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TRACING SEDIMENT DISPERSAL ON NOURISHED BEACHES: TWO CASE STUDIES

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Abstract: The event- to decade-scale patterns of sediment dispersal on two artificially nourished beaches have been mapped using a combination of geophysical surveys, closely-spaced vibracores, and repeated beach profiles. At both Wrightsville Beach, NC and Folly Island, SC the sediment used for beach nourishment is macroscopically distinct from native sediment and can be used to identify sediment transport pathways and infer mechanisms for across-shelf transport. The data from both sites demonstrate that significant quantities of nourishment sediment are being transported seaward onto the inner continental shelf. The time and space scales of this transport are of engineering interest for the planning, design and long-term maintenance of nourished beaches.

INTRODUCTION

Very few studies have examined the fate of beach nourishment projects (National Research Council 1995). Rather, most studies of nourished beach evolution have inferred sediment transport from morphologic changes in sequential shoreline positions or beach profiles (e.g., Hanson 1989; Kraus and Wise 1993), or been based on a combination of technical and anecdotal data (e.g., Leonard et al. 1990; Ebersole et al. 1996; Houston 1996; Pilkey et al. 1996). For a wide variety of reasons, ranging from the petrographic similarity of nourishment sediment and

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native beach-shoreface-shelf sediment to the lack of project monitoring, knowledge of sediment dispersal mechanisms and pathways on nourished beaches is lacking.

An improved understanding of the processes governing nourished beach evolution is needed to improve the design and performance predictions of beach behavior. Improving this understanding is all the more important today, since beach nourishment has become the preferred alternative in the U.S. for temporarily restoring and stabilizing eroding shorelines that provide beachfront communities with storm protection, recreation, and an important tourism resource (Houston 1991; National Research Council 1995).

Here we present two case studies that document the dispersal of beach nourishment sediment in barrier island systems, focusing in particular on the cross-shore component of sediment transport between the beach and the inner continental shelf. The shoreface region that connects these two environments is the interface between the subaerial coastal plain and the subaqueous continental shelf. In the broadest sense, the shoreface can behave as a source, barrier, filter, or conduit for the 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 hours to years to millennia. Our results indicate that over event- to decade-scale time scales, beach nourishment sediment is transported between the beach and shelf in quantities and to locations of primary importance to the planning, design and long-term maintenance of coastal engineering projects.

STUDY AREAS

Wrightsville Beach

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, relatively high-energy shelf environment between Cape Lookout and Cape Fear. This portion of Onslow Bay is microtidal, with a mean tidal range of about 1 m. The coast is lined by transgressive barrier islands (Hayes 1979) backed by narrow, marsh-filled lagoons. 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.

The dominant direction of wave approach at Wrightsville Beach 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. Hindcast wave data (WIS studies) indicate a mean wave height of 1.1 m, with a 7 s period. The dominant direction of wave approach is from the southeast, but the net longshore drift in this region is to the southwest (Jarrett 1977).

The Onslow Bay shelf is sediment-starved (Cleary and Pilkey 1968; Riggs et al. 1996) due to: 1) no fluvial input (coarse sediments are trapped in the upper estuarine system); and 2) minimal sediment exchange between adjacent shelf embayments (Blackwelder et al. 1982). The modern, native sediments on the Wrightsville Beach shoreface and inner shelf are derived from shoreface bypassing of unconsolidated, ancient sediments and the physical- and bio-erosion of marine hardbottoms (exposed rock outcrops) (Thieler et al. 1995).

Wrightsville Beach is one of the most-nourished beaches on the U.S. East Coast (Pilkey and Clayton 1987; 1989). Major nourishments (Fig. 2) have been carried out at approximately four-year intervals since 1965, each of which involved the placement of material dredged from the backbarrier lagoon and portions of Masonboro Inlet (Fig. 1). The nourishment sediment constitutes another source of modern sediment in this coastal system (Pearson and Riggs 1981; Thieler 1997).

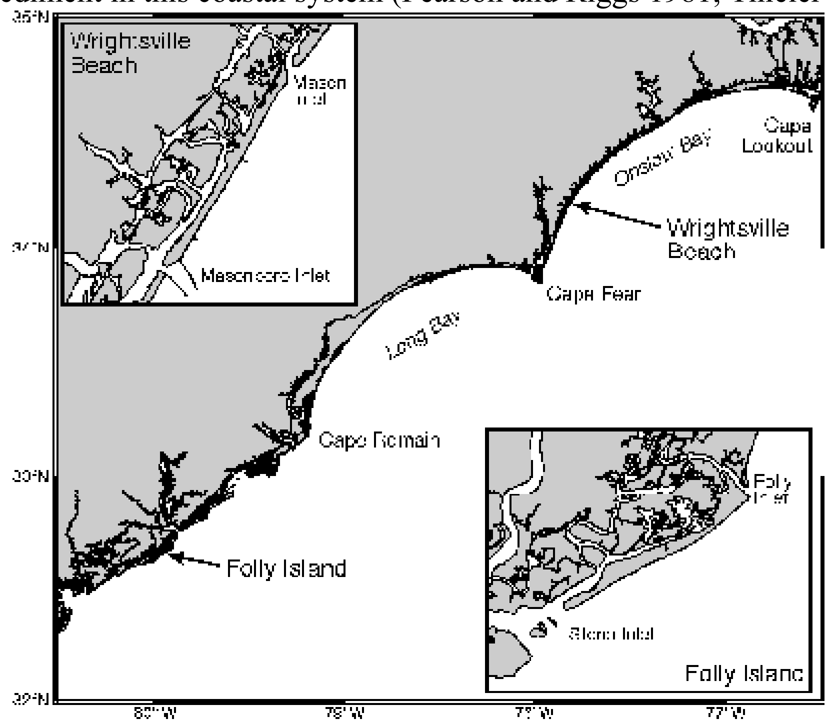

Fig. 1. Location of the Wrightsville Beach, North Carolina and Folly Island, South Carolina study areas.

