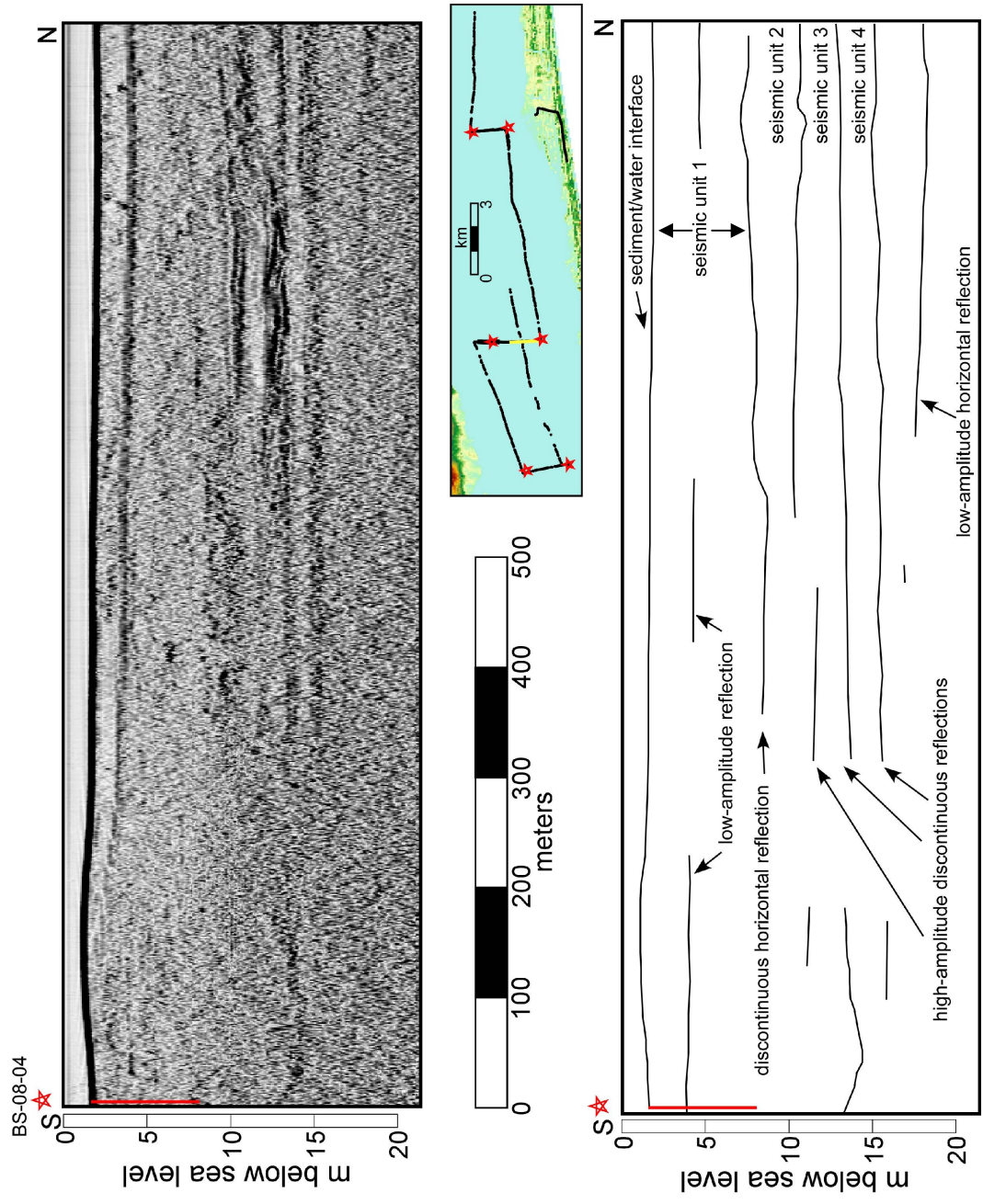


Figure 40. Filtered and interpreted seismic line L6f1 from Bogue Sound. Inset: Black lines represent all seismic data collected, L6f1 is shown in yellow. Black lines on Bogue Banks indicate GPR data.

salinity depositional facies) and shelly sand (flood tide delta depositional facies) in BS-08-04 (Figure 40; Appendix B). A series of high-amplitude, horizontal reflections comprise the boundaries between seismic units 2, 3, and 4. The contact producing the reflection between seismic units 1 and 2 is potentially visible in BS-08-04 (Figure 40). While this reflection does not extend to the core, it can be extrapolated to correlate with the boundary between an interbedded mud and sand unit and a shelly sand unit. Seismic unit 3 is bounded on the top by a discontinuous, high-amplitude reflection and on the bottom by higher-amplitude reflection (Figure 40). The bottom reflection represents the Holocene/Pleistocene boundary, at 12-14 m below MSL, dipping slightly to the south. Seismic unit 4 is bounded on the top by the Holocene/Pleistocene boundary and an additional high-amplitude, discontinuous reflection at ~16 m below MSL. This reflection also dips slightly to the south. An additional low-amplitude reflection is located below seismic unit 4 at ~17 m below MSL. This reflection only extends for ~350 m at the northern-end of the line, and is almost completely attenuated in the seismic data.

Line L5f1

Line L5f1 was collected along an east-west transect on Bogue Sound (Figure 41). BS-08-01 is located at the eastern edge of this line. Two small infilled channels are present immediately below the sediment/water interface, located at ~3 m below MSL. These small paleochannels reach a maximum depth of ~4 m below MSL. A discontinuous, sub-horizontal reflection is present between 5-9 m below MSL. This reflection could possibly be extrapolated to the very base of BS-08-01, however the reflection is very

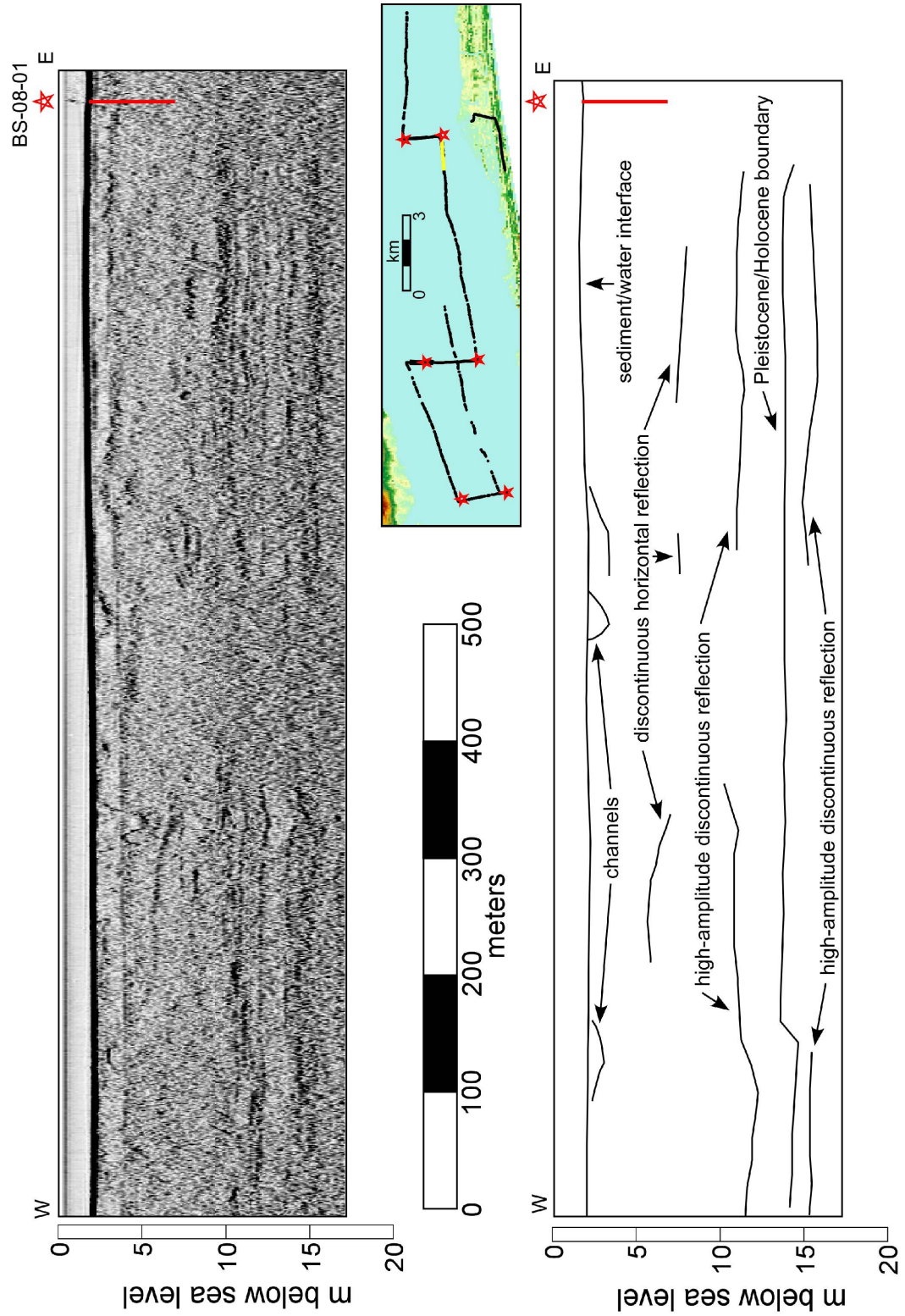


Figure 41. Filtered and interpreted seismic line L5f1 from Bogue Sound. Inset: Black lines represent all seismic data collected, L5f1 is shown in yellow. Black lines on Bogue Banks indicate GPR data.

discontinuous and no lithologic evidence in that core suggests a change in lithofacies. A high-amplitude, discontinuous reflection persists throughout the line at ~11 m below MSL. Below this reflection lies a continuous, lower-amplitude reflection at ~ 14 m below MSL which represents the Holocene/Pleistocene boundary. The Holocene/Pleistocene boundary in this location is lower amplitude than in other lines in the study area, however, it is located at the same approximate depth. Below the Holocene/Pleistocene boundary lies a second high-amplitude, discontinuous reflection which appears to mimic the reflection that occurs at 11 m below MSL. This reflection is located at ~15 m below MSL.

Line L8f1

Line L8f1 was collected along a north-south transect in the western portion of the study area in Bogue Sound (Figure 42). BS-08-06 is located at the northern edge of this line. Seismic data in this line was not especially well-resolved. The sediment/water interface is located at ~1 m below MSL. A continuous, high-amplitude, subhorizontal reflection is present at ~7-8 m below MSL, dipping slightly to the south (Figure 42). A second, lower-amplitude reflection is present ~11-13 m below MSL and represents the Holocene/Pleistocene boundary in this location. A map of the depth of the Holocene/Pleistocene boundary in all seismic lines (where it was identified) in the study area is shown in Figure 43. No reflections are present in the upper 5 m of data (Figure 42), which is corroborated by core material; BS-08-06 is composed of a fining-upward sequence of shelly sand, interpreted to be part of the flood tide delta environment.

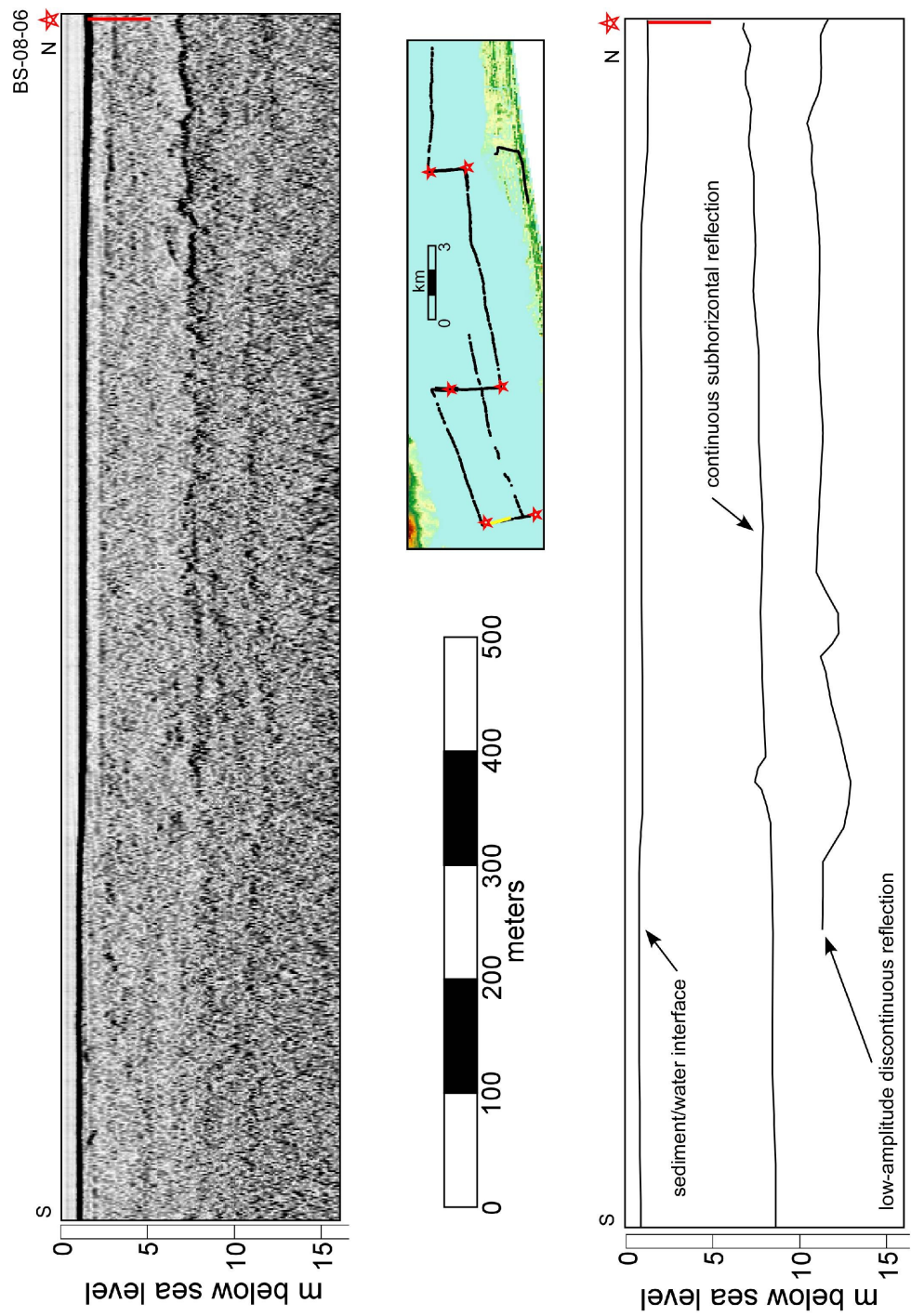


Figure 42. Filtered and interpreted seismic line L8f1 from Bogue Sound. Inset: Black lines represent all seismic data collected, L8f1 is shown in yellow. Black lines on Bogue Banks indicate GPR data.

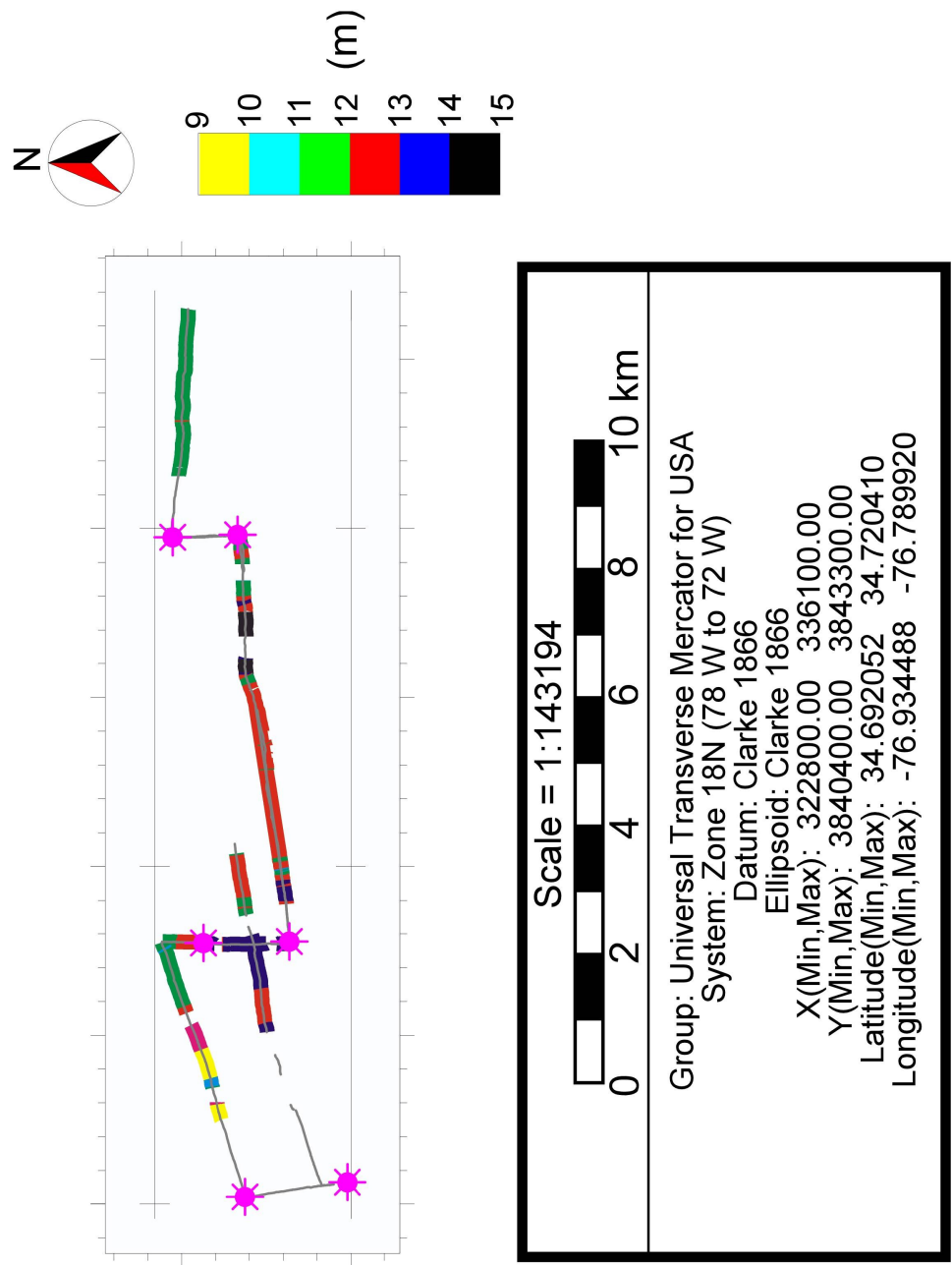


Figure 43. Map of seismic data collected from Bogue Sound indicating the depth to the Holocene/Pleistocene boundary. Pink stars indicate core locations. Where no color is indicated, a lack of seismic data occurred, most likely due to attenuation. Note the depth of the Pleistocene ranges from ~8-14 m below MSL.

Line L1f2

Line L1f2 was collected along an east-west transect in the eastern portion of the study area in Bogue Sound (Figure 44). BS-08-02 is located along the western edge of this line. This seismic line does not reveal much reflection data. The sediment/water interface is located at ~3 m below MSL. Immediately below this reflection is a small channel, ~1 m deep and 50 m wide (Figure 44). The only other reflection in this seismic line is a ~100 m long, discontinuous, subhorizontal reflection located at ~10 m below MSL, dipping slightly to the east.

Line L5f3

Line L5f3 was collected along an east-west transect in the central portion of the study area in Bogue Sound, between cores BS-08-04 and BS-08-01 (Figure 45). The sediment/water interface is located at ~1.5 m below MSL. Below this interface, two discontinuous, horizontal to subhorizontal reflections are present at ~3.5 and 11 m below MSL (Figure 45). The shallow reflection is located at the approximate depth of the boundary between DF II and DF VI in BS-08-04, although this core is a few kilometers west of this seismic line (Figure 45). A high-amplitude continuous reflection is found at 8 m below MSL. This reflection contains three convex-up structures, which are most likely caused by attenuation and are not actual representations of subsurface seismic stratigraphy (Figure 45). A continuous, high-amplitude reflection is located at ~13 m below MSL, and represents the Holocene/Pleistocene boundary. Two other continuous, high-amplitude, horizontal reflections are located below the Holocene/Pleistocene boundary at 16 and 18.5 m below MSL, respectively (Figure 45).

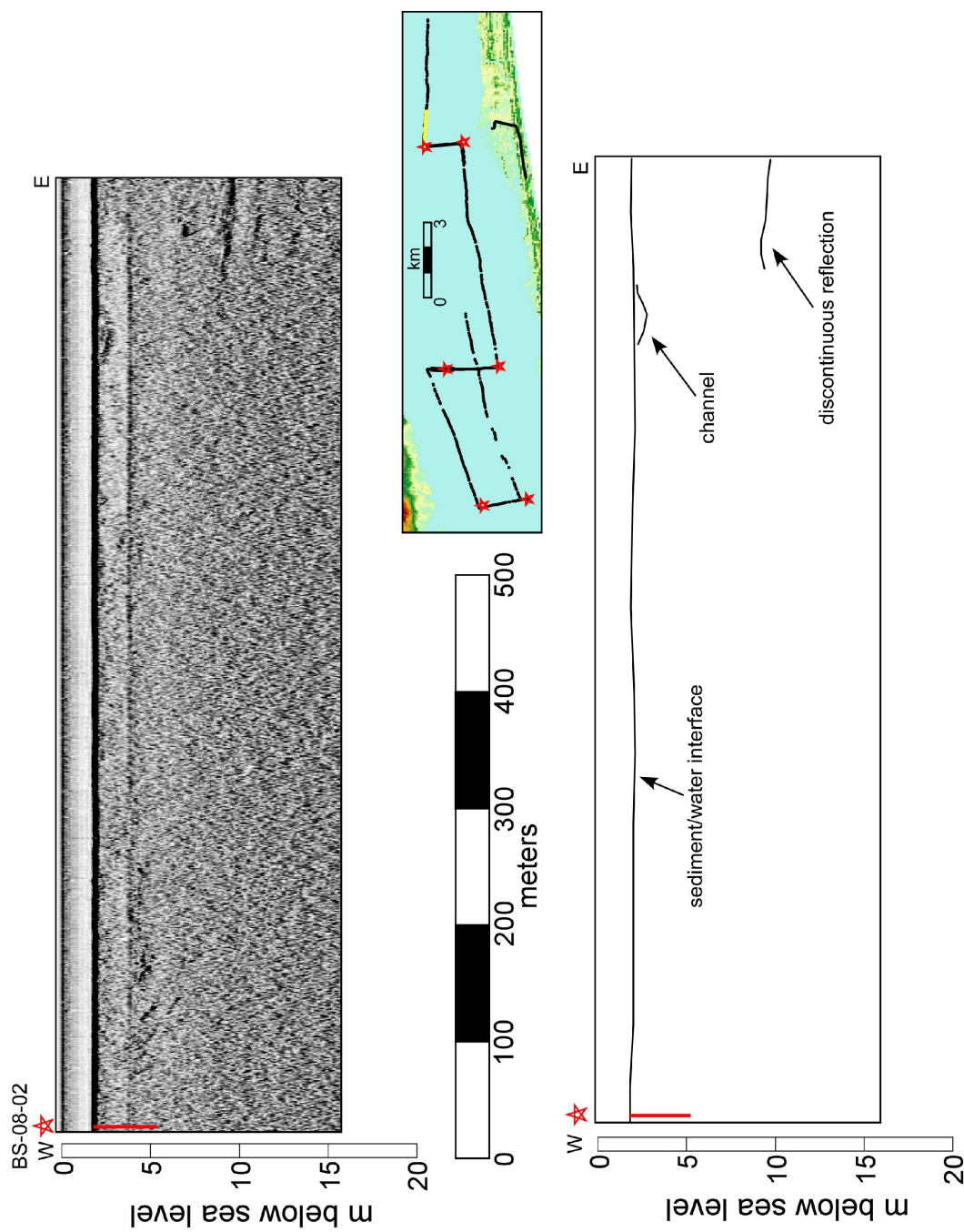


Figure 44. Filtered and interpreted seismic line L1f2 from Bogue Sound. Inset: Black lines represent all seismic data collected, L1f2 is shown in yellow. Black lines on Bogue Banks indicate GPR data.

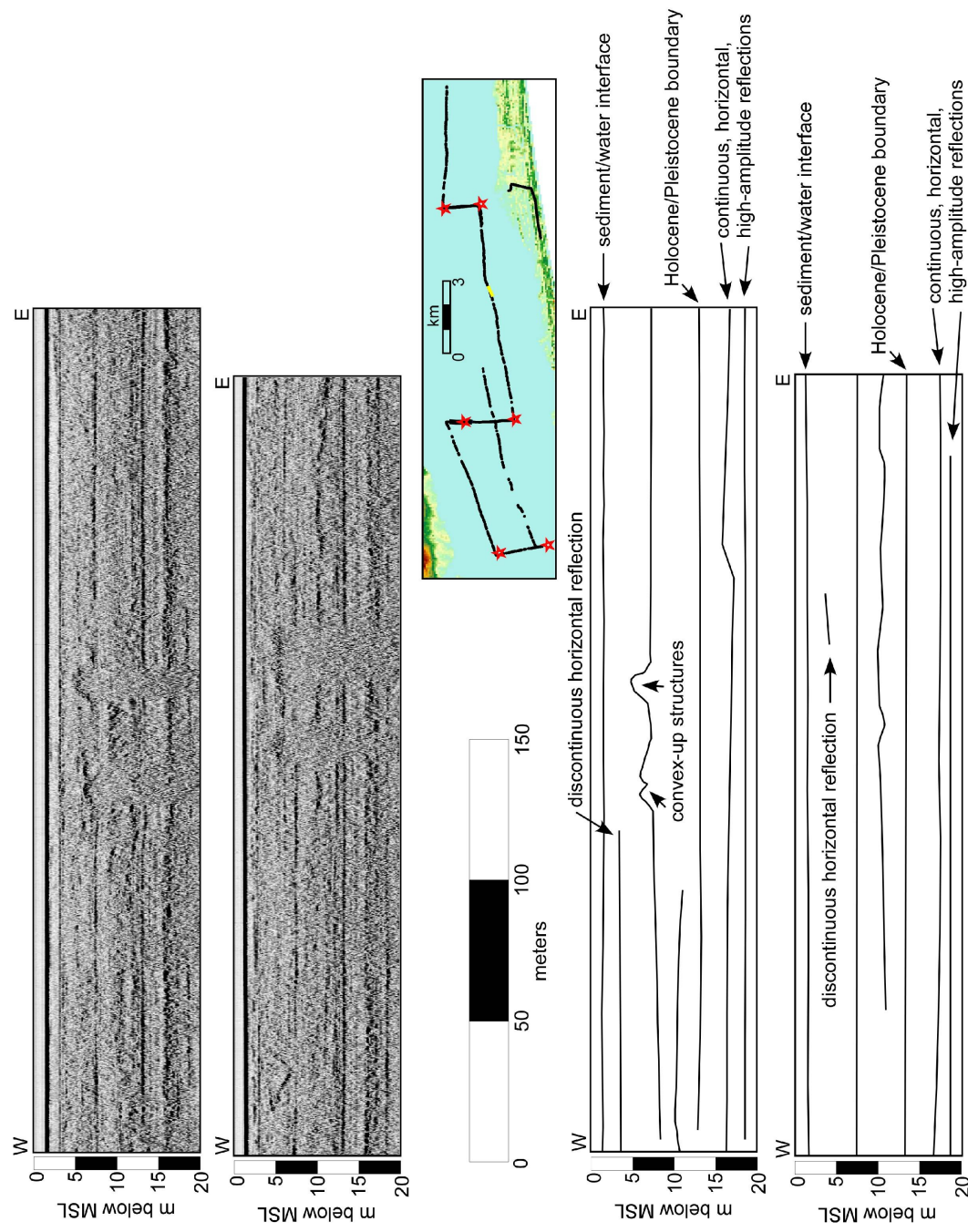


Figure 45. Filtered and interpreted seismic line L5f3 from Bogue Sound. Inset: Black lines represent all seismic data collected, L5f3 is shown in yellow. Black lines on Bogue Banks indicate GPR data.

Paleoenvironmental Reconstruction

Seven depositional facies were identified in 11 geoprobe cores and six vibracores in the Croatan Beach Ridge Complex, Bogue Sound, and Bogue Banks study area. Four cross sections of depositional facies were constructed to characterize the Quaternary geological evolution of the study area (Figure 46). Two transects run oblique to the beach ridges and through Bogue Sound to Bogue Banks (Figure 47, 51). A third transect runs perpendicular to the beach ridges in the Croatan Beach Ridge Complex (Figure 52). The last transect runs shore-parallel through three vibracores in Bogue Sound (Figure 53).

Transect A

Transect A is an 18 km-long, north to south, beach ridge-oblique/shore-perpendicular transect extending from the Croatan Beach Ridge Complex, through Bogue Sound, to Bogue Banks (Figure 46). This transect is composed of four geoprobe cores and two vibracores (Figure 47). Three of the four geoprobe cores were obtained from the Croatan Beach Ridge Complex (Croatan-08-GP6, Croatan-08-GP7, Croatan-08-GP5), with the fourth core taken on Bogue Banks (BB08-GP2). Both vibracores were taken in Bogue Sound (BS-08-03, BS-08-04). Seven depositional facies are identified in Transect A.

DF II (low energy normal marine salinity) is the deepest unit in the Croatan Beach Ridge Complex (Croatan-08-GP5; Croatan-08-GP6, Croatan-08-GP7). This depositional

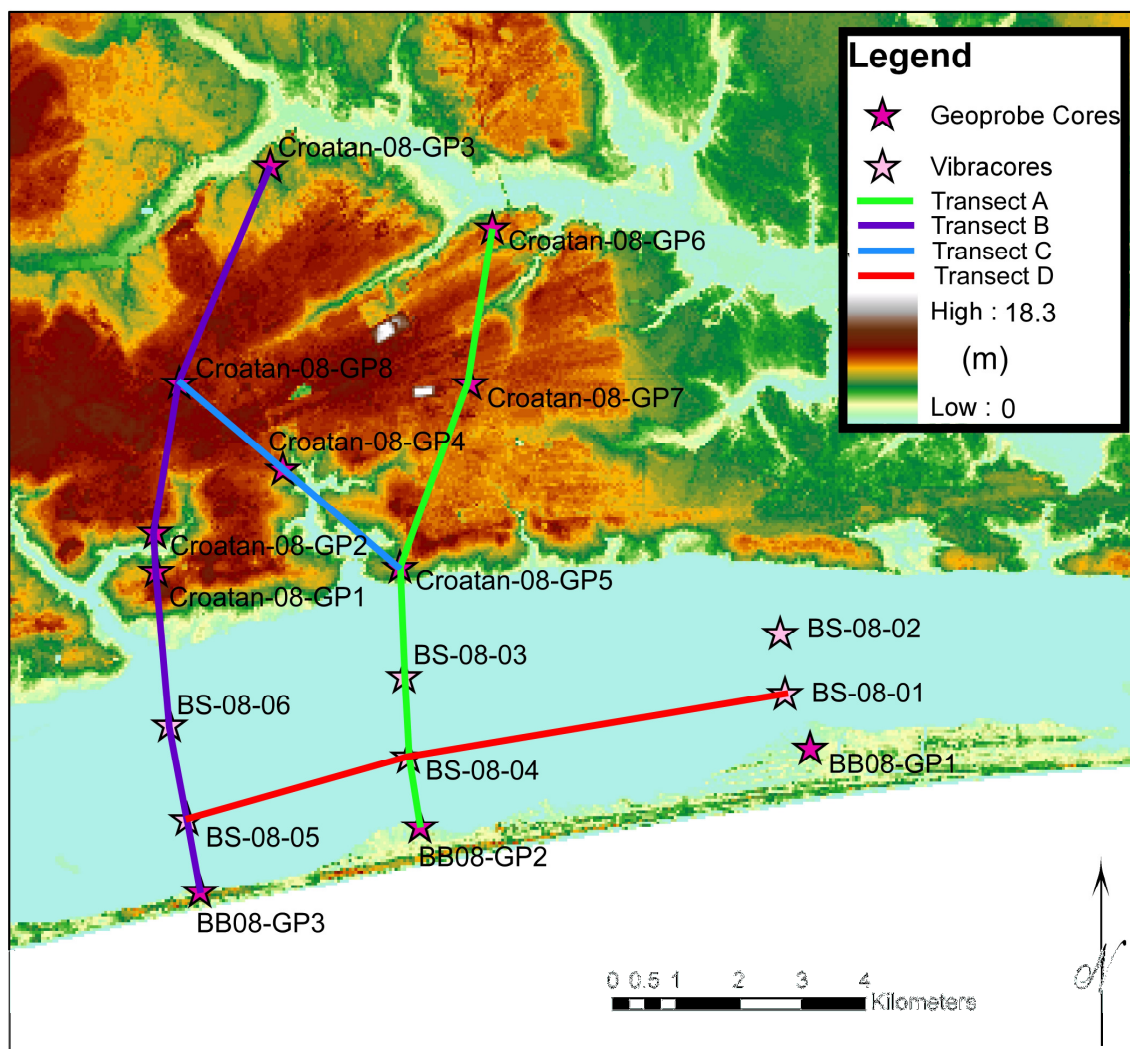


Figure 46. Map of study area showing core locations and transects. Transect A shown in green, Transect B shown in dark blue, Transect C shown in light blue, and Transect D shown in red.

