# LATE HOLOCENE EVOLUTION OF A RETROGRADING BARRIER: HUTAFF ISLAND, NORTH CAROLINA

Benjamin Adam McGinnis

A Thesis Submitted to the
University of North Carolina at Wilmington in Partial Fulfillment
Of the Requirements for the Degree of
Master of Science

Department of Earth Sciences

University of North Carolina at Wilmington

2004

Approved by

Advisory Committee

Lynn A. Leonard

Paul A. Thayer

William J. Cleary
Chair

Accepted by

Robert D. Roer
Dean, Graduate School

This thesis has been prepared in a style and format

consistent with

The Journal of Coastal Research

TABLE OF CONTENTS

ABSTRACT ..... v

ACKNOWLEDGEMENTS ..... vii

DEDICATION ..... viii

LIST OF TABLES ..... ix

LIST OF FIGURES ..... x

INTRODUCTION ..... 1

Study Area ..... 1

Background ..... 4

Storm History ..... 6

Objectives ..... 7

METHODS ..... 10

Shoreline Change ..... 10

Topography ..... 13

Shoreface Geology ..... 14

Back-barrier Estuary History ..... 17

RESULTS ..... 17

Shoreline Change ..... 17

Long-term Shoreline Change Rates ..... 20

Short-term Storm Induced Shoreline Changes ..... 22

Influence of Adjacent Tidal Inlets ..... 25

Morphologic Changes ..... 35

Reach Identification ..... 36

Topography ..... 40

Shoreface Geology ..... 47

Underlying Stratigraphic Units ..... 47

Sediments ..... 56

Back-barrier Estuary History ..... 61

DISCUSSION ..... 66

Influence of Storm Impacts ..... 66

Influence of Adjacent Tidal Inlets ..... 70

Morphologic and Topographic Change ..... 78

Shoreface Geology ..... 81

Conceptual Model ..... 84

CONCLUSIONS ..... 86

LITERATURE CITED ..... 88

ABSTRACT

Hutaff Island is a 6.0-km (3.7-mile) long undeveloped barrier located in southwestern Onslow Bay, North Carolina. The barrier is bordered by New Topsail Inlet to the northeast and Rich Inlet to the southwest, and has historically been influenced by several adjacent tidal inlets with contrasting behaviors. Severe storm events have frequently impacted the barrier throughout the 1938 – 2002 study period, resulting in dramatic erosion and overtopping of the barrier. The development of major washover terraces coupled with storm-induced dune erosion has dramatically lowered the barrier's topography. Consequently, the island is poised to migrate landward at accelerated rates during future high-energy storm events.

The shoreface that fronts the barrier consists of a thin veneer of modern sand and gravelly sand. The mobile surface veneer is generally less than 1.0 m thick and overlies an easily eroded Oligocene siltstone unit that frequently crops out on the inner shoreface forming low-relief hardbottoms. Vibracore sequences recovered from the estuary contain inter-bedded clean and muddy sand units. The sand-rich intertidal and shallow subtidal sequences recovered near the barrier reflect the role of the numerous inlets that have cycled trough the area.

Long-term shoreline change rates showed that Hutaff Island had experienced an average net loss of ~ 2.1 m/year (7.0 ft/year) between 1938 and 2002. A dramatic lowering of the barrier profile accompanied this landward translation. The relatively high erosion rates and increased washover susceptibility appear to be attributable to a combination of variables, including the region's low sediment supply and the persistent presence of unstable inlets. An understanding of the processes influencing Hutaff Island's evolution can be used as a model in formulating management decisions on nearby barriers where it is often difficult to assess the active processes

and changes taking place as a result of dense coastal development and its associated anthropogenic effects.

ACKNOWLEDGMENTS

I wish to express my utmost gratitude to my wife Katie McGinnis, for her undying support, dedication, and sacrifice throughout my graduate education. I would also like to thank my entire family for the continued support of my educational aspirations. It has been a pleasure working under Dr. William J. Cleary for the last three years. His expertise and guidance proved to be an invaluable asset to my research and career preparation. Dr. Paul A. Thayer and Dr. Lynn Leonard are thanked for their outstanding moral support and guidance as members of my graduate committee. I would like to express a sincere debt of gratitude to C.J. Jackson, John Welsh, David Doughty, Adam Knierim, Kenny Wilson, and Leighann Budde, for their friendship and support over the past three years while working with me as graduate students in the Coastal Geology Laboratory.

Special thanks is extended to Lyn Jack, of the Wilmington District, U.S. Army Corps of Engineers for the use of aerial photographs, and to Melissa Smith, of the UNCW Center for Marine Science for providing a computer graphics template used in this study to produce stratigraphic profiles. I would also like to thank the UNCW Graduate School and the UNCW Department of Earth Sciences for their grant support of my research, and the UNCW Center for Marine Science for making boats and equipment available for support of my field research.

# DEDICATION

This thesis is dedicated to my wife, Katie McGinnis for her love, and immense support and encouragement during the course of my graduate education.

LIST OF TABLES

Table Page

1. Summary of storm events that have made landfall or passed within 100 km of Hutaff Island ..... 8

LIST OF FIGURES


Figure Page

1. Regional map of the southeast North Carolina coast ..... 2

2. Location map of Hutaff Island, North Carolina ..... 3

3. Long-term average annual shoreline change rates published by the North Carolina Division of Coastal Management ..... 5

4. Map illustrating the recent (1996-1999) hurricane tracks ..... 9

5. Map depicting the constructed baseline and transects (1-76) used in the SCARPS! shoreline change analysis ..... 12

6. Map depicting the constructed baseline and transects (26-64) used to determine topographic profiles from LIDAR elevation data ..... 15

7. Map showing the locations of shoreface vibracore and diver survey sites and sidescan sonargraph mosaic used in the study ..... 16

8. Map showing the locations of back-barrier vibracores used in this study ..... 18

9. Net shoreline changes at each transect across Hutaff Island ..... 19

10. Shoreline change rates at each transect across Hutaff Island ..... 21

11. Map illustrating the shoreline and inlet positions in 1938 and 2002, at the beginning and end of the period studied ..... 23

12. Shoreline change as the result of Hurricane Fran (09/05/1996) at each transect across Hutaff Island ..... 26

13. Map illustrating the zones of historical tidal inlet locations adjacent to Hutaff Island throughout the study period ..... 27

14. Rich Inlet ebb-channel orientations and shoreline changes observed on the SW shoulder (Figure Eight Island) and the NE shoulder (Hutaff Island) of the inlet between 1938-2002 ..... 29

15. Map depicting Rich Inlet's 1993 ebb-channel position and adjacent shorelines projected onto 1996 aerial photographs ..... 30

16. Old Topsail Inlet ebb-channel orientations and shoreline changes observed on the SW shoulder (Coke Island) and the NE shoulder (Lea Island) of the inlet between 1938-2002 ..... 32

17. New Topsail Inlet ebb-channel orientations and shoreline changes observed on the SW shoulder (Hutaff Island) and the NE shoulder (Topsail Island) of the inlet between 1938-2002 ..... 33

18. Map showing the identified reaches with respect to the influence of adjacent tidal inlets, shoreline change, topographic relief, and morphologic characteristics ..... 38

19. Composite LIDAR grids showing elevation data from LIDAR surveys conducted in 1996-2000. Warm (red) colors represent higher elevations and cool (blue) colors represent low elevations ..... 41

20. Representative topographic profile for Reach I derived from LIDAR elevation grid data ..... 42

21. Representative topographic profiles for Reach II derived from LIDAR elevation grid data ..... 44

22. Representative topographic profiles for Reach III derived from LIDAR elevation grid data ..... 45

23. Representative topographic profiles for Reach IV derived from LIDAR elevation grid data ..... 46

24. Map illustrating stratigraphic profiles transects derived from vibracore and diver survey data ..... 48

25. Stratigraphic profile along shore parallel Transect A – A' ..... 49

26. Stratigraphic profile along shore parallel Transect B – B' ..... 50

27. Stratigraphic profile along shore parallel Transect C – C' ..... 51

28. Stratigraphic profile along shore parallel Transect D – D' ..... 52

29. Stratigraphic profile along shore parallel Transect E – E' ..... 53

30. Map illustrating the vibracore and diver survey sites where underlying stratigraphic units where encountered ..... 54

31. Map depicting the locations of observed hardbottom exposures and sites where sediment cover was less than 30 cm ..... 55

32. Map depicting the locations of paleo-fluvial channels identified in this study at vibracore and diver survey sites, and in previous studies by CLEARY (2003), HDR (2002), and MCQUARRIE (1998) ..... 57

33. Map depicting the shoreface surface sediment types observed at vibracore and diver survey sites ..... 58

34. Map depicting the sediment thickness observed at vibracore and diver survey sites and the identified sediment thickness areas across the shoreface ..... 60

35. Back-barrier stratigraphic profile along shore parallel Transect F – F' ..... 62

36. Back-barrier stratigraphic profile along shore parallel Transect G – G' ..... 63

37. Back-barrier stratigraphic profile along shore parallel Transect H – H' ..... 64

38. Back-barrier stratigraphic profile along shore parallel Transect I – I' ..... 65

39. Aerial photographs depicting the migration and eventual closure of Old Topsail Inlet ..... 74

40. Map illustrating the location of back-barrier marsh islands as formed by historical tidal inlets ..... 77

41. Conceptual model depicting the evolution of a retrograding barrier in a sediment starved, storm-influenced environment ..... 85

# INTRODUCTION

The understanding of barrier island evolution has become progressively more important due in part to increased coastal development and the associated problems with transgressive barrier islands. Many of the developed shorelines along the southwestern portion of Onslow Bay, North Carolina have been repeatedly nourished, and as a result, recession rates and long-term storm impacts are difficult to assess on these retrograding barriers. One exception to this is Hutaff Island. The location and undeveloped nature of Hutaff Island provides an exemplary barrier setting to study the long-term role of storms, and the influence of the adjacent inlets and shoreface on the recent evolution of the barrier.

## Study Area

Low relief, retrogradational barrier islands characterize southwestern Onslow Bay between New River Inlet and the Fort Fisher Headland. The barrier islands in this high-energy coastal reach are situated along the northeast-southwest trending flank of the Cape Fear foreland (Figure 1).

Hutaff Island extends 6.0 km (3.7 mile) along the southeastern coast of North Carolina, in the aforementioned segment of Onslow Bay (Figure 2). The barrier is bounded by New Topsail Inlet to the northeast and Rich Inlet to the southwest. When Old Topsail Inlet, located along the northeastern one-third of the island, closed in 1997 – 1998 it formed a contiguous barrier consisting of Coke (Hutaff) and Lea Islands, herein referred to as Hutaff Island. Neighboring Figure Eight and Topsail Islands are highly developed barriers where nourishment activity is commonplace.

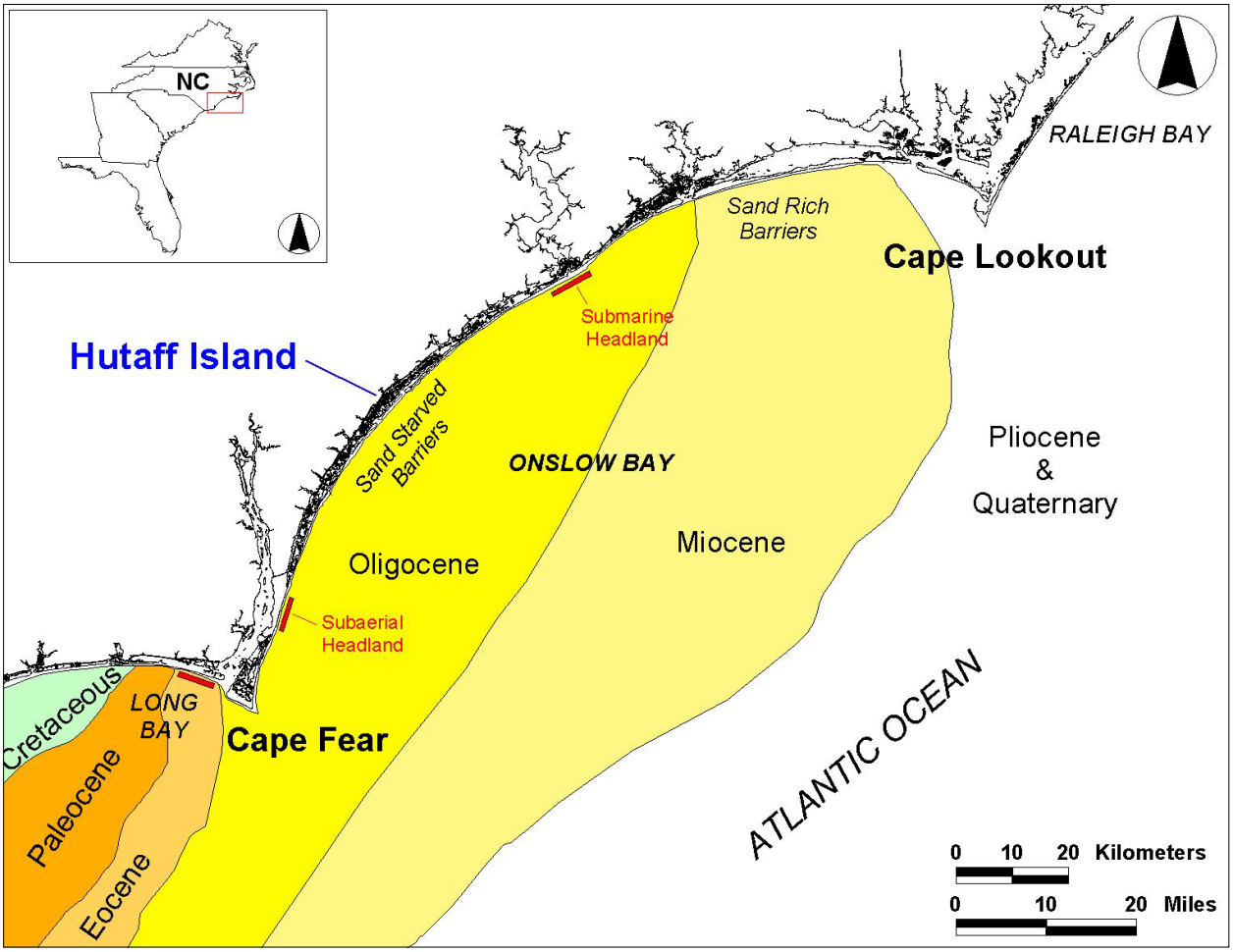


Figure 1. Regional map of the southeast North Carolina coast. This map illustrates the continental shelf geology (After SNYDER *et al*., 1982) and the locations of headlands (After CLEARY, 2002).

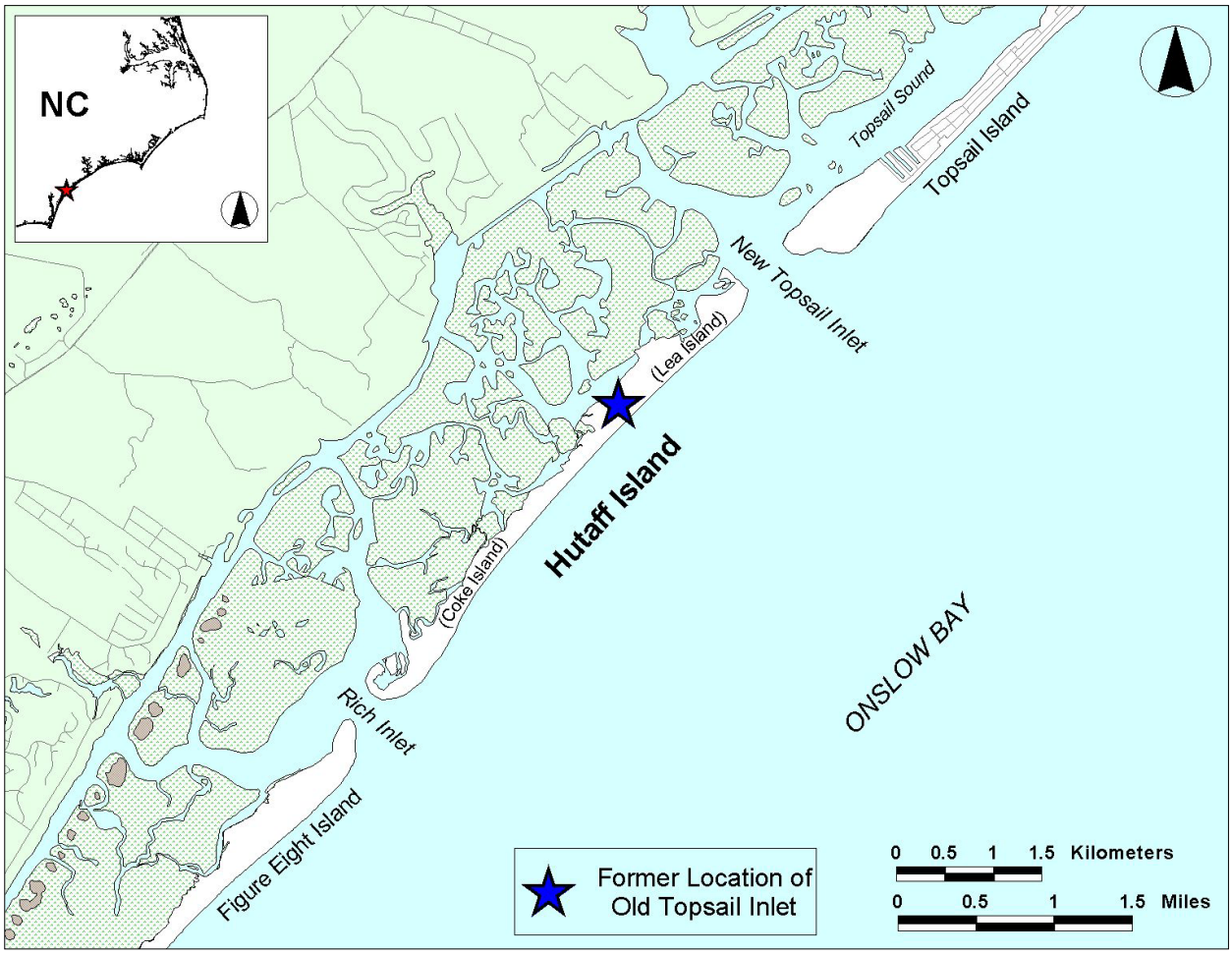


Figure 2. Location map of Hutaff Island, North Carolina.

## Background

The southeastern North Carolina coast from Cape Lookout to the South Carolina border is underlain by geologic units (Figure 1) that range in age from Upper Cretaceous to Pliocene (SNYDER *et al.*, 1994; RIGGS *et al.*, 1995; and CLEARY and PILKEY, 1996). These units are associated with the Carolina Platform, a structural feature that underlies the region. The south-to-east dipping units that comprise the platform have been truncated by the landward migrating shoreline, resulting in rock exposures on the shoreface (RIGGS *et al.*, 1995).

The area offshore Hutaff Island is a broad, shallow, high-energy shelf system with only a thin and variable sediment cover. An easily eroded Oligocene dolo-siltstone unit underlies the shoreface in the region. On a regional basis, the negligible accumulations of Holocene sediments in Onslow Bay are the result of low fluvial input and a lack of sediment exchange with nearby Long and Raleigh Bays (CLEARY and PILKEY, 1968; CLEARY and THAYER, 1973; and RIGGS *et al.*, 1995). The distribution of modern sediments is controlled by the erosion and reworking of outcropping Tertiary and Quaternary geologic sequences (CLEARY and PILKEY, 1968; CLEARY and THAYER, 1973; SNYDER *et al.*, 1982; MARCY, 1997; and JOHNSON, 1998).

Published long-term average annual erosion rates exceed 0.9 m/year (3 ft/yr) (BENTON *et al.*, 1992; NC DCM, 2003) along much of Hutaff Island (Figure 3). Previous work by HUNT (1979) characterized the back-barrier marsh sediments of nearby Topsail Sound, located to the northeast on the opposite side of New Topsail Inlet from Hutaff Island. Her study found the modal grain-size throughout the sound to be fine sand, with the finer clays and silts dominating the salt marsh and the coarser silts and sands dominating the sound's channels. GAMMILL (1990) attributed the increased development of marsh behind Hutaff Island to the migration of

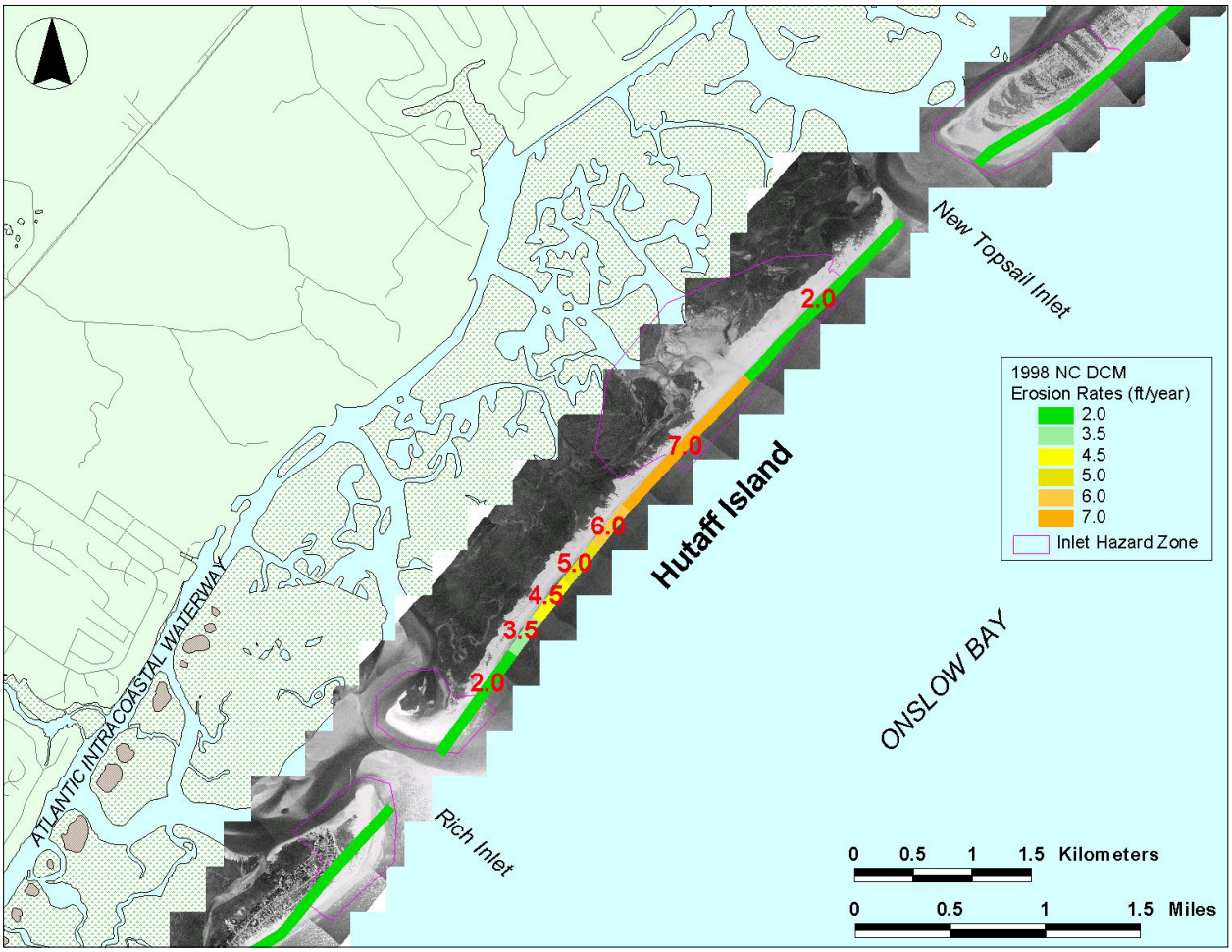


Figure 3. Long-term average annual shoreline change rates published by the North Carolina Division of Coastal Management (NC DCM, 2003). Rates are based upon shoreline data updated through 1998.

Old Topsail and New Topsail Inlets. His historical analysis of inlet position not only showed the migration of these inlets, but also indirectly showed the landward migration of the shoreline. Volumetric changes along Hutaff Island's shoreline where examined between 1997 and 2000 by WHITE (2002) and WHITE and WANG (2003). Their studies used highly spatially accurate and high spatial resolution digital-elevation model (DEM) data derived from light detection and ranging (LIDAR) datasets. A net volumetric gain was shown to have occurred along Hutaff Island between 1997-1998 and 1999-2000, and a net volumetric loss was shown between 1998-1999. The authors attributed the net volumetric loss observed between 1998 and 1999 to the impacts of hurricanes that directly affected the study area during that period. WHITE (2002) also supported DOLAN'S (1973) suggestion that natural, undeveloped barrier islands are better suited to handle both extreme storm events and uniform coastal processes than developed barrier islands.

Geological and geophysical data from published (MCQUARRIE, 1998; CLEARY, 2002; and HDR, 2002), unpublished (CLEARY *pers. comm.*, 2003.), and ongoing investigations (USACE) were utilized in the study. The combined data set includes information from diver and ship-retrieved vibracores and SCUBA based diver surveys, which provide information on the nature of the shoreface sediment sequence and underlying stratigraphic units.

## Storm History

Prior to 1996, southeastern North Carolina had not experienced the landfall of a major hurricane (Category 3 or higher) since 1954 when Hurricane Hazel made landfall near the North Carolina/South Carolina border. Two Category 4 hurricanes, Helene in 1958 and Diana in 1984, passed offshore in Onslow Bay. Hurricane Helene moved further offshore and Hurricane Diana

was weakened to a Category 1 hurricane before making landfall just north of Cape Fear. National Oceanic and Atmospheric Administration (NOAA) data, summarized in Table 1, show that 16 hurricanes and numerous recorded tropical and extra-tropical storms have made landfall or passed within 100 km (62 miles) of Hutaff Island since 1938. A spate of hurricane activity from 1996 to 1999 involved four major storms that made landfall in the region with another two passing nearby (Figure 4).

The number of storms whose short-term shoreline change effect can be quantified is somewhat limited. This is not only true to Hutaff Island, but also general to all shoreline change studies. Until recently, pre and post-storm aerial photography had not always been collected. The availability of historical aerial photographs is limited, with large time gaps between flights prior to the 1980's, making short-term shoreline change quantification difficult for older storms. In order to quantify the short-term, storm-induced shoreline change, aerial photographs should have been collected as close as possible, prior to and after the storm impacted the shoreline.

## Objectives

The objectives of this study are to examine the long-term role of storms, and the influence of the adjacent inlets and shoreface on the recent evolution of Hutaff Island, a retrograding barrier in a sediment starved, storm-influenced environment. The main objectives will be supported by several sub-objectives that will aid in the understanding of the observed barrier evolution. These sub-objectives include:

- Determine long-term shoreline change rates.
- Determine the short-term changes in shoreline position and topography with respect to storm events and inlet behavior.

Table 1. Summary of storm events that have made landfall or passed within 100 km of Hutaff Island. Storm category abbreviations: H1-H5=Hurricanes (Categories 1-5), TS=Tropical Storms, TD=Tropical Depressions, SS=Subtropical Storms, SD=Subtropical Depressions, E=Extratropical Storms, L=Tropical Low.

| Date | Name | Pressure (mb) | Wind (kts) | Wind (mph) | Category | Landfall |
|---|---|---|---|---|---|---|
| 10/24/1938 | Not Named | | 40 | 45 | E | X |
| 8/1/1944 | Not Named | 990 | 80 | 90 | H1 | X |
| 6/25/1945 | Not Named | | 60 | 70 | TS | |
| 7/6/1946 | Not Named | | 40 | 45 | TS | X |
| 9/27/1953 | Florence | | 35 | 40 | E | |
| 10/15/1954 | Hazel | 937 | 110 | 125 | H3 | X |
| 8/12/1955 | Connie | | 85 | 100 | H2 | |
| 8/17/1955 | Diane | | 75 | 85 | H1 | X |
| 9/19/1955 | Ione | | 90 | 105 | H2 | X |
| 9/26/1956 | Flossy | | 30 | 35 | E | |
| 9/27/1958 | Helene | 943 | 115 | 135 | H4 | |
| 7/29/1960 | Brenda | | 45 | 50 | TS | |
| 9/12/1960 | Donna | 958 | 95 | 110 | H2 | X |
| 9/14/1961 | Not Named | | 30 | 35 | TD | X |
| 8/28/1962 | Alma | 1002 | 45 | 50 | TS | |
| 9/13/1964 | Dora | | 45 | 50 | TS | |
| 6/12/1968 | Abby | | 25 | 30 | TD | X |
| 10/20/1968 | Gladys | | 75 | 85 | H1 | |
| 8/17/1970 | Not Named | | 30 | 35 | TD | X |
| 8/27/1971 | Doria | 998 | 50 | 60 | TS | X |
| 9/30/1971 | Ginger | 984 | 65 | 75 | H1 | X |
| 6/21/1972 | Agnes | 990 | 30 | 35 | TD | |
| 6/28/1975 | Amy | 1011 | 25 | 30 | TD | |
| 10/27/1975 | Hallie | 1002 | 45 | 50 | TS | |
| 9/6/1977 | Clara | 1012 | 25 | 30 | TD | |
| 8/20/1981 | Dennis | 999 | 50 | 60 | TS | X |
| 6/19/1982 | SubTrop1 | 992 | 60 | 70 | SS | X |
| 9/12/1984 | Diana | 949 | 115 | 135 | H4 | X |
| 11/22/1985 | Kate | 996 | 45 | 50 | TS | X |
| 8/17/1986 | Charley | 993 | 60 | 70 | TS | |
| 8/8/1987 | Arlene | 1016 | 10 | 10 | L | |
| 6/6/1995 | Allison | 995 | 40 | 45 | E | |
| 6/19/1996 | Arthur | 1005 | 40 | 45 | TS | |
| 7/12/1996 | Bertha | 974 | 90 | 105 | H2 | X |
| 9/6/1996 | Fran | 954 | 100 | 115 | H3 | X |
| 10/8/1996 | Josephine | 988 | 45 | 50 | E | |
| 8/27/1998 | Bonnie | 963 | 95 | 110 | H2 | X |
| 9/4/1998 | Earl | 995 | 50 | 60 | E | |
| 9/16/1999 | Floyd | 956 | 90 | 105 | H2 | X |
| 10/18/1999 | Irene | 976 | 80 | 90 | H1 | |
| 6/14/2001 | Allison | 1007 | 25 | 30 | SD | |
| 7/14/2002 | Arthur | 1009 | 30 | 35 | TD | |
| 10/12/2002 | Kyle | 1012 | 30 | 35 | TD | X |

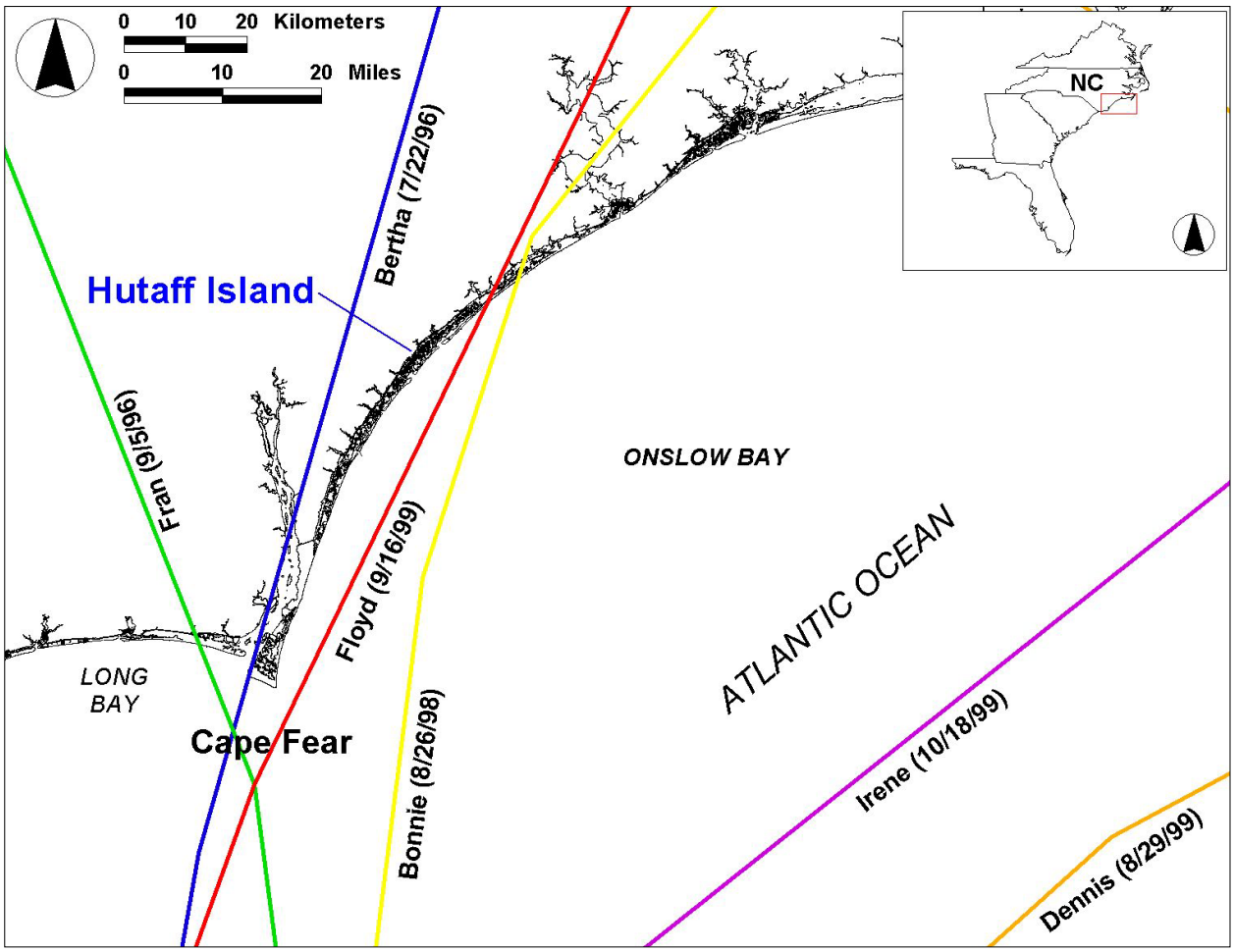


Figure 4. Map illustrating the recent (1996-1999) hurricane tracks on record with the National Oceanic and Atmospheric Administration (NOAA).

