

# Origin, evolution, and distribution of shoreface sand ridges, Atlantic inner shelf, U.S.A.

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## ABSTRACT

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A computer mapping system was employed to document the location of 259 shoreface-attached and detached sand ridges in water < 20 m deep and the temporal and spatial distribution of 309 historical and active tidal inlets along the U.S. Atlantic coast (Montauk Point, New York, to Miami Beach, Florida). This database was compiled through the analysis of over 600 historical maps, 50 bathymetric charts, and other published data. A genetic relationship between the location of certain historical and active tidal inlets and shoreface-attached sand ridges is documented. It is inferred that ebb-tidal deltas provided the initial sand source for the development of many shoreface-attached sand ridges.

Although shoreface-attached sand ridges appear to have several different modes of formation, a two-step process for the development of most shoreface-attached and detached sand ridges along U.S. Atlantic barrier island and cape coastlines is proposed: (1) sand is deposited as ebb-tidal deltas or river deltas along the lower shoreface and/or inner continental shelf prior to or during transgression, followed by (2) further transgression, which reworks the deltaic sand bodies into linear sand ridges at the base of the shoreface by shelf processes. The best-developed shoreface sand ridge fields along the U.S. Atlantic shelf lie adjacent to shorelines characterized by all of the following: (1) transgression, (2) mixed energy, wave-dominated barrier islands, and (3) laterally migrating tidal inlet systems. Tidal inlet systems are natural sediment sinks that capture sand carried by longshore sediment transport. Ebb-tidal delta deposits associated with these migrating tidal inlets provide the initial sand body for the development of shoreface-attached sand ridges. The oblique orientation and linear form of shoreface-attached sand ridges appear to be a function of shoreline transgression, lateral inlet migration, and wave reworking of ebb-tidal delta deposits concentrated along an ebb-tidal delta retreat path. Shelf processes act as modifying agents in the evolution of sand ridges during and after ebb-tidal delta deposition. In general, shoreface-attached sand ridges are poorly developed or absent along eroding headlands, spits, and barrier island shorelines characterized by naturally stabilized tidal inlets. These latter inlets and shoreline types are dominated or influenced by one or all of the following: (1) antecedent topography, (2) higher tidal ranges, (3) larger tidal prisms, (4) lower wave energies, or (5) finer grain sizes.

The coupling of shoreline and shallow marine sedimentary processes during a transgression is critical to the origin, evolution, and distribution of shoreface sand ridges in the study area. Modern shoreface-attached sand ridges are also known to occur in different coastal and shelf settings where large amounts of sediment were supplied to the shoreface and inner shelf during, or immediately before, transgression.

Commonly observed vertical and lateral interrelationships of Holocene shoreface-attached sand ridges and tidal inlets or distributary channels have important ramifications for the development of shelf sandstone facies models. In addition, the geometric relationship documented in this study provides predictive petroleum and hard mineral exploration models of the spatial and temporal distribution of shoreface and shelf sand ridges.

## Introduction

The origin of sand ridges on continental shelves around the world has been well debated since the late 1930s. Although numerous hypotheses have

been proposed for the formation and development of shore-oblique sand ridges, no single theory has conclusively accounted for the origin, orientation, and distribution of these features. In fact, most hypotheses are speculative because of logistical

difficulties of data collection on the shoreface and inner continental shelf. By recognizing and incorporating the influence of coastal as well as shelf processes, this study takes a significant step towards the systematic, regional analysis of shoreface-attached and detached sand ridges along the U.S. Atlantic inner shelf.

Shoreface sand ridges are oriented at oblique angles in relation to the shoreline along the U.S. Atlantic inner shelf (Duane et al., 1972; Figueiredo et al., 1981). These shoreface-attached and detached sand ridges consist of unconsolidated fine-to-medium-grained sand and are normally characterized by a closed bathymetric contour (Duane et al., 1972; Swift et al., 1972a). They are generally over 1000 m long, have relief up to 10 m, side slopes that average less than  $1^\circ$ , and are 1–3 km wide with wavelengths of 1–8 km [Duane et al., 1972; Field, 1980; Figueiredo et al., 1981; Figueiredo, 1984 (pp.17–21)].

Previously published hypotheses for the origin of shore-oblique shelf and shoreface sand ridges can be divided into two broad categories. First, it has been postulated that modern shelf and shoreface sand ridges are static in nature, being relict, pre-transgressive features (i.e., barrier islands, beach ridges, the result of fluvial drainage patterns, etc.) and remnants of the Holocene transgression (Veatch and Smith, 1939; Sanders, 1962; Shepard, 1963; McKinney and Friedman, 1970; Kraft, 1971; McClennen and McMaster, 1971). Second, the oblique ridges are considered a product of shelf processes (post-transgressive) and are in equilibrium with the modern shelf hydraulic regime [Moody, 1964 (pp.13, 145, and 159); Uchupi, 1968]. Subsequent studies by Duane et al. (1972), Swift et al. (1972a, b, 1973, 1978, 1984), Stahl et al. (1974), Stubblefield and Swift (1976), Field (1980), Figueiredo et al. (1981), Swift and Field (1981a, b), Parker et al. (1982), Niedoroda et al. (1985), Swift (1985), Green (1986), Hoogendorn and Dalrymple (1986), and Rine et al. (1986) have concluded that significant amounts of ridge and swale topography on the inner shelf and shoreface develop in response to intense storms (extratropical and tropical) on the surficial sand sheet at the base of the shoreface (ravinement) during erosional

shoreface retreat. Stubblefield and McGrail (1979) and Stubblefield et al. (1983, 1984a, b) also conclude that shore-oblique ridges are post-transgressive, but suggest that shore-parallel ridges form in association with degraded barriers. Dolan et al. (1979a) and Dolan and Hayden (1980) also have suggested that edge waves may be responsible for the development of these shore-oblique features while Boczar-Karakiewicz and Bona (1986) proposed infragravity waves as a mechanism for ridge development.

Although previous studies have documented the relief, morphology, and evolution of shoreface-attached sand ridges on the U.S. Atlantic shelf, no systematic, field-tested explanation has been presented for the origin, orientation, and distribution of these features. To our knowledge, only five studies [Field and Duane, 1976; Field, 1976 (pp.54–57, 169–170 and 131–135), 1980; Halsey, 1978 (pp.437–452); Figueiredo, 1984 (pp.357–371)] have suggested a genetic link between sand ridges on the shoreface and sand deposits (i.e., ebb-tidal deltas) associated with the contemporaneous shoreline. It is postulated that ebb-tidal deltas are the concentrated sinks of sand from which many shoreface sand ridges develop. This paper supports and refines this hypothesis. Furthermore, the present study recognizes the importance of shelf processes, which act upon ebb-tidal delta deposits and rework the sand body into one or more shoreface sand ridges. This investigation focuses on shoreface-attached and shoreface-detached sand ridges along a 2200 km stretch of the U.S. Atlantic shelf (Fig.1). In this paper, we (1) examine the geographic, geologic, and genetic relationships between and among the barrier island coastline, the shoreface, and the inner continental shelf in those areas where sand ridges occur, (2) analyze the distribution of shoreface-attached and detached sand ridges and tidal inlets along the Atlantic coast of the United States, (3) present a six-stage model for the development of shoreface sand ridges, (4) present three case studies showing the relationship between tidal inlet systems and shoreface sand ridges, and (5) discuss the implications of the model for shelf stratigraphy in modern and ancient settings.

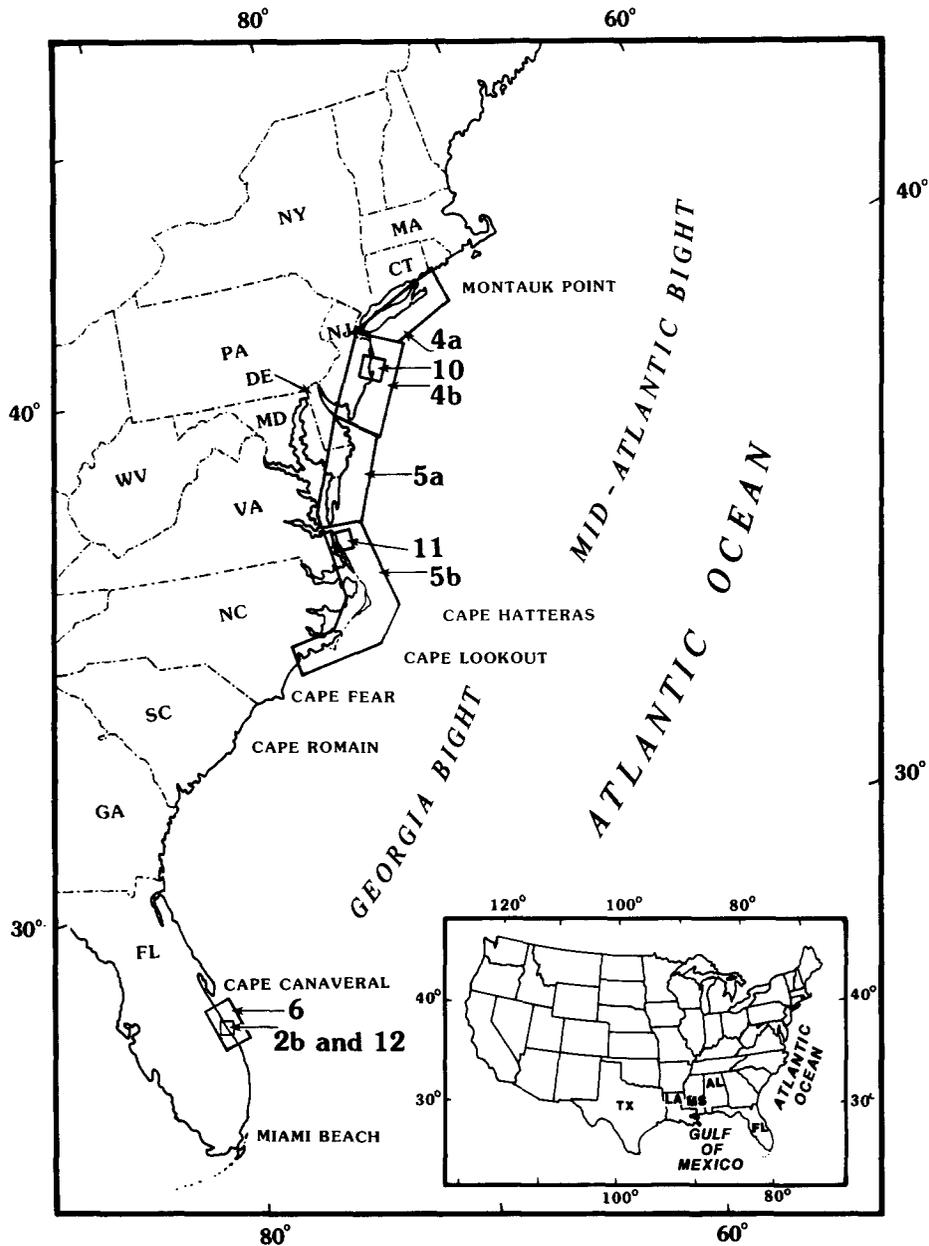


Fig.1. Study area along the U.S. Atlantic coast and inner shelf (Montauk Point, New York, to Miami Beach, Florida). Numbered boxes represent locations of figures in this paper.

