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The Effects of Underlying Geology on the Equilibrium Profile: A Case Study off Duck, North Carolina

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THE EFFECTS OF UNDERLYING GEOLOGY ON THE EQUILIBRIUM PROFILE:

A CASE STUDY OFF DUCK, NORTH CAROLINA

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Presented to
The Faculty of the School of Marine Science
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Of the Requirements for the Degree of
Master of Arts

by
Patricia L. Tiedeman
1995

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Patricia L. Tiedeman

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This thesis is dedicated to my parents, George and Dorothy Tiedeman, and my grandparents, George and Emily Sammis.

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ABSTRACT

The shoreface off Duck, North Carolina was studied to determine the possible effects of underlying geology on the shoreface profile and to test the validity of equilibrium pro-file models. Digitized sonograms were run through least square regressions to solve for A and m of the logarithmically transformed model $h = Ax^m$. Active sand lens volumes were determined from seismic profiles and sediment samples analyzed. A shoreface translation model was run to examine the evolution of past depositional environments on the present shoreface profile.

Best-fit equilibrium profiles off Duck, North Carolina were "unique" for the bottom surface and lagoonal substrate profile over which the modern Holocene sand sheet has migrated. "Universal" constants as applied to the site's equilibrium profile were not successful in representing the unique profile for this particular study site. Systematic residuals of best fit parameters indicate the influence of the active envelope of change onshore and the outcropping lagoonal substrate offshore on the shoreface profile. Shoreface translation modelling also supports the effect of the underlying substrate on the shape of the shoreface profile.

The Effects of Underlying Geology on the Equilibrium Profile:

A Case Study off Duck, North Carolina

INTRODUCTION

Coastal engineers have been modeling shoreface processes for many years using the concept of a shoreface equilibrium profile. Models have been based on the theory that a concave upward profile of equilibrium exists, bounded by a seaward limit past which there is no net transport of sediment. Schwartz (1982) defines an equilibrium profile as "a long-term profile of ocean bed produced by a particular wave climate and type of coastal sediment." Shorefaces are usually in disequilibrium but are approaching a natural equilibrium (Pilkey et al., 1993; Inman et al., 1993; Wright, 1995) dependent on grain size, energy dissipation, and slope.

These models make various assumptions, some of which have come under criticism recently. Pilkey et al. (1993) point out that underlying geology and varying sediment grain-sizes are ignored in one of the most widely used engineering models, the Bruun "Rule" (Schwartz, 1967). Relict substrates may greatly affect shoreface profile morphology resulting from transgressive and regressive sea-level phases. These factors, along with variations in physical processes, likely influence the shape of a shoreface profile and should be addressed.

This study examines the shoreface off the U.S. Army Corps of Engineers, Waterways Experiment Station (WES), Coastal Engineering Research Center (CERC), Field Research Facility (FRF) at Duck, North Carolina (Figures 1 and 2). The site was chosen to examine the relationships of the profile with shallow stratigraphy. This thesis is focused on the general objective of explaining the relationship of the present shoreface surface profile and relict subsurface substrate profile to "accepted" concepts for equilibrium profile models.

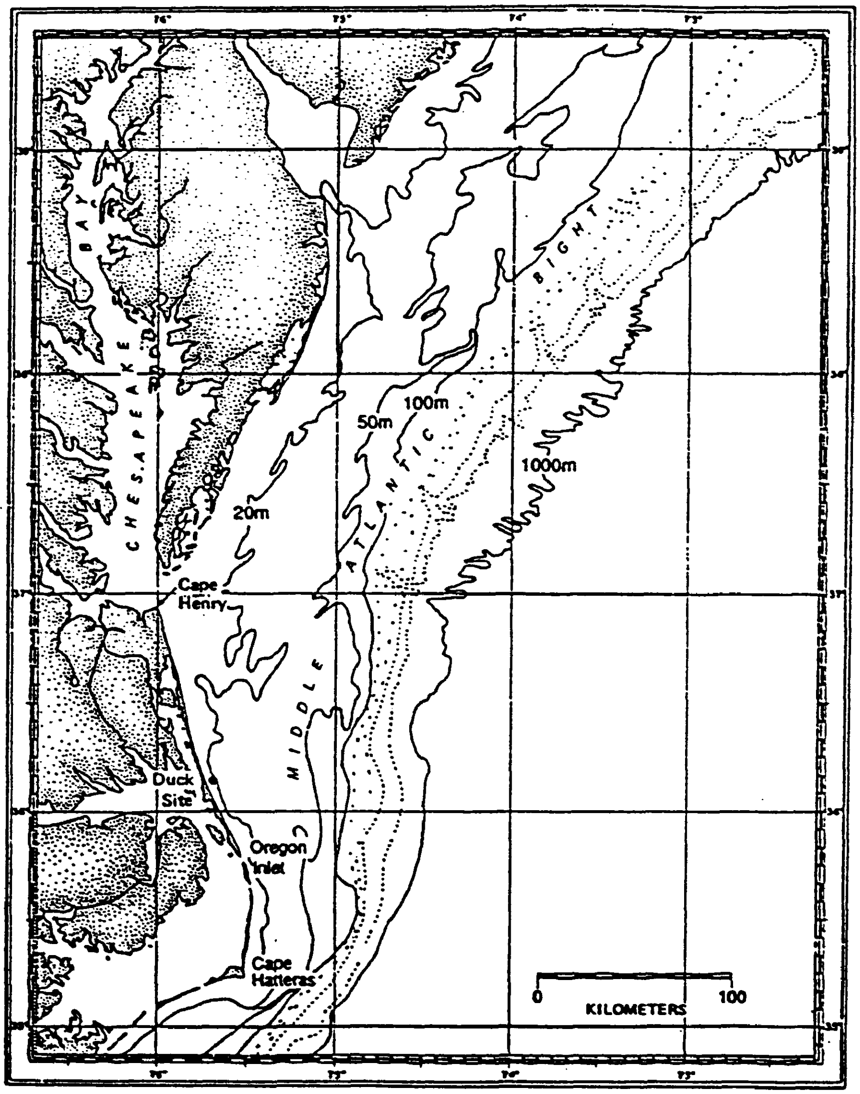
Underlying this study are the following working hypotheses:

> **(1) Shallow, underlying geology creates a substrate over which modern shorefaces migrate, landward (in a transgressive phase) or seaward (in a regressive phase). (2) This substrate provides a platform that has influenced the present profile shape and may continue to influence future shoreface profiles.**

Specifically the thesis addresses the following questions:

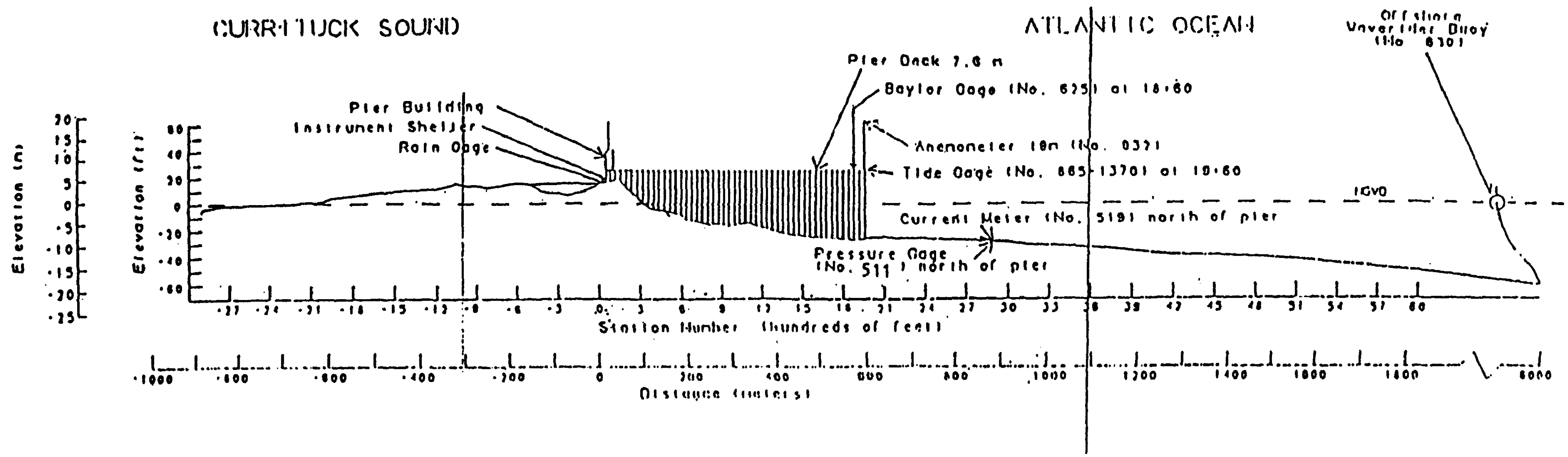
1) Does the shoreface profile conform to the equilibrium shape as defined by "classical" models?
2) Which one of the existing equilibrium models best represents the shoreface based on the existing conditions?

Figure 1. Map indicating the locations of the Corps of Engineers' Field Research Facility at Duck, North Carolina.



CHESAPEAKE
BAY
MIDDLE ATLANTIC BIGHT
Cape Henry
Duck Site
Oregon Inlet
Cape Hatteras
20m
50m
100m
1000m
0
100
KILOMETERS

Figure 2. Cross-section of the Duck Field Research Facility site from Currituck Sound to the Atlantic Ocean (from Preliminary Data Summary, February 1984, Field Research Facility, Coastal Engineering Research Center, U.S. Army Engineer Waterways Experiment Station.)


CURRITUCK SOUND
ATLANTIC OCEAN
Offshore Unverified Buoy (No. 630)
Pier Deck 7.6 m
Baylor Gage (No. 625) at 18+60
Pier Building
Instrument Shelter
Rain Gage
Anemometer 18m (No. 032)
Tide Gage (No. 865-1370) at 19+60
NGVD
Current Meter (No. 519) north of pier
Pressure Gage (No. 511) north of pier
Elevation (m)
Elevation (ft)
Station Number (hundreds of feet)
Distance (meters)

3) Does this shoreface shape require "adjustment" of empirical constants or its own varibles when modelling profile change? (i.e. Does the profile conform to universal models or is it "unique?")

4) Does the relict profile, as expressed by the underlying substrate, conform to a similar model fitting the modern surface?

5) Can the underlying substrate be used as a base on which to recreate the present profile and predict future profiles? How has the old substrate influenced the existing surface profile?

BACKGROUND

MODELS

-Historical-

Shoreface profiles in wave-dominated, inner shelf areas can be characterized by their concave upward shapes and decreasing grain size with increasing distance off-shore. The theory of an equilibrium condition, reflected by these profiles, goes back to the late 1800's when Paulo Cornaglia (1889) wrote that there was a balance of sediment fluxes, influenced by wave processes and changing bed slopes, that resulted in no net shore-normal transport. Such ideas are reiterated in today's "profile of equilibrium" theories.

Bruun (1954) developed an equilibrium profile equation that related the depth, h, of the sediment surface to offshore distance, x, via the exponential form:

$$h = Ax^m \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where A is a scaling parameter dependent on sediment characteristics and m is a shape parameter initially found to equal 0.67 (2/3). Dean (1977) proposed the values m = 0.67 when shoreface equilibrium was defined on the basis of uniform rate of dissipation per unit volume (applicable to the surf zone) and m = 0.4 when the rate of dissipation per unit area of bed was uniform (appropriate to the inner shelf; see discussion in Wright, 1995 for rationale). After

Dean studied over 500 beach profiles, he concluded that 0.67 was an acceptable value for m and that it could be considered constant. Boon and Green (1989) found m = 0.5 for carbonate sand beaches they studied in the Caribbean. Other researchers have obtained varying values of m, questioning the validity of m being a constant value in the equilibrium profile model. Inman et al. (1993) concluded that m = 0.40, a value consistent with the notion of equal dissipation per unit area of bed.

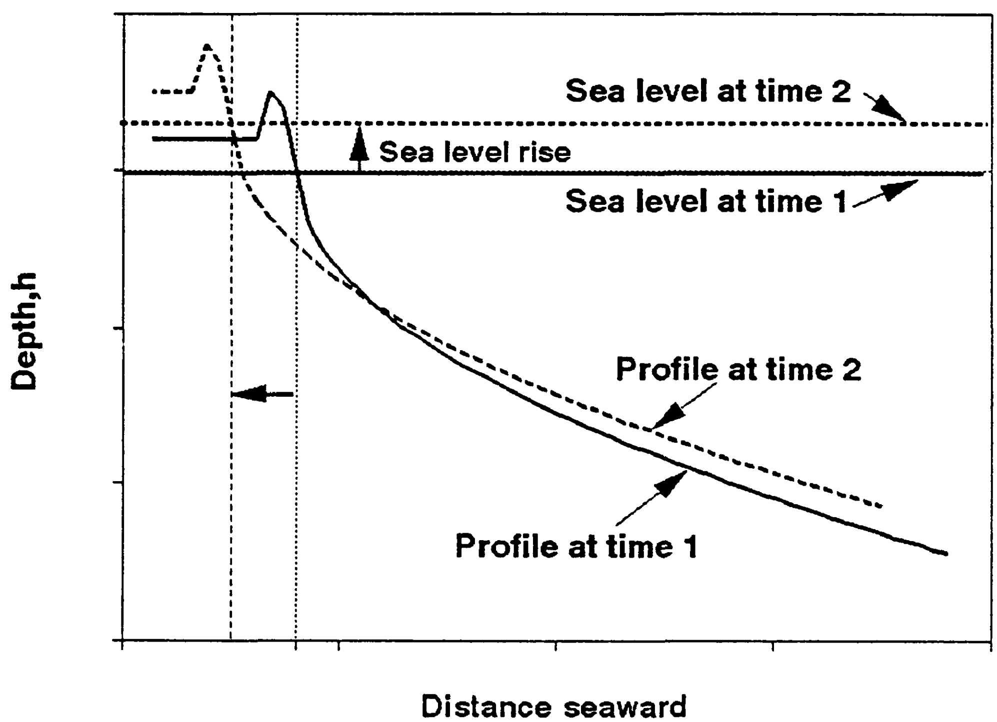
Another constant defined in the original equation is A. Dean (1990) determined that the value of A depends on the sediment's grain size and settling velocity as represented by the following empirical relationship:

$$A = 0.067 w_s^{0.44} \qquad (2)$$

where A is represented in Equation (1) and w_s is the sediment fall velocity (cm/s) dependent on the grain size, shape, density, and water temperature. As Wright (1995) points out, the matter of units for A "leaves one with the unpleasant impression that A possesses strange units which must be countered by equally strange units on the part of m." For a linear profile with m = 1 (Equation 1), A is simply the slope.

Bruun (1962) proposed that with rising sea level, there is a net landward transgression of the equilibrium profile (Figure 3). This theory became known as "the Bruun Rule" (Schwartz, 1967). It assumed that: (1) the profile shape,

Figure 3. "The Bruun Rule" showing landward transgression of the equilibrium profile (Wright, 1995 based on Schwartz, 1967).


Sea level at time 2
Sea level rise
Sea level at time 1
Depth,h
Profile at time 2
Profile at time 1
Distance seaward

bounded by a seaward limit past which there would be no net transport of sediment, remains unchanged; (2) eroded sediment from a landward transgression is deposited offshore; and (3) the processes influencing cross-shore sediment transport remains unchanged with changing sea level. The seaward limit of deposition or depth of closure was described by Hallermeier (1981) and varies based on three types of zonation: littoral, shoal, and offshore zones. It describes the conceptual maximum depth of onshore-offshore sediment exchange across the shoreface by surface wave effects on the bottom and is dependent on grain-size and bed-slope effects. The maximum depth of disturbance by waves is actually deeper than the "closure" depth (Wright, 1995).