- Identify the barrier's long-term morphologic changes.
- Determine the influence of adjacent, migrating tidal inlets.
- Identify similar reaches along the barrier with respect to the influence of adjacent tidal inlets and shoreline change.
- Ascertain the nature of shoreface Holocene sediments and the underlying stratigraphic units from pre-existing data.
- Collect and determine the nature of sediment sequences in the back-barrier estuary to help identify the historic role of inlets along the barrier's length.

## METHODS

A multi-faceted approach was used to fulfill the objectives of this study. Fulfillment of the objectives was achieved by determining: a) historical shoreline positions and morphologic characteristics between 1938 and 2002 from aerial photographs, b) recent topographic relief profiles, c) the historic role of inlets along the barrier's shoreline, and d) the general nature of shoreface and estuarine sediments.

### Shoreline Change

Shoreline positions between 1938 and 2002 were determined from historic aerial photographs rectified in a geographical information system (Arcview® GIS). Twenty-six aerial photograph sets of Hutaff Island were initially inspected for use in this study. Missing individual aerial photograph frames from 13 of the 26 available sets yielded 13 complete aerial photograph sets that were chosen and used for detailed analysis. An aerial photograph set of the island was

used from each of the following dates: 1938, 1945, 1956, 1962, 1974, 1986, 1989, 1993, 1996 (post-Hurricane Bertha), 1996 (post-Hurricane Fran), 1998, 2001, and 2002.

The aerial photographs were rectified using the North Carolina Division of Coastal Management (NC DCM) 1998 digital orthographic photographs, which are referenced to the North Carolina State Plane (feet) projection. These digital orthographic photographs were used to provide a geo-referenced base map.

Shoreline positions were digitized into the GIS based on the location of the visible wet/dry line on the photographs. The wet/dry line feature imaged on aerial photographs represents the maximum high water position during a given tidal cycle. This feature is commonly used to digitize shoreline positions because of its relative ease of recognition on historical aerial photographs (CROWELL *et al*., 1991).

An offshore baseline was constructed parallel with the shoreline, from which 76 transects (Figure 5) where constructed at an interval of 152.4 meters (500 feet). Using the SCARPS! (Simple Change Analysis of Retreating and Prograding Systems) extension for ArcView® GIS, shoreline change data were collected along each of the transects. These data were cross-checked using a similar, and previously run analysis using the USGS Coastal and Marine Geology Program's DSAS (Digital Shoreline Analysis System) extension for ArcView® GIS. The use of the SCARPS! extension rather than the DSAS extension was due to the volume of data and statistical output, and the flexibility provided by the SCARPS! extension.

The end point rate (EPR) and linear regression rate (LRR) methods of shoreline change rate calculations (DOLAN *et al.*, 1991) were used to show the shoreline changes observed along Hutaff Island. The EPR method determines a shoreline change rate from two shorelines, and is useful for showing short-term changes and long-term changes with low variability in the rate of

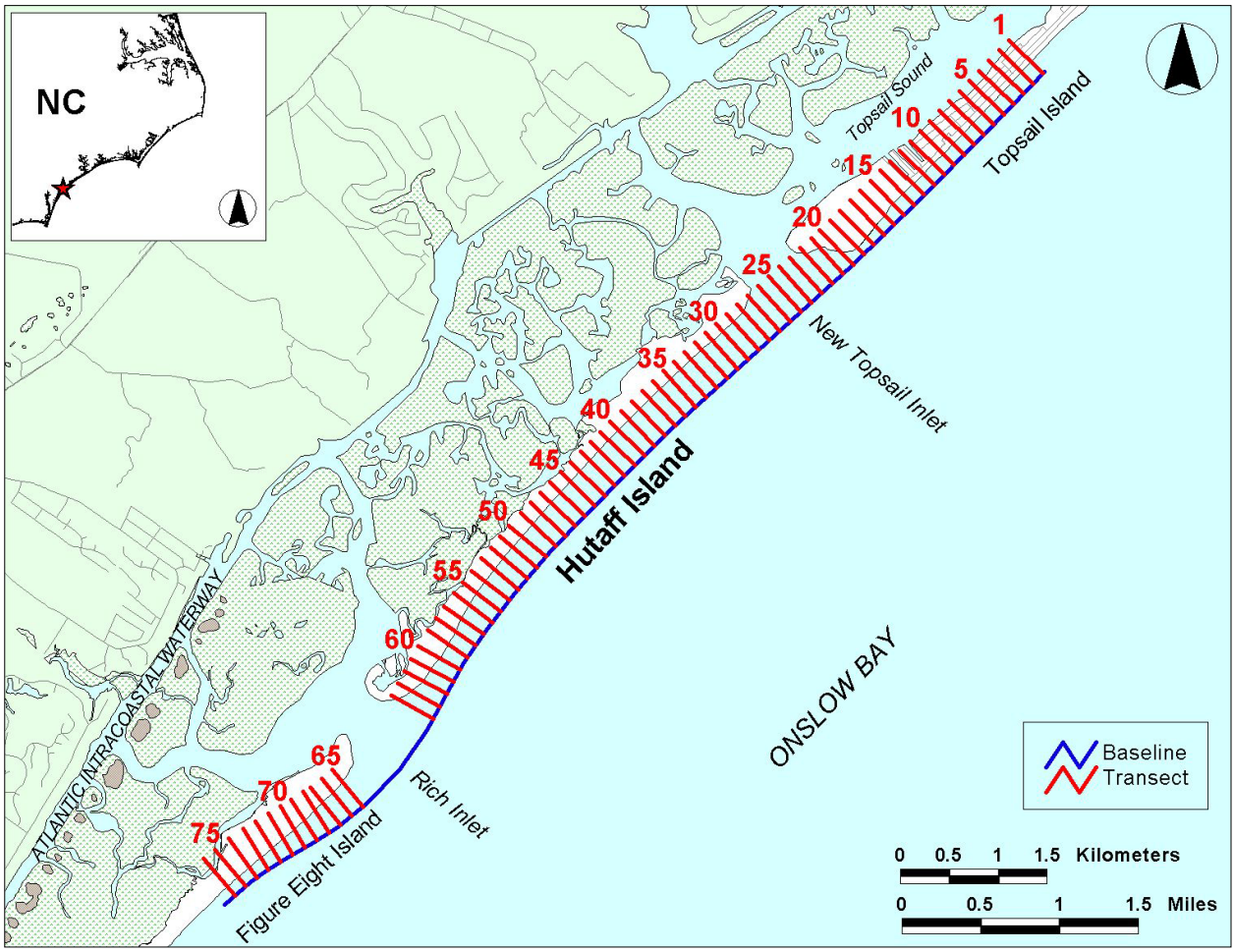


Figure 5. Map depicting the constructed baseline and transects (1-76) used in the SCARPS! shoreline change analysis.

shoreline change between the two selected shoreline positions. The LRR method estimates a shoreline change rate from the slope of a best-fit line, using the Least Squares method, through all shoreline positions. The LRR method is generally useful for both long and short-term shoreline change where at least three shoreline positions exist and the rate needs to take account of the variability in shoreline positions.

In addition to the shoreline change data, characteristics of adjacent tidal inlets were examined to understand their influence on the adjacent shorelines. The variability in ebb-channel orientations, the size of the ebb-tidal deltas, and the migration of tidal inlets are important variables controlling shoreline and morphologic change. Shoreline change interpretations where supplemented by data collected from the digitization of these inlet features.

Using the same aerial photograph sets from the shoreline change analysis, each of the ebb-channels was digitized into the GIS for analysis. Appreciable changes in the size and shape of the ebb-tidal deltas were also documented. Using the SCARPS! extension for ArcView® GIS, azimuths for the ebb-channels were determined for each adjacent inlet in the aerial photograph sets. Ebb-channel orientations, the size of the ebb-tidal deltas, and the measured shoreline change were used for comparison.

Topography

In order to understand the short-term, storm-induced topographic changes on Hutaff Island, topographic profiles were constructed along the barrier on the same transects used in the shoreline change analysis (Figure 5). Data to produce these profiles were derived from Light Detection and Ranging (LIDAR) datasets with 1.5-m (5.0-ft) grid spacing and the NAD83 horizontal datum. This LIDAR data was collected by the Airborne LIDAR Assessment of

Coastal Erosion (ALACE) project using the Airborne Topographic Mapper II (ATM), which measured elevation with a vertical resolution of 0.15 m (0.49 ft) (MEREDITH *et al.,* 1998) and a horizontal accuracy of 0.80 cm (2.62 ft) assuming a constant survey altitude of 0.70 km (0.43 miles) (MEREDITH *et al.*, 1999). The ALACE project involved the collection of LIDAR data along the U.S. coast between 1996 and 2000, and was a partnership between the NOAA Coastal Services Center, the U.S. Geological Survey (USGS) Center for Coastal Geology, and the NASA Observational Sciences Branch. These datasets where obtained from the NOAA Coastal Services Center.

The LIDAR data were imported as a binary raster file into a GIS and converted into a Grid file format. Using the GridProfiler utility of NOAA's LIDAR Data Handler extension for Arcview® GIS, transects where constructed across the grid theme in the same locations as transects used for the shoreline change analysis (Figure 6). The GridProfiler utility created a topographic profile along the assigned transects and recorded the elevation and distance for each grid intersected into a tab delimited text file.

Shoreface Geology

The nature and thickness of shoreface surface sediments and underlying stratigraphic units were determined from a combination of 119 pre-existing diver and ship-retrieved vibracores and 42 SCUBA based diver surveys (Figure 7). Published (MCQUARRIE, 1998; CLEARY, 2002; and HDR, 2002), unpublished (CLEARY *pers. comm.*, 2003), and ongoing investigations (USACE, 2003) previously collected this data during research efforts off the Hutaff Island and Topsail Island shorelines. Data from the vibracores and diver surveys were mapped in a GIS and used along with approximately 100 km of sidescan sonargraphs

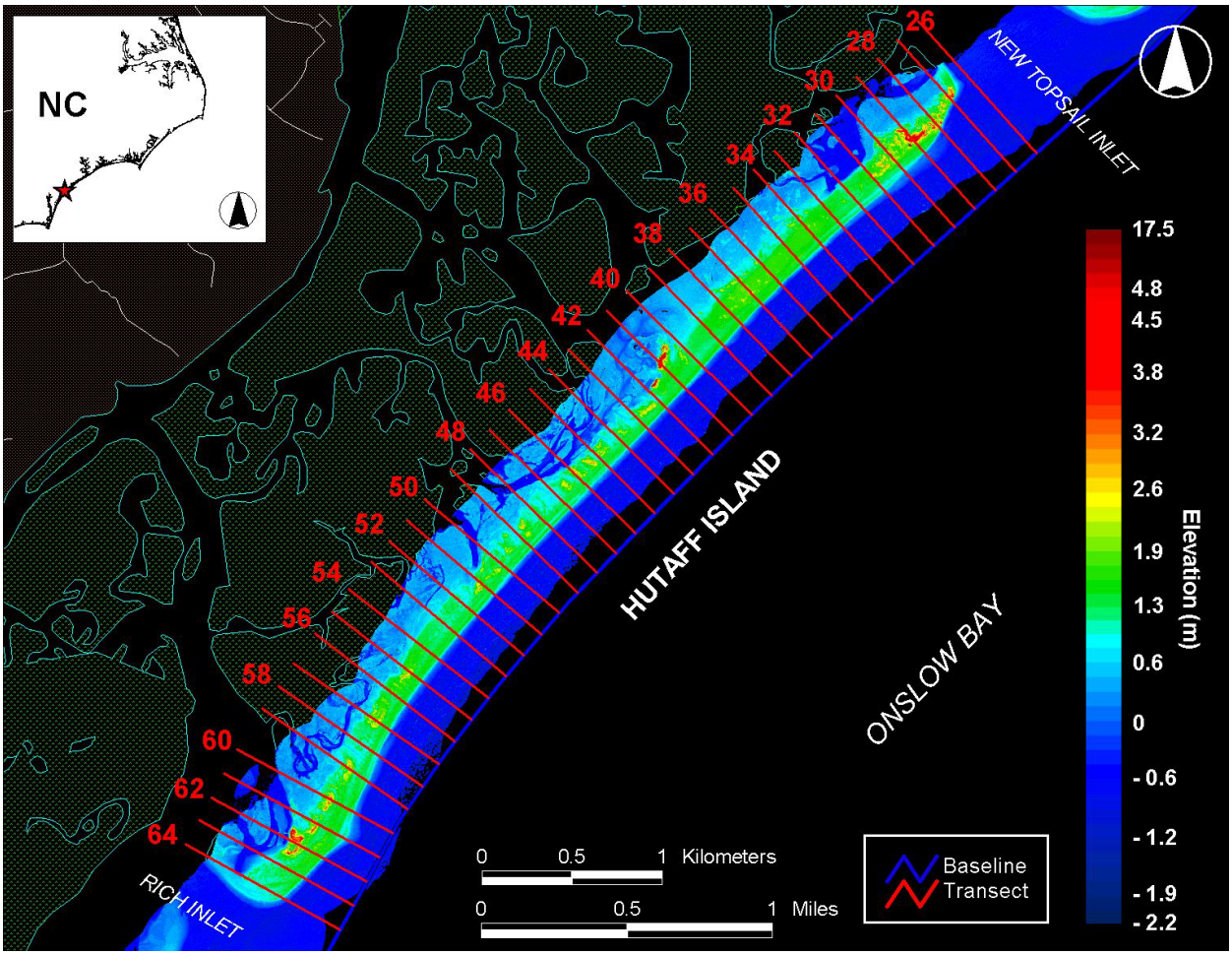


Figure 6. Map depicting the constructed baseline and transects (26-64) used to determine topographic profiles from LIDAR elevation data. The transects are shown overlying the 2000 LIDAR grid as and example of data coverage.

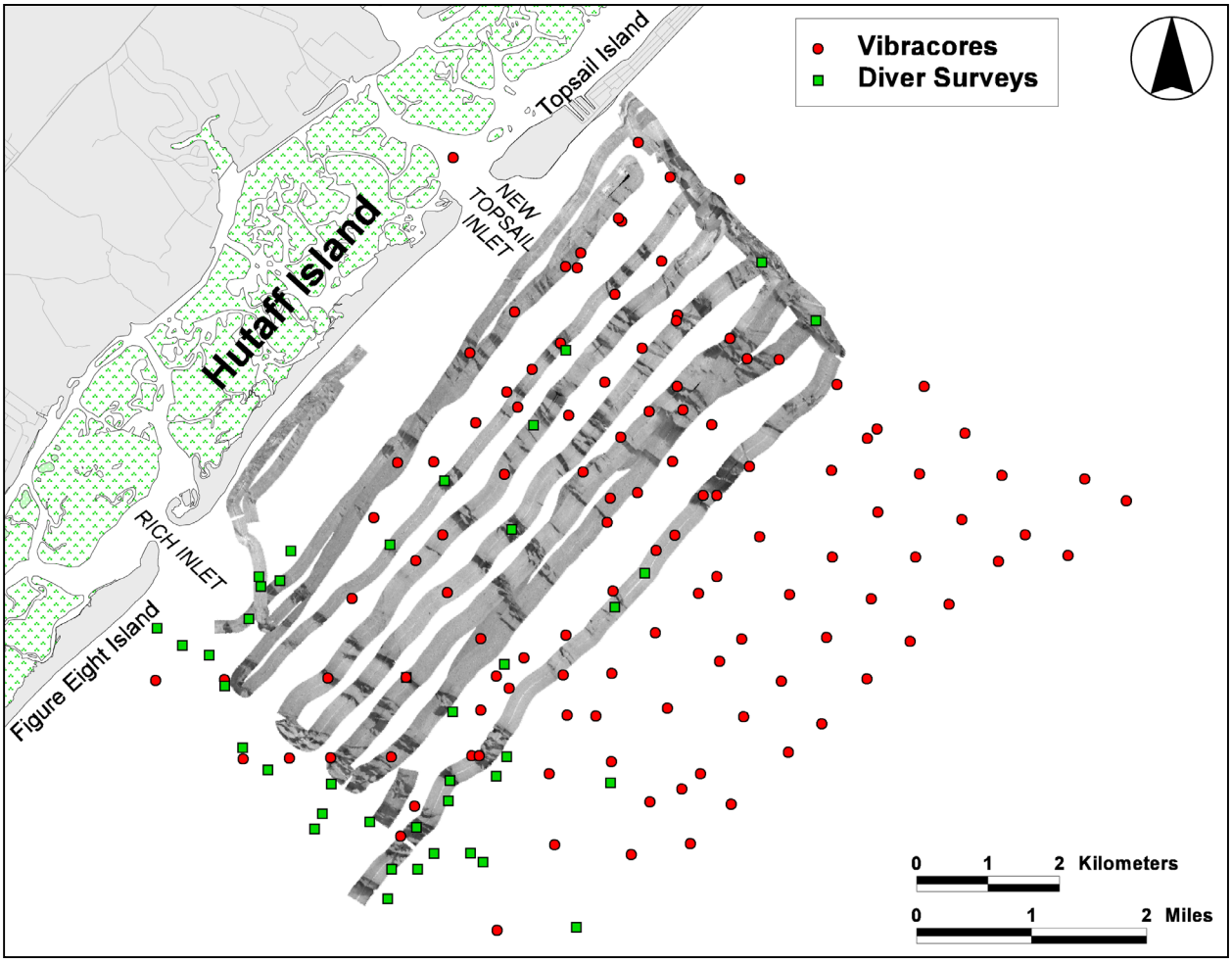


Figure 7. Map showing the locations of shoreface vibracore and diver survey sites and sidescan sonargraph mosaic used in the study. These data were obtained from published (MCQUARRIE, 1998; CLEARY, 2002; and HDR, 2002), unpublished (CLEARY *pers. comm.*, 2003), and ongoing investigations (USACE, 2003).

(MCQUARRIE, 1998) to determine the nature, thickness, and spatial distribution of shoreface surface sediments. This information was also used in an attempt to correlate paleo-fluvial channels identified in this study to modern tidal creeks found landward of Hutaff Island.

### Back-barrier Estuary History

The history of the back-barrier estuary was investigated utilizing 5.0-m (16.4-ft) long vibracores collected from 12 sites along shore parallel and shore perpendicular transects in the back-barrier estuary and one vibracore collected during ongoing investigations by the USACE (2003) in the vicinity of New Topsail Inlet (Figure 8). The vibracores were described to determine the sediment composition and characteristics. Identification of sandy intertidal facies deposited by stable and migrating tidal inlets were used to determine the historic role inlets have played along the Hutaff Island shoreline.

## RESULTS

### Shoreline Change

The first phase in studying Hutaff Island's evolution was to determine long-term changes resulting from short-term storm impacts and the influence of adjacent tidal inlets. Hutaff Island had experienced a net shoreline loss along its entire length between 1938 and 2002 (Figure 9). Shoreline position data for both 1938 and 2002 were available for Transects 36-62 (Figure 5), and were used to calculate the net shoreline changes for the entire study period.

Net shoreline change calculations at the remaining transects along Hutaff Island were complicated by the influence of adjacent tidal inlets. To the southwest, at Transects 63 and 64 (Figure 5), variations in Rich Inlet's Hutaff Island shoulder position did not allow for

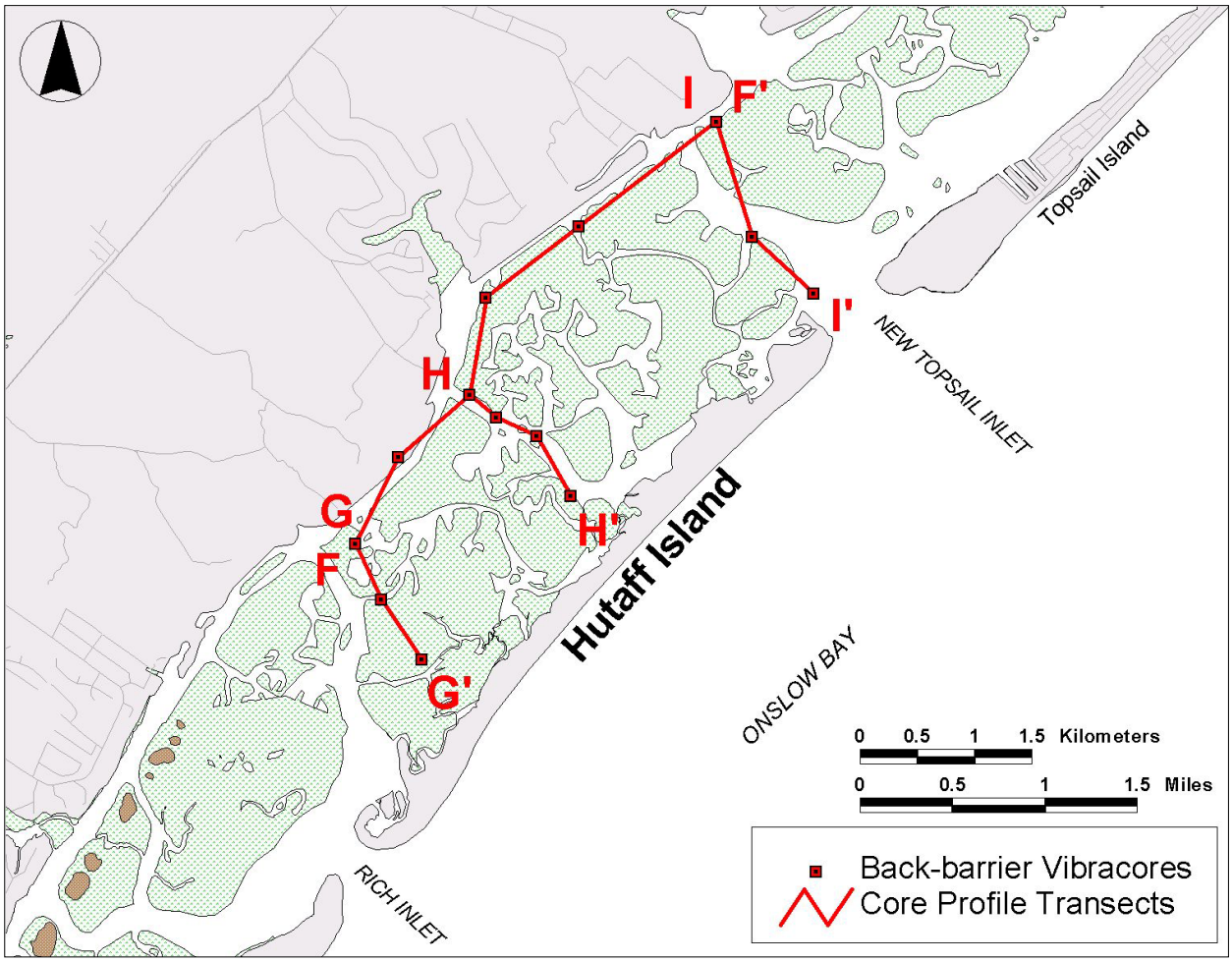


Figure 8. Map showing the locations of back-barrier vibracores used in this study.

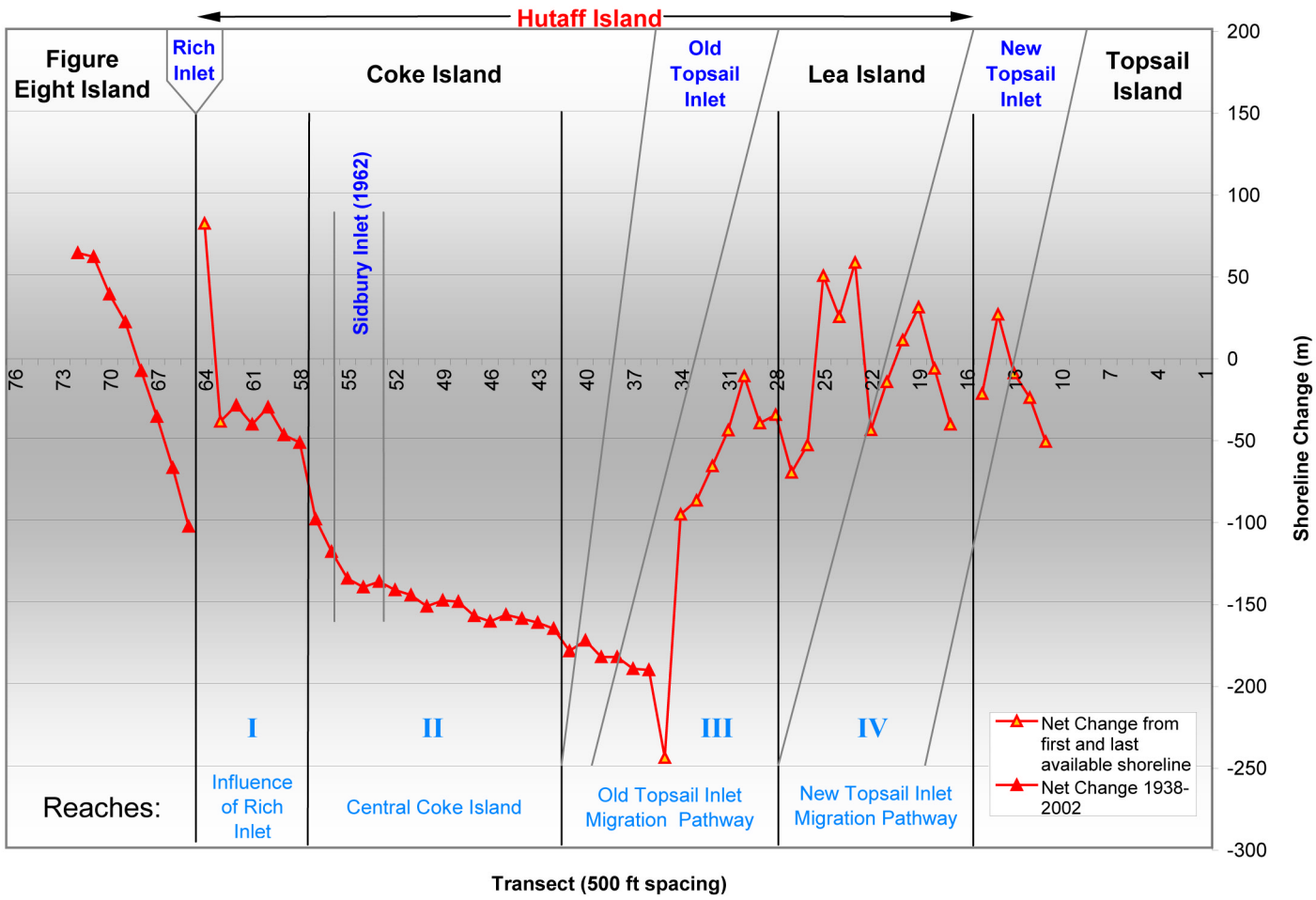


Figure 9. Net shoreline changes at each transect across Hutaff Island.

calculations of shoreline change between 1938 and 2002. Old Topsail and New Topsail Inlets, to the northeast, had migrated southwest between Transects 16 and 35 (Figure 5). Their migrations did not allow for calculations of shoreline change due to occupation of several transects by one of the inlets during 1938 or 2002, or to avoid comparing shoreline positions from Hutaff Island in 1938 to Topsail Island shoreline positions in 2002. At transects where net shoreline change between 1938 and 2002 could not be calculated, net shoreline change was determined using the earliest and latest available shoreline position data at each particular transect (Figure 9).

Average net shoreline change observed along Transects 36-62 between 1938 and 2002 was -135 m (-443 ft). The average net shoreline change observed along Hutaff Island (Transects 29-62) between the earliest available shoreline position and the 2002 shoreline was -125 m (-409 ft). A maximum shoreline loss of 245 m (804 ft) occurred between 1956 and 2002 at Transect 35 in the vicinity of Old Topsail Inlet. Net shoreline losses less than 100.0 m (30.5 ft) occurred in the vicinity of Rich Inlet and the former inlet migration pathway of Old Topsail Inlet.

Long-term Shoreline Change Rates

Understanding the rates at which shoreline changes occur is beneficial to coastal management decisions. Published erosion rates, such as those determined by the State of North Carolina (NC DCM, 2003), are used to calculate setbacks for coastal development. As part of this study, long-term shoreline change rates were calculated along the length of Hutaff Island. Results from the shoreline change analysis show that the entire length of Hutaff Island's shoreline, as it existed in 2002 (between Transects 29 and 62), is experiencing net long-term erosion. The average EPR (end point rate) along the island was -2.1 m/year (-7.0 ft/year) whereas the average LRR (linear regression rate) was -2.4 m/year (-8.0 ft/year), with both rates having a potential error of ± 0.2 m (0.7 ft) (Figure 10).

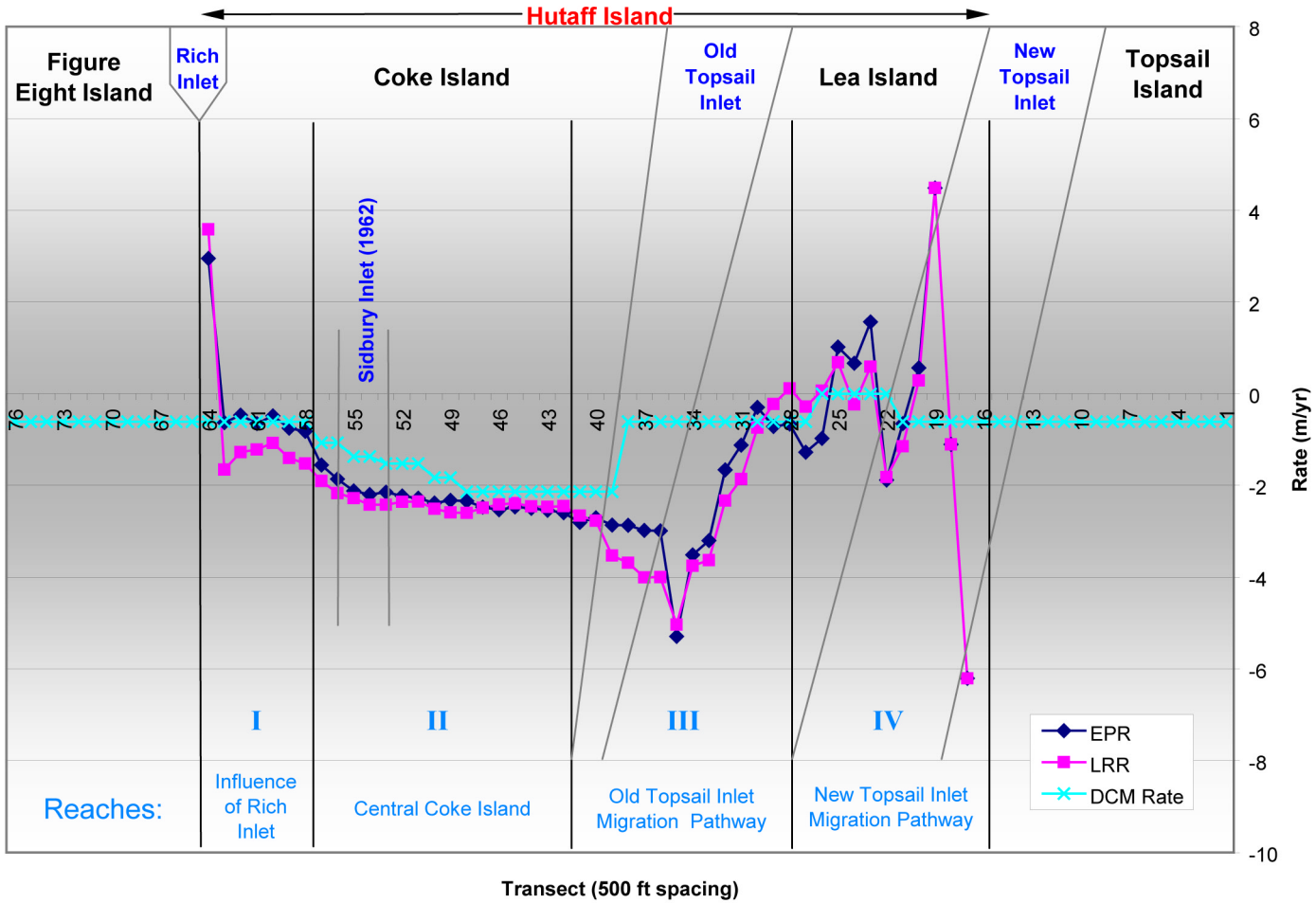


Figure 10. Shoreline change rates at each transect across Hutaff Island.