## Methods

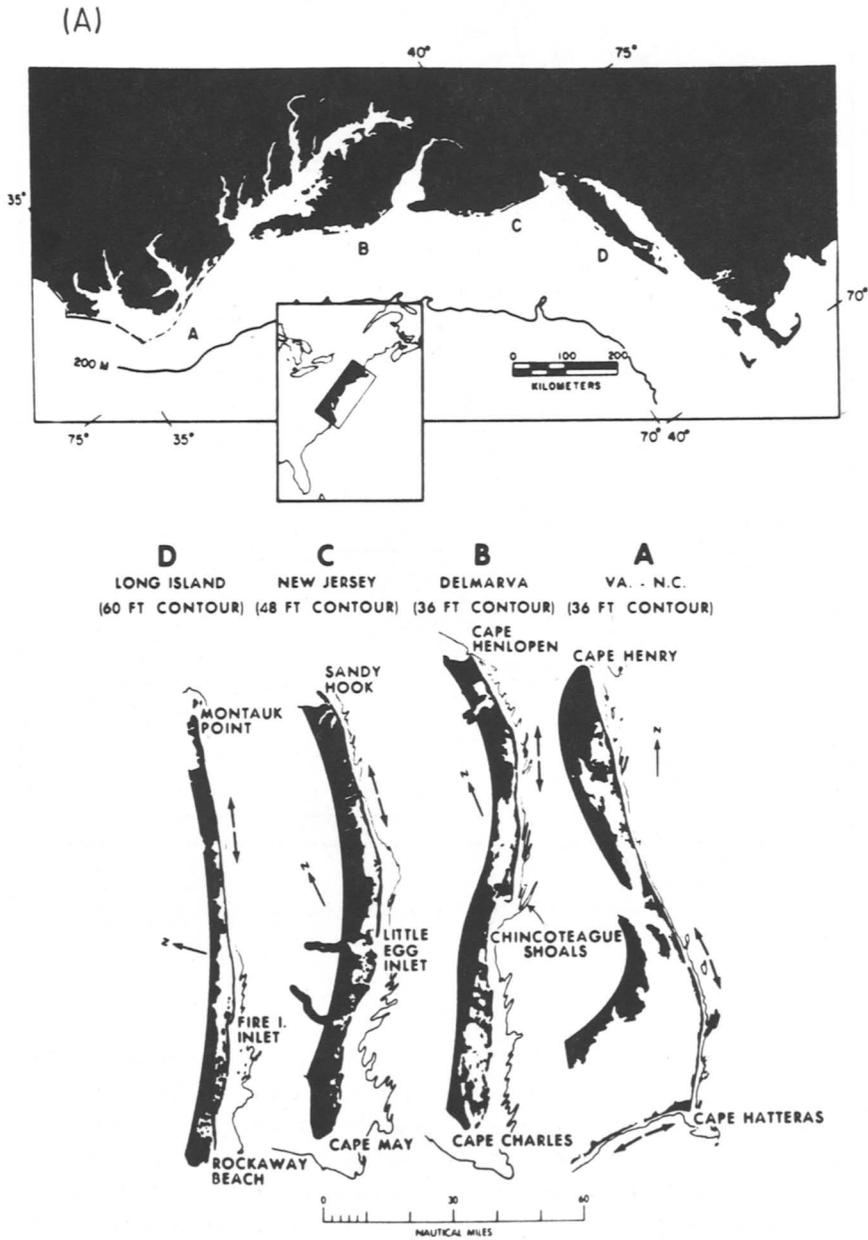
Only shoreface-attached and detached sand ridges (linear shoals as defined by Duane et al., 1972, p.453) lying in water less than 20 m deep on wave- and storm-dominated parts of the U.S.

Atlantic inner continental shelf were examined to investigate the link between shoreface retreat and modern-day ridge formation. This depth restriction limits this study to the active shoreface and the most landward part of the inner continental shelf, thereby excluding mid-shelf and outer shelf sand

ridges. Also, tide-built sand ridges are not a part of this study. The ridges under study occur within the friction-dominated and transition zones, which lie between the surf and geostrophic zones (Swift et al., 1985, p.345).

A set of base maps depicting shoreline position, tidal inlet location, and bathymetry was required to determine whether a relationship exists between ebb-tidal deltas and shoreface sand ridges. To meet

this need, a regional database of bathymetric and tidal inlet data was created using an Intergraph computer mapping system that combines computer cartography, computer-aided design and drafting (CADD), and a geographical information system (GIS). Intergraph provided the tool to compile all the different data into a common database. The database was created in three steps. First, shorelines and nearshore bathymetry (0–20 m) along



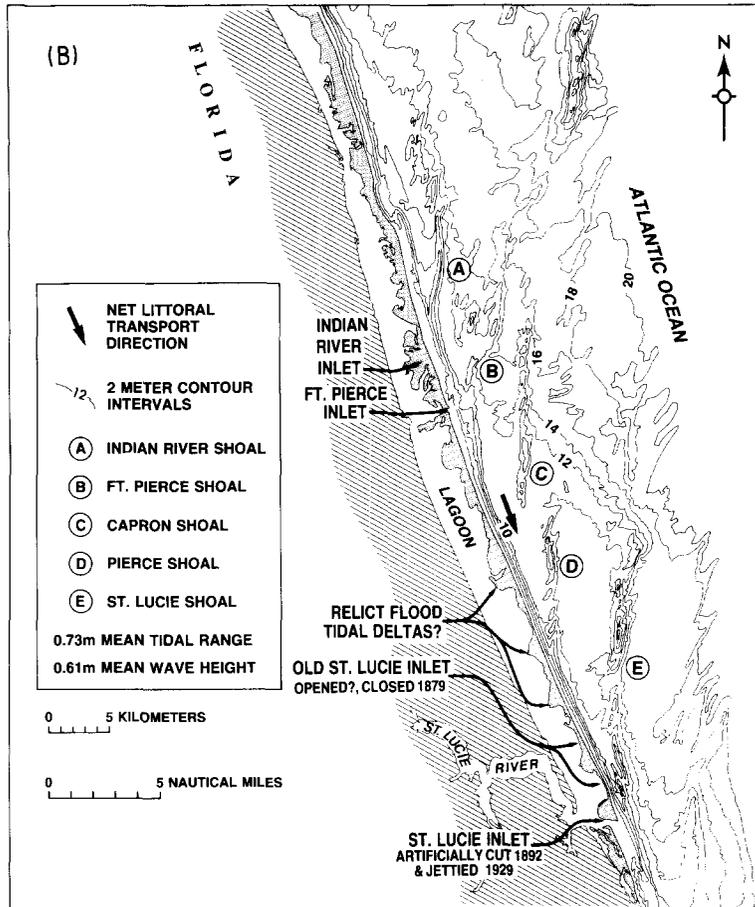


Fig.2. (A) Shorelines of the Mid-Atlantic Bight. Four well-developed sand ridge fields occur along Long Island, south-central New Jersey, Maryland, and northern North Carolina (from Duane et al., 1972 and Swift, 1975). (B) Intergraph map showing tidal inlet locations along the Fort Pierce sand ridge field, south-central Florida. Note the well-developed relict flood-tidal delta morphology along the back side of the barrier island shoreline, suggesting former tidal inlet locations. These relict flood-tidal deltas are adjacent to the position where the sand ridges are attached to the shoreface.

the entire Atlantic coast from Montauk Point, New York, to Miami Beach, Florida, were digitized into the computer mapping system at the CADGIS Research Laboratory, Louisiana State University, Baton Rouge. Fifty bathymetric and topographic-bathymetric charts (scales 1:100,000 and 1:250,000) published by the National Ocean Survey (NOS) and the U.S. Geological Survey (USGS) were analyzed; from these charts, 259 shoreface sand ridges were identified and digitized (e.g., Fig.2b).

Second, tidal inlet data (i.e., location, name(s), years opened, and presence/absence of artificial stabilization) were derived from primary and secondary sources, such as core-hole data, published and unpublished documents, and over 600

historical maps. These data yielded information about the temporal and spatial distribution of 309 historical, active, and artificial tidal inlets along the U.S. Atlantic coast. Inlets identified primarily on the basis of historical data (i.e., maps, nautical charts, or air photos) or stratigraphic observations (i.e., cores) are referred to as historical or closed inlets. Currently open tidal inlets are referred to as either active or artificial. Active inlets open naturally, whereas artificial inlets are created exclusively by human activity.

Finally, the tidal inlet data were integrated with the shoreline and bathymetric data. As a result, eight computer-generated maps depicting tidal inlet information as well as barrier island morphol-

ogy, bathymetry (0–20 m), tidal ranges, and wave heights were produced and serve as the primary database for this study (McBride, 1986a, b, 1987).

### Regional setting

The continental shelf along the east coast of the United States is an offshore extension of the gently seaward dipping coastal plain. The continental shelf is bounded on the west by one of the longest barrier island chains in the world and on the east by a break in slope at an average depth of 80 m, marking the beginning of the continental slope (Emery and Uchupi, 1984). The Atlantic seaboard is referred to as a trailing edge (passive margin) coast characterized by depositional landforms, the most common of which are barrier islands (Inman and Nordstrom, 1971; Glaeser, 1978).

Fisher (1967, 1982) developed a coastal compartment classification for the Mid-Atlantic Bight, which divided the coast into four shoreline types based on descriptive geomorphology: (1) northern or cusped spit, (2) eroding headland, (3) southern spit, and (4) barrier island chain. This model was modified by the authors of this study by incorporating a coastal classification based on coastal processes (Nummedal et al., 1977; Nummedal and Fischer, 1978; Hayes, 1979; Davis and Hayes, 1984). As a result, the “modified Fisher model” used in this study includes the following shoreline types: (1) cusped foreland or spit, (2) eroding headland, (3) wave-dominated barrier islands, (4) mixed energy, wave-dominated barrier islands, (5) mixed energy, tide-dominated barrier islands, and (6) tide-dominated barrier islands.

Tides along the U.S. Atlantic coast are semidiurnal. Mean tidal range varies from north to south from 0.6 m at Montauk Point, New York, to 1.1 m at Cape Lookout, North Carolina, to 2.2 m at St. Helena Sound Entrance, South Carolina, and to 0.6 m at Jupiter Inlet, Florida (U.S. Department of Commerce, 1987). Spring tidal ranges at these locations are 0.7 m, 1.3 m, 2.6 m and 0.9 m, respectively. Average significant wave heights based on hindcast calculations vary from 0.68 m at Montauk Point, New York, to 0.74 m at Cape Lookout, North Carolina, to 0.58 m at St. Helena Sound

Entrance, South Carolina, and to 0.82 m at Jupiter Inlet, Florida (Jensen, 1983).

### Results

Different types of shoals as discussed by Duane et al. (1972, p.456) occur irregularly along the entire inner continental shelf from Montauk Point, New York, to Miami Beach, Florida [McBride, 1986a, (plates 1–8)]; however, particularly well-developed fields of shoreface-attached and detached sand ridges (linear shoals) occur along five specific sections of the coastline: (1) Long Island, New York, (2) New Jersey, (3) Maryland, (4) northern North Carolina, and (5) southern Florida (Fig.2).

#### *Sand ridge orientation*

A common characteristic of all five sand ridge fields is the similar range of sand ridge orientations (5–50°) in relation to the shoreline, despite changes in shoreline orientation for each coastline (Fig.3). Orientations were determined by means of a technique described by Figueiredo et al. (1981), which measures the angle between the axis of the sand ridge and the adjacent shoreline.

The average orientation of the 259 shoreface sand ridges measured in this study is 29°. The 54 sand ridges on the Long Island shoreface and inner shelf have an average orientation of 39° (Fig.3A). The primary mode occurs between 45° and 49°, with a secondary mode between 25° and 29°. Average orientations of the 71 New Jersey and 77 Delmarva shoreface and shelf sand ridges are 26° and 25°, respectively (Figs.3B and C). Primary modes for both lie between 15° and 19°. The 43 sand ridges on the North Carolina and Virginia shoreface and inner shelf have an average orientation of 26° with a primary mode between 20° and 24° (Fig.3D). Overall, the southern Florida inner continental shelf has fewer sand ridges, but they are large and well developed. The average orientation for the fourteen Florida ridges is 26°, with a primary mode between 20° and 24° (Fig.3E). The common range of orientations of the major shoreface sand ridge fields suggests that the ridges develop in response to a similar process or mecha-