Inman et al. (1993) describe an equilibrium profile composed of two parabolic curves meeting at a breakpoint bar, each curve fitting Dean's equation, $h = Ax^m$. The curve studied in the present project relates to the outermost or "shorerise" curve (Figure 4). Inman et al. (1993) found $m = 0.4$ for both portions of their profile in most cases. Seasonal wave height changes over the profiles were related to changes in the width of the surf zone and were reflected by the variable A. Table 1 lists the results of their best-fit determinations for the Duck profile.

Pilkey et al. (1993) point out that paleotopographic features occur frequently along the inner continental shelf

Figure 4. Zones of shoreface profile used in curve fitting by Inman et al. (1993). X_1 is the horizontal distance between the reference benchmark for the profile range and the origin of the bar-berm curve, Z_1 the vertical distance above mean sea level (MSL), X_2 the best fit for the shore-rise curve from bar berm origin, Z_3 the intersection of bar-berm and shorerise curves (depth of the breakpoint bar below MSL), X_3 the horizontal length of the bar-berm profile, x_1 and x_2 are the horizontal coordinates, and h_1 and h_2 the vertical coordinates.

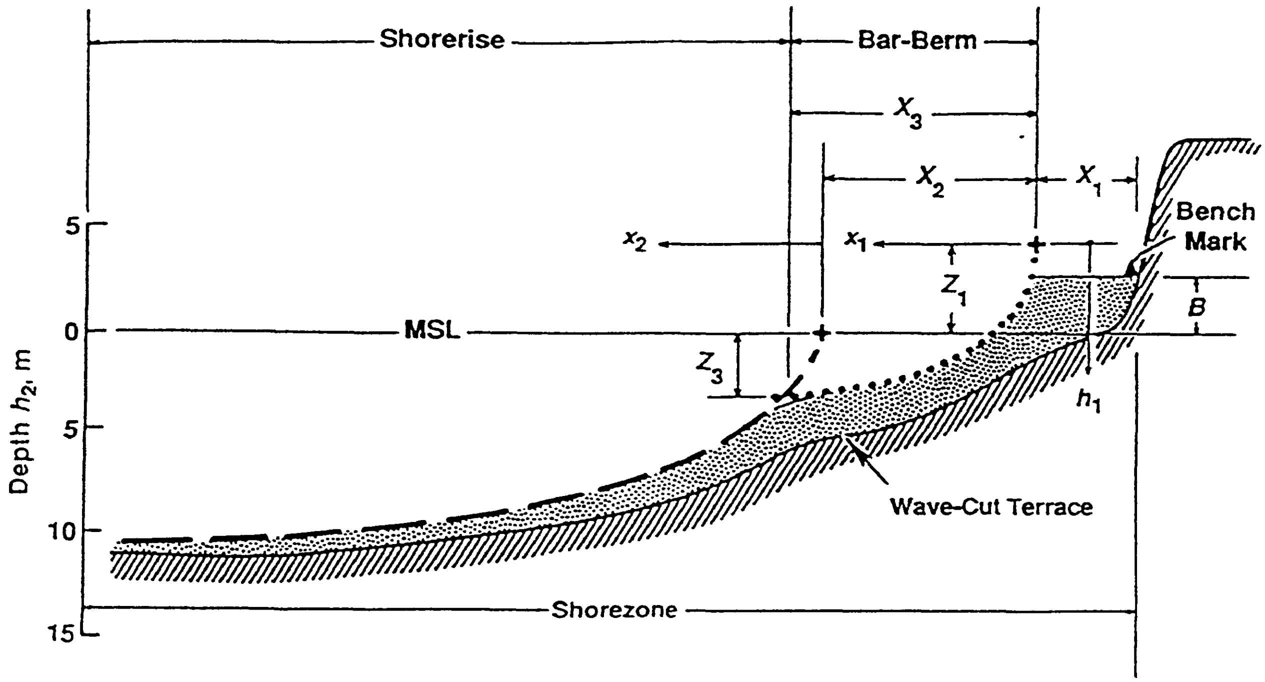

Shorerise
Bar-Berm
X_3
X_2
X_1
Bench Mark
x_2
x_1
Z_1
B
5
0
MSL
Z_3
h_1
Depth h_2, m
5
10
Wave-Cut Terrace
Shorezone
15

TABLE 1
BEST FIT FOR THE PARAMETERS A AND m
OF THE CURVES $h = Ax^m$
BAR-BERM AND SHORERISE PROFILES
DUCK, NORTH CAROLINA
(from Inman et al., 1993)

Date	Type	Bar-Berm		Shorerise	
		A	m	A	m
August 1985	summer inner bar	1.62	0.34	0.70	0.36
	summer second bar	1.54	0.31	1.60	0.26
March 1985	summer inner bar	1.70	0.33	0.62	0.38
	summer second bar	3.10	0.23	1.62	0.25

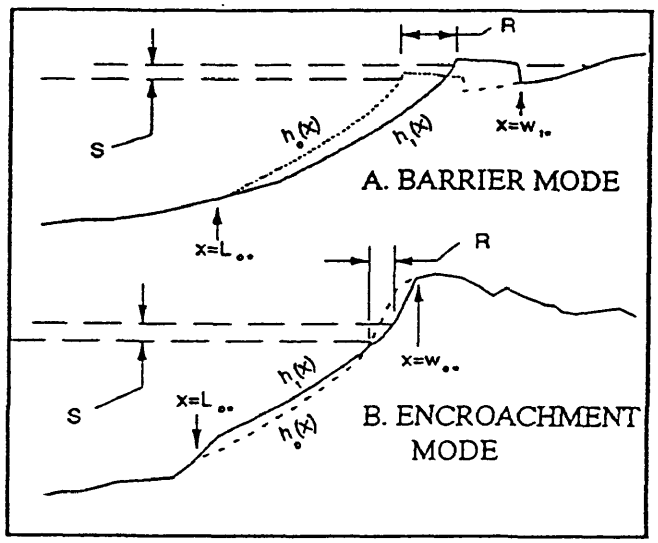
and modify incoming energy regimes that in turn affect sediment erosion, transport, and deposition. Therefore, pre-existing geology should be addressed when applying any of the shoreface profile theories. Outcropping stratigraphic units of different sediment characteristics could influence the shape of the shoreface profile. By influencing the geometry of ripples, grain-size variability could cause alterations in the energy dissipation over the profile and loss of sediment from the system. Settling velocities (therefore the value of A), depth of closure, and loss of sediment from the system could be influenced by all these things, questioning the basic assumptions of shoreface modelling techniques.

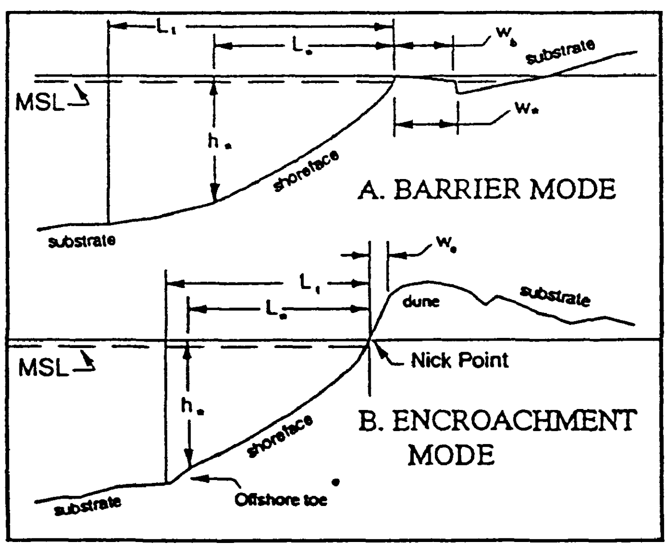
-Model Used in Study-

Cowell et al. (1992) created a shoreline transgression model that simulates successive shoreface profiles through two-dimensional, parametric, morphological-behavior modelling for sea-level change using sand-mass conservation and geometric rules for shoreface and barrier morphology. Geometric rules are derived from process studies and are empirical, analytical, and/or numerical (Cowell and Thom, 1994; Figure 5).

The model uses vertical and horizontal translations of coastal sand bodies over pre-existing substrates that are then reworked (Cowell et al., 1992). The user can add

Figure 5. Example of sea level rise and shoreface response in both (A.) trangressive barrier mode and (B.) encroachment mode by Cowell et al. (1992) shoreface translation model. Sea-level increment (S), recession distance (R), x for transgressive barriers (equal to w_{l*}) or encroachment barriers (equal to w_{c*}),and depth h for active profiles (h_l) or existing substrate (h_o).


R
S
x=w
A. BARRIER MODE
x=L
R
x=w
S
x=L
B. ENCROACHMENT
MODE


substrate
MSL
shoreface
A. BARRIER MODE
substrate
dune
substrate
MSL
Nick Point
shoreface
B. ENCROACHMENT
MODE
substrate
Offshore toe

"uncodified expert knowledge" (Cowell et al., 1992) between steps by changing parameters relevant to site-specific environments and geologic history. It allows for incremental sea level change in one of two modes. The transgressive barrier mode depicts the landward migration of a barrier island. The erosional encroachment mode, based on the Bruun Rule, models the offshore movement of sediment with the erosion of a barrier superstructure with increasing sea level.

The shoreface translation model assumes that there is a one hundred percent shoreface response to each incremental rise in sea level. It also assumes that the shoreface of the migrating sand body has an equilibrium profile shape characterized by Equation 1. The model accounts for sand-mass conservation but assumes that any fines deposited in the back barrier lagoon are lost to the outer shelf, and therefore to the system, when exposed on the seaward side of the profile during sea-level trangression.

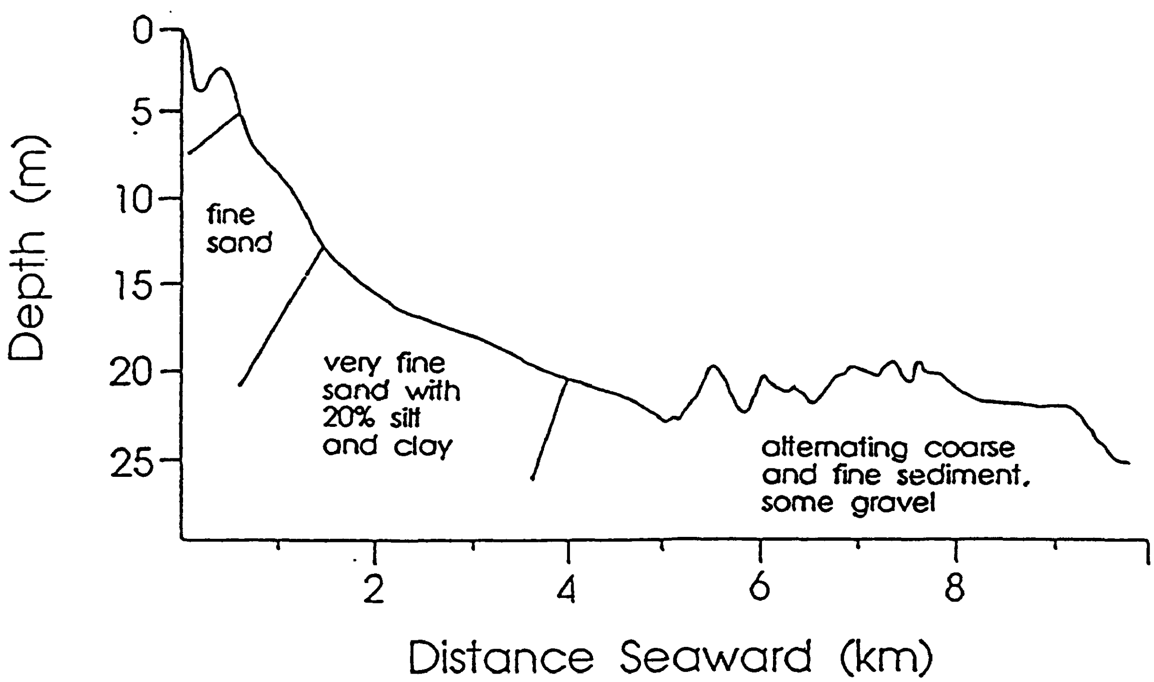
STUDY AREA

-Geologic Setting-

The study site is located in the southern part of the Middle Atlantic Bight and is bounded shoreward by a sandy barrier island separating Currituck Sound on the west and the Middle Atlantic Bight on the east. The tectonic setting is that of a trailing continental margin with relative subsidence and relative sea-level transgression. The barrier and back barrier deposits are composed of Holocene and Pleistocene material as described by Meisburger et al. (1989). The site is part of the Outer Banks barrier island chain that formed seaward of today's shoreline position during the Holocene transgression. Subsequently, the island migrated to its current location with rising sea level (Field and Duane, 1976) and has recently become almost stationary.

The shoreface profile is concave up and is qualitatively consistent with the equilibrium model of Dean (1977, 1990). Sediments fine seaward to approximately 18 m depth (Figure 6), with mean grain-sizes ranging from 0.13 to 0.09 mm. A cross section of the inner shelf off Duck, North Carolina (Figure 7) indicates the relationship of the modern shoreface to the underlying lagoonal deposits. Figure 8 shows the overall stratigraphic cross-section at Duck. Pilkey et al. (1993) describe many North Carolina

Figure 6. Generalized cross-section depicting gross sediment-type of the sea floor at Duck, North Carolina (from Wright, 1993).



0
5
10
15
20
25
Depth (m)
fine
sand
very fine
sand with
20% silt
and clay
alternating coarse
and fine sediment,
some gravel
2
4
6
8
Distance Seaward (km)

Figure 7. Map and cross-section of Duck, North Carolina's inner shelf (From Field et al., 1979).