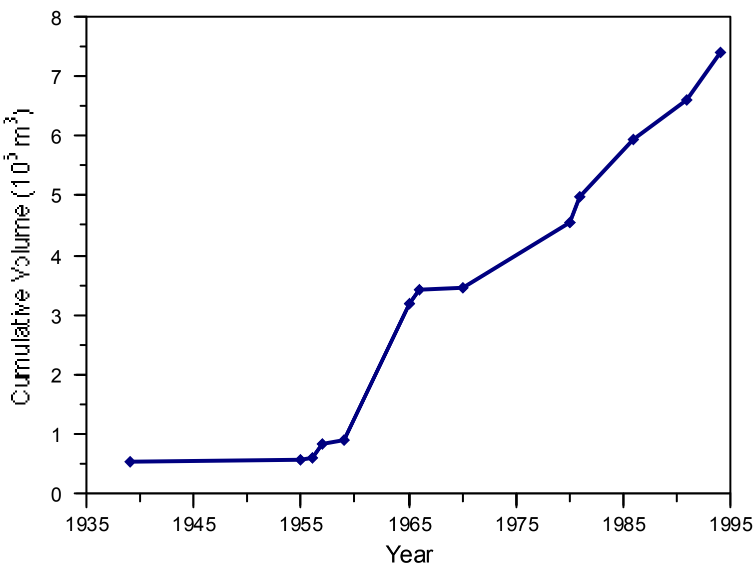

Fig. 2. Beach nourishment history of Wrightsville Beach.

Folly Island

Folly Island, and the community of Folly Beach, is located 20 km south of Charleston, South Carolina. This region is the type-section for mesotidal barrier island geomorphology defined by Hayes (1979). Hindcast wave data (WIS studies) indicate a mean wave height of 1 m, with a 7 s period. The rates of shoreline change along this reach of the South Carolina coast are variable and range from 8.0 m yr^{-1} erosion to 0.35 m yr^{-1} accretion (Anders et al. 1990).

While the hydrographic setting at Folly Island is different from Wrightsville Beach (e.g., the tidal range is about 2 m, or twice that of Wrightsville Beach), there are similarities in geologic framework. Tertiary deposits outcrop extensively seaward of the Folly Island shoreface, reflecting that the inner shelf is virtually starved of Quaternary sediment (Gayes et al. 1998).

There have been several engineering projects completed at Folly Beach to mitigate the effects of coastal erosion. The most recent was a beach nourishment project completed in 1993 that placed 1.9 million m^3 of fine sand along 8.6 km of shoreline at Folly Island (Ebersole et al. 1996). While the behavior of the overall project has been somewhat controversial (Katuna et al. 1995; Ebersole et al. 1996; Houston 1996; Pilkey et al. 1996; Gayes et al. 1998), there is general agreement that local hot spots of erosion are present on the island, including a major one in the north-central portion of the island known locally as the "Washout."

METHODS

Wrightsville Beach

An extensive database from the shoreface and inner shelf off Wrightsville Beach, North Carolina forms the basis for this paper. This includes seismic-reflection profiles, repeated sidescan-sonar surveys, diver vibracores, and diver-based seafloor mapping. Details of the acquisition and processing of the specific data sets are given by Thieler (1997) and Thieler et al. (1998). Techniques of particular relevance to the present paper, however, are summarized below.

High-resolution 3.5 kHz seismic-reflection data were collected along 375 km of trackline in the study area with a Datasonics SBP-5000 subbottom profiler. An additional 21 km of trackline was surveyed with a Geopulse boomer system (500-4000 Hz).

Three digital sidescan-sonar and bathymetric surveys were conducted in March 1994, July 1995 and July 1996. Each survey provides continuous, high-resolution coverage of the seafloor over a 53 km^2 area of the shoreface and inner shelf. An additional 15 km^2 is covered by non-overlapping sonar swaths, some of which have been presented by Thieler et al. (1995). The mosaics depict areas of high acoustic backscatter as light to white-colored, and low acoustic backscatter as dark to black-colored (Fig. 3).

Over 200 diver vibracores up to 3.5 m in length have been obtained in the study area (Fig. 4; see also Thieler 1997). Core sites were selected on the basis of the geophysical data described above. The locations of most cores were determined using either a high-accuracy Falcon Mini-Ranger or DGPS. The remaining cores were located using a combination of standard GPS and LORAN-C.

Surface sediment samples were obtained by divers at each vibracore location. Additional samples were obtained by divers or Shipek grab sampler at more than 30 locations on the shoreface and inner shelf.

Fourteen transects on the shoreface and inner shelf were surveyed by divers using weighted lines and buoys at positions located by real-time DGPS (Thieler 1997). The ability to consistently occupy the target features or contacts between sediment types confirmed the geographic accuracy of the sidescan-sonar imagery described above. Diver observations included photography and videography, mapping of sediment type, bottom morphology (e.g., local bathymetry, ripple dimensions and orientation) and probing sediment thickness using a steel rod or crowbar. Similar observations were made around each vibracore location.

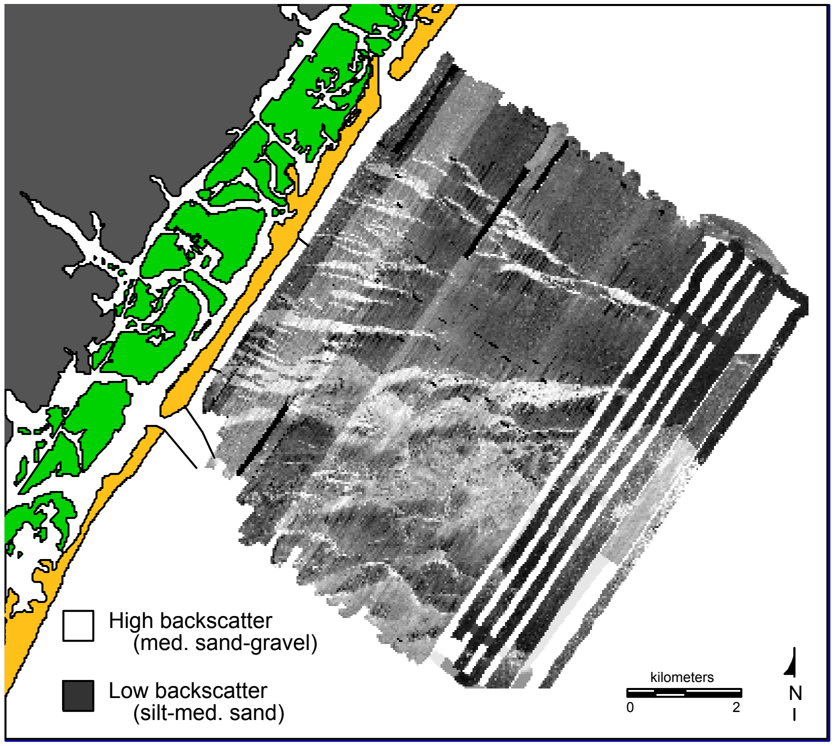

Fig. 3. Sidescan sonar mosaic of the shoreface and inner shelf off Wrightsville Beach, North Carolina. (Thieler et al., submitted.)