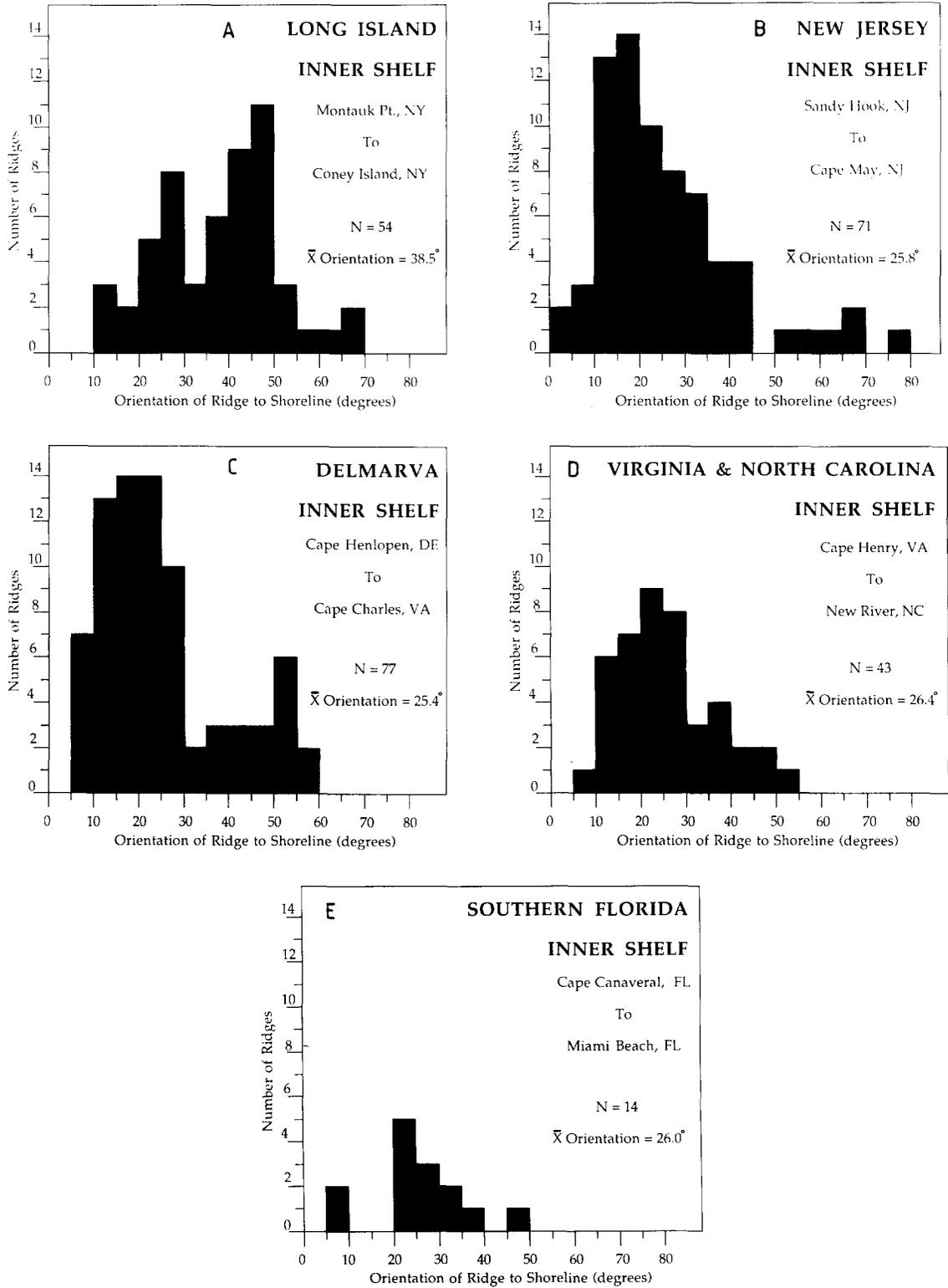


Fig.3. Histograms showing the orientation of shoreface-attached and detached sand ridges in relation to the adjacent shoreline along Long Island (A), New Jersey (B), Delmarva (C), southern Virginia and North Carolina (D) and southern Florida (E).

nism occurring specifically along the five sections of coastline mentioned above.

### *Tidal inlet distribution and barrier island morphology*

Hydrographic conditions, such as tidal range, wave energy and direction, storm magnitude and occurrence, and tidal prism, in addition to the influence of antecedent topography and substrate, are believed to be major factors controlling the distribution, morphology, and migrational behavior of tidal inlets (Hayes, 1981). Many site-specific studies have been completed on active tidal inlets (see Barwis, 1976; Weishar and Fields, 1985; Boothroyd, 1985). However, on a regional scale, a relatively limited number of studies have focused on the location, physical characteristics, length of time open, and migrational behavior of historical tidal inlets [Haupt, 1906; Fisher, 1962 (pp.8–9, 20–37, 45–52, 88–116, and fig.9); Moody, 1964 (pp.136–140); Truitt, 1967; Rice et al., 1976 (pp.150, 152–345); Everts et al., 1983; Leatherman and Allen, 1985; McBride, 1986a, b, 1987]. Fisher (1962) stands out as a classic in terms of historical inlet studies. Researchers that have examined the distribution and morphology of active tidal inlets on a regional basis include Hayes and Kana [1976 (p.1–96)], Nummedal et al. (1977), Nummedal and Fischer (1978), and Hayes (1979). The present study reflects a compilation of historical, active, and artificial tidal inlets along a majority of the U.S. Atlantic coast, permitting a regional analysis of the spatial distribution of tidal inlets over a 2200 km stretch of coastline.

The spatial distribution of 164 historical and 145 active tidal inlets along the U.S. Atlantic coast is compiled in Tables 1 and 2. Five distinct trends are identifiable: (1) historical tidal inlets are twice as dense along mixed energy, wave-dominated barrier islands as along mixed energy, tide-dominated or tide-dominated barrier islands (0.14 vs. 0.07 inlets/km), (2) the density of active inlets located along mixed energy, tide-dominated and tide-dominated barrier islands is 4.3 times greater than along mixed energy, wave-dominated and wave-dominated barriers (0.13 vs. 0.03 inlets/km), (3) the number of active tidal inlets has a tendency

TABLE 1

Historical, active, and artificial tidal inlets, Atlantic coast, USA

LOCATION	INLETS			TIDAL RANGE <sup>1,2</sup>	WAVE HEIGHT <sup>3,4</sup>
	Historical	Active	Total		
A. EASTERN LONG ISLAND (Montauk Pt. NY to Fire Island Inlet, NY)	26	3	29	0.60-1.25	0.67
B. WESTERN LONG ISLAND (Fire Island Inlet, NY to Coney Island, NY)	7	4	11	1.25-1.43	0.53
C. NORTHERN NEW JERSEY (Sandy Hook, NJ to Little Egg Inlet, NJ)	26	4	30	1.13-1.43	0.50
D. SOUTHERN NEW JERSEY (Little Egg Inlet, NJ to Cape May, NJ)	6	10	16	1.13-1.34	0.62
E. NORTHERN DELMARVA (Cape Henlopen, DE to Chincoteague Inlet, VA)	24	2*	26	1.04-1.25	0.58
F. SOUTHERN DELMARVA (Chincoteague Inlet, VA to Cape Charles, VA)	5	18	23	0.91-1.10	0.57
G. VIRGINIA/NORTHERN N. CAROLINA (Cape Henry, VA to Bogue Inlet, NC)	25	12*	37	0.58-1.10	0.65
H. SOUTHERN N. CAROLINA/NORTHERN S. CAROLINA (Bogue Inlet, NC to Cape Romain, SC)	19	27	46	0.67-1.37	0.57
I. SOUTHERN S. CAROLINA/GEORGIA/NORTHERN FLORIDA (Cape Romain, SC to Nassau Sound, FL)	4	45	49	1.37-2.19	0.64
J. NORTH-CENTRAL FLORIDA (Nassau Sound, FL to Cape Canaveral, FL)	8	7*	15	0.70-1.65	0.74
K. SOUTHERN FLORIDA (Cape Canaveral, FL to Key Biscayne, FL)	14	13*	27	0.60-1.07	0.73
<b>TOTAL</b>	<b>164</b>	<b>145</b>	<b>309</b>		

<sup>1</sup> Data from U.S. Dept. of Commerce (1987)

<sup>2</sup> High and low fluctuations in mean tidal range (meters)

<sup>3</sup> Data from Jensen (1983)

<sup>4</sup> Average significant wave height for the past 20 years (meters)

\* Includes artificially cut inlets

Location	Total Number	Artificial Inlets	Date(s) Open
Northern Delmarva	1	Indian River Inlet	1929
Northern North Carolina	1	New Drum Inlet	1970
Northern Florida	2	New St. Augustine Inlet	1940
		Fort Canaveral Inlet	1954
Southern Florida	7	Sebastian Inlet	1924, 1945
		Fort Pierce Inlet	1921
		St. Lucie Inlet	1892
		Lake Worth Inlet	1917
		South Lake Worth Inlet (Boynton)	1927
		Port Everglades	1928
		Government Cut	1902

to increase as tidal range increases, (4) the density of tidal inlets (historical and active) along both mixed energy, wave- and tide-dominated barrier islands tends to be similar (0.17 and 0.21 inlets/km), and (5) the density of inlets (i.e., historical and active) tends to be greater along mixed energy, wave-dominated and wave-dominated barrier shorelines that are adjacent to well-developed shoreface sand ridge fields.

As indicated in Table 1, coastal segments with more historical tidal inlets (A, C, E, G, H, and K) appear to alternate with regions characterized by fewer such inlets (B, D, F, I, and J). In general, coastlines with more historical tidal inlets are characterized by predominantly microtidal barrier islands (mixed energy, wave-dominated) and, to a

TABLE 2

Number and density of historical and active tidal inlets and shoreface sand ridges along different shoreline types, Mid-Atlantic Bight, USA

	Inlets		Ridges	Coastline length (km)	Inlets/km	Ridges/km
	Historical	Active				
<i>Mixed energy, wave-dominated and wave-dominated barriers</i>						
1. Long island, NY	25	3	37	108	0.26	0.34
2. New Jersey	11	2	30	78	0.17	0.38
3. Delmarva	23	2	63	86	0.29	0.73
4. Virginia/northern North Carolina	25	11	43	334	0.11	0.13
Total	84	18	173	606	0.17 (average)	0.29 (average)
<i>Mixed energy, tide-dominated and tide-dominated barriers</i>						
1. Long Island, NY	7	4	13	63	0.17	0.20
2. New Jersey	6	10	32	83	0.19	0.39
3. Delmarva	6	18	9	108	0.22	0.08
4. Virginia/northern North Carolina	0	0	0	0	0.00	0.00
Total	19	32	54	254	0.21 (average)	0.20 (average)
<i>Eroding headland</i>						
1. Long Island, NY	1	0	3	36	0.03	0.08
2. New Jersey	13	2	9	24	0.63	0.38
3. Delmarva	1	0	5	16	0.06	0.31
4. Virginia/northern North Carolina	0	1	0	21	0.05	0.00
Total	15	4	17	97	0.19 (average)	0.18 (average)
<i>Cuspate foreland/spit</i>						
1. Long Island, NY	0	0	0	9	0.00	0.00
2. New Jersey	2	0	0	13	0.15	0.00
3. Delmarva	0	0	0	6	0.00	0.00
4. Virginia/northern North Carolina	0	0	0	5	0.00	0.00
Total	2	0	0	33	0.06 (average)	0.00 (average)

lesser extent, by eroding headlands and cusped forelands or spits. The long and narrow microtidal barrier islands are broken by few intervening active tidal inlets (Table 1, column 3) and are backed by large, open-water lagoons, with the exception of the lagoons of southern Florida (K) and those along the northern part of southern North Carolina (H), which are distinctly long and narrow. These tidal inlets tend to have large, well-developed flood-tidal deltas and smaller ebb-tidal deltas.

Coastal segments with fewer historical tidal inlets (B, D, F, I, and J) are characterized by either low mesotidal (mixed energy, tide-dominated) or mesotidal (tide-dominated) barrier islands. These barrier islands are typically short and drumstick-shaped, and have more intervening active tidal inlets because of higher tidal ranges [Hayes and

Kana, 1976 (p.1–96); Nummedal and Fischer, 1978; Hayes, 1981]. Previous studies (Hayes and Kana, 1976; Hayes, 1981) have documented that mixed energy, tide-dominated and tide-dominated barrier islands have more active inlets than mixed energy, wave-dominated and wave-dominated barrier islands. However, when both the number and density (number of inlets divided by coastline length) of historical and active tidal inlets were examined (Table 2), the mixed energy, wave-dominated and wave-dominated barriers were associated with inlet densities that tended to be about equal to mixed energy, tide-dominated or tide-dominated barrier shorelines in the Mid-Atlantic Bight. In some cases however, wave-dominated barrier shorelines show higher than normal inlet densities. This occurs when tidal inlets open,

migrate laterally, and close more frequently (e.g., in response to more storms) causing the number of inlets to increase through time (These inlets are more than just storm breaches and must be open for at least 3 years.) As a result, the density of tidal inlets along these mixed energy, wave-dominated or wave-dominated barrier islands will be greater than along other types of barrier islands for any period of (geologic) time. This causes more ebb-tidal deltas (i.e., sand sinks) to exist on these shorefaces than those associated with other types of shorelines. This results in more point sources of sand for the development of shoreface sand ridges. Interestingly, the Maryland inner shelf, which is characterized by the most well-developed shoreface sand ridge field along the U.S. Atlantic shelf, lies adjacent to wave-dominated barriers with the highest density of inlets — 0.29 inlets/km.

*Tidal inlets, barrier islands, and shoreface sand ridges: spatial relationships*

A working hypothesis about the relationship between shoreline and shelf morphodynamics was developed for this study using observations by Duane et al. (1972, pp.460–461). We hypothesize that the major physical processes responsible for shaping and controlling coastal geomorphology also dictate the morphology and type of sand body on the adjacent shelf floor. If this is true, a link or coupling could be established between certain coastal morphologies and shelf sand bodies. The distribution of historical and active tidal inlets and shoreface sand ridges along five coastal segments with different shoreline types was compiled and examined to determine what relationship, if any, exists between coastal and shelf morphology (Figs.4, 5 and 6).

