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DISTRIBUTION OF GRAIN SIZES ACROSS A TRANSGRESSIVE SHOREFACE

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Abstract

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Distributions of seventeen grain sizes in the sand fraction of the shoreface sediments south of Long Island, New York, can be categorized into middle and lower shoreface species (very fine sand), upper shoreface species (fine sand), shoreface-depleted species (medium sand), and swash-zone species (coarse sand). The long-term fair-weather wave base of the study area at a depth of about 16 m is determined on the basis of the characteristic response of grain sizes to the average shoreface hydrodynamics. The crosshore deviations from the mean distribution for each grain size were examined by using empirical orthogonal function (EOF) analysis. These results show differential associations of grain-size deviations with various dynamic zones on the shoreface. The hydrodynamic processes of the modern shoreface are speculated to winnow out fine and very fine sands and transport them onshore, leaving behind on the lower shoreface and inner continental shelf a lag deposit of transgressive sand sheet composed mainly of medium sand.

Introduction

In coastal marine environments, geologists and engineers are often challenged by the needs for predicting shoreline changes. These changes result from sediment movement driven by waves and currents. Therefore, the first step toward coping with the dynamic nature of a coastal environment is to understand the sediment dispersal as an equilibrium response to the hydrodynamic regime in that environment. The term "equilibrium" here is used in a static sense in that if there is no significant external sediment source, the distribution pattern of a certain grain size will be maintained with some consistency once it has been attained. Although it will be subject to temporal modifications such as seasonal changes, the general distribution pattern will remain unchanged, and this pattern represents the long-term response of that grain size to the shoreface hydrodynamics.

A conventional way of studying net sediment dispersion in coastal marine environments is through sediment texture (McKinney and Friedman, 1970; Scheidegger et al., 1971; Swift et al., 1971; Gorsline and Grant, 1972; Stubblefield and Swift, 1981). It has been concluded that the texture of natural sediment contains information regarding the source, mode of transport and energy level of the transporting processes. Various schemes have been employed to decipher this information from grain-size frequency distributions of sediments. These schemes involve using statistical granulometric parameters such as sample mean, mode, sorting and skewness to characterize the sediment deposit under study (Taney, 1961a),

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as well as methods to dissect the sediment population into subpopulations that presumably represent different transport modes (Visher, 1969; Bein and Sass, 1978). Efforts have also been made to link (or predict) the distribution of the texture of natural sediment with environmental attributes such as the hydrodynamics, the bottom slope, and the existence of topographic irregularities in coastal and beach environments (Miller and Zeigler, 1964; Murray, 1967; Graf, 1976).

Most of these methods mentioned above treated sediments as a bulk entity and failed to recognize the fact that a sediment deposit is composed of individual particle sizes, each possessing unique hydraulic properties (Bridge, 1981). In other words, each sediment size responds to the same hydrodynamics differently, as indicated by differential movement of tracer sand in coastal marine environments (Ingle, 1966; Duane, 1970). In addition, the calculation of the statistical parameters such as the mean grain size is an averaging (smoothing) process, and consequently some information will be lost (Rayner, 1971).

In this study, size classes of natural sediments are viewed as natural tracers. This is analogous to short-term sediment tracer studies in which the spatial distribution of tagged sediment grains is monitored after the tracer is released into an environment (Ingle, 1966; Murray, 1967; Duane, 1970; Yasso, 1976). The drawback of conventional tracer studies is that they are limited by a short experimental period and cannot reveal long-term dispersal patterns. Also, the results are often biased by choosing tracer sands that are out of equilibrium with the physical environment. The distribution of individual grain sizes of natural sediment, however, is in equilibrium with the time-averaged hydrodynamic regime (Miller and Zeigler, 1964; Zenkovich, 1967; Jago, 1981), and is more representative of long-term dispersal patterns in that environment than the injected tracers. Therefore, the objective of this study is to examine the distributions of grain sizes of natural sediments to identify their spatial characteristics, in order to understand in a qualitative way, their response to shoreface hydrodynamics.

Study area

The study site is the shoreface of the south shore of Long Island, New York, between Fire Island Inlet and Montauk Point (Fig.1). The surficial relief of Long Island is dominated by two distinctive glacial moraines, the Harbor Hill Moraine in the north, and the Ronkonkoma Moraine in the south (Taney, 1961b; Rampino, 1978). The gently S-sloping terrain south of the two hilly moraines is formed from the glacial outwash plains that intersect the Atlantic Ocean (Williams, 1976). The south shore of Long Island is a wave- and storm-dominated coast (Lavelle et al., 1978). Almost three-quarters of deep-water waves approach Long Island from the directions east-northeast

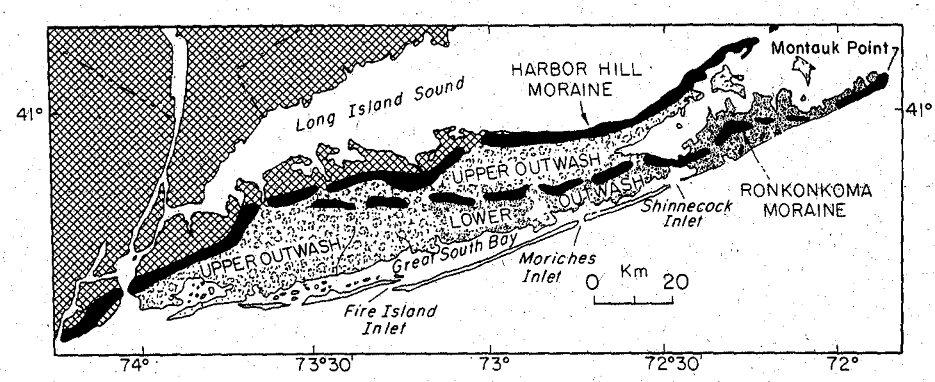

Fig.1. Index map of the study area.

through to south-southeast, resulting in a net westward littoral drift (Williams, 1976). This net westward longshore drift is indicated by the closing of small bays and fluvial drainage channels from the ocean near the eastern end of the study area, as well as by the westward migration (Taney, 1961a) and the NE–SW orientation of tidal inlets (Kaczorowski, 1971). Tides on the south shore of Long Island are semidiurnal. The ocean tidal range decreases eastward from 1.4 m at Rockway Inlet to 1.3 m at Fire Island Inlet and 0.6 m at Montauk Point (Williams, 1976). Tidal energy plays a role in the shoreface hydrodynamics (Beardsley et al., 1976; Han and Mayer, 1981), especially near tidal inlets.