The characteristics of the gravel-sized carbonate fraction – primarily whole shells and shell fragments – in surface sediments and core subsamples were determined by standard point-counting techniques using an average of 160 pieces per sample. The roundness of the carbonate fraction was classified using a five-point scale developed by Pilkey et al. (1967). Carbonate grains were also classified on the basis of color as black, brown, or original/other. The term "black" includes a range of color from light gray to dark bluish gray to true black (Munsell values N 6 to N 1). "Brown" includes colors from tan and orange to dark reddish brown (Munsell values 10YR 8/6 to 10R 3/4). "Original" or "other" color refers to shells or fragments possessing their original life coloration or having neither distinctly black nor brown characteristics (usually white). The degree of shell polish was determined using a three-category scale consisting of "bright," "moderate," or "none" similar to that used by Davies et al. (1989) and Powell and Davies (1990). Brightly polished specimens exhibit little to no surface pitting, and have a shiny luster when dry. Moderately polished shells have some pitting. When wet, they appear to be brightly polished, but lose their luster as they dry. Shells lacking polish typically are extensively pitted, and do not appear shiny even when wet.

Folly Island

The Folly Beach study area, like Wrightsville Beach, has also been studied extensively by geophysical and geologic methods. In addition, there has been comprehensive monitoring of beach and nearshore profile changes along the entire island. The data described here consist of the following:

1) a regional sidescan sonar mosaic (Swift et al. 1997) and an associated extensive set of surficial sediment samples used to define sea floor characteristics and sediment distribution on the inner shelf (Gayes et al. 1998);
2) a time series of sidescan sonar mosaics constructed for an area of the island's shoreface and inner shelf dominated by a field of linear rippled scour depressions. This time series is used to assess the activity and movement of the features over a 21-month period subsequent to a beach nourishment project;
3) a time series of sled-based long beach and nearshore profile surveys to document the behavior of the beach nourishment project; and
4) an extensive network of high-resolution seismic-reflection profiles (Geopulse) and vibracores used to document the regional shallow framework geology.

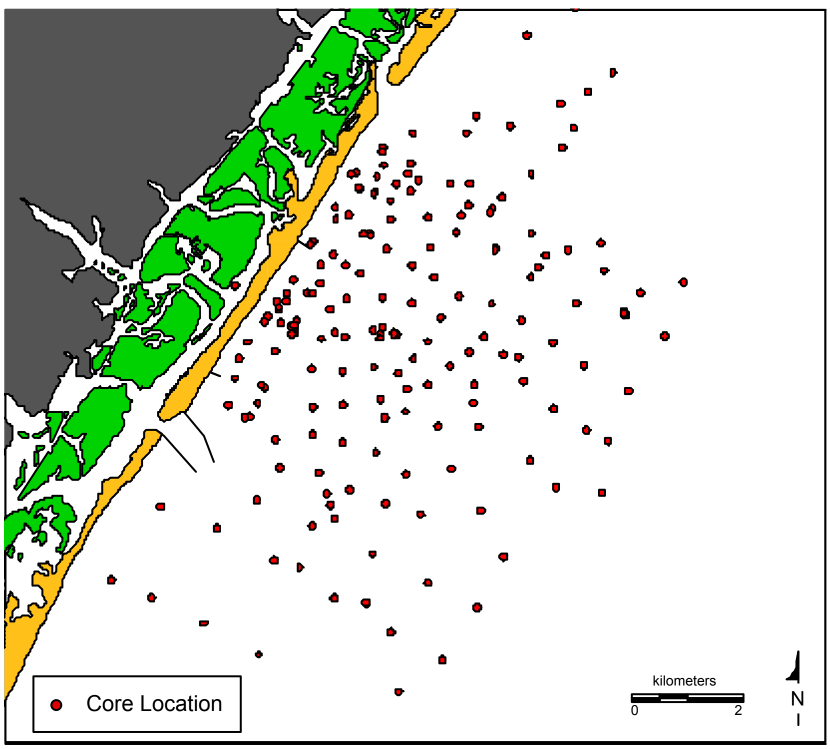

Fig. 4. Location of vibracores on the Wrightsville Beach shoreface and inner shelf.

RESULTS
Wrightsville Beach

The shoreface off Wrightsville Beach is composed of a thin (<4 m thick), seaward-thinning, modern sediment cover overlying an unconsolidated, early Oligocene sandy silt, which has been dissected by Plio-Pleistocene and Quaternary fluvial channels (Snyder et al. 1994; Thieler 1997). The surficial morphology of both the shoreface and inner shelf is dominated by linear, cross-shore rippled scour depressions (RSDs; Cacchione et al. 1984) extending from just seaward of the surf zone to over 4 km onto the inner shelf. On the upper shoreface, the RSDs are incised up to 1 m below surrounding areas of fine sand, and have an asymmetric cross-section that is steeper-sided to the north. On the inner shelf, the RSDs have a similar but more subdued cross-sectional profile. The RSDs are floored primarily by shell hash and quartz gravel. Vibracore data show a thick (up to 1.5 m) sequence of modern RSD sediments that unconformably overlie ancient coastal lithosomes (Thieler 1997; Thieler et al. 1998).

Seaward of the shoreface, the inner shelf is a sediment-starved, active surface of marine erosion. Modern sediments, where present, form a patchy veneer over the Tertiary and Quaternary units. The lithology of the underlying units exerts a primary control on the distribution, texture, and composition of surficial sediments, as well as inner shelf bathymetry (Thieler et al. 1995; 1998; Thieler 1997).

In this sediment-starved setting, rippled scour depressions probably form on pre-existing coarse-sediment substrates such as modern lag deposits of paleofluvial channel lithosomes or ancient tidal inlet thalwegs (Thieler et al. submitted). The gross morphology of the seafloor (e.g., the distribution of coarse and fine sediments shown in Fig. 3) did not change significantly over a five-year observation period that included two landfalling hurricanes (Bertha and Fran) in the summer of 1996. This short-term data, coupled with the vibracore data, suggests that the present seafloor morphology is either relatively stable or represents a recurring, preferential morphologic state to which the seafloor returns after storm-induced perturbations. The apparent stability is interpreted to be the result of interactions at several scales that contribute to a repeating, self-reinforcing pattern of forcing and sedimentary response which ultimately causes the RSDs to be maintained as bedforms responding to both along- and across-shore flows (Thieler et al. submitted).

