1990

Cross-shore and longshore sediment size distribution on southern Currituck Spit, North Carolina

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Recommended Citation

Calliari, Lauro Julio, "Cross-shore and longshore sediment size distribution on southern Currituck Spit, North Carolina" (1990). *Dissertations, Theses, and Masters Projects.* Paper 1539616594.
https://dx.doi.org/doi:10.25773/v5-ftfs-5268

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Cross-shore and longshore sediment size distribution on southern Currituck Spit, North Carolina

Calliari, Lauro Julio, Ph.D.

The College of William and Mary, 1990

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Ann Arbor, MI 48106

CROSS-SHORE AND LONGSHORE SEDIMENT SIZE DISTRIBUTION ON SOUTHERN CURRITUCK SPIT, NORTH CAROLINA.

A Dissertation
Presented to
The Faculty of the School of Marine Science
The College of William and Mary in Virginia

In Partial Fulfillment
Of the Requirements for the Degree of
Doctor of Philosophy

by
Lauro J. Calliari
1990

APPROVAL SHEET

This dissertation is submitted in partial fulfillment of
the requirements for the degree of

Doctor of Philosophy

Lauro J. Calliari

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ACKNOWLEDGEMENTS

This research was funded by the Coordenação de Pessoal de Nível Superior (CAPES/MEC/BRASIL) through a scholarship (Processo 769/83) and the Virginia Institute of Marine Science (VIMS).

I would like to express my sincere gratitude to my advisor, Dr. L. D. Wright and committee members Dr. John Boon III, Dr. Suzette Kimball, Dr. Evon P. Ruzecki, Dr. Gerald Johnson, and Dr. Robert Diaz for their guidance and constructive criticism during this study. I specially thank Dr. John Boon III for the orientation provided in factor analysis.

Sincere appreciation is extended to the many friends and colleagues for countless hours of assistance during my field work: Mal Green, Tracy and Steve Skrabal, Becky Savage, Luis Barbieri, João Paes Viera, Cassiano Monteiro Neto, Pat Barthle, Pam Mason, Jane DiCosimo, Mary Sue and Mohamed Zaki Moustafa, Danny Gouge, Joe Boyer, George Vadas, Lino Gallo, Hakan Ozalpasan, Bo Dame, Durand Ward, Bob Gammish, Steve George and Sarah Dydak. I thank my work colleague João Paes Vieira (FURG/BRASIL) for helping me with graphics during the period of data analysis.

I am grateful to Cindy Fischler for her dedication and competence in managing the sediment laboratory where the grain-size analyses were performed.

A special thanks is extended to Mr. William Birkemeier of the Field Research Facility in Duck, North Carolina for providing a data set which enriched this research.

I thank Marcia Bermam and Marlene Davis for their assistance in reviewing this work, and for improving my English writing skills.

I would also like to thank all the staff and students in the Division of Geological and Benthic Oceanography. A special thanks is due to Sung Chang Kim and Mal Green for helpful geological discussions, computer expertise and daily conversations.

Finally, I would like to thank Rosaura and Carolina for their patience and love which helped make this degree a reality.

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CROSS-SHORE AND LONGSHORE SEDIMENT SIZE DISTRIBUTION ON SOUTHERN CURRITUCK SPIT, NORTH CAROLINA.

ABSTRACT

Using Q-mode factor analysis, 87 surficial sediment samples collected from Duck and Whalehead beach, North Carolina, were analyzed using the weight percent of the gravel and sand fraction subdivided at 0.5 phi class interval as variables. An additional data set composed of 178 surficial sediment samples from Duck beach (bimodal) and Coquina beach (unimodal fine) representing three years of sampling at monthly intervals were analyzed by the same technique using only the sand fraction.

The spatial and temporal patterns of sediment factor groups support three main inferences. 1) Bimodal beaches display a more distinct sediment zonation than unimodal beaches. 2) On a long term basis (yearly), cross-shore grain-size distributions represent depositional processes. Particularly on bimodal beaches, the association of sediment factor groups with specific zones of the beach profile delineates a textural differentiation produced by the type and amount of energy inherent in each zone. Combinations of Q-mode factor analysis and other environmental sensitive techniques (e.g. log-probability plots of grain-size distributions) proved to be useful for interpreting sedimentary processes at the depositional site. 3) The cross-shore patterns which represent an average of the sedimentary processes occurring under fair weather and storm conditions indicate that coarse sediments are concentrated on the backshore. In contrast, fine sediments are located landward or shoreward of this zone where they are exposed to energy conditions that result in their depletion in the subaerial beach.

Using the Q-mode factor model, 350 new sediment samples from beaches located between Duck and Oregon Inlet were "mapped" in the factor space defined by the Duck-Coquina data set. The along-coast results support the cross-shore trends observed in the previous studies and indicates that there are several sources of coarse sediments between Duck and Oregon Inlet. Sedimentologic, stratigraphic and seismic data offshore and landward of the barrier substantiate these findings and demonstrate that differences in subaerial beach morphology in this part of Currituck Spit, is primarily due to the availability of coarse sediments from the paleodrainage of the Albemarle river.

CROSS-SHORE AND LONGSHORE SEDIMENT SIZE DISTRIBUTION ON SOUTHERN CURRITUCK SPIT, NORTH CAROLINA

1. INTRODUCTION

Spatial grain-size distributions of beach deposits have been widely studied. Among the several interests of geologists is the identification of true shorelines facies due to its importance in paleogeographic reconstructions mostly related to delimitation of of coastal areas during a particular time interval. Most of the studies, however concentrate on the foreshore and dunes (Folk and Ward, 1957; Mason and Folk, 1958; Friedman, 1961; Giles and Pilkey, 1965; Hails, 1967). A number of studies have investigated cross-shore variations in sediment grain size and the degree of sediment sorting across the beach profile (Krumbein, 1938; Evans, 1939; Bascom, 1951; Fox, Ladd, and Martin, 1966; Miller and Zeigler, 1958).

Early research in grain size distribution has used the statistical measures of mean, standard deviation, skewness, and kurtosis to distinguish beach from dune environments and draw inferences about processes of sediment transport or deposition. Recent studies (Andrews and Van Der Lingen, 1968; Solohub and Klovan, 1970) showed that attempts at utilizing grain-size statistics (skewness, degree of sorting, kurtosis etc..) to identify depositional environments in the ancient rock record as well as in modern sediments have not been particularly successful. They attribute the lack of success of these methods to one or more of the following factors: (1) The most commonly used standard bivariate plots cannot adequately express the complex processes producing grain-size distributions. (2) Grain size parameters may not contain enough information required to determine environments of deposition. (3) Combinations of amount and type of kinetic energy, which may be primarily responsible for the grain-size distribution of a sand may produce similar distributions in different environments. In addition, environmental recognition is based on subtle parameters, such as skewness, which may easily be altered by diagenesis. The parameters generally used may not be the best descriptors of most grain-size distributions. For instance, moments of unimodal distributions are realistic descriptors only if applied to unimodal distributions, which in nature are rather rare. Skewness and kurtosis, for example, are measures of deviation of normality for unimodal distributions and their meaning becomes obscure in multimodal situations.

Attempts to relate grain size distribution to the depositional processes responsible for their formation appear to be more successful in the characterization of sedimentary environments. Different rationale have been proposed to define the mechanisms responsible for sediment transport. All of them are based on the premise that differing modes of transport (rolling, saltation and suspension) induce measurably different textural responses in the sediment and act selectively on certain grain sizes (Inman, 1949). These textural variations can be examined by considering the cumulative size curve on log-probability axes. An important contribution of the relationship between textural distributions and depositional processes is the concept that a sand sample is composed of a number of elementary populations and that each population can have a different transportational, and depositional history (Moss, 1962). Textural variations in the sample are assumed to be caused by different transport mechanisms related to one or several of the elementary populations, which produces variability in the overall properties of the sample.

Many researchers (Doeglas, 1946; Tanner, 1964; Visher, 1969) have recognized that each straight-line segment of the cumulative curve of sediment grain-size represents a distinct log-normal sub-population. A review of some studies, particularly Visher (1969), indicate that the method of dissecting the cumulative curves seem to delineate the dynamic provenance of the sediment as well as the environment of deposition.

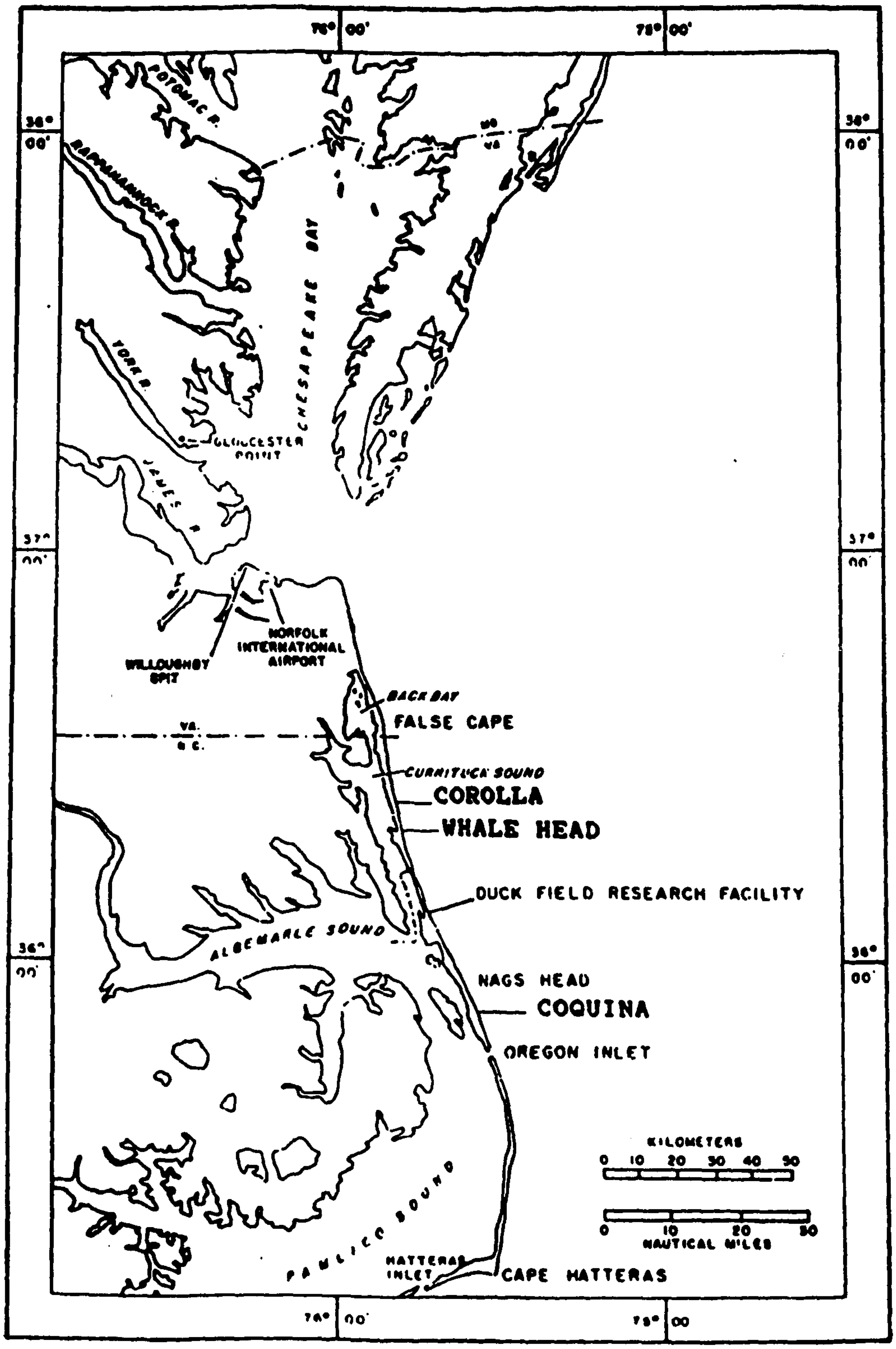
More recently, the use of multivariate statistical methods, particularly factor analysis (Klovan, 1966; Davis, 1970; Solohub and Klovan, 1970; Allen, Castaing and Klingebiel, 1971; Castaing, 1973; Dal Cin, 1976) to interpret grain-size distribution data appears to be more successful than the grain-size statistics in the differentiation of both modern and ancient environments.