Niedoroda et al. (1984) and Swift et al. (1985) summarized the hydrodynamics of Long Island's south shore. Under fair-weather conditions, wave processes dominate the upper and middle (depths shallower than 10 m) shoreface, whereas current processes dominate the lower shoreface. Niedoroda and Swift (1981) and Vincent et al. (1983) demonstrated that during non-storm conditions, the lower shoreface sediment was not transported even by combined effects of strong mean and tidal currents. During storm events, sediment is transported alongshore and offshore across the shoreface, forming a temporary sediment reservoir on the shoreface. Because of the strength and frequency of storms, the sediment transport on Long Island's shoreface is described as intermittent and storm-dominated (Lavelle et al., 1978; Swift et al., 1981). The temporary reservoir on the shoreface is depleted by the slow return of sediments to the upper portion of the shoreface during periods of fair-weather conditions (Niedoroda et al., 1984; Swift et al., 1985). Fair-weather sediment transport processes, however slow, are equally important as storm transport in determining the equilibrium shoreface profile (Niedoroda et al., 1984).

Morphologically, the south shore of Long Island is divided into two sections; a headland approximately 53 km long in the east, and a barrier island 140 km long in the west (Taney, 1961a). The easternmost 16 km of the headland is a bluff roughly 20–30 m high, consisting of outwash and till deposits of the Ronkonkoma Moraine. The bathymetry of the shoreface of the two sections is distinguished by their respective major morphological components (Liu, 1987; Zarillo and Liu, 1988). The barrier island upper shoreface is characterized by a steep beachface, and a flat terrace 200 m wide, having a gentle seaward slope (Fig.2). The terrace is also superimposed by a sinuous longshore bar located approximately 300 m offshore, having a wide landward trough. The outer channels of the two tidal inlets within this section have greatly altered the bathymetry of the shoreface (Liu, 1987). The headland shoreface is characterized by a steep beachface and a larger scale nearshore bar, which has a deep landward trough and steep seaward slope (Fig.2). A smaller inner bar appears at various locations on the slope of the beachface in this section. The positions of the crests of both the inner and outer bars in this section is rhythmic in the longshore direction (Liu, 1987; Zarillo and Liu, 1988).

The shoreface sediments south of Long Island show close affinity to the transgressive lag deposits of the inner shelf (Liu, 1987). These latter deposits (Fig.3a) were derived from the initial outwash plain sediments during the sea-level rise. The bluff and a remnant morainal lobe complex on the shoreface and inner shelf within the headland section (Fig.3b) are the major but not significant external sources

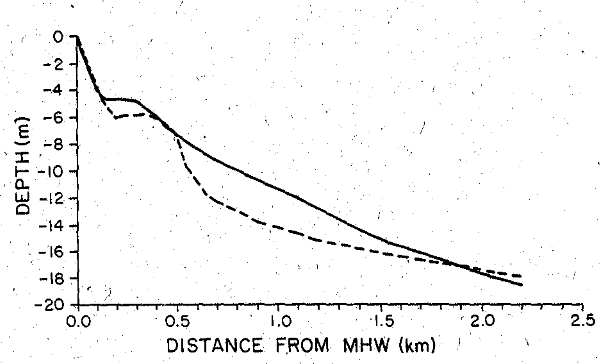

Fig.2. Mean profile of the barrier island section (continuous curve), and the mean profile of the headland section (dashed curve).

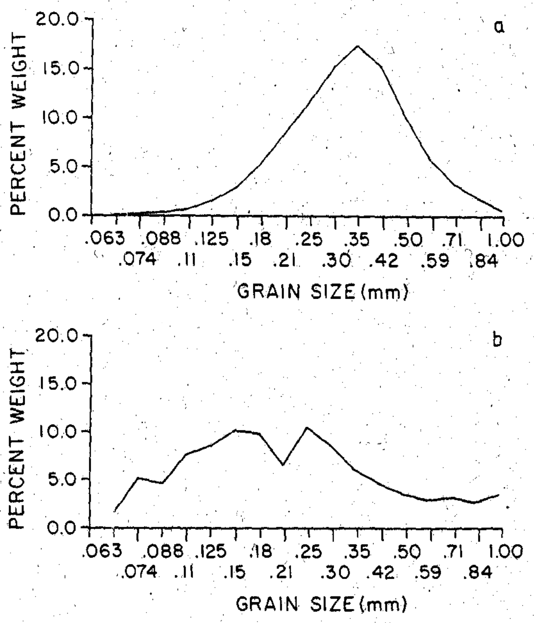

Fig.3. a. Grain-size frequency distribution of the lag deposit on the lower shoreface and inner shelf. b. Grain-size frequency distribution of the moraine-related deposit.

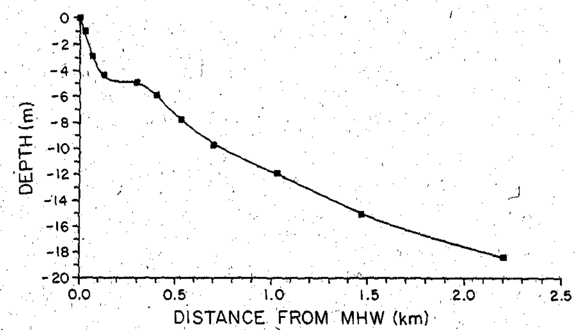

Fig.4. Sampling stations across the shoreface.

contributing sediments to the littoral sediment budget of the study area (Liu, 1987).

Methods

Surficial sediment samples were taken on 52 shore-normal transects along the south shore of Long Island in the summer during July and August at an average spacing of 2.6 km. On each transect, sediment samples were taken from eleven positions including the mean high water and the mean low water (corresponding to the swash zone), the zone of wave breaking, the base of the beachface in the landward trough of the longshore bar, the crest of the longshore bar, the seaward slope of the longshore bar, and at the depths of 8, 10, 12, 15 and 18 m, corresponding to the middle and lower shoreface (Fig.4). The intertidal samples and the surf-zone samples were taken by hand. The offshore samples were taken with a grab sampler from a ship. The objective of this sampling scheme was mainly to examine the influence of the progressive onshore change of the shoreface hydrodynamic regime on the surficial sediments.

