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Marine Geology 126 (1995) 271–287

MARINE GEOLOGY
INTERNATIONAL JOURNAL OF MARINE GEOLOGY, GEOCHEMISTRY AND GEOPHYSICS

Geology of the Wrightsville Beach, North Carolina shoreface: Implications for the concept of shoreface profile of equilibrium

E. Robert Thieler [a], Andrew L. Brill [a], William J. Cleary [b], Carl H. Hobbs III [c], Robert A. Gammisch [c]

[a] *Duke University, Department of Geology, Campus Box 90228, Durham, NC 27708-0228, USA*
[b] *Department of Earth Sciences, University of North Carolina at Wilmington, Wilmington, NC 28403, USA*
[c] *Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, VA 23062, USA*

Received 15 February 1994; revision accepted 13 January 1995

Abstract

Nearly 300 km of 3.5 kHz subbottom profile and 100 kHz sidescan-sonar data, a suite of over 100 short (~2 m) percussion cores and vibracores have been collected on the shoreface and inner continental shelf off Wrightsville Beach, North Carolina. Sidescan-sonar images were analyzed for acoustic backscatter to delineate the surface sediment distribution. Groundtruth data for the sidescan-sonar interpretations were provided by surface grab samples.

Cross-shore sediment transport by combined waves and currents is the predominant sedimentologic signature on this shoreface. The shoreface is dominated by a shore-normal system of rippled scour depressions that begin in 3–4 m water depth and extend to the base of the shoreface about 1 km offshore, at 10 m depth. The depressions are 40–100 m wide, and up to 1 m deep. They are floored by coarse, rippled shell hash and gravel; some are separated by rock-underlain fine sand ridges. On the inner shelf, the bathymetric and sedimentary fabrics become shore-oblique, due to a series of relict ridges with 1–2 m of relief. The ridges are coarse on their landward sides and covered on their seaward flanks by thin veneers of fine sand.

Field evidence from the Wrightsville Beach shoreface demonstrates that a shoreface equilibrium profile as defined by Dean (1991) and others does not exist here. For example: (1) the grain size varies widely and inconsistently over the profile; (2) shoreface profile shape is controlled predominantly by underlying geology, including Tertiary limestone outcrops and Oligocene silts; and (3) sediment transport patterns cannot be explained by simple diffusion due to wave energy gradients, and that transport occurs seaward of the assumed engineering "closure depth" of 8.5 m. This has several implications for the application of equilibrium profile-based numerical models used to investigate coastal processes and design coastal engineering projects at Wrightsville Beach. The most important practical implication is that a number of assumptions required by existing analytical and numerical models (e.g., Dean, 1991; GENESIS; SBEACH) used for the design of shore protection projects and large-scale coastal modeling over decadal time scales cannot be met.

1. Introduction

The shoreface is a critical interface between the continental shelf and the subaerial coastal plain. The shoreface can behave as a barrier, a filter, or a conduit for exchange of materials between the land and the sea. Oceanographic and geologic processes in this environment determine how a shoreline will respond to storms, to sea-level rise and to human-induced changes in sand supply over time scales from years to millennia. Understanding shoreface processes is also critical to understanding the behavior of natural and replenished beaches, which provide beachfront

SSDI 0025-3227(95)00082-8

communities with storm protection, recreation, and an important tourism resource.

The shoreface of barrier islands is the generally concave upward surface extending from the surf zone to the point where the slope becomes the same as the very gentle slope of the inner and middle continental shelf. Off southeastern North Carolina, the base of the shoreface is usually at 10–12 m water depth, as defined by this concave-up zone.

Sediment transport across the shoreface is a key factor affecting (1) short- and long-term fluctuations of beach and surf zone sand storage (Wright et al., 1985); (2) the morphology and stratigraphy of the shoreface (Niedoroda et al., 1985); and (3) the nature of the inner shelf sand sheet (Swift, 1976). On retreating barrier island coasts, the shoreface is also a major source of new sediment to the system, via the erosion and release of previously deposited lagoonal and fluvial sediments. This process was termed "shoreface bypassing" by Swift (1976), a process made all the more important on the southeastern U.S. Atlantic coast by the absence of a modern fluvial contribution.

The shoreface is usually thought to achieve an equilibrium shape related to wave climate and surficial sediment grain size (Dean, 1977; Zeidler, 1982). In empirical relations presented by Dean (1977, 1991), however, grain size is the only variable. As applied to beach replenishment, the profile of equilibrium is considered to be the stable configuration that a replenished beach will try to achieve under the influence of incident waves (Dean, 1983). Maintenance of the profile of equilibrium during shoreline retreat is also central to the concept of Bruun Rule response to sea-level rise (Bruun, 1962).

The profile of equilibrium concept makes several fundamental assumptions about the nature of the shoreface and the processes acting on it (Dean, 1977, 1991; cf. Pilkey et al., 1993). Pilkey et al. (1993) argued that several basic assumptions of the shoreface profile of equilibrium concept are not met in most real-world situations: (1) sediment movement is driven only by diffusion due to wave-energy gradients across the shoreface; (2) closure depth exists and can be quantified; (3) the shoreface is sand-rich, and underlying geologic framework does not influence the profile shape; and (4) the profile described by the equilibrium profile equation (Dean, 1977) must provide a useful approximation of the real shoreface shape for use in coastal engineering projects.

The shoreface is one of the most important, complex, and least understood coastal environments (Wright, 1987). We are only just beginning to understand that nearly all shoreface environments are different, where processes and controls vary in importance both spatially and temporally (Kraft et al., 1987; Nummedal, 1991; Oertel et al., 1992; Wright et al., 1991, 1994). Thus, there is a great need for field studies to provide insight into the geologic setting and sedimentary processes present in beach, shoreface and shelf environments. Such studies provide a basis not only for characterizing the geologic attributes of a given coastal system, but also for evaluating the degree to which commonly held assumptions used in numerical and analytical models of coastal behavior are met at various locations.

This paper describes the shoreface geology off Wrightsville Beach, including the surface sediment cover, underlying geology, and evidence of cross-shore sediment transport linking the surf zone, shoreface and inner shelf. These descriptions are used to discuss the impact of shoreface geology on sedimentary processes, and its implications for the shoreface profile of equilibrium concept.

2. Study area

Wrightsville Beach is a low, transgressive barrier island in southeastern North Carolina (Fig. 1). It is located in the southern portion of Onslow Bay, a broad, shallow, high-energy shelf environment. This portion of the North Carolina coast is composed of both transgressive and regressive barrier islands backed by narrow lagoons, with short stretches of mainland beach near the southern end of the embayment. Most of the shoreline is developed (e.g., single-family homes, duplexes, and large hotels and condominiums). Wrightsville Beach has some of the highest-density development along the Onslow Bay shoreline.