According to Davis (1970), multivariate methods can be used to analyze the relative accuracy of sediment-size descriptors and investigate sediment distribution patterns by calculating directly from the histogram. Since the entire histogram is used, rather than the summary statistics, more information can be obtained. The primary advantage of this method it that a large number of samples representing the entire environment, can be analyzed together, without having to examine and dissect each individual cumulative grain-size curve. Visher (1969) and Klovan (1966) assume that mean grain size is a crude measure of energy conditions at the time of deposition, and therefore can be used as a tool to identify transport processes and possible depositional environments.

Most of the above mentioned studies of grain-size associated with the beach environment do not address the temporal variability, which should be considered. Most of the work that does account for temporal variability has concentrated on the foreshore in order to evaluate textural changes associated with the tidal cycle and its variations. Few attempts (Sonu, 1972) have been made to characterize grain-size changes along constantly shifting beach profiles or to understand the processes responsible for grain-size distributions across the entire beach. The studies have also been primarily related to beaches which have a small grain-size range. There is a lack of data related to beaches composed of gravel and sand with strong bimodal or even polymodal sediment composition. A few studies (Sonu, 1972; Taira and Scholle, 1979; Moustafa, 1988) were conducted under these circumstances.

Studies of beach sedimentary processes and grain-size distributions along the North Carolina coastline between Corolla and Oregon inlet (**Figure 1**) are particularly interesting. These beaches, located 15 to 20 miles apart, are markedly different.

Figure 1. Location of the study area in North Carolina


76° 00'
75° 00'
38° 00'
37° 00'
36° 00'
POTOMAC R.
RAPPAHANNOCK R.
MD
VA
CHESAPEAKE BAY
YORK R.
GLOUCESTER POINT
JAMES R.
NORFOLK INTERNATIONAL AIRPORT
WILLOUGHBY SPIT
BACK BAY
FALSE CAPE
VA.
N.C.
CURRITUCK SOUND
COROLLA
WHALE HEAD
DUCK FIELD RESEARCH FACILITY
ALBEMARLE SOUND
NAGS HEAD
COQUINA
OREGON INLET
KILOMETERS
0 10 20 30 40 50
0 10 20 30
NAUTICAL MILES
PAMLICO SOUND
HATTERAS INLET
CAPE HATTERAS

Beaches near Duck are narrow and steep. In contrast, the beaches at Corolla and Coquina (20 miles south of Duck) are broad and flat. Near Duck, the sediments are strongly bimodal (Birkmeier et al. 1986) (coarse gravel is mixed with coarse and medium sand), whereas Corolla and Coquina contain medium to fine sands. The occurrence of nearby beaches with different characteristics concerning sediment texture provide a unique opportunity to improve the knowledge about the spatial and temporal grain-size distributions across the beach.

1.1 Hypotheses

The fact that adjacent beaches along Currituck Spit are different in terms of morphology and grain-size is particularly important to studies related with the beach environment. From the cross-shore point of view the relationship between sediment textural characteristics and beach processes in a natural contemporary system can give us some clues to the identification of ancient sand bodies in the geological record where no paleogeographic information is available. Sediment distribution trends which may emerge from the present study could lead to a better understanding of the sedimentary processes in each beach zone. A link between a particular sediment-size distribution and a site specific area of the beach profile may provide some useful insight for beach nourishment projects, as well as the analysis of morphological changes in the beach profile. From the along coast point of view, differences in sediment types along this microtidal transgressive barrier island should have a reasonable geological explanation. If we can find the geological reasons for these differences, it may help us to have a better understanding about beach evolution and differentiation along the study area, as well as, in similar sedimentary environments in any part of the world.

There are three primary working hypothesis involved in this research. The first is that a grain-size distribution, analyzed by Q-mode factor methods can reflect depositonal processes in the subaerial beach which in turn will be associated with a particular morphologic zone of the beach profile. This association will provide some insight to delineate distinct sedimentary processes and their relationship across the entire beach.

Cross-shore sediment transport on the subaerial beach is accomplished by aqueous and aeolian processes. This results in the development of two genetically distinct beach and dune sediment populations. The genetic distinctions between these populations should be manifested in their size frequency distributions as a result of differences in transport dynamics.

The second hypothesis is that beaches with strong bimodal sediment characteristics will display more distinct cross-shore textural zonations than unimodal beaches.

Different grain-size distributions behave differently under the aqueous and aeolian beach sedimentary processes. Textural variations are due to: different responses to sediment transport processes, changes in settling velocity, selective winnowing and differences in porosity and permeability. All of these factors will affect the cross-shore distribution of sediments. It is expected that as a result of greater variability in available sediment types, the area between the dunes and the step at Duck beach will display a more distinct sediment distribution than Whalehead beach.

By analyzing samples collected along the entire beach profile (landward side of the dune seaward to the step) on an extremely low frequency basis (monthly) and during any tide cycle, can we differentiate zones of sedimentation? If so, is it possible to differentiate the intensity of the processes acting in each area? How constant is the textural distribution associated with a particular zone? On a long term basis, how does the textural distribution of a strongly bimodal beach compare with an assumed unimodal beach?

The last hypothesis is that existing differences in the general morphology (width and steepness) between adjacent beaches along Currituck spit are in part, caused by localized input of coarse sediments. The sediment groups, identified by Q-mode factor analysis, will be used to quantify these additions and will provide insight into understanding the geomorphological evolution of the beaches associated with this barrier island strip.

1.2 Objectives

The objectives of this dissertation are as follow:

1) Evaluate on a long term basis (yearly), spatial and temporal variations in surficial sediment size distributions across the entire beach (dunes to step).

2) Compare the spatial and temporal variability of surficial sediment size distributions between beaches composed of sands reflecting different sediment sources.

3) Characterize spatially, surficial grain size distributions sampled between the landward side of the dunes and the step of 14 beaches located on the northern reach of the Outer Banks barrier island complex.

4) Verify the associations among particular grain size distributions and depositional processes across the beach profile

5) Verify and map the possible existence of lateral gradients in sediment groups along the study area.

2. RELATED PRIOR RESEARCH

Geologists for many years have been interested in extracting environmental information from the grain-size analysis of sediments. The use of statistical parameters to distinguish between sedimentary environments is discussed frequently in the literature with differing conclusions about the sensitivity of this method in discriminating them.

According to Komar (1976), three main factors control the mean grain size distribution of beach sediments: the sediment source, the wave energy level, and the general offshore slope on which the beach is constructed. Particularly for the foreshore, it is generally true that the particle size is larger where the wave energy is greater. According to King (1961), this relationship applies both in space and time.

Seasonal variations in sand-size across the profile has been demonstrated by Trask and Johnson (1955). At any time, they found finer sand on the upper foreshore, with coarse sand on the lower foreshore and on the crest of the berm.

Fox et al. (1966) have examined the variation in sediment grain-size parameters along a 100 meter profile normal to the shore in the non tidal region of South Have, Michigan. The main sediment modes are a medium sand and a very coarse sand to gravel. The profile covers the backshore, berm, foreshore, plunge point (step), nearshore zone and an offshore bar. According to the results, a close parallelism exists among the mean, standard deviation, skewness and kurtosis. According to Fox et al. (1966) between the backshore and the berm the mean grain size is fine and remains fairly constant. Moving down the foreshore, the mean grain size increases and attains its maximum value on the step at the base of the beach face. In the nearshore zone, between the step and the offshore bar, the mean grain size decreases again, but is slightly coarser than the values for the backshore. On the offshore bar, the mean size increases. The finest material is found seaward of the offshore bar. Although mean grain size and standard deviation are theoretically independent, the sorting is comparable; the poorest sorting is at the step and on the offshore bar. The skewness is negative throughout the profile, with the exception of the samples located at the step. Small values of kurtosis are located at the step and the offshore bar. Given these observations, Fox et al. (1966) related grain size variations to the changes in energy conditions across the profile. The incoming waves first break on the offshore bar, however, the dissipation and concentration of energy is not very intense. Most of the energy dissipates at the plunge point at the base of the beach face. The grain-size distribution reflects the energy level in each zone. The intensity of the swash decreases up the foreshore and is reflected in the decrease in grain-size. The sediment sorting is poorest at the step and over the offshore bar, since at these locations the sediment consists of mixture of medium sand and very coarse sand granules.

Similar distributions of mean grain-size normal to the beach have been found in other areas. Bascom (1951) identified the berm as the next zone of the beach profile to have coarse grains after the step. He hypothesized that the coarse deposit associated with the berm was deposited by maximum wave runup.