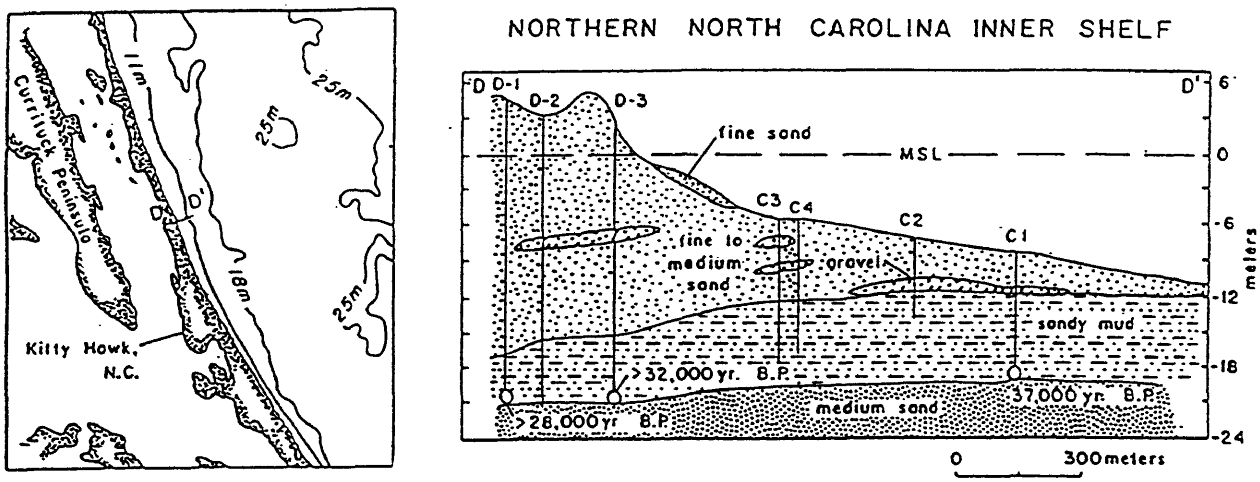
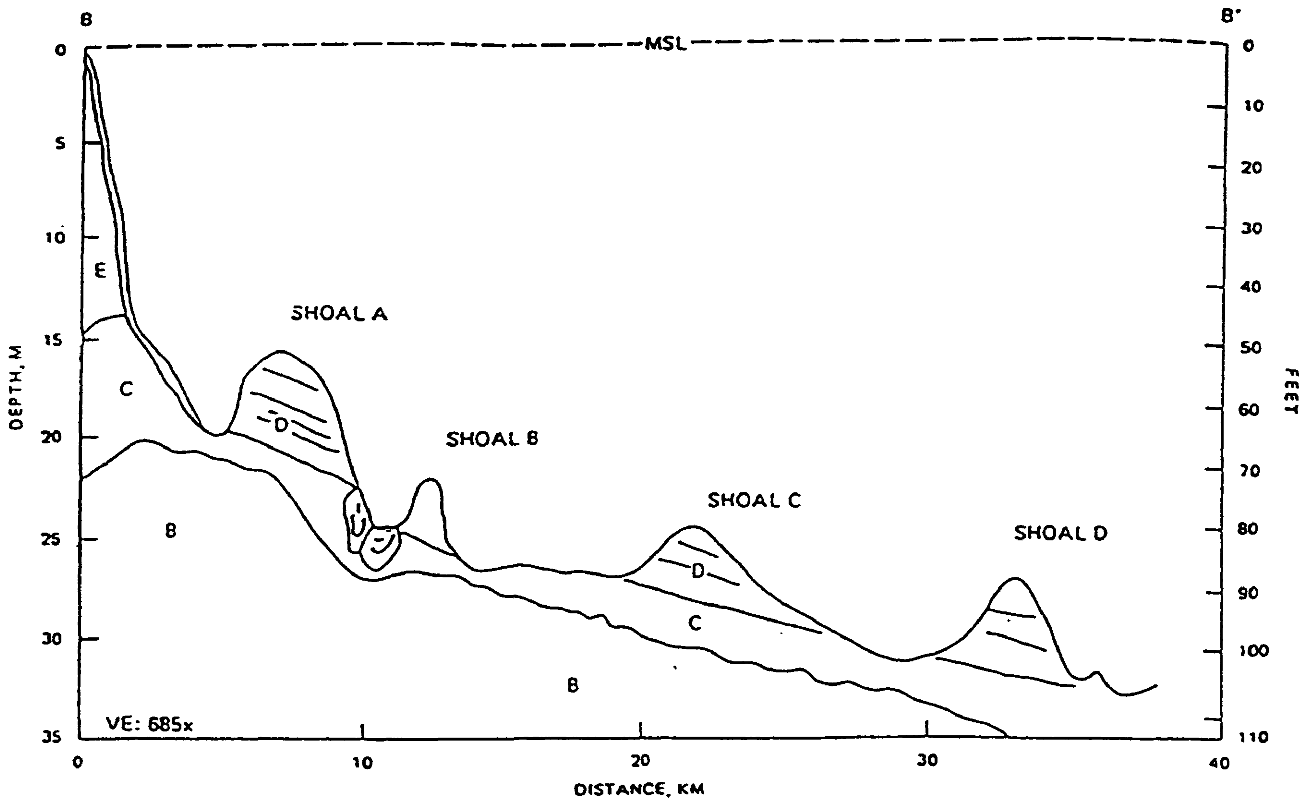

NORTHERN NORTH CAROLINA INNER SHELF
Currituck Peninsula
11m
25m
25m
D
D'
18m
25m
Kitty Hawk, N.C.
D
D-1
D-2
D-3
D'
6
fine sand
MSL
0
C3
C4
C2
C1
-6
meters
fine to medium sand
gravel
-12
sandy mud
-18
>32,000 yr. B.P.
37,000 yr. B.P.
medium sand
>28,000 yr B.P.
-24
0
300 meters

Figure 8. Profile showing the configuration of the shoreface and inner shelf in the vicinity of the study area (from Meisburger et al., 1989).



B
B'
MSL
SHOAL A
SHOAL B
SHOAL C
SHOAL D
E
C
D
B
VE: 685x
DEPTH, M
FEET
DISTANCE, KM
0
5
10
15
20
25
30
35
0
10
20
30
40
50
60
70
80
90
100
110
0
10
20
30
40

barriers as perched on sediments with various paleo-topographic surfaces of variable cohesiveness.

Meisburger and Williams (1987) summarized the underlying geology by correlating units with those described by Shideler et al. (1972) as units A-D. Unit A occurs below those cores reported by Meisburger and Williams (1987) and is Tertiary in age. Unit A is separated from Unit B by a probable Pliocene or early Pleistocene erosional surface.

Unit B is a silty medium to coarse sand devoid of shell fragments, foraminifera, and other faunal debris (Meisburger et al., 1989). Sandy-peat samples found by Field et al. (1979) at the top of Unit B, and some within the unit, are non-marine in origin (Meisburger and Williams, 1987; Meisburger et al., 1989). This places the unit in the late Pleistocene, possibly indicating a Sangamon (last interglacial) High-stand of sea level (Hobbs et al., 1994).

Unit C is a silty, very fine sand containing mollusk shells and foraminifera tests (Meisburger and Williams, 1987; Meisburger et al., 1989). The fine micaceous character of the sediment reflects a low-energy depositional environment. This along with the fossils identify the Unit C as being of marginal marine, lagoonal, or marshy in origin. Channels found in Unit C are described by Meisburger and Williams (1987) and Meisburger et al. (1989) as being of tidal inlet or lagoonal character in nature. The unit was deposited during the last glacial maximum.

The reflector between Units B and C is described by Shideler and Swift (1972) as being a prominent, widespread unconformity. It represents both subaerial and surf zone erosional surfaces formed during the regression and interstadial transgression of the last glacial maximum, repectively. They also describe the reflector between Units C and D as a widespread unconformity representing the Pleistocene-Holocene boundary. This reflector tends to crop out on the sea floor and reflects subaerial erosion of the last regression and shoreface erosion during the Holocene transgression.

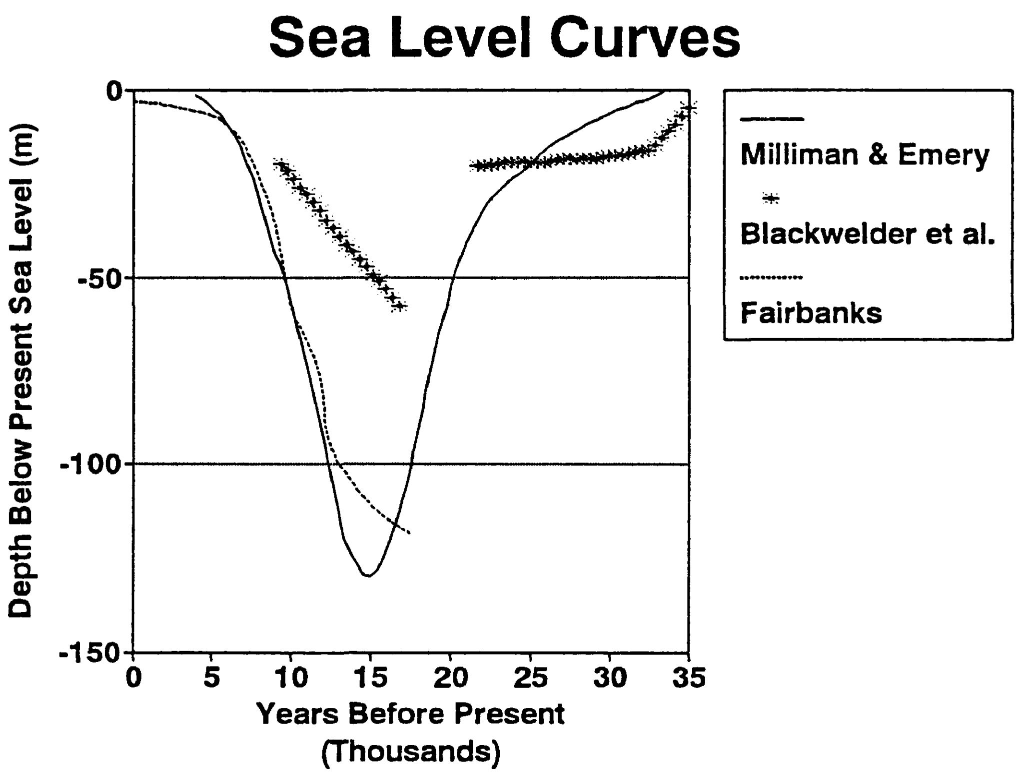
Unit D represents a shoreface deposit with fine sands interspersed with poorly sorted sand, gravel, and pebbles (Meisburger et al., 1989). This unit forms a thin, surficial Holocene sand-sheet overlying Unit C, and the ridges found offshore that may be related to relict ebb tidal deltas or estuary-mouth bars (Wright, 1995). Unit E is composed of clean sand and gravel, characteristic of beach and dune deposits (Meisburger et al., 1989). Unit E contains an unbroken accumulation of this sediment over 18.3 meters thick. Meisburger et al. (1989) speculate that this is due to little or no retreat of the barrier as usually found along the Atlantic coast, apparent by the presence of underlying back barrier deposits at shallow depths. They also mention that this type of sand accumulation may be the result of past inlet processes, although their study found no evidence of a past inlet at the site. The back barrier deposits occur at greater than 15.2 meters below sea level under the FRF site whereas they crop out directly on the beaches of many barrier islands including False Cape, Virginia and those north of the Chesapeake Bay mouth.

-Sea Level History-

Sea level curves show depth below present sea level with time (Figure 9). Milliman and Emery (1968) based their curve on radiocarbon dates of shallow-water mollusks, oolites, coralline algae, beachrock, and salt-marsh peat from Atlantic coastlines. Fairbanks (1989) used oxygen isotopes and radiocarbon dates from shallow subtidal coral reefs in Barbados. Blackwelder et al. (1979) took vibra-cores off the Atlantic continental shelf from Delaware to Florida and used in-place lagoonal and salt marsh sediments to construct their curve.

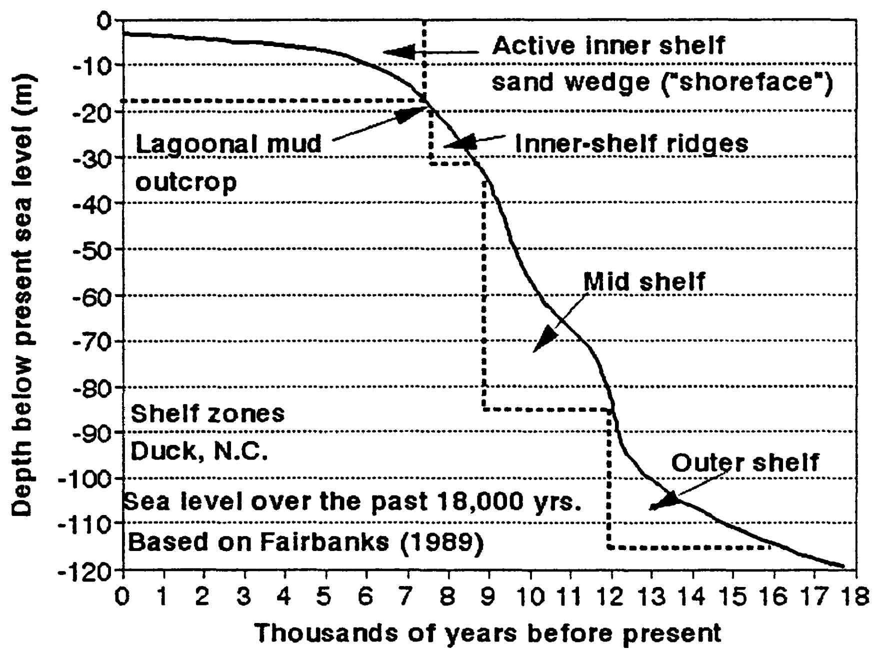
Hobbs et al. (1994) indicate the location of offshore features in relation to sea level history (Figure 10). The lagoonal mud that outcrops at the 20 meter isobath appears to have been deposited 7,000 to 8,000 years ago. The location of the inner-shelf ridges indicate their activity 8,000 to 9,000 years ago. Shelf exposure to lower sea level stands occurred 9,000 to 12,000 years ago for the mid-shelf and 12,000 to 16,000 years ago for the outer-shelf.

Figure 9. Sea level curves digitized from Milliman and Emery (1968), Blackwelder (1979), and Fairbanks (1989).



Sea Level Curves
0
-50
-100
-150
Depth Below Present Sea Level (m)
0
5
10
15
20
25
30
35
Years Before Present
(Thousands)
Milliman & Emery
Blackwelder et al.
Fairbanks

Figure 10. A sea level curve for the past 18,000 years, based on Fairbanks (1989), superimposed with information about the inner continental shelf adjacent to the Duck Field Research Facility (from Hobbs et al., 1994).

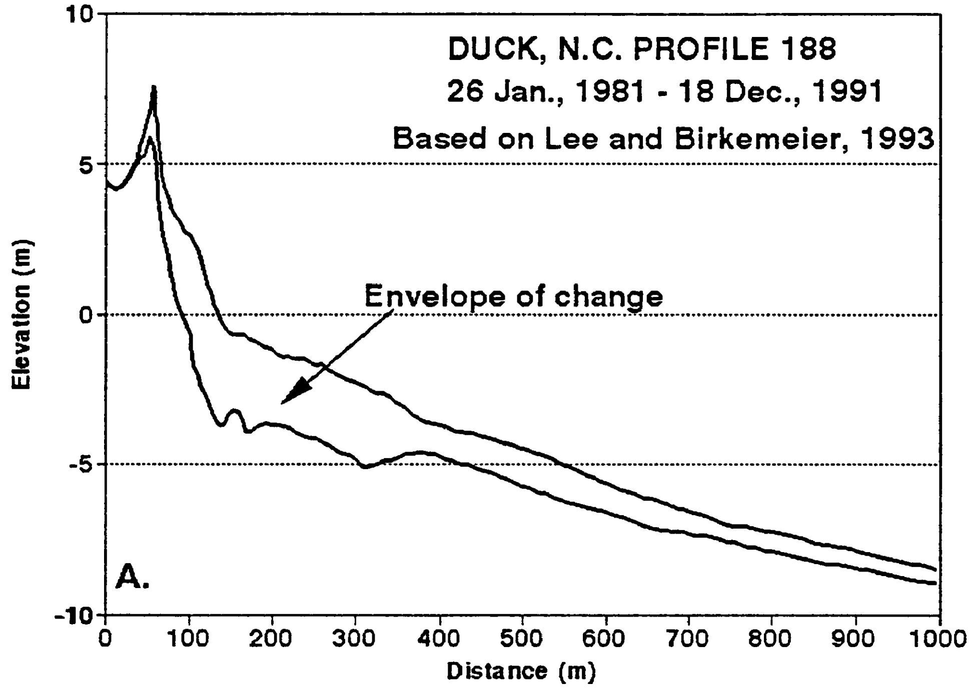

0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
-120
Depth below present sea level (m)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Thousands of years before present
Active inner shelf
sand wedge ("shoreface")
Lagoonal mud
outcrop
Inner-shelf ridges
Mid shelf
Outer shelf
Shelf zones
Duck, N.C.
Sea level over the past 18,000 yrs.
Based on Fairbanks (1989)

-Physical Setting-

Wright and coworkers (Wright, 1995; Wright et al., 1991, 1994) have studied the sediment-water couplings of the continental shelf in the vicinity of Duck. In order for the initiation of sediment transport to occur, critical bed-stresses must be reached. Wright et al. (1991) and Wright (1993) state that these bed-stresses can be reached through the combination of surface gravity waves and wind-driven currents. Dynamic action initiating sediment transport primarily occurs during extra-tropical storms (nor'easters) and secondarily during tropical storms, classifying Duck as a storm dominated coast (Vincent et al., 1981).