Onslow Bay is a wave-dominated, microtidal

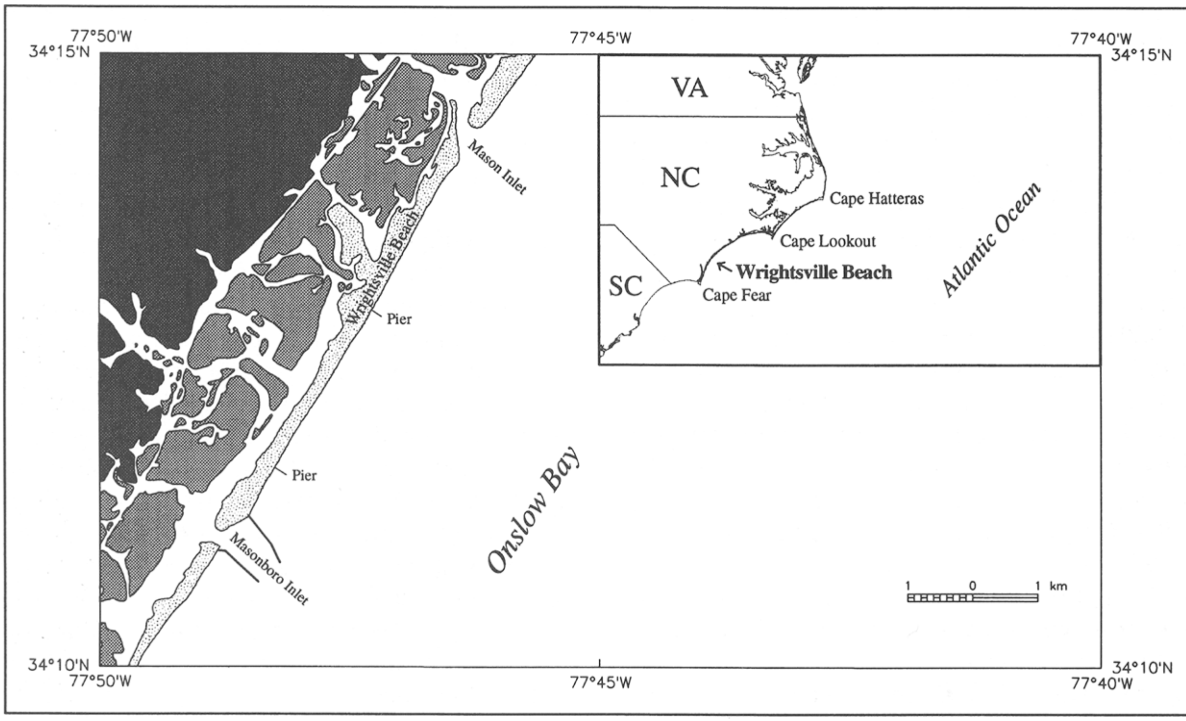

Fig. 1. Wrightsville Beach is a transgressive barrier island located in the southern part of Onslow Bay, North Carolina, between Cape Lookout and Cape Fear (inset).

environment (Hayes, 1979), with a mean tidal range of about 1 m. Based on four years of wave gage data obtained at Wrightsville Beach during 1971–1975 (Jarrett, 1977), the average significant wave height at Wrightsville Beach is 0.78 m, with a corresponding period of 7.88 s. The dominant direction of wave approach is from the northeast during the winter months, and from the southeast during the summer. Typically, storm waves approach from the northeast, but the area is also subject to episodic storm wave events from the east and south during the passage of tropical and extratropical cyclones. The net longshore drift is to the south (Jarrett, 1977).

Introduction of new sediment to Onslow Bay is negligible due to: (1) no fluvial input (coarse sediments are trapped in the estuarine system); and (2) minimal sediment exchange between adjacent shelf embayments (Cleary and Pilkey, 1968; Blackwelder et al., 1982). Milliman et al. (1972) classified the Onslow Bay shelf sediment cover as residual (derived from the erosion of underlying sediments and rocks). The major native sources of sediment for the Wrightsville Beach shoreface and inner shelf are bioerosion of rock outcrops and shoreface bypassing of unconsolidated sediments.

Wrightsville Beach is one of the four most-replenished beaches (i.e. large, federally-funded replenishment projects) on the U.S. East Coast (Pilkey and Clayton, 1987, 1989). Major replenishments have been carried out at approximately four-year intervals since 1965, each of which involved the placement of approximately 1×10^6 m^3 of material dredged from the backbarrier lagoon and portions of Masonboro Inlet. Numerous engineering studies have investigated various aspects of the Wrightsville Beach nearshore system and its predicted response to jetty construction and beach replenishment (e.g. Sager and Seabergh, 1977; Winton et al., 1981; U.S. Army Corps of Engineers, 1982).

Hallermeier (1981a,b) suggested that closure depth at Wrightsville Beach, as defined for beachfill project design or modeling coastal changes over a period of a few decades, occurs at 5.35 m. Engineering projects at Wrightsville Beach, however, typically assume a deeper closure depth of 8.5 m (U.S. Army Corps of Engineers, pers. commun., 1993). Closure depth, or a seaward limit of sand transport, is an important assumption made in the design of beach replenishment projects and in sediment budget calculations.

The study area described here includes approximately 105 km^2, from 2.2 km south of Masonboro Inlet to 0.5 km north of Mason Inlet, and extends offshore approximately 11 km (Fig. 1). This area includes the outer surf zone, shoreface, and extends onto the inner shelf to a depth of about 19 m.

3. Methods

Wrightsville Beach has been the site of intensive analog sidescan-sonar, analog seismic, vibracore and surface sediment sample data collection. Approximately 142 line-km of sidescan-sonar and seismic data gathered on 9, 15, and 16 June 1992 are used in this study (Fig. 2). The surveys bracket a minor northeast storm that passed through the Wrightsville Beach area on 13 June 1992.

Sidescan-sonar data were obtained using an EG&G SMS 960 operating at 100 kHz and configured for a 200 m swath. A Datasonics SBP-5000 high-resolution subbottom profiler was used to obtain 3.5 kHz seismic reflection and 200 kHz bathymetric data. Navigation data were obtained using a combination of GPS and Loran-C, yielding an average positioning error of about 30 m.

Bathymetric data were digitized and processed to remove water depth variations due to tidal fluctuations. The vertical resolution of the bathymetric data is approximately 50 cm. The data were gridded and contoured on a 50 m grid using the GMT software package (Wessel and Smith, 1991).

The sidescan-sonar data were analyzed qualitatively for acoustic reflectivity and mapped at a scale of 1:20,000 as swaths of high ("dark") relative acoustic backscatter and low ("light") relative

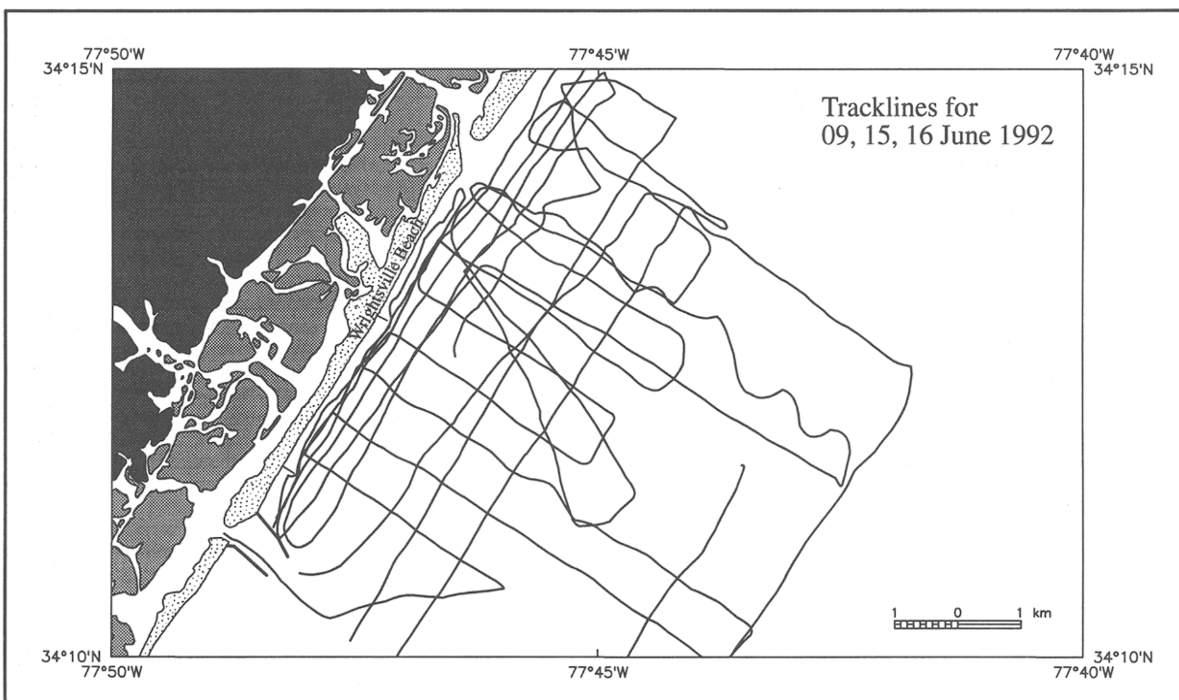

Fig. 2. Sidescan-sonar, 3.5 kHz seismic and 200 kHz bathymetric survey tracklines in the Wrightsville Beach area for 9, 15 and 16 June 1992. Sidescan swaths cover 100 m on each side of the tracklines.