The shoreline position in 2002 was consistently landward of the 1938 position. Not only had the island transgressed landward, but the migration of Old Topsail and New Topsail Inlets had greatly shortened the length of the island (Figure 11). In 1938, Coke and Lea Islands (today's Hutaff Island) were located between Transects 16 and 63. The migration pathway (later identified as Reach IV) for New Topsail Inlet (Transects 16-28) represents the difference in the barrier's length between 1938 and 2002. As a result of this migration, EPR and LRR shoreline change rates could not be calculated between 1938 and 2002 for transects 16-18 because in 1938, these transects were located on the northeast shoulder of Lea Island (Hutaff Island) and in 2002 were located on the southwest shoulder of Topsail Island. Net shoreline change calculations using shoreline positions from two separate islands would produce erroneous results, and are therefore not used in this study. However, the average EPR within the New Topsail Inlet migration pathway (calculated from Hutaff Island shorelines only) was 0.3 m/year (0.9 ft/year) while the average LRR was also determined to be 0.3 m/year (0.9 ft/year).

Short-term Storm Induced Shoreline Changes

One of the principle factors affecting shoreline and morphology changes along barrier islands is the impact of severe storm events. As shown previously in Table 1, numerous storms impacted the island between 1938 and 2002. Unfortunately, pre and post-storm aerial photographs are not available for most of these storm events.

With the exception of Hurricane Fran (September 5, 1996), no other storm event between 1938-2002 had pre and post-storm aerial photography available, from the dataset used for this study, to document the shoreline changes resulting from the individual storm impact. However, aerial photographs were available for two separate groupings of multiple storm events. These photos were used to determine the combined storm effects. Post-storm shoreline recovery and

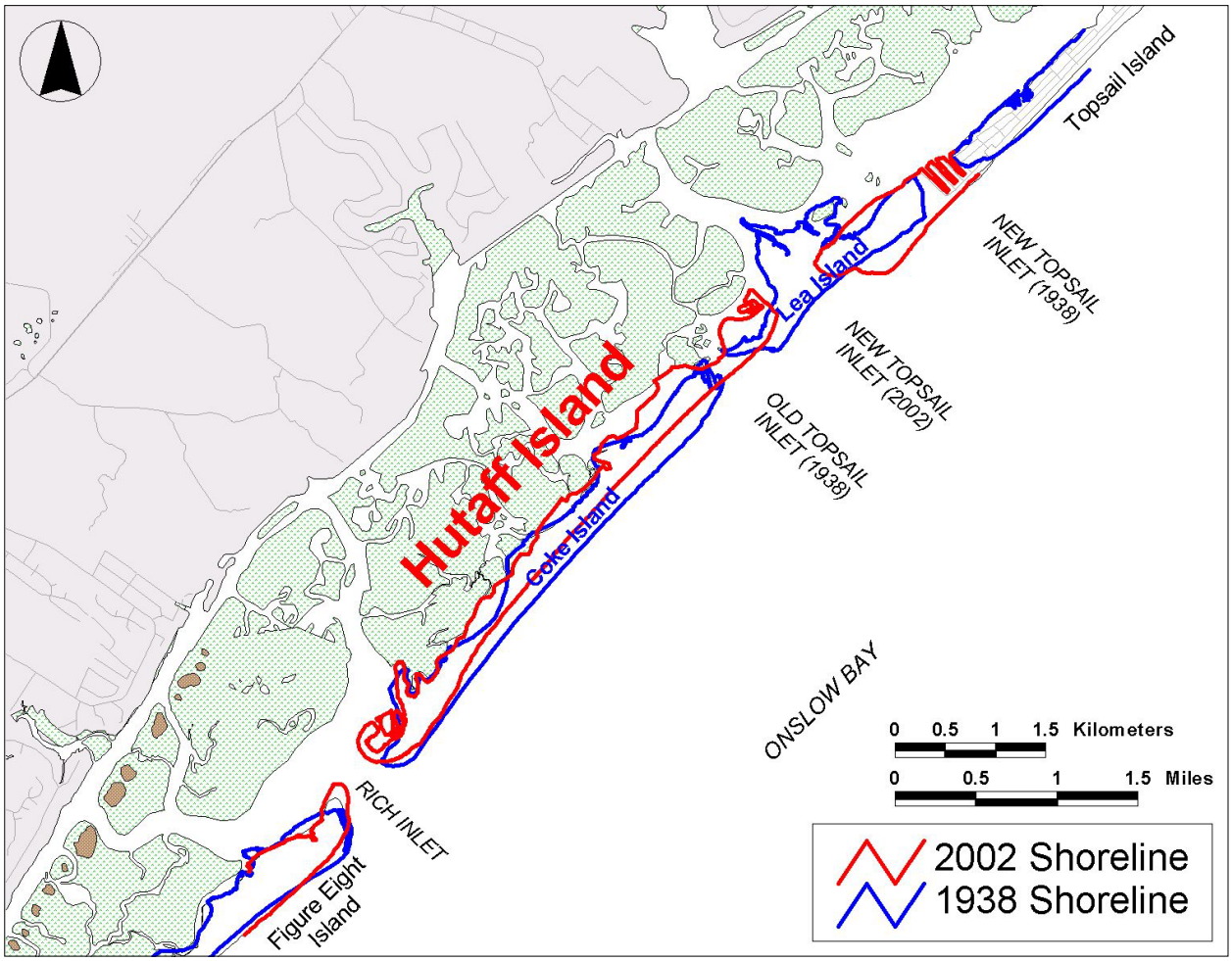


Figure 11. Map illustrating the shoreline and inlet positions in 1938 and 2002, at the beginning and end of the period studied.

the larger time gap between photographs makes it difficult to assess the true shoreline change as a result of these combined storm impacts. The first combined storm set included Hurricane Helene (September 27, 1958), Hurricane Donna (September 12, 1960), and the Ash Wednesday Storm (March 7, 1962). The second combined storm set included Hurricane Bonnie (August 26, 1998), Hurricane Dennis (August 29, 1999), Hurricane Floyd (September 16, 1999), and Hurricane Irene (October 18, 1999).

The impact from the first set of storms was determined using pre-storms (02/21/1956) and post-storms (03/13/1962) aerial photographs with a time gap of 6.06 years. The average net shoreline change along Hutaff Island as a result of Hurricanes Helene and Donna, and the Ash Wednesday Storm was -38 m (-126 ft). This equates to an average EPR of around -6.3 m/year (-20.8 ft/year). A maximum shoreline change of -80 m (-263 ft) occurred at Transect 59, along the southwestern shoulder of Hutaff Island in the vicinity of Rich Inlet. The areas between Sidbury Inlet and Rich Inlet (Transects 57-62) to the southwest and New Topsail Inlet and Old Topsail Inlet (Transects 21-29) to the northeast where heavily impacted by these storms. Many of the transects in these two locations experienced a shoreline loss in excess of 50 m (164 ft) and an EPR in excess of -8.3 m/year (-27.2 ft/year).

The impact from the second set of storms was determined using pre-storms (06/19/1998) and post-storms (02/07/2001) aerial photographs with a time gap of 2.64 years. The average net shoreline change along Hutaff Island as a result of Hurricanes Bonnie, Dennis, Floyd, and Irene was -12 m (-40 ft). This equates to an average EPR of around -4.6 m/year (-15.1 ft/year). A maximum shoreline change of +87 m (+286 ft) occurred at Transect 60, along the southwestern shoulder of Hutaff Island in the vicinity of Rich Inlet. A maximum shoreline loss of -45 m (-149 ft) occurred at Transect 39 in the vicinity of the former location of Old Topsail Inlet.

Hurricane Fran's impact along Hutaff Island was documented by pre-storm (08/08/1996) and post-storm (09/23/1996) aerial photography with a time gap of just 52 days. Analysis of the digitized shorelines showed that the average net shoreline change along Hutaff Island, as the result of Hurricane Fran, was -40 m (-131 ft) (Figure 12). A maximum shoreline change of -74 m (-242 ft) occurred at Transect 38 on the southwestern end of Lea Island, along the shoulder of Old Topsail Inlet. Many of the adjacent transects on this northeastern side of Old Topsail Inlet experienced shoreline losses in excess of 50 m (164 ft).

Influence of Adjacent Tidal Inlets

Inspection of aerial photographs showed the existence of four tidal inlets that have influenced Hutaff Island during the 1938–2002 study period. These inlets, from southwest to northeast, include Rich Inlet, Sidbury Inlet, Old Topsail Inlet, and New Topsail Inlet (Figure 13). An 1880 T-sheet survey map showed the presence of a fifth inlet, Old Inlet, located 1.0 km (0.62 miles) northeast of Old Topsail Inlet's location in 1880.

Variability in ebb-channel orientations, the size of the ebb-tidal deltas, and the migration of tidal inlets were investigated to understand their controls on shoreline and morphologic change. Analysis of inlet-induced shoreline change was conducted at Rich, Old Topsail, and New Topsail Inlets. Sidbury Inlet's brief opening during the study period did not allow for a comparative analysis.

Rich Inlet is a historically deep and stable inlet located on Hutaff Island's southwest border. A shore-normal orientation of 128° is assumed for an optimum ebb-channel orientation that would produce equal shoreline changes on either side of the inlet and not initiate drastic shoreline changes of one inlet shoulder over the other. The size and shape of the ebb-tidal delta also controls oceanfront shoreline change along the adjacent barriers. The stability of Rich Inlet

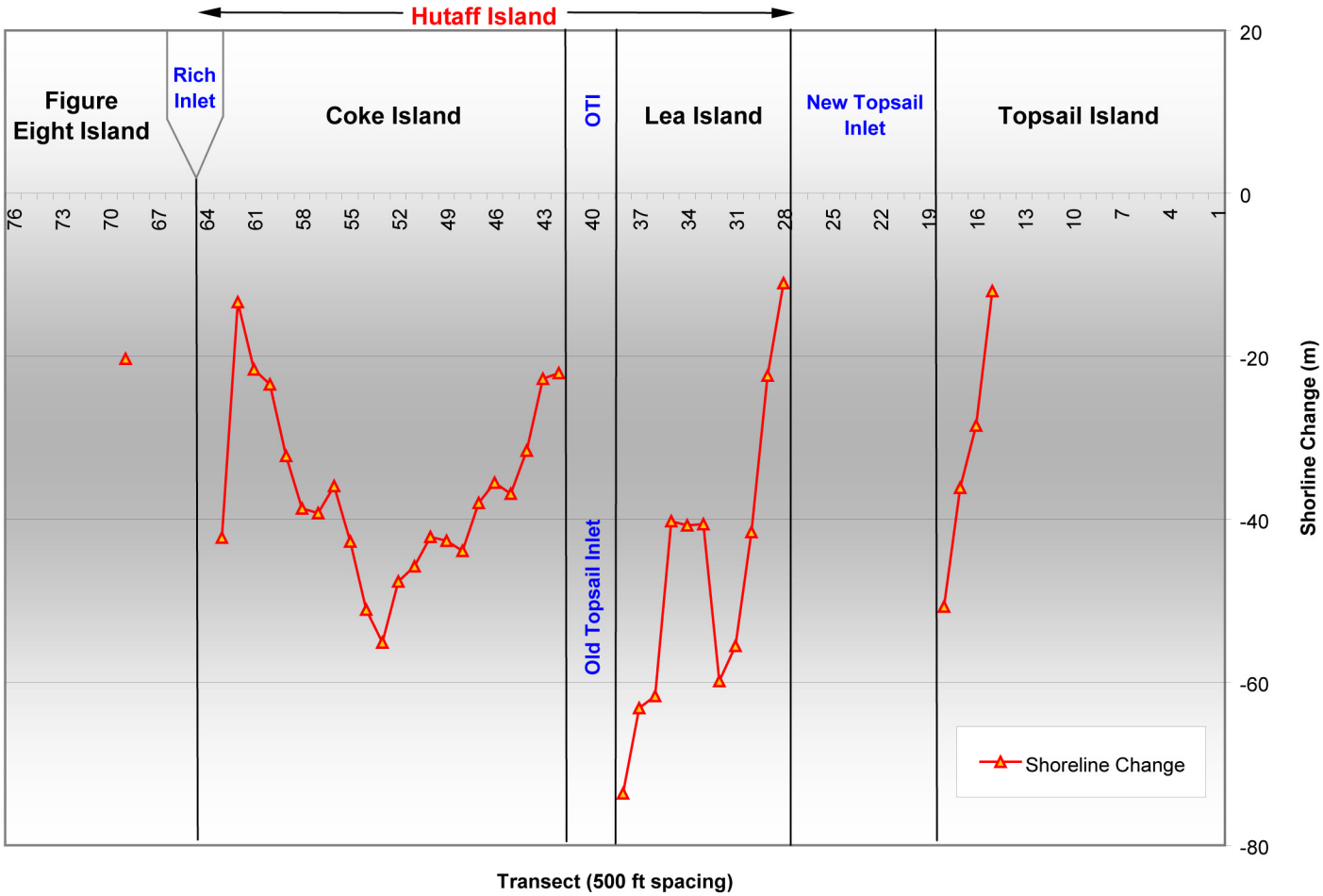


Figure 12. Shoreline change as the result of Hurricane Fran (09/05/1996) measured at the wet/dry line (HWL) at each transect across Hutaff Island.

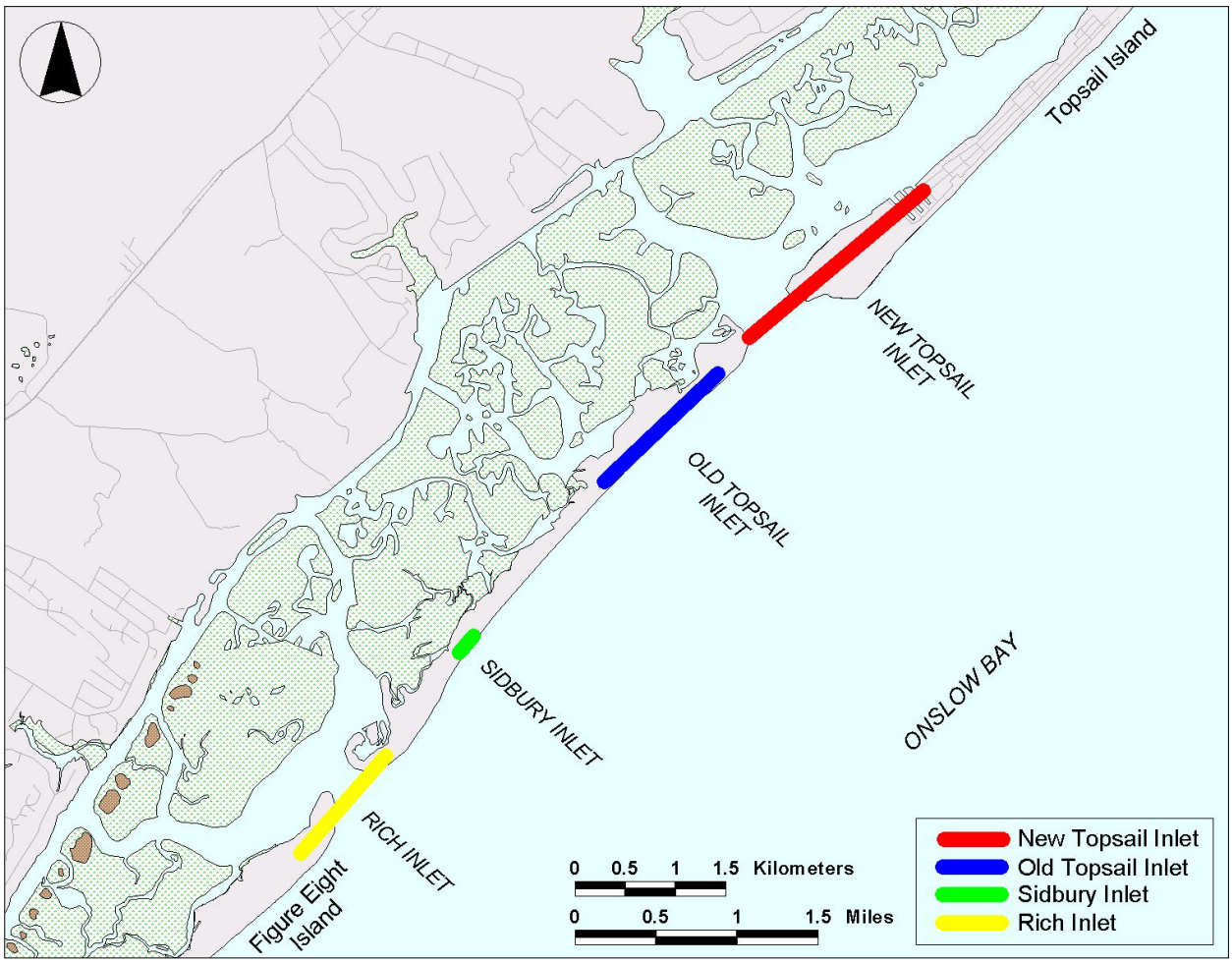


Figure 13. Map illustrating the zones of historical tidal inlet locations adjacent to Hutaff Island throughout the study period. Rich Inlet and New Topsail Inlets are currently open, but Old Topsail Inlet closed between 1997-1998 and Sidbury Inlet was only open during the study period around 1962.

has allowed its ebb-tidal delta to remain fairly constant in size with variations in shape related to the orientation and position of the ebb-channel. A recent study (JACKSON and CLEARY, 2003) indicated that a direct relationship exists between oceanfront shoreline change, and the orientation and position of the ebb-channel at Rich Inlet. Throughout the majority of the study period, Rich Inlet's ebb-channel was oriented to the southwest between 135° and 196° favoring the shoreline of Figure Eight Island (Figure 14). The study's dataset showed that the ebb-channel was only oriented to the northeast in the 1996 and 1998 aerial photographs. Accretion, or a lesser degree of erosion, on Hutaff Island occurred primarily during periods when the ebb-channel orientation was at or northeast of the 128° shore-normal orientation. Figure 15 shows a typical ebb-channel to oceanfront shoreline change relationship at Rich Inlet using digitized shoreline and ebb-channel positions from November 1993 overlaying an August 1996 aerial photograph.

Sidbury Inlet, a small inlet located 2.1 km (1.2 miles) northeast of Rich Inlet on Coke Island, was only imaged during the study period in the 1962 aerial photograph. Previous work by GAMMILL (1990) indicated that the inlet was open during the study period between 1959 and 1962. That study also showed the inlet had been open earlier between 1909 and 1925. Sidbury Inlet had previously existed in the 1800's as shown in the 1857 and 1880 T-sheet survey maps. The influence of Sidbury Inlet on the adjacent shoreline could not be determined from the single set of aerial photographs. Any influence would have been limited based upon the small, almost non-existent ebb-tidal delta imaged in the 1962 aerial photograph.

Old Topsail Inlet, which had previously separated Coke Island from Lea Island, was located along the northeastern one-third of Hutaff Island. The inlet closed sometime between the September 1997 LIDAR survey and the June 1998 aerial photography flight of the area. Old

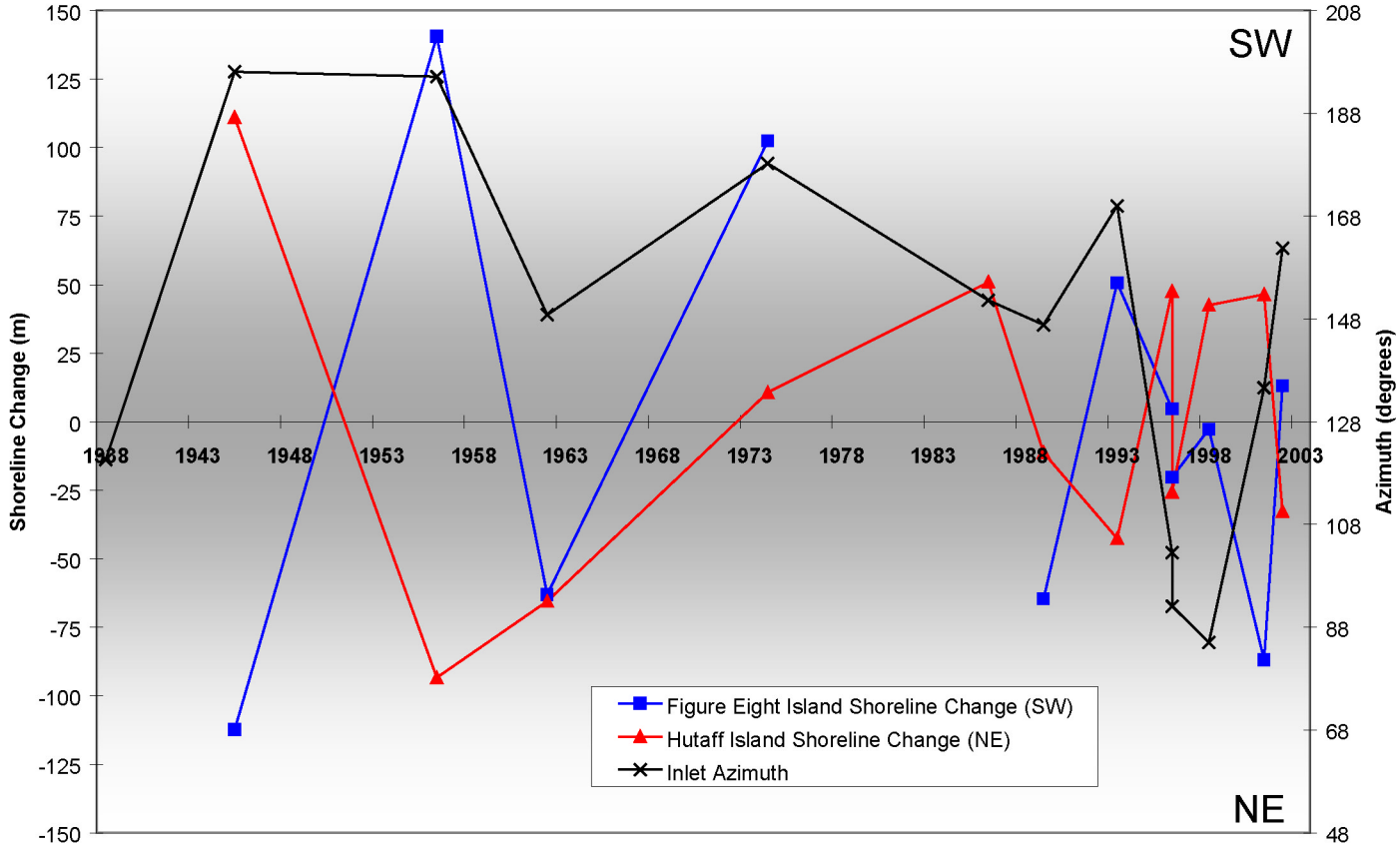


Figure 14. Rich Inlet ebb-channel orientations and oceanfront shoreline changes on the SW shoulder (Figure Eight Island) and the NE shoulder (Hutaff Island) of Rich Inlet between 1938-2002.

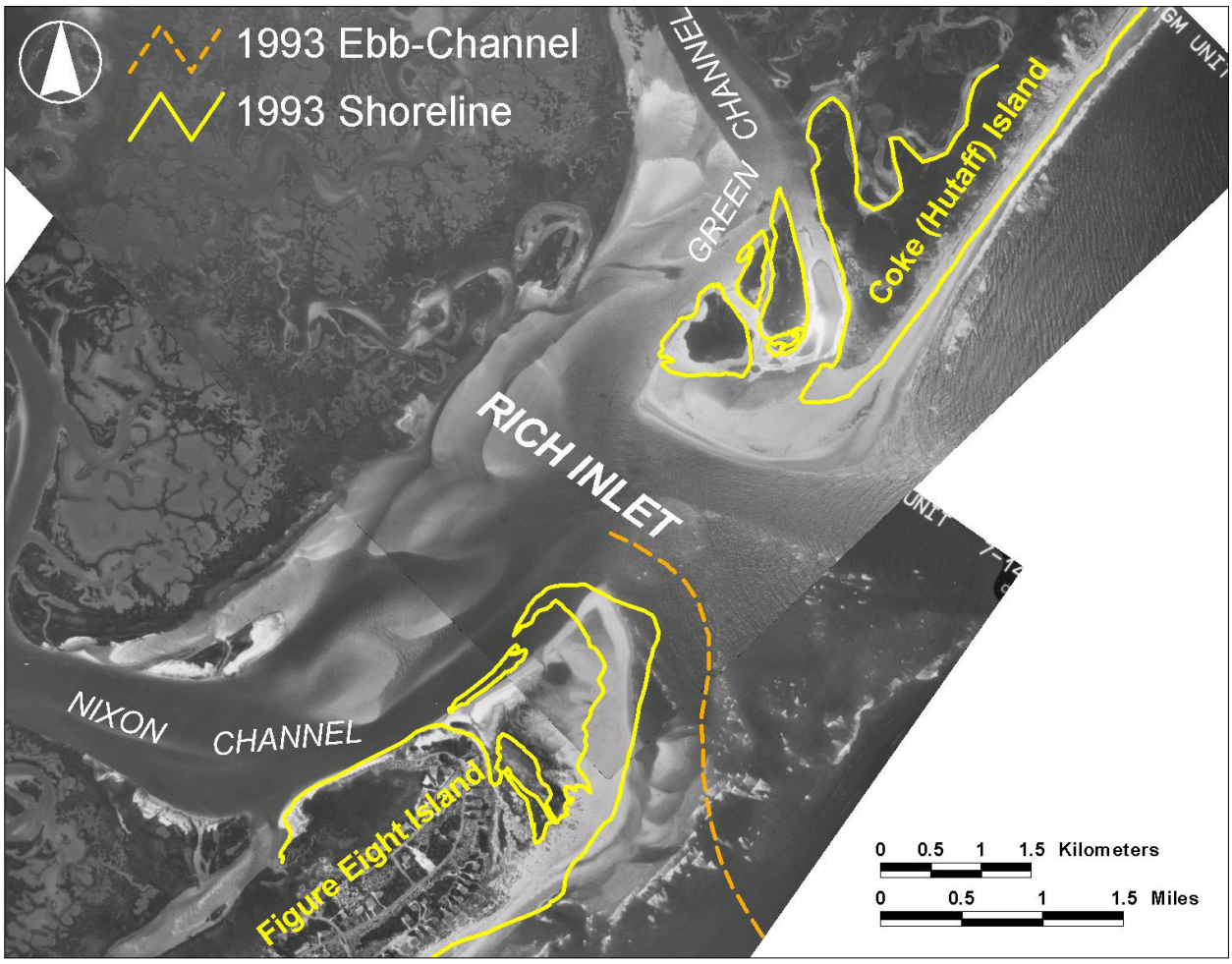


Figure 15. Map depicting Rich Inlet's 1993 ebb-channel position and adjacent shorelines projected onto 1996 aerial photographs. A migration of Rich Inlet's ebb channel to a northeasterly orientation in 1996 brought about an accretionary trend on the southwest Hutaff Island shoreline.

Topsail Inlet's 1.3 km (0.8 miles) southwest migration between 1938 and its closure in the late 1990's, has certainly had a major influence on the shoreline of Hutaff Island. Cursory inspection of aerial photographs during the period of Old Topsail Inlet's migration showed that by 1986 the inlet's ebb-tidal delta had greatly diminished in size to the point were it was almost visibly non-existent in the subsequent photographs prior to its closure. The influence of Old Topsail Inlet on the adjacent shorelines would have likely been reduced correspondingly with the decreasing size of the ebb-tidal delta.

A shore-normal orientation of 136° is assumed for an optimum ebb-channel orientation, for Old Topsail Inlet, that would benefit both inlet shoulders and not initiate drastic shoreline changes of one inlet shoulder over the other. With the exception of the 1974 ebb-channel orientation of 128°, the ebb-channel orientations were located to the southwest of the shore-normal orientation between azimuths of 139° and 225° (Figure 16). These orientations favored accretion, or a lesser degree of erosion, on the Coke Island side of Old Topsail Inlet, with the exception of the 1974 orientation previously mentioned and the 1986 ebb-channel orientation of 139°. The 1986 orientation was just 3° to the southwest of the shore-normal orientation, and produced a smaller measure of shoreline change on the Lea Island side of Old Topsail Inlet than on the Coke Island side.

New Topsail Inlet, located at the northeastern border of Hutaff Island throughout the entire study period, is a large migrating inlet. A shore-normal orientation of 140° is assumed for an optimum ebb-channel orientation, for New Topsail Inlet, that would produce equal shoreline changes and not initiate drastic shoreline changes of one inlet shoulder over the other. New Topsail Inlet's ebb-channel was oriented northeast of the 140° shore-normal orientation in ten of the thirteen aerial photographs (Figure 17). Ebb-channel orientations that were observed and

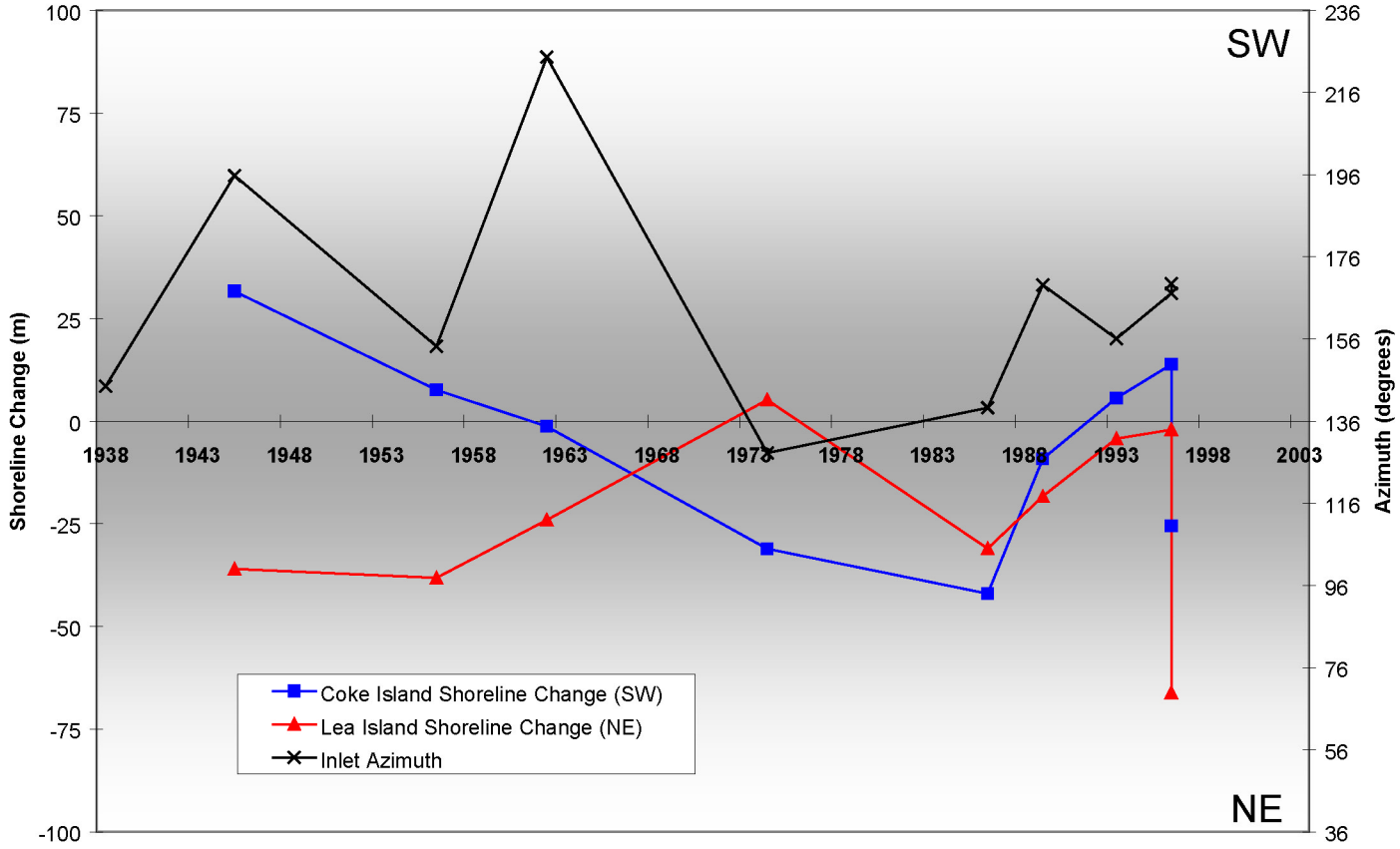


Figure 16. Old Topsail Inlet ebb-channel orientations and oceanfront shoreline changes on the SW shoulder (Coke Island) and the NE shoulder (Lea Island) of Old Topsail Inlet between 1938-2002.