An isopach map (Fig. 5) shows that significant accumulations of modern sediment on the shoreface-associated sediment wedge (>50cm, the smallest unit resolvable with confidence using cores and shell petrographic data) are restricted to the shoreface and portions of the inner shelf. The physiographic base of the shoreface at 10 m water depth also corresponds to a sedimentologic boundary as defined by the roundness, color, and degree of polish of the gravel-sized carbonate fraction (Table 1; see also Thieler 1997 and Thieler et al. submitted). The differences between shoreface and inner shelf samples are statistically significant (ANOVA) for color, rounding and polish.

In general, the color of the carbonate fraction of shoreface sediments off Wrightsville Beach is more black than brown (Table 1). This is in contrast to most beaches as well as the nearshore zone in southern Onslow Bay, which have a readily observable brown-dominated carbonate fraction (Pilkey et al. 1969a; 1969b).

The significance of rounding due to energetic nearshore processes has been previously discussed by Pilkey et al. (1967; 1969a). This relationship is readily apparent at Wrightsville Beach, as there is little well-rounded, gravel-sized material seaward of the shoreface (located at approximately the 1 m isopach on Fig. 5).

The strongest relationship between cross-shore location and shell characteristics is the degree of shell polish, which is presumably acquired by frequent physical abrasion. The significance of shell polish, however, is not understood. It appears that polish is generally lost due to corrosion (Davies et al. 1989), release of carbonate crystals during shell decomposition (Fitzgerald et al. 1979), and microboring endolithic fungi and algae (Perkins 1976; Poulicek et al. 1981). The rate at which these processes occur, and also the rate at which shells become polished (Chave 1964; Estes 1967) is poorly known.

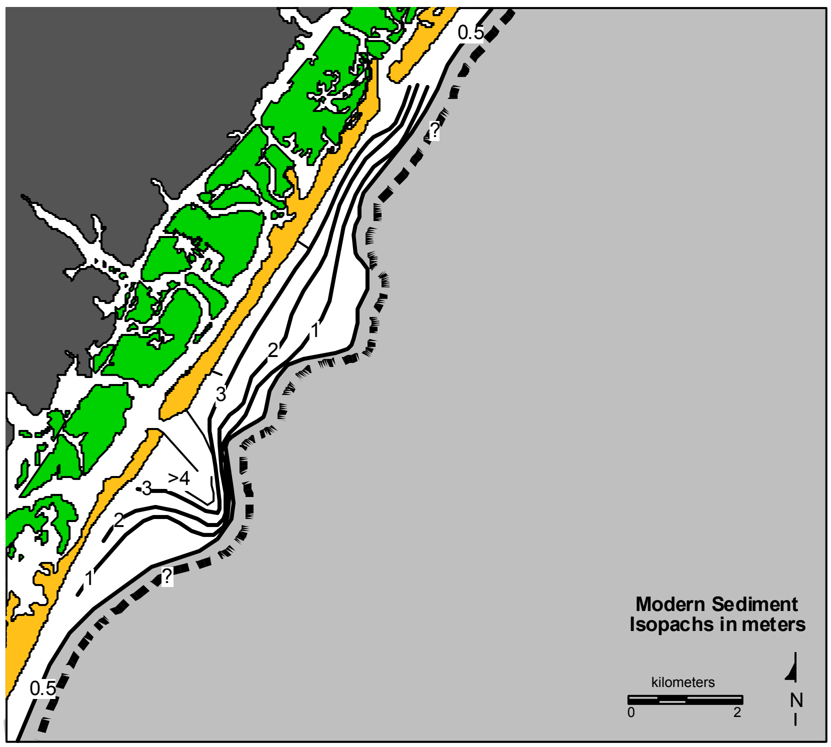

Fig. 5. Isopach map of modern sediment thickness on the shoreface and inner shelf off Wrightsville Beach. The dashed line indicates the resolvable limit of the modern sediment deposits. (Modified after Thieler et al., submitted.)

The cross-shore distribution of well-rounded, polished carbonate grains indicates that, except for south-central Wrightsville Beach, they are confined to areas landward of the base of the shoreface (<10 m, or landward of the 1 m isopach on Fig. 5). While sediments with shoreface textural attributes do comprise much of the Masonboro Inlet ebb-tidal delta, they generally fall within the physiographic base of the delta.

Seaward of the base of the shoreface, the shoreface-associated carbonate fraction is less well-represented, probably due to dilution with inner shelf sediment, dissolution and size reduction of the gravel-fraction, and secondary breakage by marine organisms (Pilkey et al. 1969a).

Some of the sediment from the beach nourishment projects can be found on the shoreface and inner shelf. Pearson and Riggs (1981) were the first to document the presence of beach nourishment sediment on the shoreface off Wrightsville Beach, which is recognizable in part by its gray-stained quartz fraction and black-stained carbonate fraction. Subsequently, Thieler (1997) identified the geographic extent of this sediment on the shoreface and inner shelf. In addition to the gray-black sand and shell material, Thieler (1997) also identified a brown-orange stained nourishment sediment on the shoreface and inner shelf that reflected a change in dredging borrow areas from the backbarrier lagoon (gray-black) to the tidal deltas and navigation channel of Masonboro Inlet (brown-orange). Both of these sediment types are recognizable in vibracores (Thieler 1997; Thieler et al. submitted). The nourishment sediment is nearly identical to the native beach and shelf material in terms of its grain size distribution and carbonate content (Thieler 1997).

Table 1. Sediment Attributes, $CaCO_3$ Fraction (Mean ± SE).*

	Total	Black Shells	Brown Shells	Other Shells
Shell Roundness				
Shoreface	3.90 ± 0.09	3.91 ± 0.02	3.55 ± 0.03	2.96 ± 0.04
Inner Shelf	3.04 ± 0.10	3.27 ± 0.02	2.95 ± 0.02	2.30 ± 0.01
Shell Polish				
Shoreface	2.05 ± 0.16	2.10 ± 0.01	1.73 ± 0.01	1.86 ± 0.02
Inner Shelf	1.19 ± 0.03	1.14 ± 0.01	1.22 ± 0.01	1.33 ± 0.03

*Note that differences between shoreface and inner shelf sediments in terms of roundness and polish are statistically significant with ANOVA p-values < 0.05. Shell roundness is based on a 1-5 scale of increasing roundness (Pilkey et al. 1969). Shell polish is based on a 1-3 scale of increasing polish (Powell and Davies 1989).