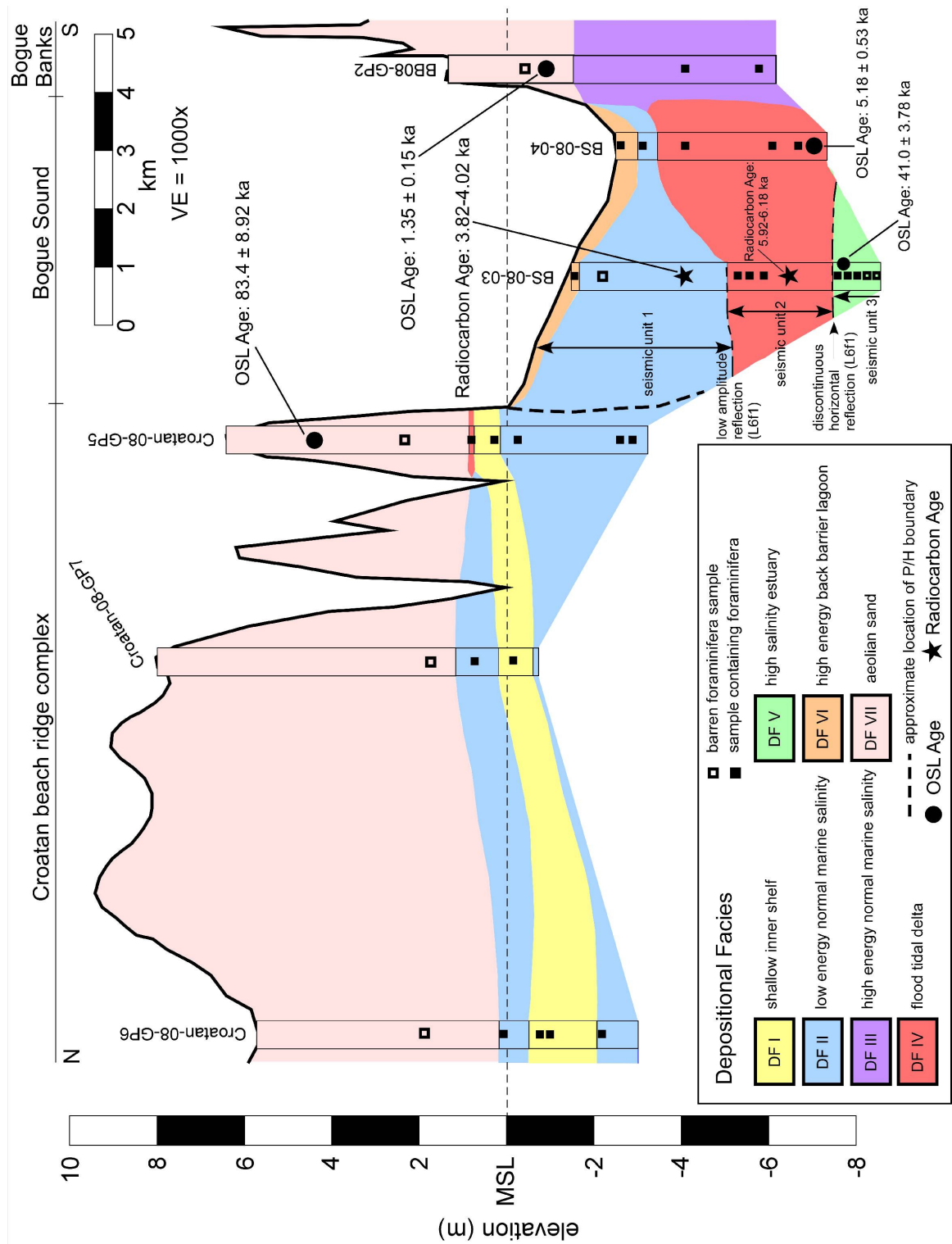


Figure 47. Cross section of depositional facies along Transect A.

facies is composed primarily of shelly muddy sand (shmS) and shelly sandy mud (shsM). DF II is relatively thick, ranging in thickness from 0.5-5 m (Figure 47).

Underneath the Croatan Beach Ridge Complex, DF II is interbedded with a 0.75-2 m-thick unit composed of DF I (shallow inner shelf; Figure 47). DF I is composed of shelly sand (shS), shelly sandy mud (shsM), sandy mud (sM), and mud (M) lithofacies. It is thickest in the northern section of the study area (~2 m), and thins seaward (to ~0.75 m).

A thin section of DF IV overlies DF I at the southern edge of the Croatan Beach Ridge Complex in Croatan-08-GP5. In this location, DF IV is only ~0.2 m thick, and composed of primarily the shelly sand (shS) lithofacies. This depositional facies is interpreted to be a flood tide delta environment, and this is its only occurrence outside Bogue Sound. However, the existence of this depositional environment underneath the Croatan Beach Ridge Complex is based on one foraminiferal sample from Croatan-08-GP5. While this sample clustered with Biofacies D (flood tide delta), it is more likely that it was an outlier in this cluster (Figure 28). It could be more reasonably grouped with the shallow inner shelf depositional facies (DF I), which is found immediately below this thin (0.2 m) segment of flood tide delta (Figure 47).

DF VII (aeolian) caps the cores in the Croatan Beach Ridge Complex to a thickness of 8 m in some areas (Figure 47). In Croatan-08-GP5, sedimentological data reveal a peak in mean grain size at 3.7-4 m (Figure 48). This coarse interval may suggest the base of the swash zone, however it is more likely that shoreface is located within DF I or

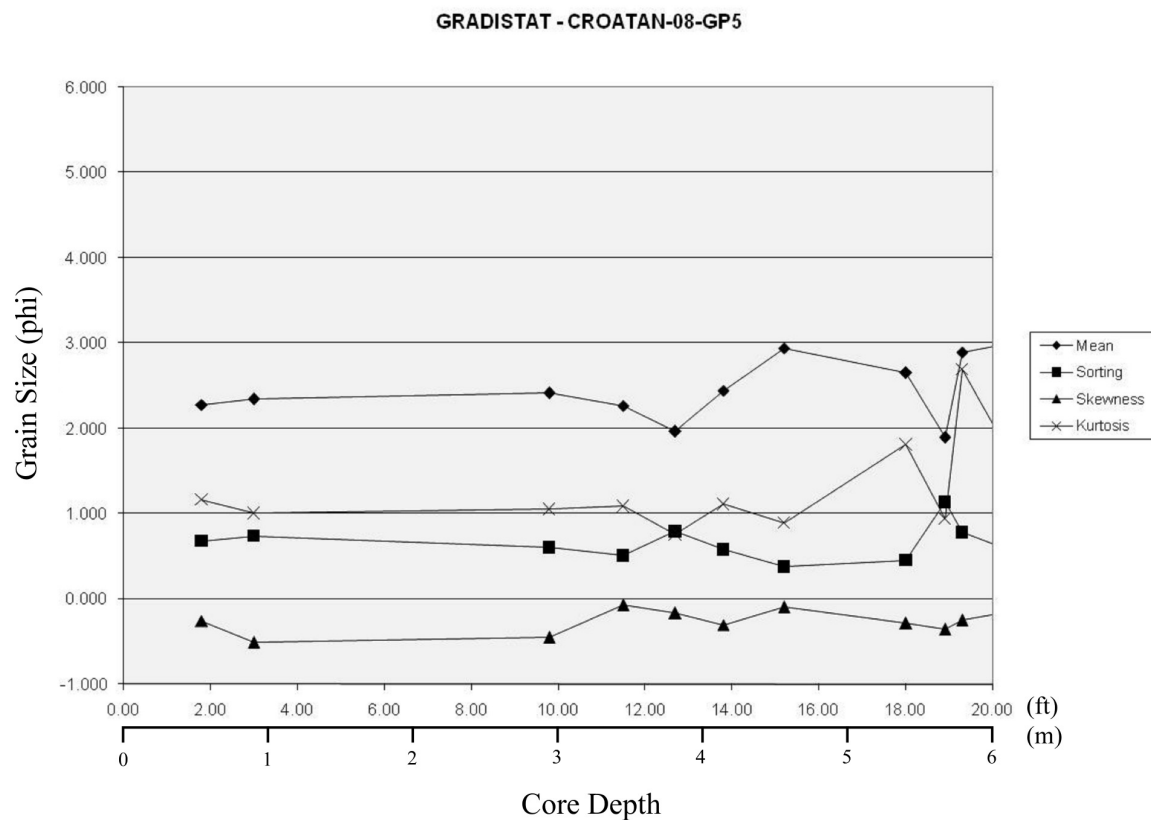


Figure 48. GRADISTAT plot of grain size data for Croatan-08-GP5. Note the change from less-negatively skewed to more-negatively skewed which occurs at ~3.4 m (~11 ft; shown in triangles).

DF II. These depositional facies are located directly below DF VII in the Croatan Beach Ridge Complex. GPR line 1845, located 3 km to the west of Croatan-08-GP5, indicates an old berm shoreface, which combined with sedimentological data, indicate a boundary between the aeolian sands of DF VII and a shoreline facies at approximately 1 m above MSL within DF IV/I. DF VII is dated as Pleistocene (83.4 ± 8.92 ka) in Unit 2 in the Croatan Beach Ridge Complex (Figures 2, 47; Table 7).

The Pleistocene-Holocene boundary occurs between the Pleistocene beach ridges of Unit 2 and the sediments of Bogue Sound (Figure 47). DF V (high salinity estuary) is located at the bottom of BS-08-03 in Bogue Sound (Figure 47). It is composed of numerous muddy lithofacies (muddy sand [mS], shelly mud [shM], and mud [M]), and represents the lowest-energy depositional facies in the study area. An OSL sample in this depositional facies at the base of BS-08-03 yielded an age estimate of 41.0 ± 3.78 ka (Figure 45; Table 7). However, it is believed that this age estimate is not an accurate representation of the depositional age of the unit, and is in fact Holocene in age (see Discussion). Data collected from seismic line L6f1 in Bogue Sound suggest DF V may correlate with seismic unit 3, a seismic package bounded on the top by a discontinuous horizontal reflection and separating DF V from DF IV (Figures 40, 47).

DF IV (flood tide delta) overlies DF V underneath Bogue Sound and at the northern terminus of Bogue Banks, in BS-08-03 and BS-08-04 (Figure 47). DF IV covers the entire width of Bogue Sound and is interpreted as a flood tide delta paleoenvironment, composed primarily of numerous shelly lithofacies and the sand (S) lithofacies. Radiocarbon and OSL age estimates date the base of DF IV between 4.7-6.18 ka (5.92-

6.18 ka [radiocarbon]; 5.18 ± 0.53 ka [OSL]; Figure 47). Seismic data in this area (Line L6f1) indicate DF IV comprises seismic unit 2, a seismic package bounded on the bottom by seismic unit 3 (DF V) and on the top by a low-amplitude reflection at an approximate depth of 3.5 m below MSL (Figure 49). This is the approximate depth of the boundary between DF IV and the finer-grained low energy normal marine salinity depositional facies DF II (Figures 38, 49). Additional seismic data from Line L6f2 indicate a discontinuous reflection at ~3-4 m below MSL (Figures 40, 50). This could approximately represent the boundary between DF IV (flood tide delta depositional facies and DF II (low energy normal marine salinity depositional facies) in BS-08-03 (Figures 40, 50). Another boundary exists in the seismic data between 7-8 m below sea level, indicating a change from DF V (high salinity estuary depositional facies) to DF IV (Figure 50).

DF II overlies DF IV in Bogue Sound. The sedimentology of DF II in Bogue Sound is similar to Pleistocene DF II deposits located within the Croatan Beach Ridge Complex. Seismic line L6f1 indicates this depositional facies composes part of seismic unit 1. This seismic package, composed of DF II and DF VI (DF VI overlies DF II), is bounded on the bottom by seismic unit 2 (DF IV) and on the top by the water/sediment interface. A sample from DF II in BS-08-03 yielded a radiocarbon age estimate of 3.82-4.02 ka.

DF VI (high energy back barrier lagoon) is the uppermost unit (0-5 m thick) overlying DF II beneath Bogue Sound (Figure 47). DF VI is composed of shelly sand

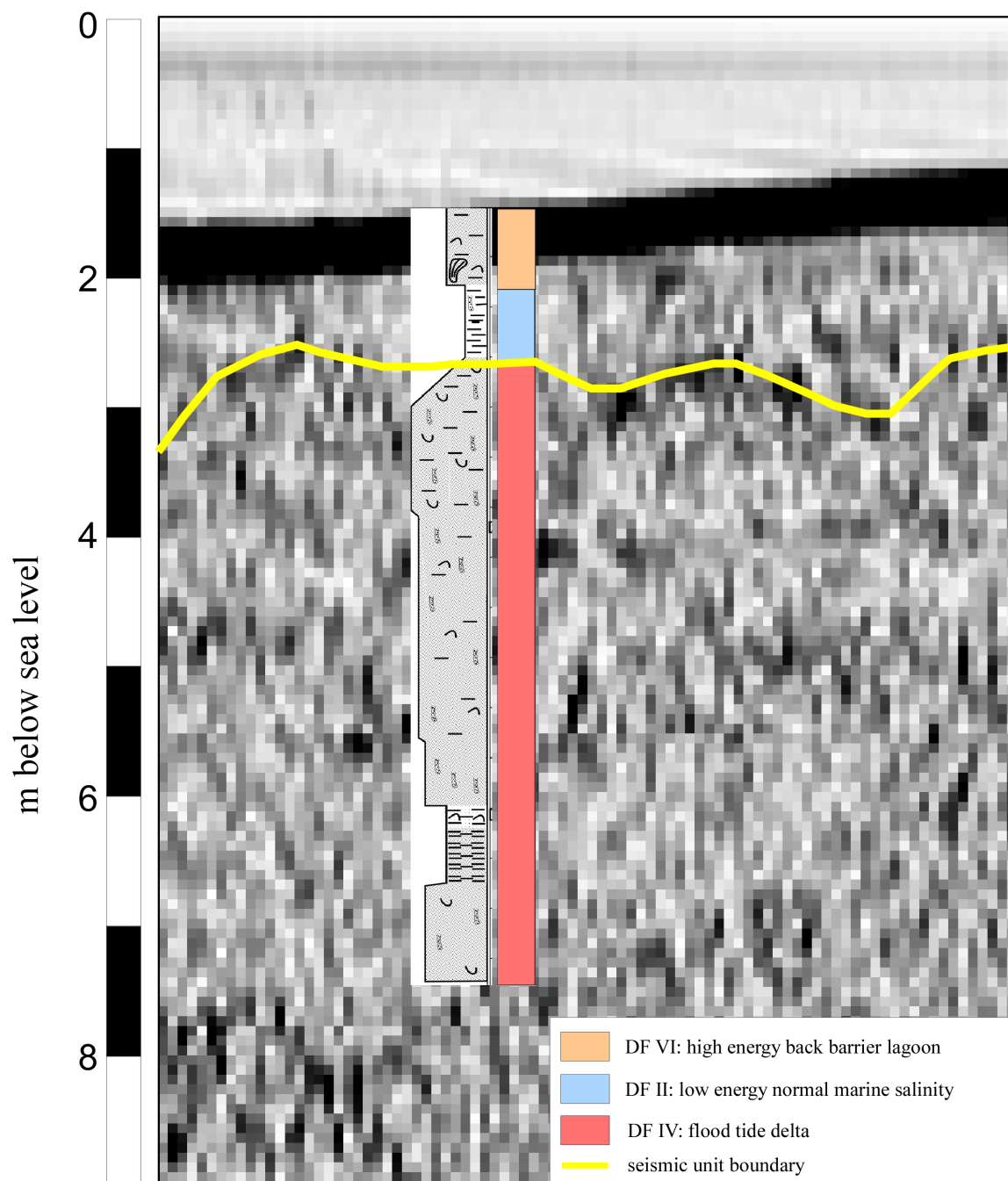


Figure 49. Lithologic core log and depositional facies log from BS-08-04 superimposed on seismic line L6f1. Yellow line illustrates boundary between seismic unit 1 (above) and seismic unit 2 (below).

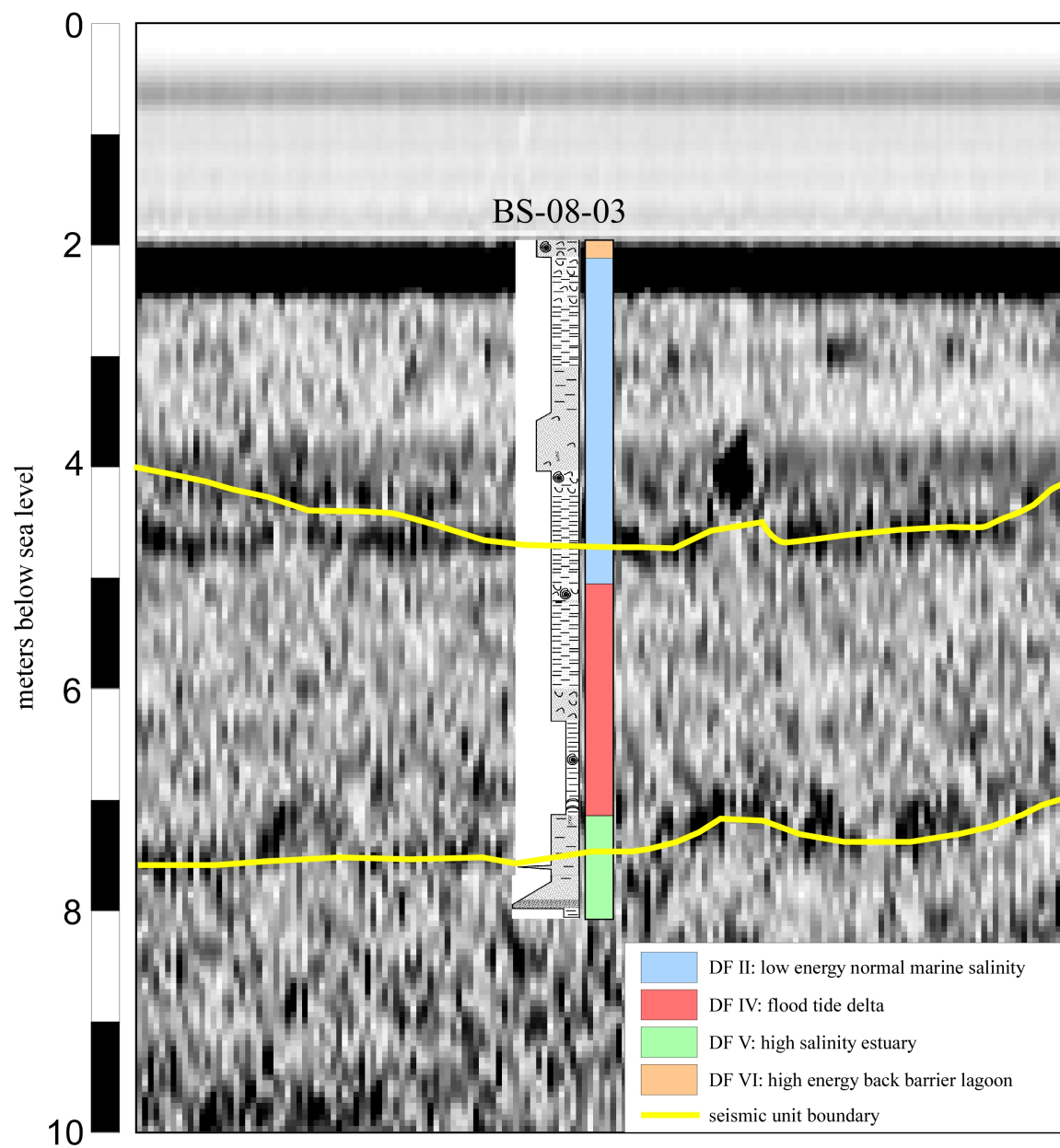


Figure 50. Lithologic core log and depositional facies log from BS-08-03 superimposed on seismic line L6f2. Yellow lines show seismic reflections interpreted at approximate lithologic changes within the core..

(shS lithofacies) and a large shell deposit (Sh lithofacies). This large shell deposit is located between 3.5-3.8 m below mean sea level in BS-08-04. This deposit includes an oyster reef, with oysters in life position.

DF III is a Holocene deposit located below DF VII in BB08-GP2 on Bogue Banks (Figure 47). This depositional facies is composed of primarily shelly sand and mud deposits, and comprised a section ~4 m thick. DF III was interpreted to be a high energy normal marine salinity paleoenvironment. GPR data indicate subhorizontal, tangential, and hummocky reflections just east of BB08-GP2, associated with the boundary between DF III and overlying DF VII (Figures 37, 47).

The primarily fine-grained sand with shell lithofacies which comprises DF VII is similar to Pleistocene DF VII aeolian deposits in the Croatan Beach Ridge Complex (Figure 47). The deposits on Bogue Banks are occasionally poorly sorted and contain greater amounts of shell material at a shallower core depth. However, the carbonates which are present in DF VII on Bogue Banks are typically small fragments (<5 mm), similar to what is found within dune sediments along a modern active shoreline. These carbonates have likely been leached out of the upper segments of DF VII in the Pleistocene-age Croatan Beach Ridge Complex.

Transect B

Transect B is a 12.5 km-long, north to south, beach ridge-oblique/shore-perpendicular transect extending from the Croatan Beach Ridge Complex, through Bogue Sound, to Bogue Banks (Figure 46; 51). This transect is the western-most in the study

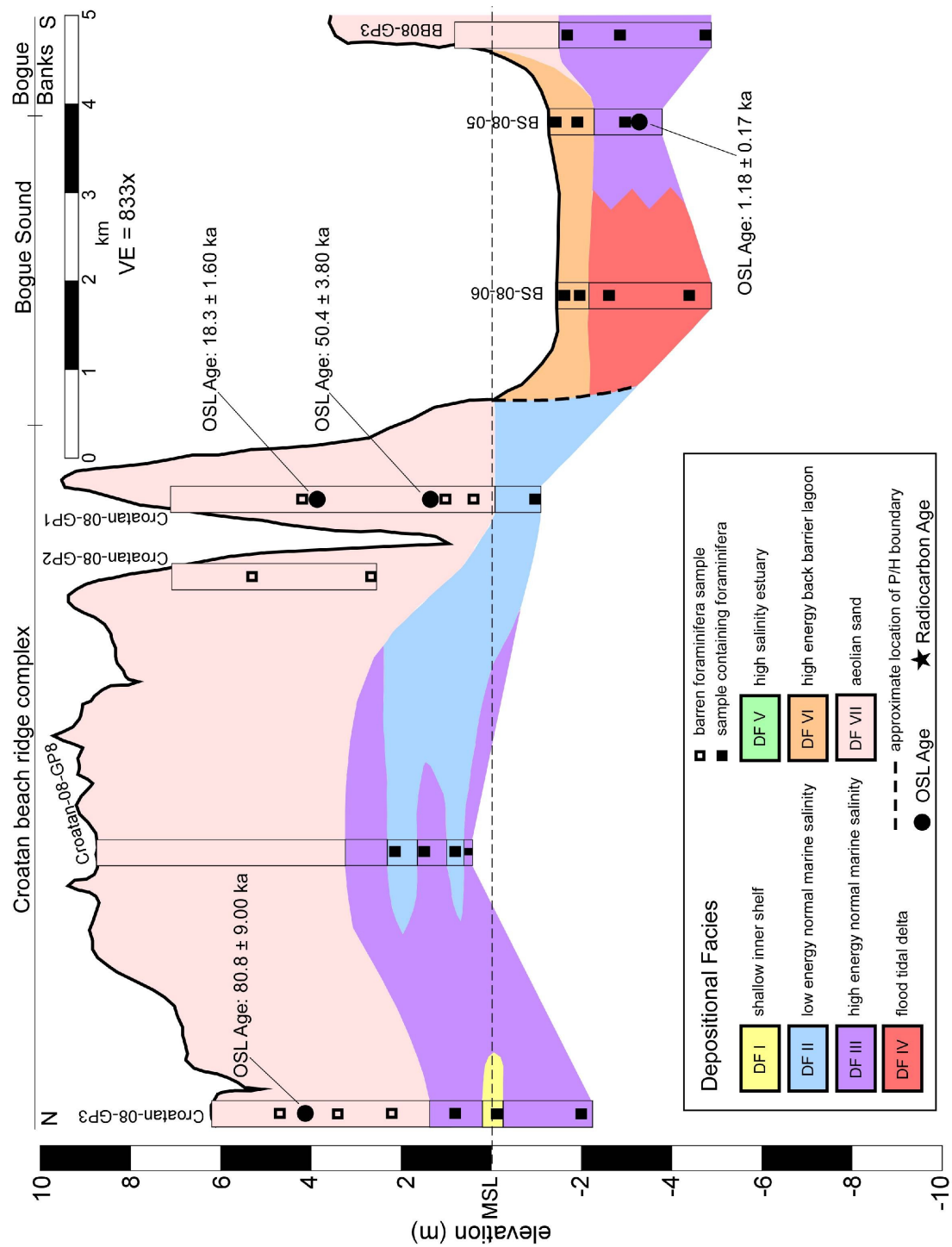


Figure 51. Cross section of depositional facies along Transect B.

area, and is composed of five geoprobe cores and two vibracores (Figure 51). Four of the five geoprobe cores were obtained from the Croatan Beach Ridge Complex (Croatan-08-GP3, Croatan-08-GP8 and Croatan-08-GP2 in Unit 1, and Croatan-08-GP1 in Unit 2), with the fifth core taken on Bogue Banks (BB08-GP3, Unit 3). Both vibracores were taken in Bogue Sound (BS-08-05, BS-08-06). Six depositional facies are identified in Transect B (Figure 51).

DF II (low energy normal marine salinity) and DF III (high energy normal marine salinity) comprise the oldest Pleistocene depositional facies in the Croatan Beach Ridge Complex (Units 1 and 2). DF III underlies the beach ridge complex in the north, and DF II underlies the complex in the center of the transect (underneath Croatan-08-GP1; Figures 46 and 51). DF II and III are interbedded in the bottom 3 m of Croatan-08-GP8. An OSL age estimate for DF II in Croatan-08-GP1 was 50.4 ± 3.80 ka (Figure 51).

DF I is interbedded with DF III in Croatan-08-GP3 (Figure 51). This depositional facies is ~0.5 m thick and located at approximately mean sea level. It is composed of sand (S), shelly muddy sand (shmS), and shelly sandy mud (shsM). This shallow inner shelf depositional facies is also present in Transect A.

DF VII caps all of the cores in the Croatan Beach Ridge Complex (Figure 51). This aeolian depositional facies is thickest underneath the beach ridge crests, reaching a maximum thickness of ~7 m. The geometry of this depositional facies is similar in Transects A, B and C. The northern-most core in this transect, Croatan-08-GP3, yielded an OSL date in this depositional facies of 80.8 ± 9.00 ka. The southern-most core in the Croatan Beach Ridge Complex, Croatan-08-GP1, yielded an OSL age estimate in this

depositional facies of 18.3 ± 1.60 ka, interpreted as representing aeolian reactivation during the last glacial maximum (LGM). The commencement of beach ridge formation in this area (~80 ka) began during MIS 5a, coeval with the formation of the Suffolk Scarp (Mallinson et al., 2008; Parham, 2009).

The Pleistocene-Holocene boundary, as in Transect A, occurs between the Pleistocene beach ridge of Unit 2 and the sediments of Bogue Sound (Figure 51). DF III (high energy normal marine salinity) occurs at the base of BS-08-05 and BB08-GP3, underneath Bogue Banks and the southern portion of Bogue Sound (Figure 51).

DF IV is laterally equivalent to DF III below Bogue Sound (Figure 51). DF IV in BS-08-06 is composed of shelly sand (shS) and large shell deposits (Sh), and is interpreted to represent flood tide delta deposits. This is corroborated by a fining-upward sequence (Smith et al., 2009) and the presence of large shell deposits composed of echinoid spines, *Gemma gemma*, oysters, and numerous other bivalves. A layer of imbricated shell fragments is present at ~4 m below mean sea level. These large shell deposits possibly represent storm beds.

DF VI (high energy back-barrier lagoon) represents the most recent deposit in Bogue Sound, and is present in BS-08-05 and BS-08-06. It reaches a maximum thickness of ~1 m in BS-08-05 (Figure 51). In this transect, it is composed of the interbedded mud and sand with shells (shI) and shelly sand (shS) lithofacies.

DF VII overlies DF III on Bogue Banks (Figure 51). DF VII in this location is characterized by the fine-grained sand lithofacies similar to DF VII deposits in BB08-GP2 in Transect A. It is also interpreted as a dune environment along a modern

shoreline.

Transect C

Transect C is a 4.5 km-long, west to east, beach ridge-perpendicular/shore-oblique transect extending through the Croatan Beach Ridge Complex (Figure 46). This transect is composed of three geoprobe cores (Croatan-08-GP8, Croatan-08-GP4, Croatan-08-GP5; Figure 46). Five depositional facies of Pleistocene age are identified in Transect C. Three large topographic highs are shown in cross section; Croatan-08-GP8 and Croatan-08-GP4 are located in the largest and western-most high, and Croatan-08-GP5 is located in the eastern-most high.

The basal depositional facies in this transect are DF III (high energy normal marine salinity) to the west and DF II (low energy normal marine salinity) to the east (Figure 52). DF III is interbedded with DF II in the western portion of the transect in Croatan-08-GP8 (Figure 52). DF III is dominated by sands with heavy minerals (S) and gravelly sands (gS). DF II in Croatan-08-GP8 is typically composed of mud (M) and sandy mud (sM). The lower 3 m of Croatan-08-GP8 is composed of interbedded mud/sandy mud and sand/gravelly sand units. The interbedded nature of the lithofacies is also reflected in the depositional facies of this core.

DF III is interbedded with DF I, interpreted to be shallow inner shelf in origin, in Croatan-08-GP4 (Figure 52). In this core, DF I is composed of interbedded mud and

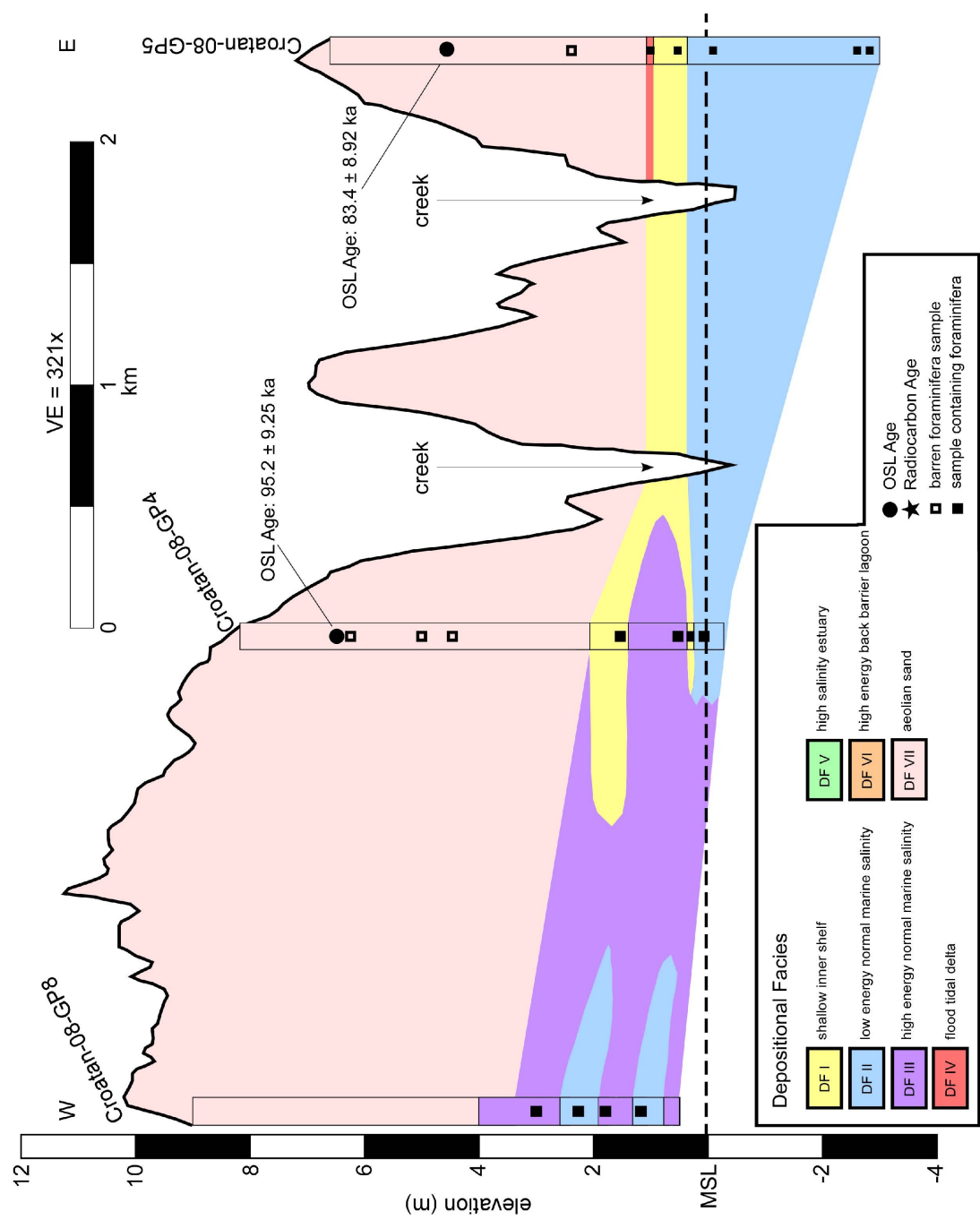


Figure 52. Cross section of depositional facies along Transect C.

sand with shells (shI), shelly sandy mud (shsM) and sandy mud (sM), while DF III is composed of sand (S), gravelly sand (gS), and shelly muddy sand (shmS). The primary distinction between DF III and DF I is their foraminiferal content. DF III is characterized by the more robust species of Biofacies C, whereas DF I contains the more delicate species of Biofacies A.

DF IV is located above DF I in the eastern-most ridge (Figure 52). It is represented in Croatan-08-GP5 as a unit 0.2 m thick. This thin unit is composed of coarse, shelly muddy sand (shS), and is only found in this part of the transect. As discussed in Transect A, it is possible that this small unit could be a part of the underlying DF I (shallow inner shelf).