The penetration depth of the grab sampler was 10 cm. This depth was considered adequate to include the maximum mixing depth of the surficial shoreface sediments which are constantly reworked by the day-to-day fair-weather shoreface hydrodynamic processes. In other words, the samples were assumed to represent a long-term, time-averaged (over seasonal cycles) influence of the fair-weather hydrodynamic processes. Therefore, the temporal variations of the surficial sediments were not considered important, as was also suggested by Stubblefield et al. (1977) and Davis (1985).

Each sample was treated with 30% hydrogen peroxide solution for 24–48 h to eliminate organic materials, and then wet-sieved to exclude gravel (larger than 2 mm or $-1\ \phi$) and mud (finer than 0.063 mm or $4\ \phi$), which normally comprised less than 1% of the sample by volume. The sand fraction ($4\ \phi$ to $-1\ \phi$) was analyzed for the grain-size frequency distribution with a custom-built rapid sediment analyzer, and recorded at quarter-phi intervals. For each sample, there were seventeen grain-size classes recorded (from $4\ \phi$ to $0\ \phi$). The data of each recorded grain-size class was then put into a matrix, having the dimension of 52 by 11.

The barrier island section and the headland section are two separate morphodynamic entities subject to different morphodynamic conditions (Liu, 1987; Zarillo and Liu, 1988). Since the objective of this study is to determine the grain-size response to the hydrodynamics in the on–offshore direction, it was appropriate to separate data in the barrier island section from the headland section. Therefore, each of the 17 grain-size matrices was divided into two subsets; the barrier island subset containing 40 transects, and the headland subset containing 13 transects, each sharing the dividing transect. The sediment response to the shoreface hydrodynamics was represented by the mean crossshore distribution of each grain size in each section. Each mean distribution was obtained by taking the alongshore average of the grain-size abundance at each sampling depth.

In addition, the spatial deviations from the mean crossshore distribution for each grain size were examined. This deviation is expressed as $d'(x,y)_{ij} = d(x,y)_{ij} - m(y)_j$, where $i = 1,52$, $i = 1,11$, and $m(y)_j$ is the alongshore mean abundance at each j station. Since $d'(x,y)$ was longshore (x) and crossshore (y)- correlated, in other words, $d'(x,y)$ values depended on the sampling location in both the x and y directions, empirical orthogonal (eigen) function (EOF) analysis was used to examine the deviations. EOF analysis separated the longshore- and crossshore-correlated data into unrelated longshore and crossshore modes. The crossshore modes are of particular interest to this study, because they presumably reflect the onshore hydrodynamic changes on the shoreface.

The hydrodynamic regime is composed of various processes, each dominating in different subenvironments on the shoreface. For example, in the case of the south shore of Long Island, sediment transport within the surf zone is dominated by breaking waves and wave-driven longshore currents. On the seaward slope of the nearshore bar, sediment transport is dominated by shoaling waves and wind- or tide-induced longshore currents. Farther seaward on the middle and lower shoreface, sediment transport is dominated by storm-generated waves and currents. If a grain size is at equilibrium with a particular set of hydrodynamic processes, it would be more susceptible to the variability of those processes. Consequently, the spatial distribution of that grain size will show greater variability at locations corresponding to the morphodynamic zones in which those hydrodynamic processes dominate, and less variability outside these zones. This is the conceptual basis on which the EOF results are interpreted.

To determine whether the eigenmodes statistically differ from one another, a significance test was employed. The null hypothesis can be expressed as:

H_o; $\lambda_{p+1} = \lambda_{p+2} = \cdots = \lambda_m$ (Daultrey, 1976)

which means that among the $p+1^{\text{th}}$ to the m^{th} eigenvalues (m is the rank of the data matrix, $p<m$), they do not differ from one another, and thus are not significant. In other words, only the first p eigenmodes are significant. The chi square value of H_o was calculated as (Daultrey, 1976):

$$\chi^2 = -(N - V - 0.5) \cdot T \cdot \ln \times \left[\left(\prod^{T} \lambda_j \right)^{1/T} \Big/ \left(1/T \cdot \sum^{T} \lambda_j \right) \right]$$

where T is the number of eigenvalues under consideration, N is the number of observations, and V is the total number of eigenvalues (variables). The degree of freedom is $d = 1/2 \cdot [(V-K+2) \cdot (V-K-1)]$, where K is the number of eigenvalues not under consideration ($V-T$).

Results

The mean crossshore abundance curves of the seventeen grain sizes in both the barrier island section and headland section are presented in Figs.5 and 6, respectively. According to the characteristic shape of the mean crossshore distribution curves in both sections, sediment grain sizes can be classified into the following categories:

(1) *The middle and lower shoreface species (0.063–0.125 mm, corresponding to very fine sand)*: These grain sizes begin to increase in abundance landward of a zone between 1.5 and 2.2 km offshore in the barrier island section (Fig.5) and landward of 1.0 km offshore in the headland section (Fig.6). Their abundance

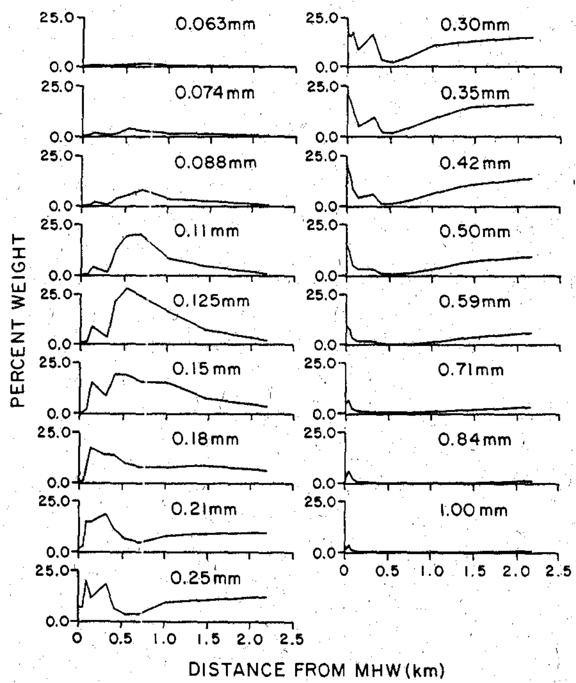

Fig.5. Mean crossshore grain-size distribution curves within the barrier island section.