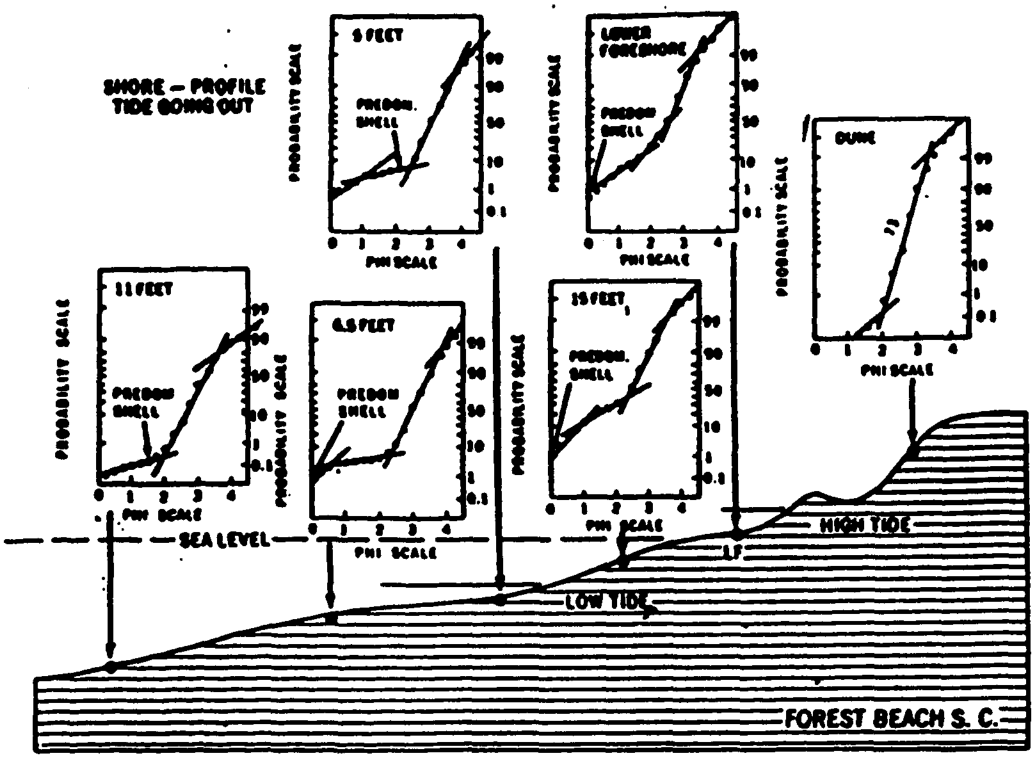
Greenwood (1969) used discriminant analysis in such a way that all the grain-size statistical parameters can be used simultaneously to distinguish among dune, backshore and foreshore sands. The most important variables were the skewness, followed in order by the mean grain size, standard deviation and kurtosis. Foreshore sands showed a larger mean size than the backshore and dune and had a tendency to be more poorly sorted. Wave deposited sediments exhibited marked negative skewness, whereas aeolian sediments have near symmetrical size-frequency curves with both, negative and positive skewness. The results obtained, as well as the proposed mechanisms, support previous work on unimodal beaches (Friedman, 1961; Mason and Folk, 1958; Duane, 1964;).

Miller and Zeigler (1958), based on considerations of the "null point" theory, presented a model for the expected patterns of sediment-size and sorting in the nearshore, breaker zone and beach foreshore. Comparisons with detailed observations and previously published sediment size and sorting patterns were in agreement with the model. The trend map for median grain size presents evidence of coarse material in the breaker zone (step) and fine material both onshore and offshore. The trend map for sorting showed the poorest sorting located at the step. Away from this zone, this parameter improves reaching maximum values at the extreme ends of the study area (i.e. top of the foreshore and the beginning of the wave shoaling zone). According to Miller and Zeigler (1958), the composite trend map model is valid for a sediment dispersal system in a state of equilibrium. Departure from the equilibrium state such as an accreting or eroding beach should be reflected in a departure of the model.

Schifmann's (1965) studies relating energy and sediment data in the swash-surf zone, demonstrated changes across these areas. The velocity and grain-size distributions along with the corresponding energy patterns typically display three definitive zones: (1) the swash, (2) the surf, and (3) a transition zone separating the two. This transition zone is characterized by the area where the return backwash collides with the base of the next incoming surf bore. It is typified by a markedly bimodal surface sand distribution and a broad velocity spectrum. According to Schifmann (1965), shoreward and seaward of the transition zone, both velocity and grain size distributions are essentially Gaussian, implying that a single regime is active in each zone. Visher (1969) conducted extensive textural studies of both modern and ancient sands in several different environments around the United States. Using log probability paper and the early concepts of sediment dynamics Visher found that size distributions are composed of several log-normal subpopulations. Assuming that each transportation process (i.e.rolling, saltation and suspension) is reflected in a single grain-size distribution, the proportions of each population should be related to the relative importance of the corresponding process in the generation of the whole distribution. Samples collected along normal beach and nearshore profiles, showed that there were several different fundamental log-probability curve shapes (**Figure** 2). According to the curve shape, beach, aeolian, wave action and breaking waves processes were identified. Although differences occur in the log probability plots of foreshore samples, all of them show a common characteristic; the presence of a double saltation population. The differences can be easily understood on the basis of different sample locations and position within the beachface (lower, middle or upper foreshore). The occurrence of two saltation populations with a high degree of sorting was attributed to the different transport processes associated with the swash and backwash which produces two separate saltation populations one for each flow direction on the foreshore.

Wave tank experiments conducted by Kolmer (1973) also showed the presence of two saltation populations on the foreshore of a model beach. He demonstrated that individual swash and backwash distributions showed no saltation break. However, when the swash and backwash distributions were mixed, the saltation break was formed. The two separate saltation population are assumed to be produced by the swash and backwash, since these represent to some extent different flow conditions. Kolmer concluded that the saltation break is due to the influence of the swash-backwash action of the waves forming different grain-size distributions due to two different modes of sediment transport and deposition. A single saltation population appears in all the dune samples and according to Visher (1969), it represents nearly 98 per cent of the distribution. The high degree of sorting is characterized by the slope of the curve, and overall is better sorted than foreshore samples. The percent of the traction population was very small,

Figure 2. Changes in the subpopulations within the grain-size distributions across the beach. From Visher, (1969)


SHORE – PROFILE
TIDE GOING OUT
5 FEET
PREDOM. SHELL
LOWER FORESHORE
PREDOM. SHELL
DUNE
11 FEET
PREDOM. SHELL
6.5 FEET
PREDOM. SHELL
15 FEET
PREDOM. SHELL
PROBABILITY SCALE
PHI SCALE
0 1 2 3 4
99 90 50 10 1 0.1
SEA LEVEL
HIGH TIDE
LOW TIDE
LF
FOREST BEACH S. C.

always less than 2 per cent. The occurrence of a suspension population and the truncation of the coarse population gives a positive skewness.

According to Visher (1969), marine sands from wave zones show three well developed populations. The main characteristics of these curves are: a poorly sorted coarse rolling population, a very well sorted saltation population and a variable percentage of the suspension population.

Surf zone deposits are characterized by relatively high percentages of material in the coarse rolling population (Visher, 1969). This population appears to be more poorly sorted than the rolling population present in foreshore sands. Mixing occurs between the saltation and the rolling populations and the fine end of the saltation population is truncated. These characteristics are inherited from surf zone processes where breaking waves and the consequent energy dissipation associated with other factors generate strong currents. The suspended material is carried out of the breaker zone. Mixing between the saltation and rolling population occurs as the breaker position changes.

An important result of Visher's approach is that log probability plots of ancient sands are directly comparable to those of modern sands. However, according Visher (1969), this approach is empirical and is not based on quantitative hydraulic studies. The textural criteria should properly be considered an additional set of criteria to be used in conjunction with many others.

Stapor and Tanner (1975) applied step discriminant analysis to grain size statistical parameters in an attempt to differentiate among beach, beach ridge and dune sands from the Apalachicola region in Florida. They were able to differentiate four major regions: surf zone, upper beach, beach ridge and coastal dunes. Skewness and standard deviation were the most important parameters in the discriminant analysis. The other parameters (mean grain size and kurtosis) were of minimum importance for determining hydrodynamic conditions of transport and deposition in a regional study. As these samples came from one reasonably restricted geographic area and contain sand which ranges in size from 0.5 to 0.125 mm. they assumed that the important roles of skewness and standard deviation have some hydrodynamic significance. In order to study the physical meaning, they examined individual grain-size probability plots. The four categories previously discriminated by Stapor and Tanner (1975) produced probability plots having different appearances. Plots of the surf-zone consist of three parts: a coarse fraction, a middle fraction, and a tail of fines (less than 1 per cent). The coarse fraction had poorer sorting than the middle fraction. The two dominant fractions were separated by a distinct "surf break" not far from the 50th percentile. The foreshore (upper beach) and the beach ridge, although distinct on the basis of statistical parameters, had the same appearance. Both have three parts being the sorting of the coarse fraction slightly better than the coarse fraction of the surf zone and with the "surf break" closer to the coarse end of the distribution. In addition to a "surf break" closer to the coarse end, the coarse portion of the dune plot showed a typical convexity toward the coarse end of the size scale near the middle of the curve. The most important conclusion about the plots is that they represent a progression as sand is transferred from one environment to another, (i.e. from the surf zone landward to the dunes).

Nordstrom (1977) studied foreshore sediments of four beaches subjected to different wave regimes. He found that despite the seasonal variations in energy there was a great similarity in the means of the grain-size statistics. Nordstrom attributed this to the similarity of the source sediment and the similarity of foreshore processes.

Sonu (1972) showed that sediments deposited on a continuously changing subaerial beach composed of a mixture of sand and gravel exhibit variations in size distributions ranging from unimodal coarse through bimodal intermediate to unimodal fine. According to his studies, the shift among these ranges coincides with the progression of a beach cycle where the eroding post storm profile recovers to a fully accretionary state.

Moustafa (1988) conducted experiments in order to detect spatial and temporal variations in grain-size distributions across the foreshore of a bimodal beach composed of sand and gravel. The experiments were carried out under different wave energy conditions and under opposite stages of the lunar tide (spring-neap). She was able to identify four groups of sediments corresponding to distinct zones on the foreshore. According to the study, this textural zonation is controlled by the stage of the tide, and by the dominance of transport processes acting selectively on certain grain sizes.

Comparative size analysis of foreshore, berm and dune sediments located between Cape Henry, Virginia and Cape Hatteras, North Carolina, (Shideler, 1973a) indicated statistically significant textural differences between the three genetic populations, as well as the presence of component sub-populations. The sediment characteristics supported the proposed conceptual process-response model of a barrier sediment transverse transport system along the Middle Atlantic Bight. In accordance with this model, the general textural differentiation of genetic populations indicate that this transverse transport system is dominated by the sequential evolutionary processes associated with fair weather conditions; whereas, the textural responses resulting from storm mixing (washover fans) are largely ephemeral, and promptly canceled. According to Shideler (1973a), the beach face population is generated largely through aqueous processes associated with the normal swash-backwash regime, with only minor influence due to aeolian processes; whereas, the berm population is generated by high water swash-backwash regimes, and is largely modified by subsequent aeolian processes. The dune population is generated entirely by the aeolian regime, and represents a clastic filtrate derived from adjacent berm and aeolian flat deposits.

Comparative polynomial trend analyses of textural parameters using the same data set (Shideler 1973 b) showed that systematic textural patterns exhibited by the barrier sediments consist of both regional trends and local cyclicity. Regional trends exhibited by central tendency measures in both the foreshore and berm populations, reflect a progressive southerly increase in average wave energy toward Cape Hatteras due to the regional wave refraction patterns established by the shoreface morphology, and the continuous reduction in shelf width to the south. The wave length of the local cyclicity, especially along the foreshore, appears to be established by the spatial distribution of source material along the barrier shoreface which is being excavated from a heterogeneous Pleistocene substrate.

3. DESCRIPTION OF THE STUDY AREA

3.1 Physiography

The study area is located between Whalehead beach and Oregon Inlet (**Figure 1**) and is geographically known as Currituck Spit. This spit is part of the well-developed North Carolina barrier island system, the Outer Banks.