DF VII caps all the cores in the transect (Figure 52). DF VII, aeolian in origin, is thicker in this transect than in any other, reaching a maximum thickness of 6 m (in Croatan-08-GP4). This depositional facies is composed of sand (S) and organic-rich sand (orgS) and comprises the beach ridge features (Unit 1) visible in the LiDAR data (Figure 2).

Transect D

Transect D is a 10 km-long, west to east, shore-parallel transect extending through Bogue Sound (Figure 46). This transect is composed of three vibracores (BS-08-05, BS-08-04, BS-08-01; Figure 46, 53). Four depositional facies of Holocene age are identified in Transect D.

DF IV, representing the flood tide delta paleoenvironment, comprises much of the

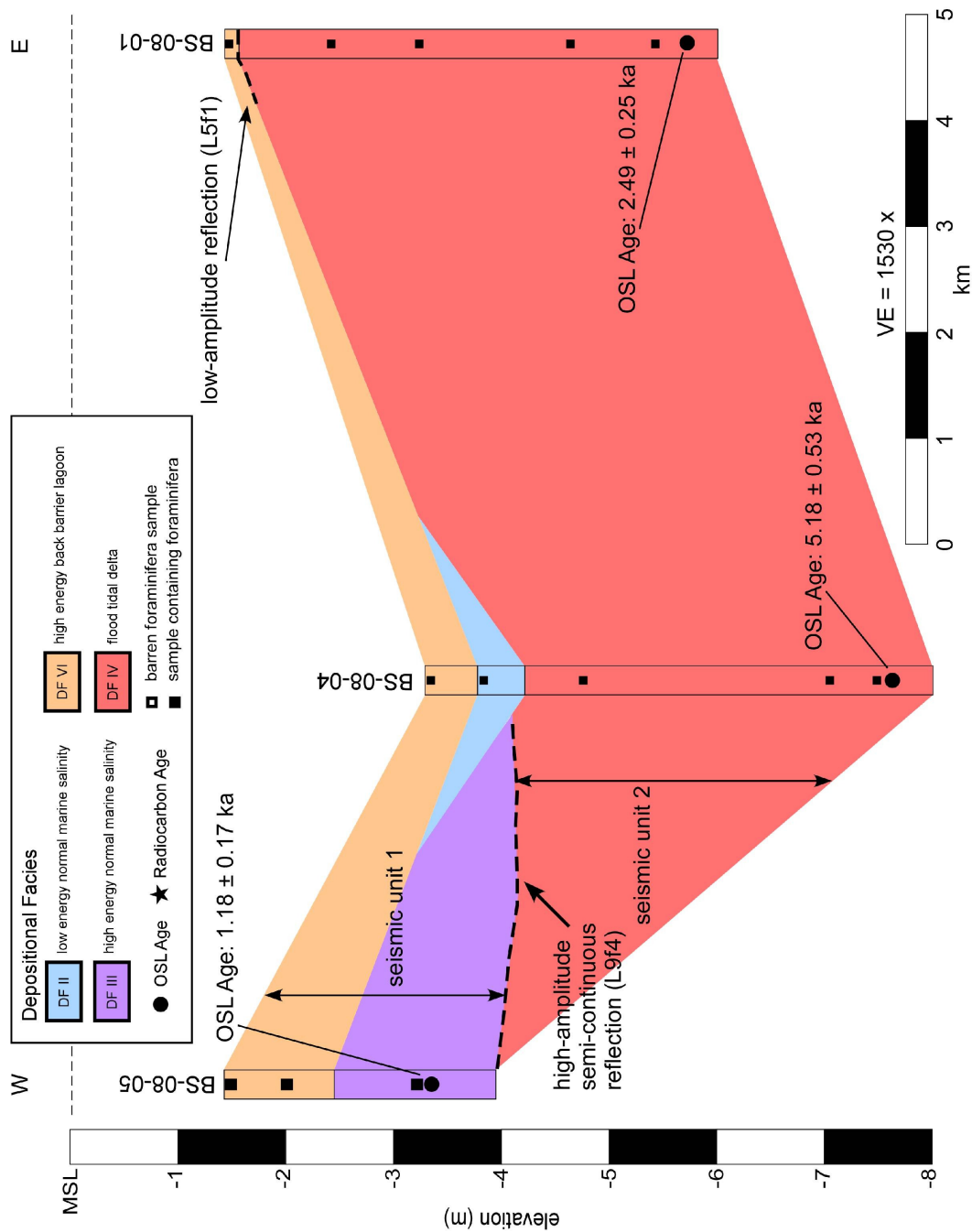


Figure 53. Cross section of depositional facies along Transect D.

BS-08-04 and BS-08-01 (Figure 53). It has a maximum thickness of 4.5 m (BS-08-01) in the east (Figure 53). An OSL sample taken from the bottom of BS-08-04 yielded an age estimate of 5.18 ± 0.53 ka. Another OSL sample, to the east in BS-08-01, yielded an age estimate of 2.49 ± 0.25 ka.

DF II overlies DF IV in the central portion of the transect (BS-08-04; Figure 53). This depositional facies represents a low energy normal marine salinity environment and is composed of mud with few organics and burrows.

In the western section of the transect, DF III (high energy normal marine salinity) overlies DF IV (Figure 53). This depositional facies is ~1.5 m thick in core BS-08-05. It is composed of shelly sand (shS) and large shell deposits. An OSL sample taken in this unit within BS-08-05 yielded an age estimate of 1.18 ± 0.17 ka.

DF VI (high energy back barrier lagoon) caps every core in this transect, and represents the most recent back-barrier estuarine deposits of Bogue Sound (Figure 53). This depositional facies reaches a maximum thickness of ~1 m in the western section of the transect in BS-08-05 and thins eastward. It is composed of shelly sand (shS) and interbedded mud and sand with shells (shI).

A discontinuous reflection at ~4 m below MSL provided the boundary between seismic units 1 and 2 in seismic line L6f1. This could represent the boundary between DF III (the lower unit of seismic unit 1) and DF IV (seismic unit 2), illustrated in Transect D (Figure 53). A low-amplitude reflection is also present in seismic line L5f1, forming a boundary between DF VI and DF IV at ~ 2 m below MSL (Figure 54).

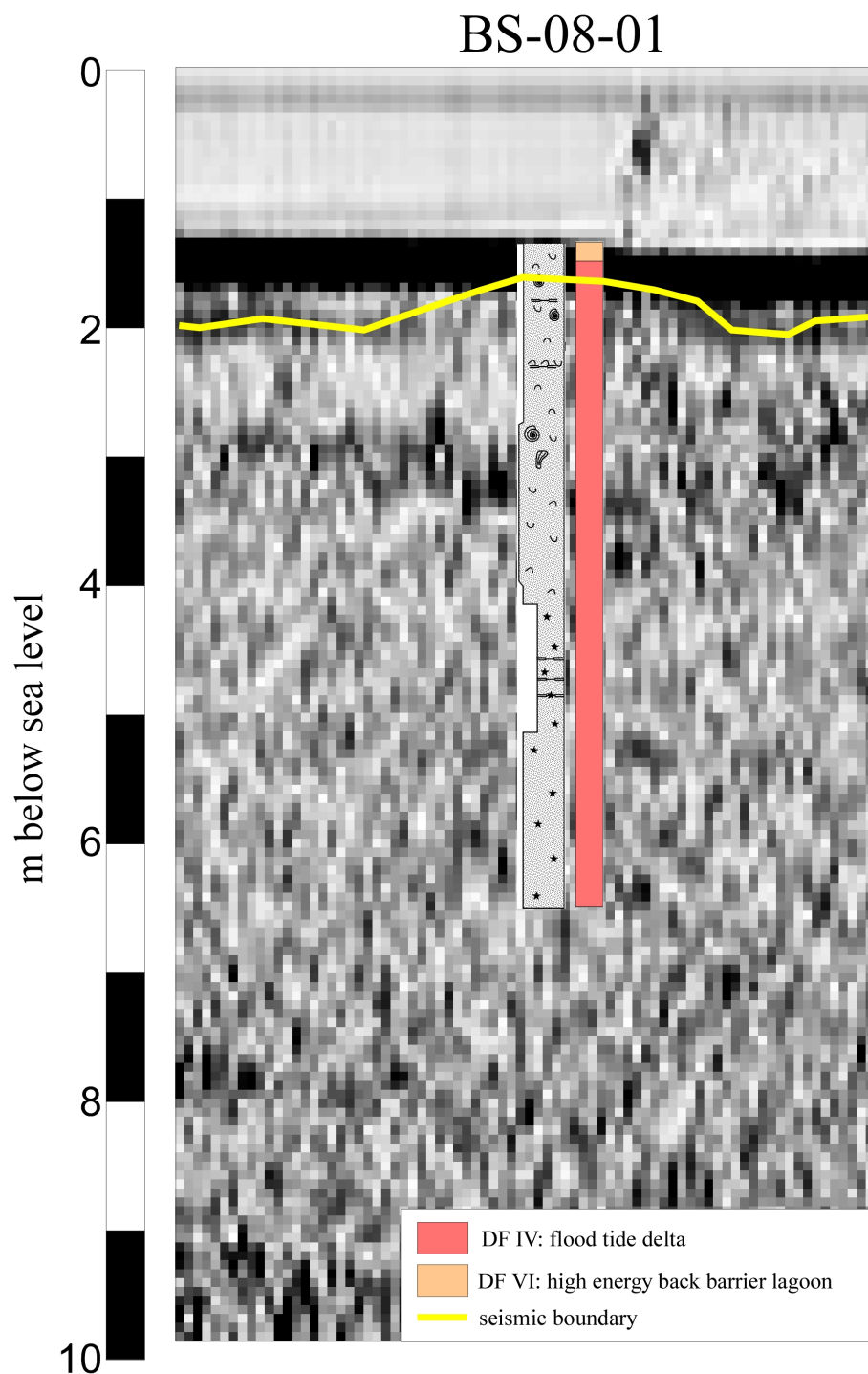


Figure 54. Lithologic core log and depositional facies log from BS-08-01 superimposed on seismic line L651. Yellow line indicates a seismic reflection interpreted at approximate lithologic change within the core.

DISCUSSION

Late Quaternary Deposits Related to Sea-Level Change

Sea-level fluctuations and climate change have shaped the coastal system of North Carolina. The oscillations between glacial and interglacial periods during the late Quaternary was first demonstrated by Emiliani (1955). He created a deep-sea sedimentary oxygen isotope curve which illustrates changes in $\delta^{18}\text{O}$ through time, which has been used as a proxy for glacial/interglacial stages over the past 1 Ma. The oxygen-isotope curve has since been modified and refined by numerous workers (Chappell and Shackleton, 1986; Lucchi et al., 2004; Figure 55). Each oscillation is numbered, starting with the present Holocene interglacial numbered “1”; subsequent interglacials are given odd numbers and glacials even numbers. Small-scale fluctuations within a glacial/interglacial event are named stadials (colder temperatures during an interglacial event) or interstadials (warmer temperatures during a glacial event) and are identified using a letter following the number of the glacial/interglacial event. These events are typically referred to as marine isotope stages (MIS).

Numerous geomorphic features of the North Carolina coastal plain have been created or altered by climate and sea-level change since the end of MIS 6, discussed below (Riggs et al., 1995; Mallinson et al., 2005, 2008a, 2008b; Parham et al., 2008; Parham 2009).

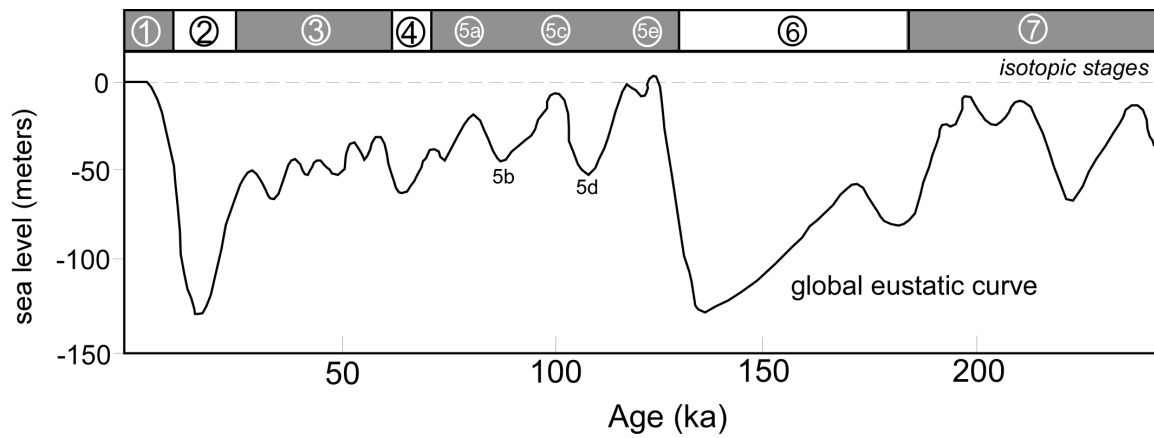


Figure 55. Oxygen isotope curve derived from Chappell and Shackleton (1986), modified by Lucchi et al. (2004). This curve serves as a graphical representation of global glacial/interglacial events and a proxy for sea level over the past 240,000 years. Note the Marine Isotope Stage nomenclature for each glacial/interglacial is depicted above its corresponding trough/peak.

MIS 6 to MIS 5e (150-120 ka)

Studies of northeastern North Carolina and southern Virginia suggest that the earliest formation of the Suffolk Shoreline was associated with eroding interfluvial areas of the York, James, and Susquehanna Rivers (Oertel and Foyle, 1995; Parham, 2009). During rising sea-level accompanying the MIS 6/MIS 5 transition, interfluvial areas became eroding headlands and sediment sources for the Suffolk Shoreline (Table 9). This assertion is further supported by OSL age estimates of tidal estuarine deposits located west of the Suffolk Shoreline, which yield an age estimate within MIS 5e (Parham 2009).

MIS 5c to 5a (110-70 ka)

The Suffolk Shoreline was reoccupied during MIS 5a (Wehmiller et al., 2004; Mallinson et al., 2008b; Parham, 2009). MIS 5a relative sea levels ranged from +6 to +9 m MSL in records from North Carolina and Bermuda (Potter and Lambeck, 2004; Mallinson et al., 2008b). Two sea-level highstands comprising the Suffolk Shoreline were documented by Thompson and Goldstein (2005); two geomorphic features inferred to be relict shorelines were also described by Mallinson et al. (2008b). The highstands were U/Th dated at 84 and 77 ka, while the shorelines described by Mallinson et al. yielded an OSL age of ~80 ka. It is probable that the two geomorphic features recorded by Mallinson et al. (2008b) are in fact a product of the sea-level highstands described by Thompson and Goldstein (Parham 2009). Several other dates derived from shelly substrate east of the scarp yield similar dates within MIS 5a (Cronin et al., 1981; Mixon et al., 1982; Wehmiller et al., 2004; Parham, 2009).

Geologic Evolution of the Croatan Beach Ridge Complex, Bogue Sound, and Bogue Banks	MIS Stage	Age (ka)	Pertinent Geologic Evolution of the Suffolk Shoreline and Outer Banks
Spit progradation closes Bogue Banks	1	~1 - present	
Open bay conditions (normal marine salinity) persist in Bogue Sound, behind central Bogue Banks		1.1	Collapse of segments of the Outer Banks; open bay conditions in southern Pamlico Sound (Culver et al., 2007)
Spit progradation continues to eastern tip of Salter Path		1.3	
Seaward and westward spit progradation begins in Pine Knoll Shores area		1.7	
		3	Formation of the Outer Banks (Mallinson et al., 2008a)
		4	Overtopping of the Hatteras Flats Interstream Divide; open bay conditions in southern Pamlico Sound (Culver et al., 2007)
Occurrence of flood tide delta deposits behind Bogue Banks		6-2.5	
Earliest formation of Bogue Banks		6	
Aeolian reactivation of upper segments of the Croatan Beach Ridge Complex	2	18	
	3	43-55	Proto-barrier islands begin to form on the Pamlico Terrace in the northern Outer Banks (Mallinson et al., 2005)
		60-70	Parts of Suffolk Shoreline reoccupied (Scott, 2006; Parham, 2009)
Formation and southern-progradation of the Croatan Beach Ridge Complex producing a cape structure	5a	80-95	Proto-Cape Lookout begins to form in association with the Suffolk Shoreline (Figure 56; Parham, 2009)
	5e	125	Earliest formation of the Suffolk Scarp (Parham, 2009)

Table 9. Summary of geologic evolution of the Croatan Beach Ridge Complex, Bogue Sound, and Bogue Banks and pertinent histories of the Suffolk Shoreline and Outer Banks over the past 150 ka.

Late MIS 5a deposits also suggest an eastward-building cape complex beginning to form at the southern terminus of the Suffolk Shoreline (Figure 56). Parham (2009) suggested that this feature represents a proto-Cape Lookout (Figure 56; Table 9).

In this study, OSL samples from DF VII in the northern-most beach ridges in the Croatan Beach Ridge Complex yielded an age date of ~81 ka (Figure 57). This suggests formation of the beach ridges in the northern portion of the study area began during MIS 5a and confirms that the development of this beach ridge complex is an integral component of the formation of the Suffolk Shoreline in the southern coastal plain of North Carolina and confirms that the Croatan Beach Ridge Complex is a MIS 5a cape (Figure 57; Table 9).

The basal units of the Croatan Beach Ridge Complex (Unit 1) are comprised of both high- and low-energy normal marine salinity deposits. This confirms that during their deposition, sea level was higher than at present. Above the basal normal marine salinity units, a shallow inner shelf deposit occurs throughout Transect A and in Croatan-08-GP3 in Transect B (Figures 47, 51). This also corroborates a higher sea level during MIS 5a. Aeolian sand deposits occur above these normal marine salinity deposits. These deposits occur at a shallower elevation in the northern segments of Transects A and B (Croatan-08-GP3, Croatan-08-GP6; Figures 47, 51). This suggests that aeolian deposits began to form in Unit 1 as sea level began to fall, beginning to form the geomorphology of the beach ridge complex visible in LiDAR data (Figures 1, 2). These deposits began to prograde to the south, following the drop in sea level. Unit 2, the southern-most ridge in

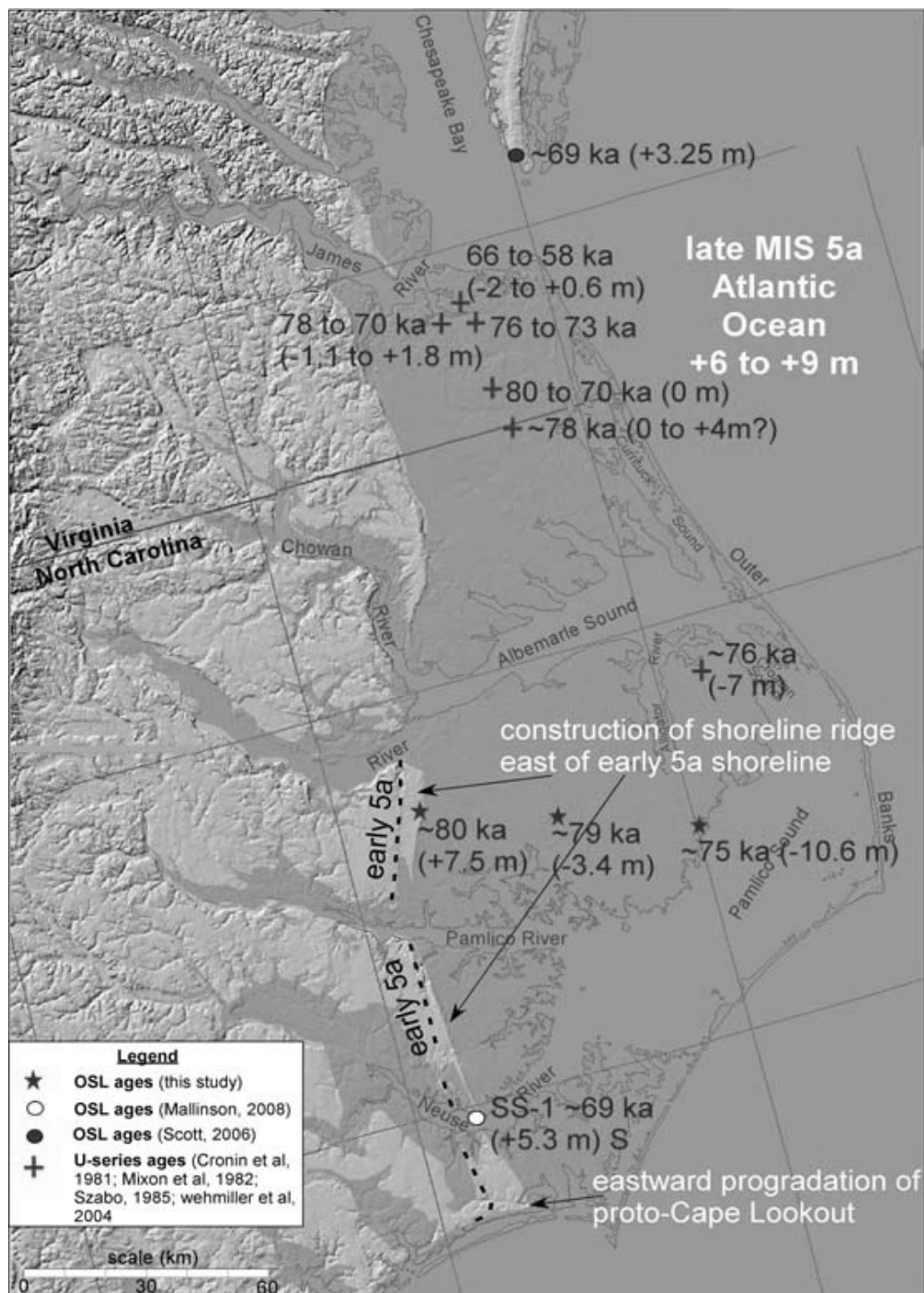


Figure 56. Shoreline model of sea-level during late MIS 5a. OSL dates taken from Cronin et al. (1981), Mixon et al. (1982), Szabo (1985), Wehmiller et al. (2004), Scott et al. (2006), Mallinson et al. (2008b), and Parham (2009). From Parham (2009).

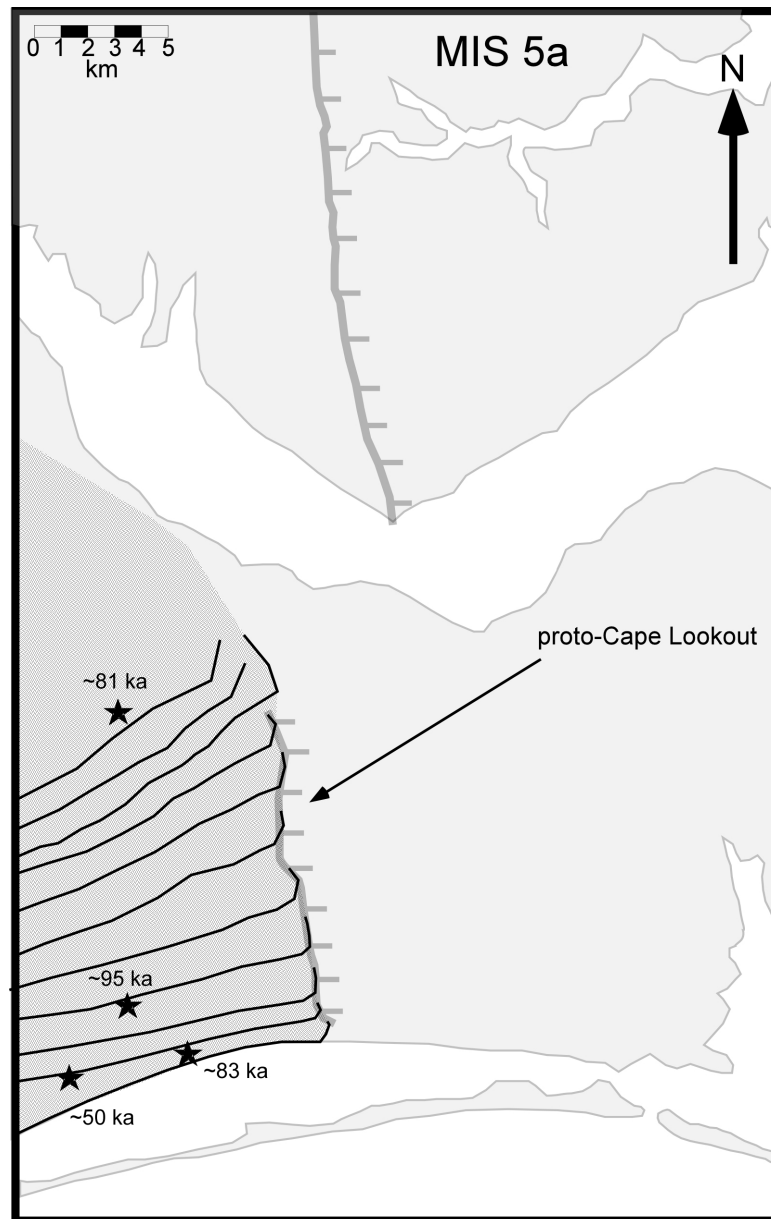


Figure 57. Map of shoreline associated with MIS 5a. The Suffolk Shoreline is hatched, and its location determined from LiDAR data. The development of the Croatan Beach Ridge Complex through this period is shaded. The modern shoreline is shown for the purpose of orientation.

the Croatan Beach Ridge Complex, comprises an old shoreline and, currently the northern margin of modern Bogue Sound. Unit 2 represents the last ridge in the Croatan Beach Ridge Complex and its point of southern-most progradation.

Fluvial influences are evidenced in portions of the Croatan Beach Ridge Complex during MIS 5a. Croatan-08-GP3, located in the northern section of the study (Figure 46), contains significant amounts of mud and sandy-mud interbedded with the typical fine to medium-fine sand comprising the aeolian sand depositional facies (DF VII; Figure 58). Mud is only present within DF VII in small quantities in the other cores originating from the Croatan Beach Ridge Complex. This mud is inferred to have originated from flooding of a nearby river, most probably the paleo-Neuse (located further north). DF III, a high energy normal marine salinity depositional facies, underlies the muddy sands of DF VII in Croatan-08-GP3. This represents open marine deposition near a river mouth.

MIS 3 (60-40 ka)

During MIS 3, relative sea level in North Carolina ranged from +3 to as much as +5 m MSL (Mallinson et al., 2008b; Parham 2009). OSL age estimates of the Sedgfield Member suggest that sea level was approximately +5 m MSL, and occupied portions of the Suffolk Scarp (Scott 2006; Table 9). This is evidenced by truncation of the Suffolk paleoshoreline south of Albemarle Sound (Parham, 2009). Several barrier islands also began to form on the Pamlico Terrace landward of the modern northern Outer Banks (Table 9). Five OSL dates on the Currituck ridges (Land of Promise Ridge, Powells

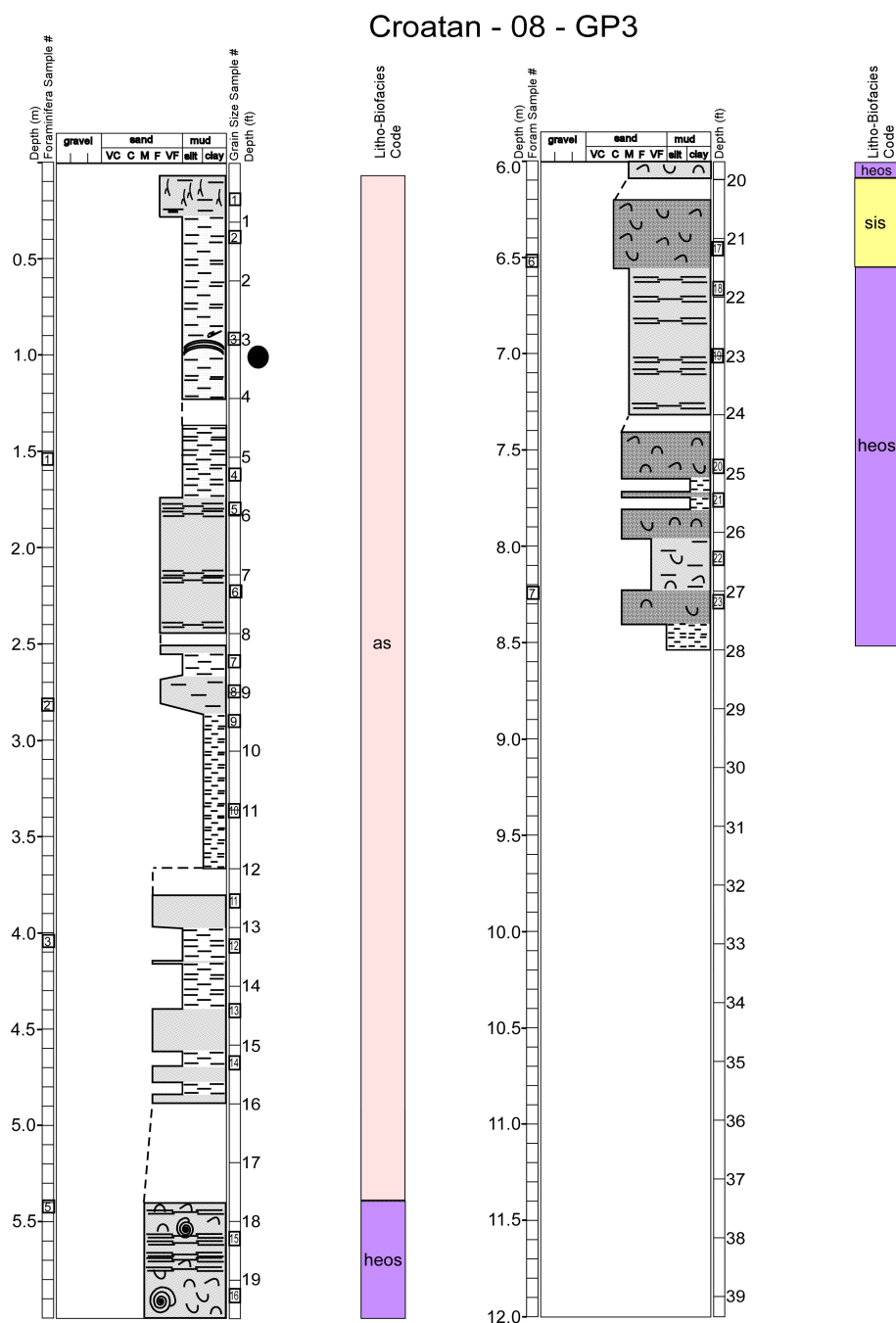


Figure 58. Lithologic core log of Croatan-08-GP3. Note the extent of muddy deposits within the aeolian sand depositional facies from 0.3-5 m (represented as dashes). Litho-biofacies Code abbreviations: As = aeolian sand depositional facies (equivalent to DF VII); heos = high energy open shelf (equivalent to DF III); sis = shallow inner shelf (equivalent to DF I).

Point Ridge) confirm this, ranging in age from 43-55 ka (Mallinson et al., 2008b).

An OSL sample from DF II (low energy normal marine salinity) +1.30 m MSL in Croatan-08-GP1 yielded an age estimate of ~50 ka (during MIS 3). This core was taken from one of the southern-most ridges (Unit 2) in the Croatan Beach Ridge Complex. As discussed previously, three OSL age estimates throughout the Croatan Beach Ridge Complex (Units 1 and 2) range from ~80-95 ka. Furthermore, a sample from a higher stratigraphic unit (DF VII; aeolian sand) in the same Unit 2 ridge to the east, yielded an OSL age estimate of ~83 ka (Croatan-08-GP5). Thus, it is likely that 50 ka does not accurately reflect the age of deposition of Unit 2. The Croatan-08-GP1 core could have been partially exposed to light during recovery or sample collection, resetting the traps of some sand grains and not others, thus resulting in a younger age. This younger age could also be the result of an increased dose rate over time due to leaching of overlying sediments and a concentration of radioisotopes at depth.

MIS 2 to MIS 1 (30 ka to present)

Sea level fell rapidly during MIS 2 to -120 m MSL (Fairbanks, 1989; Bard et al., 1990; Chappell et al., 1996; Fleming et al., 1998; Yokoyama et al., 2001; Lambeck et al., 2002), resulting in the subaerial exposure of the U.S. Atlantic continental shelf. An OSL sample from one of the southern-most ridges in the Croatan Beach Ridge Complex at +3.80-3.87 m MSL yielded an age of ~18 ka (from Croatan-08-GP1). This suggests aeolian reactivation of the upper portion of the beach ridge complex during MIS 2 (Table 9). A similar interpretation was made to explain the ages of an aeolian sand sheet and

dunes above beach facies in Swansboro, NC, an area immediately west of the study area (Mallinson et al., 2008a). Three similar units were described in this area and yielded similar OSL age estimates. The oldest unit, an initial beach ridge feature, was dated to at least 45 ka. Above the beach ridge, an aeolian sand sheet and dune complex was identified, yielding an OSL age estimate corresponding to the Younger Dryas (12.9 to 11.6 ka). This dune system was also found to be reactivated, yielding an OSL age estimate of ~10 ka (Mallinson et al., 2008a). This sequential formation, reworking, and reactivation of the aeolian sand sheet follows a similar pattern to the development of the Croatan Beach Ridge Complex.

Sea level rose dramatically from MIS 2 to MIS 1 (Figure 17). This rise began to slow at ~ 8-6 ka (Horton et al., 2009). Bogue Banks sit in Onslow Bay, a sediment-starved area with little fluvial sediment input. Lack of sediment inhibits barrier island formation and development, suggesting that barrier islands did not exist until the rate of Holocene sea-level rise decreased. The stratigraphically oldest Holocene deposits in Bogue Sound belong to the high salinity estuarine depositional facies (Figure 47). An OSL sample from this unit yielded an age estimate of ~41 ka. This date is most likely unreliable, due to similar conditions which affected the previously discussed ~50 ka age estimate for a sample from Croatan-08-GP1, as well as the lack of a clear contact above the sample. Sea level was also likely too low at 41 ka to create an estuarine deposit at this location. Another explanation for this OSL age estimate is a potentially rapid scouring of Pleistocene sands and redeposition of these grains in the Holocene, causing grains in this sample to be only partially bleached. This partial bleaching would result in

a bimodal distribution of the OSL sample, and would yield an age estimate that was the result of averaging the Holocene ages (~ 2 ka) and original Pleistocene deposition ages (~ 80 ka).