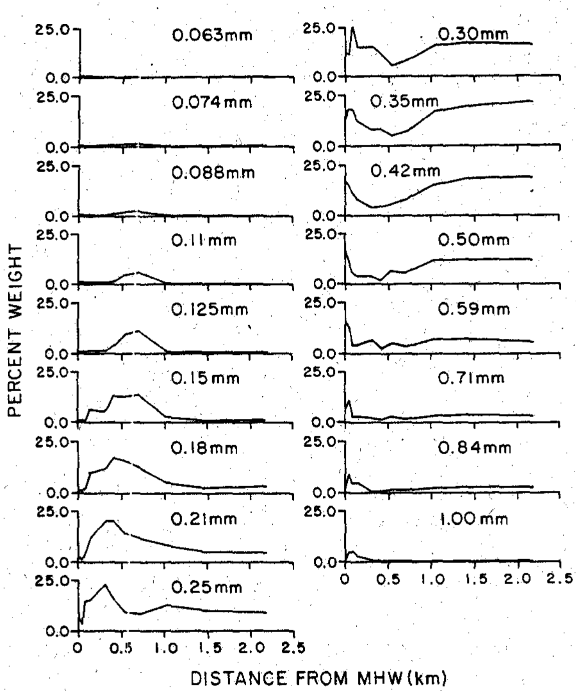

Fig.6. Mean crossshore grain-size distribution curves within the headland section.

peaks just seaward of the edge of the terrace in the barrier island section (about 500 m offshore, Fig.2) or just seaward of the larger scale nearshore bar in the headland section (between 600 and 700 m offshore, Fig.2). Among the grain sizes in this group, the abundance patterns of 0.063 and 0.074 mm are not as pronounced as the others due to their low abundance in the system. For 0.088, 0.11 and 0.125 mm sediment sizes, the shoreward increase in the abundance curves starts farther seaward in the barrier island section than in the headland section. After the curves peak, they drop more abruptly landward in the barrier island section than in the headland section. A secondary (inner) peak on the distribution curves appears only on the barrier island curves (Fig.5). This peak and the trough on its seaward side correspond bathymetrically to the landward trough and the crest of the longshore bar on the terrace in the barrier island section (Fig.7). In contrast, the crossshore distribution curves of these three sizes in the headland section do not reflect any influ-

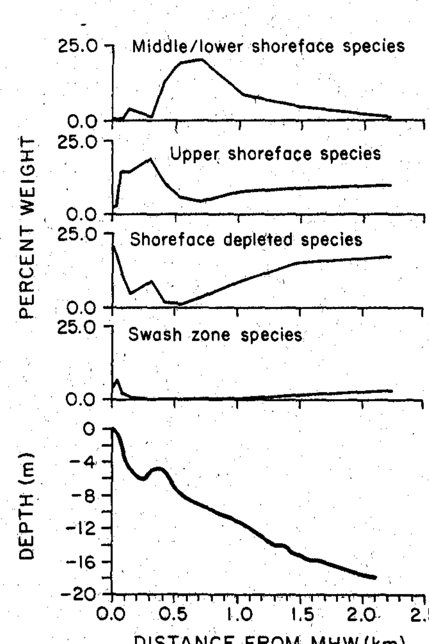

Fig.7. Representative distribution curves of the four grain-size abundance groups and the corresponding representative shoreface profile in the barrier island section.

ence of other bathymetric features apart from the larger scale nearshore bar (Fig.8).

(2) *The upper shoreface species*: Sediment grain sizes in this group, which includes 0.15, 0.18, 0.21, 0.25 and 0.30 mm sizes (corresponding to fine sand), are generally concentrated over the terrace or the larger scale nearshore bar on the upper shoreface (Figs.5 and 6). The distribution curves of these grain sizes further reflect the morphodynamic characteristics of the upper shoreface (Figs.7 and 8). In the barrier island section, there is a gradational change of the curves such that two peaks, one corresponding to the surf zone and the other to the crest of the longshore bar, become more prominent when the sizes become coarser (Fig.5). In the headland section, a similar trend also exists, except there is only a single peak corresponding to the crest of the larger scale nearshore bar (Fig.6). This suggests that unlike their barrier island counterparts (Fig.5), the hydrodynamic processes in the landward trough of the larger scale nearshore bar in the

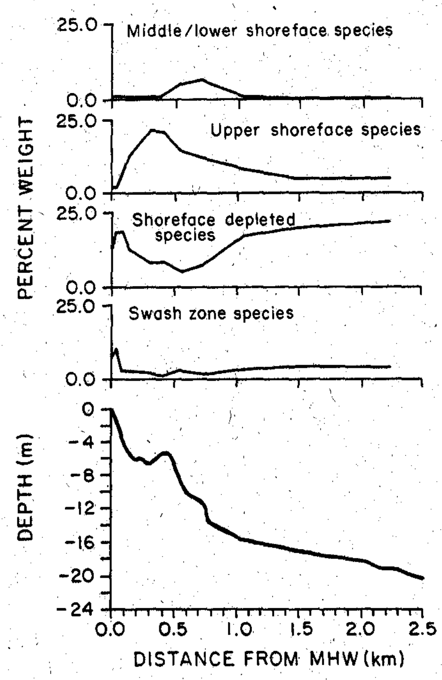

Fig.8. Representative distribution curves of the four grain-size abundance groups and the corresponding representative shoreface profile in the headland section.

headland do not dominate the distribution of grain sizes in this group.

(3) *The shoreface-depleted species*: this group includes grain sizes of 0.35, 0.42, 0.50 and 0.59 mm (corresponding to medium sand). The dominant characteristics of this group are that the crossshore distribution curves show a wide concave-upward section (Figs.5 and 6), which corresponds to almost the entire width of the shoreface (Figs.7 and 8). The curvature of the concave portion is greater on the headland curves than on their barrier island counterparts (Figs.5 and 6).