Association between shoreline configuration and continental shelf width contributes to the highest wave energy climate (1.5 m average wave height) found on a barrier coastline of the Eastern United States (Moslow and Heron 1989) providing a good example of a wave-dominated barrier island chain.

Currituck Spit is separated from the mainland by a large lagoonal system consisting of Pamlico and Albemarle Sounds. The latter incorporates a northern extension, Currituck Sound, which ends in the vicinity of the Virginia/North Carolina State line. The length of the study area is 50 nautical miles (84 km) and varies in width from 0.3 nautical mile (0.59 Km) at the northern portion to a maximum of 2.8 nautical miles (5.24 Km) in the southern half of the spit. The barrier is characterized by well-developed beach, dunes and aeolian-flats. According to Fisher (1967) most of the barrier is formed by aeolian flats which are frequently surmounted by sets of relict beach ridges.

Beaches located between Corolla and Oregon Inlet show variable width. At the two extreme ends of the study area, beaches are broad and flat. In between, especially near Duck, beaches are narrow and steep. Long-term morphologic changes display a seasonal cycle. The most dramatic changes are associated with storm events. **Figure** 3, illustrates beach morphology changes as represented by three dimensional plots at Whalehead and Duck Beach corresponding to data obtained from pre and post-storm events which occurred in October of 1986. Strong northeast winds generated by a Canadian high pressure system affected the region early on October 10. Winds reached 15 m/s and blew over 10 m/s for 41 consecutive hours producing a storm surge of about 0.5 m. Wave height measured from a wave rider gage located 1 km from the shore was 3.25 m with a period of 8.71 sec (U..S. Army Corps of Engineers, 1986). This particular storm shows extreme changes associated with the subaerial beach at Whalehead. At Duck, changes were predominantly associated with the subaqueous beach.

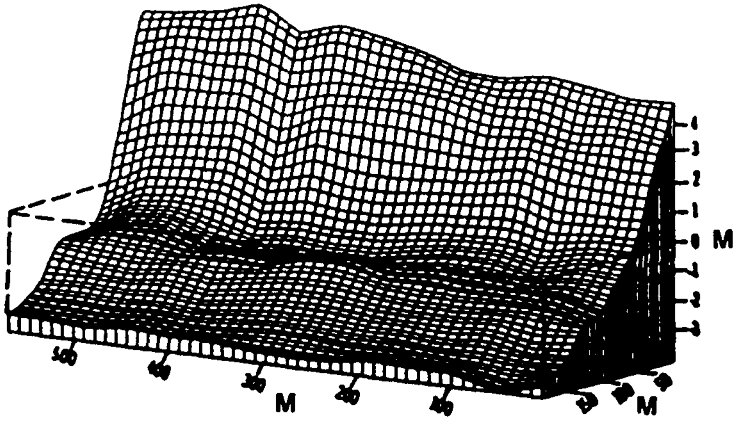
A three-year beach and nearshore profile data set from the beach located adjacent to the Duck research pier was analysed by Birkemeier (1984) using empirical eigenfunction analysis. Birkemeier identified a seasonal offshore transport of sand from the beach to the inner bar during winter, and a gradual return of sediment to the beach face during the summer.

According to the classification scheme proposed by Wright et al. (1984) and Wright et al. (1985) beaches along the North Carolina coastline oscillate between the "longshore bar trough" and the "rhythmic bar and beach" states. According to their results, the greatest changes associated with these states are related to the bar crest position and trough width. Data obtained by Mason et al. (1984) and Sallenger et al.(1985) at Duck, N.C. indicate that while the bar migrates over horizontal distances of approximately 200 m, the beach face advances and retreats across a zone only about 20 m wide. According to Wright et al. (1986) the low mobility of the foreshore is probably due to the filtering effect of the bar and trough system preventing a large fluctuation in breaker height, and to the role of standing waves in the trough providing a barrier to cross-shore sediment exchange.

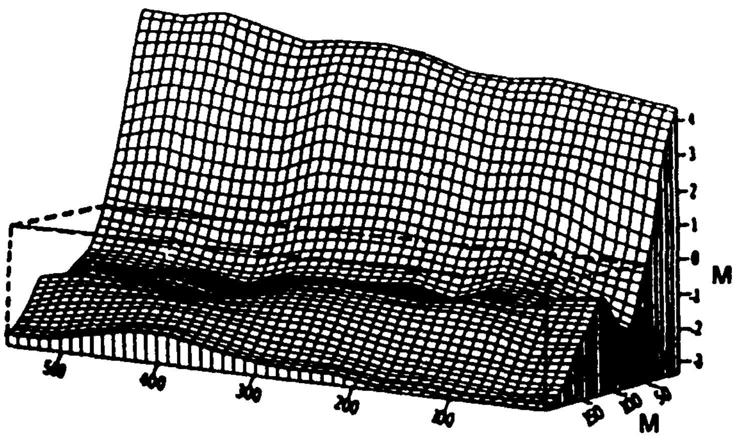
The morphologic complexity of the shoreface and inner shelf is the result of several episodes of transgressions and regressions generated by glacial and post-glacial changes in sea level. According to Swift (1972), the actual morphology is defined as a "palimpsest" surface, where the inherited features have been partially modified by actual shelf hydrodynamic processes. Shoals and ridges are common features on the inner shelf. Recent studies indicate that many of these shoal areas are comprised of a discontinuous accretionary sand sheet which has been molded into a ridge and swale topography by the Holocene hydraulic regime (Swift et al. 1972). **Figure 4**, which depicts the shoreface and part of the inner shelf between Corolla and Duck, illustrates this morphology. As Wright et al. (1987) point out, these offshore shoals sometimes merge with the nearshore bar system and become shoreface connected. This fact accounts for the wider shoreface near Whalehead relative to Duck.

Figure 3. Three-dimentional beach changes related with storm events. Duck beach picture is based on 13 profiles, spaced 45 m apart, obtained by the FRF at Duck, N.C. Whalehead picture is based on 4 profiles with the same spacing.

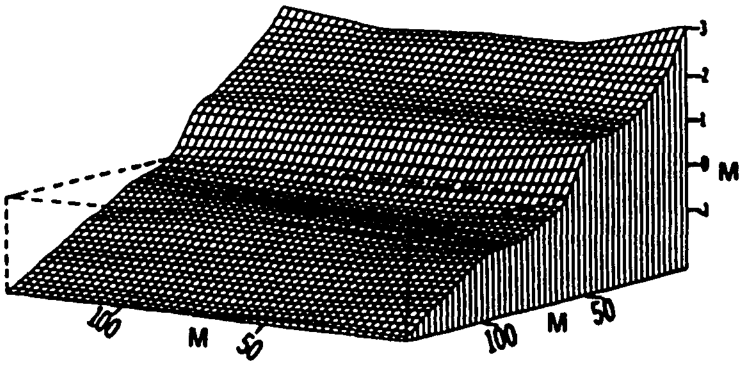
DUCK BEACH OCT 06 86



DUCK BEACH OCT. 13 86



WHALE HEAD BEACH OCT 05 86



WHALE HEAD BEACH OCT 13 86

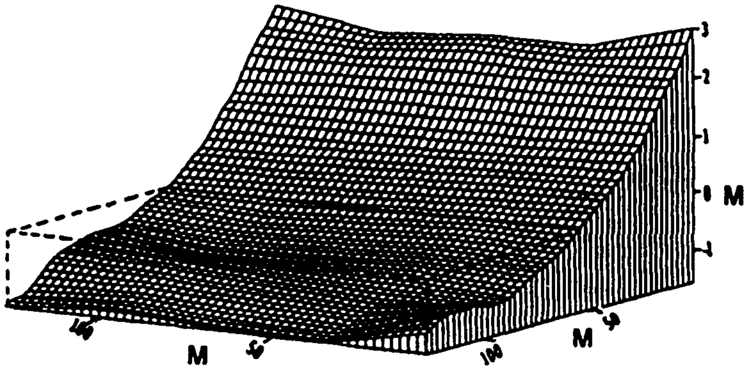
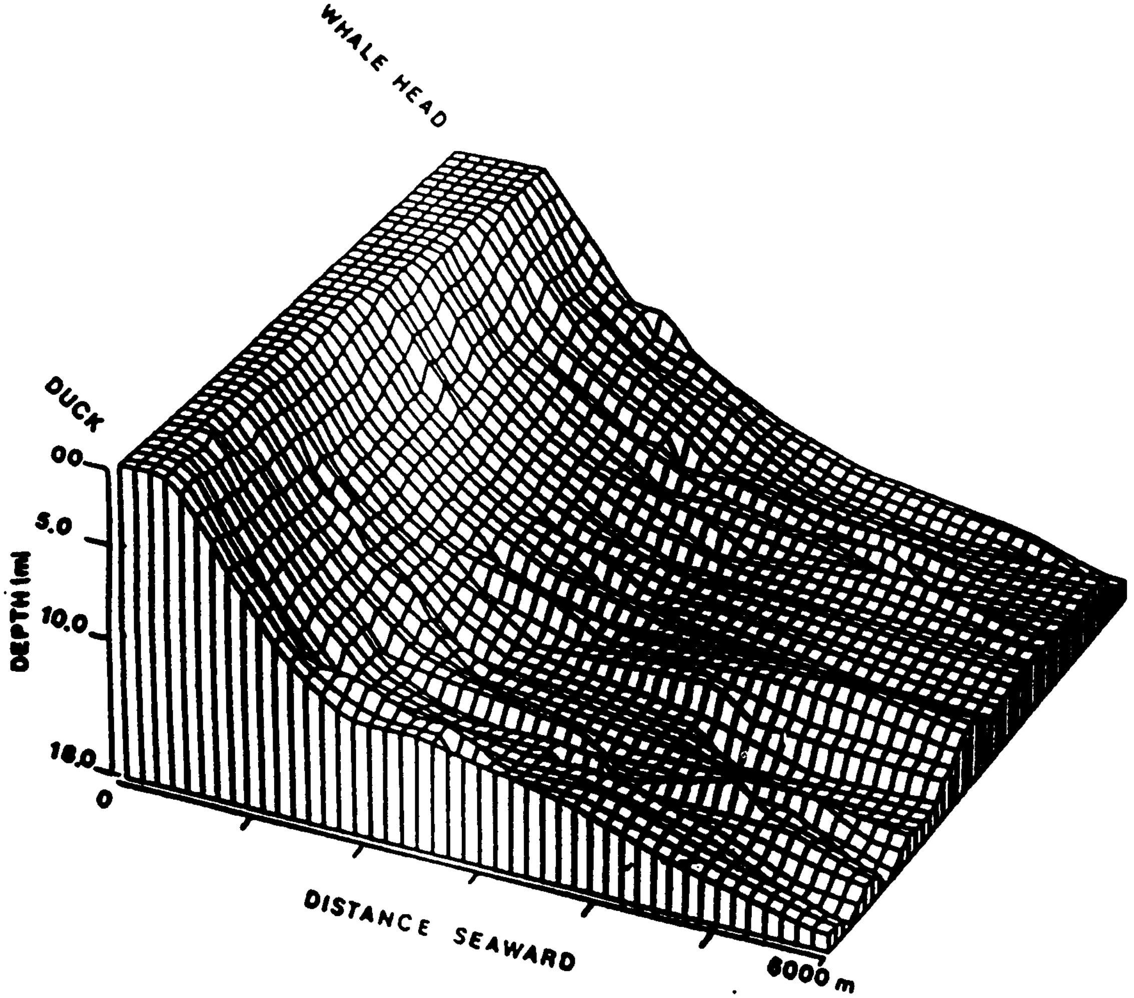


Figure 4. Shoreface morphology between Whalehead and Duck beach.