Two OSL age estimates in Bogue Sound, behind Pine Knoll Shores, from the flood tide delta depositional facies, yielded ages of 2.49 ± 0.25 and 5.18 ± 0.53 ka (BS-08-01 and BS-08-04, respectively; Figure 53). One radiocarbon age estimate of ~ 6 cal. ka was also acquired from this depositional facies (BS-08-03; Figure 47). Thus, Bogue Banks barrier islands existed by ~ 6 cal. ka (Table 9), somewhat earlier than the Outer Banks barrier islands to the north which began to form around 3 ky BP (Riggs et al., 1995; Mallinson et al., 2005, 2008a; Culver et al., 2007; Table 9). The low energy normal marine salinity depositional facies (DF II) is present in Bogue Sound by 3.82-4.02 cal ka (BS-08-03, BS-08-04; Figure 47). This suggests that the barrier island was overtopped or breached at the same time as the Hatteras Flats Interstream Divide (the precursor to the Outer Banks) was overtopped by sea level rise (Table 9).

The dune ridges present on Bogue Banks (Unit 3) suggest progradation occurred (Figure 59; Table 9); shell material from these ridges has been radiocarbon dated to 3.8 ka (Steele, 1980; Heron et al., 1984). Two OSL samples taken from ~ 1 m MSL on the sound side of Bogue Banks (BB08-GP1 and BB08-GP2) yielded age estimates of 1.72 and 1.35 ka, respectively. The older OSL age estimate is found in the eastern-most core on the island, which suggests westward- and seaward-progradation of the beach ridges along Bogue Banks (Figure 59; Table 9), consistent with the geomorphology of the system (documented by LiDAR data). Moreover, the rate of progradation suggested by

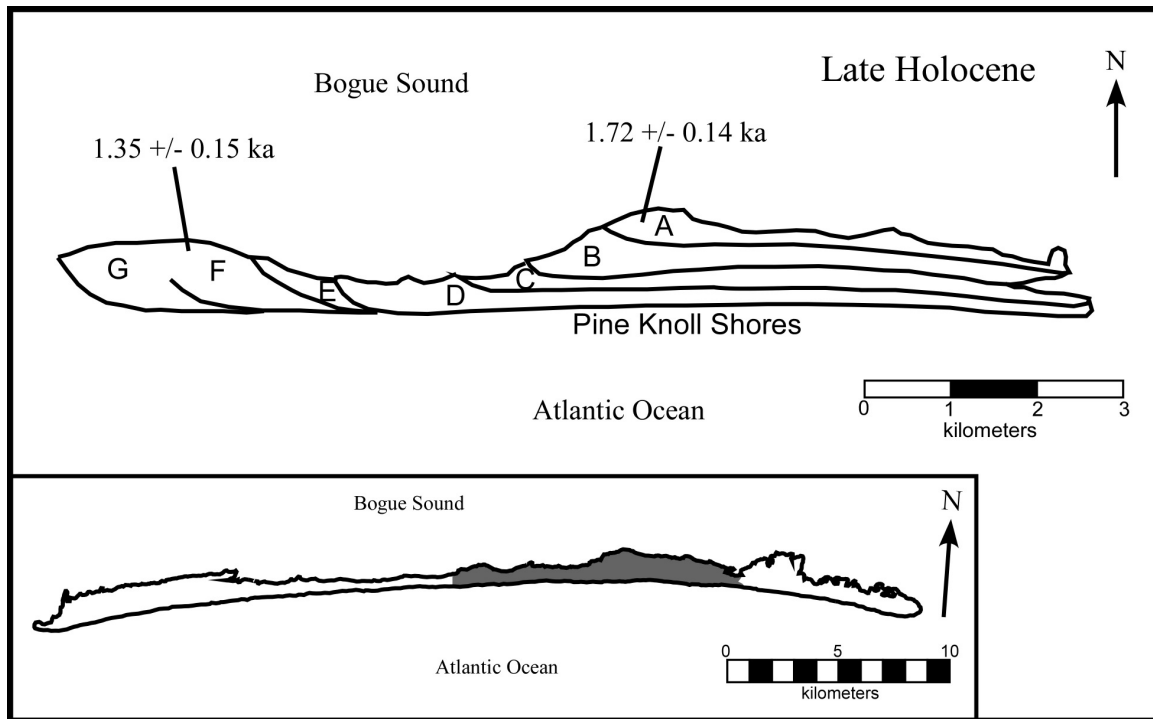


Figure 59. Spit development of Bogue Banks. Letter A illustrates the beginning of a westward- and seaward-progradation of the barrier island (continuing to G). OSL age estimates are labeled at their collection sites. Progradation is shown to occur over ca. 400 years. Inset: Bogue Banks, with the area of spit development shaded.

the ages (~6 km in 400 years, or 15 m/yr) is similar to rates of progradation of the spit associated with the southward migration of inlets (c. 23 m/yr; Riggs and Ames, 2009).

The lack of tidal marsh areas on the sound-side of the island suggests that large areas of inlet activity have not occurred along Bogue Banks in recent history (Cleary and Pilkey, 1996). However, Steele (1980) documented large areas of inlet fill in the Pine Knoll Shores area (Figure 5), suggesting localized inlet activity. Sedimentological and foraminiferal data from this study indicate large sections of flood tide delta deposits along the eastern portion of Bogue Sound, directly behind the Pine Knoll Shores area of Bogue Banks (Figure 5). Adjacent to Pine Knoll Shores is the Atlantic Beach area, which was developed over the flood tide delta of Cheeseman's Inlet, which was open ca. 1850 (Cleary and Pilkey, 1996; Figure 5). Beaufort Inlet, which separates Bogue Banks from Shackleford Banks, is one of the most stable inlets in North Carolina (Cleary and Pilkey, 1996; Figure 5). The inlet lies over an antecedent fluvial drainage pattern, which has kept this inlet stationary for at least the past 300 years (Stick, 1958). The persistent presence of an inlet in this area could suffice to explain the extensive flood tide delta deposits found in this study in Bogue Sound.

At approximately 1.1 ka, open bay conditions were present in Pamlico Sound, associated with the collapse of segments of the Outer Banks barrier island chain. This trend is also seen in Bogue Sound. In BS-08-05 (Figures 51, 53), a high energy normal marine salinity depositional facies (DF III) is OSL dated to 1.18 ka.

The sea-level rise and subsequent flooding of the estuaries to form Pamlico Sound to the north seemingly also removed portions of Bogue Banks to the point that open shelf

conditions occurred in Bogue Sound (Table 9). This is evidenced by the presence of this facies (DF III) underneath both Bogue Sound and Bogue Banks, with the aeolian sand depositional facies overtopping it on the island and flood tide delta deposit overlying it in Bogue Sound (Figure 51). Underneath Bogue Banks, DF III most likely represents shoreface sands similar to DF III deposits located immediately below the aeolian sand depositional facies in the Croatan Beach Ridge Complex, and are not necessarily indicative of a collapse.

BB08-GP1 was dated to ~1.72 ka (sample depth of 0.20 m below MSL) and BB08-GP2 was dated to ~1.35 ka (sample depth of 0.85 m below MSL; Table 7), suggesting that only portions of the island were eroded and breached. The original location of Bogue Banks was more landward than at present by ~1.7 ka (Figure 59). The island then prograded south and west, maintaining (or reopening to) normal marine salinity conditions, to the area of BS-08-05 by ~1.1 ka (Figure 60; Table 9). This is evidenced in Transect D, illustrating no normal marine salinity depositional facies on the eastern sections of the transect (Figure 53). A contact between the high energy normal marine salinity depositional facies (DF III) and high energy back-barrier lagoon depositional facies is visible in seismic line L9f4 (Figure 60). A discontinuous reflection at ~2.5 m below MSL represents the bottom of seismic unit 1 in this seismic line (Figure 60). This reflection could indicate the closing of central Bogue Banks (between 1.1 ka and the present; Figure 60; Table 9).

BS-08-05 lies behind the Salter Path portion of the island, one of the narrowest and most vulnerable places for overwash and sea-level rise flooding on Bogue Banks

(Figures 5, 20, 60). Fisher (1967) illustrated the development of the dune system on Bogue Banks, and indicated an erosional period during which the island was segmented (Figure 60). The largest area of erosion on the island was located in the modern Salter Path region, and could explain the presence of high energy open shelf deposits in Bogue Sound cores in this location (Figures 5, 53, 60).

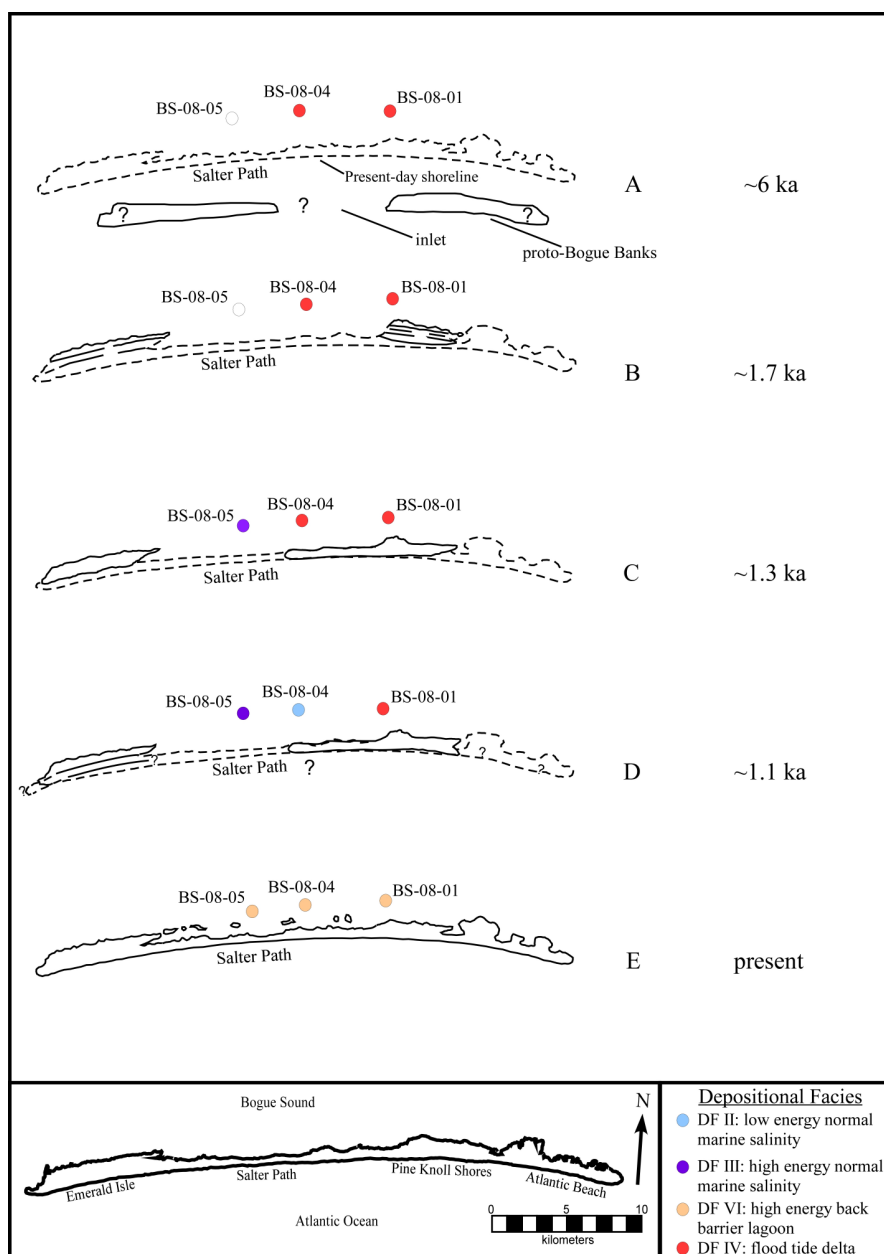


Figure 60. Evolution of Bogue Banks as described by Fisher (1967). Age of time slices (A-E) based on the OSL and ^{14}C age estimates of this study. (A) Initial formation of the island; (B-C) Seaward and westward spit progradation; (D) Normal marine salinity conditions persist in Bogue Sound; (E) Eventual closing of the island through spit progradation; present configuration of the island. Depositional facies of Bogue Sound cores are shown at each time slice. Inset: Map of Bogue Banks, with each community of the island labeled.

The evolution of Bogue Banks (Unit 3) can be broken into six time slices (Figure 60). At approximately 6 ka, Bogue Banks began to form near its present location (as evidenced by age estimates in the flood tide delta deposit behind the island)(Table 9). Only small segments of the barrier island existed at this point, most probably in the modern Pine Knoll Shores and Emerald Isle areas (Figure 60; Table 9). At ~1.7 ka, a seaward and westward progradation began in western Pine Knoll Shores. This progradation is documented until at least ~1.3 ka, creating ~6.5 km of a spit complex over ca. 400 years (Figure 60; Table 9). This results in a spit progradation rate of 16.25 m/yr, a rate similar to that found at Oregon Inlet today (Riggs and Ames, 2009). At ~1.1 ka, normal marine salinity conditions were present in Bogue Sound (due to overwash or island breaching). This is the same timing as the collapse of the southern Outer Banks (Culver et al., 2007) which led to normal marine salinity conditions in southern Pamlico Sound for ca. 500 years (Figure 60; Table 9). As the southern Outer Banks barriers reformed, spit progradation on Bogue Banks continued seaward and westward, eventually filling in the central portions of the Banks and resulting in high energy back-barrier lagoonal conditions in Bogue Sound. The eventual progradation of the spit complex across the Salter Path region resulted in the modern configuration of Bogue Banks (Figure 60; Table 9).

SUMMARY

- 1) This study reconstructs the late Quaternary evolution of the Croatan Beach Ridge Complex, Bogue Sound, and Bogue Banks areas using micropaleontological (foraminifera), lithologic, geophysical (ground penetrating radar and seismic), and chronostratigraphic data (OSL and AMS ^{14}C).
- 2) Eleven geoprobe cores and six vibracores were collected along three shore-normal and one shore-parallel transects. Thirteen lithofacies were identified: sand, organic-rich sand, muddy sand, shelly muddy sand, shelly sand, gravelly sand, mud, sandy mud, shelly mud, shelly sandy mud, interbedded mud and sand, interbedded mud and sand with shells, and large shells.
- 3) Six foraminiferal biofacies were identified: shallow inner shelf, low energy open shelf, high energy open shelf, flood tidal delta, high salinity estuary, and high energy back-barrier lagoon. Typically aeolian sand capped cores in the Croatan Beach Ridge Complex and Bogue Banks and was barren of foraminifera.
- 4) Seven depositional facies were identified using a combination of lithofacies and biofacies data: shallow inner shelf, low energy normal marine salinity, high energy normal marine salinity, flood tidal delta, high salinity estuary, high energy back-barrier lagoon, and aeolian sand.
- 5) The Croatan Beach Ridge Complex formed ca. 95-80 ka (MIS 5a).
- 6) Croatan-08-GP3 was OSL dated to 80.8 ka and represents the northern-most construction of the Croatan Beach Ridge Complex. The eastern-extent of the complex also represents the southern terminus of the Suffolk Shoreline during

MIS 5a. These beach ridges represent a cape structure associated with this shoreline.

- 7) Reworked eolian deposits began to cap the beach ridges during the lower sea levels of MIS 2 (~18 ka).
- 8) The occurrence of flood tidal delta deposits behind Bogue Banks indicate inlet activity near the Atlantic Beach/Pine Knoll Shores and Salter Path areas between 6 ka and 2.5 ka. This suggests a barrier island was present ca. 6 ka.
- 9) Approximately 4 ka, the Hatteras Flats Interstream Divide was overtopped along the Outer Banks in Pamlico Sound and barrier islands began to form. At this time, Bogue Banks had already formed and low energy normal marine salinity facies were being deposited in Bogue Sound.
- 10) A spit complex began prograding westward and southward along Bogue Banks at ~1.7 ka and built westward by ~6 km in ca. 400 years, building the barrier island in its present location.
- 11) Approximately 1.1 ka, normal marine salinity conditions were present in Bogue Sound, suggesting removal of at least the narrowest parts of Bogue Banks. This is coincident with the collapse of the barrier islands along the Outer Banks.
- 12) Integrating sedimentological, foraminiferal, geophysical and chronostratigraphic tools has been a successful method of reconstructing environmental change through time.

REFERENCES

- Abbene, I.J., 2004. Reconstruction of Recent Paleoenvironments of Pamlico Sound, North Carolina using Foraminifera, Stable Isotopes ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$), and Sedimentation Rates. Unpublished Master's Thesis, East Carolina University, Greenville, NC, 159 p.
- Abbene, I.J., Culver, S.J., Corbett, D.R., Buzas, M.A., and Tully, L.S., 2006. Distribution of Foraminifera in Pamlico Sound, North Carolina, over the past century. *Journal of Foraminiferal Research* 36: 135-151.
- Abbott, P.T., 1954. *American Seashells*, Van Nostrand, New York, 541 p.
- Aitken, M.J., 1998. *Introduction to Optical Dating*. Oxford University Press, 280 p.
- Akers, W.H., 1971. Estuarine foraminiferal associations of the Beaufort area, North Carolina. *Tulane Studies in Geology and Paleontology* 8: 147-165
- Andersen, H.V., 1952. *Buccella*, a new genus of the rotaliid Foraminifera. *Journal of the Washington Academy of Sciences* 42: 143-151.
- Applin, E.R., Ellisor, A.E., and Kniker, H.T., 1925. Subsurface stratigraphy of the coastal Plain of Texas and Louisiana. *Bulletin of the American Association of Petroleum Geologists* 9: 79-122.
- Baldock, T.E., Weir, F., and Hughes, M.G., 2008. Morphodynamic evolution of a coastal lagoon entrance during swash overwash. *Geomorphology* 95: 398-411.
- Bandy, O.L., 1954. Distribution of some shallow-water foraminifera in the Gulf of Mexico. *United States Geological Survey Professional Paper* 247-G: 179-204.
- Bandy, O.L., 1956. Ecology of Foraminifera in northeastern Gulf of Mexico: *United States Geological Survey Professional Paper* 254-F: 125-141.
- Bard, E., Hamelin, B., and Fairbanks, R.G., 1990. U-Th ages obtained by mass spectrometry in corals from Barbados: sea level during the past 130,000 years. *Nature* 346: 456-458.
- Berelson, W.M., 1979. Barrier island evolution and its effect on lagoonal sedimentation: Shackleford Banks, Back Sound, and Harker's Island: Cape Lookout National Seashore. Unpublished Master's Thesis, Duke University, Durham, NC 225 p.

- Berger, G.W., Murray, A.S., and Havholm, K.G., 2003. Photonic dating of Holocene back-barrier coastal dunes, northern North Carolina, U.S.A. *Quaternary Science Reviews* 22: 1043-1050.
- Boss, S.K., Hoffman, C.W., and Cooper, B., 2002. Influence of fluvial processes on the Quaternary geologic framework of the continental shelf, North Carolina, USA. *Marine Geology* 183: 45-65.
- Bradley, R.S., 1999. *Paleoclimatology: Reconstructing Climates of the Quaternary*. International Geophysics Series 64, Harcourt, San Diego, CA, 613 p.
- Brady, H. B., 1881. On some Arctic foraminifera from soundings obtained on the Austro-Hungarian North Polar Expedition of 1872-1874. *Annals and Magazine of Natural History* 5(8): 393-418.
- Brady, H.B., 1884. Report on the foraminifera dredged by the H.M.S. Challenger, during the years 1873-1876, *In: Report on the Scientific Results of the voyage of the H.M.S. Challenger during the years 1873-1876*. *Zoology* 9, 814 p.
- Brewster-Wingard, G.L. and Ishman, S.E., 1999. Historical trends in salinity and substrate in central Florida Bay: a paleoecological reconstruction using modern analogue data. *Estuaries and Coasts* 22: 369-383.
- Brill, A.L., 1996. The Suffolk Shoreline, a Pleistocene barrier in Beaufort and Pamlico Counties, NC. Unpublished Master's Thesis, Duke University, Durham, NC, 154 p.
- Bumpus, D.F., and Pierce, E.L. 1955. Hydrography and the distribution of Chaetognaths over the continental shelf off North Carolina. *In: Deep-Sea Research, Suppl. to vol. 3. Papers in Marine Biology and Oceanography*. Pergamon Press, New York, p. 193-197.
- Burdette, K., 2005. Chronostratigraphy of the Currituck sand ridges, Currituck County, North Carolina. Unpublished Master's Thesis, East Carolina University, Greenville, NC, 184 p.
- Cabanes, C., Cazenave, A., and Le Provost, C., 2001. Sea level rise during the past 40 years determined from satellite and in situ observations. *Science* 294: 840-842.
- Cazenave, A. and Nerem, R.S., 2004. Present-day sea level change: Observations and causes. *Reviews of Geophysics* 42: RG3001.
- Chappell, J. and Shackleton, N.J., 1986. Oxygen isotopes and sea level. *Nature* 324: 137-140.

- Chappell, J., Omura, A., Esat, T., McColloch, M., Pandolfi, J., Ota, Y., and Pillans, B., 1996. Reconciliation of Late Quaternary sea levels derived from coral terraces at Huon Peninsula with deep sea oxygen isotope records. *Earth and Planetary Science Letters* 141: 227-236.
- Church, J.A., White, N.J., Coleman, R., Lambeck, K., Mitrovica, J.X., 2004. Estimates of the regional distribution of sea-level rise over the 1950-2000 period. *Journal of Climate* 17: 2609-2625.
- Church, J.A., and White, N.J., 2006. A 20th century acceleration in global sea-level rise. *Geophysical Research Letters* 33: L01602.
- Cinquemani, L.J., Newman, W.S., Sperling, J.A., Marcus, L.F., Pardi, R., 1982. Holocene sea level changes and vertical movements along the East Coast of the United States. IGCP Annual Meeting, Columbia, South Carolina, 13-39.
- Cleary, W.J., and Hosier, P.E., 1979. Geomorphology, washover history, and inlet zonation: Cape Lookout, N.C. to Bald Island, N.C., *In*: Leatherman, S.P. (ed.), *Barrier Islands, Gulf of St. Lawrence to the Gulf of Mexico*. Academic Press, New York, 325 p.
- Cleary, W.J. and Pilkey, O.H., 1996. *Environmental Coastal Geology: Cape Lookout to Cape Fear, North Carolina Regional Overview*. Carolina Geological Society, Guidebook for 1996 Annual Meeting: 73-107.
- Cole, W.S., 1931. The Pliocene and Pleistocene Foraminifera of Florida. *Florida State Geological Survey Bulletin* 6: 77 p.
- Collins, E.S., 1996. Marsh-estuarine benthic foraminiferal distributions and Holocene Sea-level reconstructions along the South Carolina Coastline. Unpublished PhD dissertation, Dalhousie University, Halifax, NS, Canada, 204 p.
- Collins, E.S., Scott, D.B., and Gayes, P.T., 1999. Hurricane records on the South Carolina coast: Can they be detected in the sediment record? *Quaternary International* 56: 15-26.
- Cronin, T.M., Szabo, B.J., Ager, T.A., Hazel, J.E., and Owens, J.P., 1981. Quaternary climates and sea levels of the U.S. Atlantic Coastal Plain. *Science* 211: 233-240.
- Cronin, T.M., Willard, D., Karlsen, A., Ishman, S., Verardo, S., McGeehin, J., Kerhin, F., Homes, C., Colman, S., and Zimmerman, A., 2000. Climatic variability in the eastern United States over the past millennium from Chesapeake Bay sediments. *Geology* 28: 3-6.

- Cronin, T.M., Dwyer, G.S., Kamiya, T., Schwede, S., and Willard, D.A., 2003. Medieval Warm Period, Little Ice Age and 20th century temperature variability from Chesapeake Bay. *Global and Planetary Change* 36: 17-29.
- Culver, S.J., and Buzas, M.A., 1980. Distribution of recent benthic foraminifera off the North American Atlantic coast. *Smithsonian Contributions to the Marine Sciences*, no. 6, 512 p.
- Culver, S. J., 1987. Foraminifera, *In*: J. H. Lipps (ed.), *Fossil Prokaryotes and Protists*, Knoxville, TN, University of Tennessee: 169-212.
- Culver, S.J., Woo, H.J., Oertel, G.F., and Buzas, M.A., 1996. Foraminifera of coastal depositional environments, Virginia, USA: distribution and taphonomy. *Palaaios* 11: 459-486.
- Culver, S.J., and Horton, B.P., 2005. Infaunal marsh foraminifera from the Outer Banks, North Carolina, U.S.A., *Journal of Foraminiferal Research* 32: 148-170.
- Culver, S.J., Ames, D.V., Corbett, D.R., Mallinson, D.J., Riggs, S.R., Smith, C.G., and Vance, D.J., 2006. Foraminiferal and sedimentary record of late Holocene barrier island evolution, Pea Island, North Carolina: the role of storm overwash, inlet processes, and anthropogenic modification. *Journal of Coastal Research* 22: 836-846.
- Culver, S.J., Grand Pre, C.A., Mallinson, D.J., Riggs, S.R., Corbett, D.R., Foley, J.A., Hale, M.E., Ricardo, J.P., Rosenberger, J.E., Smith, C.G., Smith, C.W., Snyder, S., Twamley, D.F., Farrell, K.M., and Horton, B.P., 2007. Late Holocene barrier island collapse: Outer Banks, North Carolina, U.S.A. *The Sedimentary Record* 5(4): 4-8.
- Cushman, J.A., 1922. Shallow-water Foraminifera of the Tortugas Region. *Publications of the Carnegie Institution* 17(311): 85 p.
- Cushman, J.A., 1926. Recent Foraminifera from Porto Rico. *Publications of the Carnegie Institution* 344: 73-84.
- Cushman, J.A., 1932. Some Recent Angulogerinas from the Eastern Pacific. *Contributions from the Cushman Laboratory for Foraminiferal Research* 8: 44-48.
- Cushman, J.A., 1933. Some new recent foraminifera from the tropical Pacific. *Contributions from the Cushman Laboratory for Foraminiferal Research* 9: 77-95.
- Cushman, J.A., 1944. Foraminifera from the shallow water of the New England Coast.

- Cushman Laboratory for Foraminiferal Research, Special Publication 12: 1-37.
- Cushman, J.A., 1947. New species and varieties of Foraminifera from off the southeastern coast of the United States. *Contributions from the Cushman Laboratory for Foraminiferal Research* 23: 86-92.
- Cushman, J. A., and Bronnimann, P., 1948. Some new genera and species of foraminifera from brackish water of Trinidad: *Contributions from the Cushman Laboratory of Foraminiferal Research* 24: 15-21.
- Cushman, J.A., and Ponton, G.M., 1932. The foraminifera of the Upper, Middle, and part of the Lower Miocene of Florida. *Bulletin of the Florida Geological Survey, Tallahassee, Florida, USA* 9: 147 p.
- Carter, R.W.G., Forbes, D.L., Jennings, S.C., Orford, J.D., Shaw, J., and Taylor, R.B., 1989. Barrier and lagoon coast evolution under differing relative sea-level regimes: Examples from Ireland and Nova Scotia. *In: Ward, L.G., and Ashley, G.M., eds. Physical processes and sedimentology of siliciclastic-dominated lagoonal systems. Marine Geology* 88: 221-242.
- Dean, R.G., 2002. Beach nourishment: theory and practice. *Advanced Series on Ocean Engineering*. World Scientific, Singapore, 399 p.
- Devoy, R.J.N., Delaney, C., Carter, R.W.G., and Jennings, S.C., 1996. Coastal stratigraphies as indicators of environmental changes upon European Atlantic coasts in the late Holocene. *Journal of Coastal Research* 12: 564-588.
- Donnelly, C., Kraus, N., and Larson, M., 2006. State of Knowledge on Measurement and Modeling of Coastal Overwash. *Journal of Coastal Research* 22: 965-991.
- Donnelly, J.P., Cleary, P., Newby, P., and Ettinger, R., 2004. Coupling instrumental and geological records of sea-level change: evidence from southern New England of an increase in the rate of sea-level rise in the late 19th century. *Geophysical Research Letters* 31: GL018933.
- Douglas, B.C., 1991. Global sea-level rise. *Journal of Geophysical Research* 94: 6981-6992.
- Douglas, B.C., 1995. Global sea level change: determination and interpretation. *Reviews of Geophysics Supplement*: 1425-1432.
- Douglas, B.C., 1997. Global sea rise: a redetermination. *Surveys in Geophysics* 18: 279-292.

- Douglas, B.C., 2001. Sea level change in the era of the recording tide gauge. *In*: Douglas, B., Kearney, M., and Leatherman, S., eds. *Sea Level Rise: History and Consequences*, International Geophysical Series 75, Academic, San Diego, California, 37-64.
- Edwards, R.J., Wright, A.J., and van de Plassche, O., 2004. Surface distributions of salt-marsh foraminifera from Connecticut, USA: modern analogues for high-resolution sea level studies. *Marine Micropaleontology* 51: 1-21.
- Ehrenberg, C.G., 1840. Eine weitere Erläuterung des Organismus mehrerer in Berlin lebend beobachteter Polythalamien der Nordsee. *Koenigliche Preussischen Akademie der Wissenschaften, Berlin, Deutschland*, p.18-23.
- Ehrenberg, C.G., 1841. Über noch jetzt zahlreich lebende Thierarten der Kreidebildung und den Organismus der Polythalamien: *Physikalische-Mathematische Abhandlungen der Koniglichen Akademie der Wissenschaften, Berlin*, v. 1839, p.81-174.
- Elfrink, B. and Baldock, T.E., 2002. Hydrodynamics and sediment transport in the swash zone: a review and future perspectives. *Coastal Engineering* 45: 149-167.
- Ellison, R. L., and Nichols, M. M., 1970. Estuarine foraminifera from the Rappahannock River, Virginia. *Contributions from the Cushman Foundation for Foraminiferal Research* 21:1-17.
- Ellison, R.L., and Nichols, M.M., 1976. Modern and Holocene foraminifera in the Chesapeake Bay region, *In*: Schafer, C.T. and Pelletier, B.R., eds: *First International Symposium on Benthonic Foraminifera of continental margins. Part A - Ecology and Biology: Maritime Sediments*, Special Publication, 1:131-151.
- Emery, K.O., and Wigley, R.L., 1967. Freshwater peat on the continental shelf. *Science* 158: 1301-1307.
- Emiliani, C., 1955. Pleistocene Temperatures. *The Journal of Geology* 63: 538-578.
- Fairbanks, R.G., 1989. A 17,000-year glacio-eustatic sea-level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. *Nature* 342: 637-642.
- Field, M.E., and Meisburger, E.P., 1979. Upper Quaternary peat deposits on the Atlantic inner shelf of the United States. *Geological Society of America Bulletin* 90: 618-628.

- Fitzgerald, D.M., Baldwin, C.T., Ibrahim, N.A., and Humphries, S.M., 1992. Sedimentologic and morphologic evolution of a beach-ridge barrier along an indented coast: Buzzards Bay, Massachusetts. *Quaternary Coasts of the United States: Marine and Lacustrine Systems*, SEPM Special Publication no. 48: 65-75.
- Fisher, J.J., 1962. Geomorphic expression of former inlets along the Outer Banks of NC. Unpublished Master's Thesis, University of North Carolina, Chapel Hill, NC 120p.
- Fisher, J.J., 1967. Development Pattern of Relict Beach Ridges, Outer Banks Barrier Chain, North Carolina. Unpublished Ph.D Dissertation, University of North Carolina, Chapel Hill, North Carolina, 250 p.
- Fleming, K., Johnston, P., Zwart, D., Yokoyama, Y., Lambeck, K., and Chappell, J., 1998. Refining the eustatic sea-level curve since the Last Glacial Maximum using far- and intermediate-field sites. *Earth and Planetary Science Letters* 163: 327-342.
- Foley, J.A., 2007. Sedimentological and Foraminiferal Indicators of Holocene Environmental Change in Pamlico Sound, North Carolina. Master's Thesis, East Carolina University, Greenville, NC, 167 p.
- Folk, R.L., 1980. *Petrology of Sedimentary Rocks*. Hemphill Publishing Company, Austin, Texas, 182 p.
- Fournet, S.C., 1990. Pleistocene-Holocene sediment aggradational history of the lower Tar River and upper Pamlico River estuary, North Carolina. Master's Thesis, East Carolina University, Greenville, NC, 197 p.
- Fraser, G.S., and Hester, N.C., 1977. Sediments and sedimentary structures of a beach-ridge complex, southwestern shore of Lake Michigan. *Journal of Sedimentary Petrology* 47: 1187-1200.
- Galloway, J.J., and Wissler, S.G., 1927. Pleistocene foraminifera from the Lomita Quarry, Palos Verdes Hills, California. *Journal of Paleontology* 1: 35-87.
- Gawthorpe, R.L., Collier, R.E., Alexander, J., Bridge, J.S., and Leeder, M.R., 1993. Ground penetrating radar: application to sandbody geometry and heterogeneity studies. *Geological Society Special Publication* 73: 421-432.
- Gehrels, W.R., 1999. Middle and late Holocene sea-level change in Eastern Maine reconstructed from foraminiferal salt marsh stratigraphy and AMS ^{14}C Dates on basal peat. *Quaternary Research* 52: 350-359.