The vibracore data indicate that the nourishment sediment is present as multiple units of 5-40 cm thick, graded sequences. On the inner shelf, these sequences comprise a seaward-thinning wedge that extends nearly a kilometer offshore to the 14 m contour. Primary sedimentary structures such as cross-bedding that would provide insight into transport mechanisms have been largely destroyed by bioturbation. Thus, it is difficult to determine whether the graded layers are the product of in-place reworking and bed cannibalization (Swift and Thorne 1991), allocthonous deposition, or both. Cores obtained shortly after hurricane Bertha in July 1996, however, do show well-developed graded beds and preserved climbing ripple laminations (Thieler 1997).

Folly Island

Three distinct patterns of acoustic backscatter are definable on a regional sidescan sonar mosaic of the shoreface and inner shelf of south-central South

Carolina (Fig. 6; Swift et al. 1997) that characterize most of the surfical sediment in the area. These patterns are:

1) A field of linear, rippled scour depressions (RSDs) off north central Folly Beach. These features extend perpendicular to the coast for a distance of 4 km from the beach ("A", "B" and "C" in Fig. 6). The surficial sediment within the RSD field is composed of medium to coarse sand (high acoustic backscatter or light tones on the image) with abundant shell fragments (Gayes et al. 1998).
2) Broad areas of uniform and featureless low backscatter (darker tones on this image; "D" on Fig. 6) characterize most of the shoreface and inner shelf on sidescan sonar records in the region. Surface sediment grab samples in these areas document the low-backscatter sediment to be fine to very fine sand, with 10-15 percent silt and clay fraction and a minor amount (<10 percent) of fine shell fragments (Gayes et al. 1998).
3) Seaward of the 9 m bathymetric contour, areas of mottled backscatter pattern ("E" on Fig. 6) are common. Bottom grabs, seismic-reflection profiles, diver observations and vibracores document these areas as a patchwork of high backscatter ledges and scarps of Tertiary deposits outcropping on the seafloor interspersed with low backscatter flats of fine to medium sand (Gayes et al. 1998).

The field of RSDs on the shoreface and inner shelf is the focus of this discussion of the Folly Beach area. These features occupy a slight (<1 m) depression on the sea floor but the relief within the overall features is irregular. The seafloor within the RSDs is characterized by oscillatory wave ripples composed of medium-grained shelly sand to coarse-grained shell hash.

The RSD labeled "B" (Fig. 6) can be traced inshore to the surf zone where the lower backscatter sediment (fine sand) of the nearshore sand bar visibly interfingers with, and locally covers, the coarse shelly rippled sands of the RSD (Fig. 6). The boundary between the RSD and the nearshore bar is very sharp and distinct in both sidescan sonar records and surficial sediment grabs (over 100 sediment grabs were collected to ground truth the sidescan mosaics [Gayes et al. 1998]).

The inshore portion of the main RSD ("B" in Fig. 6) is approximately 700 m wide and extends from the beach offshore for 3 km. Beyond 3 km, the RSD exhibits a more lobate morphology. In this region, low backscatter sediment partially covers the high backscatter sands. These lenses of fine sand increase in thickness seaward and nearly completely cover the coarse, high backscatter sediment beyond four kilometers from the beach. Between 3-4 km from the beach the high backscatter sediment begins to trend more coast-parallel (southeast).

Two smaller RSDs flank the main feature. One of these ("C" on Fig. 6) lies northeast of the main sand body from 1.5 to 2.75 kilometers from the beach. A second, smaller RSD ("A" on Fig. 6) lies to the southwest of the main RSD between the beach and two kilometers offshore. Vibracores recovered from the main sand body reveal stacked graded beds of coarse shelly sands fining upwards into fine-to-medium sand (Gayes and Donovan-Ealy 1995; Gayes et al. 1998). This sequence of storm-generated deposits is not common in cores recovered within the adjacent lower backscatter areas of the shoreface.

Three sidescan surveys imaged the RSDs off Folly Beach between August 1995 and May 1997, and were used to construct sidescan mosaics of the linear rippled scour depression field. Figure 7 superimposes the outline of the high backscatter over the 21-month period covered by successive surveys.

The inner portion of the large RSD ("B" in Fig. 6) exhibits a limited change in outline and no net movement between surveys. Substantial change, however, occurred about 3 km from the beach where its morphology becomes more lobate. In that area, lenses of fine sand expanded, contracted, and translated laterally more than 100 m.

The boundary of the smaller RSDs ("A" and "C" in Fig. 6) exhibited substantial, up to 300m, landward translation during the same period. This was particularly dramatic in RSD "A" where fine sand was removed, exposing coarse sediment and progressively covering coarse RSD sediments farther offshore. This represents an extensive localized offshore flux of fine sand from the nearshore of Folly Beach to distances of 2-3 km offshore during the 21-month period following the beach nourishment project.

A series of small paleochannels, defined by seismic reflection profiles and vibracores (Gayes et al. 1998), underlie the shoreface of Folly Beach and are also shown in Figure 7. These paleochannels trend obliquely to the scour depressions and are separated from them by a regional planar unconformity and more than a meter of sediment as indicated by seismic reflection profiles and vibracores. This demonstrates that the RSDs are recent, post-ravinement, surficial bedforms, rather than exposures of channel-fill sediments being exhumed on the shoreface.