WHALE HEAD
DUCK
00
5.0
10.0
18.0
DEPTH (m)
0
DISTANCE SEAWARD
6000 m

3.2 Barrier source materials

The outer banks barrier appears to have sediments derived from multiple sources. Grain-size and mineralogical composition studies by Swift (1969) indicate that sediments are primarily derived through coastal erosion of a Pleistocene substrate, with sediments being provided vertically by cross-shore retreat of the shoreface and laterally by longshore drift from eroding headlands. The Pleistocene section has been described as a heterogeneous assemblage comprised of fluvial, paralic and neritic lithosomes (Shideler and Swift, 1972). More recent studies (Meisburger and Williams, 1987) show that the Quaternary section is composed of four lithologic units having fairly distinct seismic signatures, mineralogy and faunal compositions.

The coarse grain-size anomaly near Duck has been attributed to a local source of gravel and sand excavated from the relic Albermarle river channel, (Swift 1971).

3.3 Aeolian Regime

Between Cape Henry and Cape Hatteras, the aeolian regime is highly variable both in velocity and direction. The dominant wind direction along the barrier is largely offshore from the south to southwest with mean annual velocities increasing southward from 17.6 Km/h at Cape Henry to 23 Km/h at Cape Hatteras (Shideler,1973 b). However, the strongest and most effective winds in transporting sand are onshore winds from the Northeast. Base on a three year observation period, Birkmeier et al. (1981) found that winds predominate from the southwest in the summer and from the northeast during winter months. The strongest winds are associated with the passage of extratropical cyclones called "northeasters".

3.4 Wave and tide regime

Shideler (1973 b) postulated that the wave regime in the area should be largely controlled by both the shelf width and topography. Therefore, he predicted an increase in wave height towards the south from Cape Henry to Cape Hatteras as a result of the progressive decline in wave energy dissipation.

Although the inference above is based on visual field observations, as well as a few in-situ measurements, more advanced studies done by Wright et al. (1987) show similar along-coast variability in wave height due to changes in shelf width.

According to Birkemeier et al. (1981), the most frequent incident waves entering the shallow water region are from the east-northeast and northeast. Northeasterly waves are generally the largest and are associated with the storm season (fall and winter). Wave height tends to be lowest from April to September (summer).

Based on data from a wave rider located at 17 m depth offshore at Duck, N.C., Birkemeier et al. (1981) found that the annual average significant wave height is 0.88 m with a period of 8.9 seconds. However, extreme waves from storms occurring between October and February can exceed 4 m in height.

The tides along the Outer Banks are semidiurnal with two nearly equal highs and lows each day. The spring range in the ocean tide averages about 1 m (Birkemeier et al. 1985).

4. METHODOLOGY AND DATA ANALYSIS

4.1 Introduction to Factor Analysis

Factor Analysis consists of a wide range of mathematical techniques based on linear algebra which is very useful for studying large sets of multivariate data. This technique theoretically can take thousands of measurements and qualitative observations and resolve them into distinct patterns of occurrence (Rummel, 1970).

Factor methods all operate by extracting the eigenvalues and eigenvectors from a square matrix generated by multiplying a data matrix by its transpose (Davis, 1986).

Applied to geological science, especially sedimentology, factor analysis is a process of grouping empirical data into significant "factors" which can be interpreted in their geological context. An example of factor analysis would be a study which includes a large data set consisting of a series of measurable parameters such as : The percentage of elements in a rock sample. After the analysis, for instance, one factor could consist of those samples having a specific combination of elements. Another "factor" could be characterized by those samples displaying another combination. Between these two end-member extremes, samples would represent proportional mixtures of these two basic factors or rock types. The analysis also determines the "amount" of each factor present in a sample, since samples are usually considered to be a mixture of different factors, with one frequently dominant. From this, a factor map can be constructed and environmental signals can be identified. Since the variables chosen in the example above can be further subdivided into other variables (i.e. phi classes, heavy minerals species and degrees of roundness and sphericity), the method has a high potential for sedimentological studies.

The above example mentioned exemplifies the Q-mode factor analysis method where, according to Davis (1986), the interrelationship between objects in a factor space is explored. Q-mode analysis is particularly applicable to variables representing compositional data where the variables of each object in the row of the raw data matrix sums to one hundred. Most Q-mode analyses proceed by extracting eigenvalues and eigenvectors from a matrix of similarities between all possible pairs of objects. Because Q-mode methods focus on the similarities between individuals in the data set, and not the relationship between variables they are not usually amenable to statistical analysis (Davis, 1986).

Another type of factor analysis, known as R-mode, is concerned with the interrelationship between variables, and is used to group measured attributes of a series of samples into associated factors having the same response to an environmental influence. An example of R-mode factor analysis would be to analyze different phi size classes. In this study, the weight of sediments in each each phi class are considered the variables. The analysis determines the factor groupings of the different phi classes in order to establish the exact size limits and relationships between sediment population (Allen et al. 1971).

According to Davis (1973), R-mode techniques are statistical procedures in the sense that the data are regarded as samples taken from a much larger population, and the results pertain to the general properties or behavior of the variables. R-mode operates by extracting eigenvalues and eigenvectors from a variance/covariance or correlation matrix.

Figure 5 summarizes the Q-mode factor analysis method as applied to grain-size distributions. From the samples collected and the study objectives, one can decide which of the two methods would be best to use. Either one will reduce the dimensionality of the original data and both present several advantages:

- The large amount of information is condensed into a small number of independent representative factors.

- The method will objectively group similar samples or variables which have the same behavior.

- The relative importance of each factor will be determined and an order among the possible causes of the observed phenomenon will be established.

(In **Figure** 5, factor I is most important as it regroups 60% of the initial information; factor II regroups only 30% and factor III is less important because it only regroups 10%)

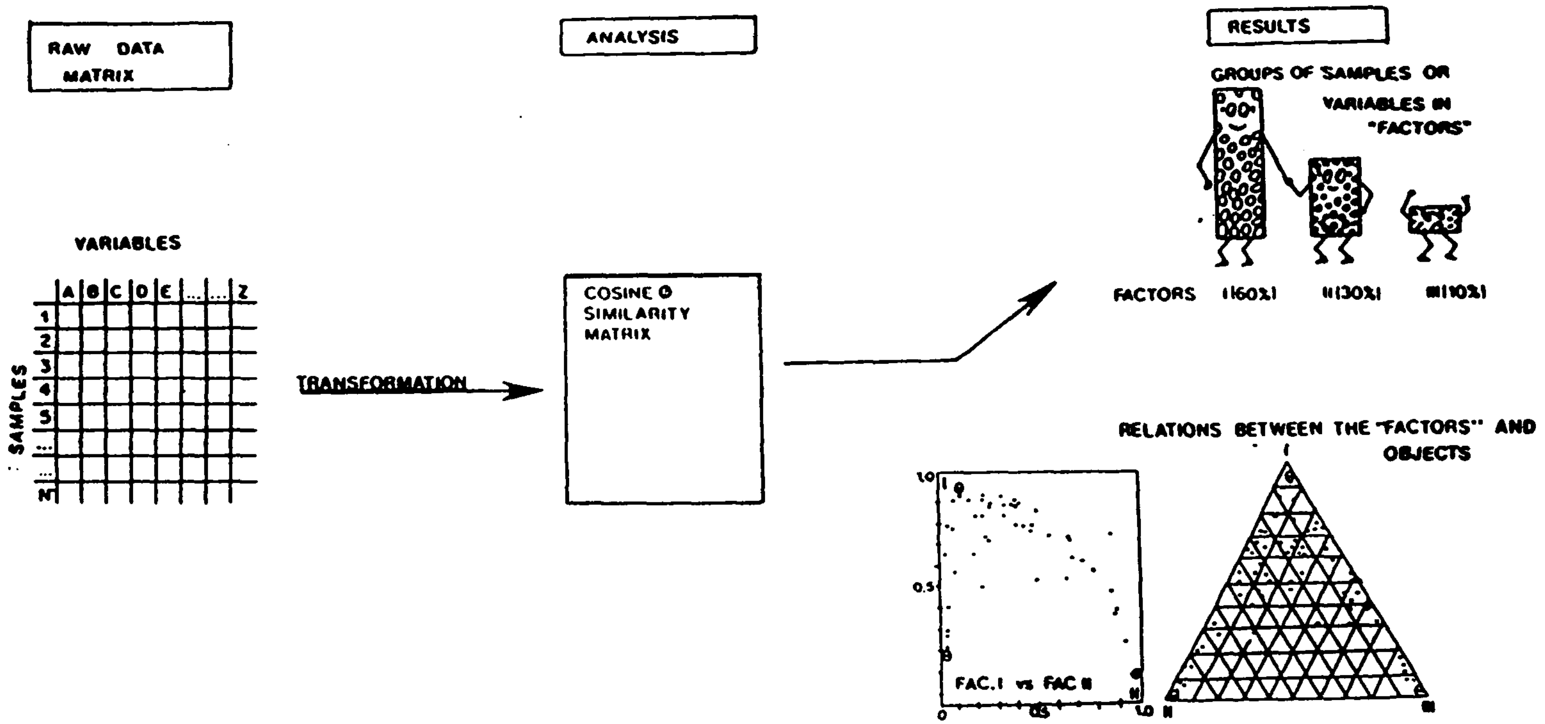
- the relationship between objects and factors which are composed of variable combinations is demonstrated.

- The "end-members" samples which represent the compositional extremes of the data set will be identified.

In **Figure** 5, the first plot (fac I vs fac II) displays the relationship of sediment samples according to the entire spectrum of their grain-size distribution. Each factor axis can be considered as a hypothetical linearly independent object which is totally dissimilar from any axis to which it is orthogonal. Samples with the highest relationship to a factor have a loading near 1.0 on an axis, while samples with little or no relationship to a factor display low loading values (near zero). Samples located midway between the two factor axes are equally influenced by them.

Another way to display the same data is using a triangular diagram. Samples occurring nearest the corner of the ternary diagram are "end-members". All other points can be considered mixtures of these three. The diagram indicates that some type of mixtures are common, while others never occur. By plotting the end-members according to their location on a map, we can draw inferences about energy conditions at the time of deposition. Based on these inferences, sedimentary environments can be better understood.

Figure 5. Cartoon representing Q-mode factor analysis. Modified from Castaing (1973).