The major sand ridge field off Long Island lies along the western part of the mixed energy, wave-dominated barrier shoreline and the extreme eastern part of the mixed energy, tide-dominated barrier shoreline (Fig.4A). A smaller sand ridge field is found along the eastern part of the mixed energy, wave-dominated barrier shoreline. The mixed energy, wave-dominated barrier shoreline and the adjacent shelf are characterized by inlet and ridge densities of 0.26 inlets/km and 0.34 ridges/km,

while further west, inlet and ridge densities decrease to 0.17 inlets/km and 0.20 ridges/km (Table 2). At present, active tidal inlets along the Long Island barrier shoreline migrate west-southwest (Kumar and Sanders, 1974). The three active inlets along the major Long Island sand ridge field today include Fire Island, Jones, and East Rockaway inlets. Fire Island Inlet migrated westward at an average rate of 64 m/yr from 1825 until the inlet was stabilized with jetties in 1955 (Kumar and Sanders, 1974). Jones and East Rockaway inlets have migrated westward at an average rate of 20 and 50 m/yr, respectively (Kassner and Black, 1984; Niedoroda et al., 1985).

Along the New Jersey coast, a large number of well-developed shoreface-attached and detached sand ridges are associated with the southern part of the mixed energy, wave-dominated barrier shoreline and the north-central part of the mixed energy, tide-dominated barrier shoreline (Fig.4B). The density of inlets and ridges along both barrier types is almost identical (Table 2). Predominant longshore sediment transport along this coastal segment is to the south (Wicker, 1950; Swift, 1975; Ashley et al., 1986). Inlets along the mixed energy, wave-dominated barriers migrate to the south; however, the migrational behavior of inlets along the mixed energy, tide-dominated barriers is quite different. These more tide-dominated inlets have a tendency to remain relatively stationary or migrate minimal distances updrift and downdrift, usually within an incised antecedent channel thalweg (Nummedal et al., 1977; FitzGerald, 1981). It should be noted that the average density of inlets for eroding headlands (0.19 inlets/km) is abnormally high because of the large number of small and poorly developed inlets along New Jersey's eroding headland (Table 2). These inlets are basically drainage channels to the ocean, and technically most should not be considered as fully functioning tidal inlets.

The Maryland/northern Virginia shelf along the Delmarva Peninsula has a large, well-developed shoreface-attached and detached sand ridge field. The largest number (63) and highest density (0.73 ridges/km) of shoreface sand ridges occur along this mixed energy, wave-dominated barrier island shoreline (Fenwick and Assateague Islands) than

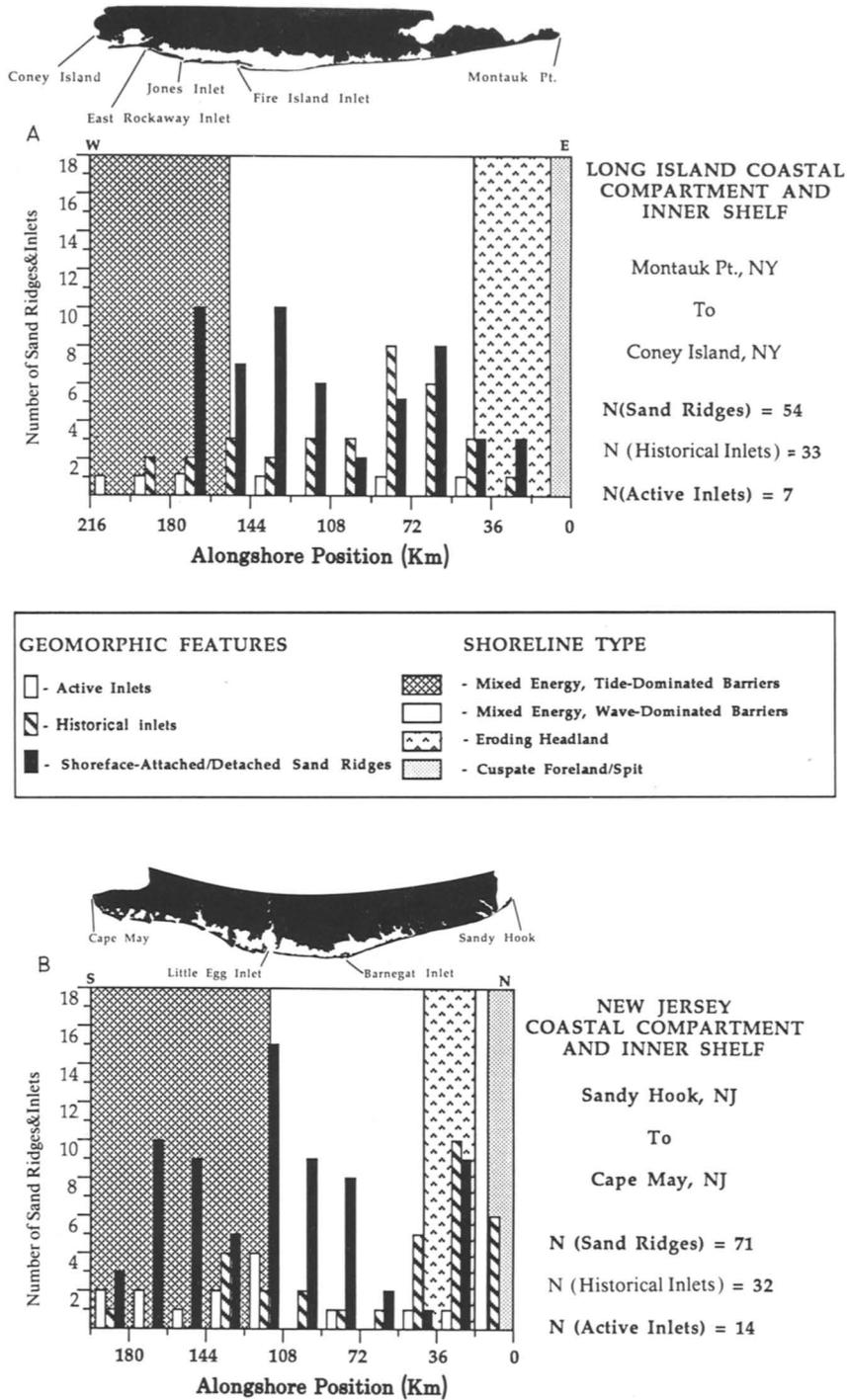


Fig.4. The distribution of tidal inlets (historical and active) and shoreface-attached and detached sand ridges along shoreline types. (A) Long Island. (B) New Jersey. For Figs.4, 5 and 6, the distribution and density of tidal inlets and sand ridges was compiled and compared using 18 km segments along the coast. (Note: Because of irregularities in the shoreline, histograms do not always correspond exactly to geographic reference maps in Figs. 4, 5 and 6.)

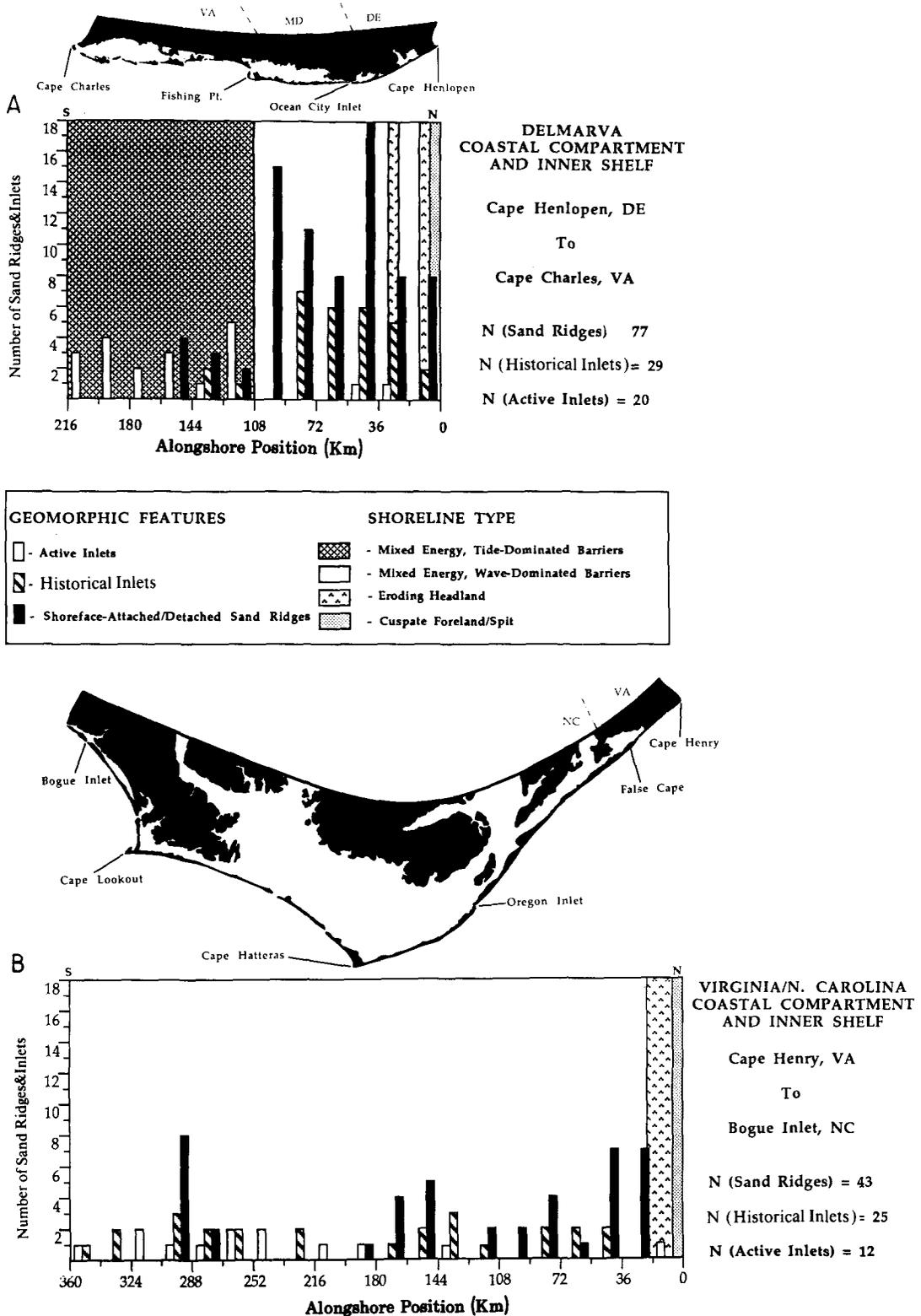


Fig.5. The distribution of historical and active tidal inlets and shoreface-attached and detached sand ridges along shoreline types. (A) Delmarva Peninsula. (B) southern Virginia and North Carolina.

along any other U.S. east coast shoreline (Fig.5A and Table 2). The abrupt disappearance of this large sand ridge field south of Fishing Point, Virginia, coincides with two geologic parameters. The first is a decrease in grain size on the shoreface and inner shelf to a finer grained sand (Swift, 1975). Swift (1975) suggests that the fine-grained nature of sediment along the southern Delmarva coast is not conducive to the formation of sand ridges. The second condition is a distinct change in barrier shoreline type from mixed energy, wave-dominated to mixed energy, tide-dominated (Morton and Donaldson, 1973; Rice and Leatherman, 1983; McBride, 1986a). The highest density of historical and active inlets (0.29 inlets/km) occurs along the mixed energy, wave-dominated part of this coastline (Fig.5A and Table 2). The wave-dominated inlets probably opened, migrated laterally over considerable distances, and closed. In contrast, inlets along the mixed energy, tide-dominated barrier coastline to the south are often naturally stabilized by pre-Holocene antecedent valleys and tend to remain open much longer (Shideler et al., 1984; Belknap and Kraft, 1985). With higher tidal ranges, larger tidal prisms, lower wave energies, and a greater influence from antecedent topography, the southern Delmarva coastline is morphologically quite similar to the coasts of southern New Jersey, southern South Carolina, Georgia, and northern Florida. These particular barrier shorelines generally have few shoreface sand ridges or none at all. Ridges found in these coastal settings normally are tide-built and are well-developed in estuaries (see Off, 1963).