acoustic backscatter sediment. In all cases, an attempt was made to preserve the geometries of features from the original sidescan records, using methods from Klein Associates (1985). Likely sea floor types were interpreted from the sonographs using the methods of Belderson et al. (1972) and Johnson and Heferty (1990) and verified by surface sediment samples and diver observations. The sidescan data were used to delineate zones of grain size $>1.5\phi$, $<1.5\phi$, rock outcrop, and inlet sediments (generally fine sands characterized by pronounced sandwave development). Over 100 surface grab samples collected in the field area were visually classified into these major size classes using an American–Canadian Stratigraphic grain size card. As a check against the visual size estimates, selected samples were analyzed using standard sieving techniques. Finally, known contacts from the sidescan images, those inferred from the sediment samples, and apparent trends in the distribution of sediments in the area were combined into a composite, acoustic sedimentary facies map.

4. Results

The surficial sediments on the Wrightsville Beach shoreface can be classified on the basis of grain size, provenance, thickness, and areal distribution. There are also several different bathymetric features that can be classified based on their morphology. The acoustic signature of the surface sediments in the sidescan-sonar data, coupled with the grain-size data, provide the basis for an acoustic, sedimentary facies map of the shoreface and inner shelf.

4.1. Surface sediments

Fig. 3 shows that the grain size distribution is highly variable across the shoreface and inner shelf

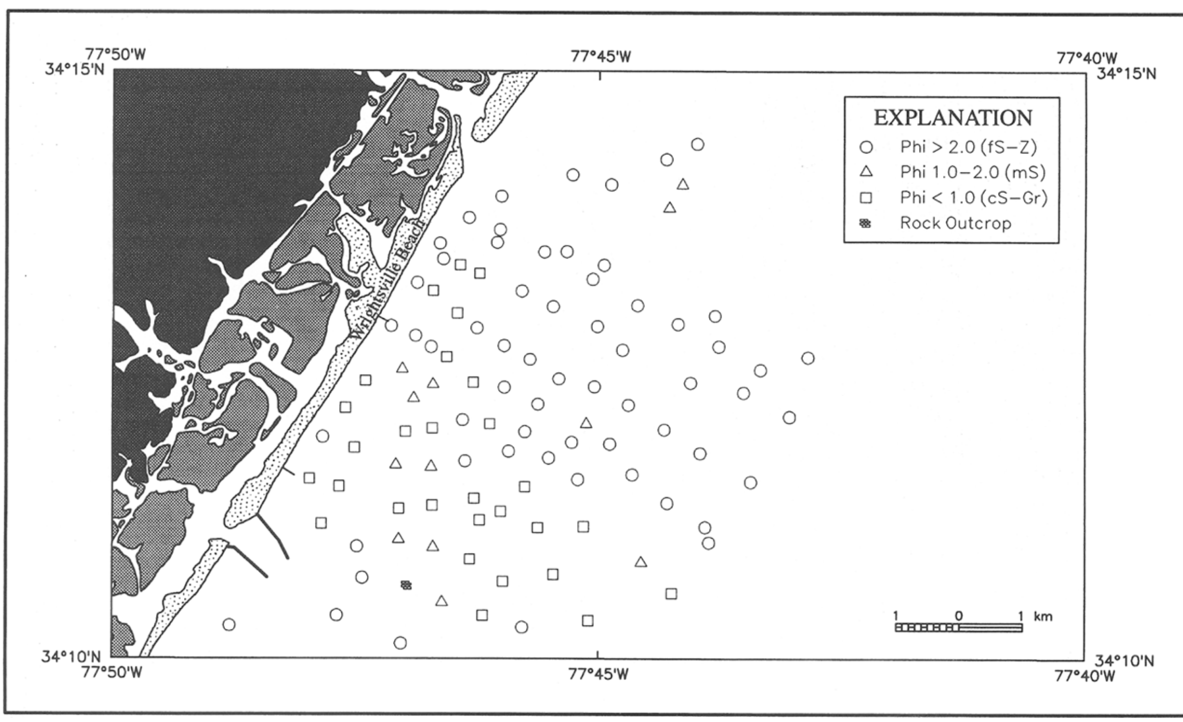

Fig. 3. Grain size classification for surface sediment samples obtained off Wrightsville Beach. There is little uniformity in grain size distribution across the shoreface.

off Wrightsville Beach. This finding agrees with other studies of shoreface and shelf sediments in Onslow Bay, which describe the floor of the bay as sediment-starved, with a patchy cover of varying grain size, consisting mainly of residual and relict orthoquartzitic sediments (Cleary and Pilkey, 1968; Pilkey, 1968; MacIntyre and Pilkey, 1969; Milliman et al., 1972).

Seismic and vibracore data indicate that the modern shoreface sediment cover is a thin, patchy veneer blanketing low-relief, relict units. The modern sediment averages only 30 cm in thickness. Cores from this and other studies (Hoffman et al., 1991; Zarra, 1991) indicate the primary underlying relict units are a Plio-Pleistocene arenaceous limestone and an unconsolidated Oligocene silt sequence. The seismic signature and distribution of these units has also been identified by Snyder et al. (1994) (Fig. 4).

Petrographic analysis of the surface sediment samples indicates three distinct sediment source areas. The sources include both of the relict units, as well as the beach. For example, there are a number of locations in the study area where rock outcrops are present, some of which are productive hardbottom habitats (Fig. 5). Bioerosion of the outcrops produces a residual mix of sediment ranging from gravels to lime mud. These residual sediments are mixed with outcrop-associated, relatively fresh invertebrate fragments, including small corals and shell material.

Numerous vibracores in the northern portion of the study area display a sharp, erosional contact between the thin, active modern sediment cover and the underlying Oligocene silt unit (Fig. 6), indicating periodic erosion and bypassing of material onto the shoreface. The similar mineralogy of the modern and relict sediments further indicates that the Oligocene unit is contributing glauconite-rich silt and very fine sand to the surface sediments.

The modern beach also contributes sediment to the shoreface and inner shelf. Specifically, some of