RAW DATA MATRIX
ANALYSIS
RESULTS
VARIABLES
SAMPLES
A
B
C
D
E
...
...
Z
1
2
3
4
5
...
...
N
TRANSFORMATION
COSINE Θ SIMILARITY MATRIX
GROUPS OF SAMPLES OR VARIABLES IN "FACTORS"
FACTORS
I(60%)
II(30%)
III(10%)
RELATIONS BETWEEN THE "FACTORS" AND OBJECTS
1.0
0.5
0
0.5
1.0
FAC. I vs FAC II
I
II
III

4.2 Factor Analysis Applied to Grain-size data

Factor analysis has proved its value in a series of sedimentary petrology studies such as, heavy mineral distribution and provenance (Imbrie and Van Handel, 1964; Firek et al., 1975; Berquist, 1986; Clemens and Komar, 1988), evaluation of faunal assemblages and their ecological controls (Allen and Pujos-Lamy, 1970; Prasda Rao et al. 1973) and in the recognition and analysis of depositional facies (Imbrie and Purdy, 1962; Klovan, 1966; Solohub and Klovan, 1970; Allen and Klingebiel, 1972). This method had also been applied with success in geochemistry (Allen et al. 1970) and stratigraphy (Visher, 1965).

This section includes a review of the known references related to factor analysis applied to size-frequency distribution of terrigenous sediments.

In order to determine the hydrodynamic processes of transport in fluvial environments, Visher (1965) applied Q-mode factor analysis to ancient (Pennsylvanian fluvial sands from the Missourian of central Oklahoma) and recent (Arkansas River and the Brazos River) fluvial deposits. The data consisted of eleven variables recorded from each probability plot and include : the 1, 5, 50 and 95 percentiles, the Folk and Ward (1957) values of mean, sorting and skewness, the grain-size at the inflection point, the angle between curve segments, and a measure of intermixing of the two populations.

The factor analysis applied by Visher (1965) defined four unique classes of grain-size distributions curves each related to a different sedimentary structure: Class A- cross-bedding, Class B- current lamination, Class C- small scale cross-bedding, Class D- small scale cross lamination with climbing ripples. Inter-gradation exists between classes A-B-D and A-C-D. However, B-C and A-D are always strongly separated. Visher (1965) suggested that classes B and C are products of different flow regimes. The transition between A to C was considered to represent a decrease in turbulence and may be related to the upper and lower portion of the lower flow regime. The transition from A to B represents a decrease in energy and may be related to the upper flow regime. Class D represents the "suspension" population and is differentiated by the presence of only one population.

Klovan (1966) and Solohub and Klovan (1970) applied Q-mode factor analysis to raw-grain size data in order to determine the hydraulic regime in Barataria Bay, Louisiana and Lake Winnipeg, Canada. In both cases, three factors accounted for more than 95% of the information in the original data. Both researchers used a three-component diagram to display the trends. According to the authors, the results do not enable them to classify environments of deposition in a physiographic sense; however, the fact that the samples are classified on the basis of mean grain size shows that the resulting factors represent the energetic conditions at the depositional site. Thus factors I, II and III correspond respectively to medium, low and high energy conditions. Based on this approach, Klovan (1966) hypothesizes that three fundamental processes sufficiently explain the grain-size distribution of sediments in Barataria Bay: current action, gravitational settling and wind wave action.

The position a sample occupies in the three-component diagram appears to be characteristic of the spectrum of energy at the sample locality. The study of Lake Winnipeg sediments, also showed that the three factors representing processes are not restricted to specific environments; however, the pattern produced by them correspond to a large degree with the distribution of the environments (beach, aeolian, off-beach, channel and lake delta).

Davis (1970), applying principal component analysis (PCA) to the same data set used by Klovan (1966), showed that PCA is as efficient as the standard statistical parameters(mean, mode, standard deviation, skewness and kurtosis) for separating sediment types. However, considerably less effort is necessary when PCA is applied.

Allen et al. (1972) applied R-mode factor analysis on grain-size samples of 100 sediment samples from the Gironde Estuary, France, in order to group sieved grain size classes (taken as variables) into dynamically significant factors. They found that three factor groupings were sufficient to explain 73 percent of the grain-size variation in the data set. By comparing the different grain size groups with various grain-size interpretation methods (especially Visher's method), they identified the following distinct transport mechanisms: uniform suspension, graded suspension, graded suspension plus bed load and "pure" bed load.

Castaign et al. (1972) applied Q-mode factor analysis on the grain-size data of 116 surficial samples from the continental shelf adjacent to Bordeaux, France. Three principal factors corresponding to three different lithologic units were found. By plotting the samples in a triangular diagram according Klovan's technique, they noted that most of the points were concentrated at the apex. However, the fine sands were located both at the apex and along the side of the diagram. Based on the facies map, two fine sand zones corresponding to coastal and offshore sands were identified. Coastal sands were located at the apex while offshore sands were distributed along the sides of the triangle. This fact, in conjunction with other studies of the same area, lead them to differentiate the fine sand into modern (coastal) and "palimpsest" (offshore) facies.

Stubblefield et al. (1975) applied Q-mode factor analysis to 191 grab samples collected along the ridge and swale topography on the central New Jersey shelf. The analysis produced three distinct groupings of the grain-size distribution. Each group was found to characterize a particular part of the ridge topography. The flanks are composed of fine, moderately sorted sands. Medium to fine sand with moderate sorting occurs on the crest. The troughs are characterized by two populations; coarse, poorly sorted sands and fine, very well sorted sands.

According to Stubblefield et al., this grain-size variation supports a hypothesis of up-flank flow and suspension transport of medium sand during severe storms and subsequent down-flank winnowing of fine sand during less intense hydrodynamic conditions.

Beall (1970) applied Q-mode factor analysis to 93 fine-sand (median between 2-3 phi) samples from the Colorado River Deltaic complex using weight percentages calculated at 0.25 phi intervals as variables. Comparing the groups obtained by factor analysis with conventionally derived measures of median, sorting, skewness and kurtosis allowed him to explain the overlap between the fluvial, beach and deltaic environments and verify the existence of a relationship between textural groups and environmental settings within these major environments.

Dalcin (1976) employed Q-mode factor analysis on both grain-size data and statistical parameters on 179 foreshore beach samples in order to distinguish between receding and advancing beaches. He found that four factors ranging from fine to coarse sand accounted for 95.7% of the variance in the data set. Using various comparisons between the four factors he was able to distinguish receding from advancing beaches. Advancing beaches were rich in fine and medium-fine sands; receding beaches were rich in medium-coarse and medium sands. According to Dalcin (1976) this was caused by differences in energy level and the varying sediment supply on the two types of beaches. The best results were obtained through factor analysis of grain-size data because it contains the maximum information needed. If only the statistical parameters are used, an important part of the information is lost.

Moustafa (1988) found that it is possible to distinguish between grain-size populations from the swash zone using Q-mode factor analysis. Her studies also show that textural characteristics across the beach face vary with the tidally induced movement of the swash zone. Therefore, it becomes possible to predict the manner in which foreshore sediments will respond to the position of the swash on the beach face.

4.3.Explanation of Q-mode factor analysis

4.3.1 Introduction

Q-mode is a type of factor analysis extremely useful for analyzing closed data sets, i.e., where the row-sums of the data matrix are constant across all rows. The close data set, also called "compositional data", provides a series of advantages that can be applied to factor analysis. The Q-mode method: 1) identifies the samples represented in the data set that are of extreme composition and describes the rest of the objects as percentages of these "end members" whose composition is expressed as factor scores; 2) allows the development of a factor model that can be used to reproduce the original data in units of proportions or percent. These advantages result from the fact that the constant sum (generally 100% in the case of Q-mode applied to grain-size data) provides a means for scaling the sample vectors in the factor solution so the analysis can be expressed in terms of the original units of measurement.

Q-mode factor analysis examines the interobject similarities (or proportional similarities) between sand samples with a grain size distribution divided into classes. If,for example, a sediment sample is sieved into eleven size-class-intervals, the sample can be defined as a vector in eleven-dimensional space whose position is uniquely determined by the amount of sediment in each of the eleven classes. In Q-mode factor analysis, only the proportional similarities due to sample composition are important; not the magnitude; After the position of each sample vector is determined, the angles between each vector and every other vector can be calculated. The cosine of these angles can then represent the degree of proportional similarity between samples. If two sample vectors or objects are colinear, then the angle between them is zero and the cosine will be 1.0. Therefore, the two objects have perfect similarity in terms of their composition. In contrast, if the vectors are 90 degrees apart, the cosine value will be zero indicating total dissimilarity.

4.3.2 The original matrix

In dealing with sediment samples, the original data matrix can be represented as an **nxm** matrix, where **n** is the number of rows (or objects), **m** is the number of columns or variables and **x** designates an element. An individual element in this matrix is denoted by X_{ij} where i is the row position and j is the column position. X_{ij} represents the percent by weight of material in a particular phi class interval of the total sample analysed.

The i_{th} sample is thus represented by a single row in the data matrix $X_{i_1} \ldots\ldots\ldots X_{i_2} \ldots\ldots X_{i_m}$, where m is the total number of phi class intervals. The total number of row samples in the original data matrix is n; thus, the matrix is of order **(nxm)** and is usually designated as [X].

4.3.3. The cosine theta similarity matrix

The first step in Q-mode factor analysis is to determine the matrix of similarity between samples. The most extensively used similarity measure in Q-mode factor analysis is the cosine theta similarity matrix. In order to develop a cosine theta similarity matrix two basic operations are needed. First, the raw data matrix [X], is row normalized. In this process each element in a row of the original data is divided by the square root of the sums of squares for that row. This will produce vectors that are of unit lengths. The operation is obtained by the following equations:

$$W_{ik} = \frac{X_{ik}}{\left(\sum_{k=1}^{m} X_{ik}^2\right)^{1/2}} \qquad (1)$$

where: W = the scale data matrix that has been row-normalized.

i - the ith row

k - sum across the variables from 1 to m (number of phi classes).

The second operation involves developing the major product moment in which the [W] matrix is post multiplied by its transpose [W]'. The major product moment is the cosine theta similarity matrix. The operation is described as;

$$\underset{nxm}{[W]}\ \underset{mxn}{[W]'} = \underset{nxn}{[Q]} \quad \text{or} \qquad (2)$$

$$\cos \theta_{ij} = \sum_{k=1}^{m} W_{ik}W_{jk} \qquad (3)$$

The cosine theta similarity matrix is a square **nxn** symmetric matrix. In this matrix [Q] all the elements along the diagonal will be 1. The "off diagonal" elements will have a value between 0 and 1 and indicate the proportional similarities between the object vectors.

The objective of Q-mode analysis is to explore this object similarity, particularly when the data set is composed of a large number of variables, and to find the most compositionally extreme vectors or end members. These "end members" define a subspace into which all other objects will fit. This subspace defines a "basis" for factor problems the main purpose of which is to define the smallest set of dimensions and then reduce the "dimensionality" of the problem while describing the relationships between sample objects. If we have three compositional extreme sediment samples in a data set, all the other samples can be explained in terms of linear combinations of these extreme end-members.