The envelope of change studied over the past 10 years (Lee and Birkemeier, 1993) at the FRF occurs in Unit D (Figure 11). Wright (1993) and Wright et al. (1991, 1994) have concluded that the onshore and off-shore sediment transport is occurring in the surficial sand sheet (Unit D) across the inner shelf to at least the 15 meter isobath. Moderate wave conditions at Duck, North Carolina are enough to initiate sediment motion at depths less than 26 meters while storm conditions can initiate sediment motion even farther off-shore (Figure 12).

Figure 11. The envelope of change along two Field Research Facility profile lines for the beach, surf zone, and shoreface at Duck, North Carolina (Wright, 1995; digitized and redrawn from Lee and Birkemeier, 1993).


DUCK, N.C. PROFILE 188
26 Jan., 1981 - 18 Dec., 1991
Based on Lee and Birkemeier, 1993
Envelope of change
A.
Elevation (m)
Distance (m)
10
5
0
-5
-10
0
100
200
300
400
500
600
700
800
900
1000

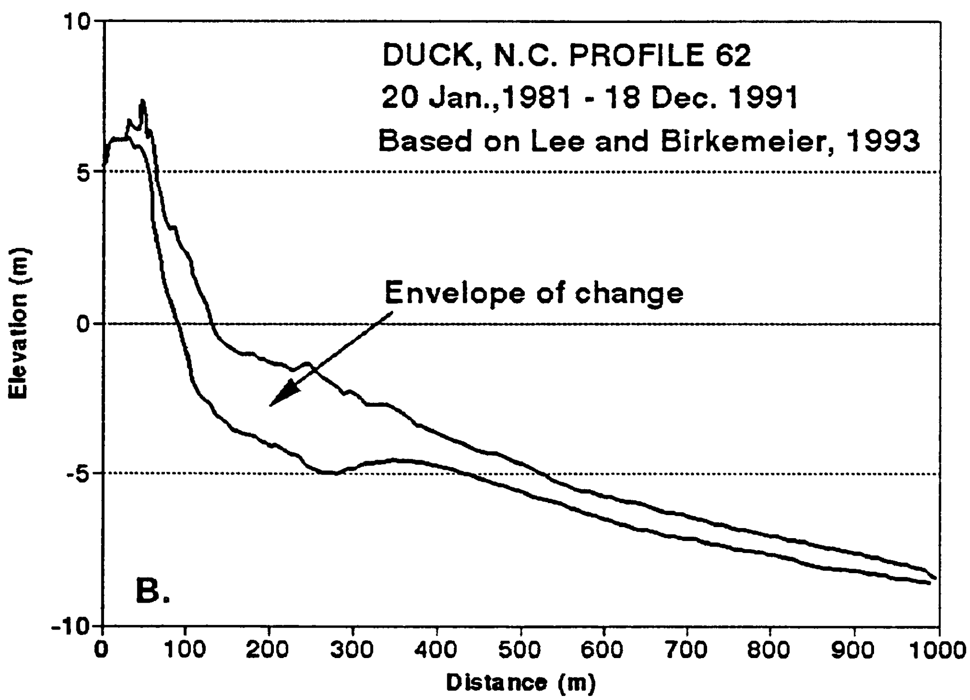
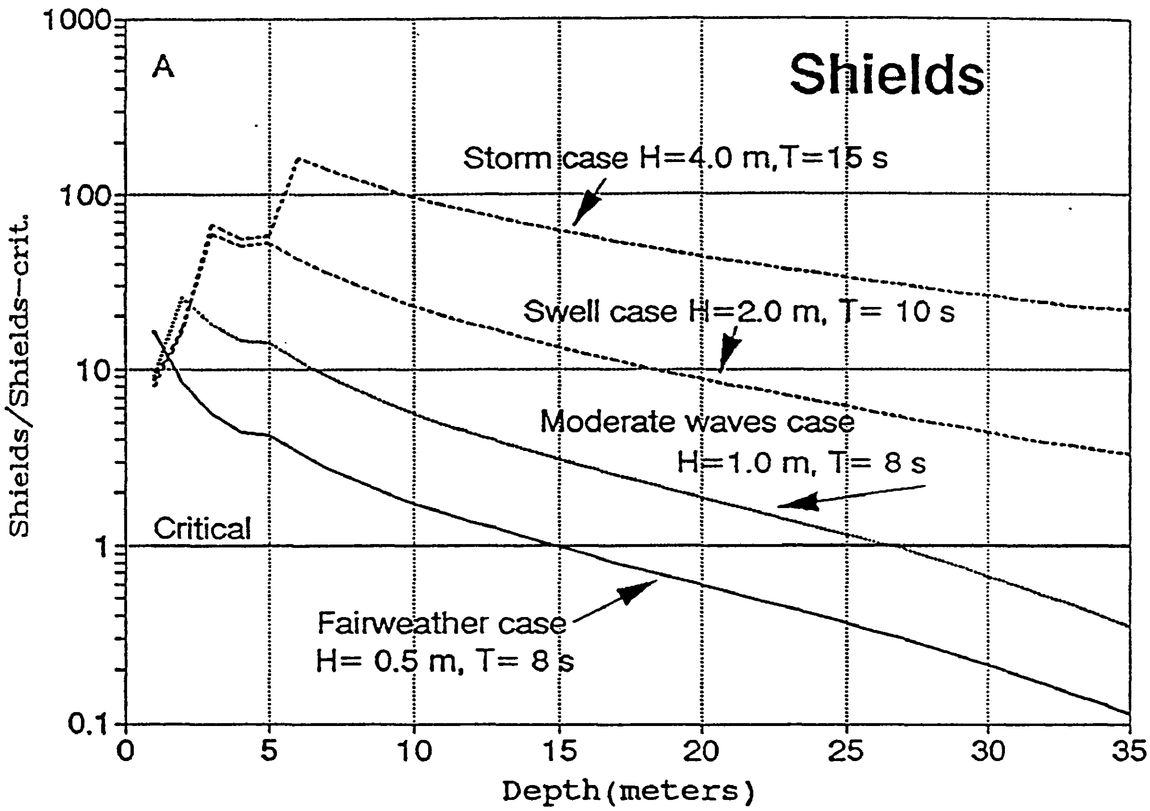

DUCK, N.C. PROFILE 62
20 Jan.,1981 - 18 Dec. 1991
Based on Lee and Birkemeier, 1993
Envelope of change
B.
Elevation (m)
Distance (m)
10
5
0
-5
-10
0
100
200
300
400
500
600
700
800
900
1000

Figure 12. The critical Shields parameter required for initiation of sediment transport plotted against depth for varying wave conditions typical of Duck, North Carolina (from Wright, 1993).



A
Shields
Storm case H=4.0 m,T=15 s
Swell case H=2.0 m, T= 10 s
Moderate waves case
H=1.0 m, T= 8 s
Critical
Fairweather case
H= 0.5 m, T= 8 s
1000
100
10
1
0.1
Shields/Shields-crit.
0
5
10
15
20
25
30
35
Depth(meters)

METHODS

-Field-

The data set used in this study was obtained off Duck, North Carolina July 14-15, 1993 and July 5-7, 1994 aboard the Research Vessel Bay Eagle. Seismic profiles of offshore geology were obtained with a Datasonics SBP 5000 system sub-bottom profiler producing a 3.5 kHz acoustic signal. Reflected signals were recorded on an EPC 4800 graphics recorder (Hobbs and Dame, 1992).

Sidescan sonar was used to record surficial evidence of change in geologic structures during the 1993 and 1994 trips. Some lines from 1993 were rerun and extended seaward in 1994 using a dual frequency 100 kHz and 500 kHz EG&G Model 260 TH side-scan sonar system.

Cores were recovered by divers on the 1994 cruise at approximately 9m and 20m. Sediment samples and short cores were logged and described. Selected subsamples were analyzed for basic grain-size characteristics including gravel: sand:silt:clay ratio and mean grain-size of the sand fraction. The former analysis used standard wet sieve and pipette methods (Folk, 1974) whereas the sand analyses used a settling tube. The silt and clay fractions were analyzed in a Micrometrics SediGraph 1500.

-Analytical-

Seismic records initially were evaluated ussuming a constant acoustic velocity of 1,500 m s^{-1} in sea water and shallow sediment. The records were reduced on an office copier for digitizing. Digitizing utilized Geocomp, Ltd.'s EASYDIG program on a Summagraphics Summasketch III Professional digitizing template.

The cross-sectional area of the sand lens bounded by the surface and Reflector 3 was calculated for each offshore seismic line by using the digitizer's software. This area was averaged along-shore to estimate the volume of the apparent Holocene sand lens. The site's active envelope of change (Figure 11) was also digitized to determine the cross-sectional area of active sand movement (Birkemeier et al., 1989).

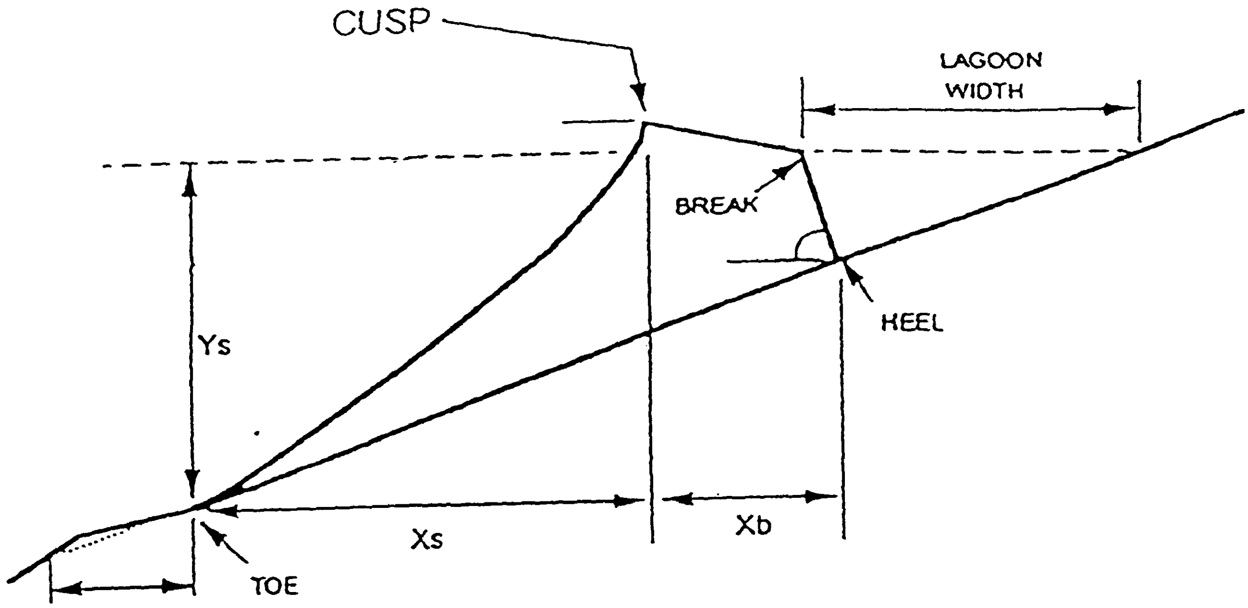
The shoreface profiles, bottom and sub-bottom reflectors, were averaged and then linearly regressed using least squares to find the best fit values of A and m (Equation 1) using commercial software (Quattro Pro 3.0). The technique used by Inman et al. (1993) was applied to the curves. Logarithmically transformed data were analyzed using least squares linear regression. The origins of the profiles were assumed to be where the averaged profiles began in the seismic records (h) and were corrected to the distance (x) from the Field Research Facility's benchmark (ie. x = 253, h = -3 for the bottom; and x = 253, h = -7 for the sub-bottom). The spatial or "virtual" origins, h_o and x_o (Equation 3), of both the sub-bottom and bottom profiles were determined through iterations using the highest correlation coefficient values, as described by Inman et al. (1993).

$$(h-h_o) = A(x-x_o)^m \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Best-fit values for the sub-bottom profile were used to extend the profile in the offshore direction. A barrier island was added to the shoreward end of the profile to simulate a possible extension of the substrate using dimensions found at the present FRF site (Figure 2).

The substrate data were used as substrate input to test Cowell et al.'s (1990) shoreface translation model (see Appendix). The erosional surface between Unit C and Units D and E was assumed to be the surface over which Holocene sediment was transported during the Holocene transgression. Assuming the erosional surface age to be 7,000 to 8,000 BP, sea level ocurred 23 m below present sea level during initial deposition and transgression over Unit C, based on Fairbanks's (1989) sea level curve (Figure 9). The shoreface translation model was run using varying input parameters for the set-up menu (Figure 13).

Figure 13. Illustration of geometric parameters used in the Input Menu and Output File of the shoreface translation model. Ys is the depth at surf base (m); Xs is the distance to the surf base (m); and Xb is the maximum sand body width (Cowell et al., 1992).


CUSP
LAGOON
WIDTH
BREAK
Ys
HEEL
Xs
Xb
TOE

RESULTS

- Shallow Seismic Stratigraphy -

Five shore-normal transects were run extending pre-existing profile lines monitored at shallow depths by the FRF (Figure 14). Four shore-parallel transects were run from near the surf zone out to the 20 m isobath. This method of running seismic lines gave a reasonable illustration of the underlying geology represented by the acoustic reflectors (Figure 15).

Across the study area, there are three discernable sub-bottom reflectors plus the sea floor defining three distinct seismo-stratigraphic units. The reflectors and units appear to correlate to the pattern described by Shideler et al. (1972), Shideler and Swift (1972), Meisburger and Williams (1987), and Meisburger et al. (1989) except that the records did not achieve sufficient penetration to record Unit A.

Unit B, lying below Reflector 2, is not exposed at the seafloor within the study area. Unit C outcrops at a depth of approximately 20m. Its lower boundary is Reflector 2 whereas its upper extent is defined either by the seafloor or Reflector 3. Although not discussed as part of this study, there also is evidence of channels within unit C as discussed in the various earlier studies.

Unit D occurs above Reflector 3. Shideler et al. (1972) and Shideler and Swift (1972) describe Unit D as a

Figure 14. Map depicting the lines of sub-bottom profiles and side-scan sonograms obtained in 1993 and 1994, respectively, offshore from the Duck Field Research Facility.