(4) *The swash zone species*: The distribution curves of the remaining three coarsest grain sizes (coarse sand) show a single peak in the swash zone (Figs.5 and 6). In general, the changes of the shape of on–offshore abundance from one group to the other are gradual and continuous. The groupings clearly reflect the differential response of grain sizes to the progressive hydrodynamic change of shoaling waves from the lower shoreface, to the beachface and swash zone. In addition, within the general trend, the major morphodynamic zones including the edge of the terrace (barrier island section), and the larger scale nearshore bar (headland section), as well as other associated minor features, can also be recognized on the abundance curves (Figs.5 and 6).

By comparing the distribution curves of the headland section (Fig.6), it was found that each curve in this section always consists of a distinctive horizontal segment seaward of 1.0 km, and a non-horizontal segment landward of this point. This offshore location corresponds to the depth of approximately 16 m on the headland shoreface mean profile (Fig.2). This implies that in water depths greater than 16 m, headland sediments are not frequently reworked by average shoaling waves, and consequently, retain the nature of the inner shelf trangressive sand sheet (Liu, 1987). This depth, therefore, represents the time-averaged fair-weather wave base on the shoreface, which is the demarcation of the shoreface and the rest of the inner shelf. The same depth corresponds to the offshore distance of 1.5 km on the barrier island mean shoreface profile (Fig.2). However, the distinction between a horizontal segment and a non-horizontal segment on barrier island distribution curves is less clearly defined (Fig.5). This suggests that the fair-weather wave base on the barrier island shoreface does not approximate a line but rather a broad zone reflecting the gentler shoreface slope. In addition, the barrier island shoreface is wider than its headland counterpart.

The EOF results for the longshore de-meaned grain-size distributions of both the barrier island and headland are listed in Table 1. Only the crosshore deviations from the mean (eigenvector curves) of the first three modes of the grain sizes were examined. To demonstrate the relationship of the eigenmodes of each grain size to the on–offshore hydrodynamic changes, the associations between the spikes on all eigenvector curves and

TABLE 1

EOF results of single grain sizes (numbers in parentheses are cumulative percents)

Sizes (mm)	Longshore de-meaned deviation					
	Barrier island			Headland		
	E_1	E_2	E_3	E_1	E_2	E_3
0.063	50.3	24.2 (74.4)	8.0 (82.4)	56.3	43.7 (100)	0.0 (100)
0.074	51.5	24.9 (76.4)	11.1 (87.5)	63.7	24.2 (88.0)	8.1 (96.1)
0.088	57.5	16.3 (73.7)	10.0 (83.7)	73.4	18.7 (92.1)	5.9 (98.0)
0.11	55.0	15.5 (62.0)	10.5 (75.4)	85.7	12.3 (95.6)	1.3 (98.4)
0.125	34.4	27.6 (56.4)	13.4 (70.4)	78.9	16.7 (80.8)	2.7 (89.5)
0.15	35.2	21.2 (56.4)	14.0 (70.4)	55.3	25.5 (80.8)	8.6 (89.5)
0.18	36.5	15.5 (52.9)	13.5 (65.5)	36.8	32.2 (69.0)	12.5 (81.5)
0.21	30.0	15.8 (45.8)	14.0 (59.8)	41.5	19.5 (61.0)	19.1 (80.0)
0.25	26.5	17.2 (43.7)	12.9 (56.6)	35.8	20.5 (56.3)	17.5 (73.8)
0.30	23.5	18.6 (42.2)	13.6 (55.8)	34.0	24.5 (58.6)	14.7 (73.3)
0.35	26.5	19.0 (45.5)	14.6 (60.2)	31.4	21.2 (52.6)	16.6 (69.2)
0.42	26.7	17.3 (44.0)	16.9 (60.9)	34.7	19.0 (53.8)	17.4 (71.1)
0.50	40.6	16.2 (56.8)	12.1 (68.8)	45.3	21.0 (66.3)	15.8 (82.1)
0.59	47.6	15.8 (63.4)	11.4 (74.8)	42.1	30.0 (71.9)	9.9 (81.8)
0.71	34.3	24.2 (61.5)	17.5 (79.0)	36.5	27.9 (64.4)	15.1 (79.5)
0.84	55.8	19.5 (75.3)	10.6 (85.9)	55.9	25.3 (82.1)	6.5 (88.7)
1.00	52.7	25.5 (78.2)	10.5 (88.7)	78.8	13.6 (92.4)	6.4 (98.8)

TABLE 2

Morphodynamic associations of grain-size eigenvectors in the barrier island section

Size (mm)	Swash zone	Surf zone	Bar trough	Bar crest	Edge of terrace	Lower shoreface
0.063			+I		+I	
			+II		−II	
	+III		+III		+III	−III
0.074			+I		+I	
			+II		−II	
			−III		+III	
0.088			+I		+I	
			+II		−II	+II
			+II			+III
0.11					+I	
			+II		+II	
			+III		−III	+III
0.125			+I		+I	
			−II	+II	−II	+II
			−III		−III	+III
0.15			−I		+I	
			+II		+II	−II
			+III			+III
0.18			+I		−I	
			+II		+II	−II
			+III		+III	+III
0.21		+I				±I
					+II	−II
	+III		+III	−III		
0.25		+I	−I	+I	−I	+I
	−II		+II	−II	−II	−II
	+III		+III	−III	+III	−III
0.30	+I		−I	+I		
	+II	−II	+II	−II		−II
	+III	−III		−III		+III
0.35		−I				±I
	+II	−II		+II		±II
	+III			+III		±III
0.42	+I	−I		+I		±I
	−II			−II		±II
	±III	−III		−III		±III
0.50	+I					±I
	±II	−II		+II		±II
	+III	−III		+III		+III
0.59	+I					−I
	±II		+II		−II	+II
			−III		+III	+III
0.71	+I					−I
	+II					+II
	+III	−III				+III
0.84	+I					
	+II	−II	+II			−II
	±III	+III				+III
1.00	+I					
	+II	−II				
		+III				−III

the morphodynamic zones on the barrier island shoreface are tabulated in Table 2. Spikes on the eigenvector curves are on–offshore distribution deviations determined by a particular eigenmode. Their sign indicates whether the spike of a particular eigenvector curve is positive (above the mean), or negative. For example, in Table 2 a +I registered for a particular grain size at the bar trough means that the first-mode eigenvector curve of that grain size has a positive peak at the location corresponding to the landward trough of the longshore bar. The focus, however, is on where on the shoreface these spikes occur.