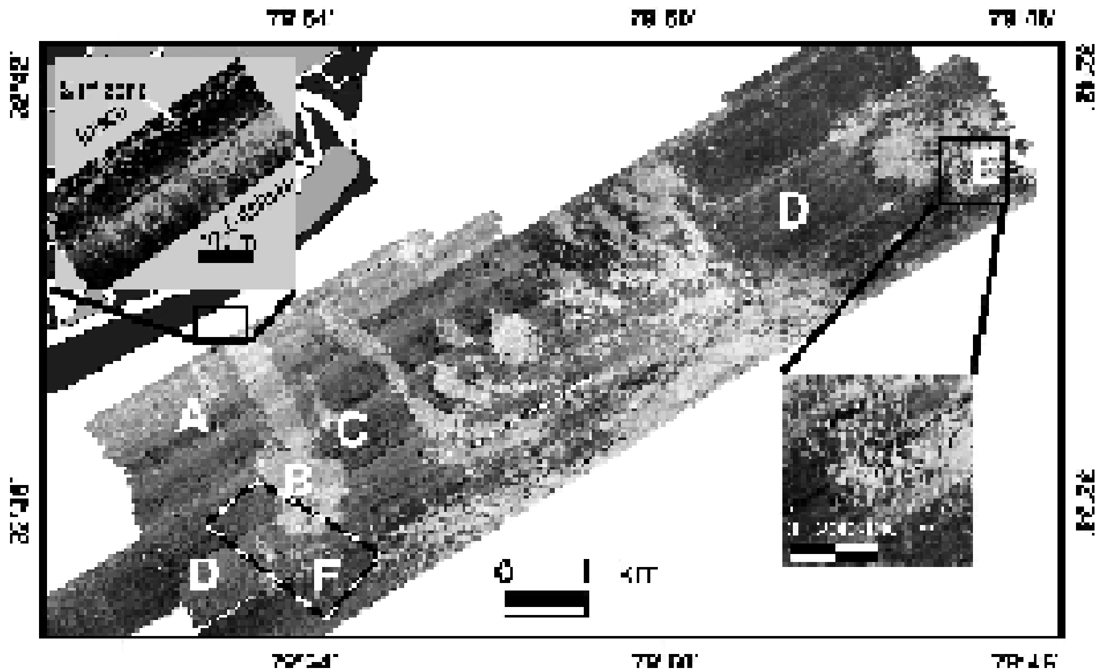

Fig. 6. Sidescan sonar mosaic of the shoreface and inner shelf off Folly Beach, South Carolina. (See text for discussion of labeled regions.)

After completion of the 1993 beach nourishment project, the beach fill was monitored using the BERM sled-based beach survey system (Ebersole et al. 1996). This monitoring program collected long beach surveys to one kilometer from the beach at 28 benchmarks locations along the island. The long-profile data were collected quarterly for the first year after completion of the fill and bi-annually for an additional two years. The location of these survey lines, relative to the RSD is shown in Figure 7. A surface model of the data was generated for each survey period from an ARC/INFO-GIS triangular irregular network (TIN), which permitted investigation of erosional and depositional patterns.

The shoreface area dominated by RSDs coincides with the region of greatest standard deviation of elevation within the spatial and temporal range surveyed (Fig. 8). The large standard deviation documents active sediment movement. The largest RSD ("B" in Fig. 6) is characterized by the largest standard deviation during the Summer/Fall and is active during all seasons. The variation of elevation in the vicinity of the smaller scour depressions ("A" and "C" in Fig. 6) is greatest during the Winter/Spring months. The areas of greatest elevation change coincide with the movement of fine sand over the offshore portion of the RSDs.

In the same area, the U.S. Army Corps of Engineers collected detailed bathymetric surveys (30 m line spacing) immediately before and after the 1993 nourishment project at Folly Beach (M. Dowd, 1993 pers. comm.; USACOE unpublished data). These data were used to construct TIN surface elevation models. The position of the –3 m NGVD contour in the region of the RSDs is shown in

Figure 7. The pre-nourishment contour exhibits a narrow mound of sand extending 200-250 m offshore within the zone of the RSDs.

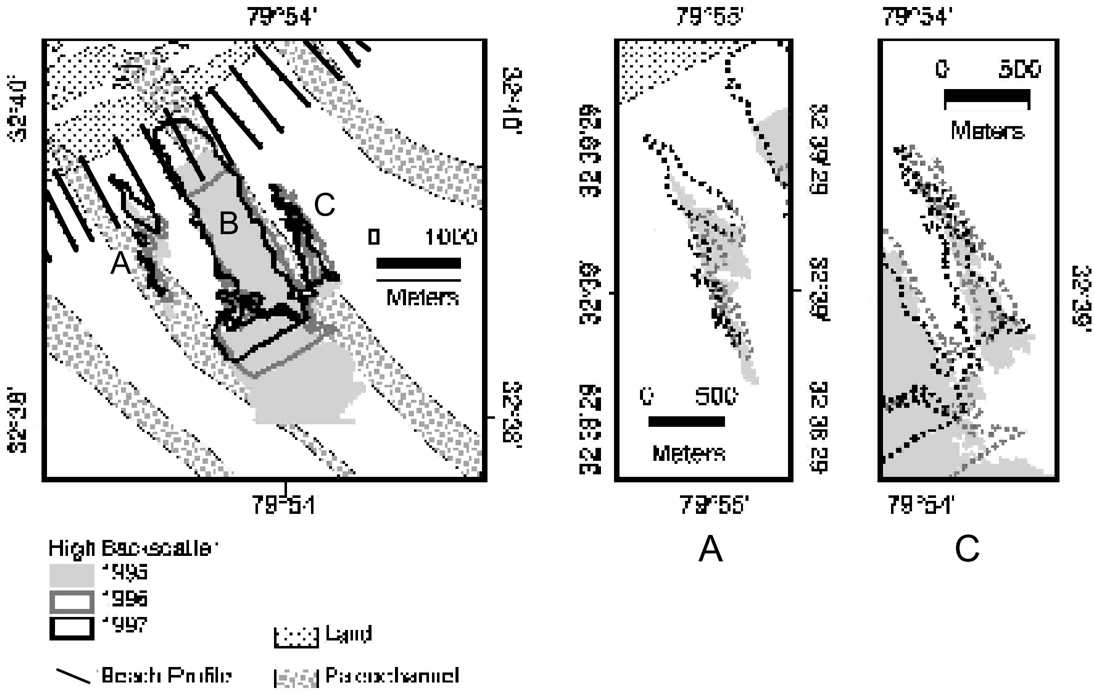

Fig. 7. Time series of changes observed in the high-backscatter regions of the Folly Beach RSD field.

During the later stages of the Folly Beach nourishment project, a major storm (the March 1993 "Storm of the Century") impacted the area. Additional beach fill was required to replace sediment lost during that storm. The post-nourishment bathymetric survey documented the lateral and seaward extent of offshore sand movement within the RSD. The USACOE data set was confined to the zone shallower than -3.5 m NGVD and as a result the full seaward extent of this flux of sand is not resolvable. The data do, however, document a persistent localized offshore flux of sand from the nearshore, presumably enhanced by the March 1993 storm, within the inshore region of the RSD field.