- Gehrels, W.R., Kirby, J.R., Prokoph, A., Newnham, R.M., Achterberg, E.P., Evans, H., Black, S., and Scott, D.B., 2005. Onset of recent rapid sea-level rise in the western Atlantic Ocean. *Quaternary Science Reviews* 24: 2083-2100.
- Goldstein, S.T., and Harben, E.B., 1993. Taphofacies implications of infaunal foraminiferal assemblages in a Georgia salt marsh, Sapelo Island. *Micropaleontology* 39: 53-62.
- Goldstein, S.T., Harben, E.B., and Kuhn, R.M., 1995. Microhabitats of salt marsh foraminifera: St. Catherine's Island, Georgia, USA. *Micropaleontology* 26: 17-29.
- Goldstein, S.T., and Watkins, G.T., 1998. Elevation and the distribution of salt-marsh foraminifera, St. Catherine's Island, Georgia: a taphonomic approach. *Palaaios* 13: 570-580.
- Goldstein, S.T., and Watkins, G.T., 1999. Taphonomy of salt-marsh foraminifera: an example from coastal Georgia. *Palaeogeography, Palaeoclimatology, Palaeoecology* 149: 103-114.
- Goodbred, S.L. and Hine, A.C., 1995. Coastal storm deposition: salt-marsh response to a severe extratropical storm, March 1993, west-central Florida. *Geology* 23: 679-682.
- Grand Pre, C.A., 2006. Holocene paleoenvironmental change in the Pamlico Sound, North Carolina: foraminiferal and stable isotope evidence. Master's Thesis, East Carolina University, Greenville, NC, 189 p.
- Graves, G.R., 2001. Factors governing the distribution of Swainson's warbler along a hydrological gradient in Great Dismal Swamp. *The Auk* 118: 650-664.
- Grossman, S. and Benson, R. H., 1967. Ecology of Rhizopodea and Ostracoda of southern Pamlico Sound region, North Carolina. *Kansas University, Paleontology Contributions* 44: 82 p.
- Hadley, W.H., 1936. Recent Foraminifera from near Beaufort, North Carolina: *Journal of the Elisha Mitchell Science Society* 52: 35-37.
- Hale, M.E., 2008. Late Holocene Back-Barrier Evolution of Ocracoke Island, Outer Banks, North Carolina: Master's Thesis, East Carolina University, Greenville, NC 213 p.
- Havholm, K.G., Ames, D.V., Whittecar, G.R., Wenell, B.A., Riggs, S.R., Jol, H.M., Berger, G.W., and Holmes, M.A., 2004. Stratigraphy of back-barrier coastal

- dunes, northern North Carolina and southern Virginia. *Journal of Coastal Research* 20: 980-999.
- Hazel, J.A., 1977. Use of certain multivariate and other techniques in assemblage zonal biostratigraphy: examples utilizing Cambrian, Cretaceous, Tertiary benthic invertebrates. *In*: Kauffman, E.G., and Hazel, J.E. (Eds.), *Concepts and Methods in Biostratigraphy*: Stroudsbourg, PA. Dowden, Hutchinson and Ross, INC.: 210-211.
- Herbert, J.R., 1978. Post-Miocene stratigraphy and evolution of northern Core Banks, N.C. Unpublished Master's Thesis, Duke University, Durham, N.C. 166 p.
- Heron, Jr., S.D., Moslow, T.F., Berelson, W.M., Herbert, J.R., Steele III, G.A., and Susman, K.R., 1984. Holocene sedimentation of a wave-dominated barrier-island shoreline: Cape Lookout, North Carolina. *Marine Geology* 60: 413-434.
- Heron-Allen, E. and Earland, A., 1913. Clare Island Survey. Part 64- Foraminifera. *Royal Irish Academy Proceedings, Dublin, Ireland* 31(3): 1-188.
- Heron-Allen, E. and Earland, A., 1930a. The Foraminifera of the Plymouth District; Part I. *Royal Microscopical Society London Journal* 50: 46-84.
- Heron-Allen, E. and Earland, A., 1930b. The Foraminifera of the Plymouth District; Part II. *Royal Microscopical Society London Journal* 50: 161-199.
- Hine, A.C., and Snyder, S.W., 1985. Coastal lithosome preservation: evidence from the shoreface and inner continental shelf of Bogue Banks, North Carolina. *Marine Geology* 63: 307-330.
- Hine, A.C., Snyder, S.W., and Neumann, A.C., 1979. Coastal plain and inner shelf structure, stratigraphy, and geologic history: Bogue Banks area, North Carolina. North Carolina Science and Technology Committee Technical Report, Chapel Hill, North Carolina, 76 p.
- Hippensteel, S.P., and Martin, R.E., 1999. Foraminifera as an indicator of overwash deposits, barrier island sediment supply, and barrier island evolution: Folly Island, South Carolina. *Palaeogeography, Palaeoclimatology, Palaeoecology* 149: 115-125.
- Hippensteel, S.P., Martin, R.E., Nikitina, D., and Pizzuto, J.E., 2000. The formation of Holocene marsh foraminiferal assemblages, middle Atlantic Coast, USA: implications for the Holocene sea-level change. *Journal of Foraminiferal Research* 30: 272-293.

- Hippensteel, S.P., Martin, R.E., Nikitina, D., and Pizzuto, J.E., 2002. Interannual variation of marsh foraminiferal assemblages (Bombay Hook National Wildlife Refuge, Smyrna, DE): Do foraminiferal assemblages have a memory? *Journal of Foraminiferal Research* 32: 97-109.
- Hobbs III, C.H., 2004. Geological history of Chesapeake Bay, USA. *Quaternary Science Reviews* 23: 641-661.
- Horton, B.P., 1999. The contemporary distribution of intertidal foraminifera of Cowpen Marsh, Tees Estuary, U.K.: implications for studies of Holocene sea-level changes. *Palaeogeography, Palaeoclimatology, Palaeoecology Special Issue* 49: 127-149.
- Horton, B.P. and Culver, S.J., 2008. Modern Intertidal Foraminifera of the Outer Banks, North Carolina, U.S.A., and their Applicability for Sea-Level Studies. *Journal of Coastal Research* 24(5): 1110-1125.
- Horton, B.P., Edwards, R.J., and Lloyd, J.M., 1999a. Reconstruction of former sea levels using a foraminiferal-based transfer function. *Journal of Foraminiferal Research* 29: 117-129.
- Horton, B.P., Edwards, R.J., and Lloyd, J.M., 1999b. U.K. intertidal foraminiferal distributions: implications for sea-level studies. *Marine Micropaleontology* 36: 205-223.
- Horton, B.P., Larcombe, P., Woodroffe, S.E., Whittaker, J.E., Wright, M.R., and Wynn, C., 2003. Contemporary foraminiferal distributions of the Great Barrier Reef coastline, Australia: implications for sea-level reconstructions. *Marine Geology* 3320: 1-19.
- Horton, B.P., Innes, J.B., Shennan, I., Lloyd, J.M., McArthur, J.J., 2004. Holocene coastal change in East Norfolk, UK: paleoenvironmental data from Somerton and Winterton Holmes, near Horsey. *Proceedings of the Geologists' Association* 115: 209-220.
- Horton, B.P., Culver, S.J., Hardbattle, M.I.J., Larcombe, P., Milne, G.A., Morigi, C., Whittaker, J.E., Woodroffe, S.A., 2007. Reconstructing Holocene sea-level change for the central Great Barrier Reef (Australia) using subtidal foraminifera. *Journal of Foraminiferal Research* 37(4): 327-343.
- Horton, B.P., Peltier, W.R., Culver, S.J., Drummond, R., Engelhart, S.E., Kemp, A.C., Mallinson, D.J., Thieler, E.R., Riggs, S.R., Ames, D.V., and Thomson, K.H., 2009. Holocene sea-level changes along the North Carolina Coastline and their

implications for glacial isostatic adjustment models. *Quaternary Science Reviews* 28: 1725-1736.

- Hughen, K.A., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C.J.H., Blackwell, P.G., Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Kromer, B., McCormac, F.G., Manning, S.W., Bronk Ramsey, C., Reimer, P.J., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Talamo, S., Taylor, F.W., Van Der Plicht, J., and Weyhenmeyer, C.E., 2004, Marine04 Marine radiocarbon age calibration, 25-0 ka BP, *Radiocarbon* 46: 1059-1086.
- Ivanova, E.V., Ovsepyan, E.A., Risebrobakken, B., and Vetrov, A.A., 2008. Downcore distribution of living calcareous foraminifera and stable isotopes in the western Barents Sea. *Journal of Foraminiferal Research* 38: 337-356.
- Jevrejeva, S., Moore, J.C., Grinsted, A., and Woodworth, P.L., 2008. Recent global sea level acceleration started over 200 years ago? *Geophysical Research Letters* 35: GL033611.
- Johnson, G.H., 1976. Geology of the Mulberry Island, Newport News North, and Hampton Quadrangles, Virginia: Virginia Division of Natural Resources Report of Investigations 41: 1-72.
- Jol, H.M., 1995. Ground penetrating radar antennae frequencies and transmitter powers compared for penetrating depth, resolution, and reflection continuity. *Physical Prospecting* 43: 693-709.
- Jol, H.M. and Smith, D.G., 1995. Ground penetrating radar surveys of peatlands for oilfield pipelines in Canada. *Journal for the Application of Geophysics* 34: 109–123.
- Jol, H.M., Smith, D.G. and Meyers, R.A., 1996. Digital Ground Penetrating Radar (GPR): a new geophysical tool for coastal barrier research (examples from the Atlantic, Gulf and Pacific coasts, USA). *Journal of Coastal Research* 12: 960–968.
- Karlsen, A.A., Cronin, T.M., Ishman, S.E., Wilard, D.A., Holmes, C.W., and Kerhin, R., 2000. Historical trends in Chesapeake Bay dissolved oxygen based on benthic foraminifera from sediment cores. *Estuaries* 23: 488-508.
- Kemp, A.C., 2009. High Resolution Studies of Late Holocene Relative Sea-Level Change, North Carolina, USA. Ph.D. Dissertation, University of Pennsylvania, Philadelphia, PA, 361 p.

- Kemp, A.C., Horton, B.P., and Culver, S.J., 2009. Distribution of modern salt-marsh foraminifera in the Albemarle-Pamlico estuarine system of North Carolina, USA: Implications for sea-level research. *Marine Micropaleontology* 72: 222-238.
- Kemp, A.C., Horton, B.P., Culver, S.J., Corbett, D.R., van de Plassche, O., Gehrels, W.R., Douglas, B.C., 2009. The timing and magnitude of recent accelerated sea-level rise (North Carolina, USA). *Quaternary Research* 71: 9-21.
- Komar, P.D., 1998. *Beach Processes and Sedimentation*. Prentice Hall, New York.
- Kornfeld, M.M., 1931. Recent littoral foraminifera from Texas and Louisiana: Stanford University Department of Geology (California) 1:77-101.
- Kraus, N.C., Militello, A., and Todoroff, G., 2002. Barrier breaching processes and barrier spit breach, Stone Lagoon, California. *Shore and Beach* 70: 21-28.
- Kraus, N.C. and Wamsley, T.V., 2003. Coastal Barrier Breaching, Part 1: Overview of Breaching Processes. Coastal Hydraulics and Engineering Technical Note ERDC/CHL CHETN-IV-56, Vicksburg, Mississippi, U.S. Army Engineer Research and Development Center. <http://chl.erdu.usace.army.mil/library/public/chetn/pdf/chetn-iv-56.pdf> (accessed September 9, 2009).
- Lambeck, K., Yokoyama, Y., and Purcell, T., 2002. Into and out of the Last Glacial Maximum: sea-level change during Oxygen Isotope Stages 3 and 2. *Quaternary Science Reviews* 21: 343-360.
- Lefurgey, A., 1976. Recent Benthic Foraminifera from Roanoke, Croatan, and Northern Pamlico Sounds, North Carolina. PhD. Dissertation, University of North Carolina, Chapel Hill, NC. 383 p.
- Leigh, D.S., 2008. Late Quaternary climates and river channels of the Atlantic coastal plain, southeastern USA. *Geomorphology* 101: 90-108.
- Leorri, E., Martin, R., and McLaughlin, P., 2006. Holocene environmental and parasequence development of the St. Jones Estuary, Delaware (USA): Foraminiferal proxies of natural climatic and anthropogenic change. *Palaeogeography, Palaeoclimatology, and Palaeoecology* 241: 590-607.
- Leuliette, E.W., Nerem, R.S., Mitchum, G.T., 2004. Calibration of TOPEX/Poseidon and Jason Altimeter Data to Construct a Continuous Record of Mean Sea Level Change. *Marine Geodesy* 27: 79-94.
- Linnaeus, C., 1758. *Systema Naturae*. Ed. 10. Holmiae, Suecia [Sweden], impensis L. Salvii 1, 824 p.

- Lucchi, F., Tranne, C.A., Calanchi, N., Pirazzoli, P.A., Romagnoli, C., Radtke, U., Reyss, J.L., and Rossi, P.L., 2004. Late-Quaternary ancient shorelines at Lipari (Aeolian Islands): stratigraphical constraints to reconstruct geological evolution and vertical movements. *Quaternary International* 115: 105-115.
- Mallinson, D.J., Riggs, S.R., Culver, S.J., Thieler, R., Foster, D., Corbett, D.R., Farrell, K., Wehmiller, J., 2005. Late Neogene and Quaternary evolution of the northern Albemarle Embayment (Mid-Atlantic Continental Margin, USA). *Marine Geology* 217: 97-117.
- Mallinson, D.J., Burdette, K., Mahan, S., and Brook, G., 2008a. Optically stimulated luminescence age controls on late Pleistocene and Holocene coastal lithosomes, North Carolina, USA. *Quaternary Geology* 69: 97-109.
- Mallinson, D.J., Mahan, S., and Moore, C., 2008b. High resolution shallow geologic characterization of a late Pleistocene eolian environment using ground penetrating radar and optically stimulated luminescence techniques: North Carolina, USA. *Southeastern Geology* 45: 161-177.
- Mamo, B., Strotz, L., and Dominey-Howes, D., in press. Tsunami sediments and their foraminiferal assemblages. *Earth Science Reviews*.
- Markewich, H.W. and Markewich, W., 1994. An overview of Pleistocene and Holocene inland dunes in Georgia and the Carolinas: morphology, distribution, age, and paleoclimate. *USGS Bulletin* 2069, Washington, D.C., 32 p.
- Masselink, G. and Hughes, M.G., 2003. *Introduction to Coastal Processes and Geomorphology*. Arnold, London.
- Mathis, M.A., 1993. Broad Reach: The Truth About What We've Missed. *In*, D. Anderson and V. Horak, eds: *Site Destruction in Georgia and the Carolinas*. Interagency Archeological Services Division, National Parks Service. 100p.
- McDowell, K.L., 2009. Holocene Geologic Development of Central Hatteras Flats and Buxton Beach Ridges, Outer Banks, North Carolina. Master's Thesis, East Carolina University, Greenville, NC, 235 p.
- Mello, J.F., and Buzas, M.A., 1968. An application of cluster analysis as a method for determining biofacies. *Journal of Paleontology* 42: 747-758.
- Metger, M.L., 2009. Holocene Paleoenvironmental Change in Southern Pamlico Sound, North Carolina: Master's Thesis, East Carolina University, 178 p.

- Mixon, R.B., Szabo, B.J., and Owens, J.P., 1982. Uranium-series dating of mollusks and corals and age of Pleistocene deposits, Chesapeake Bay area, Virginia and Maryland. U.S. Geological Survey Professional Paper, 1067-E, p. E1-E18.
- Montagu, G., 1808. Testacea Britannica, Supplement. S. Woolmer, Exeter, England, 183 p.
- de Montfort, D., 1808. Conchyliologie systematique et classification methodique des conquilles: F. Schoell, Paris, vol. 1, 409 p.
- Moslow, T.F., 1977. Quaternary evolution of Core Banks, N.C., from Cape Lookout to New Drum Inlet. Unpublished Master's Thesis, Duke University, Durham, NC 171 p.
- Moslow, T.F., and Heron, S.D., 1978. Relict inlets: Preservation and occurrence in the Holocene stratigraphy of southern Core Banks, NC. *Journal of Sedimentary Petrology* 48: 1275-1286.
- Moslow, T.F., and Heron, S.D., 1994. The Outer Banks of North Carolina. *In*: Davis, R.A., ed.; *Geology of Holocene barrier island systems*, 47-74, Berlin, Springer-Verlag.
- Muhs, D.R., 1992. The last interglacial-glacial transition in North America: evidence from uranium-series dating of coastal deposits. *In*, Clark, P.U., Lea, P.D. (eds.), *The Last Interglacial-Glacial Transition in North America*: Boulder, Colorado, Geological Society of America Special Paper 270: 31-51.
- Munsterman, D., and Kerstholt, S., 1996. Sodium polytungstate, a new non-toxic alternative to bromoform in heavy liquid separation. *Review of Paleobotany and Palynology* 91: 417-422.
- Murray, J.W., 1969. Recent Foraminifers from the Atlantic Continental Shelf of the United States. *Micropaleontology* 15: 401-419.
- Murray, J.W., and Alve, E., 1999. Natural dissolution of modern shallow water benthic foraminifera: taphonomic effects on the paleoecological record. *Palaeogeography, Palaeoclimatology, Palaeoecology* 146: 195-209.
- Murray, A.S., and Olley, J.M., 2002. Precision and Accuracy in the Optically Stimulated Luminescence Dating of Sedimentary Quartz: A Status Review. *Journal on Methods and Applications of Absolute Chronology* 21: 1-16.
- Natland, M.L., 1938. New species of foraminifera from off the West Coast of North America and from the later Tertiary of the Los Angeles Basin. *Bulletin of the*

- Scripps Institution of Oceanography, University of California 4: 137-164.
- Nichols, M., and Norton, W., 1969. Foraminiferal populations in a coastal plain estuary. *Palaeogeography, Palaeoclimatology, Palaeoecology* 6: 197-213.
- Oaks, R.A., and Coch, N.K., 1963. Pleistocene sea levels, Southern Virginia. *Science* 140: 970-983.
- Oaks, R. and Dubar, J. R., 1974. Post-Miocene stratigraphy, central and southern Atlantic Coastal Plain: Utah State University Press, Logan, UT.
- Oertel, G.F. and Foyle, A.M., 1995. Drainage displacement by sea-level fluctuation at the outer margin of the Chesapeake seaway. *Journal of Coastal Research* 11: 583-604.
- Ollerhead, J., Huntley, D.J., and Berger, G.W., 1994. Luminescence dating of sediments from Buctouche Spit, New Brunswick. *Canadian Journal of Earth Sciences* 31: 523-531.
- d'Orbigny, A., 1826. Tableau méthodique de la classe des Céphalopodes. *Annales de Sciences Naturelles, Series 7*: 245-314.
- d'Orbigny, A., 1839a. Voyage dans l'Amerique Meridionale, Foraminifères. Strasbourg, France, Levrault 5: 1-86.
- d'Orbigny, A. 1839b. Foraminifères. *In*: Ramon de la Sagra, Histoire, Physique, Politique et Naturelle de l' Ile de Cuba: A. Bertrand, Paris, 224 p.
- d'Orbigny, A., 1846. Foraminifères fossils du basin tertiaire de Vienne: Verlags Buchandlung Von Gide et Comp., Paris (Austrie), 312 p.
- Otvos, E.G., 1999. Sediment and geomorphic criteria for reconstructing sea-level positions. Reply to a Discussion. *Journal of Coastal Resources*.
- Otvos, E.G., 2000. Beach ridges – definitions and significance. *Geomorphology* 32:83-108.
- Parham, P.R., 2003. The Quaternary Lithostatigraphy, Seismic Stratigraphy, and Geologic History of the Croatan Sound Area, North Carolina. Unpublished Master's Thesis, East Carolina University, Greenville, NC, 110 p.
- Parham, P.R., Riggs, S.R., Culver, S.J., Mallinson, D.J., and Wehmiller, J.F., 2007. Quaternary depositional patterns and sea-level fluctuations, North Carolina. *Quaternary Research* 67: 83-99.

- Parham, P.R., 2009. The Late Quaternary Stratigraphy and Geologic History of Northeastern North Carolina and Southeastern Virginia. Ph.D. Dissertation, East Carolina University, Greenville, NC, 222 p.
- Parker, F.L., 1948. Foraminifera of the continental shelf from the Gulf of Maine to Maryland. *Bulletin of the Museum of Comparative Zoology at Harvard College* 100: 214-241.
- Parker, F.L., 1952a. Foraminiferal species off Portsmouth, New Hampshire. *Bulletin of the Museum of Comparative Zoology at Harvard College* 106: 391-423.
- Parker, F.L., 1952b. Foraminiferal distribution in Long Island Sound – Buzzards Bay Area. *Bulletin of the Museum of Comparative Zoology* 106: 427-473.
- Patterson, R.T., Guilbault, J.P., Clague, J.J., 1999. Taphonomy of tidal marsh foraminifera; implications of surface sample thickness for high resolution sea-level studies. *Palaeogeography, Palaeoclimatology, Palaeoecology* 149: 199-211.
- Patterson, R.T., Hutchinson, I., Guilbault, J.P., Clague, J.J., 2000. A comparison of the vertical zonation of diatom, foraminifera, and macrophyte assemblages in a coastal marsh; implications for greater paleo-sea level resolution. *Micropaleontology* 46: 229-244.
- Peltier, W.R., 2001. Global isostatic adjustment and modern instrumental records of relative sea-level history. *In*: Douglas, B.C., Kearney, M.S., and Leatherman, S.P., eds. *Sea level rise: history and consequences*, San Diego, Academic Press: 65-93.
- Peltier, W.R. and Jiang, X., 1997. Mantle viscosity, glacial isostatic adjustment and the eustatic level of the sea. *Surveys in Geophysics* 18: 239-277.
- Phleger, F.B. and Parker, F.L., 1951. Ecology of foraminifera, northwest Gulf of Mexico: Part II- Foraminifera species. *Memoirs of the Geological Society of America* 46: 1-64.
- Polyak, L., Korsun, S., Febo, L.A., Stanovoy, V., Khusid, T., Hald, M., Paulsen, B.E., Lubinski, D.J., 2002. Benthic foraminiferal assemblages from the southern Kara Sea, a river-influenced arctic marine environment. *Journal of Foraminiferal Research* 32: 252-273.
- Potter, E.K. and Lambeck, K., 2004. Reconciliation of sea-level observations in the Western North Atlantic during the last glacial cycle. *Earth and Planetary Science Letters* 217: 171-181.

- Pruitt, R.J., 2008. Foraminiferal Evidence for Recent Paleoenvironmental Change in Core Sound, North Carolina. Master's Thesis, East Carolina University, Greenville, NC, 190 p.
- Redfield, A.C., 1967. Postglacial change in sea level in the western North Atlantic Ocean. *Science* 157: 687-690.
- Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C.J.H., Blackwell, P.G., Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Hogg, A.G., Hughen, K.A., Kromer, B., McCormac, F.G., Manning, S.W., Ramsey, C.B., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Talamo, S., Taylor, F.W., Van Der Plicht, J., Weyhenmeyer, C.W., 2004, IntCal04 Terrestrial radiocarbon age calibration, 26-0 ka BP: *Radiocarbon* 46: 1029-1058.
- Reuss, A.E., 1850. Neues Foraminiferen aus den Schichten des Österreichischen Tertiärbeckens. *Denkschriften Der Kaiserlichen Academie der Wissenschaften, Mathematisch-Naturwissenschaftliche, classe 1*: 365-390.
- Reuss, A.E., 1851. Ueber die fossilen Foraminiferen und Entomostraceen der Septarienthonen der Umgegend von Berlin, *Zeitschrift der Deutschen Geologischen Gesellschaft, Berlin* 3: 49-91.
- Ricardo, J.P., 2005. Late Holocene paleoenvironmental change of the Salvo-Gull Island-Little Kinnekeet area, Outer Banks, North Carolina. Unpublished Master's Thesis, East Carolina University, Greenville, NC, 188 p.
- Riggs, S.R., York, L., Wehmiller, J., and Snyder, S., 1992. Depositional patterns resulting from high-frequency Quaternary sea-level fluctuations in northeastern North Carolina. *Quaternary Coasts of the United States: Marine and Lacustrine Systems. SEPM Special Publication* 48: 141-153.
- Riggs, S.R., Cleary, W.J., and Snyder, S.W., 1995. Influence of inherited geologic framework on barrier shoreface morphology and dynamics. *Marine Geology* 126: 213-234.
- Riggs, S.R., Rudolph, G.L., and Ames, D.V., 2000. Erosional scour and geologic evolution of Croatan Sound, northeastern North Carolina. North Carolina Department of Transportation, Report no. FHWA/NC/2000-002, Contract Research Project 98-4, 116 p.
- Riggs, S. R., 2002. Life at the edge of North Carolina's coastal system: The geologic controls. *In*: Beal, C. and Prioli, C., eds.; *Life at the edge of the sea: Essays on*

- North Carolina's coast and coastal culture, Coastal Carolina Press, Wilmington, N.C.: 63-95.
- Riggs, S.R., and Ames, D.V., 2003. Drowning the North Carolina Coast: Sea-Level Rise and Estuarine Dynamics. North Carolina Sea Grant, 152 p.
- Riggs, S.R., and Ames, D.V., 2009. Impact of the Oregon Inlet Terminal Groin on Downstream Beaches of Pea Island, NC Outer Banks. East Carolina University Printing Press, Greenville, NC. 19 pp.
- Robinson, M.M., and McBride, R.A., 2006. Benthic foraminifera from a relict flood tidal delta along the Virginia/North Carolina Outer Banks. *Micropaleontology* 52: 67-80.
- Roep, T.B., and Beets, D.J., 1988. Sea level rise and paleotidal levels from sedimentary structures in the coastal barriers in the western Netherlands since 5600 BP. *Geologie en Mijnbouw* 67: 53-60.
- Rogl, F. and Hansen, H.J., 1884. Foraminifera described by Fichtel and Moll in 1798, A revision of Testacea Microscopica. Neue deskschriften des Naturhistorischen Museums in Wien 3: Verlag Ferdinand Berger & Söhne, Wien-Horn, 147 p.
- Rosenberger, J.E., 2006. Late Holocene back-barrier development of Portsmouth Island, Outer Banks, North Carolina. Unpublished Master's Thesis, East Carolina University, Greenville, NC, 185 p.
- Saffert, H., and Thomas, E., 1998. Living foraminifera and total populations in salt marsh peat cores: Kelsey marsh (Clinton, CT) and the Great Marshes (Barnstable, MA). *Marine Micropaleontology* 33: 175-202.
- Sager, E.D., 1996. A Complex Holocene In-Fill History of Albemarle Sound, North Carolina: An Integrated Seismic, Litho-, and Chronostratigraphic Synthesis. Unpublished Master's Thesis, East Carolina University, Greenville, NC, 237 p.
- Sager, E.D., and Riggs, S.R., 1998. Models for Holocene valley-fill history of Albemarle Sound, North Carolina, U.S.A. *In*: Alexander, C.R., Davis, R.A., and Henry, V.J., (Eds.), *Tidalities*, Special Publication 61: 119-128.
- Schenk, C.J., Gautier, D.L., Olhoeft, G.R., and Lucius, J.E., 1993. Internal structure of an aeolian dune using ground-penetrating radar, *Spec. Publs. Int. Ass. Sediment.* 16: 61-69.
- Schnitker, D. 1971. Distribution of foraminifera on the North Carolina continental shelf. *Tulane Studies in Geology and Paleontology* 8: 169-215.

- Scott, D.B., and Leckie, R.M., 1990. Foraminiferal zonation of Great Sippewissett Salt Marsh (Falmouth, Massachusetts). *Journal of Foraminiferal Research* 20: 248-266.
- Scott, D.B. and Medioli, F.S., 1978. Vertical zonation of marsh foraminifera as accurate indicators of former sea levels. *Nature* 272: 528-531.
- Scott, D.B. and Medioli, F.S., 1980. Quantitative Studies of Marsh Foraminifera Distribution in Nova Scotia: Implications for Sea-Level Studies. *Journal of Foraminiferal Research Special Publication* 17, 58 p.
- Scott, D.B. and Medioli, F.S., 1986. Foraminifera as sea-level indicators. *In*: van de Plassche, O., ed.; *Sea-Level Research: A manual for the collection of data*. Geo Books (IGCP Projects 61 and 200), Norwich: 435-455.
- Scott, D.B., Medioli, F.S., and Schafer, C.T., 2001. *Monitoring in Coastal Environments Using Foraminifera and Thecamoebian Indicators*. Cambridge University Press, Cambridge, 177 p.
- Scott, D.B., Collins, E.S., Gayes, P.T., and Wright, E., 2003. Records of prehistoric hurricanes on the South Carolina coast based on micropaleontological and sedimentological evidence, with comparison to other Atlantic Coast records. *Geological Society of America Bulletin* 115: 1027-1039.
- Scott, T.W., 2006. Correlating late Pleistocene deposits on the Coastal Plain of Virginia with the glacial-eustatic sea-level curve. Unpublished Master's Thesis, Old Dominion University, Norfolk, VA, 111 p.
- Sears, P.C., 1973. *Evolution of Platt Shoals, Northern North Carolina Shelf: Inference from Areal Geology*, Old Dominion University, Norfolk, VA.
- Shackleton, N.J., Fairbanks, R.G., Chiu, T., and Parrenin, F., 2004. Absolute calibration of the Greenland time scale: implications for Antarctic time scales and for $\Delta 14C$. *Quaternary Science Reviews* 23: 1513-1522.
- Smith, C.G., 2004. Late Holocene development of Pea Island and Avon-Buxton area, Outer Banks, North Carolina, Unpublished Masters Thesis, East Carolina University, Greenville, NC, 260 p.
- Smith, C.G., Culver, S.J., Mallinson, D.J., Riggs, S.R., and Corbett, D.R., 2009. Recognizing former flood tide deltas in the Holocene stratigraphic record from the Outer Banks, North Carolina, USA. *Stratigraphy* 6: 61-78.

- Smith, C.W., 2006. Lithologic, geophysical, and paleoenvironmental framework of relict inlet channel-fill and adjacent facies: North Carolina Outer Banks. Master's Thesis, East Carolina University, Greenville, NC, 300 p.
- Sproat, A., 1999. Origin and evolutionary history of a back-barrier estuarine system, Onslow Beach, NC. Unpublished Masters Thesis, East Carolina University, Greenville, NC, 160 p.
- Steele, G.A., 1980. Stratigraphy and Depositional History of Bogue Banks, North Carolina. Masters Thesis, Duke University, Durham, North Carolina, 201 p.
- Steineck, P.L. and Bergstein, J., 1979. Foraminifera from Hommocks salt-marsh, Larchmont Harbor, New York. *Journal of Foraminiferal Research* 9: 147-158.
- Stick, D., 1958. The Outer Banks of North Carolina 1584-1958. University of North Carolina Press, Chapel Hill, 352 p.
- Stuiver, M., and Reimer, P.J., 1993. Extended ^{14}C data base and revised CALIB 3.0 ^{14}C age calibration program. *Radiocarbon* 35: 215-230.
- Stuiver, M., Reimer, P.J., Braziunas, T.F., 1998. High-precision radiocarbon age calibration for terrestrial and marine samples. *Radiocarbon* 40: 1127-51.
- Susman, K.R., 1975. Post-Miocene subsurface stratigraphy of Shackleford Banks, Carteret County, N.C. Unpublished Master's Thesis, Duke University, Durham, NC, 85 p.
- Susman, K.R., and Heron, Jr., S.D., 1979. Evolution of a barrier island, Shackleford Banks, Carteret County, NC. *Geological Society of America Bulletin* 90: 205-215.
- Sverdrup, H. V., Johnson, M. W., and Fleming, R. H., 1946. The Oceans: Their physics, chemistry and general biology. New York: Prentice-Hall, 1087 p.
- Szabo, B.J., 1985. Uranium-series dating of fossil corals from marine sediments of Southeastern United States Atlantic Coastal Plain. *Geological Society of America Bulletin* 96: 398-406.
- Tanner, W.F., 1995. Origin of beach ridges and swales. *Marine Geology* 129: 149-161.
- Terquem, O., 1875. Essai sur le classement des animaux qui vivent sur la plage et dans les environs de Dunquerque, Fasc. 1: Paris, p. 1-54.
- Terquem, O., 1876. Essai sur le classement des animaux qui vivent sur la plage et dans

les environs de Dunkerque, Fasc. 2. Paris, p. 55-100.

- Terquem, O., 1878. Les Foraminifères et les Entomostracés-Ostracodes du Pliocène supérieur de l'Île de Rhodes. *Memoires de la Societe Geologique de France*, Ser. 3 1, 135 p.
- Thieler, E.R., Pilkey, O.H., Cleary, W.J., and Schwab, W.C., 2001. Modern Sedimentation on the Shoreface and Inner Continental Shelf at Wrightsville Beach, North Carolina, U.S.A. *Journal of Sedimentary Research* 71: 958-970.
- Thompson, T.A., 1992. Beach-ridge development and lake-level variation in southern Lake Michigan. *Sedimentary Geology* 80: 305-318.
- Thompson, W.G. and Goldstein, S.L., 2005. Open-system coral ages reveal persistent suborbital sea-level cycles. *Science* 308: 401-404.
- Tsujimoto, A., Nomura, R., Yasuhara, M., and Yoshikawa, S., 2006. Benthic foraminiferal assemblages in Osaka Bay, southwestern Japan: faunal changes over the last 50 years. *Paleontological Research* 10: 141-161.
- Twamley, D.F., 2006. Holocene geologic development of Hatteras Village area, Outer Banks, North Carolina. Master's Thesis, East Carolina University, Greenville, NC, 188 p.
- Uchio, T., 1960. Ecology of living benthonic foraminifera from the San Diego, California, area. *Contributions from the Cushman Foundation of Foraminifera Research*, Special Publication 5: 1-72.
- Vance, D.J., 2004. Modern and historic trends in foraminiferal distributions and sediment dynamics in the Albemarle estuarine system, North Carolina. Unpublished Master's Thesis, East Carolina University, Greenville, North Carolina, 249 p.
- Vance, D.J., Culver S.J., Corbett, D.R., and Buzas, M.A., 2006. Foraminifera in the Albemarle estuarine system, North Carolina: distribution and recent environmental change. *Journal of Foraminiferal Research* 26: 15-33.
- van Heteren, S., 2000. Optical dating of dune sand for the study of sea-level change. *Geology* 28: 411-414.
- van Heteren, S., and van de Plassche, O., 1997. Influence of relative sea-level change and tidal-inlet development on barrier-spit stratigraphy, Sandy Neck, Massachusetts. *Journal of Sedimentary Research* 67: 350-363.