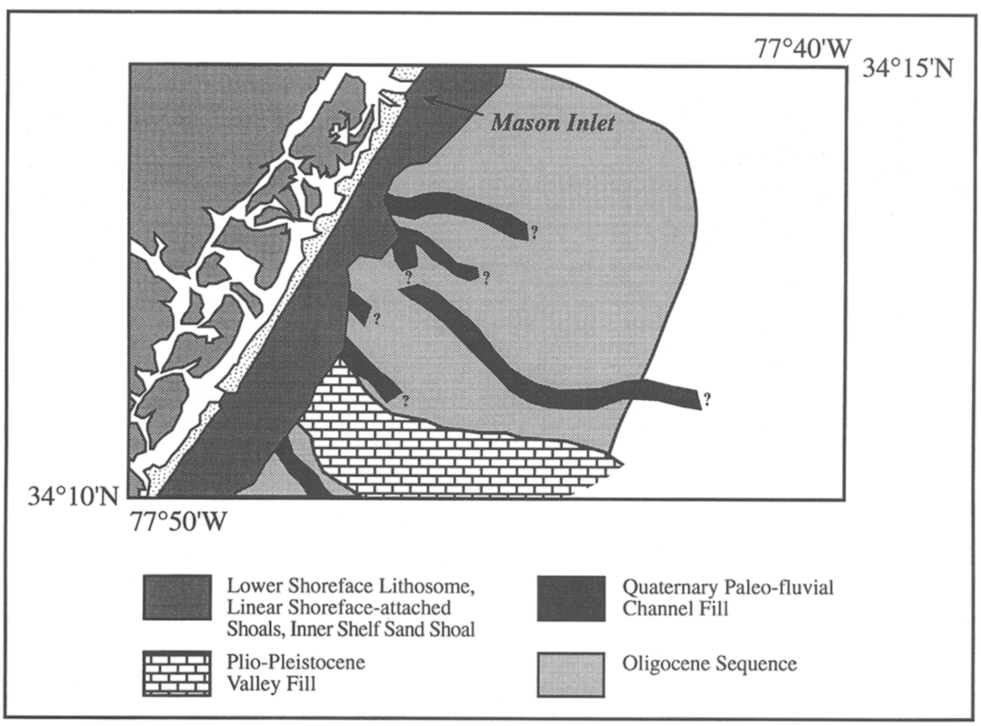

Fig. 4. An enlarged section of the near-surface geology of the Wrightsville Beach study area mapped by Snyder et al. (1994), showing the distribution of rock units described as Plio-Pleistocene valley fill limestone and Oligocene silt. These areas correlate with the sidescan-sonar, seismic and surface sample data used in this study. (Modified after Snyder et al., 1994.)

Fig. 5. The rock outcrops (marine hardbottoms) in the study area support a variety of organisms, including corals, boring clams, sponges, and gorgonians. The organisms contribute not only to the production of biogenic sediments, but also to the acoustic reflectivity of the rock outcrops.

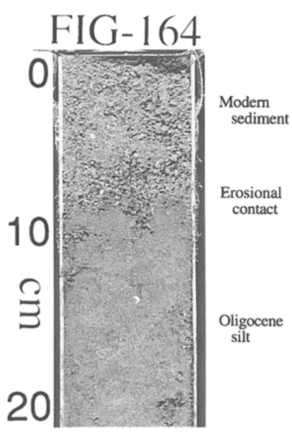

Fig. 6. The northern portion of the Wrightsville Beach shoreface is underlain by an unconsolidated, olive-green, Oligocene silt. The contact between the overlying thin, modern sediment and the underlying ancient unit (the ravinement surface) is shown in this photo of core FIG-164 as a sharp, erosional contact 9 cm downcore.

the sediment from early beach replenishment projects is a lagoonal sand that is petrographically distinct from continental shelf sediment. Pearson and Riggs (1981) first noted the occurrence of this replenishment sand, which is identifiable on the basis of its gray color, black-stained shell material, and high oyster shell content. More recently, Thieler et al. (1994) found that the coarse shell fraction of the replenishment material can be traced from the beach across the shoreface and inner shelf.

4.2. Bathymetric features

Several distinct bathymetric features are present on the Wrightsville Beach shoreface and inner shelf. A shore-normal system of bathymetric depressions up to 1 m deep is present on the shoreface. The depressions become apparent at 3–4 m depth, and extend to the base of the shoreface at 9–11 m depth. These features are shown in Fig. 7 as landward excursions of the depth contours between 8 and 10 m. Unfortunately, at the resolution limit of the processed bathymetric data, there is some loss in the details of the depressions. On the individual side-scan-sonar and bathymetric records, however, approximately 30 depressions are identifiable along the beach. The depressions are 40–100 m wide, and occur irregularly along the shore at 75–300 m intervals.

The depressions terminate and the shore-normal bathymetric trend changes at the base of the shoreface, approximately 1 km offshore. Here, the bathymetric fabric becomes shore-oblique, due to a system of east- to northeast-trending ridges (Fig. 7) with 1–2 m of relief. The ridges are irregularly spaced, variably sized, and extend offshore to the edge of the study area.

Similar shore-oblique ridges have been described along other low-elevation, retreating shorelines (Duane et al., 1972; Swift, 1976; Field, 1980; McBride and Moslow, 1991). Those reported previously, however, are typically larger and extend farther onto the continental shelf than those at Wrightsville Beach. The data presented here, as well as seismic reflection data presented by Snyder et al. (1994), indicate the ridges are relict Pleistocene depositional features; they were not formed by modern processes such as those described by McBride and Moslow (1991).

4.3. Acoustic/sedimentary facies

Comparison of the grain size classification (Fig. 3) with the acoustic signature from the side-scan sonographs results in a correlation of 0.87

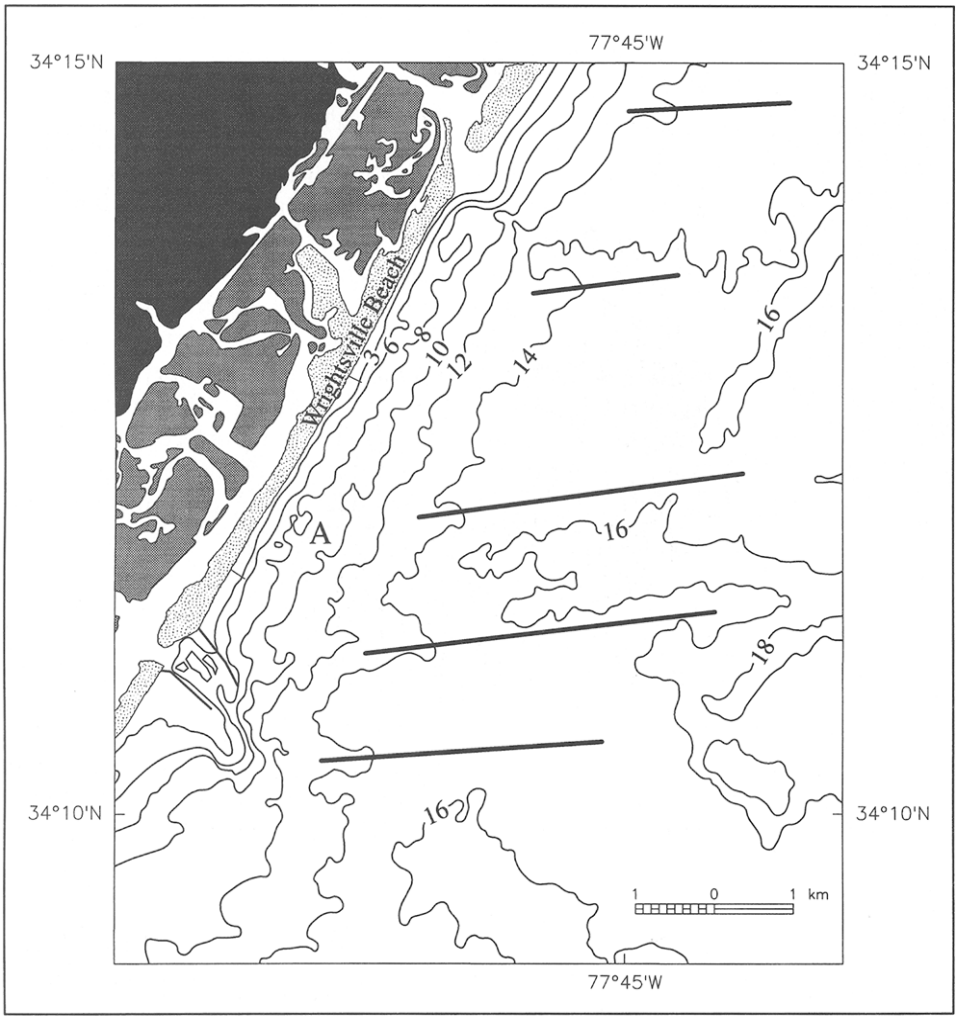

Fig. 7. Bathymetric map of the Wrightsville Beach study area, generated from surveys in June 1992. Contours are in meters below MSL. Seaward of the 6 m contour, the contour interval is 2 m. The gross morphology of the rippled scour depressions shown in Fig. 9 is visible at *A* as landward excursions of the 8 m contour. The axes of the relict, shore-oblique ridges are shown by the black lines.

between grain size and that inferred from the sidescan data. This degree of correlation is acceptable, considering the spatial variability of the sediment cover and navigational accuracy. Fig. 8 shows a composite sedimentary facies map based on the sidescan-sonar and surface sample data.