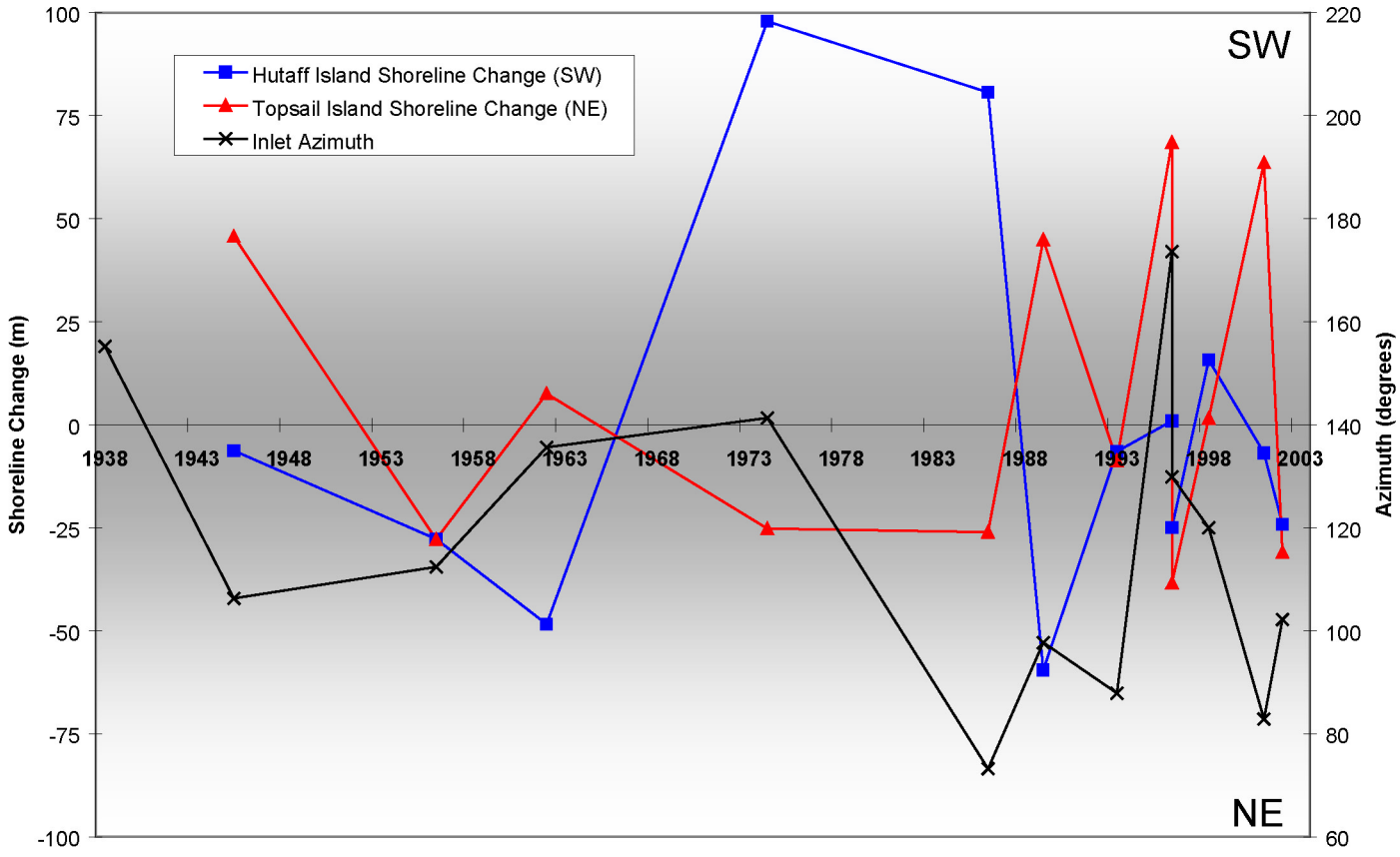


Figure 17. New Topsail Inlet ebb-channel orientations and oceanfront shoreline changes on the SW shoulder (Hutaff Island) and the NE shoulder (Topsail Island) of New Topsail Inlet between 1938-2002.

favored accretion or a lesser degree of erosion on Hutaff Island occurred only once (1974) and similarly on Topsail Island four times (1945, 1962, 1989, and 2001). In five instances (1956, 1993, 09/1996, 1998, and 2002) the ebb-channel orientation was located to the northeast of the shore-normal orientation, which should have favored accretion, or a lesser degree of erosion, on Topsail Island. In each of these instances, both sides of the inlet underwent similar shoreline changes with Hutaff Island gaining slightly more in 1998 and losing slightly less in 1956, 1993, September 1996, and 2002.

Migration and changes in the symmetry of the ebb-tidal delta of New Topsail Inlet made it difficult to interpret the influence of the ebb-channel orientation in the 1986 and August 1996 aerial photographs. A previous study by CLEARY (1994), using aerial photographs taken of New Topsail Inlet at bi-monthly and quarterly intervals between 1982 and 1991, showed the cyclic changes of New Topsail Inlet's ebb-tidal delta prior to the 1986 aerial photograph. The study indicated a shift in the ebb-tidal delta symmetry just prior to the 1986 aerial photograph. That shift should have favored accretion on Topsail Island, but based upon the proximity of the symmetry shift to the date of the aerial photograph, that change had not had time to be reflected in the shoreline change patterns on the adjacent barriers. The 1986 data show the ebb-channel oriented at 73° with Hutaff Island accreting an average of 81 m (265 ft) and Topsail Island eroding an average of 26 m (85 ft) along the three adjacent transects on each side of the inlet (Figure 17). Similar circumstances are likely the cause of the differing shoreline change to ebb-channel orientation relationship imaged in the August 1996 aerial photograph, but there is no evidence to support this. A breaching event of the ebb-tidal delta, as a result of Hurricane Bertha, may have reoriented the ebb-channel just prior to the August 1996 aerial photograph, without having allowed time for reflection in the shoreline change patterns on the adjacent

barriers. The 1996 data shows the ebb-channel to be oriented to 174° with Hutaff Island accreting an average of 1 m (3 ft) and Topsail Island accreting an average of 69 m (225 ft) along the three adjacent transects on each side of the inlet (Figure 17).

Morphologic Changes

As a result of short-term storm impacts and the influence of adjacent tidal inlets, the morphologic characteristics of Hutaff Island have varied during the study period. A brief analysis of Hutaff Island's morphology was conducted based upon visual observations of historical aerial photographs. Washover history of Hutaff Island was described as moderate, on the Coke Island segment, to severe on the Lea Island segment in a previous study by CLEARY and HOSIER (1979). Their study also showed that the dune morphology of Hutaff Island was generally comprised of a single discontinuous dune ridge.

Morphologic characteristics were determined through simple inspections of aerial photographs (1938, 1993, 1996, and 2002) to determine the long-term and short-term storm induced morphologic changes that have occurred along Hutaff Island. Interpretation of the 1938 aerial photographs showed that 56 percent of the barrier's length featured a single scarped dune ridge, while 28 percent featured washover fans, and 16 percent featured washover terraces. By 1993, despite a landward translating shoreline, the barrier was characterized by a single scarped dune ridge along 84.7% of the shoreline, with washover fans and washover terraces extending along 9.0% and 6.3% of the shoreline respectively. The impact of Hurricane Fran in 1996 leveled much of the island leaving behind washover terraces along 91 percent of the Hutaff Island shoreline. With washover terraces dominating the barrier's morphology following Hurricane Fran, scarped dunes and washover fans extended along only six and three percent of the shoreline respectively. Following a period of severe storm events (1996-1999), Hutaff Island

in 2002 was characterized by washover terraces along 59 percent of the shoreline, with scarped dunes and washover fans extending along 25 percent and 16 percent of the shoreline, respectively.

The long-term morphologic changes between 1938 and 1993 showed a 52 percent increase in the length of the barrier characterized by scarped dunes, and a decrease in the length characterized by washover fans and washover terraces of 68 and 60 percent respectively. Short-term, storm-induced morphologic changes between 1993 and 1996, resulting from Hurricane Fran, showed an increase of over 13 times the extent of washover terraces along the barrier. During the same period, a decrease of 68 percent in the extent of washover fans, and a 93 percent decrease in the extent of single scarped dune ridges, was observed along Hutaff Island. Subsequent to the impact of Hurricane Fran, the 2002 aerial photograph showed that Hutaff Island underwent a period of recovery with a 35 percent decrease in the extent of washover terraces and a three-fold increase in the extent of dunes.

These data suggest that Hutaff Island has undergone a cyclical pattern of morphologic change controlled by the impact of severe storm events and the subsequent recovery and redevelopment of a single scarped dune ridge in areas flattened by overwash.

Reach Identification

Hutaff Island can be grouped into four reaches or zones with respect to the influence of adjacent tidal inlets and shoreline change characteristics. Reaches were first identified by shoreline change patterns (Figure 9) resulting from the influence of adjacent tidal inlets. Similar topographic relief and morphologic characteristics were later found to exist within each reach. Shoreline Reaches I, II, and III have been identified along the island, as it exists today (Figure 18). Additionally a fourth reach (Reach IV) was identified, but as a result of the southwest

migration of New Topsail Inlet, this reach was only occupied by Hutaff Island during the study between 1938 and 2001.

Reach I is located within the influence of Rich Inlet, along the southwestern edge of Hutaff Island. This 1.0-km (0.6-mile) reach extends from Transect 58 in the northeast to Transect 64 in the southwest (Figure 18). This reach (excluding Transect 64 because of limited data) had an average EPR of -0.6 m/year (-2.1 ft/year), an average LRR of -1.4 m/year (-4.5 ft/year), and an average net shoreline change between 1938 and 2002 of -41 m (-133 ft). The cyclic welding of swash bars onto the Hutaff Island shoreline have led to reduced shoreline losses in comparison to those in neighboring Reach II, to the northeast. Much of the shoreline change patterns observed within Reach I are linked to the cyclic migration of Rich Inlet's ebb-channel as it is deflected and repositioned across the ebb-tidal delta during breaching events.

Reach II is located within the central portion of Coke Island. This 2.5-km (1.6-mile) reach extends from Transect 42 in the northeast to Transect 57 in the southwest (Figure 18). Besides the brief emergence of Sidbury Inlet between 1959 and 1962, Reach II was not directly influenced by tidal-inlets during the 1938 to 2002 study period. The distal boundaries of the reach may have had some peripheral influence from inlets in adjacent reaches. Reach II had an average EPR of -2.3 m/year (-7.5 ft/year), an average LRR of -2.4 m/year (-7.8 ft/year), and an average net shoreline change between 1938 and 2002 of -146 m (-480 ft). The similarities of the EPR and LRR shoreline change rates show that this reach exhibited a near linear shoreline change over the study period.

Reach III is located along the migration pathway of Old Topsail Inlet. This reach extends from Transect 28 in the northeast to Transect 41 in the southwest (Figure 18). This 2.1-km (1.3-mile) reach had an average EPR of -2.4 m/year (-7.9 ft/year), an average LRR of -2.7 m/year

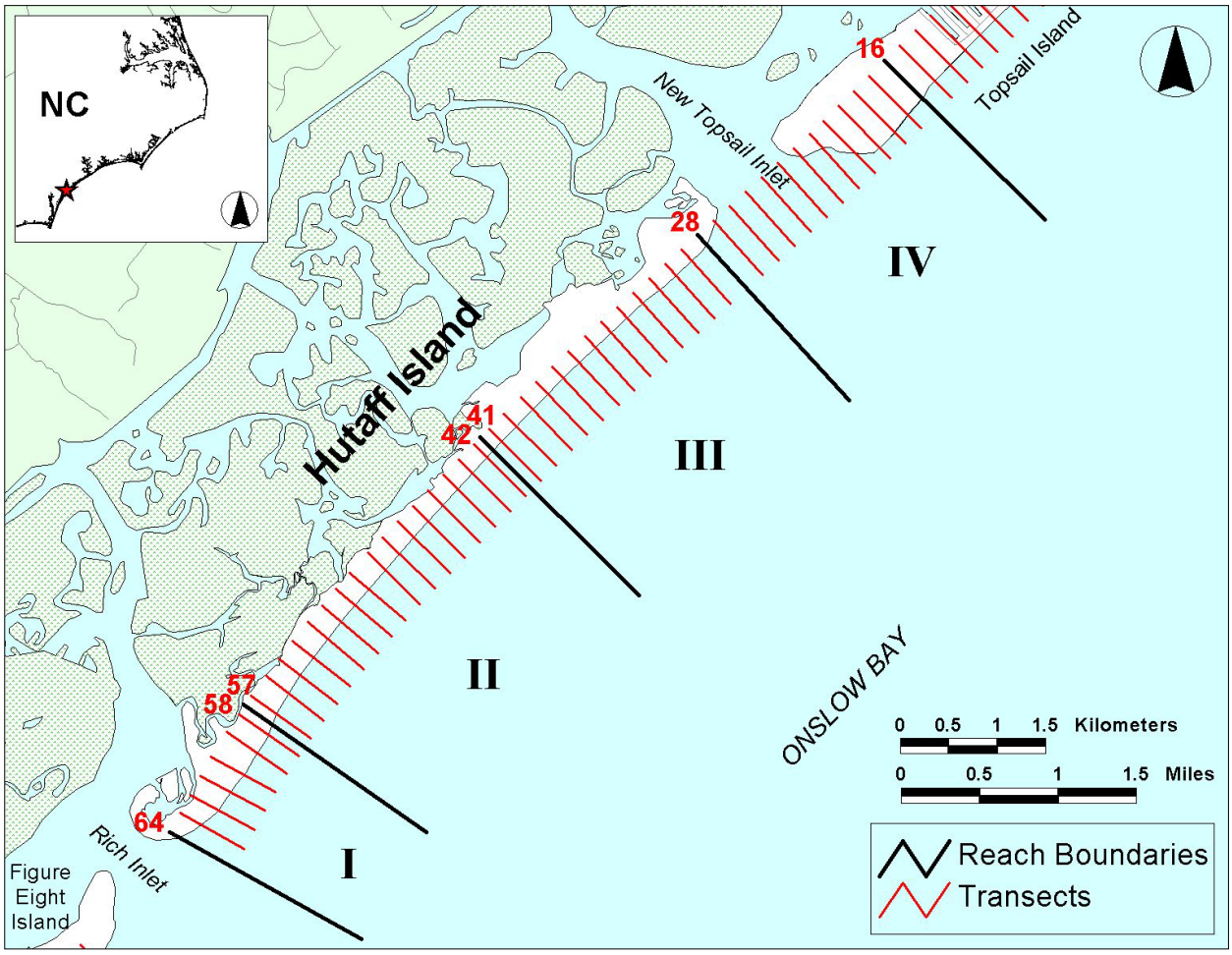


Figure 18. Map showing the identified reaches with respect to the influence of adjacent tidal inlets, shoreline change, topographic relief, and morphologic characteristics.

(-8.9 ft/year), and an average net shoreline change between the earliest and latest available shorelines of -124 m (-406 ft).

A maximum shoreline loss of 245 m (804 ft) occurred within Reach III at Transect 35 (Figure 9) as a result of the migration of Old Topsail Inlet. Prior to 1956, Transect 35 was located along the southwest shoulder of Old Topsail Inlet. The southwest shoulder of the inlet had historically received preferential accretion through the welding of swash bars as a result of the orientation of the inlet's ebb-channel. On the opposite side of Old Topsail Inlet in 1956, the shoreline position at Transect 29 was located 233 m (764 ft) landward of the shoreline position at Transect 35. By 1974, after Old Topsail Inlet had migrated to the southwest and beyond Transect 35, the shoreline translated 156 m (513 ft) landward at Transect 35. Continued landward migration of the shoreline through 2002 resulted in the net shoreline loss of -245 m (-804 ft) at Transect 35.

Reach IV is located along the migration pathway of New Topsail Inlet across Lea Island. This 1.8-km (1.1-mile) reach extends from Transect 16 in the northeast to Transect 28 in the southwest (Figure 18). The northeast edge of Lea Island was located at Transect 16 in 1938 but had migrated southwest with New Topsail Inlet to its position at Transect 28 in 2002. Reach IV had an average net shoreline change -8 m (-27 ft), an average EPR of -0.4 m/year (-1.2 ft/year), and an average LRR of -0.4 m/year (-1.3 ft/year).

As a result of the migration of New Topsail Inlet, limited historical shoreline positions were available for comparison within Reach IV. Transects occupied by the northeast edge of Lea Island early in the study period where quickly intersected by the migrating New Topsail Inlet, resulting in extremely short periods of available shoreline position data along the northeastern portion of the reach. It is difficult to accurately compare or average the long-term

shoreline changes observed along the southwestern portion of Reach IV to the short-term changes observed along the northeastern portion.

Topography

Topographic information derived from LIDAR datasets collected between 1996 and 2000, were utilized to show the recent short-term evolution of the barrier profile along each of the identified reaches. The average elevation above sea-level (NAD83) for the entire island was reduced from 1.2 m (3.8 ft) in 1996 to 0.9 m (3.0 ft) in 2000. The average dune (maximum) elevation along the entire island was 2.2 m (7.2 ft) in 1996 and 2.4 m (7.9 ft) in 2000 with an overall average dune elevation of 2.3 m (7.5 ft) throughout the 1996-2000 period. The composite LIDAR grids shown in Figure 19 represent elevations along Hutaff Island between 1996 and 2000. The warm (red) colors represent higher elevations along the island where as the cool (blue) colors represent the lower elevations.

Within Reach I, near Rich Inlet, the topography is similar between transects. The average elevation within this reach was 1.1 m (3.6 ft) in 1996 and 0.9 m (2.9 ft) in 2002 with an overall average elevation between 1996 and 2002 of 1.0 m (3.3 ft). The average dune (maximum) elevation within Reach I was 2.1 m (6.9 ft) in 1996 and 2.4 m (7.9 ft) in 2000. Figure 20 shows a representative topographic profile for the reach, measured at Transect 60.

Reach II, along the central portion of Coke Island, exhibits similar topographic relief between transects. The average elevation within this reach was 1.1 m (3.5 ft) in 1996 and 0.8 m (2.7 ft) in 2000 with an overall average elevation between 1996 and 2000 of 0.9 m (2.8 ft). The average dune (maximum) elevation within Reach II was 1.8 m (5.9 ft) in 1996 and 2.0 m (6.6 ft) in 2000. Figure 21a shows a representative topographic profile for the reach, as measured at

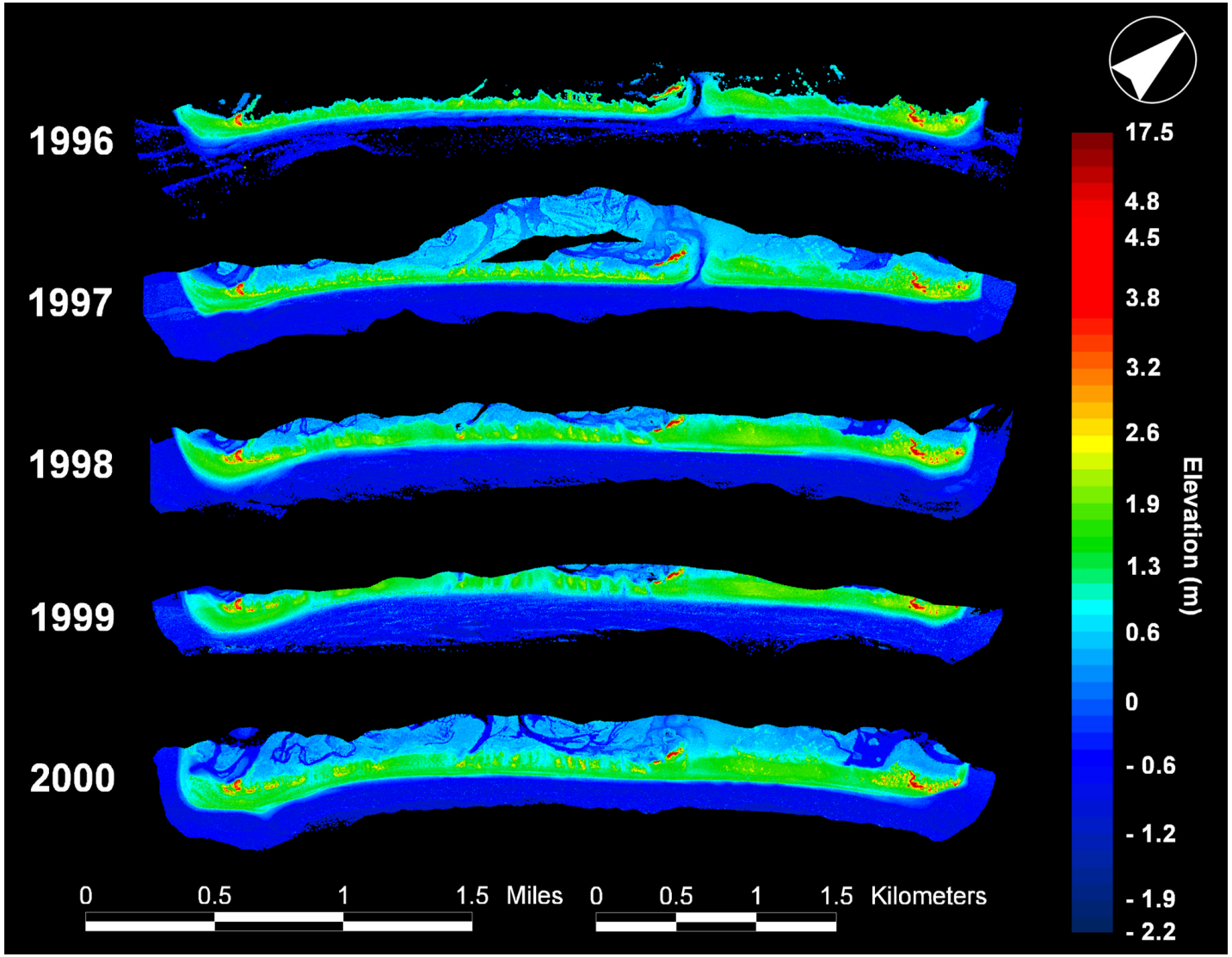


Figure 19. Composite LIDAR grids showing elevation data from LIDAR surveys conducted in 1996-2000. Warm (red) colors represent higher elevations and cool (blue) colors represent lower elevations.

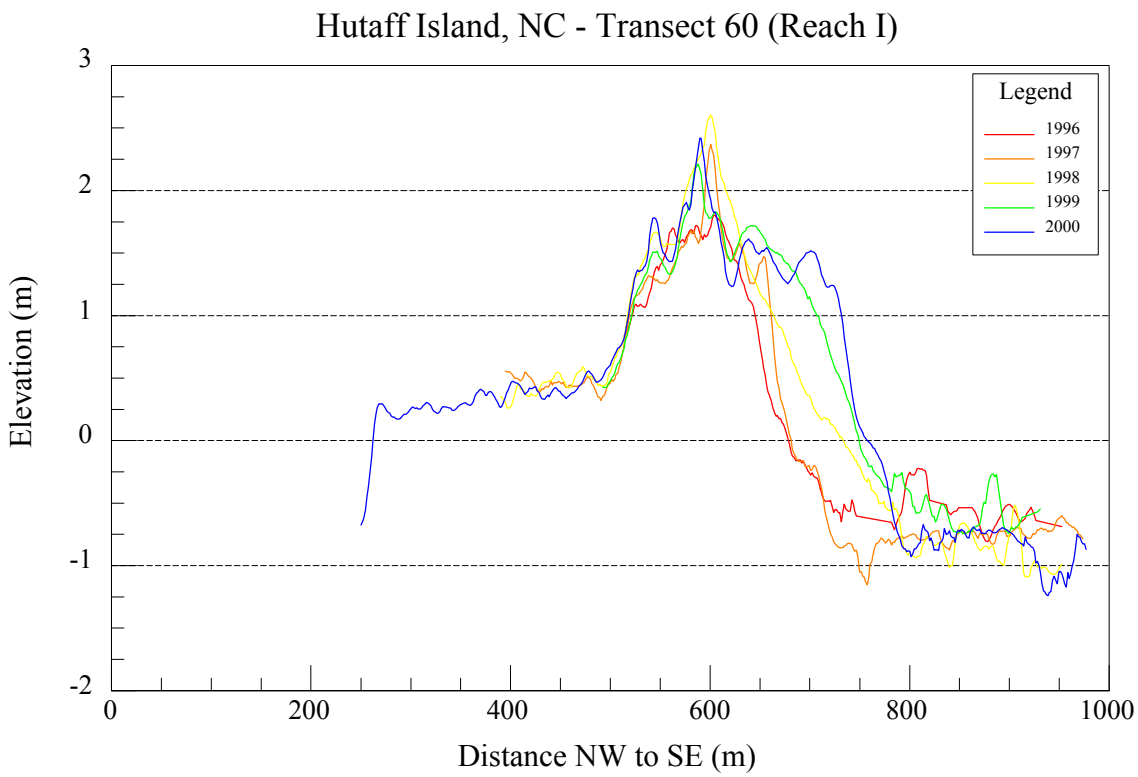


Figure 20. Representative topographic profile for Reach I derived from LIDAR elevation grid data. See Figure 6 for location.

Transect 47. A topographic profile from Transect 54 is also presented (Figure 21b) to represent the small section of Reach II in which Sidbury Inlet was located in 1962.

The barrier segment along the migration pathway of Old Topsail Inlet (Reach III) is represented by a topographic profile along Transect 31 (Figure 22a) and another along Transect 39 (Figure 22b) to represent the topography near the site of the closure of Old Topsail Inlet. The average elevation within Reach III was 1.3 m (4.2 ft) in 1996 and 1.1 m (3.5 ft) in 2000 with an overall average elevation between 1996 and 2000 of 1.2 m (3.8 ft). The average dune (maximum) elevation within Reach III was 2.8 m (9.2 ft) in 1996 and 3.1 m (10.2 ft) in 2000, but these values are skewed as a result of two uncharacteristically large dunes located near each edge of the reach. These dunes, located at Transects 29 and 41 (Figure 6), had a maximum elevation of 8.7 m (28.5 ft) and 9.4 m (30.8 ft) respectively in 2000. A more representative average dune (maximum) elevation, disregarding data from Transects 29 and 41, within Reach III was 1.9 m (6.2 ft) in 1996 and 2.2 m (7.2 ft) in 2000.

Topographic data within Reach IV were limited. Most of the reach is occupied by New Topsail Inlet in the 1996-2000 LIDAR datasets. Measured topographic profiles could only be created within Reach IV at Transects 26 and 27 (Figure 23) along the southwest shoulder of New Topsail Inlet. By 2000, as a result of the southwest migration of New Topsail Inlet, Transects 26 and 27 were also located within the area occupied by the inlet. The average elevation within this reach was 1.3 m (4.3 ft) in 1996 and 1.0 m (3.3 ft) in 2000 with an overall average elevation between 1996 and 2000 of 1.1 m (3.6 ft). The average dune (maximum) elevation within Reach IV was 2.3 m (7.5 ft) in 1996 and 2.1 m (6.9 ft) in 2000.

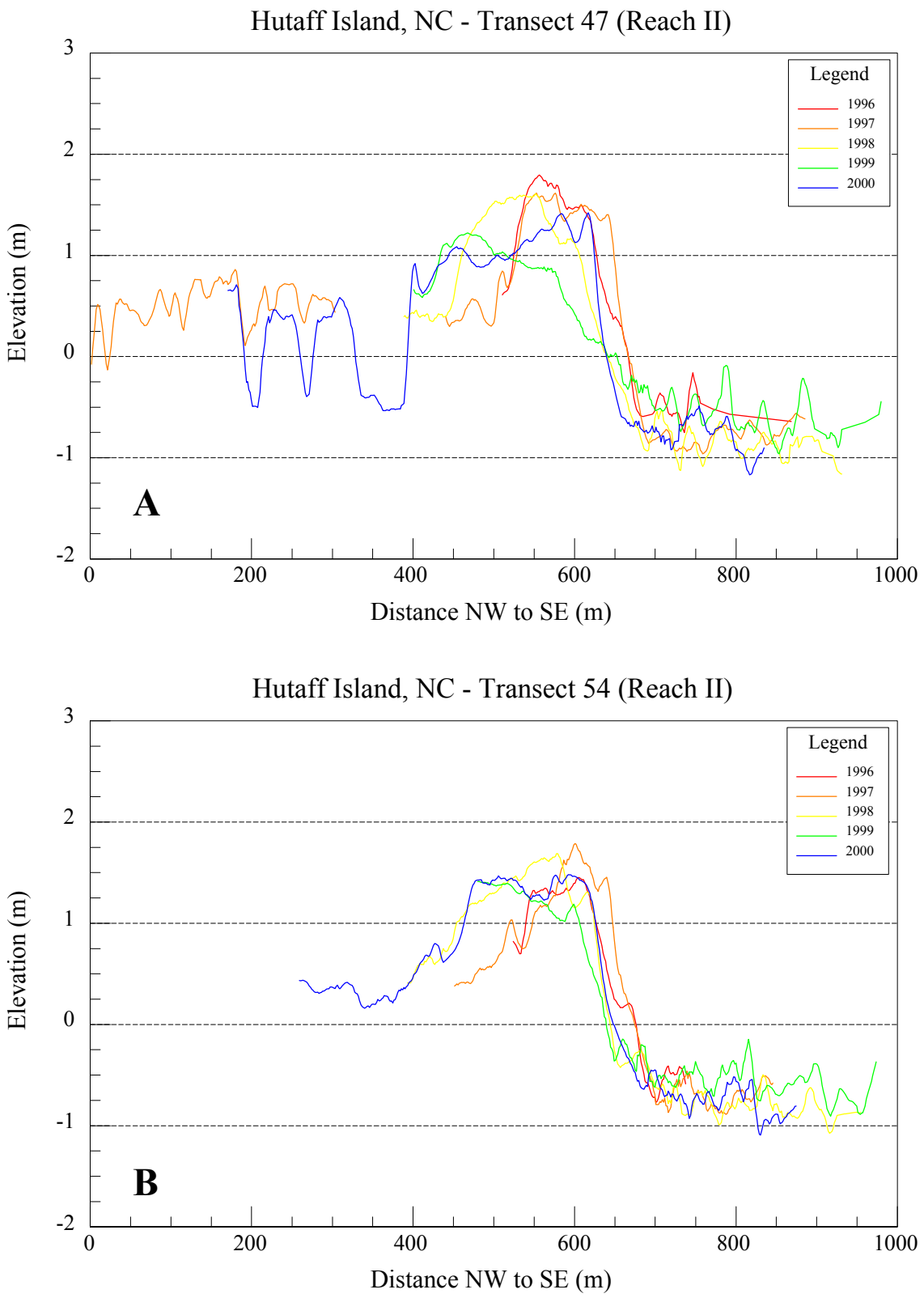


Figure 21. Representative topographic profiles for Reach II derived from LIDAR elevation grid data. See Figure 6 for location.