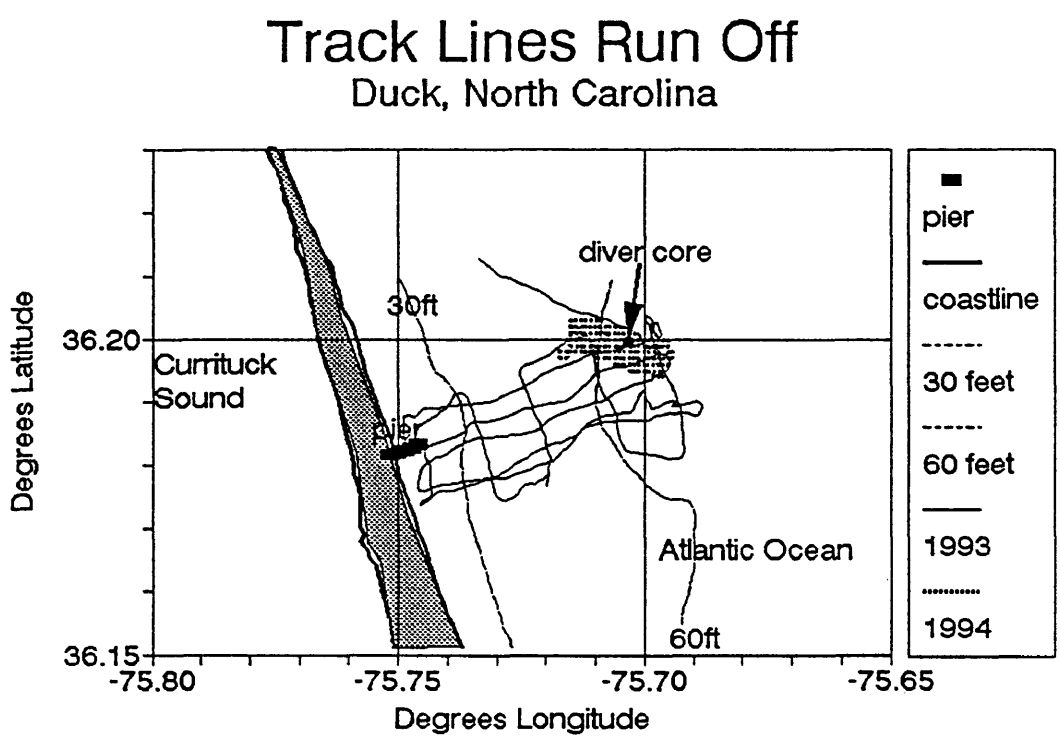
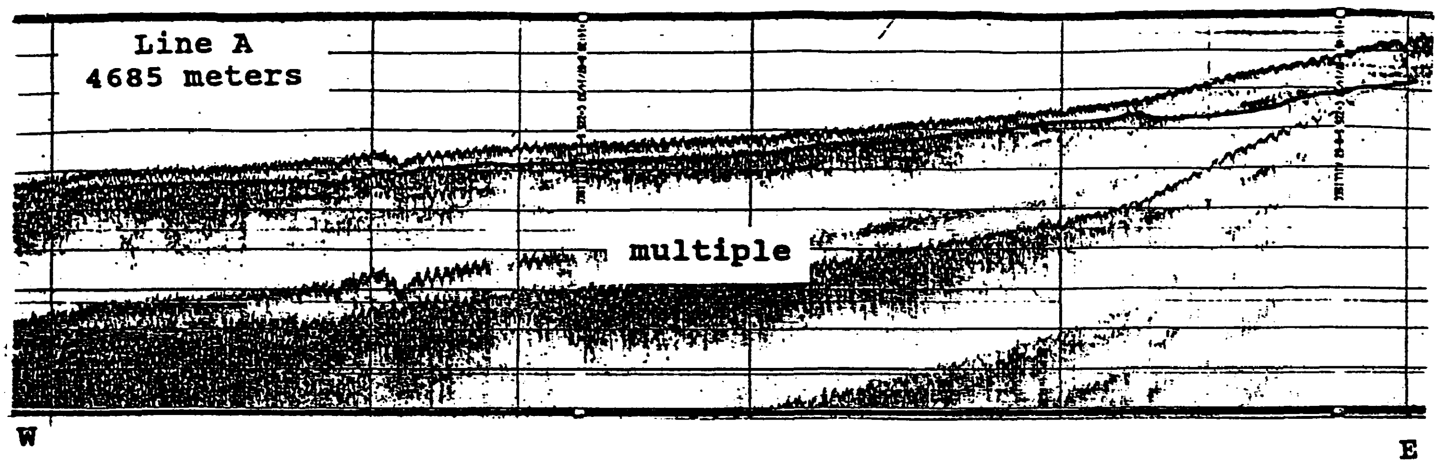
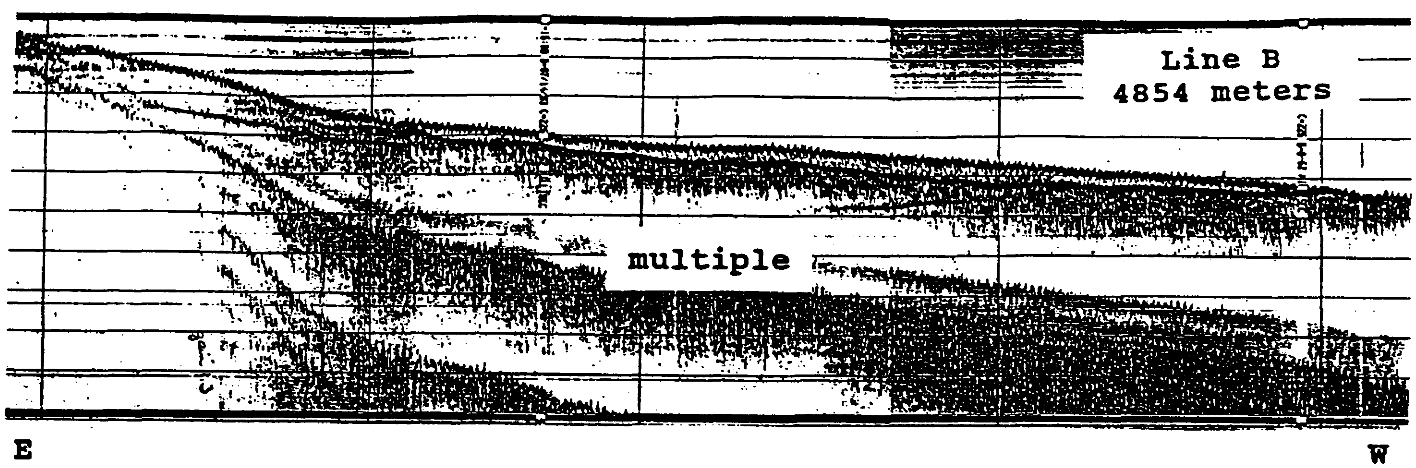
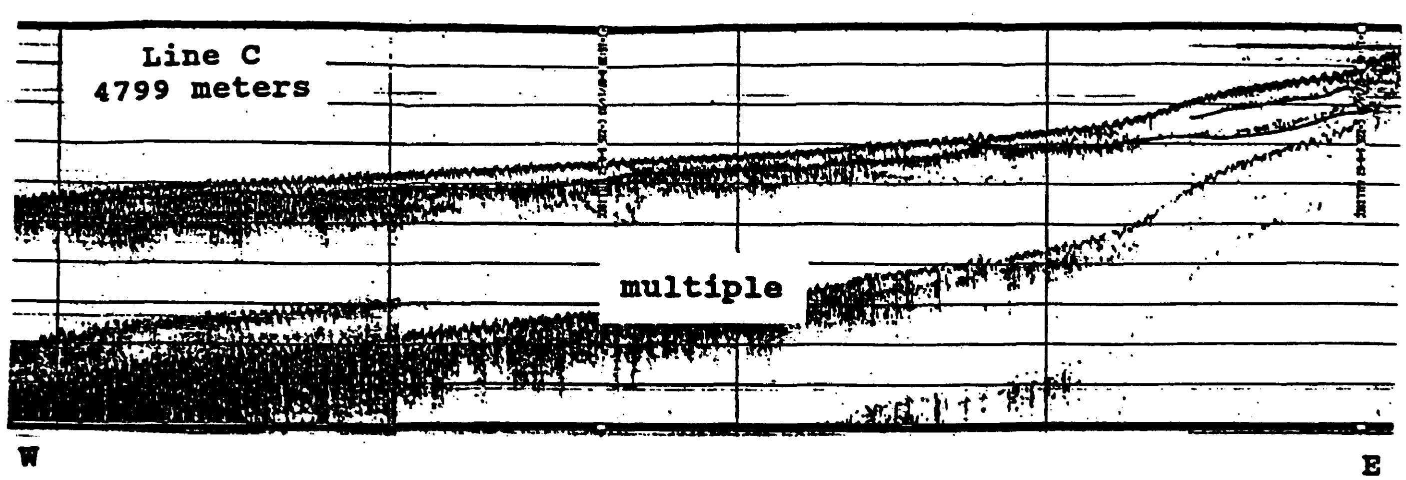
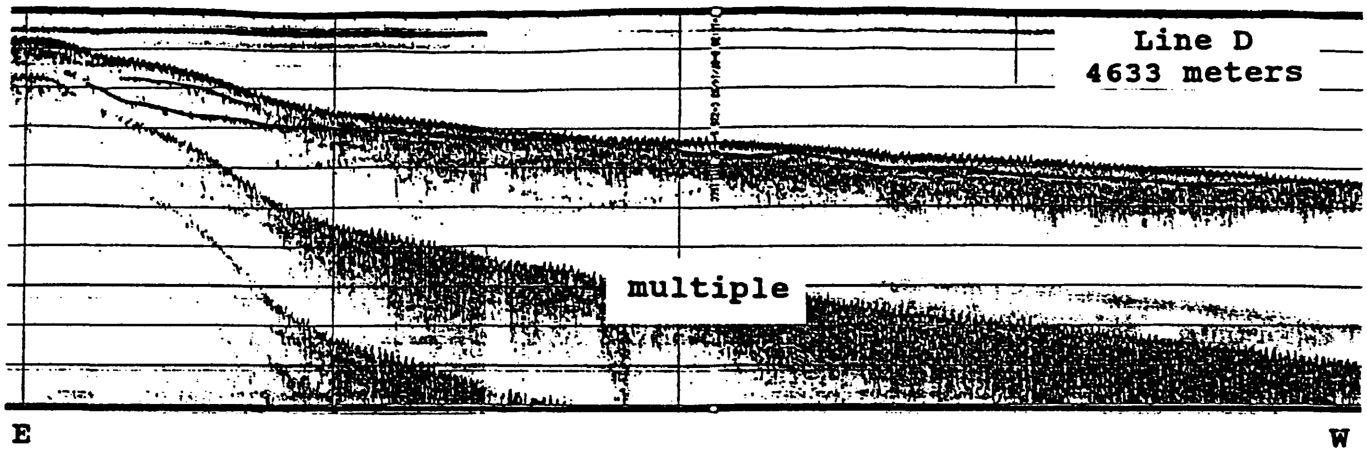

Track Lines Run Off
Duck, North Carolina
diver core
30ft
36.20
Currituck
Sound
pier
Atlantic Ocean
60ft
36.15
-75.80
-75.75
-75.70
-75.65
Degrees Longitude
Degrees Latitude
pier
coastline
30 feet
60 feet
1993
1994

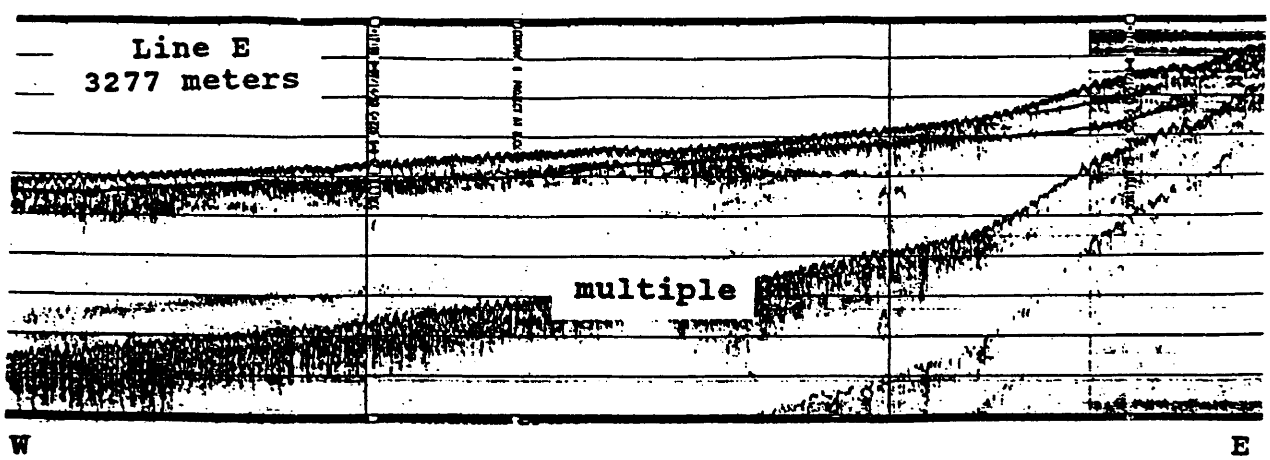
Figure 15. Copies of 5 seismograms from the 1993 field effort. The sub-bottom reflectors that were digitized have been emphasized. The vertical scale on each profile is 0.062 s or approximately 46.5 m at 1500 m/s. Distances represent track line lengths.


Line A
4685 meters
multiple
W
E


Line B
4854 meters
multiple
E
W


Line C
4799 meters
multiple
W
E


Line D
4633 meters
multiple
E
W


Line E
3277 meters
multiple
W
E

discontinuous unit between Reflector 3 and the sediment-water interface and interpret it as a Holocene transgressive sand sheet.

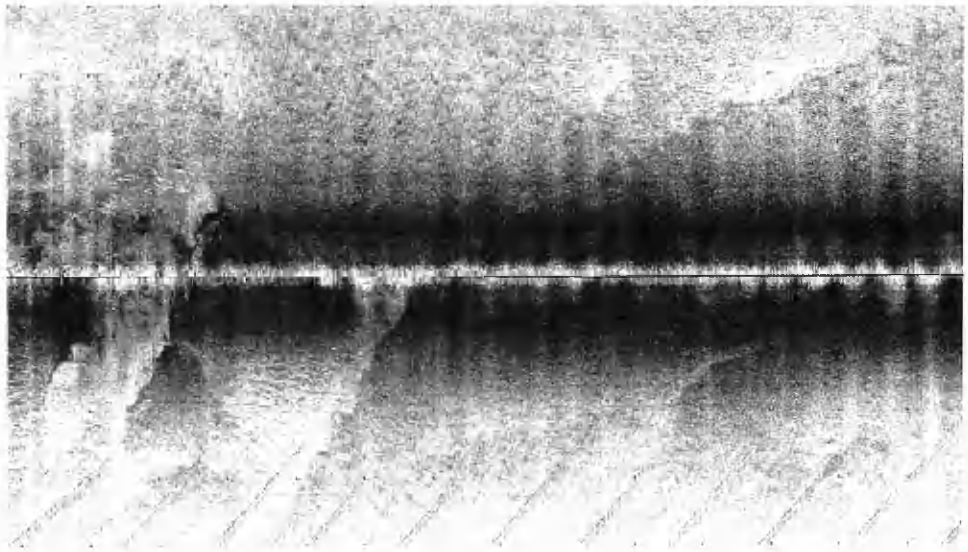
Units E (Meisburger and Williams, 1987; Meisburger et al., 1989) is stratigraphically congruent with Unit D, occurring between Reflector 3 and the sediment-water interface, but is found in shallower water shoreward of the 11 m isobath, where it pinches out. Unit E is traceable to subaerial beach and dune deposits (Figure 6).