4.3.4 The factor loading matrix

After the cosine theta similarity matrix is formed, eigenvalues and eigenvectors are extracted from this matrix. The Q-mode factor loading matrix $[A^Q]$ is formed by multiplying each element in the eigenvector matrix $[V]$ by the square root of its corresponding eigenvalue and the singular value matrix. This operation is as follows:

$$[A^Q] = [V]\,[\Lambda] \qquad (4)$$

where:

$[A^Q]$ = Q-mode factor loading matrix

$[V]$ = Eigenvectors of similarity matrix.

$[\Lambda]$ = Diagonal matrix where the singular values are the square root of the eigenvalues.

The factors in this matrix are eigenvectors that are weighted proportionally to the amount of total variance that they represent. Considering the objects as unit-length vectors in variable space, loadings represent the cosine theta projection of each object onto the mutually orthogonal factor axis. Factors may be regarded as a new set of axes to which the data may be related. Loadings can also be used to obtain a percentage of the factor represented by an object.

In the factor loading matrix, columns are factors and rows are samples. Summing the squared elements of each row gives the amount of variance the factors contribute to each sample. This value is called "communality". The communalities will quantify how well the reduced number of factors explain the original variance.

4.3.5 The factor scores matrix

The factor scores matrix $[F^Q]$ is obtained by multiplying the transpose of the scaled data set by its factor loading matrix:

$$[F^Q] = [W]'[A^Q] \qquad (5)$$

where:

$[F^Q]$ - Factor scores matrix

$[W]'$ - Transpose of the row normalized data matrix

$[A^Q]$ - Q-mode factor loading matrix.

The factor scores matrix $[F^Q]$ describes the composition of each factor in terms of the original variables. The most important variables in defining each factor are delineated and allow the factors to be plotted in variable space.

In summary, the row-normalized data matrix is factored into two conformable matrices, $[F^Q]$ and $[A^Q]$, which ultimately reduces the dimensionality of the data. This is done by finding a reduced number of factors that will approximate the original data set. The product of these two matrices, (factor loadings and factor scores) yelds an approximation of the original data matrix; however, the objects are visualized in terms of a reduced number of factors which replace certain variable combinations. Eigenvectors determine the number of factors as the number of independent mutually orthogonal vectors which create a subspace where all the object vectors are included. The number of factors is usually equal to the number of non-zero eigenvalues contained in both the major or minor product moment of the row-normalized data matrix. The number of non-zero eigenvalues in any square matrix is known as the rank of the matrix. Usually, some of the eigenvalues are small and may be neglected; thus, the same data set can be approximated by these factors. The number of factors will be determined by the object communality already mentioned under the factor loading matrix. The communalities describe if the factors are sufficient to "explain" the composition of the objects. The closer to 1.0 the better the explanation will be.

4.3.6. The Q-mode Factor Model

In the Q-mode factor model concept, the row-normalized data matrix can be represented by:

$$[W] \approx [A^Q][F^Q]' + [E] \qquad (6)$$

where:

$[A^Q]$ = Q-mode factor loadings matrix
$[F^Q]'$ = Transpose of the factor scores matrix
$[E]$ = matrix of random error terms

From the Eckart-Young theorem (Joreskog et al., 1976), any real matrix [W] can be expressed as the products of three other matrices:

$$[W] = [V]\ [\Lambda]\ [U]' \qquad (7)$$

where [V] represents the eigenvectors of the major product moment, [Λ] is the singular values matrix and [U]' is the transpose of the eigenvectors of the minor product moment which is obtained when the raw data matrix is pre-multiplied by its transpose. If we post-multiply both sides of equation (7) by [U] we obtain:

$$[W]\ [U] = [V]\ [\Lambda]$$

From equation (4):

$$[A^Q] = [W]\ [U] \qquad (8)$$

Pos-multiplying by [U]' we obtain:

$$[A^Q]\ [U]' = [W]$$

Substituting in equation (6) we obtain: :

$$[A^Q]\ [U]' \approx [A^Q]\ [F^Q]' \qquad (9)$$

and

$$[F^Q] \approx [U] \qquad (10)$$

and then:

$$[A^Q] = [W]\ [F^Q] \qquad (11)$$

This last equation can be used as a powerful tool in sedimentology to map particular textural or mineralogic assemblages based on the factor loadings. Once we obtain the factor scores and the factor loadings matrix of a determined data set, i.e. once the best factor model is chosen, new samples which are not part of the original data set can be mapped into the factor space, provided that the number and type of variables do not change.

4.3.7 Orthogonal rotation

For the most common factor analysis techniques (principal axis) the factor pattern defines decreasing amounts of variation in the data. When the position of the factor axes has been determined using the method of principal axis, each factor may involve all or most of the objects. The objects may therefore have moderate or high loadings for several factors (Rummel, 1966). In fact, the value of the loadings on the same factor flutuates between -1.0 and + 1.0. The best representation or non-representation of one object by a factor occurs when the loading values are close to -1.0 or 1.0 (perfect representation) or 0.0 (non representation). The interpretation is better as the loadings become close to the limit values.

Geometrically, this can be envisioned by placing the factor axis at the center of gravity of the various groups of objects. This is done by rotation of the original orthogonal factor axis.

According to Rummel (1966), when a factor matrix is described as "rotated factors," it means a simple structure rotation. In this "simple structure" each factor has been rotated until it defines a distinct cluster of interrelated objects.

Through this rotation, the factor interpretation shifts from the unrotated factor, delineating the most comprehensive data patterns, to factors delineating the distinct groups of interrelated data. Each object is identified with one or a small proportion of the factors. If the factors are viewed as explanations, causes or underlying influences, this is equivalent to minimizing the number of agents or conditions to account for the variation of distinct groups of objects. Factors rotated to orthogonal simple structure are called orthogonal factors. The particular method used is the Kaiser Varimax rotation (Davis, 1986). Orthogonality is a restriction placed on the single-structure search for groups of interdependent objects. The total set of factors is rotated as a rigid frame, with each factor fixed to the origin at a right angle to every other factor. The factors are rotated around the origin until the system is maximally aligned with the separate groups of objects (Rummel, 1966).

4.3.8 Oblique rotation

Once factor rotation is complete and the most compositionally extreme factors are evident, it is possible to make the factors coincide with the compositional extreme objects. This is called an oblique solution or "oblique simple structure" (Rummel, 1966). In the oblique solution the factors are rotated individually to fit each distinct group. Although the factors in an oblique solution are no longer orthogonal, they coincide with real objects. This is an advantage in some situations where the processed data set can be de-normalized and the factor loadings expressed as true percentages rather than cosine theta values or projections of each object on the factor axis. This technique in factor analysis is called "unmixing". Imbrie's method described in Joreskog et al. (1976) of determining oblique end-members is generally used in order to find the most diverse objects in the data set.

4.4 Pilot study

Introduction

In order to verify the potential of Q-mode factor analysis as a tool for characterizing sediment types across the beach profile, preliminary studies were conducted at the beaches of Whalehead and Duck, North Carolina. Marked differences in grain-size distribution and morphology were the criteria used in the selection of these two particular sites.

4.4.1. Data collection and reduction

4.4.1.1. Beach profiles

Four profile transects spaced 45 m (150 feet) apart were established on both beaches (**Figure 6**). Survey measurements were conducted with an automatic level and stadia rod. Eight temporary benchmarks were established at points located at the dune toe along both beaches. These reference benchmarks were connected by leveling to a fixed vertical datum (National Geodetic Vertical Datum or NGVD). Survey lines moved seaward, approximately normal to the shoreline, along pre-determined azimuths. The azimuth control was maintained by two range poles located at the backshore.

Profile readings were made at every change in slope or every 4.5 to 9 m (15 to 30 feet). Subaerial profile lengths averaged 70 m (207 feet) for Whalehead and 50 m (158 feet) for Duck. The time spent to survey one beach was about one hour (15 minutes for each profile line).

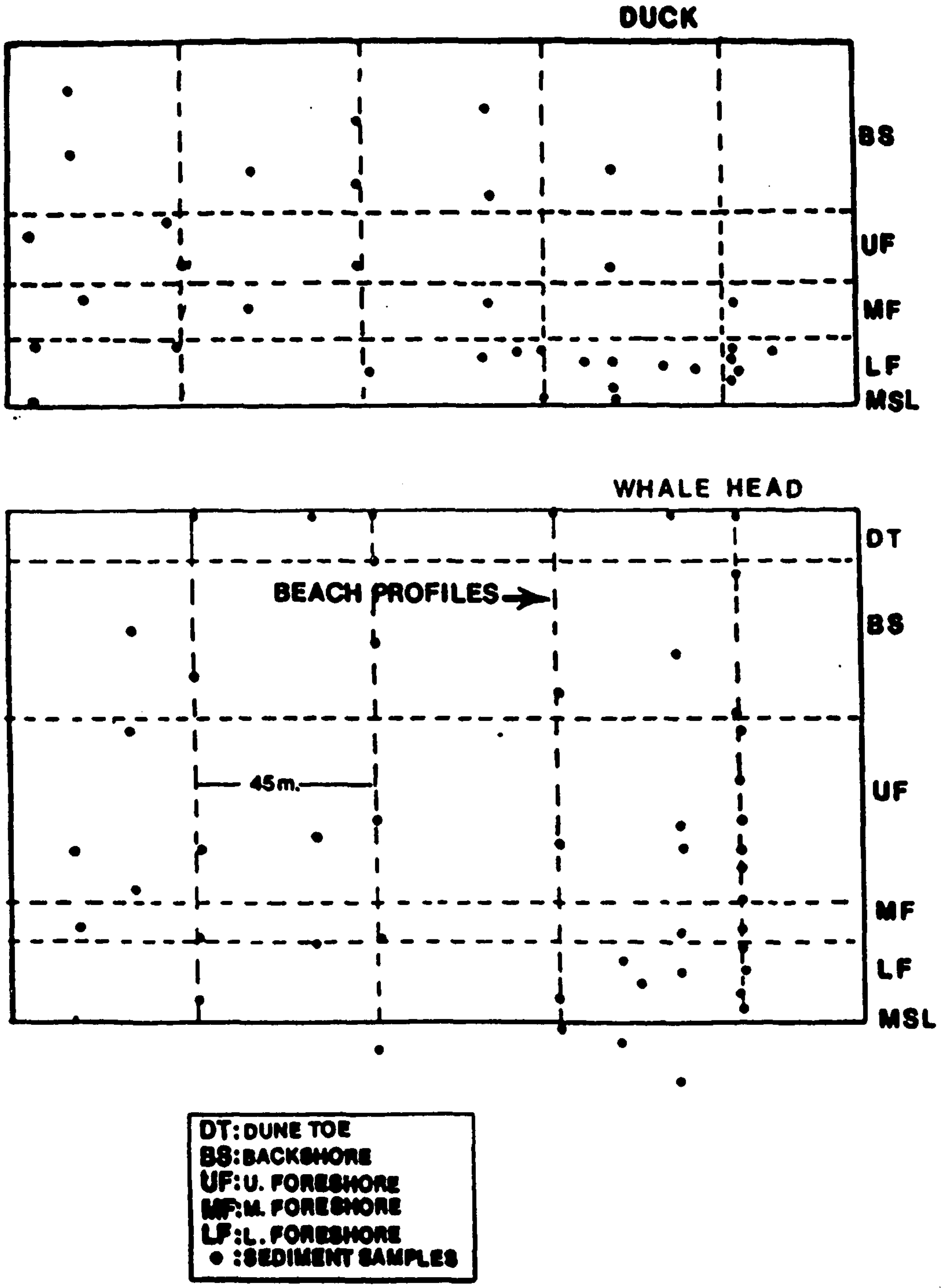
Between September, 1986 and November, 1987, a total of 59 complete surveys were conducted at both beaches (36 at Whalehead and 23 at Duck). Survey data recorded in the field were transferred to a Prime Computer for analysis. Plots of profile shape, as well as three-dimensional diagrams were obtained using the program "TP"and a program applied to the SURFACE II package.