Unlike those previously mentioned, the sand ridges off the southern Virginia and northern North Carolina coasts are distributed in small clusters along the mixed energy, wave-dominated part of the shoreline (Fig.5b). The locations of these clusters also correspond to the locations of historical tidal inlets. The density of inlets and ridges along this particular barrier type is similar — 0.11 inlets/km and 0.13 ridges/km (Table 2). Net longshore sediment transport along these barrier islands is to the south. Oregon Inlet in North Carolina has migrated largely to the south for the past 131 years (1849 to 1980), averaging 29 m/yr (Everts et al., 1983). Fisher (1962) and Hennigar

(1977a, b) documented historical inlets that opened, migrated to the south, and subsequently closed all along this barrier shoreline. Stratigraphic studies in this area have also identified several additional tidal inlet sequences in the subsurface (Moslow and Heron, 1978; Heron et al., 1984). In all but one, the shore-parallel geometry of the inlet sand bodies suggested a southerly migration.

The southernmost shoreface sand ridge field on the U.S. Atlantic shelf lies between Sebastian and Jupiter inlets, Florida. This small but well-developed sand ridge field consists of only fourteen shoreface-attached and detached sand ridges (Fig.6). It also lies adjacent to a mixed energy, wave-dominated barrier island shoreline. At present, only artificially opened inlets (Sebastian, Ft. Pierce, and St Lucie inlets) exist along this ridge field, but numerous historical inlets have been documented (McBride, 1987). The density of inlets and ridges along this 108 km stretch of coastline is 0.04 inlets/km and 0.13 ridges/km (Fig.6). Longshore transport of sediment is to the south in response to the predominant wind-wave direction, which is from the northeast [Bruun, 1966 (pp.14–30); Walton, 1974; Mehta et al., 1976]. Therefore, historical inlets in this area probably migrated to the south.

In summary, of the 259 sand ridges identified and mapped in the study area, 91% are found along barrier island shorelines. Of these, 178 (69%) are found along mixed energy, wave-dominated barrier islands and 58 (22%) along mixed energy, tide-dominated barriers. Most importantly, the inner shelves adjacent to mixed energy, wave-dominated and wave-dominated barriers consistently show the highest densities of ridges averaging 0.29 ridges/km (Table 2). The remaining 23 (9%) sand ridges are found along eroding headlands (Fig.7). The mixed energy, wave-dominated barrier shorelines have few active tidal inlets (22 or 39%) at any point in time, but a large number of historical tidal inlets (82 or 68%) are found because inlets along these shorelines are more ephemeral (open, migrate, and close) and migrate laterally over longer distances (Moslow and Heron, 1978; Moslow and Tye, 1985). The opening of these ephemeral inlets tends to be associated with greater storm activity (e.g., hurricanes or north-

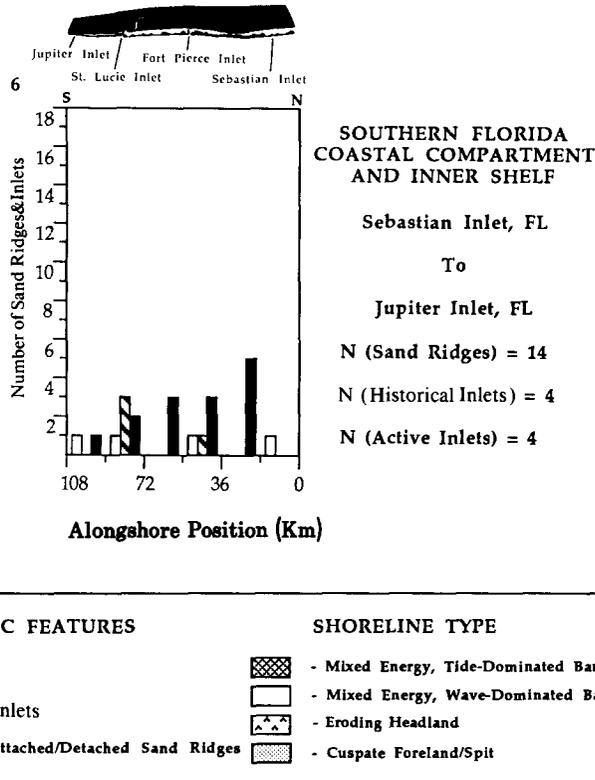


Fig.6. The distribution of historical and active tidal inlets and shoreface-attached and detached sand ridges along shoreline types of south-central Florida.

easters). The documentation of these spatial relationships along the U.S. Atlantic shelf suggests a link between shelf topography and barrier island morphology.

**A model for sand ridge development**

This study presents a morphodynamic model that defines a mechanism for concentrating sand on the shoreface in discrete depocenters, which act as nuclei for the morphogenesis of shoreface sand ridges. It is hypothesized that such a mechanism precedes the evolution of sand ridges by hydrodynamic processes. The proposed model not only helps explain the origin and evolution but also the distribution and orientation of sand ridges on a regional scale along the U.S. Atlantic inner shelf.

*Ebb-tidal deltas*

The formation of sand ridges is a function of sediment supply and shelf processes. Although the

exact amount of sand needed is undetermined, enough sand must be locally available to produce a bathymetric “high” on or seaward of the shoreface. In the case of barrier coastlines, this type of sand concentration is restricted almost exclusively to ebb-tidal deltas. Tidal inlets and their associated tidal deltas are natural sediment sinks. Sediment is eroded from source areas (e.g., deltaic headlands) and carried by longshore sediment transport along a shoreline. Tidal inlet systems capture the transported sediment and store it in the form of flood and ebb-tidal deltas (Oertel, 1975; Niedoroda et al., 1985).

Data presented in this investigation suggest that many shoreface-attached sand ridges are sourced from deposits concentrated along the retreat path of tidal inlet systems, specifically ebb-tidal deltas. The ebb-tidal delta retreat path is a function of the landward migration rate of the barrier island shoreline (0–10 m/yr) in response to waves and water level, in addition to the rate (0–70 m/yr) and

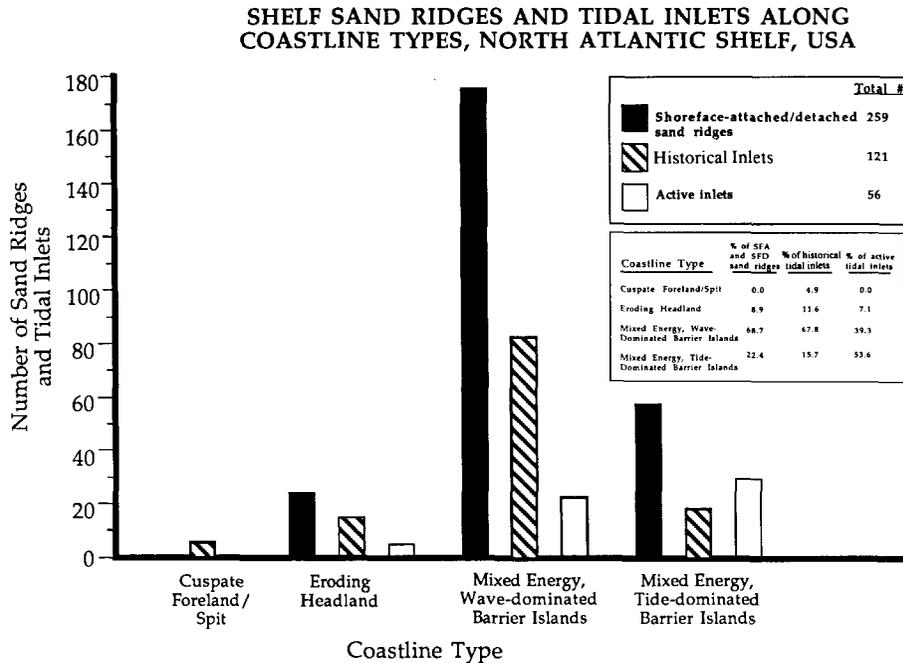


Fig.7. Composite distribution of shoreface sand ridges and tidal inlets (historical and active) versus coastline types for Figs.4, 5 and 6, Atlantic inner shelf, USA. Note that 91.1% of all sand ridges occur along mixed energy barrier island shorelines and that most (68.7%) occur in wave-dominated settings. The prevalence of sand ridges is closely tied to the presence of tidal inlets, especially historical or closed inlets. See Table 2 for densities.

direction of inlet migration (Fig.8). These ranges are typical in the study area.

The average rate of coastal retreat has slowed progressively over the last 5000 years. Most, if not all, of the inner shelf sand ridges in the study area formed during that period. The evolution and migration of the shoreline (e.g., barrier islands) across the continental shelf is a response to the latest Quaternary rise in sea level. Belknap and Kraft (1981) determined that the average coastal retreat rate 5000 years ago was 5.0 m/yr, and Dolan et al. (1979b) have calculated a present average retreat rate of 1.5 m/yr. A retreat rate of 3.0 m/yr for the past 5000 years was used in this study. The calculated angles of ebb-tidal delta retreat paths in relation to barrier island shorelines are strikingly similar to the measured oblique orientations of shoreface sand ridges along the Atlantic shelf (Fig.3). It is suggested that the oblique orientation of these ridges may be a response to the reworking and molding of ebb-tidal delta sand deposits by shelf processes along a path determined by barrier island retreat and

inlet migration. The morphodynamic transformation from ebb-tidal delta to sand ridge is not simply a “stringing together” of successive delta segments as they accumulate on the shoreface. Instead, ridges are molded out of ebb-tidal delta deposits by shelf processes (i.e., storm-generated currents and waves). Sand ridge orientation is therefore determined by the reworking and molding process concentrated along a trajectory determined by the retreat path of the tidal inlet system. Most importantly, ebb-tidal deltas are natural sediment sinks and concentrate sediment for the development of shoreface-attached ridges.

#### *Model for ridge origin and evolution*

In light of the results of the study, we propose a six-stage model for the origin and evolution of many shoreface-attached sand ridges on the eastern continental shelf of the United States. The model incorporates both coastal and shelf processes as illustrated in Fig.9.

Tidal inlets originate through various mecha-

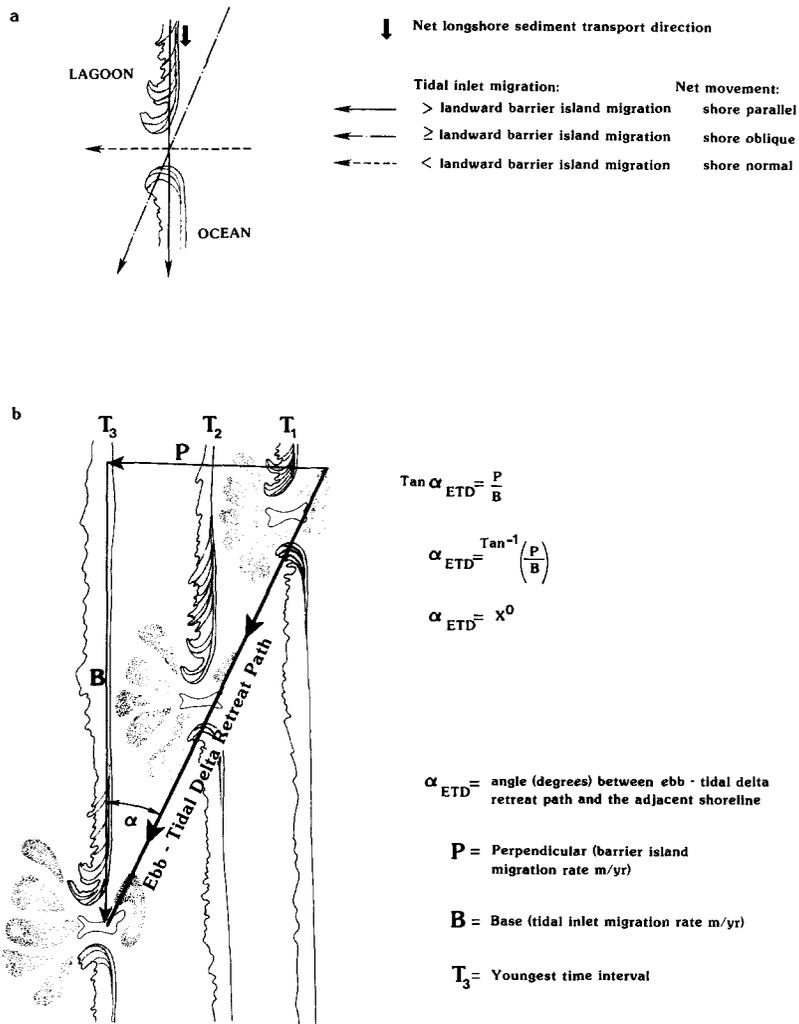


Fig.8. (a) Different resultant vector directions for tidal inlet movement through time and space as a function of tidal inlet migration processes (i.e., tidal prism, wind/wave directions, etc.) and barrier island transgression through shoreface retreat. (b) Trigonometric formula developed to calculate the ebb-tidal delta retreat path in the study area. Deposition and reworking of ebb-tidal delta deposits along its retreat path in combination with shelf processes produce the obliquely oriented sand body.

nisms including occupation of antecedent topographic depressions, storm surge, and increased wave energy, but once formed, they begin to deposit flood and ebb-tidal shoals. Ebb-tidal delta deposits cause a seaward deflection in the bathymetric contours on the adjacent shoreface (Fig.9, Stage 2). Tidal inlets begin to migrate laterally in response to the dominant longshore sediment transport direction (Fig.9, Stage 3). Landward and lateral tidal inlet migration occurs concurrently with landward migration of the barrier island in response to relative sea level rise. The resultant vector direction of tidal inlet migration is shore

oblique (Fig.8). An obliquely trending sand body is concentrated along the retreat path of the ebb-tidal delta. Acting simultaneously with tidal inlet sedimentation, shelf processes rework and mold the seaward margins of the ebb-tidal delta into shoreface sand ridges (Fig.9, Stage 4).