From Table 2, the spatial differentiation among grain sizes can be clearly seen according to the associations between their on–offshore eigen deviations and the morphodynamic zones. The finest six grain sizes (from 0.063 to 0.18 mm) have their major fluctuations in the landward trough of the longshore bar and over the seaward edge of the terrace, which suggests that these two zones are the least energetic on the shoreface because of the association with the finest grain sizes. Grain sizes 0.21, 0.25 and 0.30 mm, being the most ubiquitous group, have additional fluctuations in the swash and surf zones and over the crest of the longshore bar. The third group, composed of 0.35, 0.42, 0.50 and 0.59 mm sizes, is characterized by fluctuations in the swash zone, in the surf zone, and over the bar crest. The coarsest three sizes, 0.71, 0.84 and 1.00 mm, which form the last group, are characterized by fluctuations in the swash and surf zones, which suggests that those two zones are the most energetic. Almost all grain sizes show fluctuations on the lower shoreface below the fair-weather wave base. These fluctuations are probably not caused by the shoreface average fair-weather waves, but are either inherited from the initial glaciofluvial deposit or caused by storm-generated waves or currents.

The associations between eigen deviations of each grain size and the morphodynamic zones in the headland are tabulated in Table 3. Generally speaking, the sediment grain sizes can also be classified into a similar set of four groups. Like the barrier island, the fluctuations on the lower shoreface of the headland are mainly due to the variations of the initial source of the outwash deposits or to storm transport processes. The first group, consisting of 0.063, 0.074 and 0.088 mm sizes, is characterized by having distribution fluctuations in the swash zone and surf zone, and over the seaward edge of the primary bar. The next group, composed of 0.11, 0.125, 0.15, 0.18 and 0.21 mm sizes, shows fluctuations at the landward trough of the primary bar, over the crest of the larger scale nearshore bar, and over the seaward edge of the larger scale nearshore bar. The remainder of the sizes (from 0.25 to 1.00 mm) are included in one group, which shows fluctuations in all dynamic zones except for grain sizes of 0.84 and 1.00 mm. These two sizes do not have fluctuations over the crest of the large-scale bar. The grain size–morphodynamic associations in the headland sediments do not display spatial differentiation as clearly as those of the barrier island.

The significance tests results for the demeaned eigenmodes of the barrier island subset, the headland subset and the combined data set are tabulated in Table 4. The EOF results of the combined data set were not discussed before, but are presented here for the purpose of illustrating the limitation of the significance test. For grain sizes other than 0.25, 0.30, 0.35 and 0.42 mm, the eigenvalues are generally insignificant in the headland section, but are significant in the barrier island section if the confidence level is set at 90%. In other words, not all of the first three eigenmodes of the same grain sizes within different subsets have the same significance levels. For example, for the 0.18 mm size class, the first two eigenmodes of the combined data set are significant, whereas only the first eigenmode of the barrier island subset is significant, and none of the three eigenmodes of the headland subset is significant, since they are lower than the cutoff level of 90%. Among all three data sets, the eigenmodes for grain sizes having greater dynamic equilibrium on the shoreface (having a greater number of associated dynamic zones), are

TABLE 3

Morphodynamic associations of grain-size eigenvectors in the headland section

Size (mm)	Swash zone	Surf zone	Bar trough	Bar crest	Edge of terrace	Lower shoreface
0.063	+I		−I			
	+II		+II			
	+III					
0.074			+I		+I	
	+II		+II		±II	
			−III		±III	
0.088			+I		+I	
	+II	−II			±II	
	+III	−III			±III	
0.11			+I		+I	
			+II		±II	
			+III		±III	
0.125			+I		+I	
		+II			±II	
		+III	−III	−III	±III	−III
0.15			+I		+I	+I
			−II	+II	±II	
			−III	+III	±III	+III
0.18			+I		±I	−I
				+II	+II	+II
			−III	+III	±III	+III
0.21			+I		+I	
			−II	+II	±II	±II
			−III	−III	+III	+III
0.25	+I			+I		−I
	±II		+II		±II	±II
		−III		−III	+III	±III
0.30	+I		−I			−I
	−II	+II	−II	−II		+II
	±III	+III	+III	+III	−III	+III
0.35		+I				±I
	+II	−II		+II		−II
	+III			−III		±III
0.42	+I	+I			−I	−I
	+II		+II		+II	−II
	±III		+III	−III	±III	+III
0.50	+I			−I	−I	
	±II	−II	−II	+II	+II	−II
	+III			−III	±III	±III
0.59	+I			+I	+I	+I
	+II			−II	+II	−II
	+III		+III	−III	+III	±III
0.71	+I	−I			−I	−I
		+II		+II	+II	+II
	±III			+III	−III	
0.84		+I				+I
	±II	+II	+II		+II	+II
	−III	−III	+III		+III	+III
1.00		+I			+I	+I
	±II	−II			+II	+II
	+III	−III				

TABLE 4

Significance tests results on the longshore de-meaned single grain-size eigenmodes (numbers are confidence levels (%) at which H is rejected)

Sizes (mm)	Entire area			Barrier island			Headland		
	E_1	E_2	E_3	E_1	E_2	E_3	E_1	E_2	E_3
0.063	99.5	99.5	99.5	99.5	99.5	<10	<10	<10	<10
0.074	99.5	99.5	99.5	99.5	99.5	99	90	50	<10
0.088	99.5	90	10	99.5	50	10	97.5	50	<10
0.11	99.5	50	10	99.5	50	10	99.5	99	<10
0.125	99.5	97.5	10	99.5	50	10	99.5	99.5	90
0.15	99.5	99	90	99.5	50	10	50	50	10
0.18	97.5	99	50	97.5	10	10	10	10	10
0.21	90	50	10	50	10	10	10	<10	10
0.25	50	10	<10	50	10	<10	<10	<10	<10
0.30	50	10	<10	10	<10	<10	10	10	10
0.35	50	10	10	50	10	10	<10	<10	10
0.42	10	<10	<10	50	10	10	<10	<10	10
0.50	99.5	90	10	99.5	10	10	10	10	10
0.59	99.5	50	10	99.5	50	10	10	10	<10
0.71	99.5	97.5	90	99.5	99.5	99.5	10	10	<10
0.84	99.5	99.5	90	99.5	99.5	95	90	50	10
1.00	99.5	99.5	99.5	99.5	99.5	97.5	99.5	95	95