- van Heteren, S., Fitzgerald, D.M., McKinlay, P.A., and Buynevich, I.V., 1998. Radar facies of paraglacial barrier systems: coastal New England, USA. *Sedimentology* 45: 181-200.
- von Fichtel, L., and von Moll, J.P.C., 1798. *Testacea microscopica minuta ex generibus Agonauta et Nautilus (Microscopische und andere klein Schalthiere aus den Geschlechtern Argonaute und Schiffer)*. Wien, Osterreich, Camesina, 123 p.
- Varekamp, J.C., Thomas, E., Van de Plassche, O., 1992. Relative sea-level rise and climate change over the last 1500 years. *Terra Nova* 4: 293-304.
- Wake, L., Milne, G., and Leuliette, E., 2006. 20th century sea-level change along the eastern US: unraveling the contributions from steric changes, Greenland ice sheet mass balance and late Pleistocene glacial loading. *Earth and Planetary Science Letters* 250: 572-580.
- Walker, G., and Jacob, E., 1798. *In: Adams G., Essays on the microscope, containing a practical description of the most improved microscopes; a general history of insects. A description of 383 animalcula etc. 2nd edition with considerable additions and improvements by K. Kanmacher. Dillon and Keating, London, 712 p.*
- Walton, W.R., 1955. Ecology of living benthonic foraminifera, Todos Santos Bay, Baja California. *Journal of Paleontology* 29: 952-1018.
- Ward, L.W., Bailey, R. H., and Carter, J. G., 1991. Pliocene and early Pleistocene Stratigraphy, depositional history, and molluscan paleobiogeography of the coastal plain. *In: Horton, J. W., and Zullo, V. A., eds.; The geology of the Carolinas, University of Tennessee Press: 274-289.*
- Wehmiller, J.F., Simmons, K.R., Cheng, H., Edwards, R.L., Martin-McNaughten, J., York, L.L., Krantz, D.E., and Shen, C.C., 2004. Uranium-series coral age from the US Atlantic Coastal Plain – the “80 ka problem” revisited. *Quaternary International* 120: 3-14.
- Williams, H.F.L., 2009. Stratigraphy, sedimentology, and microfossil content of Hurricane Rita storm surge deposits in southwest Louisiana. *Journal of Coastal Research* 25: 1041-1051.
- Williamson, W.C., 1858. *On Recent Foraminifera of Great Britain*. Ray Society (London) Publication, 107 p.
- Wilcoxon, J.A., 1964. Distribution of foraminifera off the southern Atlantic coast of the United States. *Contributions from the Cushman Foundation for Foraminiferal*

Research 15: 1-24.

Wintle, A.G., and Murray, A.S., 1999. Luminescence sensitivity changes in quartz. *Radiation Measurements* 29: 81-94.

Woo, H.J., Culver, S.J., and Oertel, G.F., 1997. Benthic foraminiferal communities of a barrier-lagoon system, Virginia, USA. *Journal of Coastal Research* 13: 1192-1200.

Workman, R. R., 1981, Foraminiferal Assemblages of the Nearshore Inner Continental Shelf, Nags Head and Wilmington Areas, North Carolina, Unpublished Master's Thesis, East Carolina University, Greenville, NC, 161 p.

Yokoyama, Y., Esat, T.M., and Lambeck, K., 2001. Last glacial sea-level change deduced from uplifted coral terraces of Huon Peninsula, Papua New Guinea. *Quaternary International* 83-85: 275-283.

Zervas, C., 2004. North Carolina bathymetry/topography sea level rise project: determination of sea level trends: NOAA Technical Report NOS CO-OPS 04, 39 p.

PLATE 1
(bar = 50 μ m)

Figures

- 1** *Elphidium excavatum* (Terquem); lateral view (Croatan-08-GP3 #6)
- 2** *Elphidium galvestonense* (Kornfeld); lateral view (BS-08-01 SS)
- 3** *Elphidium gunteri* Cole; lateral view (BB08-GP2 #2)
- 4** *Elphidium mexicanum* (Kornfeld); lateral view (BS-08-01 SS)
- 5** *Elphidium translucens* (Ehrenberg); lateral view (BB08-GP2 #3)
- 6** *Elphidium poeyanum* (d'Orbigny); lateral view (BS-08-03 #5)
- 7** *Haynesina germanica* (Ehrenberg); lateral view (BS-08-02 #3)
- 8** *Ammotium salsum* (Cushman and Bronnimann); lateral view (BS-08-04 SS)
- 9** *Textularia* cf. *T. gramen*; lateral view (Croatan-08-GP8 #1)
- 10** *Buliminella elegantissima* d'Orbigny; lateral view (BS-08-01 #1)
- 11** *Bolivina lowmani* Phleger and Parker; lateral view (Croatan-08-GP8 #4)
- 12** *Bolivina paula* Cushman and Cahill; lateral view (Croatan-08-GP8 #4)
- 13** *Quinqueloculina seminula* (Linne); lateral view (Croatan-08-GP3 #6)
- 14** *Quinqueloculina lamarckiana* d'Orbigny; lateral view (Croatan-08-GP4 #5)
- 15** *Quinqueloculina jugosa* (Cushman); lateral view (BB08-GP2 #2)
- 16** *Quinqueloculina bosciana* d'Orbigny; lateral view (BS-08-05 SS)

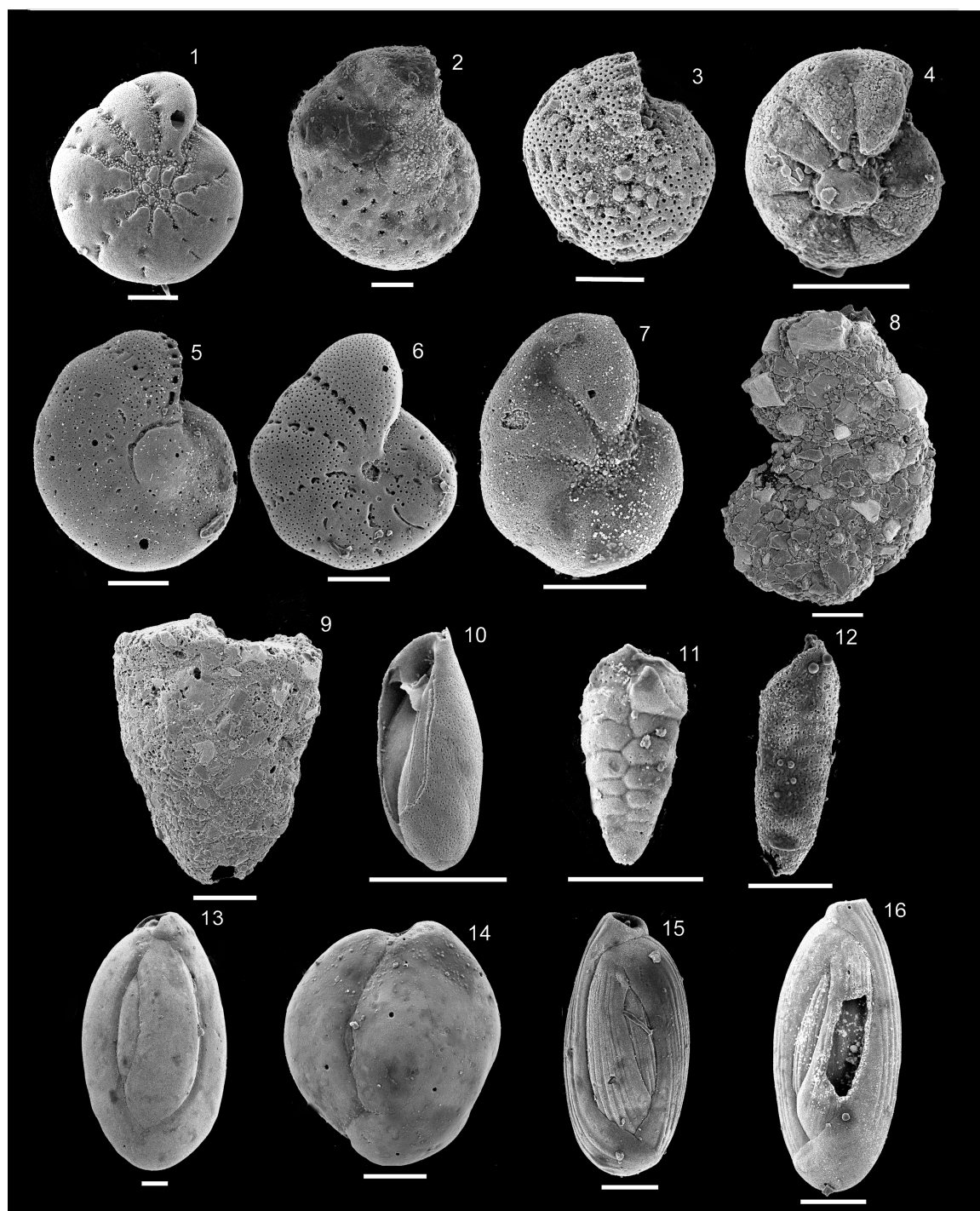
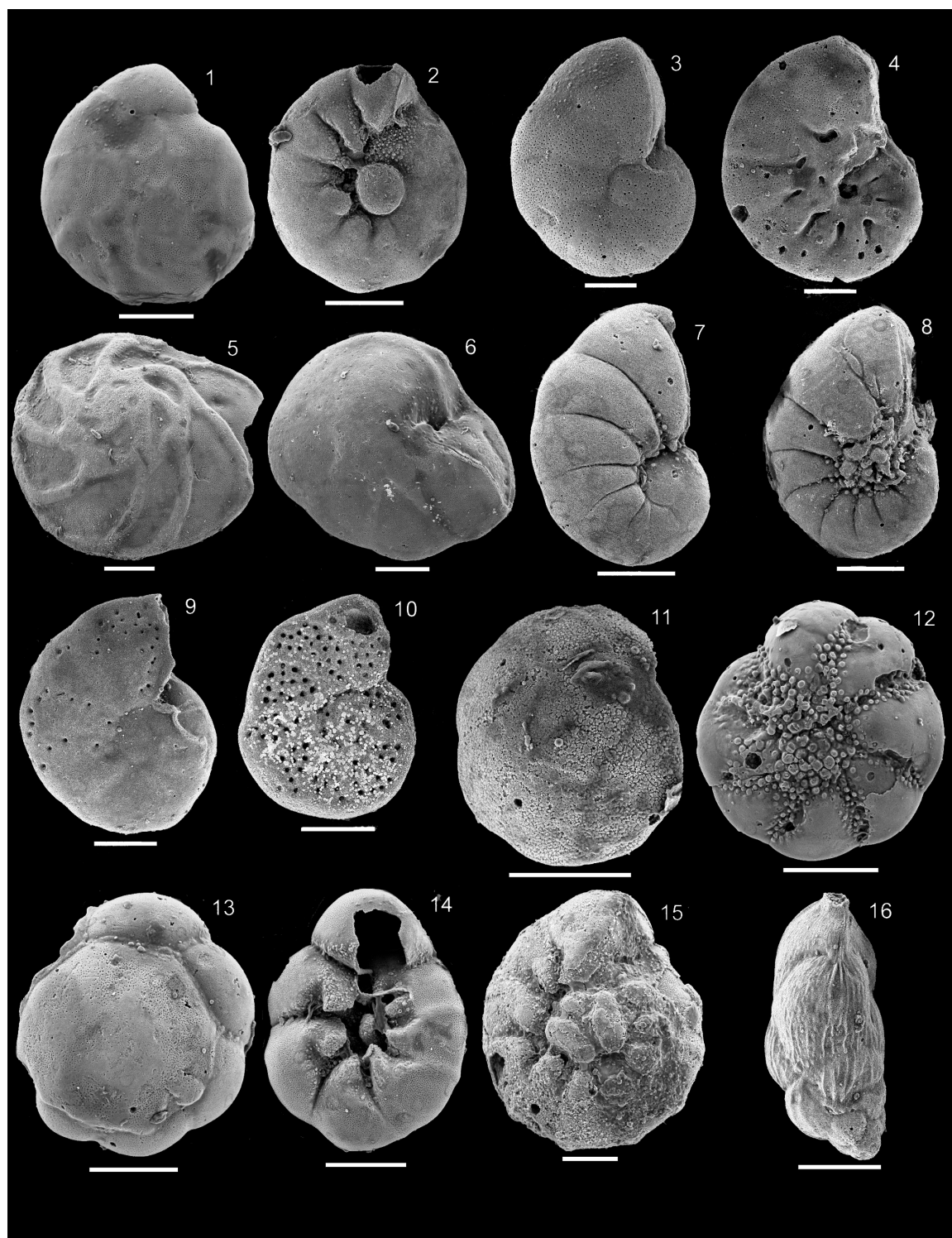


PLATE 2
(bar = 50 μ m)

Figures

- 1,2** *Ammonia parkinsoniana* (d'Orbigny); dorsal and ventral view
(BB08-GP2 #2; BS-08-05 SS)
- 3,4** *Hanzawaia strattoni* (Applin); dorsal and ventral view
(Croatan-08-GP8 #1; Croatan-08-GP8 #3)
- 5,6** *Eponides repandus* (Fichtel and Moll); dorsal and ventral view
(BS-08-05 #1; BS-08-06 #2)
- 7,8** *Nonionella atlantica* Cushman; dorsal and ventral view
(BS-08-01 #2; Croatan-08-GP8 #3)
- 9,10** *Cibicides lobatulus* (Walker and Jacob); dorsal and ventral view
(Croatan-08-GP3 #7; Croatan-08-GP4 #5)
- 11,12** *Buccella inusitata* Andersen; dorsal and ventral view
(Croatan-08-GP5 #2; BB08-GP3 #1)
- 13,14** *Ammonia tepida* (Cushman); dorsal and ventral view
(BS-08-04 #3)
- 15** *Ammonia* cf. *A. beccarii* (Linne); ventral view
(BS-08-06 SS)
- 16** *Trifarina angulosa* (Williamson); lateral view
(BS-08-03 #8; BS-08-01 #4)



**APPENDIX A: GEOPROBE AND VIBRACORE LOCATION, ELEVATION,
AND LENGTH**

	Core Name	Latitude	Longitude	Elevation (m)	Core Length (m)
Geoprobe Cores	Croatan-08-GP1	34.72836 N	76.93536 W	7.00	8.53
	Croatan-08-GP2	34.73392 N	76.93545 W	7.85	4.90
	Croatan-08-GP3	34.78624 N	76.9141 W	6.65	8.60
	Croatan-08-GP4	34.74262 N	76.913 W	7.95	8.57
	Croatan-08-GP5	34.72823 N	76.8931 W	5.80	9.75
	Croatan-08-GP6	34.77666 N	76.8758 W	8.60	8.55
	Croatan-08-GP7	34.75441 N	76.8802 W	8.80	8.55
	Croatan-08-GP8	34.75535 N	76.9307 W	9.65	8.55
	BB08-GP1	34.70093 N	76.8226 W	1.30	9.75
	BB08-GP2	34.69081 N	76.89056 W	1.65	7.33
	BB08-GP3	34.68225 N	76.929 W	0.90	6.00
Vibracores	BS-08-01	34.70879 N	76.82672 W	-1.40	5.60
	BS-08-02	34.71747 N	76.82732 W	-2.20	3.23
	BS-08-03	34.71239 N	76.89277 W	-2.00	6.42
	BS-08-04	34.70091 N	76.89229 W	-3.30	4.72
	BS-08-05	34.69258 N	76.93094 W	-1.40	2.55
	BS-08-06	34.70616 N	76.93364 W	-1.70	3.45

**APPENDIX B: CORE LOGS INCLUDING FORAMINIFERAL AND GRAIN
SIZE, OSL, and AMS ^{14}C SAMPLE LOCATIONS**

Key to core log symbols

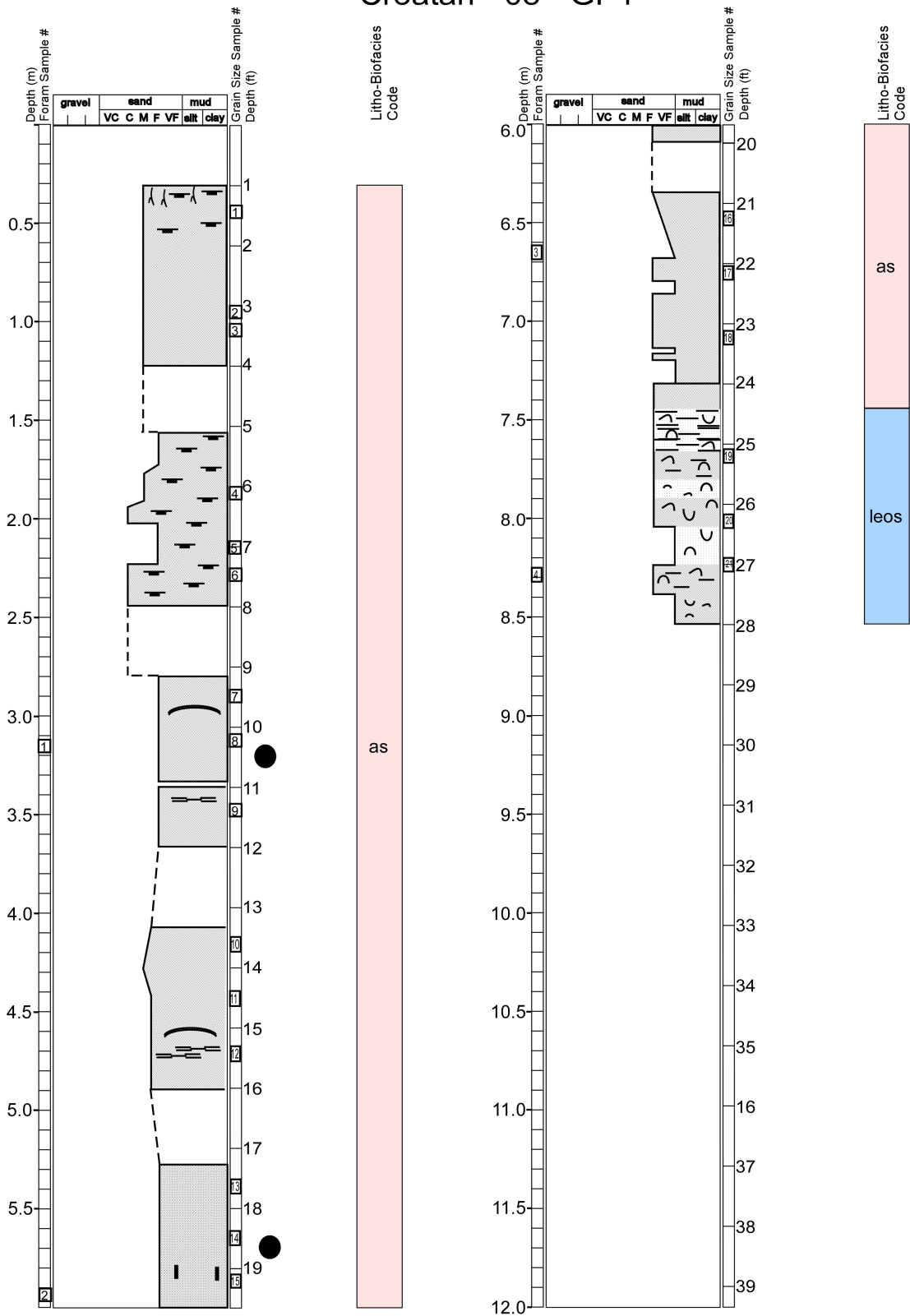
	Mud		General symbol for in place to minimally transported fossil shell material
	Sandy Mud		Reworked shell material
	Muddy Sand		Imbricated Shells
	Fine to medium sand		Large shell material
	Coarse to very coarse sand		Burrows
	Heavies (>10%)		Clay Lens
	Wood fragments		Interbedded Mud
	Root fibers		Non-visible Carbonates (reacts to HCl, but shells not visible)
	Organics (>5%)		Oysters (<i>in situ</i>)
	Peat		
	Lithologic contact		
		●	OSL Sample
		★	Radiocarbon Sample
		1	Foraminifera/Grain Size Sample
		1	Barren Foraminifera Sample

Biofacies Abbreviations

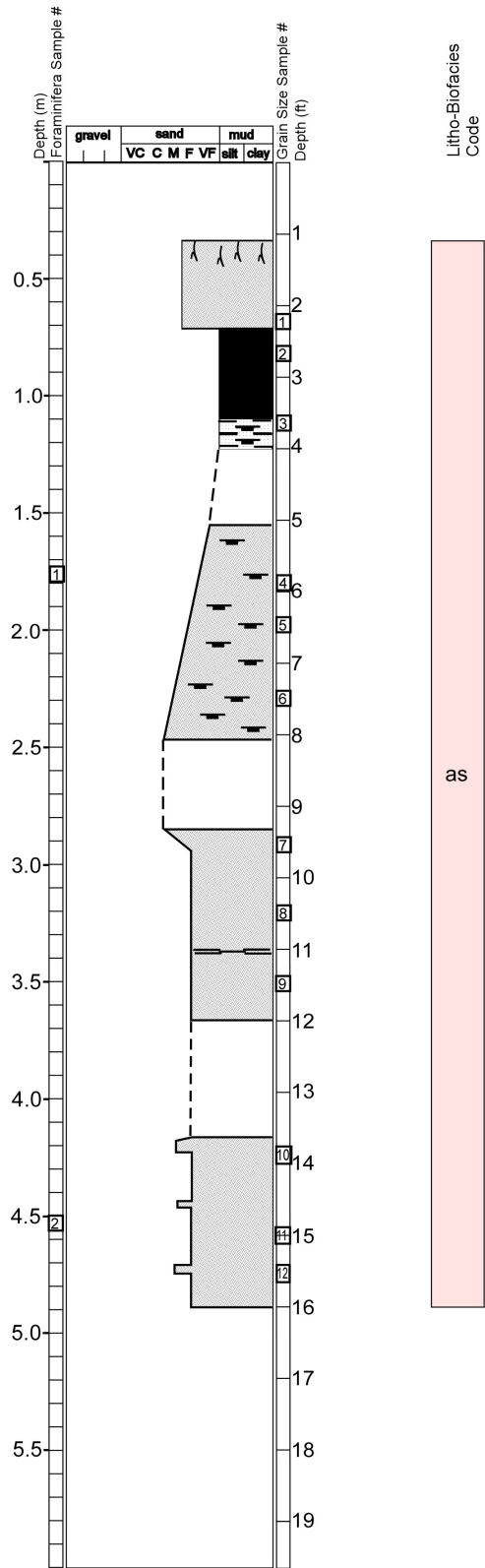
as	aeolian sand (barren of foraminifera)
sis	shallow inner shelf
leos	low energy open shelf
heos	high energy open shelf
hse	high salinity estuary
hebb1	high energy back-barrier lagoon
ftd	flood tide delta

Note. Where sand is referred to, it refers to quartz sand unless otherwise specified. Other mineral constituents rarely exceed trace amounts in the samples analyzed.