Elevation models of successive beach surveys were used to calculate beach sediment volume change (Fig. 9) within a series of cells along the beach between the summer of 1993 and 1996. Each cell is spatially bounded by adjacent survey lines alongshore and the position of the -5 and -15 ft NGVD contours in the 1993 post-nourishment condition. Sediment volume change was calculated in each cell, above -5 and -15 ft NGVD relative to the post-nourishment condition. In Figure 9 the time series of volume change progresses from right to left within each cell. The position of the RSDs is shown superimposed on this image, and the spatial coverage of the TIN model shown by the area of volume data in Figure 9.

The upper beach, above -5 ft NGVD, typically experienced immediate and progressive loss of sediment subsequent to the nourishment for most areas. The beach immediately onshore of the main sand body/scour depression ("B") had experienced the highest magnitude of sand loss after the nourishment (>50 yd^3 ft^{-1} of beach). A notable exception in this trend can be seen onshore of the smaller, southwestern scour depression "A." The upper portion of beach, landward of RSD "B," experienced initial fluctuations in volume relative to the post-nourishment condition through Spring 1994. Between Summer 1994 and 1996, however, the cells gained and maintained more sand above the –5 ft contour than existed within the cell just after completion of the nourishment.

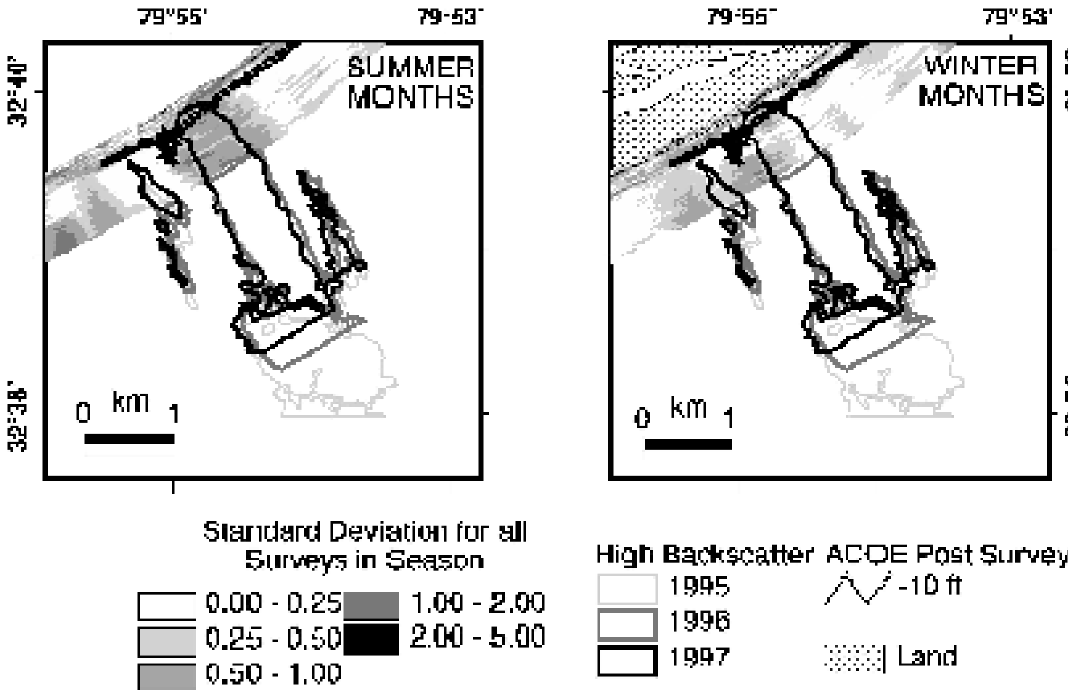

Fig. 8. Spatial distribution of the standard deviation of elevation changes at Folly Beach.

The volume change within the entire area surveyed (to -15 ft NGVD and 3000 ft from the beach) exhibited alternating deposition and erosion within the main scour depression ("B") during the first two years after the nourishment. During the third year following nourishment the inshore area experienced extensive net loss of sediment compared to the post nourishment condition. The outline of RSD "B" showed little net change inshore, but deposition of fine sand was documented by the sidescan sonar surveys 2-3 km from the beach (-14 to -20 ft NGVD) during this time.

The area onshore of RSD "A" experienced cut and fill shortly after nourishment. Between spring 1994 and winter of 1996, the period of the first two sidescan sonar surveys, this area experienced a net sediment gain in the deeper offshore portion of the profiles. This sediment was lost from the cell during the late winter of 1996. As shown in the sidescan sonar data, there was deposition of fine sand over the seaward portion of the RSD during this period.

DISCUSSION

Wrightsville Beach

As described above, the physiographic base of the shoreface corresponds to a sharp sedimentologic boundary (see Fig. 5) separating the well-rounded and highly polished carbonate fraction of the beach and shoreface from the more angular and worn carbonate fraction characteristic of the shelf. Vibracores and surface samples from the shoreface and inner shelf off the adjacent barrier islands of Topsail, Coke, Lea, Figure Eight and Masonboro Islands exhibit a similar distribution – the well-rounded and polished carbonate grains reside solely on the shoreface (McQuarrie 1998; unpublished data). This observation implies that shoreface processes have been very efficient at maintaining and pushing ashore a substantial portion of the shoreface sediment volume. This is particularly significant considering that much of this shoreline reach has been occupied by inlets in historic times (Cleary and Hosier 1979; Cleary et al. 1979). If inlets were contributing significant portions of beach-derived material to the inner shelf, a much more scattered distribution of beach-derived material on the inner shelf would be expected. Similarly efficient "shoreface recycling" has been observed off some Maine barrier islands (Kelley et al. 1995; Belknap et al. 1997).