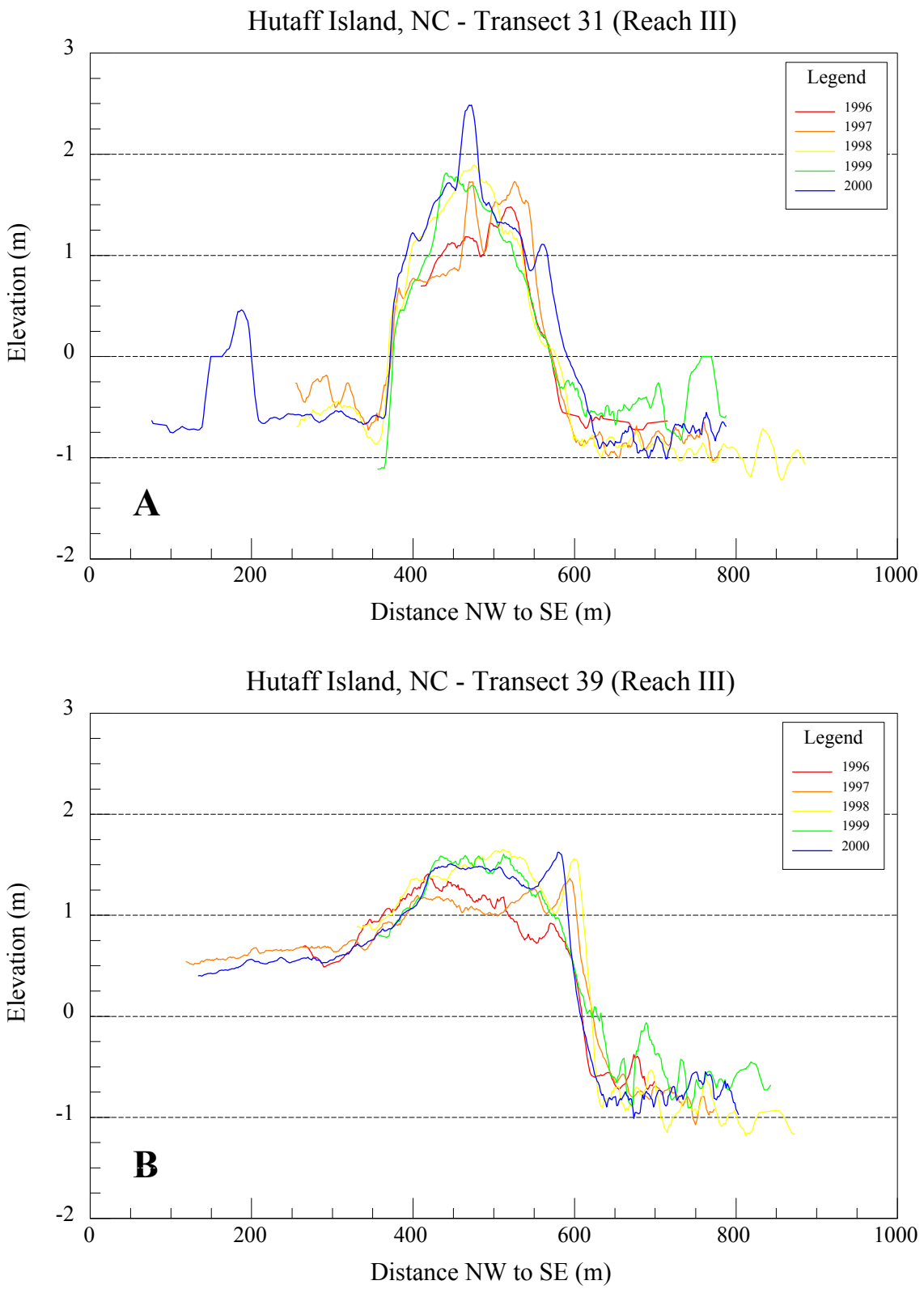


Figure 22. Representative topographic profiles for Reach III derived from LIDAR elevation grid data. See Figure 6 for location.

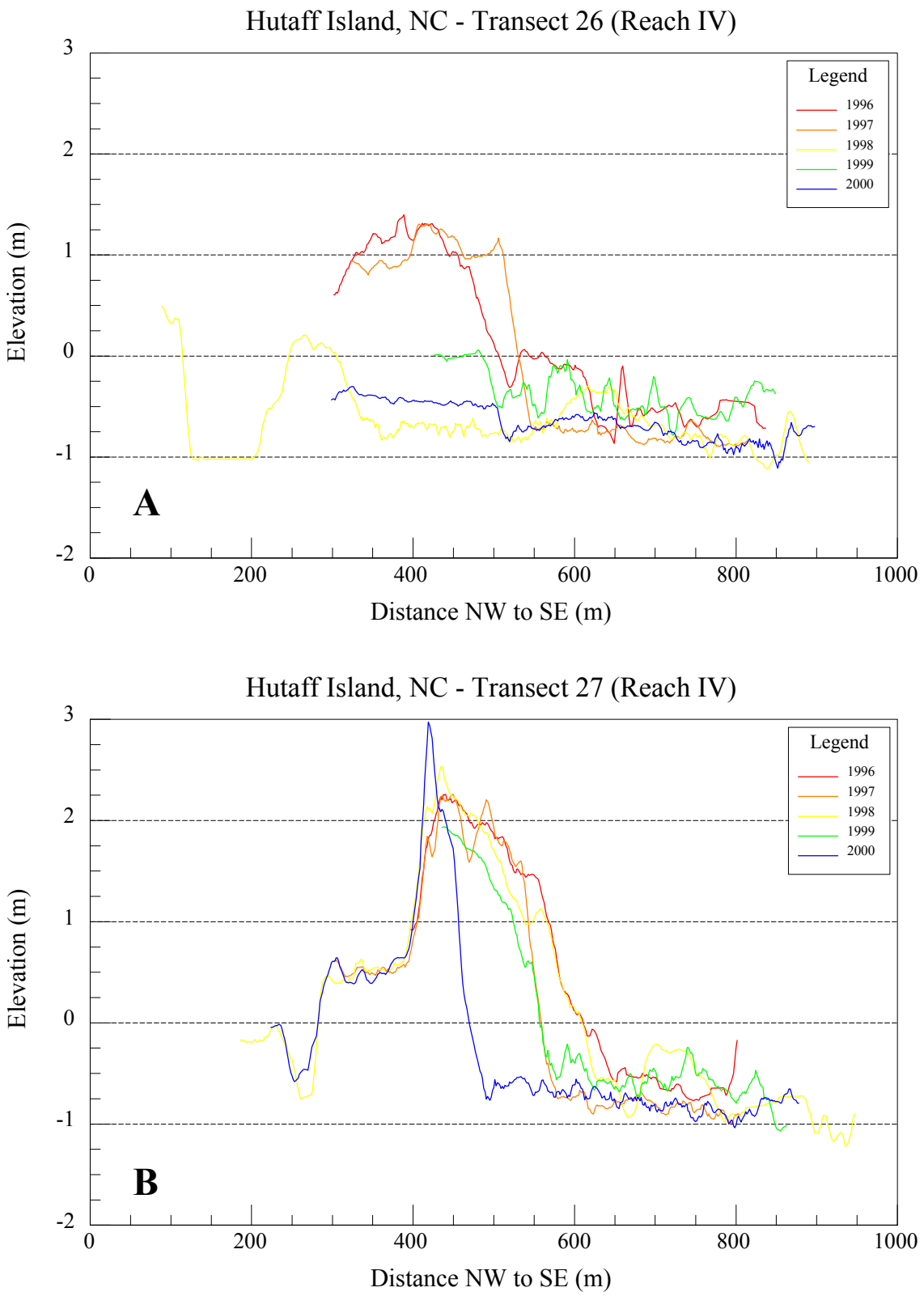


Figure 23. Representative topographic profiles for Reach IV derived from LIDAR elevation grid data. See Figure 6 for location.

## Shoreface Geology

The nature and thickness of shoreface surface sediments and underlying stratigraphic units adjacent to Hutaff Island were determined from a suite of shoreface vibracores and diver surveys. Three shore-parallel transects (A, B, and C) and two shore-normal transects (D and E) were established to ascertain this three dimensional nature of the shoreface geology. The stratigraphic profiles were derived from vibracore and diver survey data (Figure 24). Stratigraphic profiles for Transects A - E are respectively shown in Figures 25 - 29.

### Underlying Stratigraphic Units

As a result of the thin (< 100 cm) and variable shoreface sediment cover, the underlying stratigraphic units were encountered at 100 sites during coring and diving operations. An Oligocene quartz-rich, dolo-siltstone/sandstone unit is the dominant subcrop unit on the shoreface of Hutaff Island, whereas a small area is underlain by Oligocene moldic limestone found off of the southern end of Topsail Island (Figure 30), in the vicinity of the 1938 location of Lea Island (CLEARY *pers. comm.*, 2003). These Oligocene units commonly crop out on the shoreface. The siltstone unit is seldom lithified, and is commonly bored and infilled with sediments from above. Reworking of the siltstone hardbottoms through bio-erosion and wave quarrying augment a considerable volume of fine-grained sand/silt to the shoreface sediments (CLEARY and PILKEY, 1968; CLEARY and THAYER, 1973; SNYDER *et al.,* 1982; RIGGS *et al.*, 1995; and THIELER *et al.*, 1995).

Hardbottoms, or sediment cover of 30 cm or less, were encountered at 21 sites where the underlying stratigraphic units were recovered in vibracores (Figure 31). Hardbottoms without any sediment cover occurred at nine of these sites. Flat Oligocene siltstone hardbottoms were generally exposed offshore Hutaff Island and the Rich Inlet's ebb-tidal delta, whereas scarped

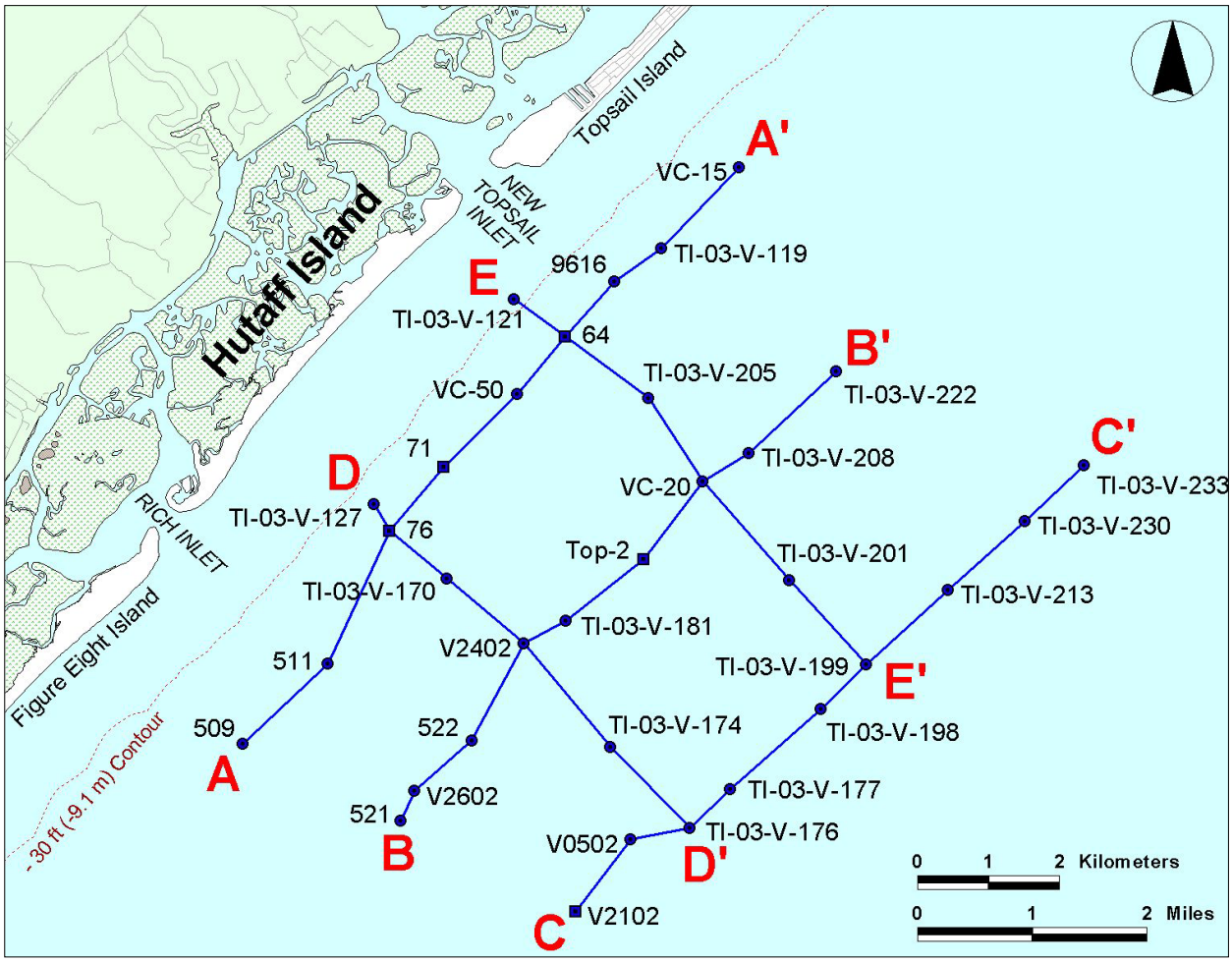


Figure 24. Map illustrating stratigraphic profile transects derived from vibracore and diver survey data.

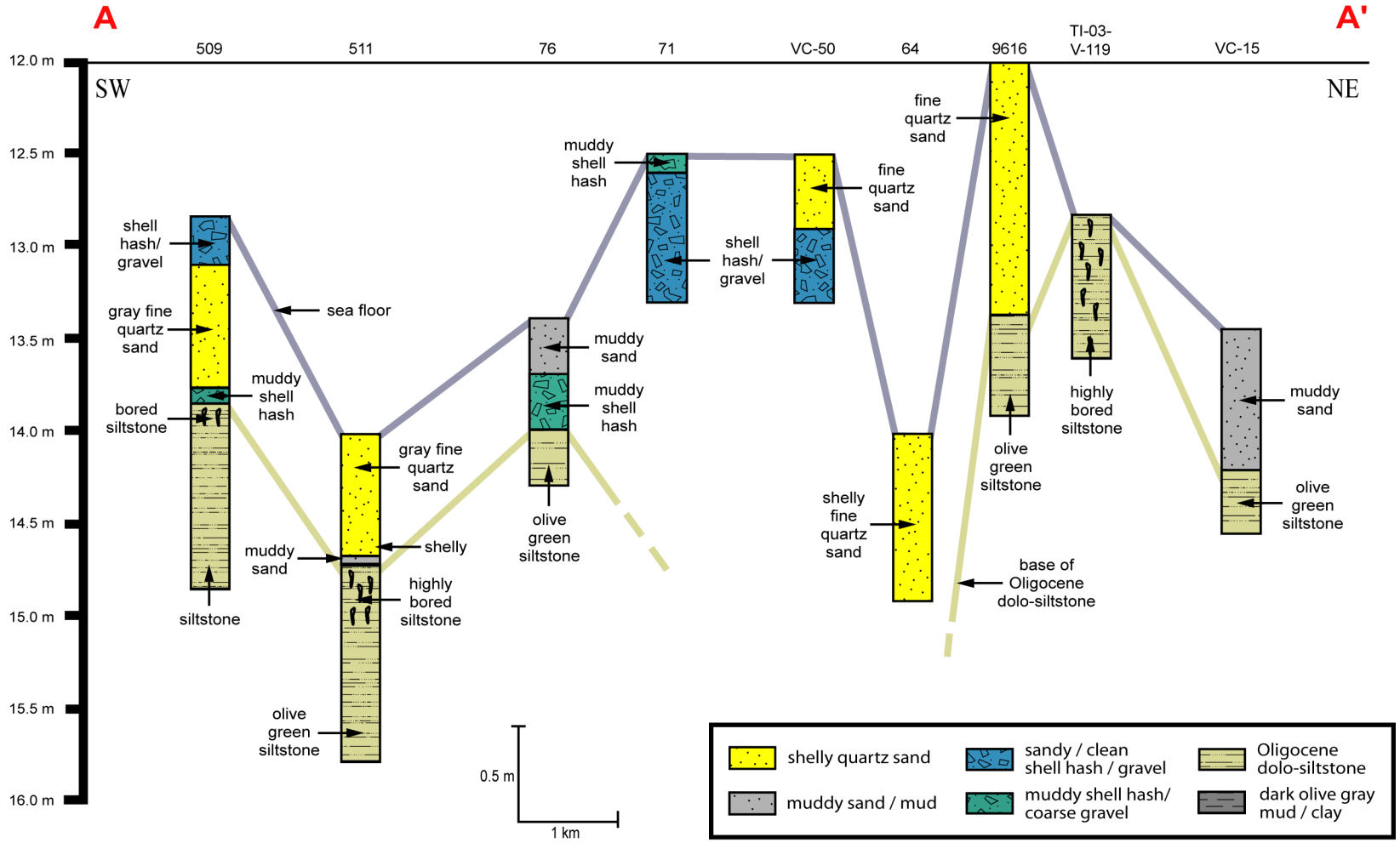


Figure 25. Stratigraphic profile along shore parallel Transect A – A'.

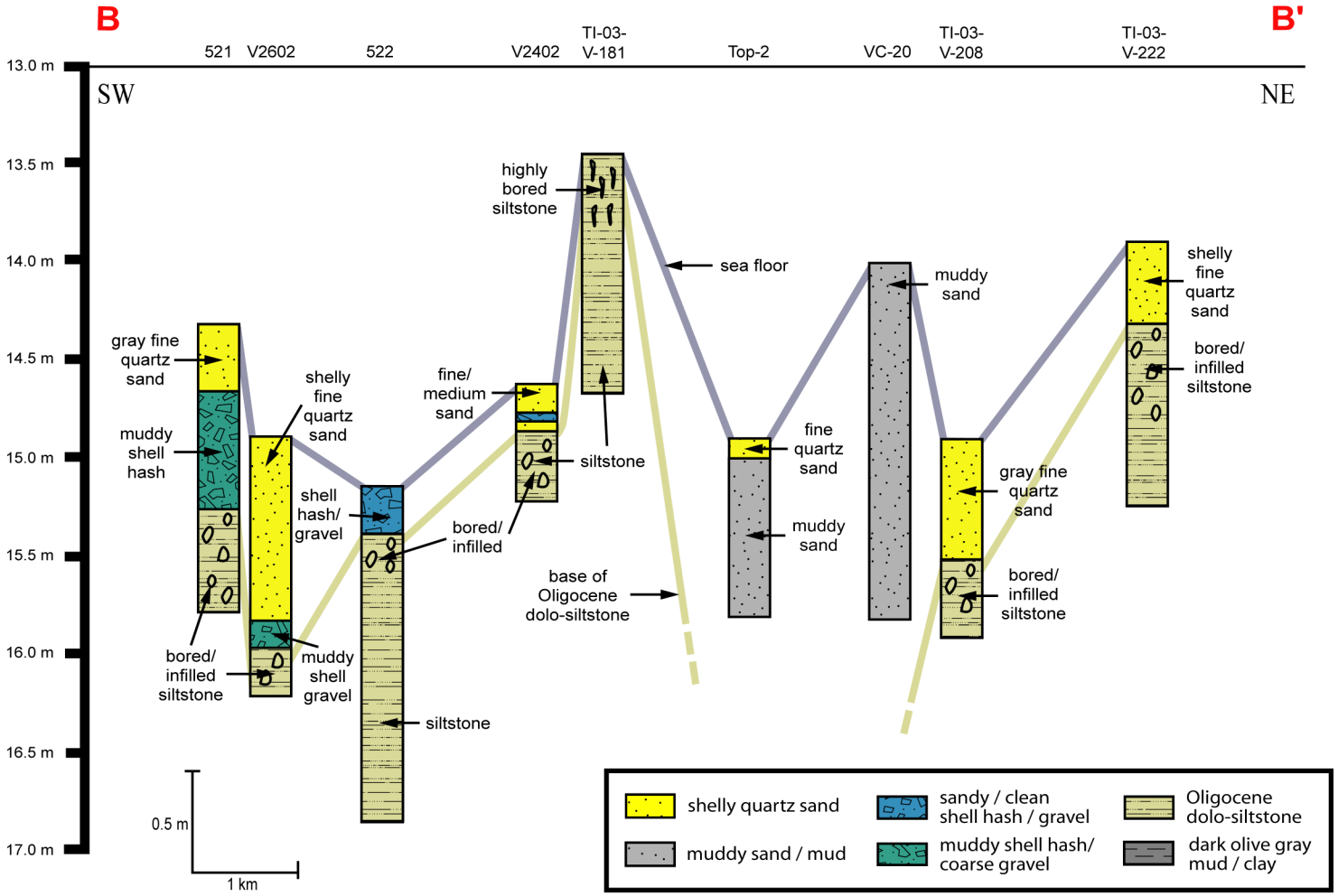


Figure 26. Stratigraphic profile along shore parallel Transect B – B'.

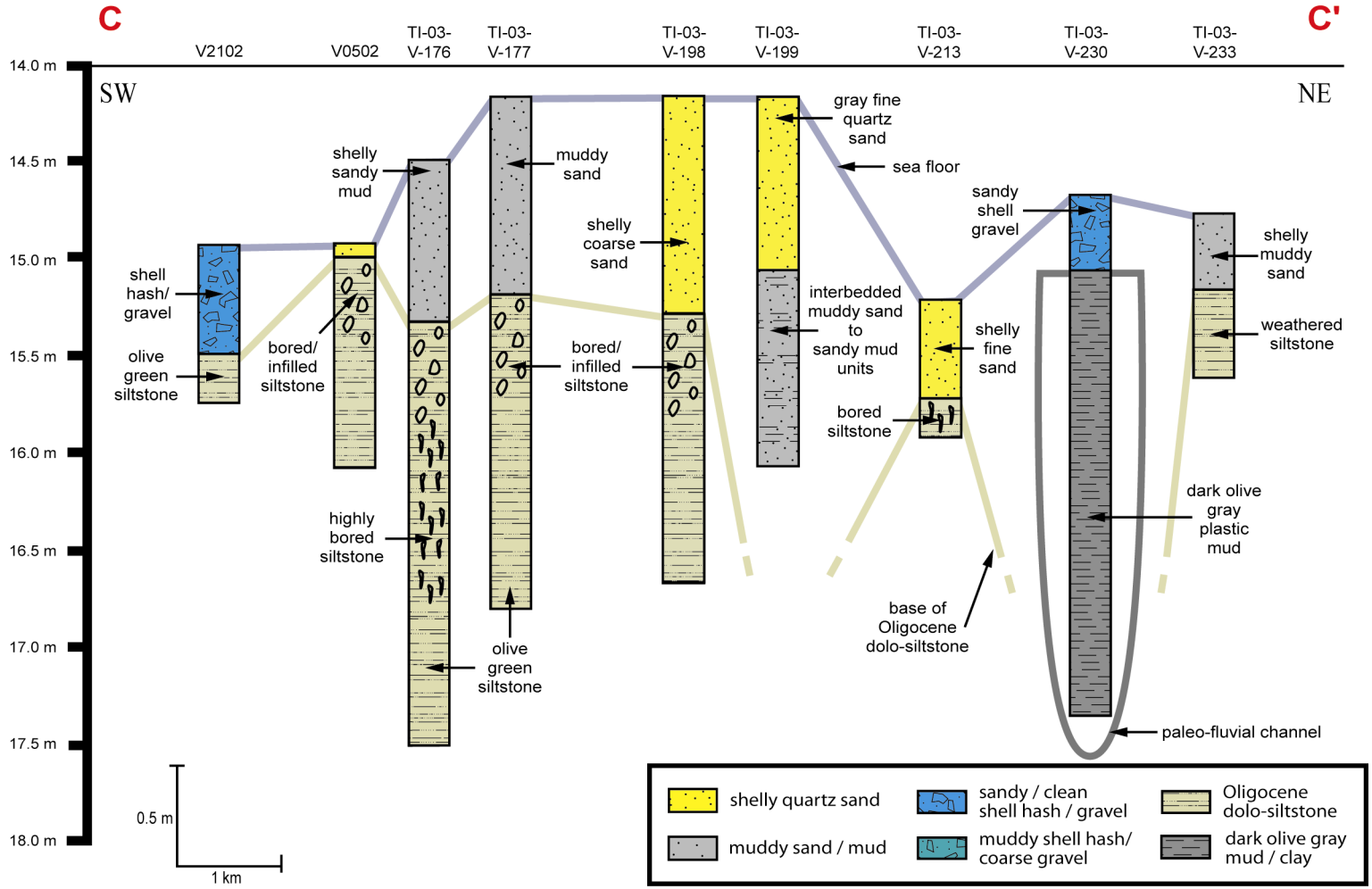


Figure 27. Stratigraphic profile along shore parallel Transect C – C'.

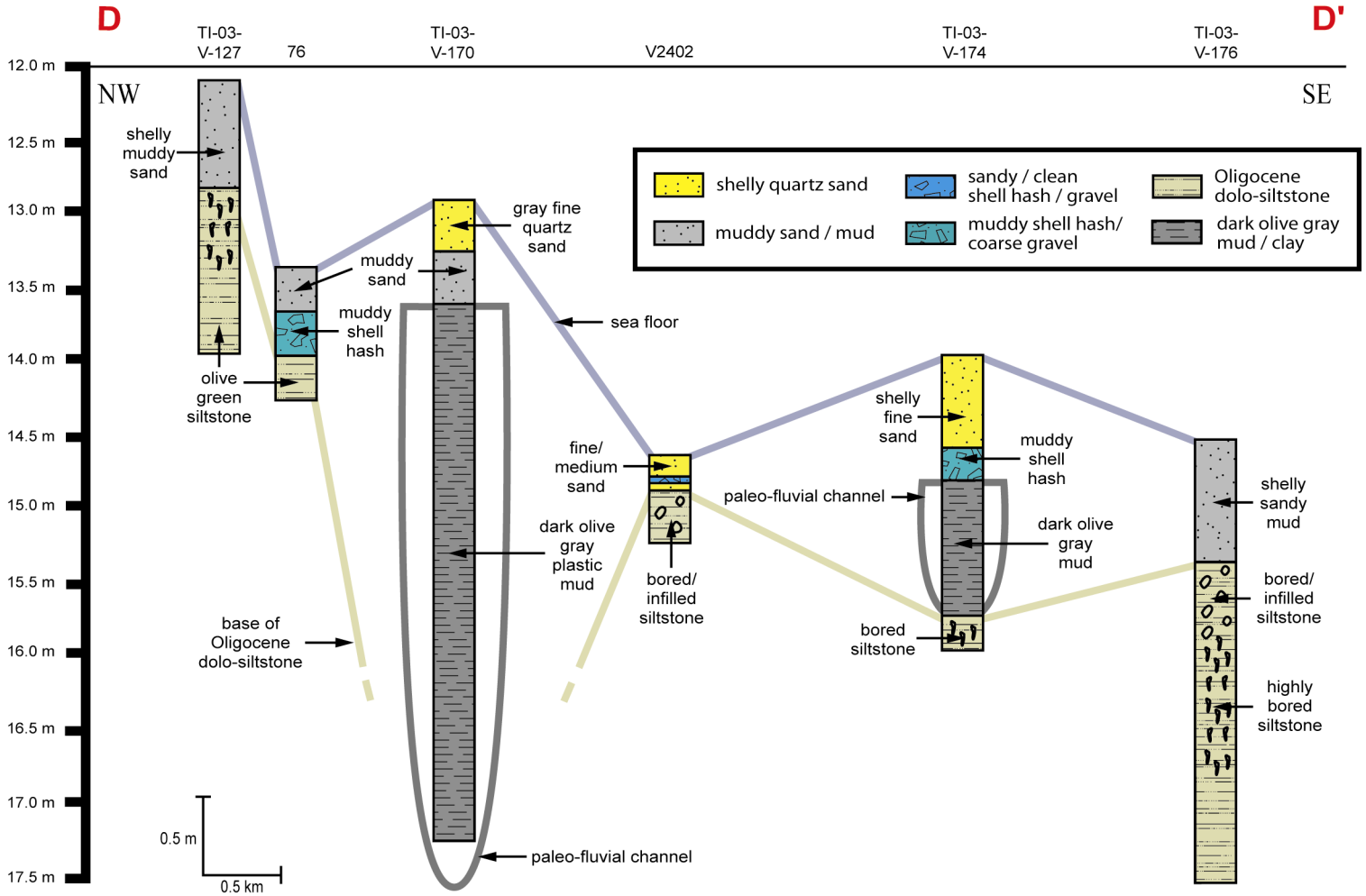


Figure 28. Stratigraphic profile along shore parallel Transect D – D'.

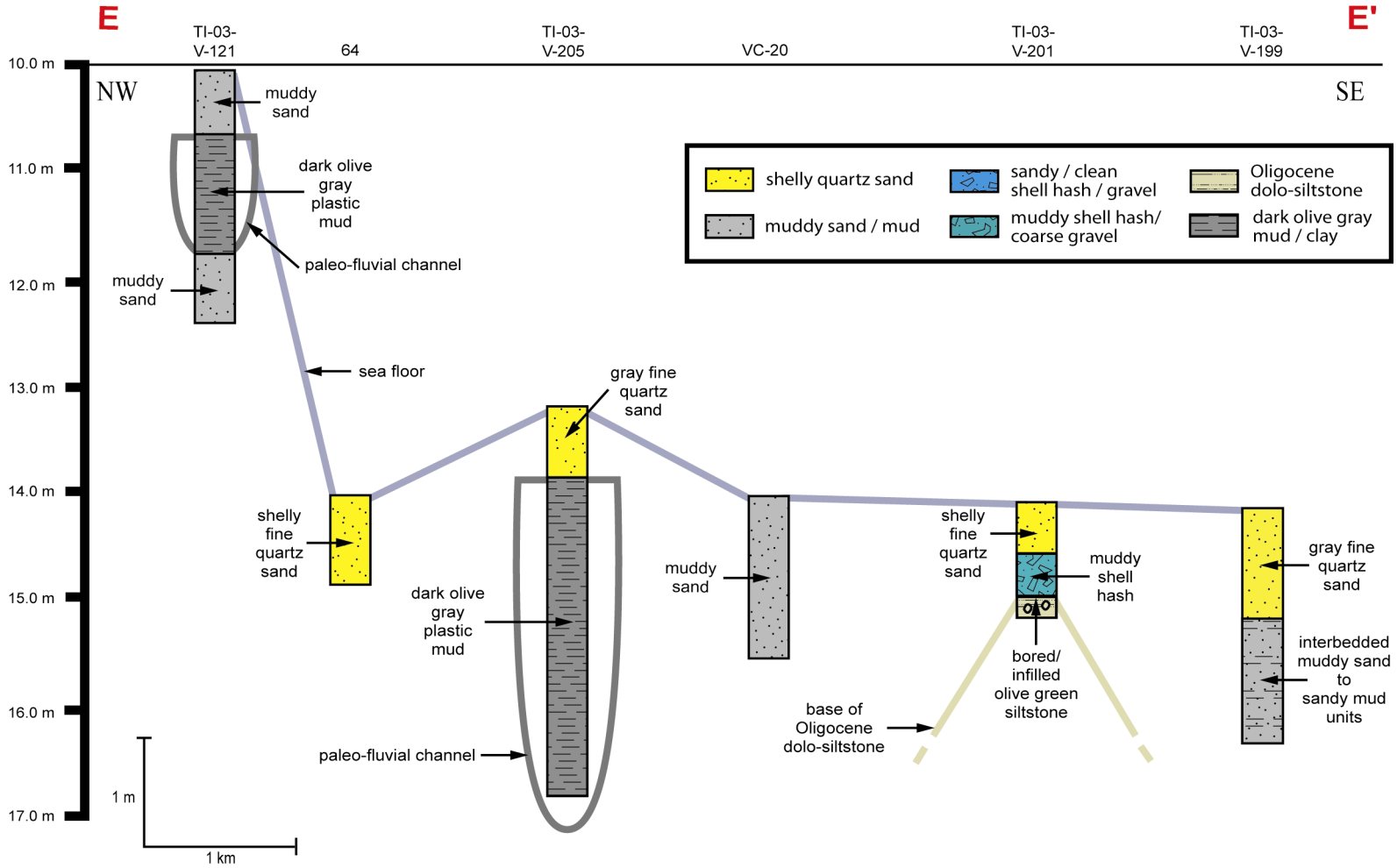


Figure 29. Stratigraphic profile along shore parallel Transect E – E'.