generally insignificant compared with eigenmodes of morphodynamically restricted grain sizes that have fewer associated dynamic zones. In the barrier island section, these ubiquitous grain sizes include 0.21, 0.25 and 0.30 mm (Table 2). In the headland section, these grain sizes are 0.25, 0.30, 0.35, 0.42, 0.50, 0.59 and 0.71 mm (Table 3). Since in the same subset (barrier island or headland), all grain size matrices have the same sample size, the fact that some grain-size eigenmodes are significant and some are not, based on the same test and the same sample size, simply reflects that some grain-size distributions are "noisier" than others by nature. This also points to the limitation of using this particular formula to compute chi-square values for the significance test, since the result is largely controlled by the sample size (N). This is demonstrated by the eigenmodes becoming insignificant for the same grain size when moving from the largest sample size of the combined data set ($N=52$) to the barrier island subset ($N=40$), and to the smallest size of the headland subset ($N=13$). Nevertheless, the de-meaned eigenvector curves of the first three eigenmodes of all sizes in both the barrier island and headland sections provide interpretable and consistent information regarding their respective "behavior" in these sections, as demonstrated in Tables 2 and 3. Therefore, all the eigenmodes discussed previously are considered meaningful, in terms of providing information.

Discussion

Although the equilibrium classification scheme based on mean crossshore grain-size abundance divides sediment grain sizes into four groups, the boundaries of these groups are slightly different from those in the scheme based on the eigen deviations. The discrepancy results from the slightly different emphases of these two schemes: one is focused on the equilibrium response of grain sizes to the overall shoreface hydrodynamic regime, the other is focused on the morphodynamic association. Nevertheless, the four grain-size groups from both schemes are comparable, which suggests that sediment grain sizes respond to the shoreface hydrodynamic regime in four major groups, i.e., coarse sand, medium sand, fine sand and very fine sand. Subsequently, the middle and lower shoreface species, the upper shoreface species, the shoreface-depleted species, and the swash-zone species are used interchangeably with very fine sand, fine sand, medium sand, and coarse sand, respectively, for the case of Long Island.

The hydrodynamic implications can be interpreted from the mean crossshore abundance curves. At the last lowstand of sealevel, the shoreface, then the glacial outwash plain, was formed by fluvial processes. Assuming that the sediment distribution was more or less uniform over the entire outwash plain, the distribution curve of any grain size in the same orientation as our present transects would appear to be a horizontal line. After the post-glacial encroachment of the ocean started, the outwash plain was gradually inundated, and hydrodynamic processes began to rework and redistribute the outwash plain sediments. As the sea level rose, the sediment reached equilibrium with the hydrodynamic regime, and subsequently assumed the present mean crossshore distribution pattern. Although these curves now are far from being a horizontal line (the initial abundance distribution), part of the assumed initial sediment abundance (the horizontal base line) can still be traced on almost every abundance curve in the headland, and on some abundance curves in the barrier island (Figs.5 and 6).

The result of the reworking of the initial outwash sediments by the hydrodynamics of the traversing shoreface can be visualized from the progressive change of the shoreface grain-size frequency distributions in the onshore direction from the transgressive lag deposit (Fig.3a), to the sediments of the lower shoreface (Fig.9a), and to the sediments of the upper shoreface (Fig.9b). The shoreface sediments have become distinctly more bimodal from the lower shoreface (Fig.9a) to the upper shoreface (Fig.9b), further departing from the unimodal (predominantly medium sand) "relict" source (Fig.3a). The key to this change comes from the

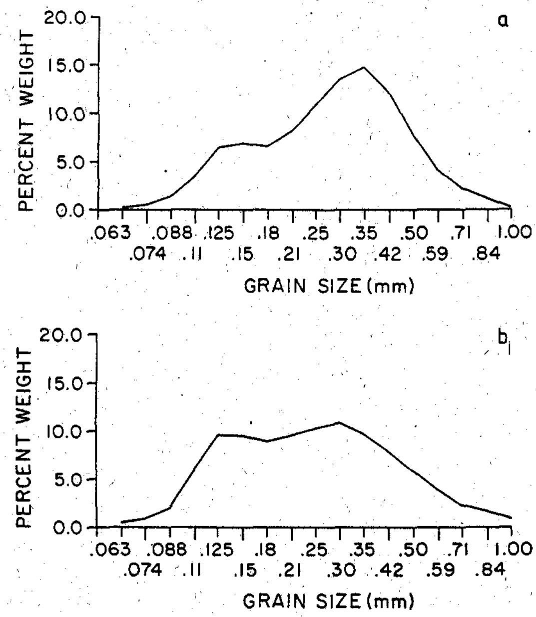

Fig.9. a. Mean grain-size frequency distribution of the lower shoreface sediments. b. Mean grain-size frequency distribution of the upper shoreface sediments.

spatial (on–offshore) variations of two major grain-size groups. The amplified concentration (retention) of the fine sand over the terrace and primary bar increases the fine grain-size fraction within the surficial sediment on the upper shoreface (Figs.7 and 8). In contrast, the medium sand fraction is depleted from the middle and lower shoreface (Figs.7 and 8). The primary cause for this retention and depletion is related to the differential response of these grain sizes to hydrodynamic processes. The intensity of depletion is greater on the gentler barrier island shoreface than on the headland shoreface, as indicated by the wider concave segments (Figs.7 and 8).

In water depths greater than 16 m on the shoreface of the study area, sediment grain sizes are little affected by the day-to-day hydrodynamic processes, as suggested by the horizontal segment of grain-size abundance curves (Fig.6). At shallower depths, the sediment grain sizes respond to hydrodynamics according to the four grain-size groups, which generally form a seaward-fining sequence on the shoreface. Coarse sand concentrates in the swash zone and surf zone on the beachface. Fine sand concentrates over the upper shoreface, seaward of the surf zone. Very fine sand accumulates on the middle and lower shoreface beyond the seaward edge of the terrace in the barrier island section and beyond the larger scale nearshore bar in the headland section. Zenkovich (1967) predicted a similar seaward-fining sequence by relating the differential threshold movement for different grain sizes and the asymmetric orbital motions of shoaling waves on a planar shoreface. He also proposed an oscillation equilibrium concept for each grain size, such that there is a shore-parallel zone on the shoreface in which a particular grain size can be moved back and forth by shoaling waves. Zenkovich's idea can thus be applied here to explain the seaward-fining sequence and zonation of the three grain-size groups mentioned above.