The shoreface sand ridge that forms along the ebb-tidal delta retreat path is composed of reworked ebb-tidal delta deposits. The upper part of these deposits may be planed off during erosional shoreface retreat, or it may supply sediment to adjacent beaches (FitzGerald et al., 1978). If the inlet closes, sand transport and deposition

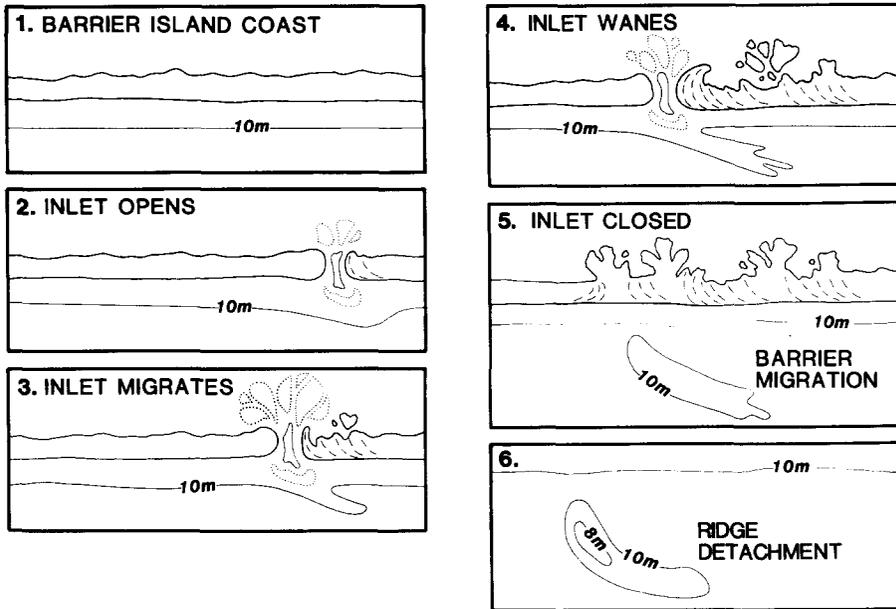


Fig.9. Six-stage ebb-tidal delta model illustrating the importance of tidal inlet and barrier island morphodynamics for the origin, evolution, and distribution of shoreface sand ridges. Note the genetic relationship between the ebb-tidal delta sand body and the location and orientation of the shoreface-attached sand ridges (synthesized from Moody, 1964; Duane et al., 1972; Field, 1976; Halsey, 1978, 1979; Swift and Field, 1981b; Figueiredo, 1984; McBride, 1986a). Dotted lines represent former tidal inlet shorelines. Overall, the barrier island shoreline experiences landward retreat during all six stages.

associated with tidal inlet processes are eliminated and the ebb-tidal delta sand body is subject to reworking by waves and currents only. However, closure of the tidal inlet does not end the evolutionary sequence of sand ridge growth and migration. During this second phase of evolution, and as recognized by Field [1976 (pp.131–135 and 169–170)] and Halsey [1978 (pp.437–452)], the seaward or distal end of the ebb-tidal delta sand body is further molded into one or more linear ridges by shelf processes, and its proximal end may or may not remain attached to the shoreface.

Shelf storm flow may affect or be affected significantly by these obliquely oriented sand bodies. Shelf storm flows generally move in a southerly direction along nearshore parts of the Atlantic shelf (Swift, 1975, 1985). As the flow passes across the shoreface-attached sand ridge, the upcurrent slope (landward flank) experiences erosion. As the flow passes over the crest of the ridge, it expands, resulting in a decrease in flow velocity (Swift and Field, 1981a, b). This deceleration causes deposition immediately seaward of the crest of the sand body. Consequently, grain-size is coarsest on the

landward flank and fines seaward from the crest across the seaward flank (Stubblefield and Swift, 1981). By this process of erosion and deposition, the ebb-tidal delta sand body eventually is reworked completely as it migrates in response to shelf storm flow. Through time, the sand body also becomes detached from the shoreface (Duane et al., 1972) and is left stranded on the inner shelf as the barrier shoreline continues to migrate landward. As the sand body reaches dynamic equilibrium with the shelf's hydraulic regime, it may undergo slight reorientation, but the sand body is able to maintain its original linear form, which is inherited from the retreat path of the ebb-tidal delta sand body (Fig.9, Stages 5 and 6).

The hydrodynamic mechanisms responsible for the origin, evolution, orientation, and distribution of shoreface sand ridges are still not well understood, even though much research has been conducted along the U.S. Atlantic coast and shelf. Erosional shoreface retreat, shoreface detachment, and storm-generated flows have been recognized as essential components of the origin and evolution of shoreface sand ridges, but detailed explanations

about specific sand sources, peculiar oblique orientations to flow, and sand ridge distribution are largely inadequate. A variety of models has been proposed for the formation and maintenance of sand ridges; these include the storm-generated helical flow model (Duane et al., 1972a; Swift et al., 1972, 1973), the Smith-Richards model (Swift and Field, 1981b; Figueiredo et al., 1981), and the Huthnance model [Figueiredo et al., 1981; Huthnance, 1982a, b; Parker et al., 1982; Figueiredo, 1984 (p.366); Swift, 1985]. Swift (1985) has suggested that the Huthnance model, which is based on shore-parallel shelf flow, explains many problems related to sand ridge development and behavior. However, it should be noted that the Huthnance model is based on "tide-built" sand ridges in the North Sea and has not been field tested for shoreface sand ridges such as those along the U.S. Atlantic shelf. Furthermore, Leckie and Krystinik (1989) dispute Swift (1985) and present paleocurrent data from ancient inner-to-middle shelf settings, indicating shore-normal flow as the major direction for shelf sediment transport. They find no evidence within inner-to-middle shelf deposits for the nearly shore-parallel orientation of currents observed in modern geostrophic flows. Clearly, the dynamics of shoreface ridge formation are still not fully understood and much debate exists as to the exact processes responsible for transporting sediment across the lower shoreface and inner shelf. It is recognized that shoreface sand ridges may have several different modes of evolution — a multiple causality — but ebb-tidal deltas, the trajectory along which they retreat, and reworking of ebb-tidal shoals by nearshore processes, provide a logical progression for ridge morphogenesis along barrier island coastlines on the U.S. Atlantic shelf. The ebb-tidal delta retreat path model not only explains the mechanism for shoreface detachment [Duane et al., 1972 (p.489)], but also accounts for the origin, orientation, and distribution of sand ridges in the study area.

### Case studies

#### *Active tidal inlets*

##### *Barnegat Inlet, New Jersey*

At present, large shoreface sand ridges are found connected to the seaward margin of the ebb-tidal

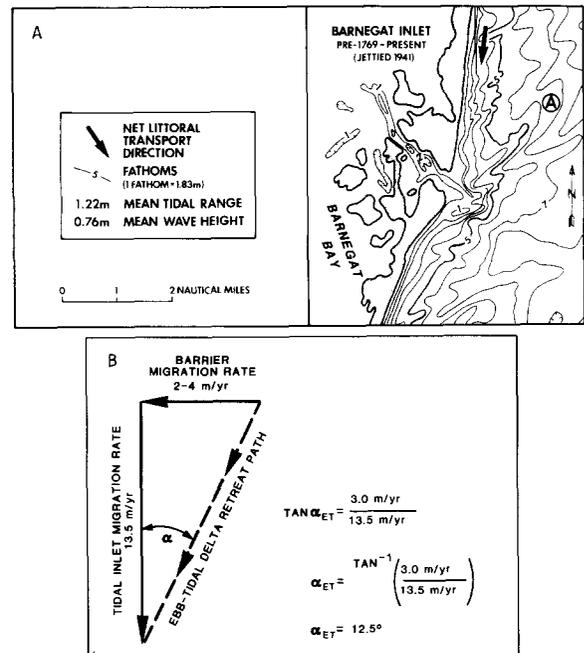


Fig.10. Barnegat Inlet, New Jersey. (A) Bathymetry showing shoreface-attached sand ridges connected to the seaward margins of the ebb-tidal delta at Barnegat Inlet, New Jersey. Bathymetry in fathoms and based on Stearns (1967). (B) Calculations for the ebb-tidal delta retreat path for Barnegat Inlet, New Jersey.

delta at Barnegat Inlet, New Jersey (Fig.10A). The ebb-tidal delta, which stores sediment captured from longshore sediment transport, feeds the developing shoreface-attached sand ridge. As a result, the location of Barnegat Inlet and its associated ebb-tidal delta controls the origin and location of the shoreface-attached sand ridge. Furthermore, between 1839 and 1937, Barnegat Inlet migrated southward at about 13.5 m/yr (Johnson, 1969). The ebb-tidal delta retreat path was calculated to produce a linear sand body oriented  $12.5^\circ$  to the shoreline (Fig.10B). The orientation of the present shoreface sand ridge at Barnegat Inlet is between  $20^\circ$  and  $24^\circ$ . This orientation suggests that the shoreface sand ridge may be regulated initially by the retreat path of Barnegat Inlet and its associated ebb-tidal delta, and that subsequently the sand body is reworked and reoriented by storm processes. It should be noted, however, that Barnegat Inlet was artificially stabilized in 1941, which may account for the exaggerated reorientation of this shoreface sand ridge by hydrographic processes

since this time. Other modern examples of active tidal inlets that have shoreface sand ridges extending from the seaward margin of their ebb-tidal deltas are Jones Inlet (New York), Little Egg Inlet (New Jersey), Oregon Inlet (North Carolina), and Petit Bois Pass (Mississippi). These active inlets display the genetic relationship between ebb-tidal deltas and shoreface sand ridges similar to that at Barnegat Inlet (Fig.10).

### Historical tidal inlets

If shoreface-attached sand ridges can be found connected to the ebb-tidal deltas of active tidal inlets, then the sites of historical inlets may be characterized by shoreface-attached sand ridges that formed when the inlet was open. Few researchers have focused on historical inlet locations, the length of time these inlets were open, and the migrational behavior of these inlets; however, this information is essential to understanding the origin, evolution, orientation, and distribution of shoreface sand ridges. The case studies presented below illustrate the importance of tidal inlets and their ebb-tidal deltas as sediment sinks along the shoreface and they are used to test the ebb-tidal delta retreat path model by documenting the location, period of time open, and migrational behavior of two historical inlets.

#### *Old Currituck Inlet, Virginia/North Carolina*

Well-developed shoreface-attached and detached sand ridges lie adjacent to and south of False Cape, Virginia (Fig.11A). According to Duane et al. (1972) and Swift et al. (1972b), these sand ridges have a maximum relief of 6.1 m, with flank slopes of  $2^\circ$  or less. The crests of the shoreface sand ridges occur between  $-6.1$  m and  $-9.1$  m mean low water (MLW), with the most shoreward ridge in the shallowest water. The long axis of sand ridge A is oriented on an azimuth of  $2.5^\circ$  and forms an angle of about  $16^\circ$  with the adjacent coastline. The long axis of sand ridge B is oriented on an azimuth of  $17^\circ$  and forms an angle of about  $27^\circ$  with the adjacent coastline.