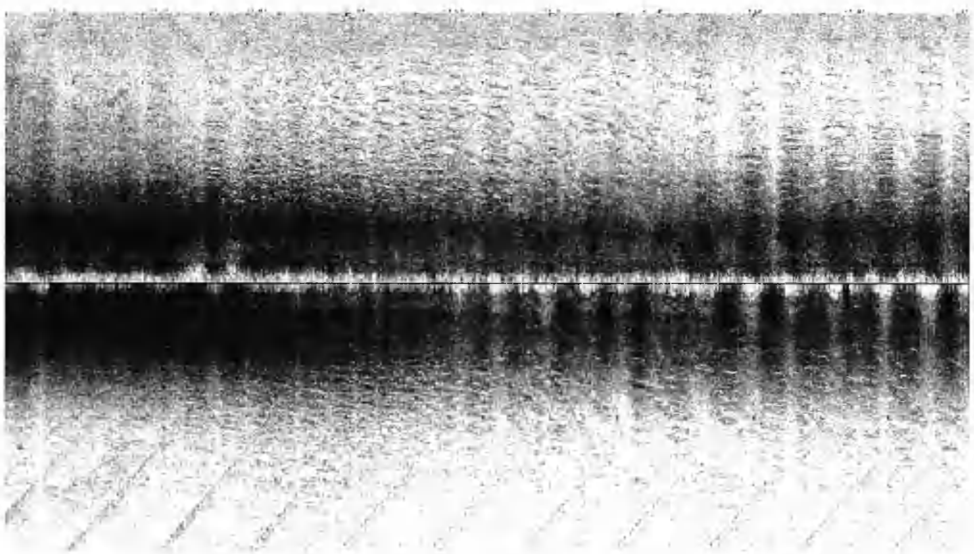
- Surface Morphology and Sediments -

Bathymetric profiles and seismic records, surveyed to aproximately the 20 m isobath, show concave upward shoreface profiles. Four reflectors, including the seafloor, appear in the seismograms (Figure 15). Side-scan sonograms from July 1994 show a rippled bottom and a change in sediment type at and near the 20m depth (Figure 16). The side-scan sonograms also show what appear to be pock-mark indentations in the bottom surface. A very thin sand-cover overlying a darker mud provides the contrast evident in Figure 17.

The 20m core was taken from a "pock-marked" bottom (related to large ripples) where the sand cover thinned to a "feather edge" over finer, darker deposits (Figures 18). Sediment analysis revealed that the diver core taken at 20m penetrated the transition between the active shoreface sand

Figure 16. Side-scan sonograms from near the 20 meter isobath. Notice the change in sediment type depicted by contrasting shades in A and the pock-like structures in B and C.





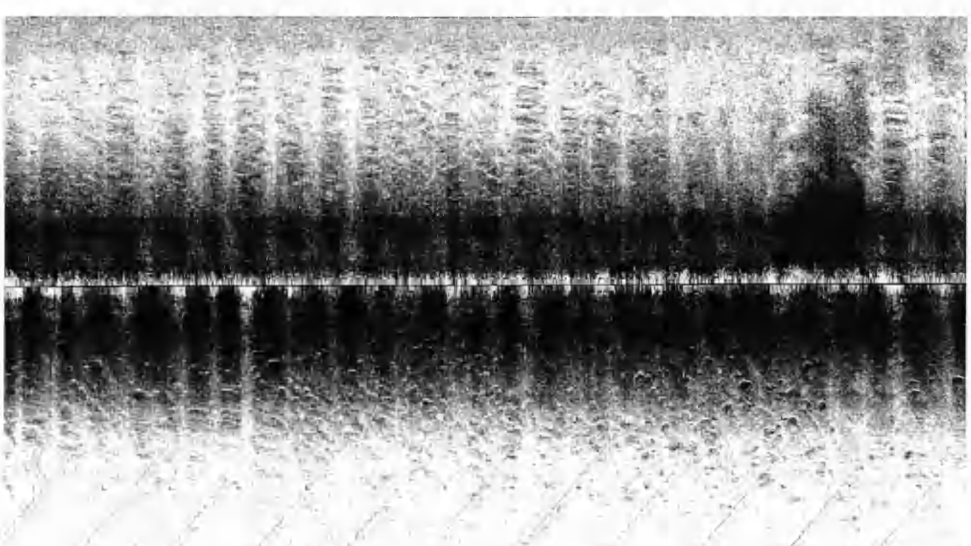


Figure 17. Photograph of the bottom at 20 meters showing morphology and thinning of Holocene sand lens over the darker, exposed lagoonal sediments and shell fragments.

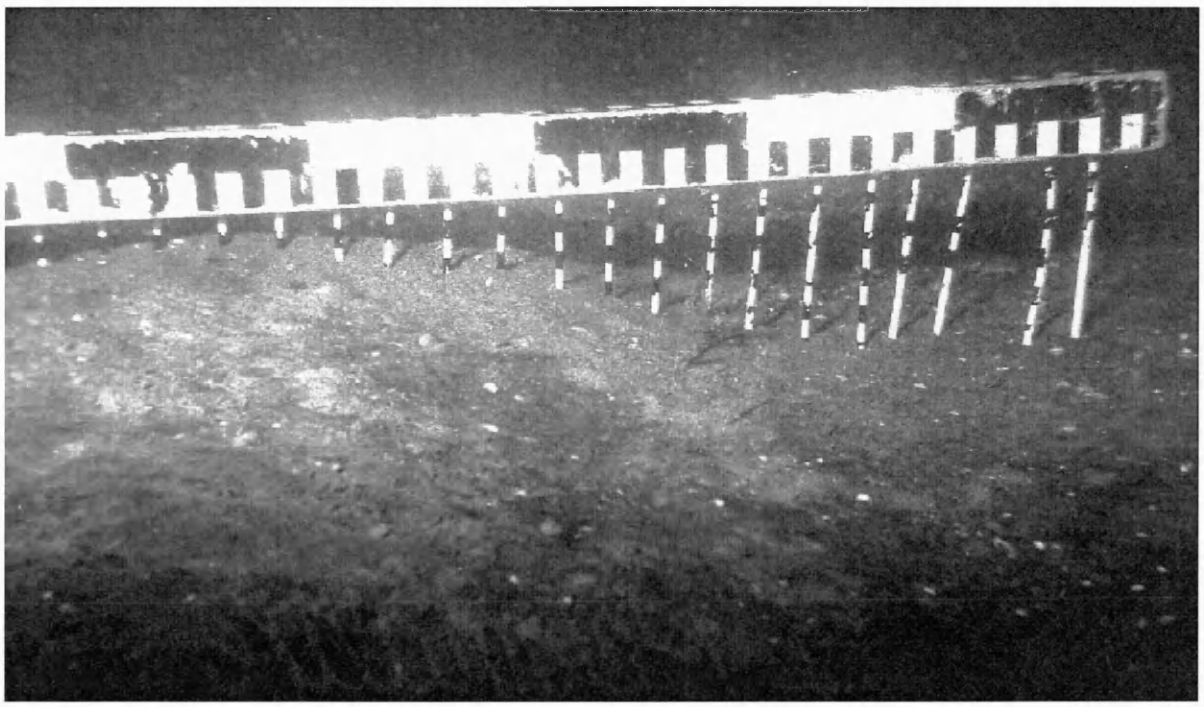
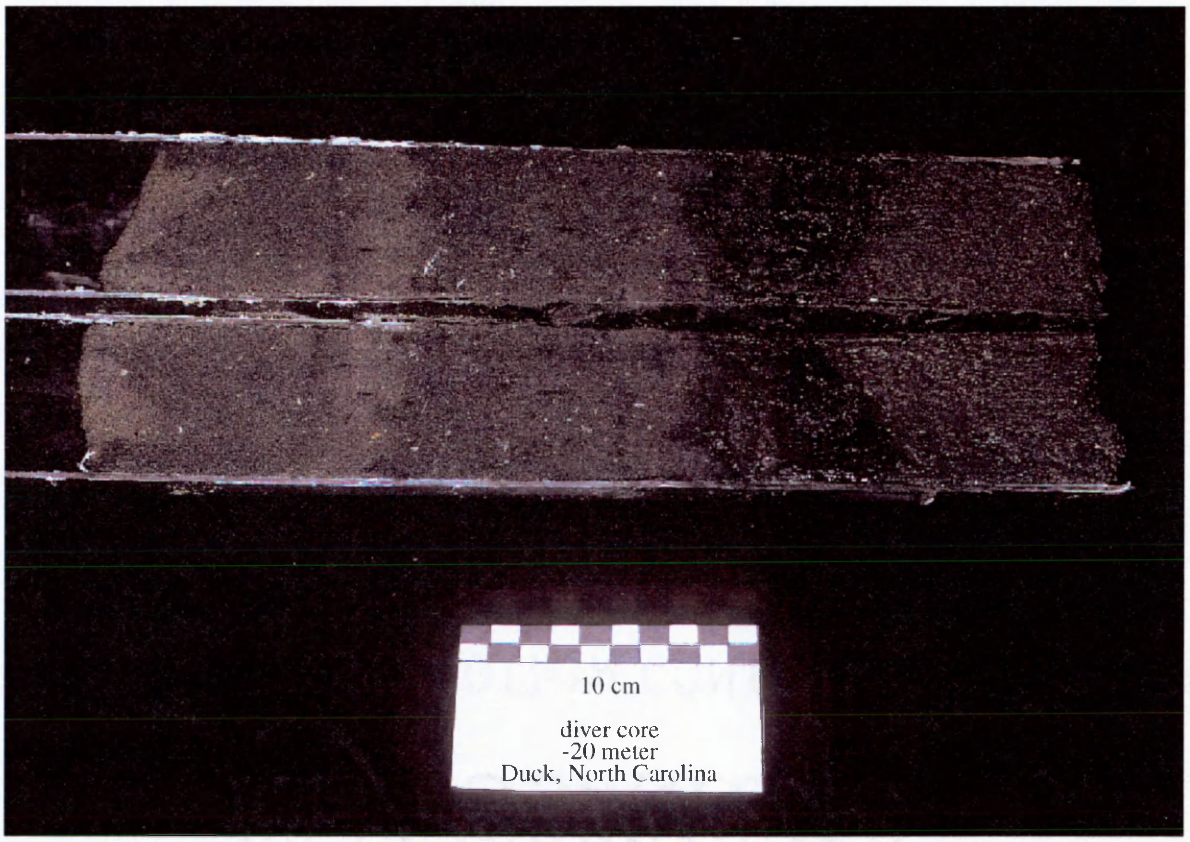


Figure 18. Photograph of the diver core taken at 20 m showing darker, lagoonal sediment (right of center) topped by Holocene sand to the right.


10 cm
diver core
-20 meter
Duck, North Carolina

wedge and the relict lagoonal deposits. The core was composed mostly of sand from the top to near 20 cm depth, where the composition became much finer (Figure 19-A); the lower portion of the core being nearly 70 percent clay and only 9 percent sand. The mean grain-size of the fine fraction greater that 95 percent of the sediment sample was 0.43 microns with a modal diameter of 0.23 microns (Figure 19-B). The core taken at 9 m depth had a nearly uniform, sandy composition (Figure 19-C). Shells (Figure 20) were found on the bottom surface of the exposed lagoonal material where the diver core was taken.

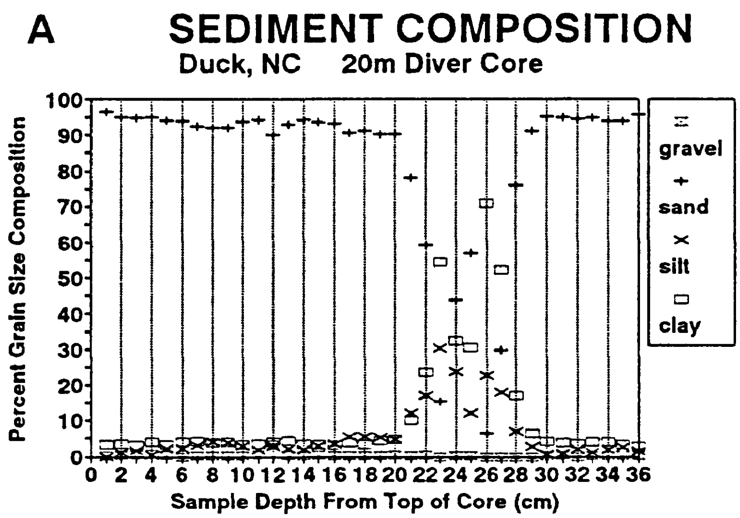
- Apparent Upper Shoreface Envelope of Change -

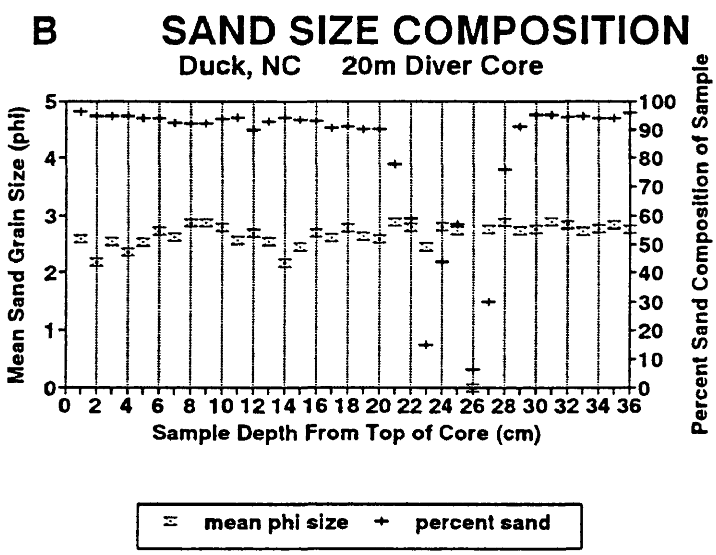
Assuming that the sediments between Reflector 3 and the seafloor constitute the Holocene sand deposit, the volume of Holocene sands in the study area is estimated to be 15.74 x 10^6 m^3 with the profiles having an average cross-sectional area of 10.01 x 10^3 m^2. Digitization and calculation of Lee and Birkemeier's (1993) envelope of change (Figure 11) yielded a cross-sectional area of 1.34 x 10^3 m^2.

- Profile Parameters -

The statistical analysis of the data resulted in curves with goodness-of-fit (Davis, 1986) values better than 0.988. The best fit values of A, m, h_o, and x_o and goodness-of-fit (R^2) are presented in Table 2. Figures 21 and 22 show the

Figure 19. Sediment composition plots of samples taken from 20m A and B, and 9 m, C, diver cores. Phi = $-\log_2$(mm), where the grain size diameter is given in millimeters.


A
SEDIMENT COMPOSITION
Duck, NC 20m Diver Core
Percent Grain Size Composition
Sample Depth From Top of Core (cm)
gravel
sand
silt
clay


B
SAND SIZE COMPOSITION
Duck, NC 20m Diver Core
Mean Sand Grain Size (phi)
Percent Sand Composition of Sample
Sample Depth From Top of Core (cm)
mean phi size
percent sand

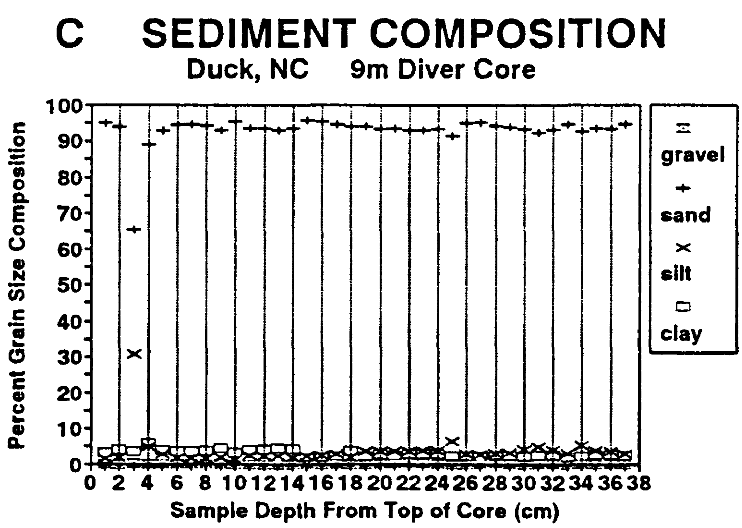

C
SEDIMENT COMPOSITION
Duck, NC 9m Diver Core
Percent Grain Size Composition
Sample Depth From Top of Core (cm)
gravel
sand
silt
clay

Figure 20. Photograph of estuarine shells found at exposed lagoonal sediment near 20 meter isobath (Figure 18). Top-center shell is *Mercenaria mercenaria*, left and right shells are well-weathered oysters.