There has been little documentation of the depletion of the medium sand group from the shoreface seaward of the surf zone, nor are there theories to explain it. However, an interpretation is attempted: From his sediment tracer experiments within and outside the surf zone, Ingle (1966) concluded that sediment grain sizes are maintained in their respective zones of dynamic equilibrium in the on–offshore direction. If a grain size is placed outside its zone of dynamic equilibrium, it will first move in the on–offshore direction to seek its dynamic zone. After reaching the zone, it then moves alongshore (Ingle, 1966). Subsequently, if a grain size is placed within its zone of dynamic equilibrium, it will move predominantly alongshore, and be depleted from that zone. By the same token, the depletion of the medium sand from the shoreface of the study area suggests that its predominant mode of transport is alongshore instead of on–offshore so that there is no on–offshore accumulation above the "base line" (Figs.5 and 6), which implies that medium sand is the species in equilibrium with hydrodynamic processes on the shoreface of the study area. This assertion is also supported by the greater number of associated morphodynamic zones for the medium sand in the study area (Tables 2 and 3). In other words, if a particular grain size is in equilibrium with more hydrodynamic processes (i.e., has a wider range of equilibrium dynamic zones), it will have greater "freedom" to be moved back and forth within those zones as suggested by Zenkovich (1967), which then results in a less spatially correlated distribution. For instance, due to their more ubiquitous distribution, the grain sizes of medium sand including 0.21–0.42 mm have very low variance explained by the first three eigenmodes (Table 1). On the other hand, the other three grain-size groups have fewer zones of dynamic equilibrium (Tables 2 and 3), and their abundance curves indicate increased concentration within particular zones (Figs.7 and 8). These facts suggest that their predominant mode of movement is on–offshore toward their respective zones of dynamic equilibrium in which their abundance increases.

The four grain-size groups in the two sections of the study area do not match each other size for size. Generally speaking, on the headland shoreface the same grain sizes usually dominate less energetic zones, compared with the barrier island shoreface. In addition, the spatial differentiation of grain-size groups in the headland is not as clear as in the barrier island section. This suggests that hydrodynamic processes on the headland shoreface are less able to separate grain sizes with respect to morphodynamic zones (perhaps less energetic). The three finest sizes, 0.063, 0.074 and 0.088 mm, show dominant distribution variations in the most energetic zones in the headland section (the swash zone and surf zone, Table 3). This association may result from excess input of these grain sizes into the swash and surf zones as the result of bluff erosion. In this case, this association does not indicate dynamic equilibrium between grain size and the swash- and surf-zone processes, but instead reflects the influence of an external source.

The average grain-size frequency distribution curve of the sediment samples from the barrier island shoreface (Fig.10a) is nearly

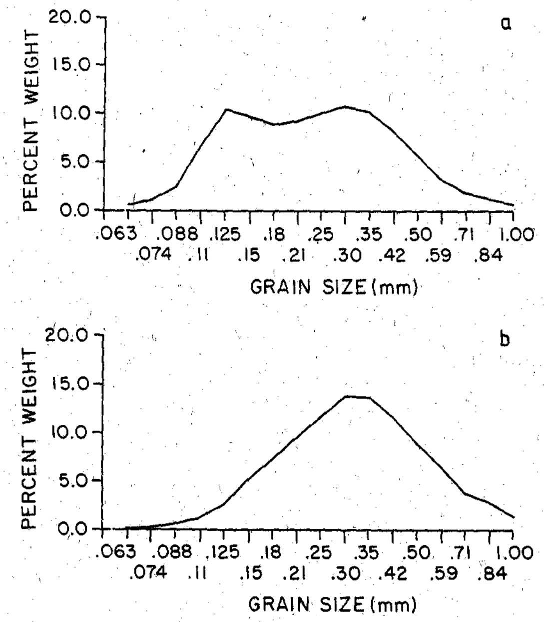

Fig.10. a. Mean grain-size frequency distribution of the barrier island shoreface sediments. b. Mean grain-size frequency distribution of the headland shoreface sediments.

identical to that of the upper shoreface for the entire study area (Fig.9b). This suggests that a similar mechanism (retention of fine sand and depletion of medium sand) is responsible for the sediment redistribution in both sub-regions. The shape of the average grain-size distribution curve of the headland (Fig.10b) suggests the depletion of very fine and fine sand fractions from their predominant source — the moraine (Fig.3b). This implies a slightly different mechanism for reworking and redistribution of the headland shoreface sediment such that the fine-grained sediments are not retained as efficiently on the headland shoreface, as indicated by the lower overall abundance of fine sand compared with that of the barrier island (Figs.5 and 6). The winnowing process of fine-grained sediments from the headland shoreface is speculated as being caused by the combined effects of shoaling waves and the net westward longshore currents (wind-and storm-induced) on the shoreface. Because of the greater depth and steeper shoreface, the average shoaling wave regime can only effectively entrain grain sizes finer than medium sand on the middle and lower shoreface of the headland section.

Conclusions

This study has demonstrated that the spatial distributions of individual sediment grain sizes can reflect their differential responses to the average shoreface hydrodynamics. The characteristic distribution of grain sizes suggests that a depth of approximately 16 m is the demarcation between the shoreface and the rest of the inner shelf. Shoreward of this depth, the reworking and redistribution of sediment grain sizes results in a seaward-fining sequence of four grain-size groups based on their on–offshore abundance. The dominant movement of coarse sand, fine sand and very fine sand is probably in the on–offshore direction, whereas the medium sand is more subject to the longshore transport process. In addition, the grain-size distributions also indicate the differential response of sediment grain sizes to the various hydrodynamics that dominate different morphodynamic zones on the shoreface. The EOF analysis also proved to be a useful tool for deciphering spatial correlation between grain sizes and morphodynamic zones on the shoreface from a spatially correlated data set.

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