Perhaps the most visible division in the coarse and fine sediments is located on the upper shoreface. Specifically, this zone is dominated by a shore-normal sedimentary fabric similar to the bathymetric fabric described above. In fact, comparison of the nearshore bathymetric and acoustic facies data indicate that the coarse sediments, which are predominantly quartz gravel and shell hash, are present in the bathymetric depressions. Cacchione et al. (1984) used the genetic term "rippled scour depressions" to describe these features. Hereafter, we adopt this term to describe the features present off Wrightsville Beach.

As defined by both the bathymetry and sidescan-sonar data, the rippled scour depressions begin abruptly at 3–4 m depth (just outside the fair-weather surf zone) and converge as they reach the base of the shoreface (see Figs. 7 and 8). The

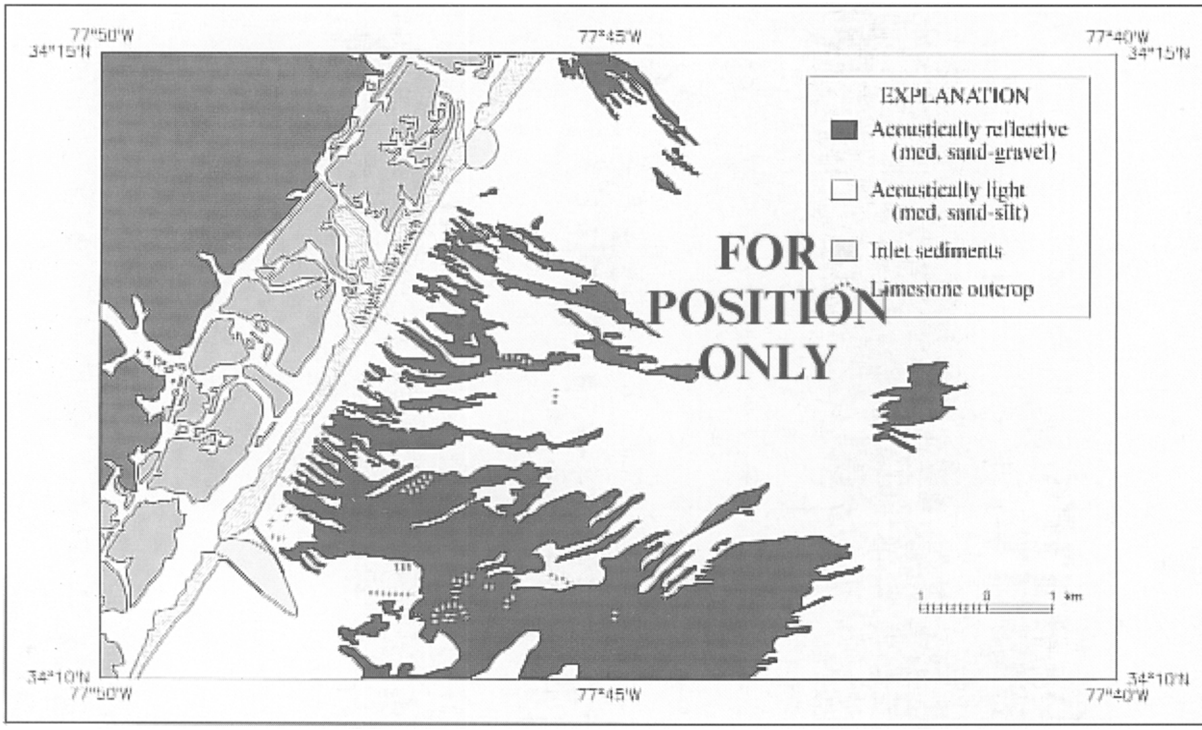

Fig. 8. A sedimentary facies map of the Wrightsville Beach shoreface, based on sidescan-sonar, seismic and surface sample data shows several important features. A zone of shore-normal rippled scour depressions are present on the shoreface. A zone of shore-oblique features (relict ridges) is present on the lower shoreface and inner shelf. See text for discussion.

depressions are floored with very coarse shell hash and quartz gravel, and appear to be scoured up to 1 m below the surrounding areas of fine sand (Fig. 9A and B). In addition, along the near-shore tracklines, small areas (20–50 m^2) of outcropping rock appear to be exposed above the fine sand between some of the depressions.

Long, straight-crested, symmetric ripples that floor the depressions have wavelengths of 0.8–1.2 m and frequent bifurcations, indicating that they are most likely oscillatory wave ripples (Reineck and Singh, 1980). Diver observations also indicate that the ripples were active under the prevailing long-period, fair-weather waves present at the time of the sidescan surveys.

The rippled scour depressions are most dense in a 1 km section of shoreline about 1 km north of the north jetty at Masonboro Inlet (see Fig. 8), where they have an average spacing of just 90 meters. Over the 2 km of shoreface north of this section, the depressions are spaced about 250 m apart.

Another visible division in the distribution of coarse and fine sediments is a transition from a shore-normal fabric in the nearshore to a more shore-oblique trend at the base of the shoreface, which continues onto the inner shelf (see Fig. 8). The nearshore zone of shore-normal rippled scour depressions grades into the shore-oblique fabric about 1 km offshore, at a depth of approximately 11 m. The sedimentary fabric here is apparently influenced by the ridges shown in Fig. 7. Seaward of about 11 m depth, areas of both coarse and fine sand also appear to become larger and less patchy in their distribution, although this could reflect the bias of the more dense nearshore side-scan coverage. There is also a fairly large area of fine sediments proximal to the navigation jetties at Masonboro Inlet (see Fig. 8).

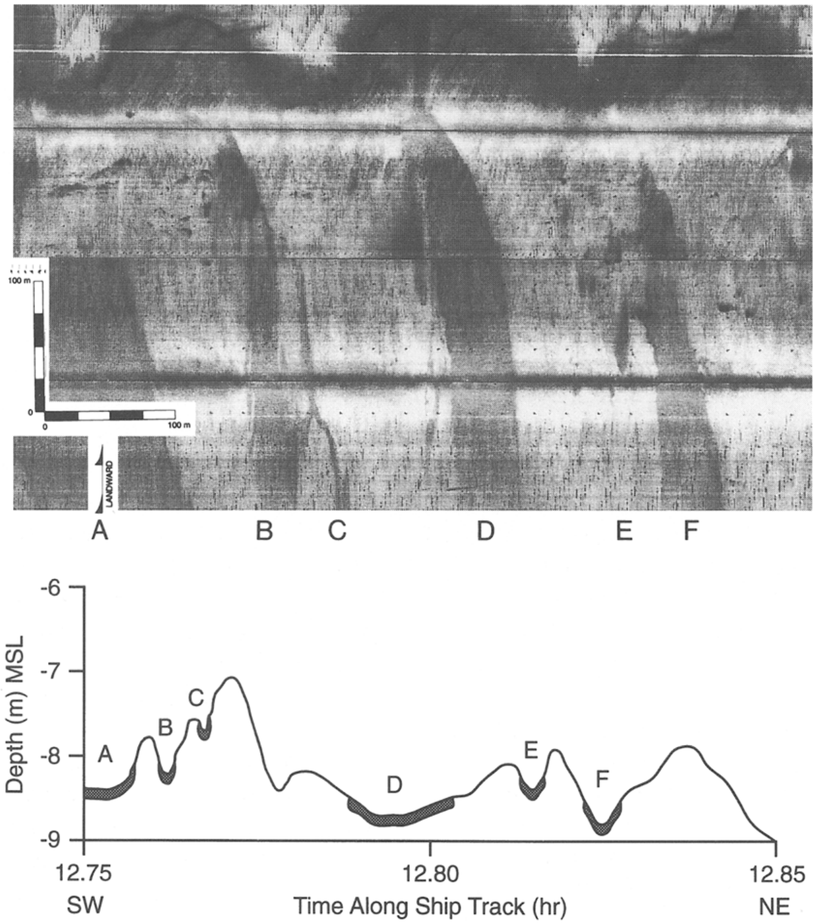

Fig. 9. (A) A section of two overlapping, shore-parallel, sidescan-sonar records, showing the rippled scour depressions (labelled *A–F*) present just seaward of the fair-weather surf zone along the southern portion of Wrightsville Beach. This area corresponds to a zone of chronic, rapid beach erosion along the beach. The coarse-grained depressions are acoustically dark; fine sand between them is acoustically light. The dark patches within the fine sand represent small rock outcrops. (B) The equivalent bathymetric data (from the centerline of the seaward trackline shown in (A) show the depressions to have up to 1 m of relief. The labels *A–F* over each depression correspond to those shown on the sidescan record. The depressions extend to the base of the shoreface.