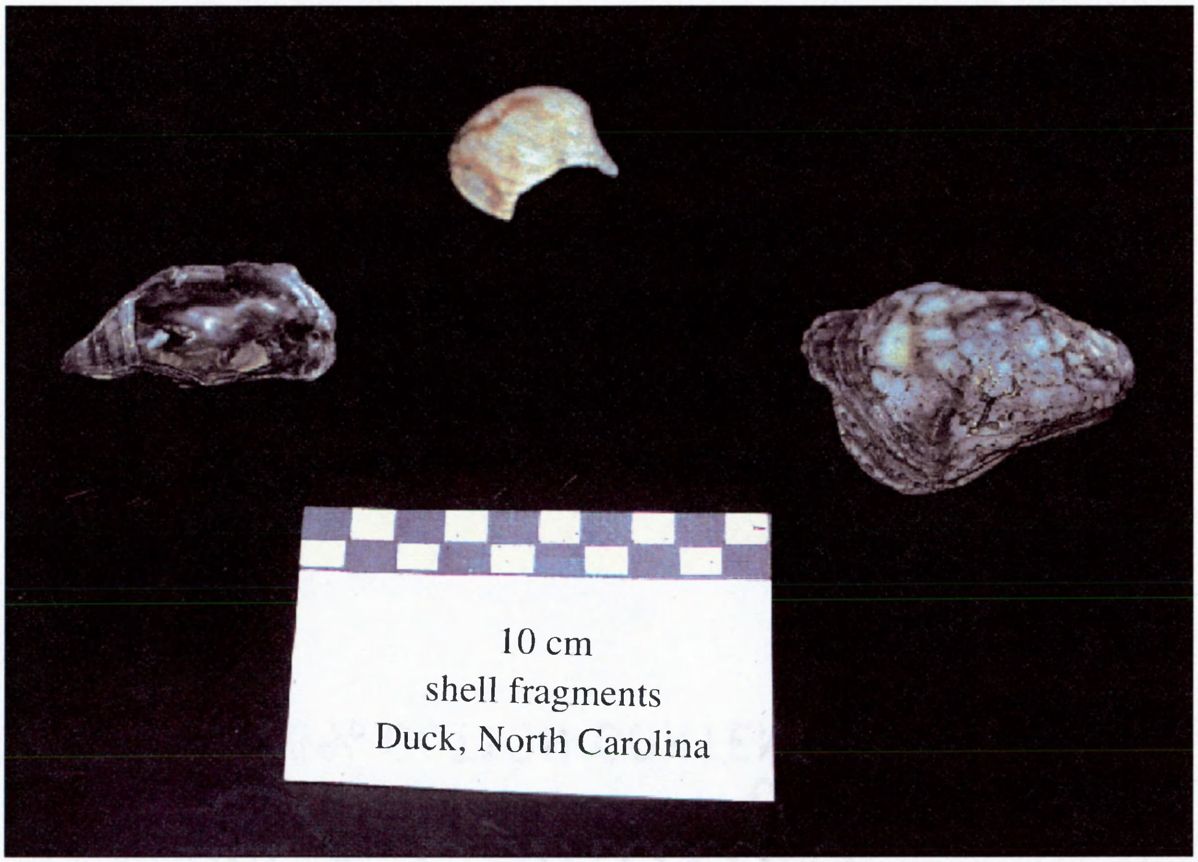
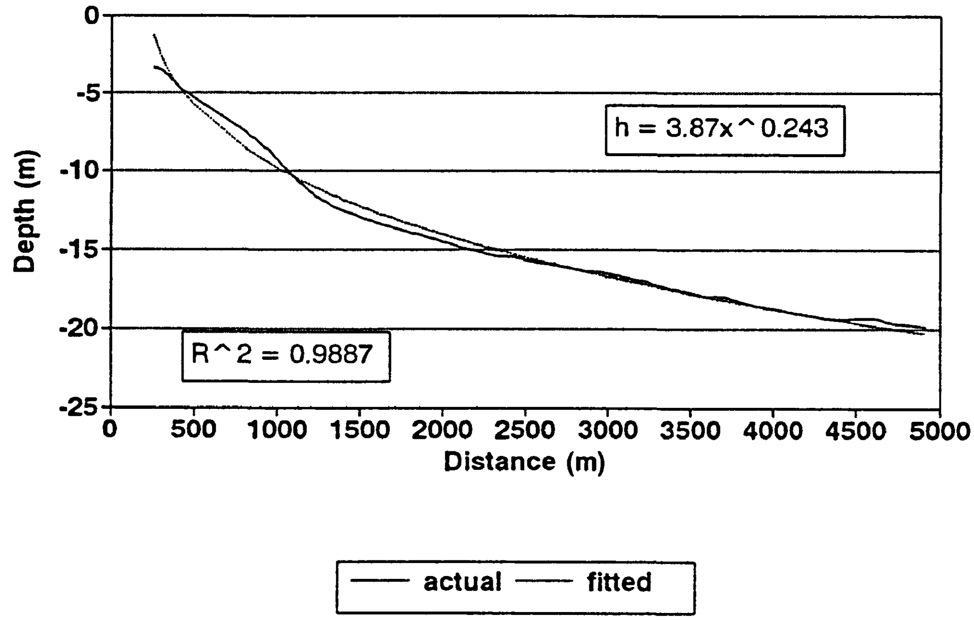

10 cm
shell fragments
Duck, North Carolina

Figure 21. Fitted profile curves depicting best fit parameters for the equation $h = Ax^m$. Distance offshore represents distance from the Field Research Facility's benchmark.

A Fitted Profile Curve
bottom



B Fitted Profile Curve
sub-bottom

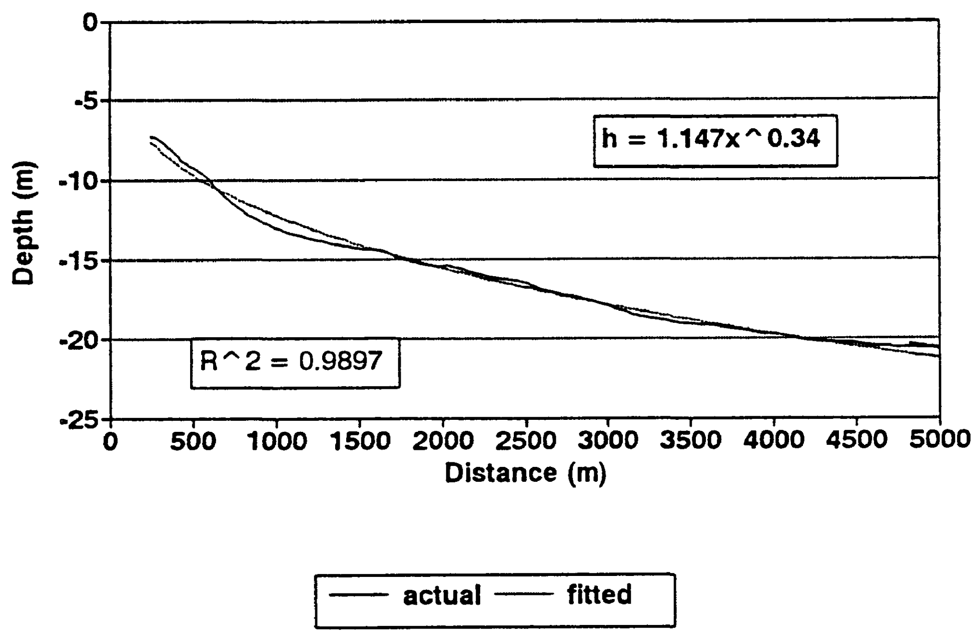
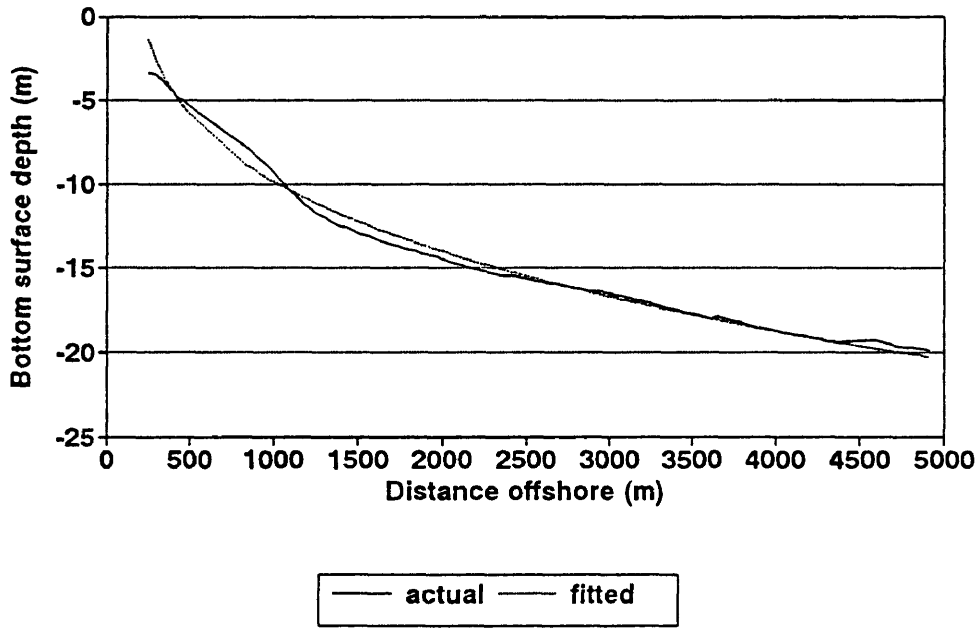


Figure 22. Fitted profile and residuals of the shoreface plotted from the Field Research Facility's benchmark.

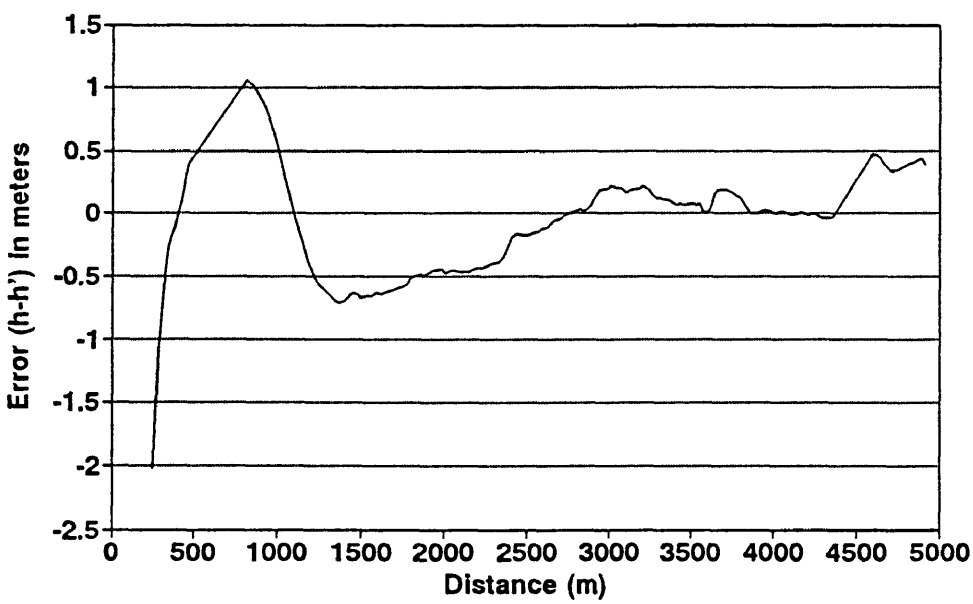
Fitted Profile Curve and Residuals

bottom and sub-bottom



Residuals

from bottom fit

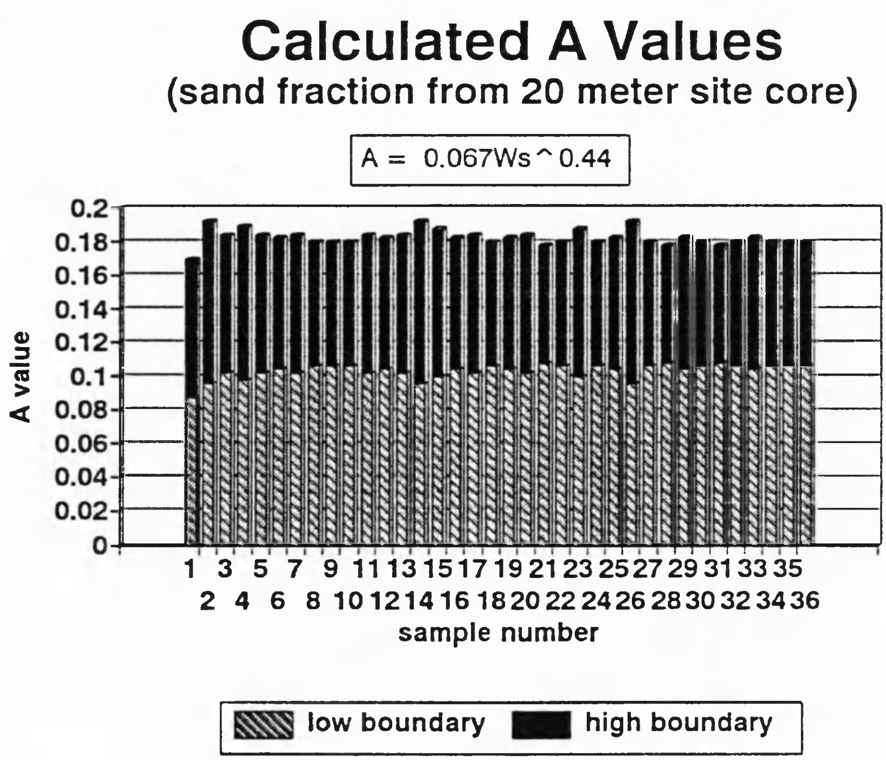


predicted and actual curves and the residuals plotted relative to offshore direction for the bottom fit, respectively. Note when h_0 and x_0 were made zero for the curve fitting procedure, A = 0.188, m = 0.561, R = 0.9944, and standard deviation of the error equalled 1.08. Values of A were estimated using settling tube (RSA) data for settling velocities of the mean grain size (Figure 23).

TABLE 2
BEST FIT FOR THE PARAMETERS A AND m
OF THE CURVE $h = Ax^m$
DUCK, NORTH CAROLINA, JULY, 1993

Parameters	bottom profile	sub-bottom profile
A	3.8700	1.1470
m	0.2430	0.3400
x_o	170.0000	0.0000
h_o	10.0000	0.0000
R^2	0.9887	0.9897

Figure 23. Estimated A values from settling tube (RSA) data. Boundaries represent phi sizes within which the mean grain size fell and their respective settling velocities.



Calculated A Values
(sand fraction from 20 meter site core)
A = 0.067Ws^0.44
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
A value
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35
2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36
sample number
low boundary
high boundary

- Model Calculations-

The second reflector from the top of the seismic record was assumed to represent the erosional reflector found in separating Unit C from Units D and E. It was also assumed that this reflector represents the substrate over which sediment migrated during the Holocene transgression.