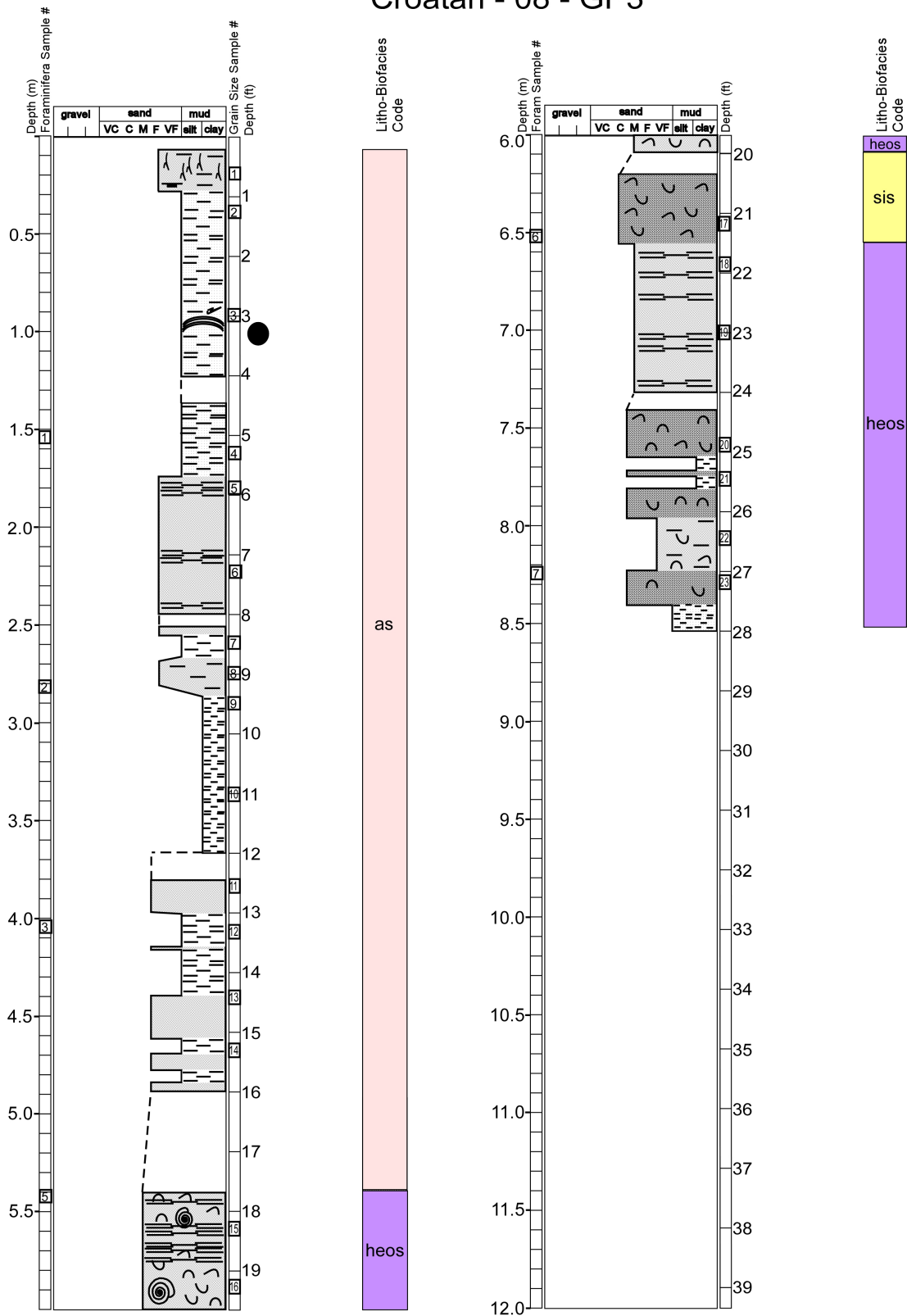
Croatan - 08 - GP1



Croatan-08-GP2



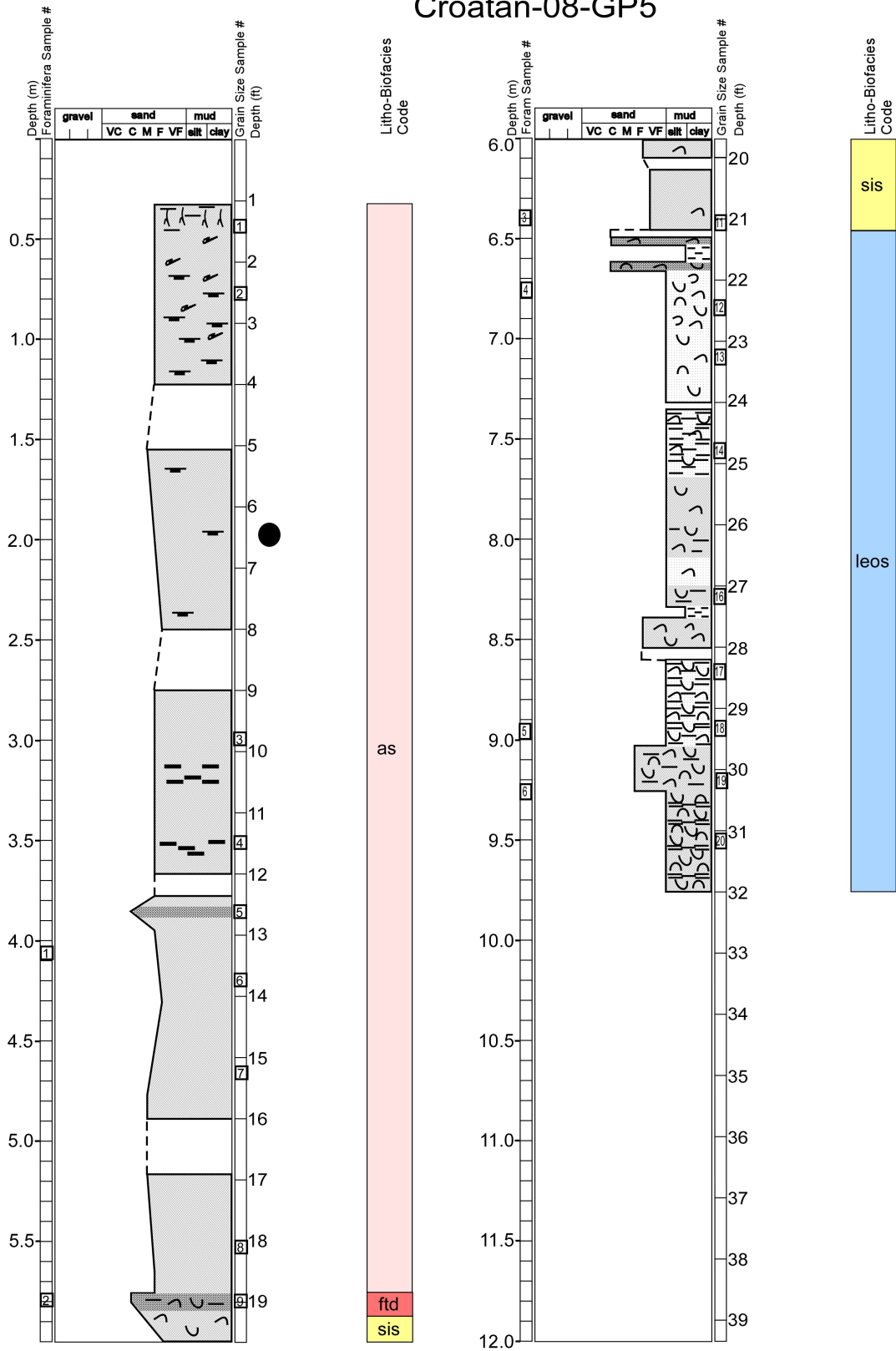
Croatan - 08 - GP3

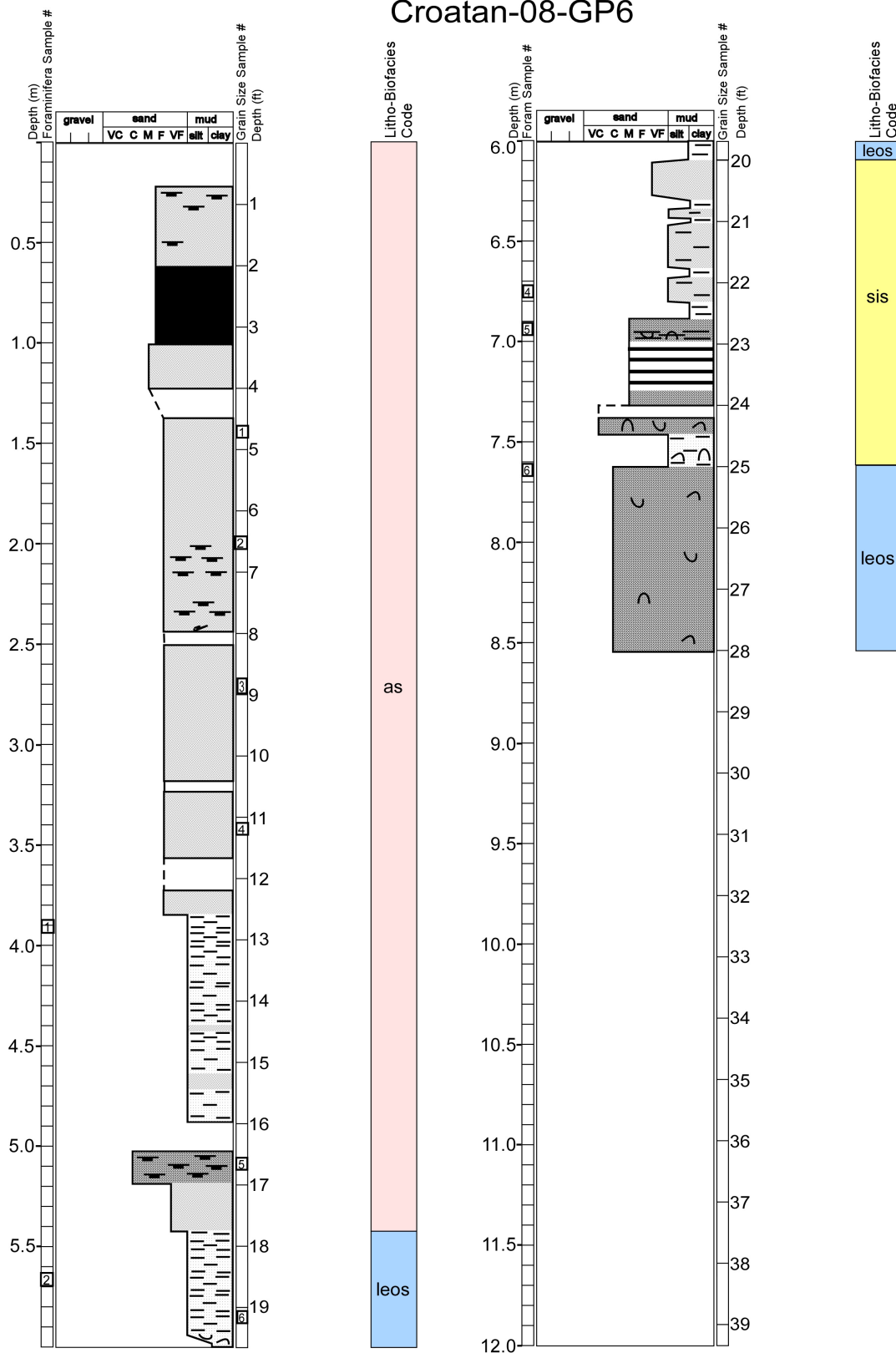




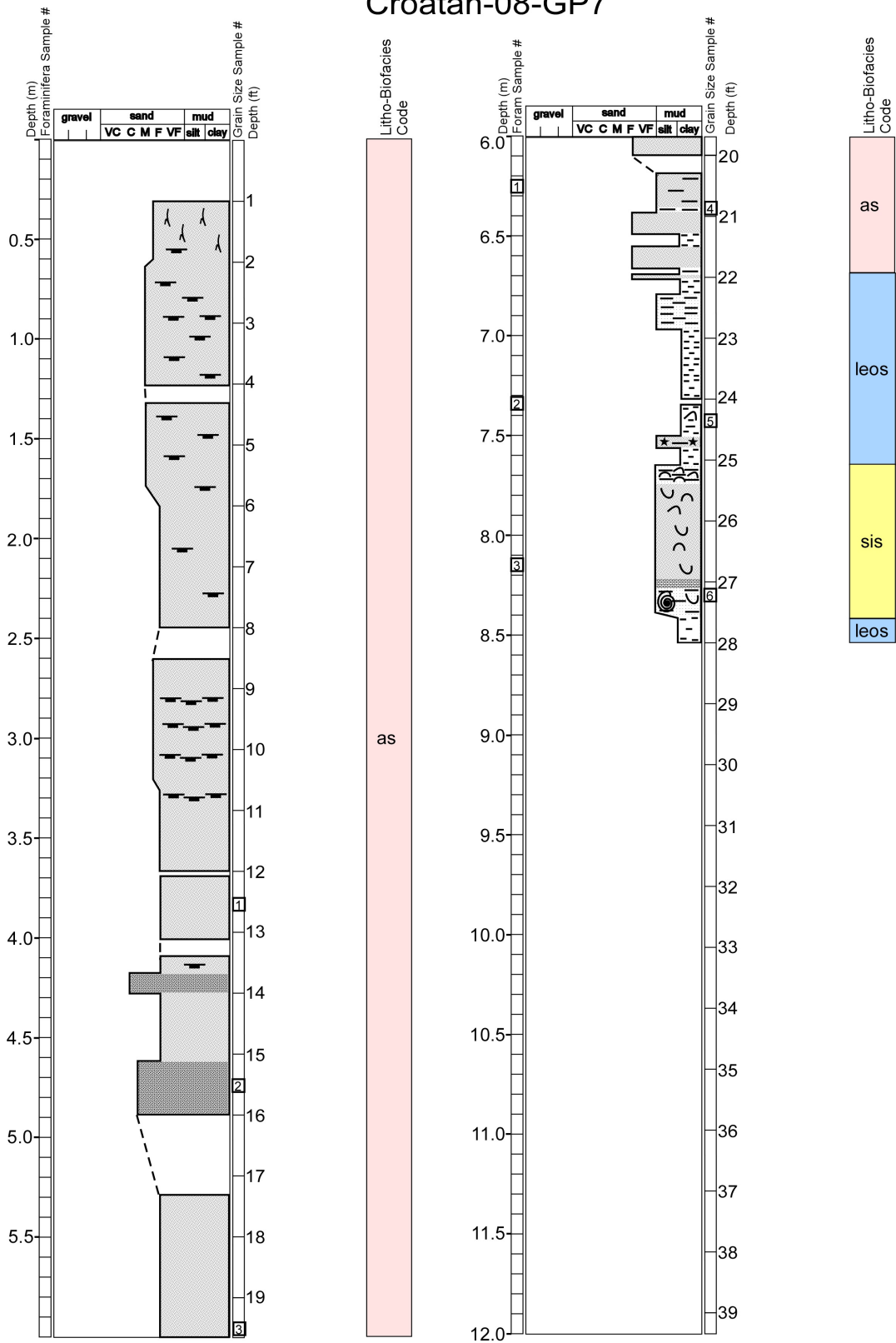
as
sis
heos
sis
leos

Croatan-08-GP5

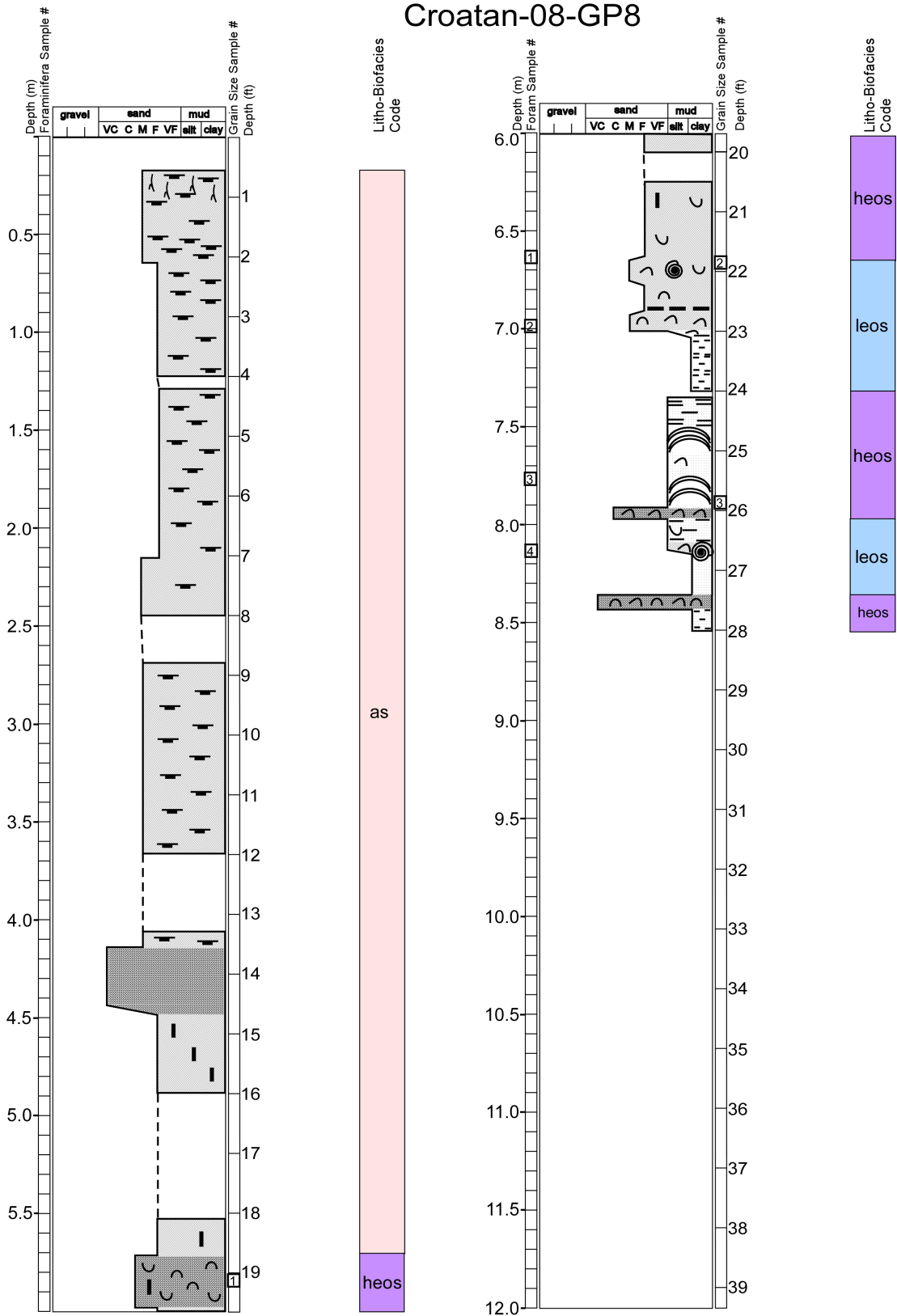


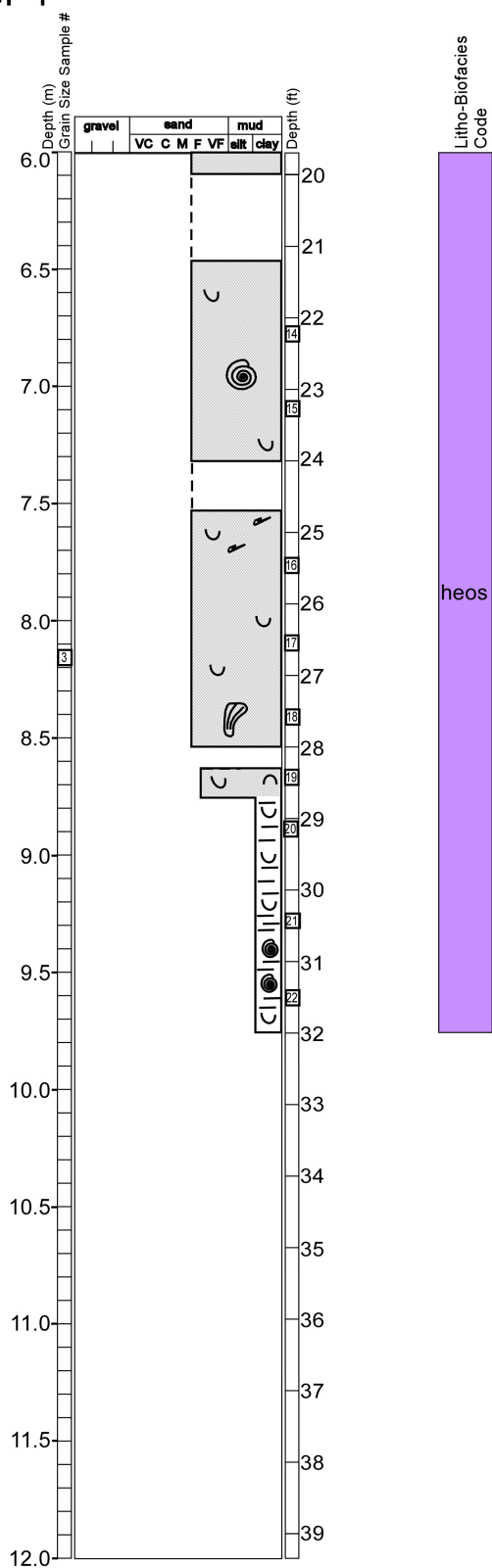


Croatan-08-GP7

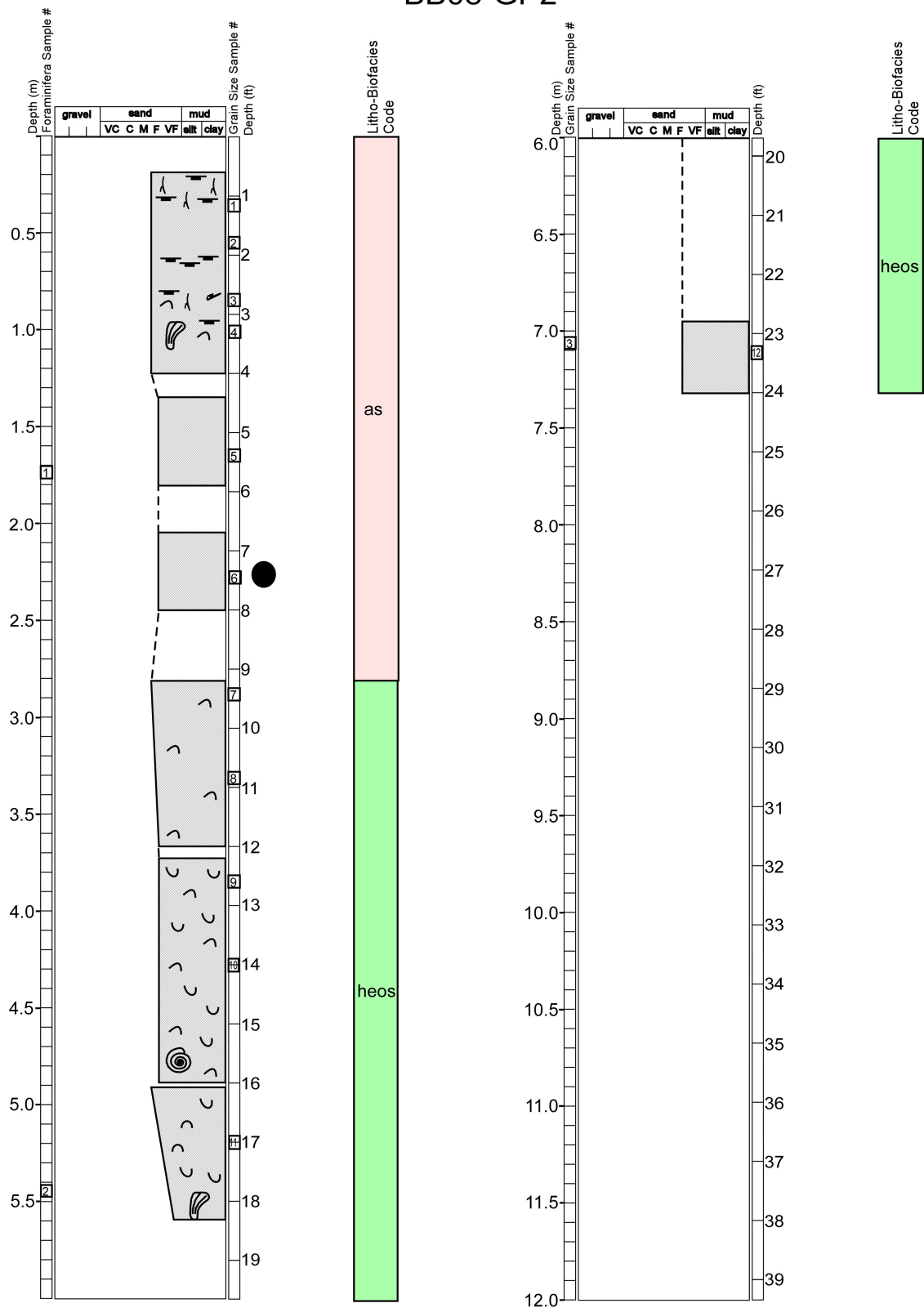


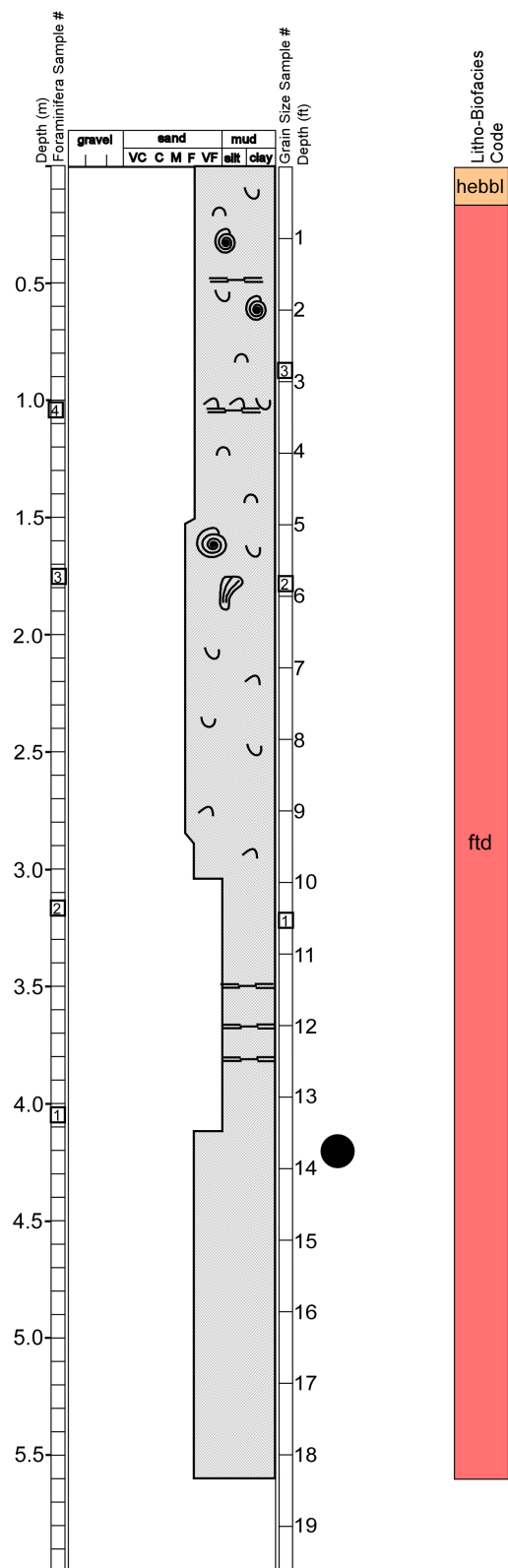
Croatan-08-GP8



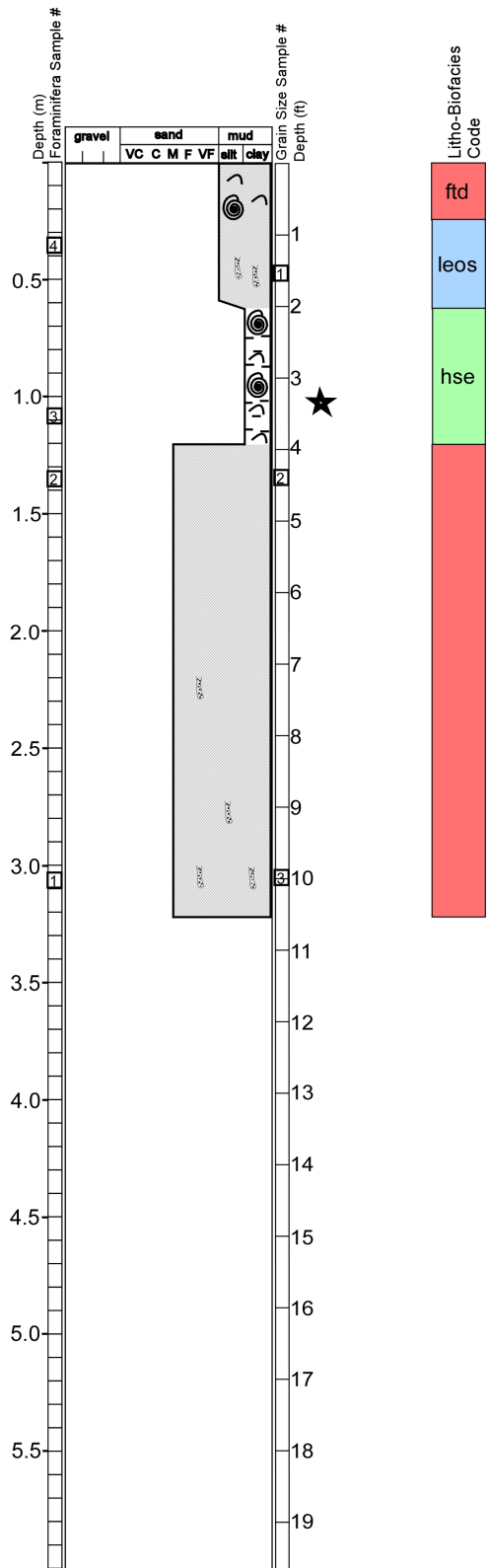


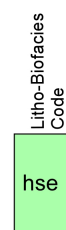
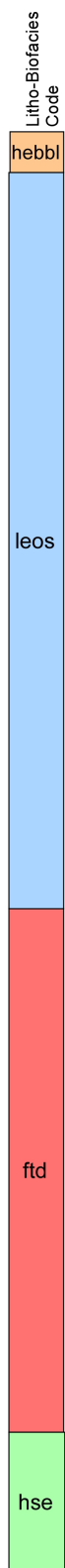
BB08-GP2



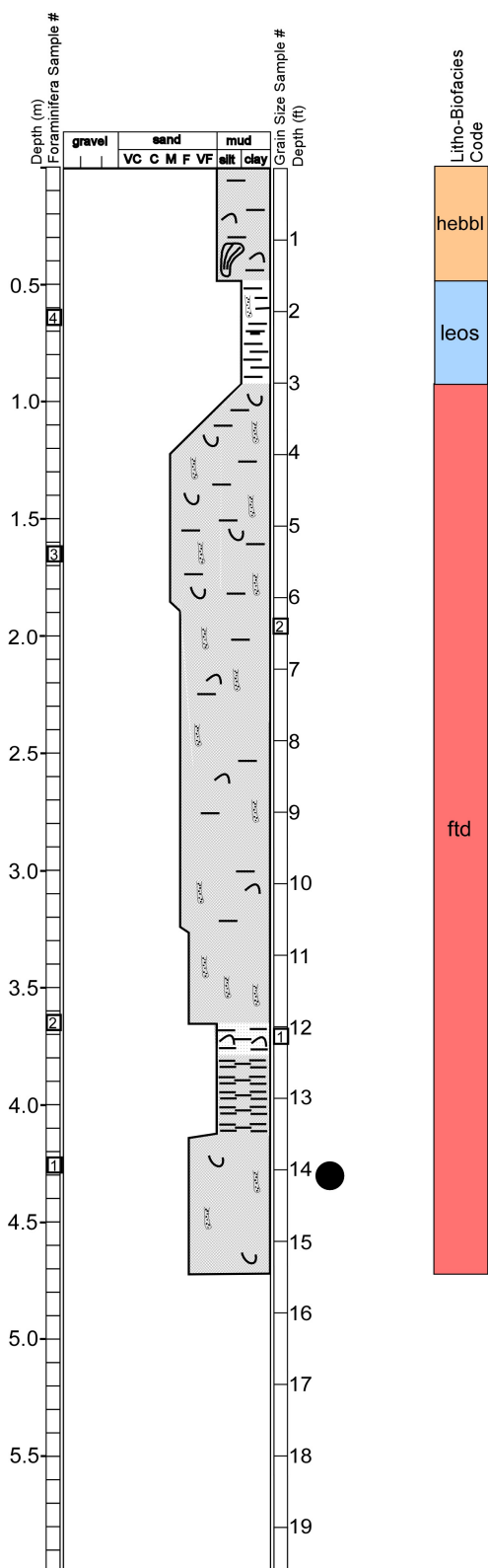


BS-08-02

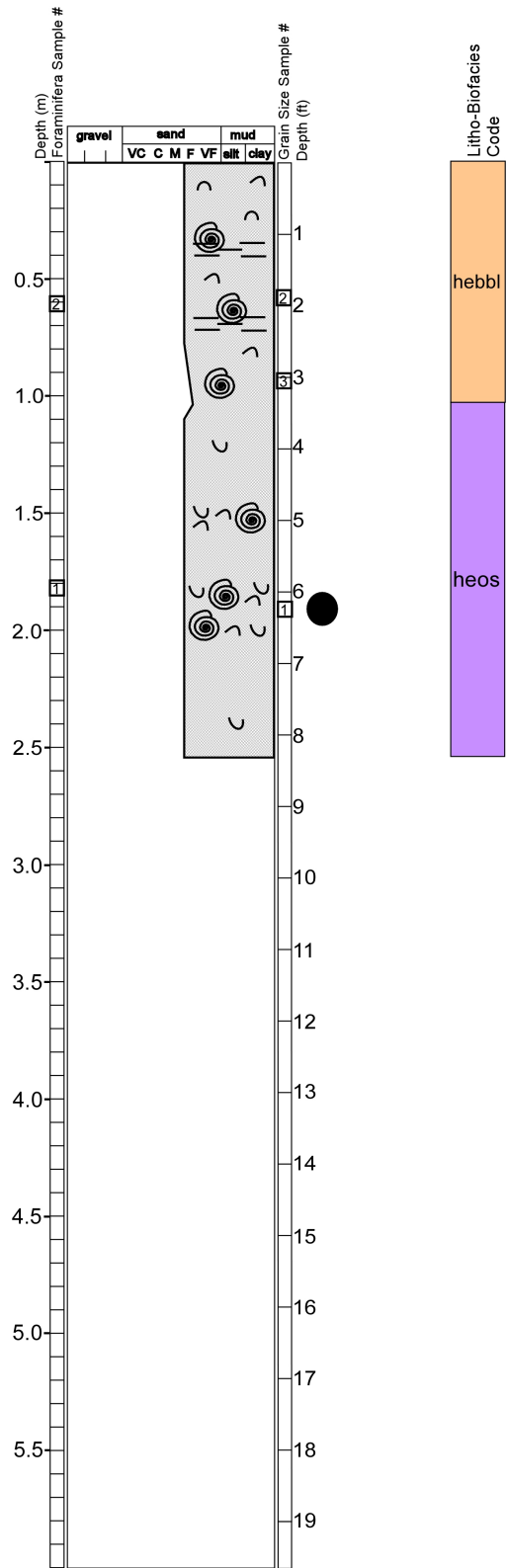




BS-08-04

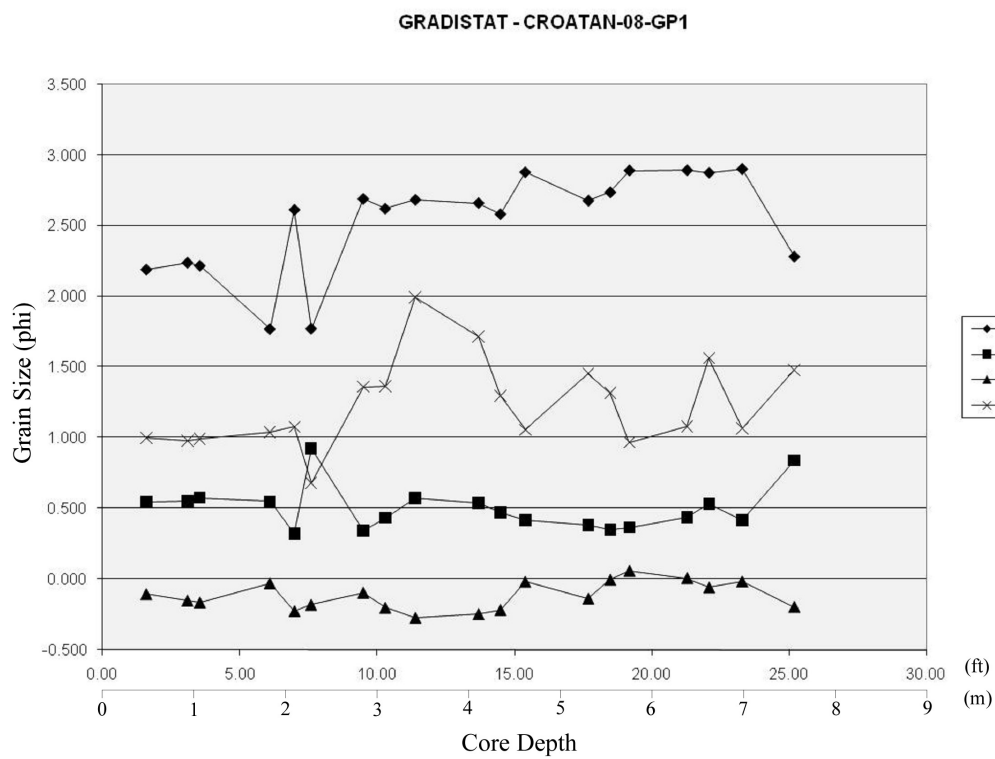
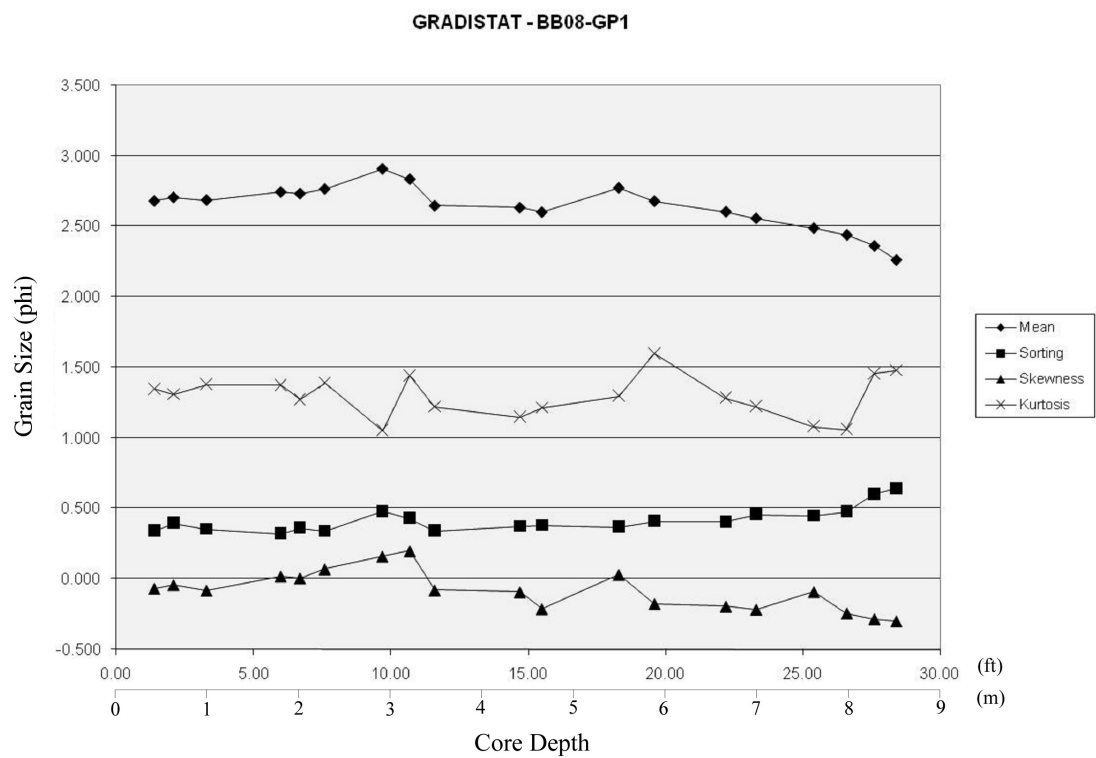


BS-08-05

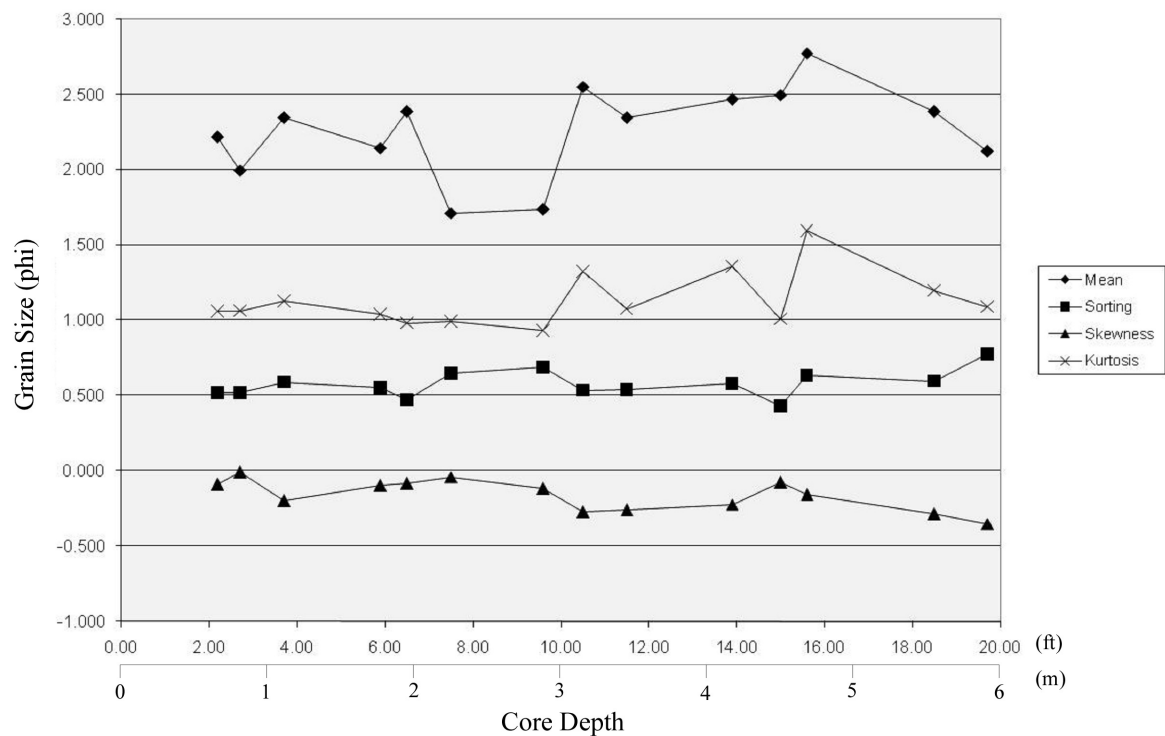


APPENDIX C: GRADISTAT STATISTICS OF GEOPROBE CORES AND VIBRACORES

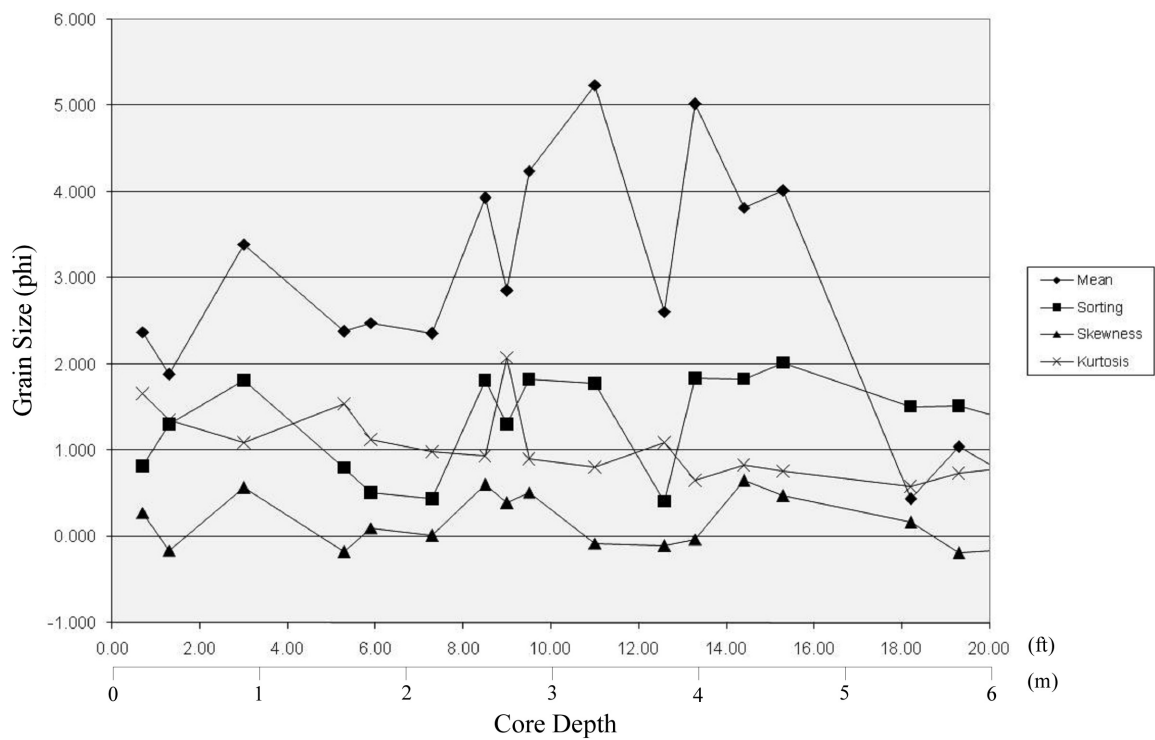
Grain size sample data from Geoprobe cores including mean grain size, sorting, skewness, and kurtosis. Only those graphs which contain enough grain size data to deduce a trend were included in this appendix.