5. Discussion

The shoreface geology of Wrightsville Beach is discussed in terms of its implications for the use of equilibrium profile-based concepts and models to describe this coastal system.

5.1. Shoreface geology

On a broad scale, the greater number of rippled scour depressions (floored by gravelly shell hash) may be the result of increased bedrock control in the south, as evidenced by the larger areas of rock outcrops. For example, outcrops exposed above the sand are visible between some of the depressions. The outcrops are visible in the same places along the shoreline both before and after the small storm on 13 June. These observations suggest that the locations of rippled scour depressions along the beach may be controlled by bedrock topography. The depressions may be relatively permanent features in the outer surf zone and on the upper shoreface.

There is also evidence that the supply of coarse sediment is relatively larger in the southern half of the study area. Sediment composition data indicate that much of the coarse material is derived from biodegradation of the rock outcrops and the coarse shell fraction of the beach replenishment material. In the northern half of the study area, however, the modern sediment cover appears to be derived primarily from shoreface bypassing of Oligocene silt and very fine sand onto the shoreface. Thus, the greater abundance of rippled scour depressions along the southern half of Wrightsville Beach may also be due to a larger supply of coarse material.

Shore-normal, rippled scour depressions similar to those on the Wrightsville Beach shoreface have been reported on high-energy shelves in other parts of the world (see review by Cacchione et al., 1984), in depths of 2–80 m. They have been attributed to scouring by strong rip currents (Reimnitz et al., 1976; Aubrey et al., 1984); rip currents forced by long period, surf-beat related mass flux (Reimnitz, 1971); wave agitation and storm setup-induced downwelling (Field and Roy, 1984; Cacchione et al., 1984; Gayes, 1990; Siringan and Anderson, 1994); turbidity currents (Reimnitz et al., 1976); and storm surge ebb return flow (MacIntyre and Pilkey, 1969).

The studies described above generally agree that channel-like, linear depressions on the shoreface and shelf are related to bottom scour by strong, offshore-directed flows. Cross-shore flows on the shoreface and shelf have been measured at more than 1.1 m s^{-1} on the Pacific coast (Reimnitz, 1971) and are known to exist on the U.S. East and Texas coasts in response to northeast gales and onshore Ekman transport (Beardsley and Butman, 1974; Snedden et al., 1988). In addition, Wright et al. (1991) have documented cross-shore mean flows of over 20 cm s^{-1} across the shoreface and inner shelf of the Mid-Atlantic Bight.

The area where the rippled scour depressions are most dense (Fig. 8) corresponds to a zone of chronic, severe beach erosion on Wrightsville Beach (U.S. Army Corps of Engineers, pers. commun., 1993). While such a depression density-beach erosion relationship may be coincidental, the densely-spaced nearshore depressions could indicate zones of pronounced offshore transport during storms, and therefore may be related to the severity of local beach erosion and nearshore sediment loss. The studies by Pearson and Riggs (1991) and Thieler et al. (1994) described above found that beach replenishment sediment is being transported from the beach onto the inner shelf. Thus, the depressions may act as conduits for offshore sediment transport. Physical oceanographic and sediment transport measurements, however, are needed to establish nature of the transport mechanisms and verify this speculation.

The studies of rippled scour depressions cited above indicate they may continue offshore to depths of more than 40 m. At Wrightsville Beach, however, the shore-oblique, offshore ridges (see Fig. 7) disrupt this pattern. The depressions do not cut across the ridges. The ridges do not appear, however, to preclude the offshore transport of sediments carried by the nearshore rippled scour depressions. This can be seen from the distribution of coarse and fine materials over the surface of the ridges.

The landward sides of the ridges (Fig. 10A and B) are composed of winnowed shell hash and gravel similar to that found in the bottom of the rippled scour depressions; the seaward sides are coated with a veneer of fine to very-fine sand. The sand wedges on the offshore sides of the ridges have a ragged, thin feather edge near the ridge top, and elongate, shore-perpendicular, scoured "windows" through which underlying, coarser sediments are exposed (Fig. 10A). The windows in the surface sediment close as the fine sand layer becomes more continuous (and most likely thicker) down the offshore side of the ridge, forming a small fillet. The sand fillet ends at the base of the next offshore ridge as a very sharp boundary, possibly a depositional slip slope. This seaward-directed sediment distribution pattern is visible from 9 to 16 m water depth along each shore-oblique ridge.

The sedimentary and geologic data presented here indicate that cross-shore sediment transport on the shoreface at Wrightsville Beach connects the beach and surf zone with the continental shelf. Evidence of significant cross-shore transport on adjacent islands in Onslow Bay, such as the onshore transport of shelf material (including limestone gravels and slabs) into barrier island over-

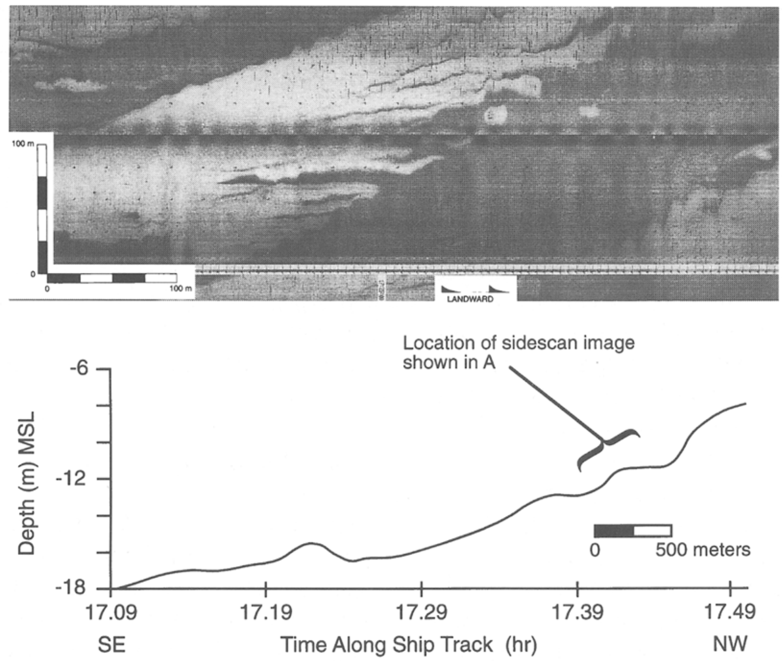

Fig. 10. (A) A section of sidescan-sonar record from approximately 12 m water depth, showing the seaward-directed sedimentary fabric on one of the shore-oblique ridges. (B) The ridges are irregularly spaced, variably sized, and extend offshore to the edge of the study area (see Fig. 7). The equivalent bathymetric data for this cross-shore profile show the ridges to have 1–2 m of relief.

wash fans (Cleary and Hosier, 1979) indicates that cross-shore transport in both directions is a widespread process. Clearly, cross-shore sediment transport, in concert with bathymetric control, plays an important role in the morphological evolution of the Wrightsville Beach shoreface.