Digitized lines were then integrated with Lee and Birkemeier's (1993) shoreface-profile to represent the shoreface from the benchmark established by the FRF out to the seaward extent of the seismic track lines, approximately the 20 m isobath.

Table 3 shows the results of curve fitting and the input data used by the model discussed earlier. Values of m ranged from 0.199 to 0.386 while A values ranged from 0.550 to 3.985.

Input parameters which resulted in m and A values closest to the actual profile included sand volume inputs ranging from 300 to 600 m^3 per one meter increment of sea level rise. The number of repetitions giving the closest values of A and m was 23. The depth of the sand body toe origin, where the model placed the first sand body below mean sea level (Figure 13), gave best results when equal to 40 meters. Closest fit values of A and m also ocurred when limiting the fit of the curve out to 20 meters depth, relating to the depth of the average seismic line fitted earlier.

TABLE 3

Input values used in the shoreface translation model, best-fit parameters, goodness-of-fit values (R), and the standard deviation of the errors. Sediment volume is in cubic meters per increment of sea level rise and depth, h_o, and x_o are in meters.

Fit #	m	A	ho	Xo	R	std err	sed vol	depth	repetitions	comments		
1	0.345	1.018	2	-7	0.999934	0.128717	500	40	24			
20 1	0.199	5.914	15	-107	0.999914	0.860136						
2	0.378	0.676	1	-3	0.99991	0.173174	500	40	22			
20 2	0.361	0.78	1	-2	0.999908	0.566633						
3	0.378	0.671	1	-3	0.999906	0.155578	700	40	22			
20 3	0.361	0.779	1	-2	0.999897	0.569627						
4	0.356	0.885	2	-10	0.999906	0.136246	500	43	20			
20 4	0.231	3.836	11	-96	0.99991	0.717184						
5	0.367	0.764	1	-2	0.999932	0.148526	500	40	23	m=0.24		
20 5	0.24	3.408	10	-88	0.999912	0.704522						
6	0.376	0.677	1	-3	0.999917	0.17356	400	40	22			
20 6	0.361	0.78	1	-2	0.999932	0.567645						
7	0.367	0.774	1	-2	0.999955	0.102417	300	40	23			
20 7	0.231	3.836	11	-96	0.99991	0.715712						
8	0.367	0.768	1	-2	0.999943	0.124567	400	40	23			
20 8	0.238	3.475	10	-84	0.999933	0.71266						
9	0.379	0.666	1	-3	0.999948	0.11279	500	40	22	1 @ 1000		
20 9	0.326	1.116	3	-18	0.999943	0.612306						
10	0.381	0.673	1	-3	0.999899	0.192743	1000	40	23			
20 10	0.325	1.218	3	-16	0.999844	0.667819						
11	0.369	0.778	1	-2	0.999907	0.158025	1000	40	24			
20 11	0.229	3.985	11	-84	0.999846	0.845007						
12	0.356	0.886	2	-10	0.999935	0.12598	500	40	23	a=0.01	b=0.50	23,22 no mud
20 12	0.24	3.408	10	-88	0.999912	0.704522						
13	0.396	0.55	1	-5	0.999522	0.360068	1000	38	23	a=0.01	b=0.50	
20 13	0.34	0.947	2	-9	0.999837	0.888978						
14	0.386	0.602	1	-4	0.999813	0.224638	500	39	22	a=0.01	b=0.50	
20 14	0.358	0.779	1	-2	0.99989	0.839607						
15	0.357	0.885	2	-10	0.999935	0.124951	500	40	23	a=0.01	b=5.00	22,23 no mud
20 15	0.232	3.795	11	-98	0.999915	0.711932						
16	0.39	0.598	1	-4	0.999809	0.244088	1000	39	23	a=0.10	b=5.00	
20 16	0.313	1.366	4	-30	0.999823	0.644392						
17	0.356	0.886	2	-10	0.99993	0.13008	500	40	23	m=0.67		
20 17	0.24	3.409	10	-88	0.99991	0.702102						
18	0.381	0.673	1	-3	0.999904	0.193124	1000	40	23	m=0.67		
20 18	0.328	1.185	3	-17	0.999866	0.898612						
19	0.367	0.768	1	-2	0.999943	0.124208	400	40	23	m=0.67		
20 19	0.24	3.44	10	-86	0.999925	0.710631						
20	0.367	0.767	1	-2	0.999944	0.127812	435.22	40	23			
20 20	0.23	3.884	11	-93	0.999935	0.08189						
21	0.367	0.768	1	-2	0.99991	0.162258	900	40	23			
20 21	0.308	1.484	4	-25	0.999886	0.108877						
22	0.367	0.771	1	-2	0.99992	0.14541	800	40	23			
20 22	0.325	1.218	3	-16	0.999881	0.111127						
23	0.366	0.776	1	-2	0.99993	0.12895	700	40	23			
20 23	0.289	1.837	5	-32	0.99991	0.096673						
24	0.366	0.777	1	-2	0.99993	0.127613	600	40	23			
20 24	0.274	2.179	6	-40	0.999914	0.094516						
25	0.366	0.786	-2	1	0.999958	0.123192	0	40	23			
20 25	0.259	2.608	7	-45	0.999959	0.0855						

Goodness-of-fit values were high with the best valueof 0.999959 with a standard deviation of error of 0.0655, which was also the best deviation value. A and m values here were 2.608 and 0.259, respectively. Ranges for h_o and x_o were 1 to 15 and -107 to -1 meters, respectively.

The profiles run through a linear regression with fixed values of m, solving for A, produced the values listed in Table 4. Goodness-of-fit values were much lower, with the standard deviation of the errors of predicted and actual profiles being higher. The Inman curve with m = 0.40 resulted in poor goodness-of-fit values also but had smaller deviation of error values.

A "smooth" transgression substrate was created using the m and A best fit values for the substrate. The shoreface translation model was run over the artificial substrate using m = 0.34, A = -1.147, and the input values listed for fit number 5 in Table 3. The original x_o and h_o for the smooth fit were not iterated for the best fit values but were kept the same for comparison. Fitting parameters changed greatly when the smooth substrate was used as opposed to the real substrate (Table 5).

TABLE 4

Results from the linear regression with fixed m values.

	m	A	R	std error
Dean 1	0.67	0.030	0.700913	1.587569
20m	0.67	0.043	0.656505	1.291823
Dean 2	0.67	0.030	0.700158	1.557052
20m	0.67	0.042	0.657322	1.284882
Dean 3	0.67	0.030	0.701884	1.603079
20m	0.67	0.043	0.656844	1.293416
5	0.67	0.030	0.700904	1.588020
20m	0.67	0.043	0.656373	1.288171
12	0.67	0.030	0.700904	1.588020
20m	0.67	0.043	0.656373	1.288171
13	0.67	0.028	0.692905	1.387656
20m	0.67	0.037	0.659087	1.293919
Inman	0.40	0.534	0.611228	0.147916
20m	0.40	0.496	0.598808	0.174288

TABLE 5

The best fit vlaues of actual substrate compared to an artificially smooth substrate.

Profile Type	m	A	h_o	x_o	R	std error
actual	0.367	0.764	1	2	0.999932	0.149
20m	0.240	3.408	10	88	0.999912	0.705
smooth	0.401	0.755	1	2	0.996588	0.935
20m	0.303	2.498	10	88	0.995586	0.690

Discussion

"Classical" equilibrium profile concepts may be used for general description of shoreface profiles, but they fall short of describing "unique" characteristics of individual profiles. Dean's (1990) method of using linear regression on the profiles for determination of A shows a decrease in the goodness-of-fit values for all profiles analyzed by linear regression. Values for A where m was fixed at 0.67 ranged from 0.028 to 0.043. These results do not correlate with the present m and A values found off the Duck, North Carolina site. Values of A where m was fixed at 0.40 were 0.534 and 0.496. These m and A values correlate more closely with those found through logarithmic regression values for Duck, but indicate that fixed m values do not characterize the profile well. Calculated values of A (Figure 23) based on grain size and settling velocities did agree with the range of 0.0 to 0.3 proposed by Dean (Pilkey et al., 1993), while solving for A with a fixed m at 0.40 gave different results.

Best fit calculations of the logarithmically transformed equilibrium profile model (Equation 1) show the present profile created within the Holocene sand lens to be similar to the findings of Inman et al. (1993). Comparisons show that shifting the point of origin for the curve using h_o and x_o does result in better fit values for the shoreface profile. Those fit values for h_o and x_o change greatly possibly due to offsets created by the logarithmic transformation. This technique, as opposed to Dean's, allows for simultaneous solutions of A and m and produces a more characteristic profile fit. The value of 0.243 for m conforms more closely to a profile with m near 0.40 rather than with the model of m = 0.67 favored by Dean (1990) et al., but still does not support either model well.

The relict shoreface, assumed to be Unit C (Meisburger et al., 1989), over which the Holocene transgression occurred, had a best fit m value of 0.34. Again, the value agrees much more closely with Inman et al.'s (1993) values for the same modern day area rather than with Dean's (1990) notion that m should be 0.67.

One way to check the resolution of a model equation is to plot the residuals. Residuals from best fit estimations indicate that Equation 1 does not account for other variables that significantly influence the profile. The best fit curve does show deviation nearshore and again offshore (Figure 22). This is most probably due to changing sediment characteristics, seasonality (nearshore envelope of change), and complicated geotopic configurations such as the exposed lagoonal material. A plot of the residuals shows a systematic pattern as opposed to a random pattern. Random distribution of the residuals would indicate that a best-fit equation accounted for most of the significant variables, suggesting a better fit.

One possible missing parameter is the seasonal activity, or envelope of change, of the Holocene sand sheet. The sand sheet is directly underlain by a relict lagoonal unit at depths less than 20 meters. Calculations of cross-sectional area of the sand unit yield values an order of magnitude larger than those of Lee and Birkemeier's (1993) modern envelope of change (Figure 11). Therefore, the modern, decadal-scale envelope of change has little effect in the millennial-scale change associated with the entire sand lens and the shoreface transgression of the profile. The modern envelope of change is, however, positioned where most of the systematic deviation from the fitted profile equation occurs, indicating an absent varible associated with modern, geologic change.

Outcropping geologic formations may account for another missing varible of "classical" models. Surface micro-morphology and grain size are affected significantly by outcropping of underlying strata which is likely to cause significant across-shelf variations in morphodynamic behavior of the shoreface. Meisburger and Williams (1987) and Meisburger et al. (1989) describe the sedimentary unit as a fossiliferous, backbarrier, lagoonal deposit. The diver core obtained at 20 meters depth (Figures 18 and 19) and the shells found at the study site (Figure 20) appear to support this description. Residuals (Figure 22) begin to uniformly increase near 20 meters depth where the outcropping formation occurs along the shoreface profile. This deviation could account for ignoring geologic influences, indicated by changing grain-size characteristics, when modelling the shoreface profile.

Cowell et al.'s (1990) shoreface translation model produced profiles similar to those found off Duck, North Carolina. The shoreface translation model's results show closest results to those of the present shoreface when fitting resultant profiles out to the 20 meter depth distance. This depth represents the extent of seismic lines run off shore and the point at which the lagoonal material of Unit C is exposed. A 23 increment sea level rise with a sediment input near 500 m^3 also resulted in best fits when translating sea level over the substrate. The estimation of the volume of sand contained in the Holocene sand lens was also divided by 23, representing 23 meters change in sea level, to determine a sediment input value per increment of sea level rise. A 435.22 m^3 per one meter increment of sea level rise resulted in a reasonable fit with values for an A and m of 3.884 and 0.23, respectively (Table 2). Most of the fitted curves produced values consistent with those found using Inman, et al.'s (1993) regression techniques.

The shoreface translation model was also used to test the possible influece of the underlying geology on the shoreface profile. Profile reproductions similar to the modern Duck, North Carolina profile were obtained using acutal substrate data. Profile reproductions over a smooth, artificial substrate did not agree as well with the modern profile. This indicates that the morphological characteristics of underlying formations should be addressed when modelling shoreface profiles.

SUMMARY

This study concluded that "classical" concepts of shoreface profile modelling can be used for overall, general application, but do not account for important variables which appear to influence the profile shape. Model residuals that show a systematic pattern possibly reiterate Pilkey et al.'s (1993) arguement that assumptions made when using Dean's model account for lost variables which should not be ignored. Deviations from the model occurred where the lagoonal substrate emerged and where the active envelope of change was located, indicating decadal- and millennial-scale geological influences on the profile.

The shoreface of the study area apparently has a locally characteristic range of values for m and A when the "profile of equilibrium" model is used. This indicates, therefore, that specific shoreface profiles cannot be accurately described using constant A and m values.

It can also be concluded that Cowell et al.'s (1992) shoreface translation model is a good tool for estimating past depositional environments which produced today's profiles. The 23 increments indicate that the deposition of the Holocene sand sheet off Duck, North Carolina began 8,000 years ago. Sediment input parameters also indicate an input of sediment near 500 m^3 for each meter rise in sea level. Dimensions used to recreate the sand body which was marched over the geologic substrate may reflect the dimensions of the past sand body as reflected by the reasonable curve fitting results. The substrate over which the translation occurred also indicated the influence of its shape, and therefore the geology, on the modern shoreface.

APPENDIX

SHOREFACE TRANLATION MODEL OPERATION

Certain values were considered constant for this study site such as Xs, Ys,and Xb which represent shoreline distance to surf base (900m), depth at surf base (8m), and maximum sand body width (700m), respectively (Figure 13). Values were determined by using Birkemeier et al.'s (1989) envelope of change, which extends out to a depth of 8m, the distance offshore where the 8m depth occurs, and the width of the barrier island at the present site for the dimensions of the sand body. Values of the exponential parameter, m, were varied using 0.240, 0.243, 0.400, and 0.670. The gradient of repose, rise in mean-sea-level, surge level, and the shelf width options were all left to default values (Figure 13). Mud deposition rate and mud volume deposited parameters were altered as shown in Table 3. Exogenous sand volume values were changed from no input to 1,000 m^3 per one meter increment of sea level rise. Negative values were not used here since it would remove the underlying substrate and not create a sand lens found in the modern or present day profile.

The model was run with varying depth values for the substrate below sea level. This value positioned a sand body with the toe (Figure 13) at that depth along the substrate profile. Repetition of sea level rise increments were also varied (Table 3). One increment represents a one meter rise in sea level. The most common number of repetitions used was 23 to simulate past sea level below present mean sea level.

Resultant profiles were then analyzed for best fit parameters of A and m to see which resultant profile was closest to today's shoreface profile and to try to estimate the possible environment of deposition for the Holocene sand lens. The procedure discussed previously for statistical analysis was used here. Iterations of x_0 and h_0 were used for best fit values. Curves were fitted twice; once for the entire length of the model output profile, and once for the length of the profile out to 20 meters depth. The 20 meter depth relates to the maximum depth of the average seismic line and the point where Unit C is exposed (Table 3).

Three curves were run through the model with m values of 0.67, three curves with values of 0.243, and one with an m value of 0.40 and were fitted for best fits for A with m fixed (Table 3). A linear regression was performed solving for A with m constant, which is similar to how Dean (1990) analyzed best-fit parameters for his curves. Dean's estimation of m was represented by the first three fits, the actual value of m found on today's profile was represented by the following three fits, and the last fit represents Inman's estimation of m with it fixed at 0.40. These curves also were fitted to the extent of the model's output profile and again out to the 20 meter depth distance on the profile.

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