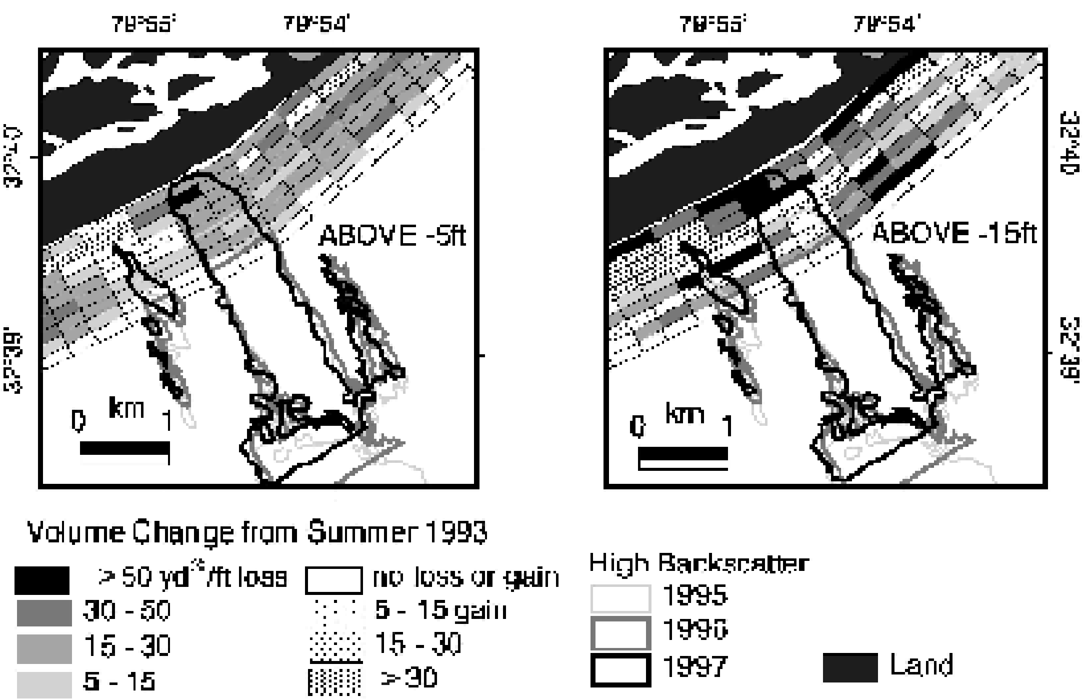

Fig. 9. Volume changes between survey lines through time at Folly Beach. Change for both the zone above -5 feet NGVD and above -15 feet NGVD are shown.

Sediment accumulation from over 30 years of intensive beach nourishment at Wrightsville Beach, however, appears to have exceeded shoreface accommodation space (i.e., the ability of the shoreface to retain the placed sediment; Muto and Steel 1997), resulting in the "leaking" of beach and shoreface sediment to the inner shelf. Seaward of the 10 m contour, the nourishment sediment is present in a seaward-thinning wedge that extends over a kilometer onto the inner shelf to waters depths of nearly 14 m. This wedge is best developed offshore of the shoreline segment that has received the greatest volume of beach nourishment (Pearson and Riggs 1981; Thieler 1997). A rough calculation based on the vibracore data suggests that nearly 2 million m^3 of nourishment sediment resides on the lower shoreface and inner shelf seaward of the assumed 8.5 m closure depth (U.S. Army Corps of Engineers, Wilmington District, pers. comm.) used for project design. This is about 25 percent of the total volume of nourishment sediment placed on Wrightsville Beach (see Fig. 2) through the period of this study. The volume of nourishment sediment on the inner shelf proper is ~950,000 m^3, or about 12 percent of the total volume of nourishment sediment.

For over 30 years, the beach at Wrightsville Beach has served as an "instantaneous" source of new sediment to the shoreface and inner shelf due to continued nourishment operations. The modern sediment thicknesses on the lower shoreface and inner shelf off Wrightsville Beach indicate net sedimentation rates on the order of 1-2 cm yr^{-1}. This contrasts with non-nourished areas in Onslow Bay, where sedimentation rates are an order of magnitude (or more) lower. Thus, long-term nourishment operations appear to have accelerated sedimentation on the inner shelf. The sequence of sedimentary structures observed in post-hurricane vibracores (Thieler 1997) suggests seaward transport and deposition in conditions of combined flow waning to oscillatory flow, perhaps following one of the tempestite depositional models suggested by Myrow and Southard (1996) or the cross-shore transport model for RSDs proposed by Cacchione et al. (1984), and provides insight into how cross-shore sediment dispersal onto the inner shelf is likely achieved.

Folly Island

Collectively, several lines of evidence argue for a localized offshore movement of sand from the nearshore at Folly Beach within the field of linear scour depressions. First, the broadening and offshore movement of the -10 ft NGVD contour (the greatest depth surveyed), occurred during the construction of the nourishment project. Subsequent sidescan sonar records document an interfingering of the fine sands of the nearshore bar over the inshore edge of the scour depression and lenses of fine sand entering the scour depression from the surf zone. The seafloor elevation within the RSD zone up to the survey limit of 3000 ft from the beach, exhibited a large and localized increase in standard deviation of elevation, indicating active transport sediment within these features. Volume calculations show this to be intermittent deposition above and erosion below the post-nourishment condition. Sequential sidescan sonar mosaics document significant lateral movement (>200 m) of fine sand over the distal portions of the scour depressions during a 21-month period following the beach nourishment. This is accompanied by a landward translation of exposure of the high backscatter sediment of the scour depression. The two trends are interpreted here to be related and thus document continued offshore movement of sand within the scour depression.

The only significant volume (800,000 yd^3) of beach-compatible sand (low R_a; Krumbein and James 1965) on the inner shelf off Folly Beach, however, is found in the seaward portion of the RSD field (Gayes et al. 1998). This area (shown in Fig. 6), is characterized by progressively greater percentages of low backscatter fine sediment cover over the high backscatter RSDs on the sidescan mosaics. While it is not possible to say that this deposit is composed entirely of nourishment sands, it is suggested that some of this sand may be. At a minimum, there is a significant and chronic loss of sand from Folly Beach to the inner shelf at this location.

The mechanism for this transport is undefined but proposed to be active during storm events when storm-induced downwelling may provide for net offshore transport well beyond simple surf zone processes (Cacchione et al. 1984; Schwab et al. 1996). The stacked, graded units within the scour depression, dominated by shell hashes inshore and sand offshore, supports storms playing an important role in sediment movement.

CONCLUSIONS

The event- to decade-scale patterns of sediment dispersal on two nourished beaches have been mapped using a combination of geophysical surveys, closely-spaced vibracores, and repeated beach profiles. At both Wrightsville Beach, NC and Folly Island, SC beach nourishment sediment is macroscopically distinct from native sediment and can be used to identify sediment transport pathways and infer mechanisms for across-shelf transport. The data from both sites demonstrate that significant quantities of nourishment sediment are being transported seaward onto the inner shelf.

We hypothesize that much of the observed cross-shelf transport at both sites is accomplished during storms by enhanced bottom stresses and intensified quasi-steady currents, such as downwelling due to storm set-up, and wave-induced oscillatory flows.

Tracing sediment dispersal patterns using the techniques reported here may have wide application for many nourished beaches.

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