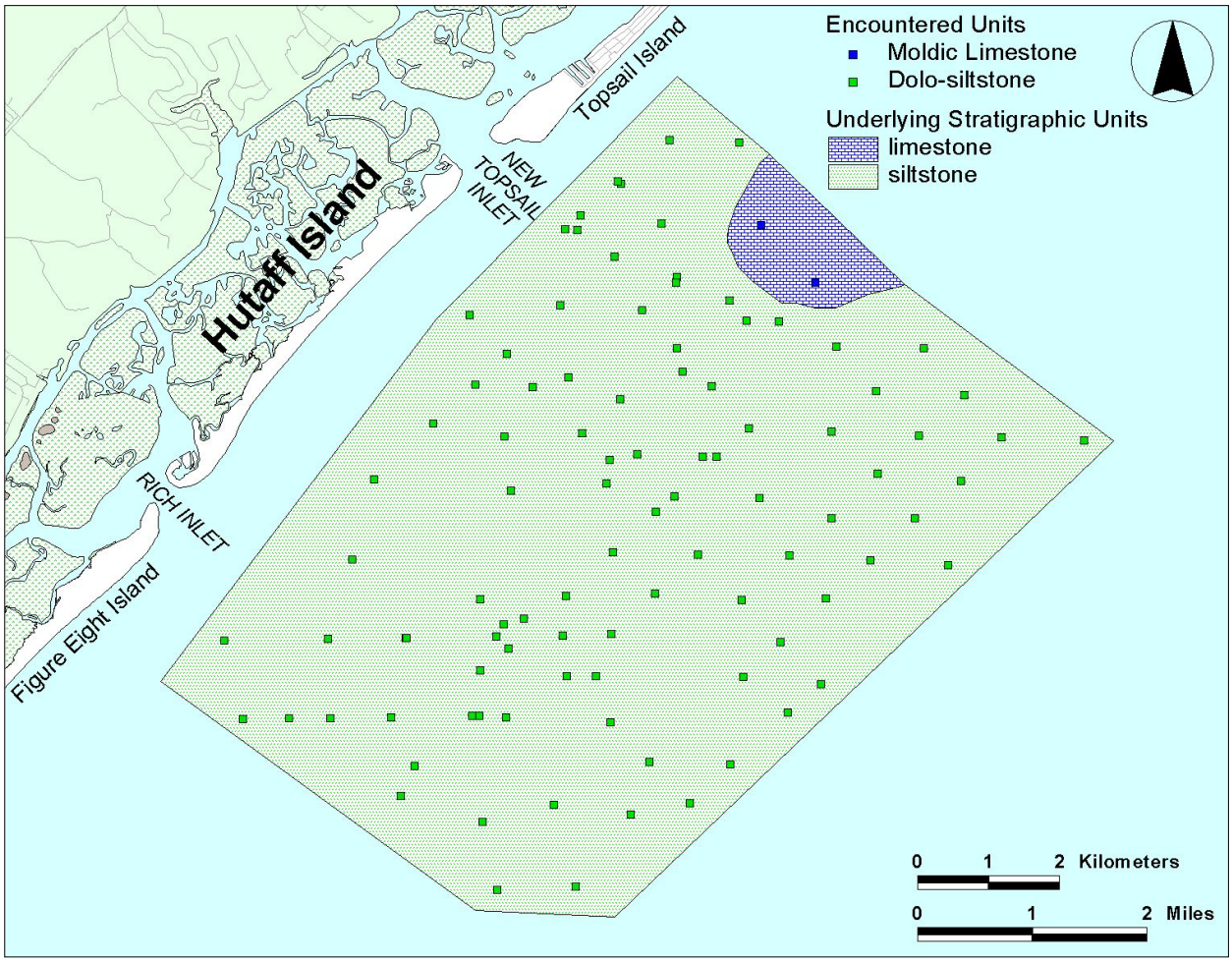


Figure 30. Map illustrating the vibracore and diver survey sites where underlying Oligocene units where encountered.

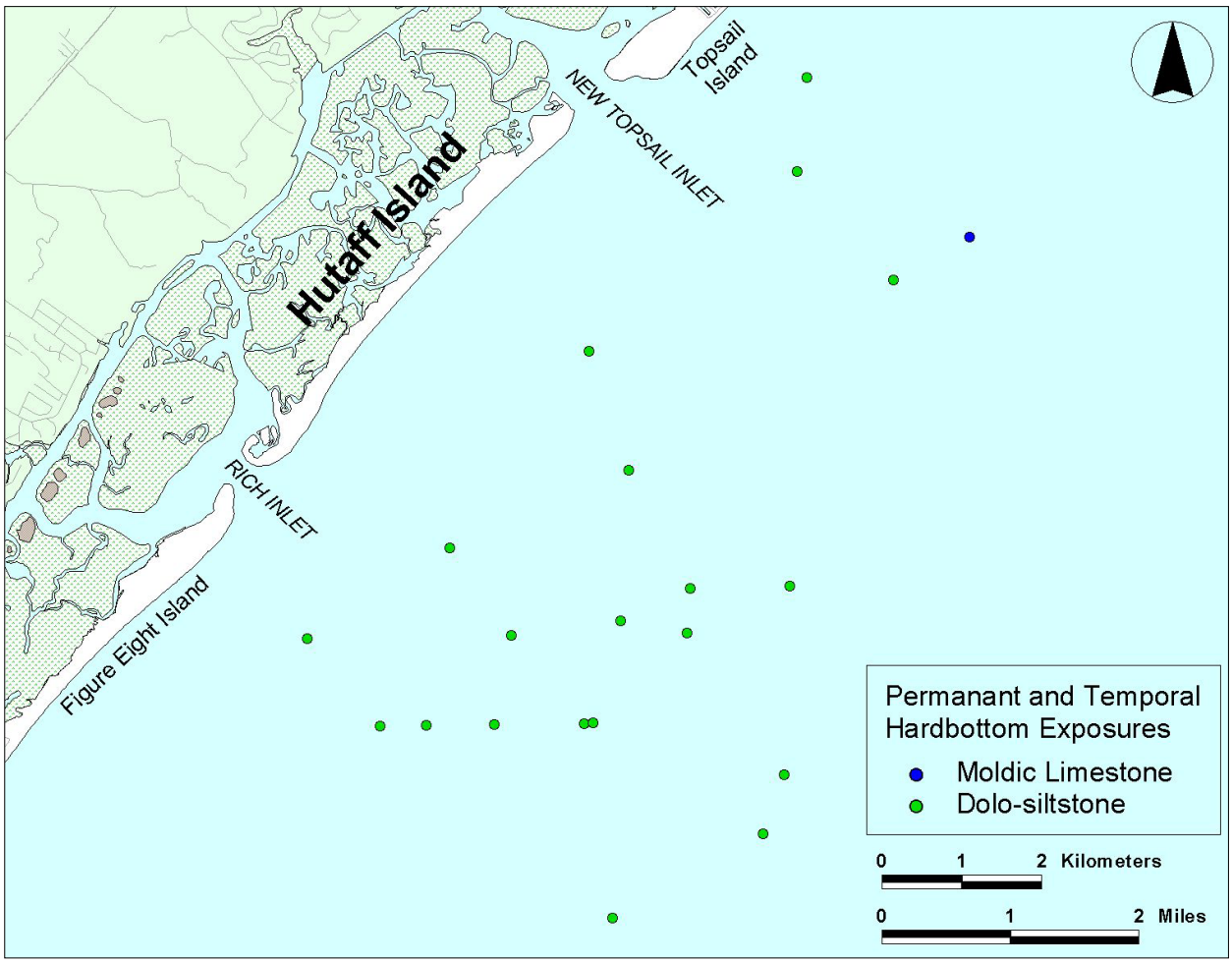


Figure 31. Map depicting the locations of hardbottom areas and sites where sediment cover was less than 30 cm. Areas with thin sediment cover are subject to exposure of the underlying siltstone or limestone units as a result of shifting sediments during storm events.

Oligocene limestone hardbottoms were located off shore southern Topsail Island (Figure 31).

Quaternary paleo-fluvial channel features were found across the entire Hutaff Island shoreface. These channel features, incised into the underlying Oligocene units, have been identified in previous studies offshore neighboring barriers (THIELER *et. al*., 1995; MCQUARRIE, 1998; CLEARY, 2002; and HDR, 2002). Sediments retrieved from vibracores indicate the paleo-fluvial channels are infilled with a dark gray estuarine mud, and are generally 3.0 – 4.0 m thick. Paleo-fluvial channel locations were identified from vibracore data at 19 sites offshore Hutaff Island (Figure 32). Previous investigations by CLEARY (2002) and HDR (2002) identified three paleo-fluvial channel segments offshore of the margins of Hutaff Island. MCQUARRIE (1998) previously identified 64 paleo-fluvial channel sites in the area through seismic data interpretations. Figure 32 shows a map depicting the paleo-fluvial channels identified in this study and sites identified in previous studies.

Sediments

The nature and distribution of the shoreface surface sediments was determined from the suite of vibracore and diver survey data (Figure 33). These data suggest that two major surface sediment types dominate the Hutaff Island shoreface. The majority of the shoreface is covered by a veneer of shelly, fine-to-medium quartz sand, with appreciable amounts of sandy shell hash to shell gravel found across the shoreface, predominately to the southwest offshore Rich Inlet. Most of the shell hash is comprised of fragmented molluscan and other shell material with appreciable amounts of fine-quartz sand. The coarser shell gravel generally consists of whole and fragmented molluscan material, and varying amounts of siltstone and limestone lithoclasts.

Examination of previously collected vibracore and diver survey data indicated that the shoreface sediment sequence is variably thin and consisted of units of clean to muddy fine-quartz

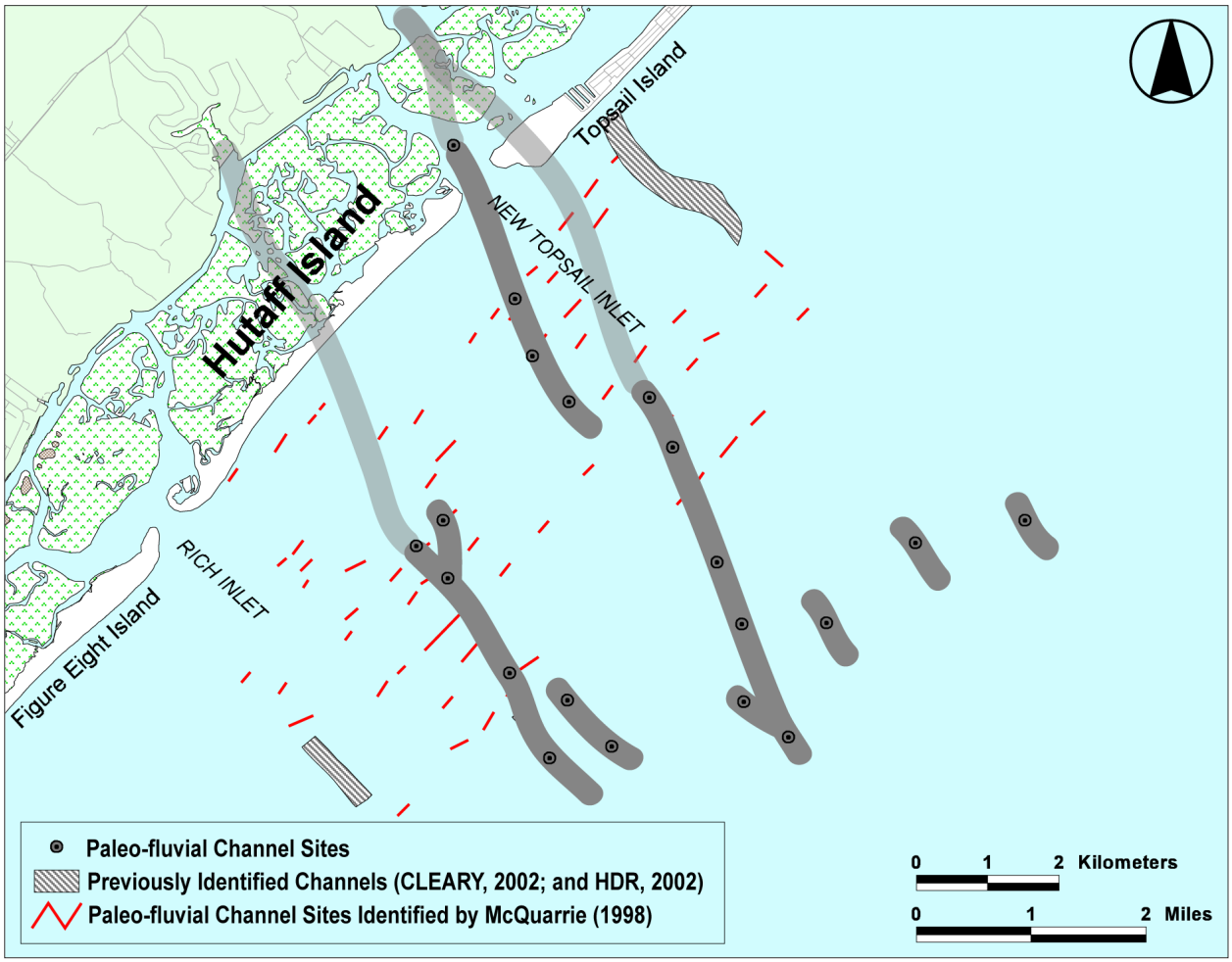


Figure 32. Map depicting the locations of paleo-fluvial channels identified in this study at vibracore and diver survey sites, and in previous studies by CLEARY (2002), HDR (2002), and MCQUARRIE (1998). The dark gray lines represent likely channel locations. The transparent, light gray lines represent possible correlations of shoreface paleo-fluvial channels with present-day tidal creeks.

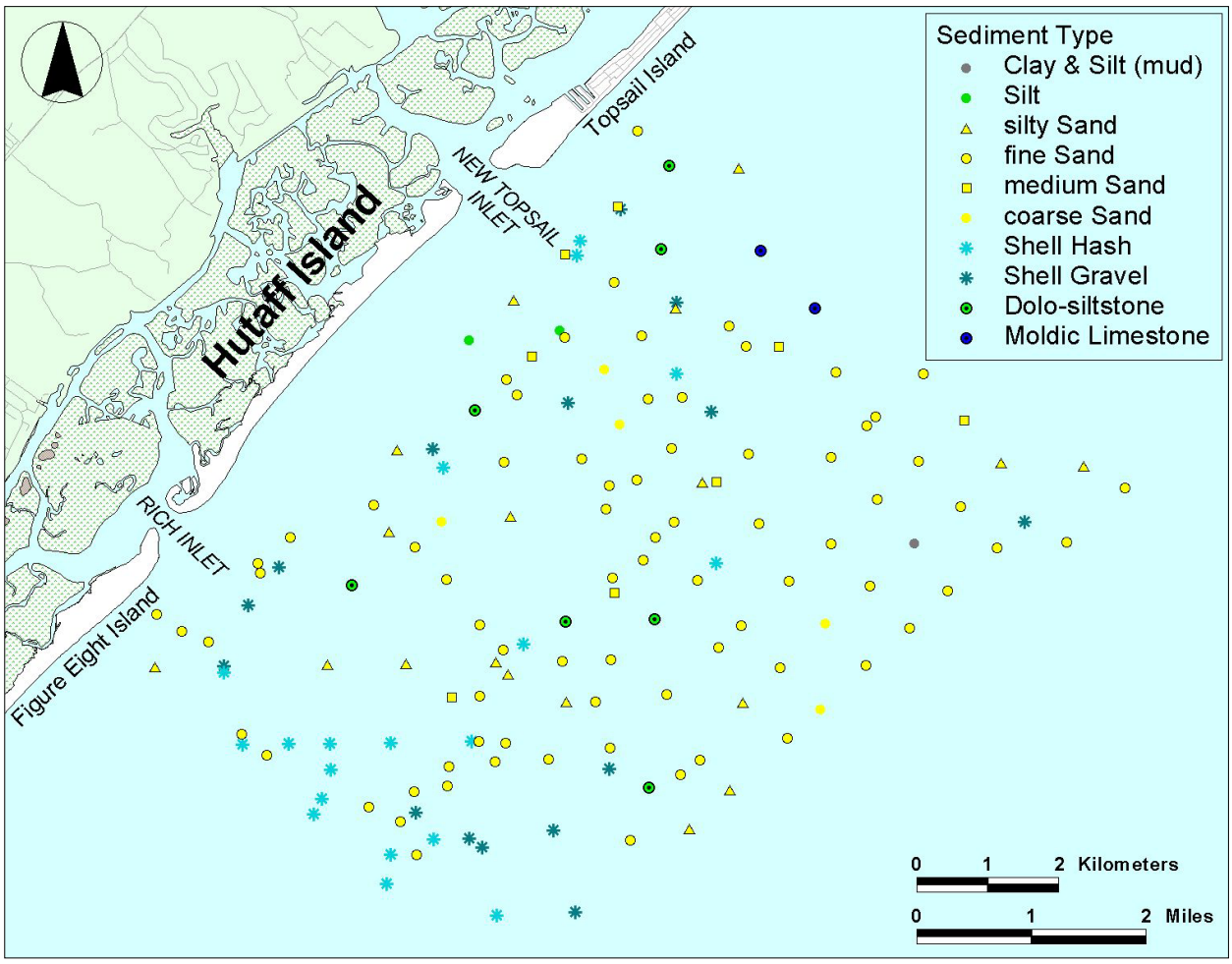


Figure 33. Map depicting the shoreface surface sediment types observed at vibracore and diver survey sites.

sand intercalated with sandy and muddy shell hash/gravel units. Holocene sediment thickness ranged from zero at hardbottom locations to 6.2 m (20.3 ft). Nearly all of the vibracores with thick accumulations of Holocene sediments were retrieved from Quaternary mud-filled paleo-fluvial channels incised into the underlying Oligocene units. These paleo-fluvial channels are infilled with a dark gray, plastic, organic-rich estuarine mud with occasional interbeds of silty sand, and were normally overlain by modern sand or shell hash/gravel.

Shore-parallel and shore-normal vibracore transects (Figures 25-29) illustrate the variability in the nature and thickness of the modern sediment sequences. The vibracore transects reveal that clean to muddy fine-quartz sand units with varying amounts of finely fragmented shell material encompass a primary portion of the modern shoreface sediment sequence. Shoreface sand units are generally less than 1.0 m (3.3 ft) thick with an average thickness of 0.7 m (2.2 ft). These sand units are intercalated with sandy to muddy shell hash and coarse shell gravel units that are generally less than 0.4 m (1.3 ft) thick. As previously mentioned, 19 paleo-fluvial channel features were identified in this study from vibracore and diver survey data. Retrieved channel sediment sequences, consisting of dark gray plastic mud, ranged in thickness between 1.0–4.0 m (3.3–13.1 ft).

Using Holocene sediment thickness data from vibracores and diver surveys, a map was produced (Figure 34) to show the shoreface sediment thickness distribution. Sediment thickness ranges from 0-619 cm (0-20.3 ft), however, shoreface sediment thickness was dominantly found to range from 31-100 cm (1.0-3.3 ft). Sediment thickness of 100 cm (3.3 ft) or less covered 78 percent of the total shoreface area mapped in Figure 34.

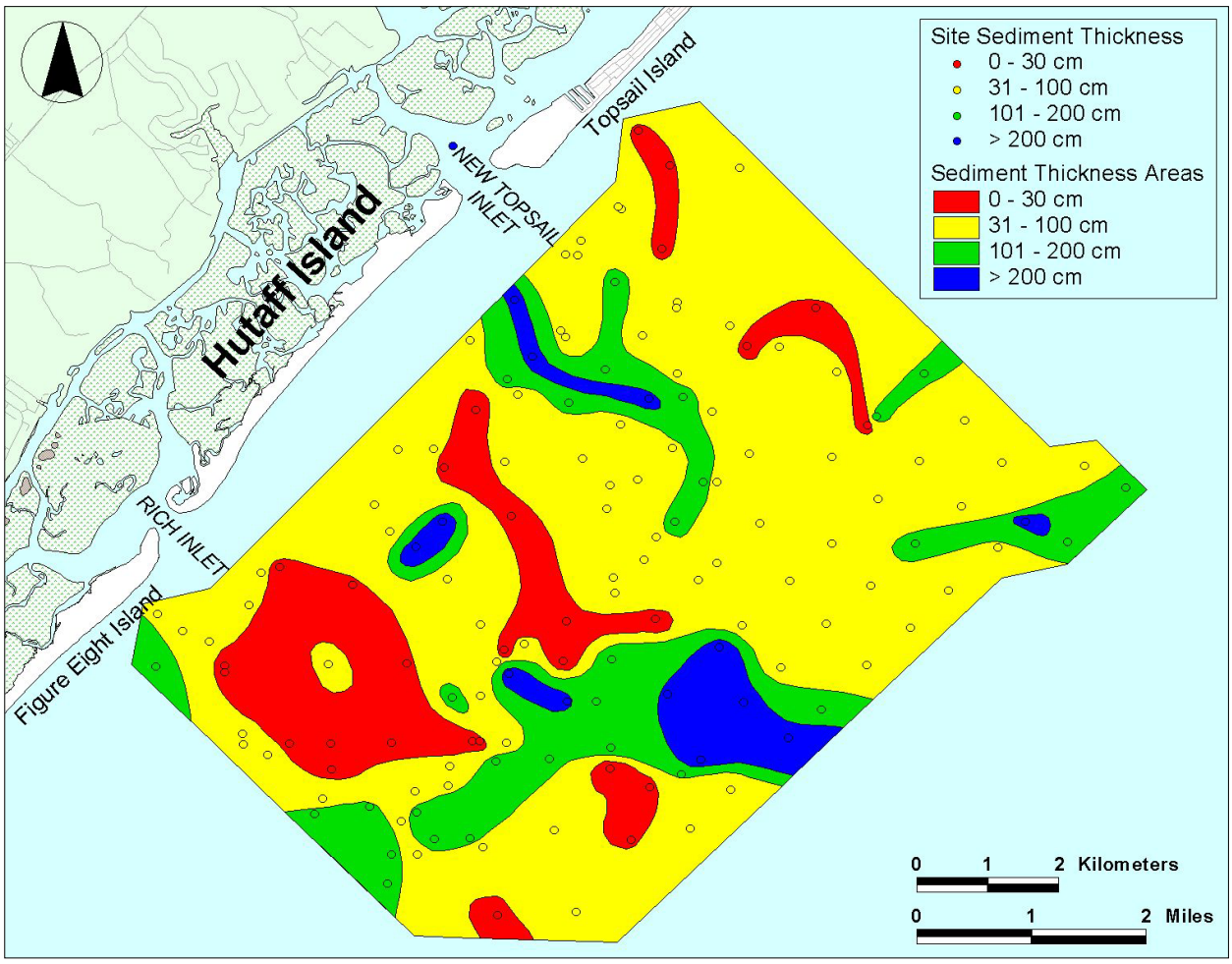


Figure 34. Map depicting the sediment thickness observed at vibracore and diver survey sites and the identified sediment thickness areas across the shoreface.

Back-barrier Estuary History

To understand the historical influence of tidal inlets on Hutaff Island, a suite of 13 estuarine vibracores where collected to determine the presence of intertidal sediments. Inlets that have historically intersected or been adjacent to Hutaff Island would have served as conduits, carrying and subsequently depositing sand-rich sediments into the intertidal back-barrier estuary during flooding tides. Summaries of the estuarine vibracores are presented using a vibracore and transect location map (Figure 8) and four stratigraphic cross-section profiles (Figures 35-38). Transect F (Figure 35), the single shore-parallel transect, and Transects G, H, and I (Figure 36-38), the three shore-normal transects, were established to ascertain the nature of the estuarine sediments.

Megascopic examinations of estuarine vibracores indicated that the sediment sequences consisted primarily of three varied sediment types. Muddy, fine-medium quartz sand to sandy mud was predominant throughout the estuarine vibracores and comprised 48.8% of the recovered sediment sequences. Abundant whole and fragmented oyster shells and mud snails were observed in varying amounts within the muddy sand to sandy mud units. Clean, fine-quartz sand was recovered in 31.9% of the estuarine vibracore sediment sequences, representing a substantial portion of the total recovered sediments. The third major sediment type, comprising 14.6% of the total recovered sediment sequences, consisted of dark olive gray, silt-rich mud with varied amounts of whole and disarticulated oyster shells. Smaller sediment sequence fractions include the modern spartina marsh root mat (4.6%) recovered in many of the vibracores, and the sandy shell gravel (0.2%) recovered in vibracore TI-03-V-143 (Figure 38).

Sand-rich sediments including the clean, fine-quartz sands, and the muddy, fine-medium quartz sands, comprised approximately 62.6% of the total sediments recovered from the

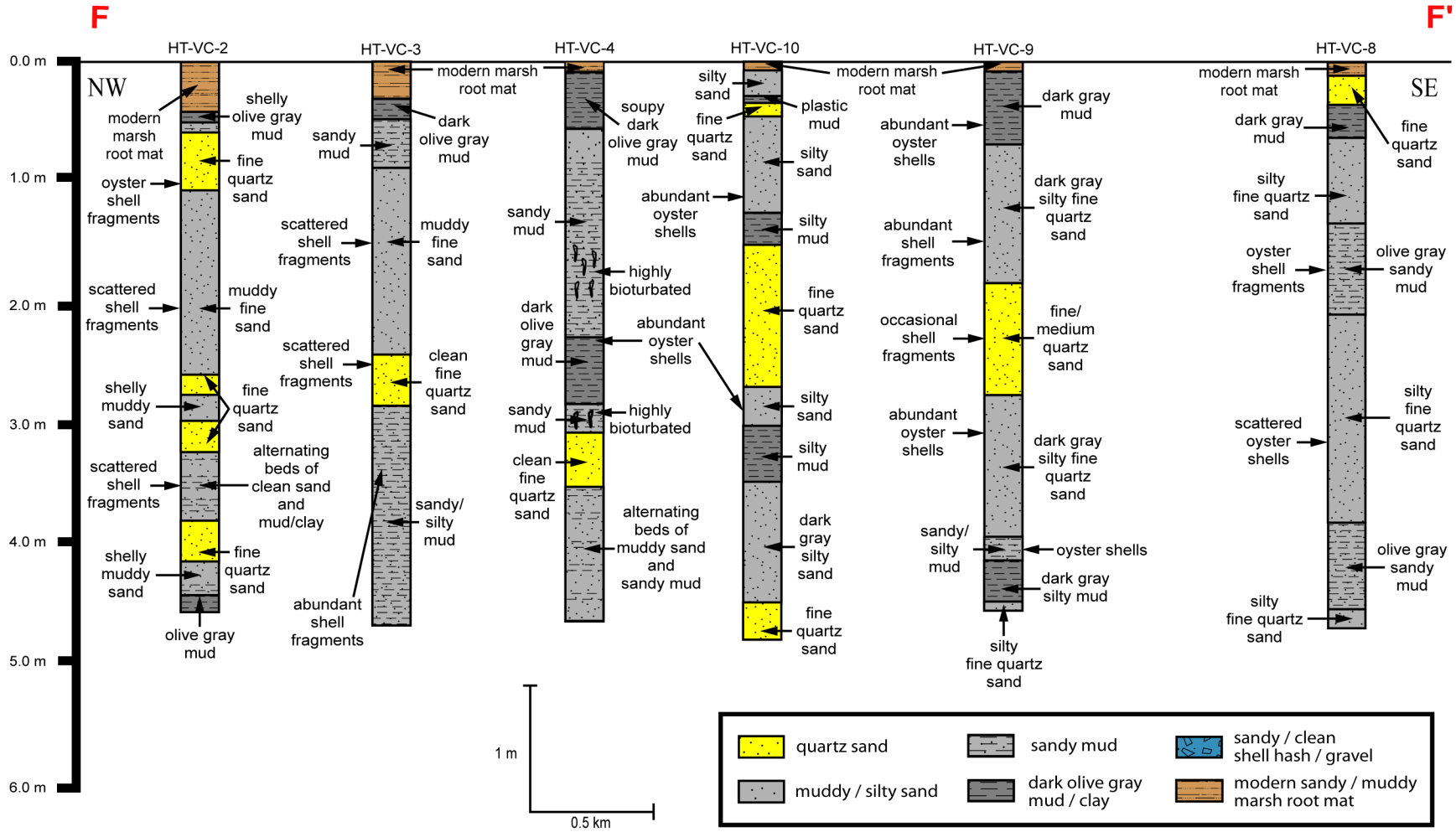


Figure 35. Back-barrier stratigraphic profile along shore parallel Transect F – F'.

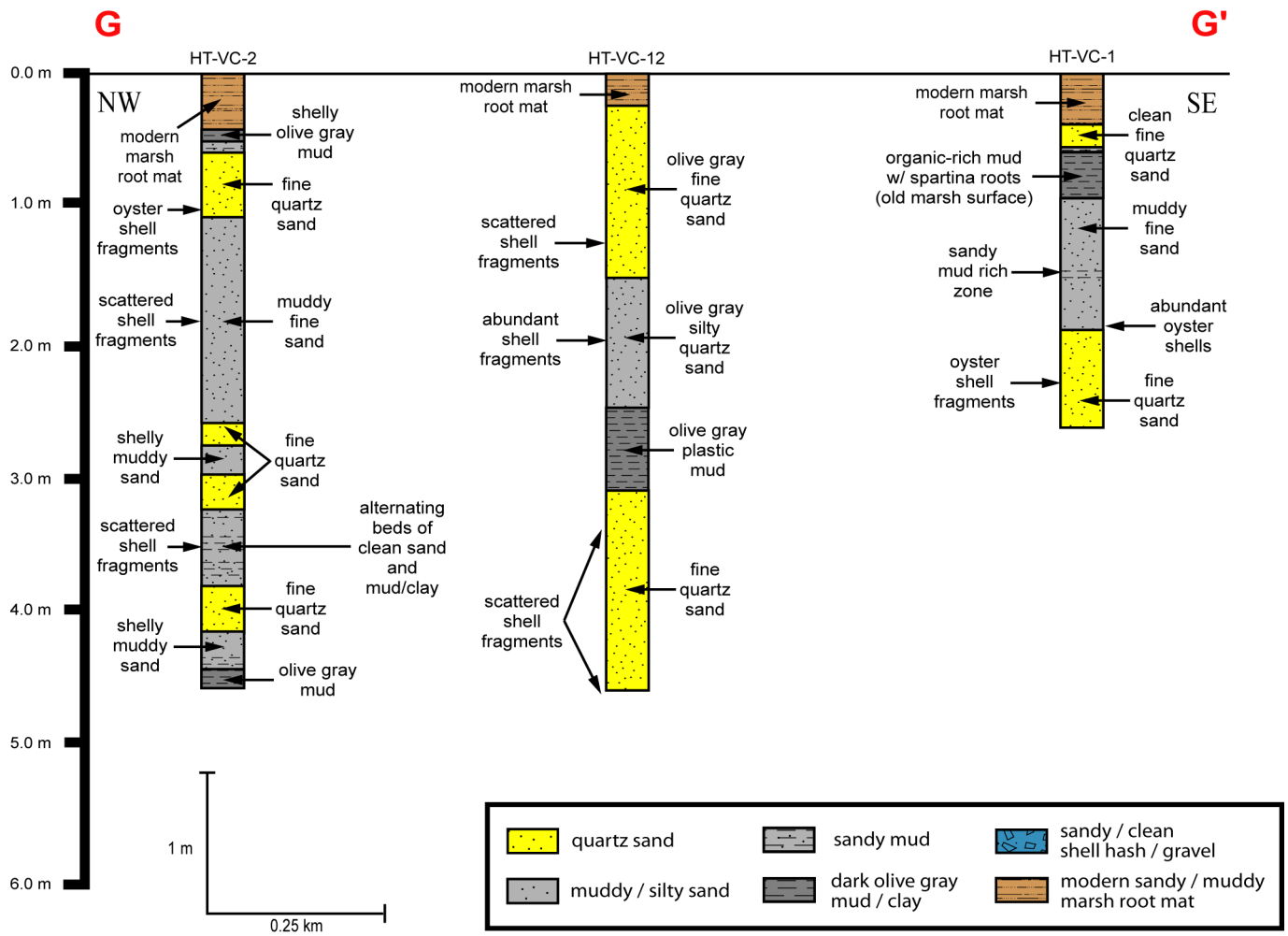


Figure 36. Back-barrier stratigraphic profile along shore normal Transect G – G'.