5.2. Implications for the equilibrium profile concept

The equilibrium profile equation was first proposed by Bruun (1954) for the Danish North Sea coast, and has the form:

$$h = Ay^{n} \tag{1}$$

where h is water depth, y is the distance offshore from the shoreline, n is a variable shape parameter and A is a scaling parameter. Bruun (1962) used this equation to develop a simple model for coastal evolution, in which a constant profile shape translates landward and upward over time in response to rising sea level.

Subsequent work by Dean (1977) used a least squares approach to fit the data of Hayden et al. (1975) to an equation of the form shown in Eq. 1, where $n = 0.67$. In fixing the value of n, Dean (1977) left the sediment scaling parameter, A, as the only independent variable in the equation. Dean (1987) related A to sediment fall velocity by transforming Moore's (1982) sediment grain size data to the equation:

$$A = 0.067w^{0.44} \tag{2}$$

where w is the sediment fall velocity in cm s^{-1}. Essentially, this relationship implies that any shoreface profile can be described solely in terms of the grain size present.

In addition to describing a shoreface profile only on the basis of sediment grain size, the profile of equilibrium concept as used in engineering design and coastal modeling makes several other fundamental assumptions about the shoreface. The most pertinent assumptions for this discussion include (Pilkey et al., 1993): (1) underlying geology does not play a role in determining profile shape; (2) sediment is moved only by diffusion due to wave energy gradients; and (3) there is no net cross-shore movement of sediment seaward of closure depth.

There has been no systematic field verification of the physical basis for the equilibrium profile equation (Kraft et al., 1987; Wright et al., 1991; Pilkey et al., 1993). The concept, however, has been accepted as valid and useful by many coastal researchers. The equilibrium profile is also a fundamental principle behind most analytical and numerical models of shoreline change used to predict large-scale coastal behavior (e.g., Hanson and Kraus, 1989) and to design replenished beaches (e.g., Hansen and Lillycrop, 1988; Larson and Kraus, 1989), including those used at Wrightsville Beach.

The diverse geology of the Wrightsville Beach shoreface illustrates several fundamental shortcomings for the application of equilibrium profile-based concepts and models to this location: (1) both the wide range and the lack of consistent trends in grain size variation across the profile are not considered by equilibrium profile models; (2) underlying geology is likely the predominant control on shoreface profile shape, not incident waves impinging on a purely sandy bed as required by equilibrium profile models; and (3) sediment transport patterns deduced from sediment distribution and bathymetric controls indicate that sediment transport cannot be explained by simple diffusion due to wave energy gradients as done by equilibrium profile models. This includes evidence of significant sediment transport seaward of the assumed engineering closure depth of 8.5 m at this location.

5.2.1. *Grain size variation*

Assumptions: As expressed by Dean (1977, 1991), grain size, as represented by A in Eq. 1, is the only variable in the equilibrium profile equation. In this relation, there is no cross-shore variation in grain size (e.g., grain size is represented by the median grain diameter, D_{50}). Recent work has added a seaward-fining grain size distribution (Larson, 1991) to the equilibrium profile, or attempted to predict shore-normal variations in grain size based on equilibrium profile concepts (Horn, 1991). The representation of an equilibrium profile by a single grain size, however, is often a fundamental requirement of numerical models currently used in applied coastal engineering [e.g., SBEACH (Larson and Kraus, 1989)].

Field evidence The sediment grain size distribution on the Wrightsville Beach shoreface is too complex to describe with one number. As shown in Figs. 3 and 8, there is no consistent cross-shore variation in grain size at Wrightsville Beach. The spatial variability of the sediment cover precludes a realistic representation by a parameter such as median grain size.

5.2.2. *Underlying geology*

Assumptions: As noted by Pilkey et al. (1993), one of the most important assumptions of the equilibrium profile concept is that of an infinitely sand-rich, unconsolidated shoreface. In addition, the GENESIS (Hanson and Kraus, 1989) and SBEACH models generally assume that either or both surf zone and shoreface bathymetry are characterized predominantly by straight and parallel contours.

Field evidence: Sidescan-sonar, seismic and vibracore data show clearly that the Wrightsville Beach shoreface is not sand-rich, and the profile shape is frequently bedrock-controlled. As discussed above, Onslow Bay is a sediment-starved system; there is little introduction of new sediment, either by longshore transport, fluvial input or onshore transport of shelf material. Thus, shoreface bypassing is the primary source of new sediment to the system. At Wrightsville Beach, the silt unit underlying the northern portion of the island is not a significant source of sand-sized sediment, which places a further limit on the sediment supply.

The rock outcrops at the southern end of the island, some of which are located in the outer surf zone, are similarly incompatible with the assumption of an infinite reservoir of unconsolidated sand. Clearly, the bedrock features preclude the formation of an equilibrium profile: where there is no sand, there can be no equilibrium profile. In addition, models such as GENESIS assume a completely sandy shoreface and surf zone in order to calculate longshore sediment transport volumes (Hanson and Kraus, 1989). The overall lack of sediment in this system makes such assumptions invalid.

The shape of the shoreface profile at Wrightsville Beach is characterized not by straight and parallel contours, but a shore-normal system of rippled scour depressions (see Figs. 7 and 8). Offshore, a series of large, shore-oblique ridges (Fig. 10A and B) further complicates the simple shoreface configuration required by equilibrium profile-based models.

5.2.3. *Sediment transport*

Assumptions: The profile of equilibrium concept assumes that sediment transport is the result of a diffusion process due to wave energy gradients. The concept as used in engineering design and coastal modeling also assumes that there is a seaward closure depth (approximately 8.5 m for Wrightsville Beach) beyond which there is no significant net sediment transport.

Field evidence: There is abundant evidence of wave-induced sediment movement on the Wrightsville Beach shoreface, predominantly in the form of oscillatory wave ripples. The dominant sedimentologic signature, however, is that of cross-shore sediment transport by mean currents (Figs. 9A and 10A), likely taking place during storm-induced downwelling events. As shown in Fig. 10A, there is evidence of significant offshore-directed sediment transport at a depth of 15 m, well beyond the engineering closure depth.

Other evidence further suggests that beach sediment is lost to the inner shelf. For example, the alongshore density of rippled scour depressions appears to be related spatially to erosion "hot spots" on the beach. In addition, the presence of beach sediment seaward of the engineering closure depth has been documented. The long-term beach replenishment requirements at Wrightsville Beach have also not decreased (Fig. 11), indicating that over a decadal time scale, the beach is not approaching an equilibrium profile in the sense of Bruun (1962) or Dean (1991).

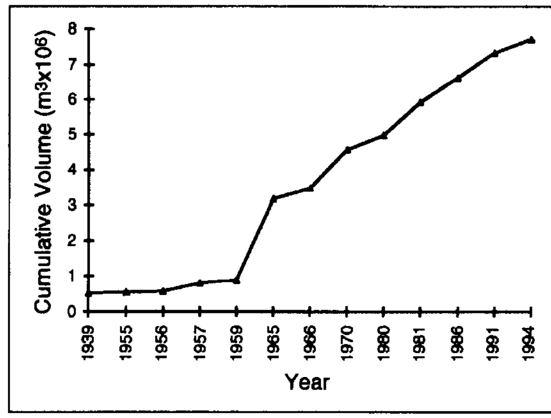

Fig. 11. The beach replenishment history of Wrightsville Beach shows that the sediment volume requirements have remained constant (about 1×10^6 m^3 emplaced every 3–4 years) over the past several decades. This would not be the case if the beach were approaching an equilibrium profile.