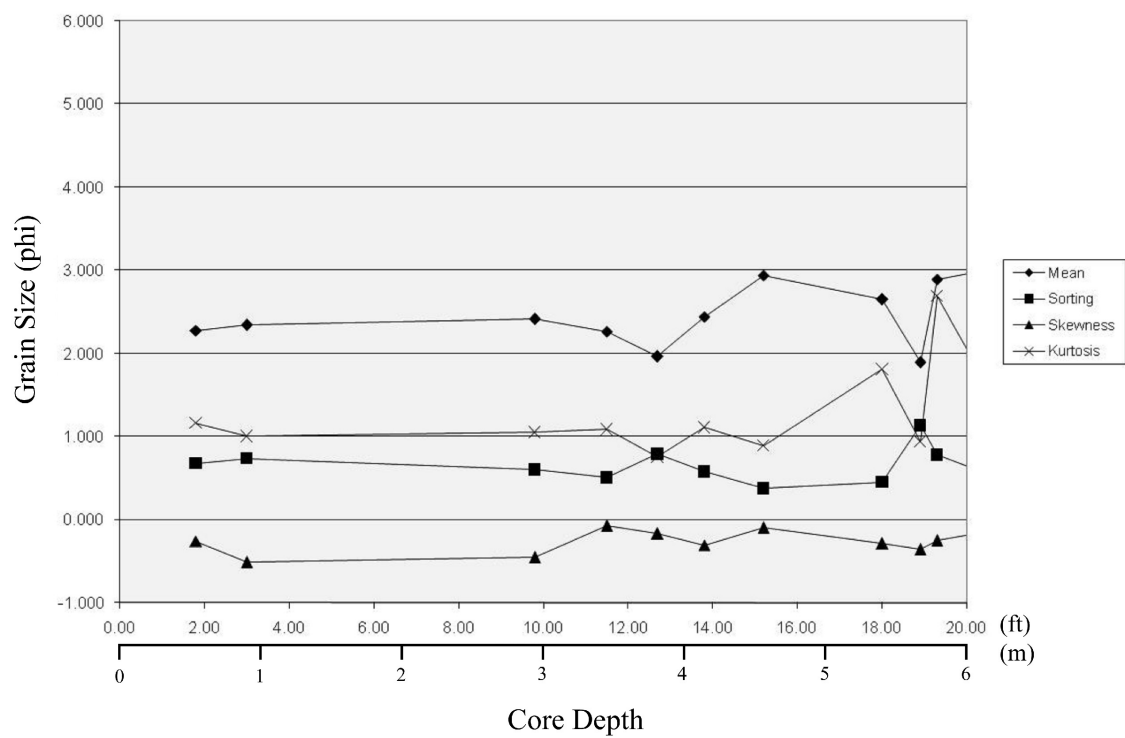
GRADISTAT - CROATAN-08-GP2



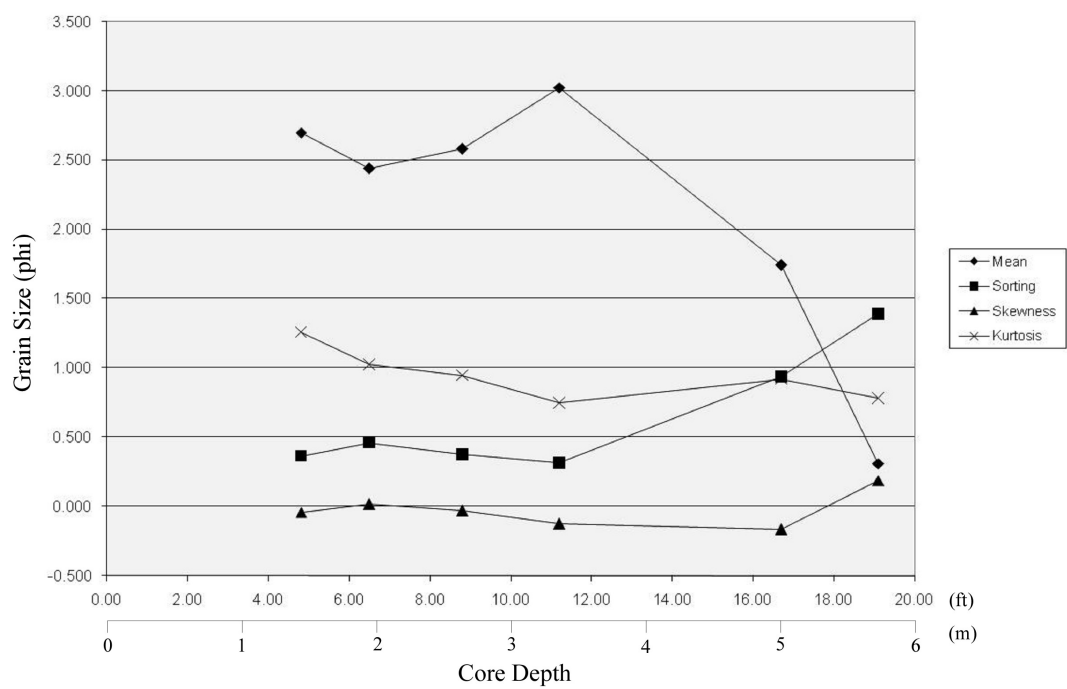
GRADISTAT - CROATAN-08-GP3



GRADISTAT - CROATAN-08-GP5



GRADISTAT - CROATAN-08-GP6



**APPENDIX D: MUD/SAND/GRAVEL PERCENTAGES FOR FORAMINIFERAL
SAMPLES**

Core	Interval (cm)	% Gravel	% Sand	% Mud
Croatan-08-GP1	316-319	0.69	99.25	0.06
	590-593	0.71	98.15	0.71
	666-669	0.00	97.08	2.92
	828-831	8.00	52.17	39.82
Croatan-08-GP2	177-180	0.78	98.96	0.26
	450-453	0.00	100.00	0.00
Croatan-08-GP3	151-154	2.16	89.59	8.24
	279-281	0.00	41.67	58.33
	402-405	0.00	13.70	86.30
	539-542	51.70	46.32	1.98
	649-652	1.34	49.64	49.02
	821-824	11.17	85.48	3.35
Croatan-08-GP4	176-179	2.36	96.91	0.73
	314-317	0.79	99.21	0.03
	367-370	0.00	97.46	2.54
	677-680	12.32	26.43	61.25
	764-767	26.67	58.08	15.25
	791-794	1.43	15.90	82.67
	818-821	55.59	40.04	4.37
Croatan-08-GP5	407-410	1.25	98.75	0.65
	578-581	3.43	94.73	5.26
	646-649	2.53	16.07	81.40
	675-678	80.66	17.23	2.11
	897-900	58.85	23.39	17.76
	927-930	10.80	21.56	67.64
Croatan-08-GP6	389-392	0.00	4.31	95.69
	567-570	0.74	74.60	24.66
	631-634	21.38	52.50	26.12
	671-674	0.31	10.99	88.70
	692-695	4.51	16.22	79.27
	763-766	20.04	68.47	11.49
Croatan-08-GP7	626-629	0.26	52.02	47.71
	731-734	9.03	6.98	84.00
	814-817	15.32	75.00	9.67

Croatan-08-GP8	660-663	11.66	86.75	1.59
	698-701	0.49	12.85	86.63
	777-780	46.36	35.11	18.53
	812-815	2.55	24.23	73.23
BB08-GP1	223-226	0.87	98.60	0.51
	555-558	1.20	97.34	1.46
	817-820	2.90	95.16	1.94
	920-923	9.08	37.69	53.23
BB08-GP2	172-175	0.00	99.90	0.10
	545-548	0.71	98.02	1.26
	706-709	0.05	99.49	0.46
BB08-GP3	311-314	2.92	95.81	1.27
	434-437	7.49	92.06	0.45
	577-580	9.93	89.81	0.26
BS-08-01	405-408	0.53	95.90	3.57
	317-320	0.00	93.22	6.78
	176-179	1.26	93.26	5.48
	101-104	0.13	75.58	24.30
BS-08-02	306-309	0.00	97.79	2.21
	134-137	0.00	97.72	2.28
	108-111	2.67	54.94	42.38
	35-38	0.00	76.37	23.60
BS-08-03	632-635	0.68	9.81	89.51
	612-615	4.73	87.74	7.53
	549-552	1.81	73.51	24.68
	508-511	1.89	33.07	65.04
	473-476	2.57	17.06	80.38
	335-338	3.23	89.38	7.39
	225-228	1.15	45.35	53.50
	193-196	0.34	96.43	3.23
	75-78	1.70	60.38	37.93
BS-08-04	425-428	0.16	99.59	0.25
	366-369	3.34	86.80	9.86
	163-166	6.82	86.28	6.91
	63-66	0.38	50.30	49.32
BS-08-05	179-182	3.96	95.21	0.82
	58-61	2.08	91.40	6.51
BS-08-06	298-301	41.83	57.66	0.51
	120-123	3.02	96.51	0.47
	21-24	7.45	85.51	7.40

APPENDIX E: RAW CENSUS DATA OF FORAMINIFERAL ASSEMBLAGES

Raw census data include counts of all benthic foraminifera in 59 samples. Planktonic taxa were included; barren samples were not included.

Core	CR-GP1	CR-GP3	CR-GP3	CR-GP3	CR-GP4	CR-GP4	CR-GP4	CR-GP4	CR-GP5	CR-GP5	CR-GP5	CR-GP5	CR-GP5	CR-GP5	CR-GP6	CR-GP6	CR-GP6	CR-GP6	CR-GP7	CR-GP7	CR-GP8
Sample Interval in core (cm)	828-831	539-542	649-652	821-824	677-680	764-767	791-794	812-815	578-581	646-649	675-678	897-900	927-930	507-570	671-674	692-694	763-766	731-734	814-817	660-663	
<i>Ammonia</i> cf. <i>A. beccarii</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Ammonia parkinsoniana</i>	16	18	2	15	5	20	4	7	43	3	20	13	9	17	2	9	14	6	12	11	
<i>Ammonia tepida</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	
<i>Ammonia</i> sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Ammotium salsum</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Amphistegina lessonii</i>	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Asterigerina carinata</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Asterigerinata mamilla</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Bolivina lowmani</i>	0	1	1	0	0	0	1	8	0	4	2	5	2	1	3	1	2	0	0	0	
<i>Bolivina paula</i>	1	0	0	0	0	0	0	1	0	0	0	8	0	0	2	0	0	1	0	0	
<i>Bolivina pseudoplicata</i>	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	1	0	0	0	
<i>Bolivina spathulata</i>	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Bolivina</i> sp.	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	
<i>Buccella frigida</i>	1	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	1	0	0	
<i>Buccella inusitata</i>	1	1	0	2	0	1	0	1	3	1	0	1	0	1	0	0	0	2	2	2	
<i>Buccella</i> sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Bulimina</i> sp.	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	
<i>Buliminella elegantissima</i>	0	0	0	1	0	0	2	0	0	0	0	1	0	0	0	0	0	2	0	0	
<i>Cassidulina subglobosa</i>	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	
<i>Cassidulina</i> sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Cibicides fletcheri</i>	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Cibicides lobatulus</i>	1	0	0	3	0	3	0	0	1	0	2	0	0	1	0	0	0	0	0	3	
<i>Cibicides refulgens</i>	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	
<i>Cibicides</i> sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Cyclogyra involvens</i>	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Dentalina</i> sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Elphidium discoidale</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Elphidium excavatum</i>	146	98	195	103	321	63	289	158	98	198	139	135	195	196	191	211	176	196	164	45	
<i>Elphidium galvestonense</i>	0	1	0	4	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	
<i>Elphidium gunteri</i>	0	2	0	4	0	0	0	0	1	0	4	0	0	0	1	1	0	0	0	0	
<i>Elphidium macellum</i>	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Elphidium mexicanum</i>	5	6	3	1	4	1	0	3	21	0	4	2	1	6	2	0	8	3	0	2	
<i>Elphidium poeyanum</i>	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Elphidium subarcticum</i>	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	
<i>Elphidium translucens</i>	1	1	0	21	1	2	4	5	32	2	4	4	2	3	2	1	0	2	1	0	
<i>Elphidium</i> sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Eponides repandus</i>	1	3	0	13	0	10	0	2	0	0	2	0	2	0	2	0	1	0	1	11	
<i>Fissurina laevigata</i>	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	
<i>Fursenkoina justiformis</i>	0	0	0	0	0	0	0	0	0	0	0	0	1	0	2	0	0	0	0	0	
<i>Gavelinopsis praegei</i>	6	0	0	1	0	4	5	1	2	1	10	6	7	0	1	1	2	7	0	0	
<i>Glabrattellina</i> sp.	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Globulina gibba</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Guttulina lactea</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Gyrodinoides</i> sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Hancovaea</i> sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Hancovaea stratonii</i>	11	17	0	21	30	1	5	32	0	1	5	2	0	0	1	3	0	9	29	0	
<i>Haynesina germanica</i>	1	0	0	0	0	0	0	1	0	0	0	2	0	0	0	0	0	0	0	0	
<i>Indeterminate rotaliid</i>	1	0	1	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	
<i>Indeterminate miliolid</i>	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Indeterminate notosariid</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Lenticulina</i> sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Marginulina</i> sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Nonionella atlantica</i>	7	5	0	3	0	5	0	2	13	0	4	2	0	5	0	0	2	1	1	7	
<i>Nonionella auricula</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Nonionella</i> sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Peneroplis</i> sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Planulina</i> cf. <i>P. foveolata</i>	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Planulina</i> sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Poropontides lateralis</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	
<i>Quinqueloculina bosciana</i>	0	0	0	0	0	0	3	0	2	0	0	2	0	0	0	0	0	0	0	0	
<i>Quinqueloculina dimidiata</i>	1	1	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	
<i>Quinqueloculina frigida</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Quinqueloculina impressa</i>	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Quinqueloculina jugosa</i>	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	3	0	
<i>Quinqueloculina lamarckiana</i>	7	6	0	1	0	9	0	0	0	0	2	0	0	0	0	0	0	0	1	18	
<i>Quinqueloculina poeyana</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Quinqueloculina seminula</i>	7	42	0	5	0	64	3	16	0	14	7	1	2	0	0	6	0	8	94	0	
<i>Quinqueloculina</i> sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Rectobolivina</i> sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	
<i>Reophax bacillaris</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Reussella atlantica</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Rosalina floridana</i>	1	0	0	0	0	5	6	1	1	2	6	3	5	0	0	1	0	4	0	0	
<i>Rosalina</i> sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Spirillina</i> sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Spiroloculina atlantica</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Textularia earlandi</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Textularia</i> cf. <i>T. gramen</i>	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	13	0	
<i>Trifarina angulosa</i>	0	0	1	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0	0	0	
<i>Trifarina</i> cf. <i>T. bradyana</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Trochammina inflata</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Trochammina</i> sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Valvulineria</i> sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Fossil <i>Cibicides</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Fossil Benthics	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	
Fossil <i>Bolivina</i>	0	0	0																		

Core	BS-08-02	BS-08-02	BS-08-02	BS-08-02	BS-08-03	BS-08-03	BS-08-03	BS-08-03	BS-08-03	BS-08-03	BS-08-04	BS-08-04	BS-08-04	BS-08-04	BS-08-04	BS-08-05	BS-08-05	BS-08-06	BS-08-06	BS-08-06
Sample Interval in core (cm)	306-309	134-137	108-111	35-38	549-552	508-511	473-476	335-338	225-228	193-196	425-428	366-369	163-166	63-66	179-182	58-61	298-301	120-123	21-24	
<i>Ammonia</i> cf. <i>A. beccarii</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	
<i>Ammonia parkinsoniana</i>	65	62	100	5	13	80	58	34	42	55	42	47	62	3	15	56	37	27	42	
<i>Ammonia tepida</i>	2	4	1	0	0	0	0	3	0	0	0	0	4	0	0	0	0	0	0	
<i>Ammonia</i> sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Ammonium salsum</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Amphistegina lessonii</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Asterigerina carinata</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Asterigerinata mamilla</i>	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	1	0	0	
<i>Bolivina lowmani</i>	0	0	0	0	0	0	4	3	1	0	0	2	0	1	0	0	0	0	0	
<i>Bolivina paula</i>	0	0	0	0	0	0	1	1	0	0	1	0	0	0	0	0	1	0	0	
<i>Bolivina pseudoplicata</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Bolivina spathulata</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Bolivina</i> sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Buccella frigida</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Buccella inusitata</i>	2	0	0	1	0	0	2	2	0	3	1	3	0	0	0	0	4	2	3	
<i>Buccella</i> sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Bulimina</i> sp.	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	
<i>Bulinella elegantissima</i>	1	0	0	0	0	2	2	3	9	4	0	1	1	0	0	0	0	0	0	
<i>Cassidulina subglobosa</i>	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	
<i>Cassidulina</i> sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Cibicides fleischeri</i>	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	
<i>Cibicides lobatulus</i>	2	7	0	0	0	0	0	3	3	2	4	1	4	1	4	1	4	4	1	
<i>Cibicides refulgens</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Cibicides</i> sp.	0	0	0	0	0	0	0	0	3	0	0	0	0	0	2	0	0	0	0	
<i>Cyclogyra involvens</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Dentalina</i> sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	
<i>Elphidium discoidale</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Elphidium excavatum</i>	99	86	86	40	16	87	121	120	118	99	135	133	77	21	111	79	121	124	95	
<i>Elphidium galvestonense</i>	0	0	0	3	0	4	2	1	0	0	0	0	0	1	2	15	0	1	21	
<i>Elphidium gunteri</i>	5	2	1	0	3	14	3	2	0	2	0	0	2	0	0	18	3	3	2	
<i>Elphidium macellum</i>	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	
<i>Elphidium mexicanum</i>	10	23	17	2	5	2	15	8	11	14	19	19	1	5	32	5	10	25	25	
<i>Elphidium poeyanum</i>	0	0	1	0	4	9	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Elphidium subarcticum</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Elphidium translucens</i>	4	7	1	0	0	1	1	2	6	6	0	9	1	2	10	2	5	1	1	
<i>Elphidium</i> sp.	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	1	0	0	
<i>Epionides repandus</i>	0	0	0	0	0	0	0	0	0	2	0	0	0	0	11	0	2	4	0	
<i>Fissurina laevigata</i>	0	0	0	0	4	2	1	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Fursenkoina fusiformis</i>	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	
<i>Gavelinopsis praegeri</i>	4	0	0	0	0	0	2	3	0	1	0	1	0	1	1	0	0	0	0	
<i>Glabratellina</i> sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Globulina gibba</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Gutulina lactea</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Gyrodinoides</i> sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Hanzawaia</i> sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Hanzawaia stratonii</i>	11	4	1	0	0	0	1	0	4	12	0	3	0	11	0	5	0	2	2	
<i>Haynesina germanica</i>	0	0	14	0	3	22	8	3	1	0	1	8	0	0	0	2	0	0	0	
<i>Indeterminate rotaliid</i>	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	
<i>Indeterminate miliolid</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Indeterminate notasariid</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	
<i>Lenticulina</i> sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	
<i>Marginalina</i> sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	
<i>Nonionella atlantica</i>	4	3	0	0	0	0	1	2	1	2	0	1	0	1	0	1	4	1	1	
<i>Nonionella auricula</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Nonionella</i> sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Peneroplis</i> sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	
<i>Planulina</i> cf. <i>P. poveolata</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Planulina</i> sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Poroeponides lateralis</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Quinqueloculina boscinia</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	
<i>Quinqueloculina dimidiata</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Quinqueloculina frigida</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	
<i>Quinqueloculina impressa</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Quinqueloculina jugosa</i>	2	0	0	0	0	0	1	0	0	0	0	1	0	7	0	0	3	1	1	
<i>Quinqueloculina lamarckiana</i>	1	0	0	0	0	0	0	0	0	0	0	0	0	10	0	0	1	0	0	
<i>Quinqueloculina poeyana</i>	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Quinqueloculina seminula</i>	1	0	0	0	0	0	1	0	0	0	0	0	0	30	1	2	2	0	0	
<i>Quinqueloculina</i> sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Rectobolivina</i> sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Reophax bacillaris</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Reussella atlantica</i>	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	
<i>Rosalina floridana</i>	0	0	0	0	0	0	4	5	3	5	0	0	0	0	0	5	0	0	0	
<i>Rosalina</i> sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Spirillina</i> sp.	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	
<i>Spiroloculina atlantica</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Textularia earlandi</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Textularia</i> cf. <i>T. gramen</i>	0	0	0	0	0	0	0	0	1	1	0	0	2	0	2	0	2	0	0	
<i>Trifarina angulosa</i>	0	3	0	0	0	0	2	2	6	1	1	0	0	0	0	0	0	0	0	
<i>Trifarina</i> cf. <i>T. bradyana</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Trochammina inflata</i>	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	
<i>Trochammina</i> sp.	0	0	1	1	0	0	0	0	0	0	0	1	2	0	0	0	0	0	0	
<i>Valvulineria</i> sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Fossil Cibicides</i>	7	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	1	
<i>Fossil Benthics</i>	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	2	0	
<i>Fossil Bolivina</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Fossil Elphidium</i>	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Fossil Nonionella</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Total Fossils (F)	12	8																		

APPENDIX F: RELATIVE ABUNDANCE DATA OF FORAMINIFERAL ASSEMBLAGES

Relative abundance data (expressed as percents) of 32 species of foraminifera (in 59 samples) included in the cluster analysis and comprising $\geq 2\%$ of the assemblage in any one sample.

APPENDIX G: TRANSFORMED ABUNDANCE DATA OF FORAMINIFERAL ASSEMBLAGES

Transformed abundance data of 32 species included in the cluster analysis comprising greater than or equal to 2% of any one sample.

**APPENDIX H: ALPHABETICAL LIST OF FORAMINIFERAL TAXA
IDENTIFIED TO THE SPECIES LEVEL WITH ORIGINAL REFERENCES**

Ammonia cf. *A. beccarii* (Linnaeus): *Nautilus beccarii* Linné, 1758, p. 710, pl. 1, figs. 1a-c.

Ammonia parkinsoniana (d'Orbigny): *Rosalina parkinsoniana* d'Orbigny, 1839b, p. 99, vol. 8, pl. 4, figs. 25-27.

Ammonia tepida (Cushman): *Rotalia beccarii* (Linnaeus) var. *tepida*. Cushman, 1926, p. 79, pl. 1, figs. 8a, b, c.

Ammotium salsum (Cushman and Bronnimann): *Ammobaculites salsus* Cushman and Bronnimann, 1948, p. 16, pl. 3, figs. 7-9.

Amphistegina lessonii d'Orbigny: *Amphistegina lessonii* d'Orbigny, 1826, p. 304, pl. 17, figs. 1-4.

Asterigerina carinata d'Orbigny: *Asterigerina carinata* d'Orbigny, 1839b, p. 118, pl. 5, fig. 25, pl. 6, figs. 1-2.

Asterigerinata mamilla (Williamson): *Rotalina mamilla* Williamson, 1858, p. 54, pl. 4, figs. 109-111.

Bolivina lowmani Phleger and Parker: *Bolivina lowmani* Phleger and Parker, 1951, pt. 2, p. 13, pl. 6, figs. 20a, b, 21.

Bolivina paula Cushman and Cahill: *Bolivina paula* Cushman and Cahill in Cushman and Ponton p. 84, pl. 12, fig. 6a-b.

Bolivina pseudoplicata Heron-Allen and Earland: *Bolivina pseudoplicata* Heron-Allen and Earland, 1930, p. 81, pl. 3, figs. 36-40.

Bolivina spathulata (Williamson): *Textularia variabilis* var. *spathulata* Williamson, 1858, pg. 76, pl. 6, figs. 164-165.

Buccella frigida Andersen: *Buccella frigida* Andersen, 1952: 147, figs. 4-6.

Buccella inusitata Andersen: *Buccella inusitata* Andersen, 1952, p. 147, figs. 10, 11.

Buliminella elegantissima (d'Orbigny): *Bulimina elegantissima* d'Orbigny, 1839a, p. 51, pl. 7, figs. 13, 14.

Cassidulina subglobosa Brady: *Cassidulina subglobosa* Brady, 1881, p. 60; Brady, 1884, p. 430, pl. 54, fig. 17.

Cibicides fletcheri Galloway and Wissler: *Cibicides fletcheri* Galloway and Wissler, 1927, p. 64, pl. 10, figs. 8-9.

Cibicides lobatulus (Walker and Jacob): *Nautilus lobatulus* Walker and Jacob, 1798, p. 642, pl. 14, fig. 36.

Cibicides refulgens de Montfort: *Cibicides refulgens* de Montfort, 1808, p. 123.

Cyclogyra involvens (Reuss): *Operculina involvens* Reuss, 1850, p. 370, pl. 46, fig. 20.

Elphidium advenum (Cushman): *Polystomella advena* Cushman, 1922, p. 56, pl. 9, figs. 11, 12.

Elphidium discoidale (d'Orbigny): Schnitker, 1971:198, pl. 7: fig. 6 [as *Elphidiella* sp., cf. *E. mexicana*].

Elphidium excavatum (Terquem): *Polystomella excavata* Terquem, 1875, p. 20, pl. 2, figs. 2 a-f.

Elphidium galvestonense (Kornfeld): *Elphidium gunteri* (Cole) var. *galvestonensis*, Kornfeld, 1931, p. 87, pl. 15, figs. 1-3.

Elphidium gunteri Cole: *Elphidium gunteri* Cole, 1931, p. 34, pl. 4, figs. 9, 10.

Elphidium macellum (Fichtel and Moll): *Nautilus macellus* var. *B* Fichtel and Moll, 1798, p. 68, pl. 10, fig. h,i,k; in Rogl and Hansen, 1984, p. 50, pl. 14, figs. 2, 5, 6; pl. 15, figs. 1-2.

Elphidium mexicanum (Kornfeld): *Elphidium incertum* (Williamson) var. *mexicanum*. Kornfeld, 1931, p. 89, pl. 16, figs. 1-2.

Elphidium poeyanum (d'Orbigny): *Polystomella poeyana* d'Orbigny 1839b, p. 55, pl. 6, figs. 25, 26.

Elphidium subarcticum Cushman: *Elphidium subarcticum* Cushman, 1944, p. 27, pl. 3, figs. 34, 35.

Elphidium translucens Natland: *Elphidium translucens* Natland, 1938, p. 144, pl. 5, figs. 3, 4.

Eponides repandus (Fichtel and Moll): *Nautilus repandus* Fichtel and Moll, 1798, p. 35, pl. 3, figs. a-d.

Fissurina laevigata Reuss: *Fissurina laevigata* Reuss, 1850, p. 366, pl. 46, fig. 1.

Fursenkoina fusiformis (Williamson): *Bulimina pupoides* d'Orbigny var. *fusiformis* Williamson, 1858, p.63, pl. 5, figs 129,130.

Gavelinopsis praegeri (Heron-Allen and Earland): *Discorbina praegeri* Heron-Allen and Earland, 1913, p. 122, pl. 10, figs. 8-10.

Globulina gibba d'Orbigny: *Globulina gibba* d'Orbigny, 1826, p. 266, no. 10, Modele no. 63.

Guttulina lactea (Walker and Jacob): *Serpula lactea*, Walker and Jacob, 1798, p. 634, pl. 14, fig. 4.

Hanzawaia strattoni (Applin): *Truncatulina americana* (Cushman) var. *strattoni*. Applin et al., 1925, p. 99, pl. 3, fig. 3.

Haynesina germanica (Ehrenberg): *Nonionina germanica* Ehrenberg, 1840, p. 23; Ehrenberg, 1841, pl. 2, figs. 1a-g.

Nonionella atlantica Cushman: *Nonionella atlantica* Cushman, 1947, p. 90, pl. 20, figs. 4, 5.

Nonionella auricula Heron-Allen and Earland: *Nonionella auriculus* Heron-Allen and Earland, 1930, p. 192-193, pl. 5, figs. 68-70.

Planulina cf. *P. foveolata* (Brady): *Anomolina foveolata* Brady 1884, Rept. Voy. *Challenger*, Zool. 9, p. 676, pl. 94, figs. 1 a-c.

Poroepionides lateralis (Terquem): *Rosalina lateralis* Terquem, 1878, p. 25, pl. 2, fig. 11a-c.

Quinqueloculina bosciana d'Orbigny: *Quinqueloculina bosciana* d'Orbigny, 1839b, p. 191, pl. 11, figs. 22-24.

Quinqueloculina dimidiata Terquem: *Quinqueloculina dimidiata* Terquem, 1876, p. 81, pl. 11, fig. 5a-c.

Quinqueloculina frigida Parker: *Quinqueloculina frigida* Parker, 1952, p. 406, pl. 3, figs. 20a, b.

Quinqueloculina impressa Reuss: *Quinqueloculina impressa* Reuss, 1851, p. 87, pl. 7, fig. 59.

Quinqueloculina jugosa Cushman: *Quinqueloculina seminulum* (Linnaeus) var. *jugosa* Cushman, 1944, p. 13, pl. 2, fig. 15.

Quinqueloculina lamarckiana d'Orbigny: *Quinqueloculina lamarckiana* d'Orbigny, 1839b, p. 189, pl. 11, figs. 14-15.

Quinqueloculina poeyana d'Orbigny: *Quinqueloculina poeyana* d'Orbigny, 1839b, p. 191, pl. 11, fig. 25-27.

Quinqueloculina seminula (Linnaeus): *Serpula seminulum* Linnaeus, 1758, p. 786.

Reophax bacillaris Brady: *Reophax bacillaris* Brady, 1884, p. 293, pl. 30, figs. 23-24.

Reussella atlantica Cushman: *Reussella spinulosa* var. *atlantica* Cushman, 1947, p. 91, pl. 20, figs. 6, 7.

Rosalina floridana (Cushman): *Discorbis floridana* Cushman, 1922, p. 39, pl. 5, figs. 11, 12.

Spiroloculina atlantica Cushman: *Spiroloculina atlantica* Cushman, 1947, p. 88, pl. 19, figs. 3-5.

Textularia earlandi Parker: *Textularia earlandi* Parker, 1952, p. 458, pl. 2, figs. 4-5 (as *Textularia* cf. *T. tenuissima* Earland).

Textularia cf. *T. gramen* d'Orbigny: *Textularia gramen* d'Orbigny, 1846, p. 248, pl. 15, figs. 4-6.

Trifarina angulosa (Williamson): *Uvigerina angulosa* Williamson, 1858, p. 67, pl. 5, fig. 140.

Trifarina cf. *T. bradyana* (Cushman): *Angulogerina carinata* var. *bradyana* Cushman, 1932, p. 45, pl. 6, figs. 9-10.

Trochammina inflata (Montagu): *Nautilus inflatus* Montagu, 1808, p. 81, pl. 18, figs. 3.

APPENDIX I: OSL AND AMS ^{14}C SAMPLE INFORMATION

	Core	Sample Elevation above MSL (m)	Sample Material
OSL Dating	Croatan-08-GP1	3.80-3.87	Medium-fine sand
	Croatan-08-GP1	1.30-1.38	
	Croatan-08-GP3	3.95-4.06	
	Croatan-08-GP4	7.19-7.14	
	Croatan-08-GP5	4.45-4.53	
	below MSL (m)		
	BB08-GP1	0.15-0.25	
	BB08-GP2	0.80-0.89	
	BS-08-01	5.67-5.77	
	BS-08-04	7.61-7.71	
	BS-08-03	7.96-8.06	
BS-08-05	3.30-3.40		
AMS ¹⁴ C Dating	BS-08-02	3.24	<i>Crassostrea virginica</i>
	BS-08-03	4.59	<i>Cyrtopleura costata</i>
	BS-08-03	7.06-7.09	<i>Elphidium excavatum</i>