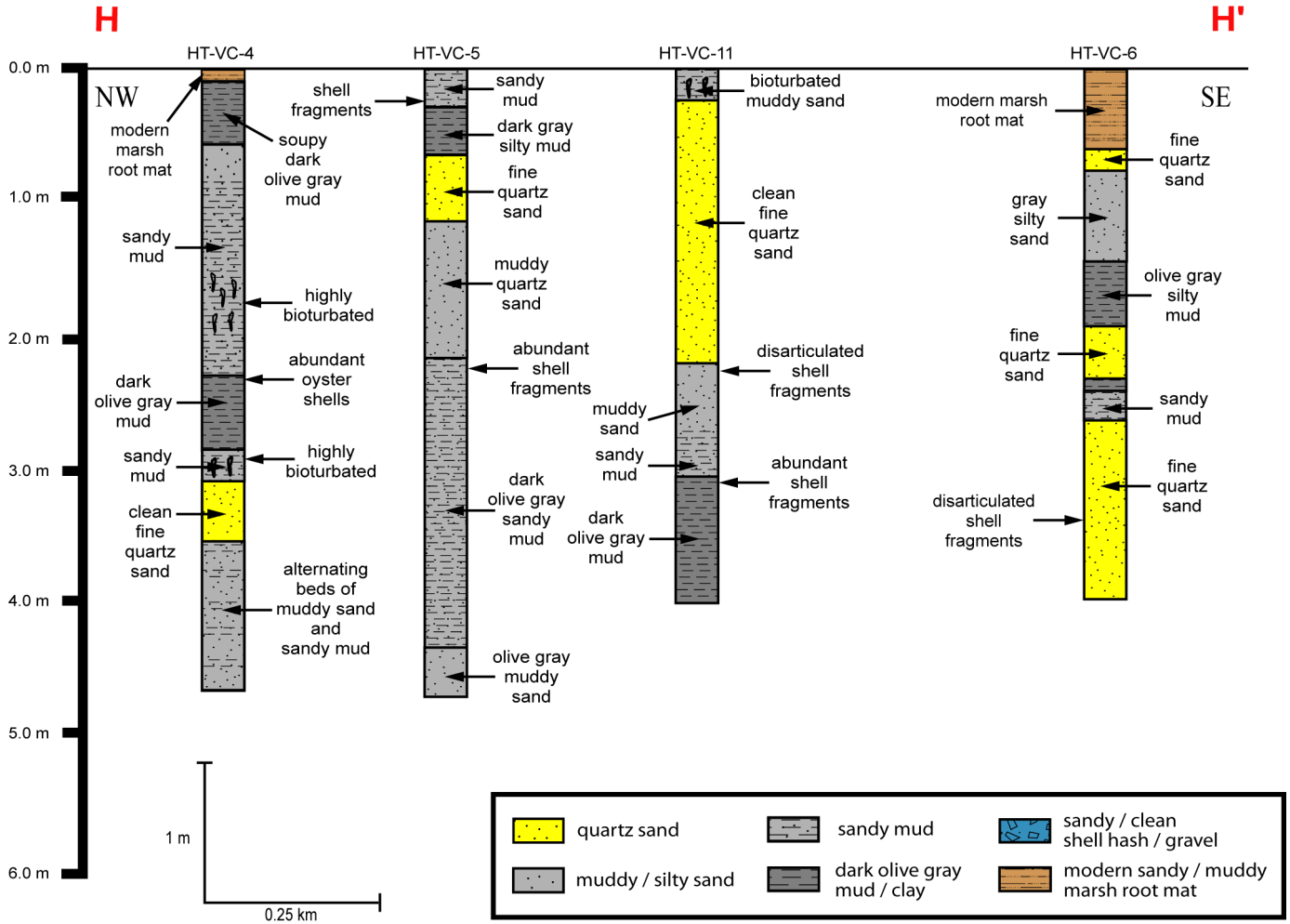


Figure 37. Back-barrier stratigraphic profile along shore normal Transect H – H'.

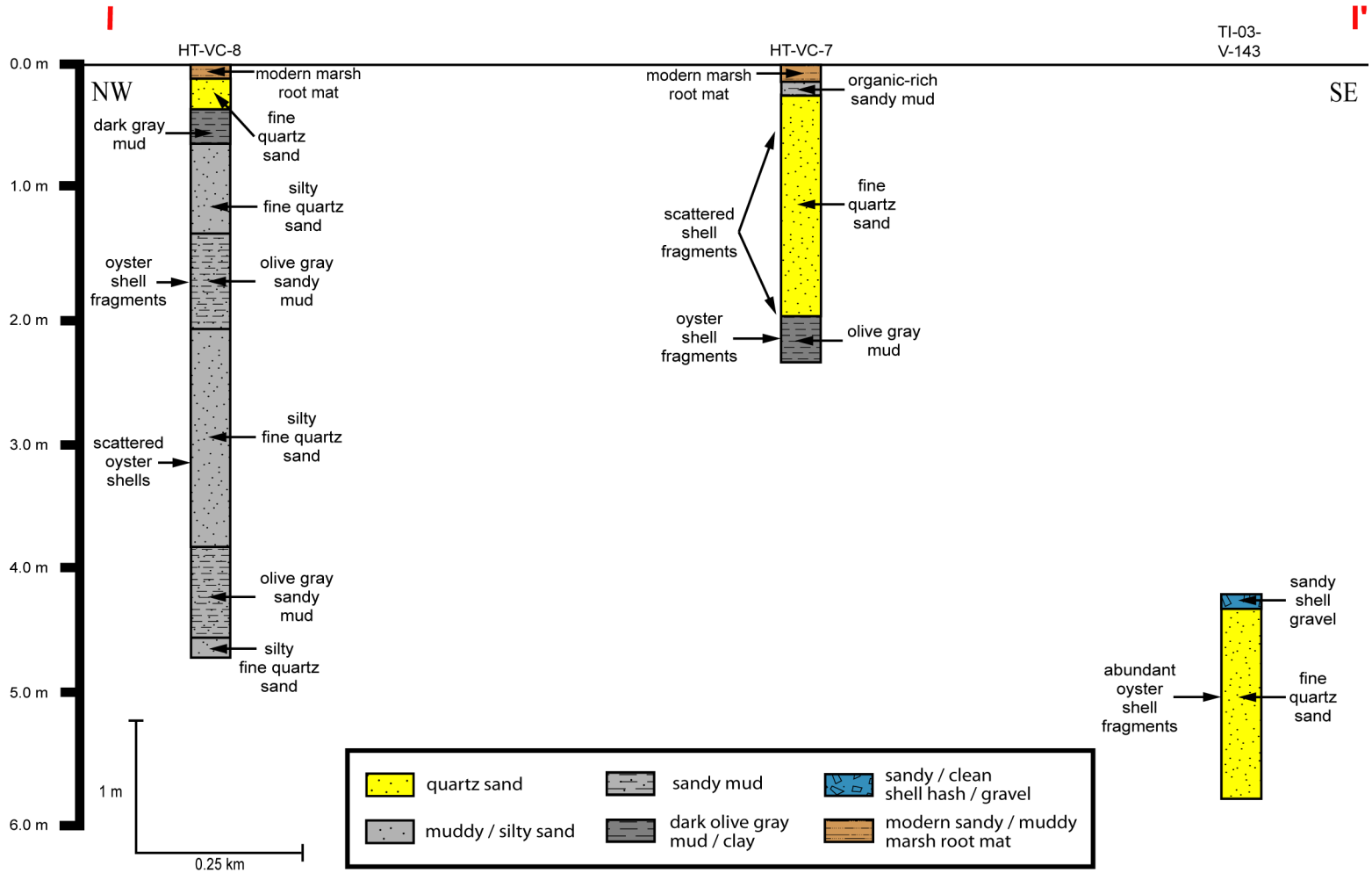


Figure 38. Back-barrier stratigraphic profile along shore normal Transect I – I'.

estuarine vibracores. Much of these sand-rich sediments contained mud snails and fragmented oyster shells, and were overlain by modern marsh muds, indicating the intertidal and shallow subtidal nature of Hutaff Island's back-barrier estuary. Identification of intertidal and shallow subtidal sediments in the estuarine vibracores indicated that tidal inlets have historically played an important role along Hutaff Island.

No evidence of the underlying stratigraphic units or any paleo-fluvial channels identified on the shoreface was observed in the estuarine vibracores. Consequently, no shoreface to back-barrier correlation can be made for any of these features using the existing vibracore data.

## DISCUSSION

Increased coastal development coupled with the impact of severe storm events and the subsequent erosion of many our barrier islands has created a need for studies of the processes taking place along natural barrier settings, devoid of human influence. Studies such as this not only further the scientific understanding of barrier islands, but can also be used in formulating management decisions on nearby barriers where it is often difficult to assess the true processes and changes taking place. This study of Hutaff Island was undertaken for this reason, as most of the barrier islands in southeastern North Carolina are densely developed or have been influenced by human activity.

### Influence of Storm Impacts

One of the primary factors controlling large-scale shoreline position, and morphologic and topographic changes on Hutaff Island is the impact of acute storm events. Throughout Hutaff Island's recent history, impacts by numerous storm events (Table 1) have led to the

increased flattening and landward translation of the barrier profile. As seen during the recent storm activity between 1996 and 1999 (Figure 4), the lowered relief of Hutaff Island will continue to lend itself to accelerated pulses of landward translation during impending high-energy storm events.

A detailed analysis from this study showed that severe storm events, such as Hurricane Fran (Figure 12), have greatly influenced the short and long-term shoreline changes along Hutaff Island. Shoreline accretion along the barrier generally occurred during periods free of major storm impacts. Severe erosion and washover resulted primarily from the impacts of a number of storm events (Table 1) that have made landfall or passed nearby.

Unfortunately, pre and post-storm aerial photographs were not available for most of the storm events (Table 1) that have impacted Hutaff Island during the 1938 to 2002 study period. One exception to this was Hurricane Fran (1996), a category three hurricane that ranks alongside Hurricane Hazel (1954) as one of the most severe storm events to impact Hutaff Island during the study period. As a result of Hurricane Fran, Hutaff Island experienced an average shoreline loss of 40 m (131 ft), measured from the August and September 1996 aerial photographs (Figure 12). SAULT *et al.* (1999) and DOUGHTY *et al.* (2004) identified similar shoreline losses resulting from Hurricane Fran, of 45 m (148 ft) and 33 m (108 ft) respectively, along a southern segment of Masonboro Island, though the latter study calculated its shoreline loss between January 1993 and September 1996. Masonboro Island is located 17.0 km (10.6 miles) to the southwest of Hutaff Island and is similarly undeveloped.

In addition to Hurricane Fran, the combined impacts of additional storm events investigated in this study, showed a pattern of increased shoreline loss and overwash susceptibility along the former Lea Island segment (Reach III) of Hutaff Island, particularly

along the northeast shoulder of Old Topsail Inlet (Figure 18). This shoreline segment experienced losses in excess of 50 m (164 ft) as a result of the combined impacts of Hurricanes Helene (1958) and Donna (1960), and the Ash Wednesday Storm (1962), whereas the average shoreline loss along the entire island during the same period was only 38 m (126 ft). Hurricane Fran (1996) caused extensive shoreline loss along the northeast shoulder of Old Topsail Inlet in excess of 60 m (197 ft), with a maximum loss of 74 m (242 ft), although the average shoreline loss for the entire island was only 40 m (131 ft). Even after Old Topsail Inlet's closure (1997-1998), shoreline losses of approximately 45 m (149 ft) occurred along this same shoreline segment as a result of the combined effects of Hurricanes Bonnie (1998), Dennis (1999), Floyd (1999), and Irene (1999). Post-storm aerial photographs from each of these storm periods and LIDAR data from 1996-2000, show that the Lea Island segment has experienced more overwash, flattening, and landward translation of the barrier profile in comparison with the remainder of Hutaff Island. This likely resulted from a combination of variables related to the influence of adjacent Old Topsail Inlet including the preferential downdrift accretion of Coke Island (Figure 16) and the low-lying topography left behind on the Lea Island shoulder following the southwesterly migration of the inlet.

Hurricane Hazel (1954), a category four hurricane at landfall, undoubtedly had a considerable impact on Hutaff Island. Although, because of its landfall over 95 km (59 miles) away, near the North Carolina – South Carolina border, its impact was likely more diminished than that of Hurricane Fran (1996). Unfortunately the time gap between pre and post-storm aerial photographs was too large to separate Hurricane Hazel's impact from the non-storm related shoreline changes that occurred between the 1945 and 1956 aerial photographs. However, it is known that regional storm surge levels reached and possibly exceeded 5.2 m (17.0

ft) above mean low water (DAVIS, 1954; and BARNES, 1995), that entire rows of beach homes disappeared, and that every pier along a 170-mile stretch of coastline adjacent to the storm's landfall was destroyed as a result of Hurricane Hazel (DAVIS, 1954). Wrightsville Beach, located 8.5 km (5.3 miles) to the southwest of Hutaff Island, lost two rows of homes as a result of Hazel's impact (CLEARY *pers. comm.*, 2004) and had endured estimated winds of 201 km/h (125 mph) (BARNES, 1995). Cursory inspection of aerial photographs from 1956, taken 16 months after Hazel, show the recent formation of extensive washover terraces and washover fans along Hutaff Island. Deductive reasoning indicated that the average measured shoreline change of -18.0 m (-59.1 ft) between 1945 and 1956, along with the formation of extensive washover terraces and fans, primarily resulted from the severe impact of Hurricane Hazel.

Investigations of Assateague Island, Maryland (LEATHERMAN, 1979; KOCHEL and DOLAN, 1986; and KOCHEL and WAMPFLER, 1989), the Isles Dernieres, Louisiana (NUMMEDAL *et al.*, 1984; and DINGLER and REISS, 1990), Nauset Spit, Massachusetts (LEATHERMAN and ZAREMBA, 1987), and the North Carolina Outer Banks (BIRKEMEIER *et al.*, 1984) are a few examples of studies that have similarly identified shoreline erosion and morphologic changes through overwash processes as mechanisms of barrier storm-response and long-term barrier evolution. Several of these studies also identified inlet and aeolian processes as additional controlling factors determining long-term barrier island evolution. While this study of Hutaff Island did not account for aeolian processes, it has shown that storm-induced shoreline change and overwash processes, and the influent processes of adjacent tidal inlets have played a principal role in the evolution of the barrier.

Influence of Adjacent Tidal Inlets

Historical aerial photographs have shown the presence of four tidal inlets that influenced Hutaff Island between 1938 and 2002 (Figure 13). Evidence from historical T-sheet coastal survey charts, estuarine vibracores, and the presence of marsh islands in the back-barrier estuary indicate that numerous tidal inlets have long affected Hutaff Island. These historical and contemporary inlets have influenced Hutaff Island through various processes including: changes in the morphology of the ebb-tidal delta, inlet migration, and the transfer and subsequent deposition of sediments into the back-barrier estuary.

A number of studies have previously shown that the morphology of an inlet's ebb-tidal delta, and the associated position and orientation of the ebb-channel have a considerable effect on the shoreline change patterns of the adjacent barrier islands (OERTEL, 1977; FITZGERALD *et al*., 1978; FITZGERALD and HAYES, 1980; and SEXTON and HAYES, 1982). This inlet to shoreline relationship is a result of a number of factors including: wave refraction around the ebb-tidal delta, ebb-tidal delta breaching events, and the breakwater effect of ebb-tidal deltas. Wave refraction around the perimeter of the ebb-tidal delta results in downdrift accretion through sediment reversal. Bar bypassing through ebb-tidal delta breaching events usually result in downdrift accretion through onshore migration of sediments preferentially accreted on the updrift ebb shoal segment prior to the breaching event. The breakwater effect of ebb-tidal deltas promotes downdrift accretion as the ebb-tidal delta complex acts as a natural breakwater for the downdrift shoulder. In each of these cases, preferential accretion may be switched to the opposite shoreline as a result of a reversal in seasonal wave conditions or a deflection of the ebb-channel and a reorientation of the ebb-delta complex.

The ebb-delta morphological characteristics and the dominant southwesterly orientations of the ebb-channels at Rich and Old Topsail Inlets throughout the study period should have theoretically encouraged preferential accretion on the downdrift shorelines based upon the three factors just discussed. Data shown in Figures 14 and 16 indicate that throughout most of the study period the dominant ebb-channel orientations at both Rich Inlet (135°–196°) and Old Topsail Inlet (139°–225°) did in fact result in accretion or a lesser degree of erosion to the downdrift shorelines. Updrift shorelines were directly exposed to incoming wave energy, particularly during storm events, and generally experienced shoreline losses or lesser degrees of accretion than the adjacent downdrift shorelines. Similar interactions between the morphological characteristics of the ebb-tidal delta and the erosional/depositional patterns of the adjacent shorelines were previously identified in studies along the Georgia coast (OERTEL, 1977) and at Price Inlet, South Carolina (FITZGERALD *et al.,* 1978; and FITZGERALD, 1984). These studies focused on inlets in a tide-dominated, mixed-energy barrier setting, whereas Hutaff Island is located in a wave-dominated to mixed-energy setting as described by HAYES (1979). Previous investigations local to Hutaff Island and southwestern Onslow Bay's wave-dominated to mixed-energy setting (BROOKS, 1988; CLEARY, 1996, JOHNSEN *et al.,* 1999; CLEARY, 2002; and JACKSON and CLEARY, 2003) have also shown ebb-delta complex to shoreline interactions corresponding to those identified in this study at Rich and Old Topsail Inlets.

Conversely, the dominant northeasterly orientations of New Topsail Inlet's ebb-channel favored accretion, or a lesser degree of erosion, on the updrift shoreline of Topsail Island throughout most of the study period (Figure 17). New Topsail Inlet's ebb-channel was oriented northeast of the 140° shore-normal orientation, between 73° and 136°, in ten of the thirteen aerial photographs used in this study. Data summarized in Figure 17, show an average shoreline loss

on Hutaff Island of 11 m (36 ft), and an average shoreline gain on Topsail Island of 33 m (108 ft) when the ebb-channel was oriented northeast of shore-normal. Using a greater number of historical aerial photographs, CLEARY (1994) determined that New Topsail Inlet had undergone a minium of six cycles of ebb-delta breaching, with varying cycle durations of 2-17 years, between 1938 and 1991. The subsequent erosional/depositional patterns identified in his study corresponded to those identified in this current study, in that Hutaff Island experienced shoreline loss and Topsail Island accreted during periods when the ebb-channel was oriented northeast of shore-normal. The detailed investigation by CLEARY (1994) also indicated that the orientation of the ebb-channel is not related to the dominant longshore drift direction, therefore accounting for the difference between the dominant ebb-channel orientation at New Topsail Inlet from those at Old Topsail and Rich Inlets.

In addition to the morphology of the ebb-delta complex, inlet-induced shoreline changes along Hutaff Island has also occurred as a result of inlet migrations and the subsequent plan-form changes to the barrier. CLEARY (1994) previously characterized the changing barrier plan-form in a study of the migration of New Topsail Inlet. The seaward bulge along the immediate shoulders of an inlet will migrate along with the inlet, accreting in the direction of migration and eroding the trailing shoreline as the bulge is repositioned. During the study period New Topsail Inlet, along the northeastern edge of Hutaff Island, and Old Topsail Inlet, along the northeastern one-third of the island, have migrated to the southwest 1.9 km (1.2 miles) and 1.2 km (0.75 miles) respectively. New Topsail Inlet had a migration rate, between 1938 and 2002, of 29.7 m/yr (97.4 ft/yr), whereas Old Topsail Inlet had migrated at 20.0 m/yr (65.6 ft/yr) between 1938 and its closure in 1997-1998. A previous investigation (CLEARY, 1994) found New Topsail

Inlet to have migrated 10.0 km (6.2 miles) since 1733, with a contemporary migration rate of 34 m/yr (112 ft/yr).

Old Topsail Inlet afforded a unique opportunity to investigate the changes in shoreline position and morphology as a result of its closure sometime between 1997 and 1998. Figure 39 depicts the migration and eventual closure of Old Topsail Inlet, and the influence on the shoreline since its closure. Previous investigations on the effects of a natural, unforced tidal inlet closure are practically non-existent. However, studies by SWAIN (1993), and RANASINGHE and PATTIARATCHI (1999) showed that a decrease in tidal prism is a primary factor in tidal inlet closures.

Throughout most of the study period the downdrift shoreline of Coke Island extended further offshore than the updrift shoreline of Lea Island, with a maximum offset of approximately 233 m (765 ft) in 1956. This offset was prompted by preferential downdrift accretion of the Coke Island shoreline as a result of the ebb-delta morphology and dominant ebb-channel orientation (139°–225°) at Old Topsail Inlet (Figure 16). Before Old Topsail Inlet's closure in 1997-1998, the inlet's shoulders were offset 120 m (394 ft). After the inlet's closure, the previous Lea Island shoreline quickly built seaward to a position in near equilibrium with the shoreline of the previous Coke Island shoreline. A slight offset still existed in the 2002 shoreline data, and full equilibrium of the shorelines may not be achieved, as the low relief (1.1 m average elevation) and the lack of any dune system on the previous Lea Island section will lend itself to accelerated landward translation during high-energy storm events (MCGINNIS and CLEARY, 2003), as seen during the impact of Hurricane Fran in 1996.

The recent southwest migrations of Old Topsail Inlet increased estuarine infilling and consequently promoted the development of tidal marsh in the estuary behind Hutaff Island

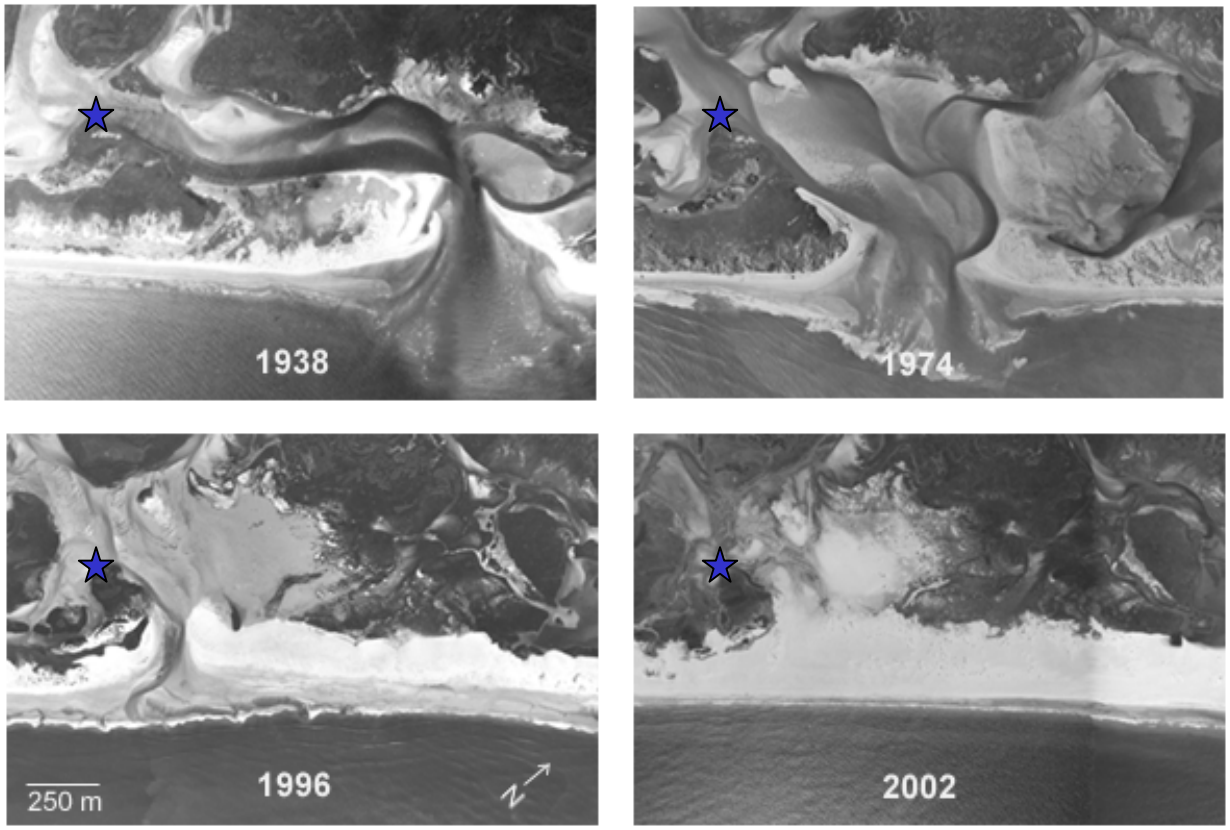


Figure 39. Aerial photographs depicting the migration and eventual closure of Old Topsail Inlet. Coke Island is visible in the photographs on the left, and Lea Island is visible on the right. The blue star represents the same geographic reference point in each photograph.

(GAMMILL, 1990). Similar infilling and marsh development was identified with the migration of New Inlet, North Carolina by SWAIN (1993), and was found to have significantly decreased the tidal prism of the inlet over time leading up to its closure. As infilling and marsh development increased, a reduction in the size of the back-barrier tidal waters would have decreased the tidal prism at Old Topsail Inlet. A severe reduction in tidal prism would have initiated the decreased southwest migration and constriction of the inlet throat as seen following the 1974 aerial photograph (Figure 39). While this study did not attempt to quantify the change in tidal prism at Old Topsail Inlet, evidence of increased marsh development (GAMMILL, 1990), the reduction in size of the ebb-delta complex, and the clogging of the interior flood channels, identified through cursory inspections of historical aerial photographs, indicates that a historically decreasing tidal prism at Old Topsail Inlet eventually lead to the inlet's closure.

Increased marsh development, identified by GAMMILL (1990), was a result of increased estuarine infilling from a migrating inlet and the consequent expansion of the flood-tidal delta in the estuary of Hutaff Island. As Old Topsail Inlet migrated to the southwest, it deposited flood-tidal delta sediments, over which the modern marsh had colonized GAMMILL (1990). Historical charts and aerial photographs have shown that Hutaff Island has been bordered or partitioned by at least five tidal inlets since 1857, each of which would have served as conduits for transporting sediment from the barrier shoreline and shoreface into the narrow and shallow estuary. A suite of 13 vibracores was collected to determine the nature of these estuarine sediments and the relative amount of intertidal sediments introduced into the estuary through tidal inlets.

Megascopic examination of the estuarine vibracores (Figures 35-38) identified three varied sediment types from the recovered sediments. Muddy, fine-medium quartz sand to sandy

mud, with abundant whole and fragmented oyster shells and mud snails, was prevalent throughout the estuarine vibracores and comprised 48.8% of the recovered sediment sequences. Clean, fine-quartz sand was recovered in 31.9% of the estuarine vibracore sediment sequences, and a dark olive gray, silt-rich mud with varied amounts of whole and disarticulated oyster shells comprised 14.6% of the total recovered sediment sequences. Sand-rich sediments including the clean, fine-quartz sand, and the muddy, fine-to-medium quartz sand, comprised approximately 62.6% of the total sediments recovered from the estuarine vibracores. Much of these sand-rich sediments contained mud snails and fragmented oyster shells, and were overlain by modern marsh muds, indicating the intertidal nature of Hutaff Island's estuary. Identification of intertidal sediments in the estuarine vibracores indicated that tidal inlets have historically played an important role along Hutaff Island.

Deposition of flood delta sediments in the estuary permitted the formation of marsh islands, providing further supporting evidence of historical inlet locations. Marsh island formation occurs landward of an inlet's flood-tidal delta, when sands from the delta overtop the marsh and form a low-relief island on top of the modern tidal marsh (CLEARY and HOSIER, 1979; and CLEARY *et al.*, 1979). At least two of these linear marsh island features, representing historic tidal inlets that no longer exist, are visible in the 1938 to 2002 aerial photographs of Hutaff Island (Figure 40). The large marsh island to the southwest represents the historic location of Sidbury Inlet. A smaller marsh island is located 1.1 km (0.7 miles) northeast of the Sidbury Inlet marsh island. This second marsh island indicates the presence of an inlet not previously identified in historical T-sheet maps and aerial photographs used in this study. It would be fair to say that additional historical inlets likely existed along the shoreline of Hutaff

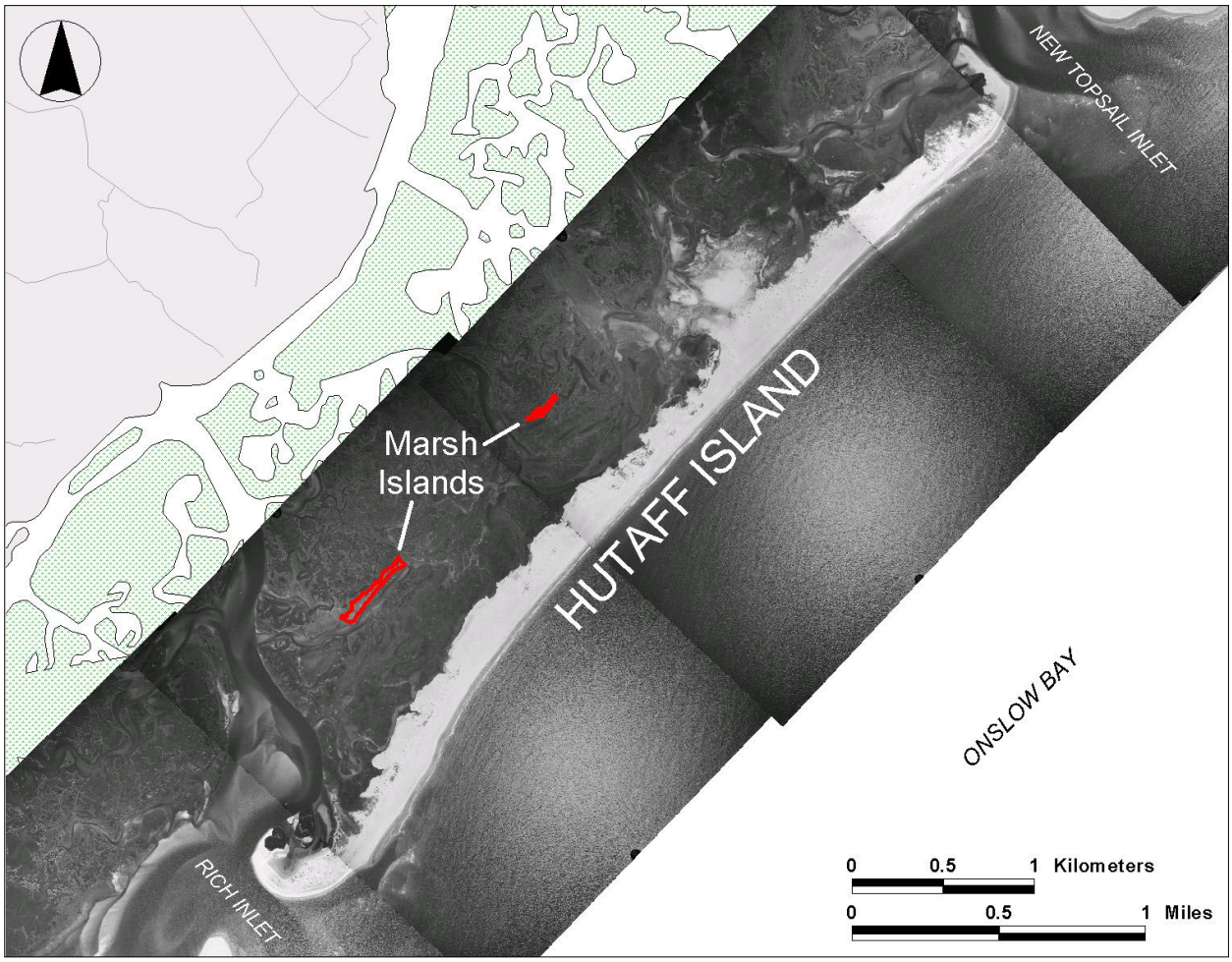


Figure 40. Map illustrating the location of back-barrier marsh islands formed by historic tidal inlets that no longer exist along the island.