Old Currituck Inlet was located south of False Cape, Virginia, adjacent to the False Cape Ridge A, and a pre-1650 date is used for the opening of

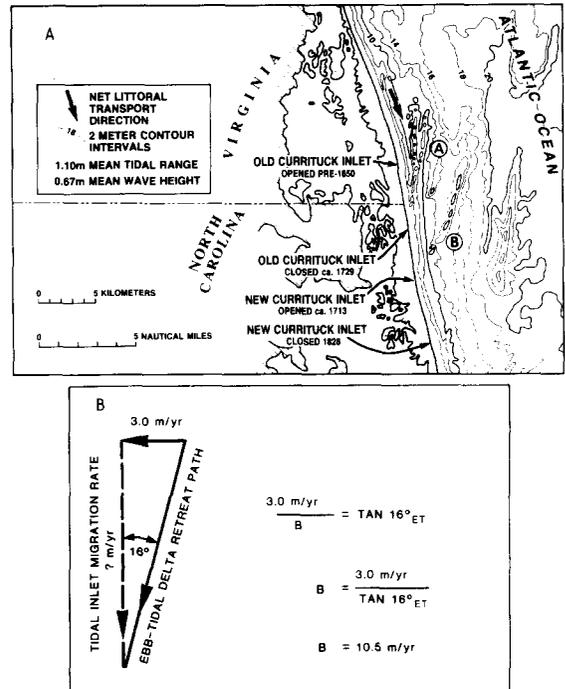


Fig.11. False Cape Shoals, Virginia and North Carolina. (A) Bathymetry showing the genetic relationship between shoreface-attached sand ridges along False Cape and Old Currituck Inlet. Note that the nearshore or proximal end of False Cape Shoal A attaches to the shoreface adjacent to the relict flood-tidal delta. (B) Calculations for the tidal inlet migration rate of Old Currituck Inlet (historical), North Carolina.

the inlet (Fisher, 1962; Hennigar, 1977a, b). Old Currituck Inlet probably provided the mechanism by which sand was concentrated on the shoreface in the form of an ebb-tidal delta. Therefore, the inlet not only provided sand by trapping longshore sediment transport for sand ridge A, but also determined the location of the shoreface sand ridge. Furthermore, Boyd (1967), Hennigar (1977a, b), and Everts et al. (1983) documented the southward migration of Old Currituck Inlet during historical times. Trigonometric calculations yield a migration rate for Old Currituck Inlet of 10.5 m/yr (Fig.11B), which is within 10% of the 11.4 m/yr rate documented by Hennigar (1977a, b). Vector analysis indicates that the retreat path of Old Currituck Inlet's ebb-tidal delta has an orientation corresponding to that of False Cape sand ridge A, suggesting that the development of False Cape ridge A may be explained by the opening and migration of Old Currituck Inlet, associated with

the deposition and molding of the ebb-tidal delta. (Figs.8 and 9).

### *Indian River Inlet, Florida*

A well-developed sand ridge field exists on the southern Florida shelf near Fort Pierce, Florida, south of Cape Canaveral between Sebastian and Jupiter inlets (Fig.2B). The long axes of the sand ridges are oriented on an azimuth of  $0^\circ$  (due north) and form angles ranging between  $16^\circ$  and  $30^\circ$  with the adjacent coastline. Tidal inlets along the eastern Florida coast are influenced heavily by human activities. Most natural inlets are jettied, and a large number of present-day inlets have been artificially cut and stabilized (McBride, 1987). At present, Matanzas Inlet and Nassau Sound are the only naturally occurring, unstructured tidal inlets along the east coast of Florida. Fortunately, numerous coastal surveys and mapping expeditions were conducted before commercial coastal development and inlet stabilization began (pre-1920s). DeBrahm, a German surveyor, mapped Indian River Inlet, also known as Hillsborough or Aye's Inlet, in 1763 [DeVorse, 1971 (p.206, plates 20 and 23)]. Indian River Inlet was open from pre-1650 to the late 1800s (DeVorse, 1971; McBride, 1986a, b, 1987). Extending northward from the inlet's relict flood-tidal delta is a large shoreface-attached sand ridge referred to as Indian River Shoal (Fig.12A). The shoal has a maximum relief of 6.0 m and an average orientation of  $21^\circ$ . The crest of Indian River Shoal lies at  $-4.5$  m MLW.

The presence of an historical tidal inlet adjacent to the location of the shoreface-attachment point of Indian River Shoal provides important information. This attachment point corresponds to the ebb-tidal shoal location or depocenter of Indian River Inlet just before inlet closure in the 1800s (McBride, 1987). It is likely that Indian River Inlet migrated in a net southerly direction during historical times because the present direction of net longshore sediment transport is to the south (Bruun, 1966). The orientation of Indian River Shoal ( $21^\circ$ ) and the barrier island migration rate (3.0 m/yr) were entered into the equation shown in Fig.12B to calculate a 7.8 m/yr migration rate for Indian River Inlet. A 7.8 m/yr migration rate is reasonable for inlets in this area and illustrates

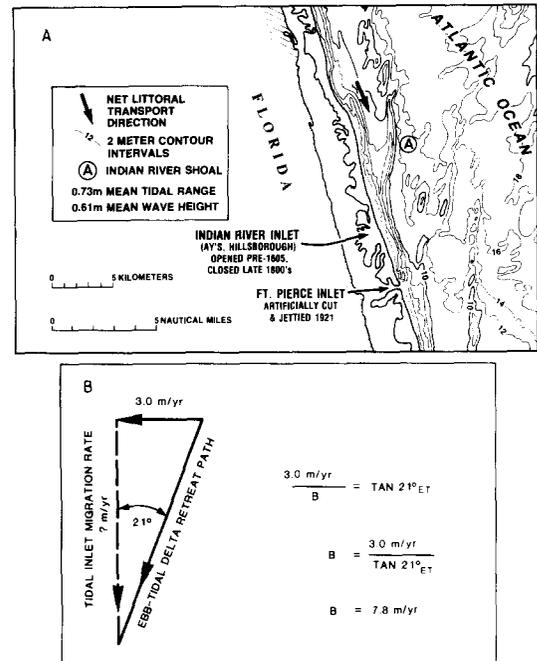


Fig.12. Indian River Inlet, Florida. (A) Bathymetry showing the genetic relationship between Indian River Inlet (relict flood-tidal delta) and Indian River Shoal (a shoreface-attached sand ridge). When open, the ebb-tidal delta of Indian River Inlet would correspond to the nearshore end of Indian River Shoal. (B) Trigonometric calculation for the tidal inlet migration rate for Indian River Inlet (historical), Florida.

the ease by which inlet retreat paths can be shore oblique (Fig.9). It is postulated that tidal inlets and their ebb-tidal deltas may account for the origin, evolution, distribution and orientation of Indian River Shoal as well as others in the Fort Pierce sand ridge field (see Fig.2B).

### **Coastal-shelf coupling: a discussion**

#### *Variations in style and setting*

Tremendous variations in the morphology and depositional setting of shoreface and inner shelf sand ridges are known to exist. Table 3 presents several modern examples and possible ancient equivalents from North America, which may represent end members of a spectrum of shoreface and shelf sand ridges. Despite geomorphic and geologic variations, and thus implied variations in origin, the examples have one important commonality:

TABLE 3 Examples of shoreface and inner shelf sand ridges from various depositional settings, North America

Location		Coastal setting	Morphologic feature	Sediment source or sink	Depositional origin	Possible ancient example
Regional		Local				
A.	U.S. Atlantic continental shelf (New York to Florida)	Coastal plain	Shoreface sand ridges and ridge fields	Ebb-tidal deltas	Marine reworking during transgression contemporaneous with deposition of sediment source	Halfway/Doig Formations, Triassic of Alberta (Campbell and Horne, 1986) and British Columbia, Canada (pers. observation)
B.	U.S. Atlantic continental shelf (New York to Florida)	Coastal plain	Shoreface and inner shelf sand ridges	Cape-shoal complex (abandoned Holocene or Pleistocene delta lobes)	Marine reworking during transgression following deposition of sediment source	
C.	Northern Gulf of Mexico, USA	Coastal and deltaic plain	Shoreface sand ridges	Cape-shoal complex (abandoned Holocene or Pleistocene delta lobes) and ebb-tidal deltas	Marine reworking during transgression following deposition of sediment source	Ferron Sandstone, Cretaceous of Utah, USA (Thompson et al., 1986); La Ventana Tongue, Cretaceous of New Mexico, USA (Palmer and Scott, 1984)
D.	Northern Gulf of Mexico, USA	Coastal and deltaic plain	Shoreface sand ridges	Abandoned Holocene delta lobe of Rio Grande	Marine reworking during transgression following deposition of sediment source	Terry Sandstone Member, Late Cretaceous, Denver Basin, Colorado, USA (Siemers and Ristow, 1986); Frontier Formation, Late Cretaceous, Green River Basin, Wyoming, USA (Moslow and Tillman, 1986)
E.	Eastern Canada continental shelf	Glaciated plain	Shoreface sand ridges	Reworked glacial and periglacial deposits (e.g. end moraines, drumlins, subglacial channels, and outwash plain deltas) <sup>1,2,3</sup>	Marine reworking during transgression following deposition of sediment source	
F.	Northern Gulf of Mexico, USA	Deltaic and chenier plain	Inner shelf shoals and sand ridges	Abandoned Holocene delta lobes and distributaries of Mississippi River	Marine reworking during transgression following deposition of sediment source	W8 Sandstone, Upper Wilcox Group, Fordoche Field, Louisiana, USA (Lowry et al., 1986)

<sup>1</sup>Pers. commun., Dec. 1986 and March 1988; R. Boyd, Centre for Marine Geology, Dalhousie University.<sup>2</sup>Hoogendoorn and Dalrymple, 1986.<sup>3</sup>McClaren and Boyd, 1988.

the association of sand ridges with marine reworking during transgression of large, isolated deposits of sand on the shoreface or shelf. The association is not a coincidence. A locus of sand deposition on the inner shelf or shoreface must be available for the formation of sand ridges. Deposition must occur during, or immediately before, transgression of the coastal to inner shelf setting. Modern-day (Holocene) examples of shoreface deposition contemporaneous with transgression include ebb-tidal deltas, tidal sand ridges, and parts of cape-shoal complexes. The marine reworking of abandoned delta lobes on the continental shelf and shoreface of the Gulf of Mexico and the Atlantic Ocean along the United States (shoal retreat massifs) and periglacial deposits on the Scotian shelf of Canada are examples of deposition before transgression (Table 3).

Shoreface sand ridges on the U.S. Atlantic inner shelf also occur at cape-shoal complexes (shoal retreat massifs) and the mouths of tidal estuaries (Duane et al., 1972; Swift et al., 1972a). Shelf and shoreface sand ridges associated with subaqueous shoals (retreat massifs) are known to exist at Capes Hatteras (Hunt et al., 1977) and Lookout, North Carolina (Moslow and Heron, 1978), and appear to occur on bathymetric charts at most other cape-shoal complexes on the U.S. east and gulf coasts (Capes Fear, Romain, Canaveral, and Apalachicola). The most widely accepted hypothesis for the origin of these cape-shoal complexes is that they are remnants of abandoned late Pleistocene or early Holocene fluvial deltas that have been stranded on the continental shelf during transgression (Hoyt and Henry, 1971; Duane et al., 1972; Swift et al., 1972a).

In the northern Gulf of Mexico, preliminary investigations have identified shoreface sand ridges at Padre Island, Texas, and Apalachicola, Florida (Table 3). These ridges are probably a product of marine reworking after deposition and abandonment of deltaic lobes of the Rio Grande and Apalachicola River, respectively. Several well-developed shoreface-attached sand ridges extending from the seaward margins of large ebb-tidal deltas are also found along the Mississippi barrier island chain (e.g., Petit Bois Pass area, Mississippi). Holocene sand shoals and ridges on the inner

continental shelf of Louisiana (e.g., Ship, Trinity, Tiger, Outer, and St. Bernard shoals) are also believed to be a product of the marine reworking of sediments derived from one or more abandoned delta lobes of the Mississippi River (Penland et al., 1986, 1988, 1989).

Shoreface sand ridges on the Scotian shelf and shoreface adjacent to Sable Island, Canada, are thought to be a product of marine processes during transgression (Hoogendorn and Dalrymple, 1986). Coarse sediment (Pleistocene) was deposited on the continental shelf as subglacial channels and periglacial deltas during a sea level lowstand (McClaren and Boyd, 1988). These deposits were subsequently transgressed and reworked into barrier islands during the Holocene sea level rise. As with all other known localities, shoreface-attached sand ridges are associated with copious quantities of deltaic and/or barrier shoreline derived sands deposited before or during marine reworking by shelf processes (Table 3).