6. Conclusions

Based on sidescan-sonar, seismic, vibracore and surface sediment data, several zones of surface sedimentation and bathymetric features can be differentiated on the Wrightsville Beach, North Carolina shoreface. From the nearshore to approximately 10 m water depth, the shoreface is characterized by a shore-normal system of rippled scour depressions. The troughs are 40–100 m wide, and are floored with granule- and larger-sized material. The sea floor between the depressions is characterized by acoustically featureless fine sand. The location of the depressions may be controlled in part by the presence of rock units, some of which are located in the outer surf zone.

The predominant seaward-directed sedimentary fabric indicates that the depressions carry sediment offshore. The area where scour depressions are most prevalent on the upper shoreface also correlates with a zone of chronic, rapid beach erosion. Other studies have documented the presence of a petrographically distinct beach replenishment material on the shoreface and inner shelf. This suggests that the shoreface connects the beach and the inner shelf, and acts as a pathway for cross-shore sediment transport.

In the southern part of the study area, most exposed sediments are shell hash and quartz of granule to gravel size. The coarse material is composed partially of residual sediments produced by biodegradation of Plio-Pleistocene limestone hardbottoms, as well as hardbottom-associated biogenic production, including coral fragments and shell material. Shell material derived from beach replenishment projects also makes up a portion of the coarse sediment. Fine sediments are being supplied to the northern half of the study area by shoreface bypassing (erosion and reworking) of an Oligocene silt unit present in the shallow subsurface.

Beyond 10 m water depth, and onto the inner shelf, cross-shore sediment transport is influenced by shore-oblique, relict ridges. The ridges are particularly well-developed off the southern part of the island. Surface sediments on these ridges consist of coarse, winnowed granules on the inshore side, and seaward-thickening wedges of fine to very-fine sand on the offshore side.

The Wrightsville Beach shoreface and inner shelf are characterized by indications of pronounced cross-shore transport in the nearshore, and continued sediment transport to at least a depth of 17 m. The sediment cover lacks a uniform grain size (sediment sizes range from mud to gravel and bare rock outcrops). Both the irregular bathymetry and sediment distributions strongly suggest that sediment distribution processes are controlled by the underlying geology.

Field evidence shows clearly that several commonly assumed characteristics of the shoreface profile of equilibrium do not exist at Wrightsville Beach. Examples from this study that contradict the assumptions of the equilibrium profile model are: (1) there is a wide range and lack of consistent grain size variation across the shoreface profile; (2) the shape of the shoreface profile is controlled predominantly by underlying geology, including limestone outcrops and unconsolidated silt subcrops of Tertiary age; and (3) the observed sediment transport patterns cannot be explained by simple diffusion due to wave energy gradients. Evidence also suggests that net offshore sediment transport occurs seaward of the assumed engineering closure depth of 8.5 m. To understand the large-scale coastal behavior of this area, the simple assumption of an equilibrium shoreface profile is inadequate.

Acknowledgements

This research was funded in part by grants to WJC, Orrin H. Pilkey and Stanley R. Riggs from the National Oceanic and Atmospheric Administration's National Undersea Research Center at the University of North Carolina at Wilmington, pursuant to NOAA award numbers NA88AA-D-UR0004 and NA36RU0060-01. Additional support was furnished to WJC by the UNCW Center for Marine Science Research. Additional support to ERT was provided by grants from Sigma Xi, the Geological Society of America, and the North Carolina Geological Survey.

Captain Dan Aspenleiter, Mission Coordinators Ken Johns, Glenn Taylor and the crew of the R/V *Elusive* are thanked for their perseverance and resourcefulness in the field. Nicolis Gilliard assisted in the laboratory analysis of the surface sediment samples.

David M. Bush, Robert S. Young, William C. Schwab, and two anonymous reviewers provided helpful reviews of the manuscript. This is Contribution Number 1914 from the Virginia Institute of Marine Science.

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Update

Marine Geology

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DOI: https://doi.org/10.1016/0025-3227(96)83355-X

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MARINE GEOLOGY
INTERNATIONAL JOURNAL OF MARINE GEOLOGY, GEOCHEMISTRY AND GEOPHYSICS

Erratum

Erratum to "Geology of the Wrightsville Beach, North Carolina shoreface: Implications for the concept of shoreface profile of equilibrium" [Mar. Geol. 126 (1995) 271–287]*

E. Robert Thieler [a], Andrew L. Brill [a], William J. Cleary [b], Carl H. Hobbs III [c], Robert A. Gammisch [c]

[a] *Duke University, Department of Geology, Campus Box 90228, Durham, NC 27708-0228, USA*
[b] *Department of Earth Sciences, University of North Carolina at Wilmington, Wilmington, NC 28403, USA*
[c] *Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, VA 23062, USA*

Received 15 February 1994; revision accepted 13 January 1995

The Publisher regrets that an incorrect figure was printed on p. 279 of the above paper. The correct Fig. 8 appears hereafter:

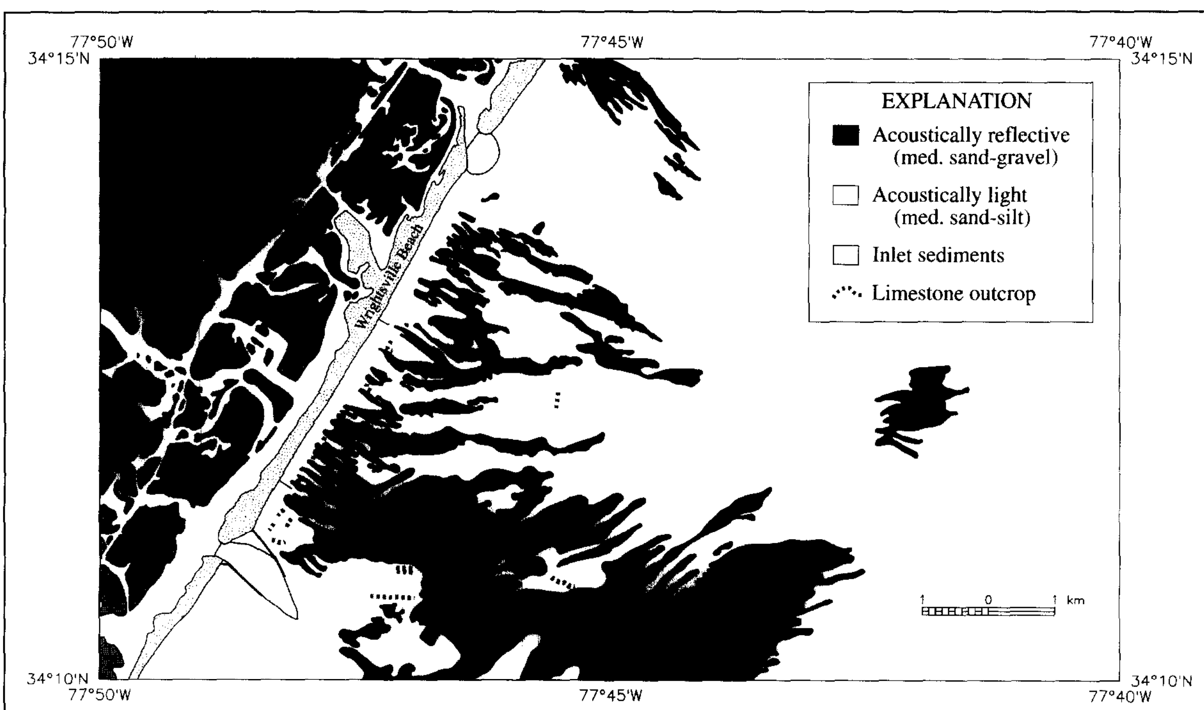

Fig. 8. A sedimentary facies map of the Wrightsville Beach shoreface, based on sidesean-sonar, seismic and surface sample data shows several important features. A zone of shore-normal rippled scour depressions are present on the shoreface. A zone of shore-oblique features (relict ridges) is present on the lower shoreface and inner shelf. See text for discussion.