Island, although further investigation would be required to determine the quantity and locality of historic tidal inlets.

Data derived from this study show that between 1938 and 2002, variations in inlet positions at Rich and Sidbury Inlets, and the migration of Old Topsail Inlet suggested that at least 35% of Hutaff Island, in 2002, would have been underlain by inlet fill. Identification of linear marsh island features in the back-barrier estuary and inspections of T-sheet survey maps from 1857, 1880, and 1927 reveal further evidence to suggest that the entire Hutaff Island shoreline in 2002, was underlain by inlet fill. This deduction is based upon the mapped migrations of Old Topsail Inlet, Old Inlet, and New Topsail Inlet, the presence of at least two marsh islands formed at previous inlet locations, and the presence of a large, shore-parallel channel (Banks Channel) that ran along the entire landward side of Hutaff Island. The presence of Banks Channel is significant because it likely served as the feeder channel for recurring southwesterly inlet migrations. Additionally, there is no visual or documented indication of peat outcrops on the beach, providing further support of extensive historical inlet migrations that deposited the underlying inlet fill.

Morphologic and Topographic Changes

The impact of severe storm events and the influence of adjacent tidal inlets have not only altered Hutaff Island's shoreline, but have also had an effect on the morphological characteristics and topography of the barrier. Results from this study indicated that the changes in morphology and topography occur in a cyclical manner with respect to the impact of storm events. These severe impacts typically result in overwash processes breaching the narrow foredunes, relocating foreshore and dune sediments into washover fan and terrace deposits, and subsequently lowering

the barrier's topographic relief. Recent work by MORTON and SALLENGER (2003) identified similar changes along a number of barriers on the United States Atlantic and Gulf Coasts, and had characterized the various morphological responses observed in aerial photographs following severe storm events. Their study along with previous work by RITCHIE and PENLAND (1990), and MORTON and PAINE (1985) showed that similar patterns of washover penetration, regardless of storm intensity, were observed along barrier islands in southcentral Louisiana and along Galveston Island, Texas. From these observations, MORTON and SALLENGER (2003) suggested that some shoreline segments are preconditioned to overwash processes and will exhibit similar morphologic responses and overwash penetration regardless of storm characteristics.

Cursory inspections of post-storm aerial photographs of Hutaff Island appear to correspond with the observations of MORTON and SALLENGER (2003). This is especially true along the low-lying Lea Island segment (Reach III in Figure 18) of the barrier, where washover terraces deposits resulting from the Ash Wednesday Storm (1962), Hurricane Bertha (1996), and Hurricane Fran (1996) exhibited similar washover penetrations ranging from approximately 80-135 m (263-443 ft) despite the diverse intensities and circumstances of each storm's impact.

Using aerial photographs from 1938, 1993, 1996, and 2002, the changes in the morphologic characteristics were determined for Hutaff Island. Long-term morphologic changes between 1938 and 1993 showed a 52 percent increase in the length of the barrier characterized by scarped dunes, and a decrease in the length characterized by washover fans and washover terraces of 68 and 60 percent, respectively. Short-term, storm-induced morphologic changes between 1993 and 1996, resulting from Hurricane Fran (1996), showed an increase of over 13

times the extent of washover terraces along the barrier. During the same period, decreases of 68 and 93 percent in the extent of washover fans and single scarped dune ridges, respectively, was observed along Hutaff Island. With an increase of over thirteen times the extent of washover terraces, resulting from the impact of Hurricane Fran, the influence of severe storm events on the morphology of Hutaff Island is clearly evident.

Hutaff Island's redevelopment of the single foredune ridge shown in the long-term analysis (1938-1993) was followed by development of extensive washover terraces and washover fans during the recent (1996-1999) storm activity. This is in contrast to observations along nearby Masonboro Island, North Carolina by CLEARY *et al.* (1999) and SAULT *et al.* (1999), in which shoreline and dune recovery was determined to have been minimal to non-existent, especially along the southern one-third of the barrier that has exhibited a similar landward translation to that observed along the low-lying Lea Island segment (Reach III in Figure 18) of Hutaff Island. At least 31 storms had passed within 100 km (62 miles) of Hutaff Island during the period between 1938 and 1993, several of which had severe impacts on the southeastern North Carolina coast. The long-term development of a dune system in the presence of these storm events indicates a cyclical pattern to the morphologic changes of Hutaff Island.

A lowering of the topographic barrier profile accompanied the morphologic changes that occurred in response to the impact of severe storm events. Topographic data obtained from LIDAR datasets (1996-2000) indicated that a net decrease in elevation occurred within each of the four reaches that extend the length of Hutaff Island (Figure 19). The average elevation above sea-level (NAD83) for the entire island was reduced from 1.2 m (3.8 ft) in 1996 to 0.9 m (3.0 ft) in 2000. However, the average dune (maximum) elevation along the entire island increased from 2.2 m (7.2 ft) in 1996 to 2.4 m (7.9 ft) in 2000, with an overall average dune elevation of 2.3 m

(7.5 ft) throughout the 1996-2000 period. The increased average dune elevation during this period likely resulted from the cyclical post-storm recovery, associated with the impact of Hurricane Fran (1996), identified in the morphologic change analysis of this study. This information coupled with the results of the shoreline change analysis and the identified morphologic changes indicated that a lowering of the barrier profile has accompanied and encouraged the landward translation of the barrier.

Adjacent tidal inlets have also served as mechanisms for controlling morphologic and topographic changes along Hutaff Island. In the case of Hutaff Island, the stability and ebb-tidal delta morphology of Rich Inlet appears to have protected the adjacent Hutaff shoreline (Reach I) from extreme morphologic and topographic change, as both appear to have remained relatively consistent throughout the study period. Conversely, the southwesterly migration of Old Topsail Inlet produced a low relief barrier segment (Reach III), and was therefore highly susceptible to overwash and landward translation during severe storm events. Throughout the 1938-2002 study period, Reach III was characterized by extensive washover terraces and had an average elevation of 1.1 m (3.6 ft). The lack of a dune system on this barrier segment lent itself to an accelerated landward translation as a result of the recent impact of Hurricane Fran in 1996 (MCGINNIS and CLEARY, 2003).

Shoreface Geology

Compounded upon the impact of severe storm events and the influence of adjacent tidal inlets, Hutaff Island suffers from the lack of an abundant supply of beach quality sand offshore. The low sediment supply common to Onslow Bay is the result of low fluvial input and a lack of sediment exchange with nearby Long and Raleigh Bays (CLEARY and PILKEY, 1968;

CLEARY and THAYER, 1973; and RIGGS *et al.*, 1995). The thin and variable shoreface sediment cover (Figure 34) provides little natural nourishment to the Hutaff Island shoreline. Flat-lying hardbottoms are commonplace across the shoreface (Figure 31), and thicker accumulations of sediment (>100 cm) are generally found seaward of the -9.1 m (-30 ft) contour (Figure 34), or are associated with mud-filled paleo-fluvial channels (Figure 32) that are incised into the underlying Oligocene stratigraphic units.

The dominant subcrop unit on the Hutaff Island shoreface is an Oligocene quartz-rich, dolo-siltstone/sandstone, but a small area off of the southern end of Topsail Island is underlain by an Oligocene moldic limestone unit (Figure 30). These underlying stratigraphic units were encountered at 62% of the vibracore and diver survey sites, and were observed as hardbottoms at 21 of the 161 combined shoreface sites (Figure 31). Reworking of the Oligocene siltstone hardbottoms through bio-erosion and wave quarrying supplement a considerable volume of fine-grained sand/silt to the shoreface sediments (THIELER *et al.*, 1995; and MARCY, 1997). Conversely, the Oligocene limestone hardbottoms provide little to no supply of sediment to the Hutaff Island shoreface.

Quaternary paleo-fluvial channel features were found across the Hutaff Island shoreface, incised into the underlying Oligocene subcrop units (Figure 32). These 3.0–4.0-m thick, mud-filled features represent former tidal creek channels from a period in time when sea-level was lower and the barrier shoreline was located further offshore, and were identified from retrieved vibracore sediments at 19 sites offshore. Previous studies by THIELER *et. al.* (1995), MCQUARRIE (1998), CLEARY (2002), and HDR (2002) identified similar paleo-fluvial features offshore neighboring barriers. MCQUARRIE (1998) had also previously identified 64 paleo-fluvial channel sites (Figure 32) on the Hutaff Island shoreface through seismic data

interpretation. While these paleo-fluvial channels represent a substantial portion of the thicker accumulations (>100 cm) of shoreface sediments (Figure 34), they provide no supply of sand for natural nourishment of the Hutaff Island shoreline.

Vibracore and diver survey data indicate that the overlying shoreface sediment sequences are variably thin and consist of units of shelly, fine-to-medium quartz sand intercalated with sandy and muddy shell hash/gravel units (Figures 25-29). Much of the shelly, fine-to-medium quartz sand that dominates the Hutaff Island shoreface is comprised of components derived from the periodic exposure and erosion of the underlying Oligocene dolo-siltstone unit (MARCY, 1997). The high shell and silt content of the shoreface surface sediments likely inhibit any natural nourishment of Hutaff Island, because of an incompatibility with the coarser, relatively clean, quartz sand found on the active beach.

Holocene sediment thickness ranged from zero at hardbottom locations to 6.2 m (20.3 ft) (Figure 34). An average sediment thickness of 1.0 m (3.3 ft) was determined from the 161 combined vibracore and diver survey sites. Shore-parallel and shore-normal vibracore transects (Figures 25-29) show that clean to muddy fine-quartz sand units with varying amounts of finely fragmented shell material constitute a key portion of the modern shoreface sediments. Shoreface sediments consisting primarily of sand are generally less than 1.0 m (3.3 ft) thick and have an average thickness of 0.7 m (2.2 ft). Sixty-five percent of the modern shoreface sediment thickness was found to range from 31–100 cm (1.0-3.3 ft). Sediment thickness of 100 cm (3.3 ft) or less encompassed 80 percent of the total shoreface area shown in Figure 34, illustrating the relatively thin nature of the modern shoreface sediments. The incompatibility and minimal supply of sediments offshore Hutaff Island restricts the available sediment for post-storm

recovery and has likely contributed to the landward translation of the barrier throughout the study period.

## Conceptual Model

Using the combined results of this study, a simple conceptual model (Figure 41) depicting the evolution of retrograding barriers in a sediment starved, storm-influenced environment was produced. The model takes into relation long-term shoreline changes, the migration and closure of tidal inlets, estuarine infilling and subsequent salt marsh development as described by GAMMILL (1990), and short-term topographic changes across the barrier profile.

Landward translation of the shoreline, and the shortening of the barrier segments as the result of inlet migrations are the two most important changes depicted in the model. Increased estuarine infilling and the subsequent back-barrier marsh development leads to a decrease in tidal prism, initially increasing the inlet migration rate before a severe reduction in tidal prism slows the inlet migration, and eventually causes the closure of the inlet. The protuberance, or "bump" in the shoreline adjacent to a closing inlet will decrease in size, and eventually equilibrate with the adjacent shoreline after the inlet's closure. Short-term topographic changes, as the result of severe storm events, cause the barrier profile to flatten and translate landward. A period of post-storm recovery of the profile shows a slight increase in elevation and seaward translation before a subsequent storm event further flattens and translates the profile landward.

The post-storm recovery of Hutaff Island contrasts to observations of Masonboro Island, located 17.0 km (10.6 miles) to the southwest, were little to no recovery of the barrier takes place following the impact of severe storm events (CLEARY *et al.*, 1999; SAULT *et. al.*, 1999; and

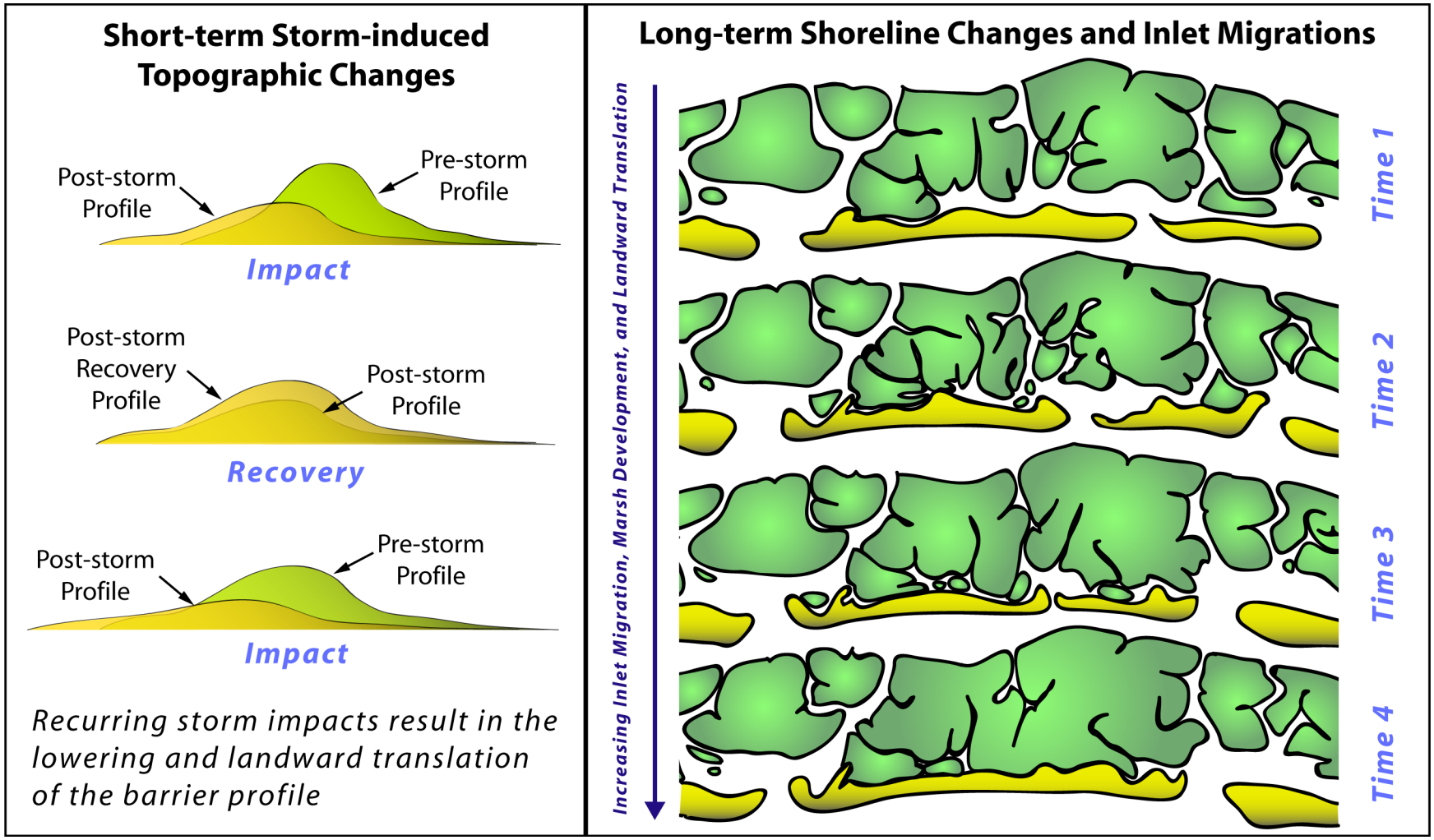


Figure 41. Conceptual model depicting the evolution of a retrograding barrier in a sediment starved, storm-influenced environment.

DOUGHTY *et al.*, 2004). While both Hutaff and Masonboro Islands are undeveloped barriers located within relative proximity to one another, several dissimilar characteristics in the geologic framework and influence of humans can likely explain the contrasting observations. Observations by CLEARY *et al.* (1999) indicate that the shoreface sediment supply offshore Masonboro Island is generally less than that determined for Hutaff Island's shoreface in this study. Masonboro Island's limited shoreface sediment supply, coupled with the anthropogenic affects of the artificially stabilized tidal inlets that border the island, have likely choked the barrier from sand sources needed for post-storm recovery.

## CONCLUSIONS

Hutaff Island underwent extensive changes between 1938 and 2002. Contributions to the barrier's evolution can be attributed to a combination of variables including the thin and variable shoreface sediment supply, the impact of severe storm events, low barrier relief, estuarine infilling and subsequent salt marsh development, and the contrasting behavior of adjacent tidal inlets. The impact of storm events and the migration of Old Topsail and New Topsail Inlets are the primary factors controlling large-scale shoreline changes and barrier evolution of Hutaff Island.

The most striking change observed along Hutaff Island during the 1938-2002 study period was the result of the southwest migration of Old Topsail and New Topsail Inlets and the eventual closure of Old Topsail Inlet sometime between 1997 and 1998. The Coke and Lea Island barrier segments were considerably shortened as a result of the inlet migrations. Increased estuarine infilling and marsh development resulting from inlet migration and the subsequent reduction in tidal prism ultimately lead to a decreased inlet migration, constriction of the inlet

throat, and eventual closure of Old Topsail Inlet. Data showed that after the inlet's closure, the offset inlet shoulders began to line up with one another, and the Lea Island segment began to develop dunes in an area once flattened by severe overwash.

The regions low sediment supply and the thin and variable shoreface sediment cover has undoubtedly contributed to a lack of natural post-storm nourishment for Hutaff Island. The high shell and silt contents of much of the shoreface sediments would make for poor quality beach material; exacerbating the sediment supply problems. Several thick accumulations of mud-filled paleo-fluvial channels were identified on the shoreface in this study, though their sediments would likely provide no supply of sand to the barrier.

Short-term changes in shoreline position and topography as a result of storm events showed a lowering and landward translation of the barrier's profile. The low relief of the barrier will lend itself to accelerated pulses of landward translation during high-energy storm events, as observed during the recent storm activity (1996-1999). With nearly all of the barrier islands in southeastern North Carolina having been developed or influenced by human activity, it is hoped that this study can be used as a model to show the natural, unmitigated barrier evolution processes taking place on our coast. Understanding the processes influencing barrier island evolution within this region can also be used in formulating management decisions on nearby barriers where it is often difficult to assess the active processes and changes taking place.

## LITERATURE CITED


BARNES, J., 1995. *North Carolina's Hurricane History.* Chapel Hill, North Carolina: The University of North Carolina Press, 304p.

BENTON, S.B., BELLIS, C.J., OVERTON, M.F., FISHER, J.S., and HENCH, J.L., 1992. *Long term average annual erosion rates of shoreline change: methods report 1992 update*. Raleigh, N.C.: North Carolina Dept. of Environmental Health and Natural Resources, Div. of Coastal Management, 16p.

BIRKEMEIER, W., DOLAN, R., and FISHER, N., 1984. The evolution of a barrier island: 1930-1980. *Shore and Beach*, 52(2), 3-12.

BROOKS, W.B., 1988. A historic and morphologic study of Mason and Rich Inlets, North Carolina. Wilmington, North Carolina: Dept. of Earth Sciences, University of North Carolina at Wilmington, Master's thesis, 87p.

CLEARY, W.J. and PILKEY, O.H., 1968. Sedimentation in Onslow Bay. In: *Guidebook for field excursion, Geological Society of America, Southeastern Section*, Durham, N.C.: *Southeastern Geology, Special Publication*, 1, pp. 1-17.

CLEARY, W.J. and THAYER, P.A., 1973. Petrography of carbonate sands on the Carolina continental shelf. *Gulf Coast Association Geological Society Transactions*, 23, 288-304.

CLEARY, W.J. and HOSIER, P.E., 1979. Geomorphology, washover history, and inlet zonation: Cape Lookout, North Carolina to Bird Island, North Carolina. *In:* Leatherman, S.P., (ed.), *Barrier Islands from the Gulf of St. Lawrence to the Gulf of Mexico*, Academic Press, New York, pp. 232-237.

CLEARY, W.J., HOSIER, P.E., and WELLS, G.R., 1979. Genesis and significance of marsh islands within southeastern North Carolina lagoons. *Journal of Sedimentary Petrology*, 49(3), 703-709.

CLEARY, W.J., 1994. New Topsail Inlet, North Carolina migration and barrier realignment: consequences for beach restoration and erosion control projects. *Union Geographique Internationale, Commission Sur de l'Environment Cotier C, Institue de Geographique*, pp. 116-130.

CLEARY, W.J., 1996. Inlet induced shoreline changes: Cape Lookout to Cape Fear. *In:* Cleary, W.J., (ed.), *Environmental Coastal Geology: Cape Lookout to Cape Fear, N.C.*, Carolina Geological Society Field Guidebook, pp. 49-59.

CLEARY, W.J. and PILKEY, O.H., 1996. Environmental coastal geology: Cape Lookout to Cape Fear, N.C., regional overview. *In:* Cleary, W.J., (ed.), *Environmental Coastal Geology: Cape Lookout to Cape Fear, N.C.*, Carolina Geological Society Field Guidebook, pp. 89-138.

CLEARY, W.J., JOHNSEN, C.D., JOHNSTON, M.K., and SAULT, M., 1999. Storm impacts and shoreline recovery in southeastern NC: role of the geologic framework. *Coastal Sediments 1999* (Long Island, NY), 3, 1798-1813.

CLEARY, W.J., 2002. Variations in inlet behavior and shoreface sand resources: factors controlling management decisions, Figure Eight Island, NC, USA. *Journal of Coastal Research Special Issue 36*, (ICS 2002 Northern Ireland), 148-163.

CROWELL, M., LEATHERMAN, S.P., and BUCKLEY, M.K., 1991. Historical Shoreline Change: Error Analysis and Mapping Accuracy. *Journal of Coastal Research*, 7(3), 839-852.

DAVIS, W.R., 1954. Hurricanes of 1954. *Monthly Weather Review*, 82(12), 370-373.

DINGLER, J.R. and REISS, T.E., 1990. Cold-front driven storm erosion and overwash in the central part of the Isles Dernieres, a Louisiana barrier island arc. *Marine Geology*, 91, 195-206.

DOLAN, R., 1973. Barrier islands: natural and controlled. *In:* Coates, D.R., (ed.), *Coastal Geomorphology, Proceedings from the Third Annual Geomorphology Symposia Series* (Binghamton, New York), pp. 263-278.

DOLAN, R., FENSTER, M.S., and HOLME, S.J., 1991. Temporal Analysis of Shoreline Recession and Accretion. *Journal of Coastal Research*, 7(3), 723-744.

DOUGHTY, S.D., CLEARY, W.J., and MCGINNIS, B.A., 2004. The recent evolution of storm-influenced retrograding barriers in southeastern North Carolina, USA. *Journal of Coastal Research Special Issue 39* (ICS 2004 Brazil), (in press).

FITZGERALD, D.M., HUBBARD, D.K., and NUMMEDAL, D., 1978. Shoreline changes associated with tidal inlets along the South Carolina coast. *Coastal Zone '78* (San Francisco, California), pp. 1973-1994.

FITZGERALD, D.M. and HAYES, M.O., 1980. Tidal inlet effects on barrier island management. *Coastal Zone '80* (Hollywood, Florida), pp. 2355-2379.

FITZGERALD, D.M., 1984. Interactions between the ebb-tidal delta and the landward shoreline: Price Inlet, South Carolina. *Journal of Sedimentary Petrology*, 54, 1303-1328.

GAMMILL, S.P., 1990. Coastal saltmarsh development at southern Topsail Sound, North Carolina. Wilmington, North Carolina: Dept. of Biological Sciences, University of North Carolina at Wilmington, Master's thesis, 51p.

HAYES, M.O., 1979. Barrier island morphology as a function of tidal and wave regime, *In:* Leatherman, S.P., (ed.), *Barrier Islands, from the Gulf of St. Lawrence to the Gulf of Mexico*, Academic Press, New York, pp. 1-27.

HDR Engineering, 2002. An assessment of the availability of beachfill quality sand offshore Topsail Beach, Pender County, North Carolina. *U.S. Army Corps of Engineers Report 11049-012-018*, 22p. and figures.

HUNT, E.L., 1979. The modern sediments of Topsail Sound, North Carolina. Chapel Hill, North Carolina: Dept. of Geology, University of North Carolina at Chapel Hill, Master's thesis, 47p.

JACKSON, C.W. and CLEARY, W.J., 2003. Oceanfront changes associated with channel repositioning in a stable system: Rich Inlet, NC, USA. *Proceedings of the International Conference on Coastal Sediments 2003* (Clearwater Beach, FL), CD-ROM.

JOHNSEN, C.D., CLEARY, W.J., FREEMAN, W.C., and SAULT, M., 1999. Inlet induced shoreline changes on the high energy flank of the Cape Fear Foreland, NC. *Coastal Sediments 1999* (Long Island, NY), 2, 1402-1418.

JOHNSON, M.K., 1998. The inherited geologic framework of the New River submarine headland complex, North Carolina, and its influence on modern sedimentation. Wilmington, North Carolina: Dept. of Earth Sciences, University of North Carolina at Wilmington, Master's thesis, 123p.

KOCHEL, R.C. and DOLAN, R., 1986. The role of overwash on a mid-Atlantic coast barrier island. *Journal of Geology*, 94, 902-906.

KOCHEL, R.C. and WAMPFLER, L.A., 1989. Relative role of overwash and aeolian processes on washover fans, Assateague Island, Virginia-Maryland. *Journal of Coastal Research*, 5(3), 453-475.

LEATHERMAN, S.P., 1979. Migration of Assateague Island, Maryland, by inlet and overwash processes. *Geology*, 7, 104-107.

LEATHERMAN, S.P. and ZAREMBA, R.E., 1987. Overwash and aeolian processes on a U.S. northeast coast barrier. *Sedimentary Geology*, 52, 183-206.

MARCY, D.C., 1997. Influence of inherited geologic framework upon a hardbottom dominated shoreface: Fort Fisher subaerial headland, Onslow Bay, North Carolina. Wilmington, North Carolina: Dept. of Earth Sciences, University of North Carolina at Wilmington, Master's thesis, 83p.

MCGINNIS, B.A. and CLEARY, W.J., 2003. Late Holocene stratigraphy and evolution of a retrograding barrier: Hutaff Island, North Carolina. *Proceedings of the International Conference on Coastal Sediments 2003* (Clearwater Beach, FL), CD-ROM.

MCQUARRIE, M.E., 1998. Geologic framework and short-term, storm-induced changes in shoreface morphology: Topsail Beach, N.C. Durham, North Carolina: Dept. of the Environment, Duke University, Master's thesis, 105p.

MEREDITH, A.W., BROCK, J.C., SALLENGER, A.H., KRABILL, W.B., SWIFT, R.N., HEARNE, M.G., LIST, J., HOLMAN, R.A., HANSEN, M., REISS, T., MORGAN, K.L.M., WRIGHT, C.W., FREDRICK, E.B., MANIZADE, S.S.,YUNGEL, J.K., MARTIN, C.F., and SONTAG, J.G., 1998. An assessment of NASA's Airborne Topographic Mapper instrument for beach topographic mapping at Duck, North Carolina. National Oceanic and Atmospheric Administration, Coastal Services Center Technical Report, *NOAA/CSC/9-98/001*, 87p.

MEREDITH, A.W., ESLINGER, D., and AURIN, D., 1999. An evaluation of hurricane-induced erosion along the North Carolina coast using airborne LIDAR surveys. National Oceanic and Atmospheric Administration, Coastal Services Center Technical Report, *NOAA/CSC/99031-PUB*, 35p.

MORTON, R.A. and PAINE, J.G., 1985. *Beach and vegetation-line changes at Galveston Island, Texas. Erosion, deposition, and recovery from Hurricane Alicia*. The University of Texas at Austin, Bureau of Economic Geology, Geological Circular 85-5, 39p.

MORTON, R.A. and SALLENGER, A.H., JR., 2003. Morphological impacts of extreme storms on sandy beaches and barriers. *Journal of Coastal Research*, 19(3), 560-573.

North Carolina Division of Coastal Management, 2003. Long-term Average Annual Shoreline Change Study and Setback Factors: Updated Through 1998. Raleigh, North Carolina: N.C. Division of Coastal Management Erosion Rate Maps, 60p.

NUMMEDIAL, D., CUOMO, R.F., and PENLAND, S., 1984. Shoreline evolution along the northern coast of the Gulf of Mexico. *Shore and Beach*, 52(1), 11-17.

OERTEL, G.F., 1977. Geomorphic cycles in ebb deltas and related patterns of shore erosion and accretion. *Journal of Sedimentary Petrology*, 47(3), 1121-1131.

RANASINGHE, R. and PATTIARATCHI, C., 1999. The seasonal closure of tidal inlets: Wilson Inlet – a case study. *Coastal Engineering*, 37, 37-56.

RICHIE, W. and PENLAND, S., 1990. *Coastline erosion and washover penetration along the Bayou Lafourche shoreline between 1978 and 1985, with special reference to hurricane impacts.* University of Aberdeen Department of Geography, O'Dell Memorial Monograph 23.

RIGGS, S.W., CLEARY, W.J., and SNYDER, S.W., 1995. Influence of inherited geologic framework on barrier shoreface morphology and dynamics. *Marine Geology*, 126, 213-234.

SAULT, M., CLEARY, W.J., and JOHNSEN, C.D., 1999. Hurricane impacts and shoreline recovery along Masonboro Island, NC. *Coastal Sediments 1999* (Long Island, NY), 1, 597-611.

SEXTON, W.J. and HAYES, M.O., 1982. Natural bar-bypassing of sand at a tidal inlet. *Proceedings of the 18th Coastal Engineering Conference* (Cape Town, South Africa), pp. 1479-1495.

SNYDER, S.W., HINE, A.C., and RIGGS, S.R., 1982. Miocene seismic stratigraphy, structural framework, and sea-level cyclicity, North Carolina continental shelf. *Southeastern Geology*, 23(4), 247-266.

SNYDER, S.W., HOFFMAN, C.W., and RIGGS, S.R., 1994. Seismic Stratigraphic Framework of the Inner Continental Shelf: Mason Inlet to New Inlet, North Carolina. *North Carolina Geological Survey Bulletin No. 96*, 59p.

SWAIN, K.W., 1993. Modification of a coastal plain/bar-built estuary in southeastern North Carolina. Wilmington, North Carolina: Dept. of Earth Sciences, University of North Carolina at Wilmington, Master's thesis, 47p.

THIELER, E.R., BRILL, A.L., CLEARY, W.J., HOBBS, C.H., III, GAMMISCH, R.A., 1995. Geology of the Wrightsville Beach, North Carolina shoreface: implications for the concept of shoreface profile of equilibrium. *Marine Geology*, 126, 271-287.

USACE, 2003. Topsail Inlet shoreface vibracore logs. U.S. Army Corps of Engineers, Wilmington District*, unpublished data*, 369p.

WHITE, S.A., 2002. Utilizing DEMs derived from LIDAR data to analyze topography: a case study of North Carolina barrier islands. Greenville, North Carolina: Dept. of Geography, East Carolina University, Master's thesis, 69p.

WHITE, S.A. and WANG Y., 2003. Utilizing DEMs derived from LIDAR data to analyze morphologic change in the North Carolina coastline. *Remote sensing of Environment*, 85, 39-47.

# BIOGRAPHICAL SKETCH

Benjamin Adam McGinnis was born in Leesburg, Virginia on September 11, 1979, and is the son of Phillip Curren McGinnis of Virginia Beach, Virginia, and Mary Elizabeth and John Matthew Reynolds of Shippensburg, Pennsylvania. He grew up in Virginia Beach, Virginia were he was active in the Boy Scouts of America, earning the rank of Eagle Scout in 1992, and later graduated from Floyd E. Kellam High School in 1997. In 2001, he graduated cum laude from West Virginia University in Morgantown, West Virginia with a Bachelor of Science in Geology. During his time as an undergraduate, Mr. McGinnis conducted a research project on the sediment characteristics of Sandbridge Beach, Virginia under Dr. Robert Behling. Following his marriage to Kathryn Lenore Britton of Quiet Dell, West Virginia in 2001, he entered the graduate program in Geology at the University of North Carolina at Wilmington. Mr. McGinnis worked as a research assistant and studied coastal geology under Dr. William J. Cleary in the Coastal Geology Laboratory at the University of North Carolina at Wilmington's Center for Marine Science. During his time under Dr. Cleary, Mr. McGinnis published and presented a portion of his thesis research at the Coastal Sediments '03 conference in Clearwater Beach, Florida, and co-authored two published papers and two technical reports. In 2004, he graduated with a Master of Science in Geology and began to pursue his professional career as an Environmental Engineer Sr., with the Habitat Management Division of the Virginia Marine Resources Commission in Newport News, Virginia. Mr. McGinnis has been a member of the Geological Society of America and the Society for Sedimentary Geology.