#### *Implications for shelf stratigraphy: Modern and ancient*

The association of shoreface sand ridges with abandoned ebb-tidal deltas or fluvial deltas implies certain facies relationships. By definition, these deltas are a product of deposition at the seaward margins of tidal inlets or distributary channels, respectively. Therefore, tidal inlet or fluvial distributary channels should be found in the subsurface immediately underlying, or updip of, shoreface sand ridges. Studies of Holocene shelf stratigraphy on the eastern U.S. and Gulf of Mexico continental shelves appear to support this facies relationship. Tidal inlet and/or distributary channel sands of Holocene age are known to immediately underlie, occur within, and/or occur in the subsurface immediately updip of Trinity and Ship shoals, Louisiana (Suter et al., 1985; Penland et al., 1987). An origin related to marine reworking of deltaic and/or barrier shoreline sediments has been proposed for these inner shelf shoals.

Figueiredo (1984) analyzed vibracore and seismic data collected from three unnamed shoreface sand ridges as well as Peahala Ridge on the New Jersey shelf. His results identified channels of

tidal inlet origin directly underlying or landward of each ridge. The channels are incised into underlying units of late Holocene or Pleistocene age. Beneath and landward of Peahala Ridge, a "tidal inlet channel" sequence was interpreted to pinch out both landward (flood-tidal delta) and seaward (ebb-tidal delta). These facies relationships suggest that Peahala Ridge is laterally equivalent to, and probably composed of, reworked ebb-tidal delta deposits. This subsurface information supports the premise that ebb-tidal delta deposits concentrated sand for ridge development in this case. Hence, the association of tidal or distributary channels with sand ridges is a facies relationship that is both common and extremely important within continental shelf stratigraphy. Several ancient examples of shelf sandstone sequences display these facies relationships, thereby supporting the proposed origin of these deposits as marine-reworked coastal or deltaic sands. Some of the better-documented ancient examples include: the Cretaceous Terry Sandstone in the Denver Basin, Colorado (Siemers and Ristow, 1986), the Paleocene-Eocene Wilcox Formation in southeast Louisiana (Self et al., 1986), the Triassic Halfway/Doig Formation in the western Canada Basin of Alberta (Campbell and Horne, 1986), and the Late Cretaceous Frontier Formation in the Green River Basin, Wyoming (Moslow and Tillman, 1986). In all four examples, inlet channel sequences are found immediately underlying, within, and/or updip of shoreface or shelf sandstones deposited as isolated ridges on a transgressed shelf.

A conceptual geologic framework displaying significant shoreface-to-inner-continental-shelf facies relationships, vertical sedimentary sequences, and sand body trends is shown in Fig. 13. The evolutionary development of shoreface sand ridge sequences is portrayed from background (top) to foreground (bottom) for barrier shoreline settings (Fig. 13A). This model is not intended to be global in nature, but rather to synthesize evolutionary patterns and facies relationships within the study area. At the top of Fig. 13A, an ebb-tidal delta is shown which has been deposited on the shoreface as a product of tidal inlet processes. In cross section A-A', inlet channel sands are shown upslope, or landward, of

the ebb-tidal delta deposits. After the inlet closes, the ebb-tidal delta is reworked by marine processes (waves and storms) and further molded into a shoreface sand ridge. This evolutionary transition is depicted in Fig. 13A by the change in shoreline and shoreface morphology from positions A-A' to B-B'. Shoreface sand ridges along B-B' and C-C' in Fig. 13A are shown to occur at the base of the shoreface, with the proximal end of the sand ridges adjacent to the sites of abandoned tidal inlets. The sites of these former inlets are marked on the surface by relict flood-tidal deltas on the lagoon side of the barrier island (mid-ground and foreground of Fig. 13A). In the subsurface, a tidal inlet sequence is observed to thin seaward and pinch out at the landward toe (proximal end) of the shoreface ridge (cross section B-B', Fig. 13B). With continued sea level rise, transgression, and translation of sedimentary facies, the shoreface sand ridge deposits eventually will overlie those of the tidal inlet channels (cross section C-C', Fig. 13B). The inlet channel sands are scoured into the underlying substrate.

A vertical sedimentary sequence is shown for each evolutionary stage of sand ridge development (Fig. 13B). In each case the sequence represents a complete Holocene section located on the landward flank of the ebb-tidal delta and shoreface sand ridges shown along A-A', B-B' and C-C' in Fig. 13A. A fining upward sedimentary unit of crossbedded sands in the mid to lower parts of each sequence is a product of inlet channel scour and lateral accretion. Accordingly, these units are labelled tidal inlets or tidal channels in each sequence. The remnants of transgressed barrier island deposits are found preserved in the basal parts of the Holocene section in A-A' and B-B'. These fine-grained deposits are of a backbarrier (i.e., lagoonal) origin. All three sequences (A-A', B-B', and C-C') are capped by a unit of variable thickness, principally composed of cross bedded and burrowed sands that coarsen upward and are a product of ebb-tidal delta and/or sand ridge deposition (Fig. 13B). With continued transgression of this shallow marine system, these sand bodies would become encased in marine shales, providing excellent stratigraphic hydrocarbon traps.

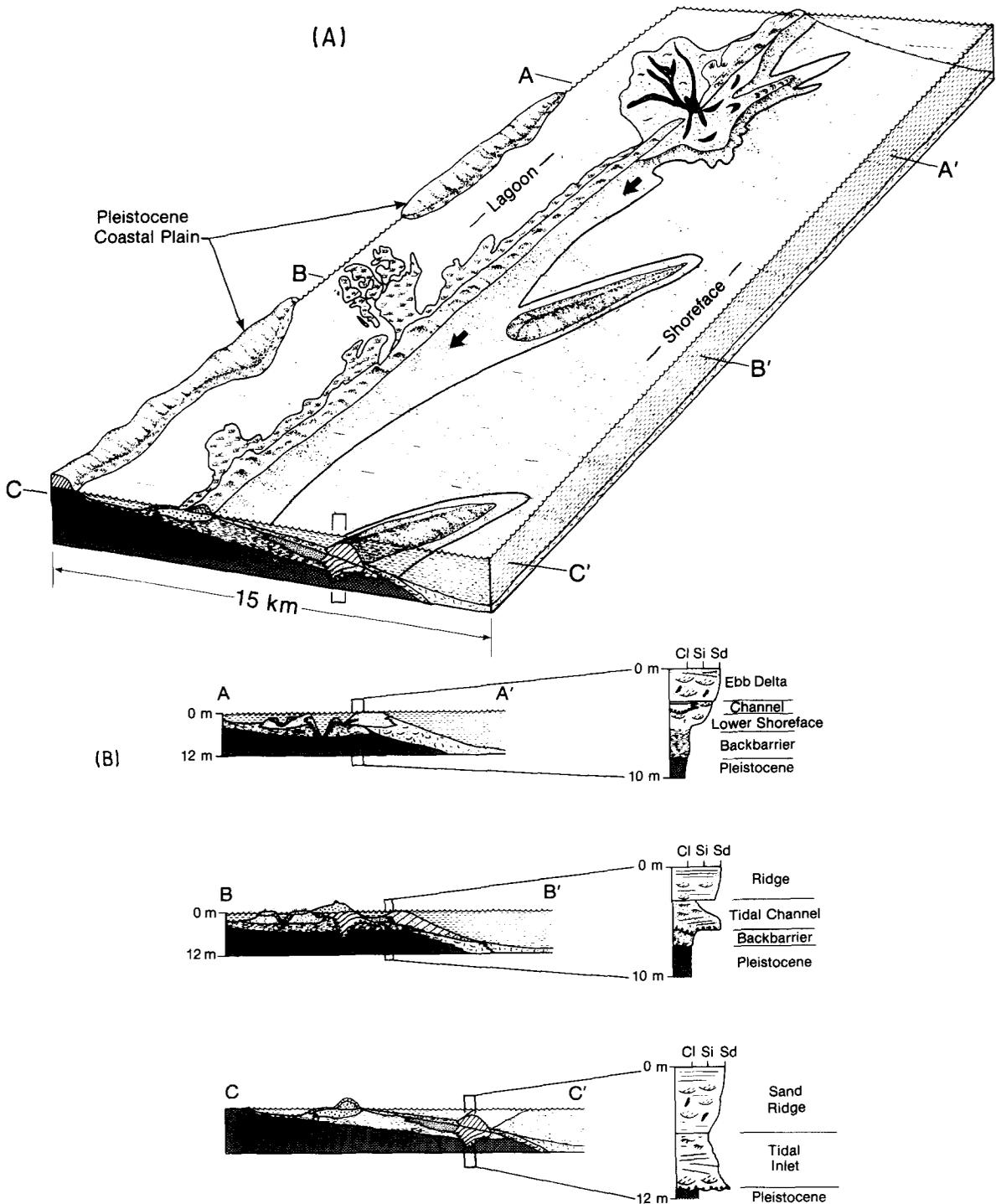


Fig.13. (A) Three-dimensional block diagram showing the geomorphic evolution of shoreface-attached sand ridges in various stages of development from "youth" in the background (top) to maturity in foreground (bottom). (B) Diagrammatic cross sections and sedimentary sequences showing the geologic framework and facies relationships for different stages of sand ridge development as depicted in Fig.13A (synthesized from Moslow and Heron, 1978; Heron et al., 1984; Figueiredo, 1984; Belknap and Kraft, 1985; McBride, 1986a, 1987; and McBride et al., 1986).

## Summary

Shoreface-attached and detached sand ridges and sand ridge fields along the Atlantic inner shelf of the United States (Montauk Point, New York, to Miami Beach, Florida) are found predominantly along mixed energy, wave-dominated barrier island coastlines. A total of 178 or 69% of all the shoreface sand ridges as well as the highest average density of ridges (0.29 ridges/km) observed in the study area are associated with this particular barrier type. The average orientation (in relation to the adjacent shoreline) of shoreface sand ridges is 29°.

A total of 68% (85) of all historical inlets in the study area occurs along wave-dominated barrier shorelines. These inlets commonly open, migrate to the south, and then close. Ebb-tidal deltas associated with these migrating tidal inlets act as point sources of sand on the shoreface, from which a bathymetric high is produced. Moreover, the highest density of inlets (0.29 inlets/km) occurs along the Delmarva coast, which is a mixed energy, wave-dominated barrier shoreline adjacent to the most well-developed shoreface sand ridge field of the entire U.S. Atlantic shelf. This ridge field also has the highest density of ridges at 0.73 ridges/km.

Ebb-tidal deltas and the trajectory along which they retreat not only provide a potential mechanism for shoal or shoreface detachment but also addresses the vexing questions of ridge origin, orientation, and distribution along barrier shoreline settings in the study area. The ebb-tidal delta retreat path is a function of landward barrier island migration in response to relative sea level rise, in addition to the rate and direction of inlet migration. The model illustrates that sand ridge morphogenesis is a result of a combination of factors: (1) tidal inlets are sediment sinks and concentrate their sediment into ebb-tidal deltas, which act as nuclei for shoreface sand ridges, (2) ebb-tidal delta sediment concentrated along the tidal inlet/ebb-tidal delta retreat path, and reworked by shelf processes, are responsible for ridge morphology and evolution, (3) the resultant vector direction of the ebb-tidal delta retreat path influences sand ridge orientation, (4) the range of

sand ridge orientations (5–40°) may be a result of different rates of tidal inlet and barrier island migration, and (5) the location of sediment depocenters (i.e., tidal inlets, rivers, etc.) dictates ridge distribution.

It is important to note that not all shoreface sand ridges are related to ebb-tidal deltas, and we recognize a multiple causality for ridge genesis.

Various mechanisms are responsible for depositing and/or concentrating significant amounts of sand (e.g., ebb-tidal deltas, river deltas, end moraines, outwash plain deltas) on the shoreface and inner continental shelf. These mechanisms are extremely important in understanding the origin and distribution of shoreface sand ridges. Although geomorphic and geologic variations exist both within and outside the study area, the spectrum of sand ridge examples discussed in this study is found in association with large reworked depocenters on the inner shelf and shoreface. Shoreface deposition occurs either contemporaneous with transgression (as in the case of ebb-tidal deltas, tidal sand ridges, and cape-shoal complexes along the U.S. east coast) or before transgression in the form of delta lobes (as in the northern Gulf of Mexico) or glacially derived deposits (as in the Scotian shelf of Canada).

This study suggests that a recognizable pattern exists in the spatial and temporal distribution of shoreline, shoreface, and inner shelf sand bodies in ancient sequences. The vertical and lateral association of tidal or distributary channels and sand ridges is a common facies relationship and thus extremely important to continental shelf stratigraphy during transgression. Holocene, Eocene, Cretaceous, and Triassic subsurface examples are known to exist where tidal inlet or distributary channels are immediately underlying, or updip of, contemporaneous shoreface sand ridges.

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