4.4.1.2 Sediments

Sediment samples (upper 15 cm) were collected between the mean sea level and the dune toe on any given day. Samples were collected from the lower, middle and upper foreshore, berm, backshore and dune toe whose locations were determined from the results of the beach profile surveys made on the same day. Due to personnel and time limitations, however, this method was applied mainly at Whalehead beach. Sample positions at Duck were primarily obtained by visual methods.

A total of 150 samples were analyzed in the laboratory. After washing and drying, forty gram subsamples were obtained from each sample. The biodetritic fraction was eliminated using hydrochloric acid. In order to separate the sand from the gravel fraction, dried samples were manually sieved through a -1 phi (2 mm) sieve (phi= $-\log_2 D$, were D is the grain diameter in mm). Individual weights of the sand and gravel were measured to within one hundredth of a gram using a micro-balance. The proportions of sand and gravel for each sample were then obtained. The coarse grain distributions between -1 and -3 (8 mm) phi was determined using 0.25 phi interval sieves. The grain size distribution of the sand fraction which encompasses the -1 to 4 phi (2.0 to 0.0062 mm) was determined by measuring the sand's settling velocity in a glass Rapid Sediment Analyzer (RSA) tube.

Figure 6. Schematic diagram of profile set-up and sediment sample locations for the pilot study. DT - dune toe; BS- backshore; UF- upper foreshore; MF- middle foreshore; LF - lower foreshore.


DUCK
BS
UF
MF
LF
MSL
WHALE HEAD
DT
BEACH PROFILES
BS
45m.
UF
MF
LF
MSL
DT: DUNE TOE
BS: BACKSHORE
UF: U. FORESHORE
MF: M. FORESHORE
LF: L. FORESHORE
● : SEDIMENT SAMPLES

4.4.1.3. Analytical Sediment Techniques

Analysis of sediments by settling in a fluid in order to determine grain-size distributions was first introduced by Oden in 1915 (Gibbs, 1972). Since then, numerous methods have been proposed. The most well known are those developed by Emery (1968), Zeigler et al. (1960) and Schlee (1966). The RSA is a sedimentation column with an active length of approximately 1.28 m. The sand sample is introduced at the top and the grains attain a constant fall velocity within a few millimeters. As larger grains fall faster, the grains sort themselves into a continuous size frequency.

The fall velocity can be measured by collecting the grains at the bottom of the tube on a pan forming one arm of a balance giving a continuous output of weight against time (Dyer, 1966). The fluid used is deionized water with known temperature and density. The sample mineralogical composition is assumed to be quartz with a density of 2.63 gm/cm^3.

The RSA interfaces with a Personal computer that starts a continuous plot of increasing weight in milligrams versus elapsed time in seconds in the form of a cumulative curve. A minimum of 2.5 minutes is required for a run. When the weight no longer increases, a program using an equation developed by Gibbs et al. (1971) converts the plot of weight versus time to size and weight percents at 0.25 phi class intervals.

The equation represents an empirical relationship for the settling velocity of spheres equivalent to the intermediate diameter D_b which is given by:

$$D_b = \frac{0.111608\ W_s^2\rho + 2[0.003114\ W_s^4\rho + g(\rho_s - \rho)(4.5\mu\ W_s + 0.0087\ W_s^2\rho)]^{1/2}}{g\ (\rho_s - \rho)}$$

where:

Ws = grain settling velocity (cm/sec)

ρ = density of the fluid (gm/cm^3)

g = acceleration of gravity (980 cm/sec^2)

ρ_s = density of the mineral grain (quartz = 2.63 g/cm^3)

μ = dynamic viscosity of water in poise units

However, since the expression above assumes grains are spherical, the values are not applicable to nonspherical grains in nature. The settling velocity for natural sand particles is less than that for the equivalent spheres because the grains spin and oscillate as they fall. Baba and Komar (1981) showed that natural settling velocity measurements W_n can be converted to the settling velocity W_s of an equivalent sphere of diameter D_b by :

$$W_n = 0.977\ W_s^{0.913}$$

The Gibbs et al.(1966) equation can then be used to convert the values of W_s to the diameter D_b.

According to Dyer (1986), the settling velocity technique has the advantage of speed and yields more information related to the hydraulic behavior of the grain, thus being more important in studies of sediment transport and deposition. However, according to Gibbs (1974) the range over the which the accuracy is acceptable extends from 0.031 mm to 2 mm.

The sieved gravel data is introduced into the computer using the "Gravel" program. Once the RSA sand data and the gravel sieved data have been entered into the computer, they are merged. The "Merger" program prints out sizes (phi and mm), settling velocity (cm/sec), cumulative weight percent, histograms, cumulative frequency plots and grain-size statistics.

4.4.1.4. Sediment statistical parameters

Grain-size distributions for each sample were analyzed using probability plots, cumulative curves and the statistical parameters of grain-size based on moment measures developed by Krumbein and Pettijohn (1938). The method of moments is a computational (vs. graphical) method of obtaining values in which every grain in the sediment affects the measure. Therefore it may more accurately describe the distribution than graphic methods which rely on only a few selected percentage lines. The general formula for the nth moment is:

$$\log n = \frac{\Sigma\ (f\ d^n)}{N}$$

where :

f - frequency (weight %)

d - log diameter(the size is taken at the center of each phi class)

N - number of measurements (100 when dealing with percents)

The first moment is the mean **(X)**

$$\mathbf{X} = \frac{\Sigma fd}{N}$$

The second moment is the variance

$$\Sigma fd^2 - \frac{(\Sigma fd)^2}{N}$$

The standard deviation is (σ)

$$\sigma = \sqrt{\text{variance}}$$

The third and fourth moments will give values interpreted as skewness and kurtosis, respectively according to the equations below:

$$\text{3th moment} = \frac{\Sigma f(d-\bar{X})^3}{100\ \sigma^3}$$

$$\text{4th moment} = \frac{\Sigma f(d-\bar{X})^3}{100\sigma^4}$$

The moment measures were used in order to determine the validity of the groups obtained by Q-mode factor analysis.

The grain-size population studied ranged from -3.25 phi (8 mm) to 4.00 phi (0.0062mm) and the sample total weight was divided in 0.25 phi classes. Samples of both beaches were merged on a single matrix consisting of 87 rows by 29 variables.

Owing to extremely low percentages of material coarser than -2 phi these fractions were included in the -3.5 to -2 phi class interval. Material finer than 2.5 phi was included in the 2 to 4 phi class interval. This caused the original matrix to be reduced from 29 to 18 variables.

In order to compare the results obtained by using different numbers of variables, a reduction using 0.5 phi class interval was also performed. This resulted in a matrix with eleven variables. Both of the matrices (18 and 11 variables) were used as input into the Q-mode factor analysis program.

5. RESULTS

Introduction

Using the factor analysis program the author attempted solutions ranging from 2 to 6 factors. Identical results were produced when different numbers of variables were used (i.e. 18 or 11). For simplicity, the results displayed here are based on the analysis of the matrices containing eleven variables.

5.1. The Factor Analysis solution

The final factor rotation used was an oblique projection of factor loadings, giving end-member factor types (individual samples coinciding with the factors) with a loading of 1.000. Other samples which "loaded" on that factor have declining values below 1.000. The two and three factor solution only explained 82.43% and 89.83% respectively of the total compositional variation of samples. Although the communalities values showed by three factors was higher than for the two factor solution, 32% of the samples displayed values lower than 0.9. The four factor solution explained 94.64% of the variance. However, 15% of the samples showed communalities less than 0.9. The six factor solution accounted for 98.42% of the variance and showed the highest communalities values. However, factors II and V as well as factors III and VI display some redundancy as they showed similar compositions for these factor axis. The best mathematical description was achieved with the five factor solution because it accounted for 97.36% of the variance, had high communalities and showed no redundancy among the factor axes.

Table 1 lists the calculated eigenvalues of the 87x11 sediment matrix along with the values of individual and cumulative percent sums of squares before and after the varimax rotation. It can be seen that after the rotation, most of the variance is explained by factors I and V.

The composition scores of the reference axis matrix, which provides an estimate of the composition of the factors is plotted in **Figure 7**. For completeness, factor scores are listed in **Table 2.**

Factor I is mainly composed of variables 9, 10 and 11 which respectively corresponds to the 1.5-2, 2-2.5, and 2.5-3.5 phi class intervals ranging from medium sand to very fine sand. However, variable 10 is the main variable representing this factor. For this reason, Factor I is denoted as fine sand.

Factor II consists of variables 5 to 8 which encompasses the coarse to medium sand intervals. This factor is mainly represented by the "coarse sand" class interval.

Factor III is mainly composed of very coarse sand. However, it also shows that variables representing coarse, medium and fine sand, as well as gravel, are also important in its composition.

The gravel factor is represented by Factor IV which is dominated by pebbles and gravel.

Factor V, the second most important factor in explaining the variability after the rotation, is dominated by variables 8 and 9 which represent the medium sand class interval.

Table 1. Eigenvalues of the 87x11 sediment data matrix explained by the first eight factors, along with the individual and cumulative sums of squares before and after the rotation.

NUM	EIGENVALUE	%INDIVIDUAL SUM OF SQUARES	CUMULATIVE SUM OF SQUARES	%INDIVIDUAL SUM OF SQUARES AFTER ROTATION	CUMULATIVE SUM OF SQUARES AFTER ROTATION
I	61.1585	70.30	70.30	33.76	33.76
II	10.5629	12.14	82.44	10.01	43.77
III	6.4350	7.40	89.84	15.12	58.89
IV	4.1860	4.81	94.65	7.32	66.21
V	2.3593	2.71	97.36	31.15	97.36
VI	0.9192	1.06	98.42		
VII	0.5009	0.57	98.99		
VIII	0.3837	0.44	99.43		

Figure 7. Histogram of the composition scores of reference factor axes for the pilot study. FS- fine sand; CS- coarse sand; VCS- very coarse sand; P- pebbles; Gr- gravel; Ms- medium sand.

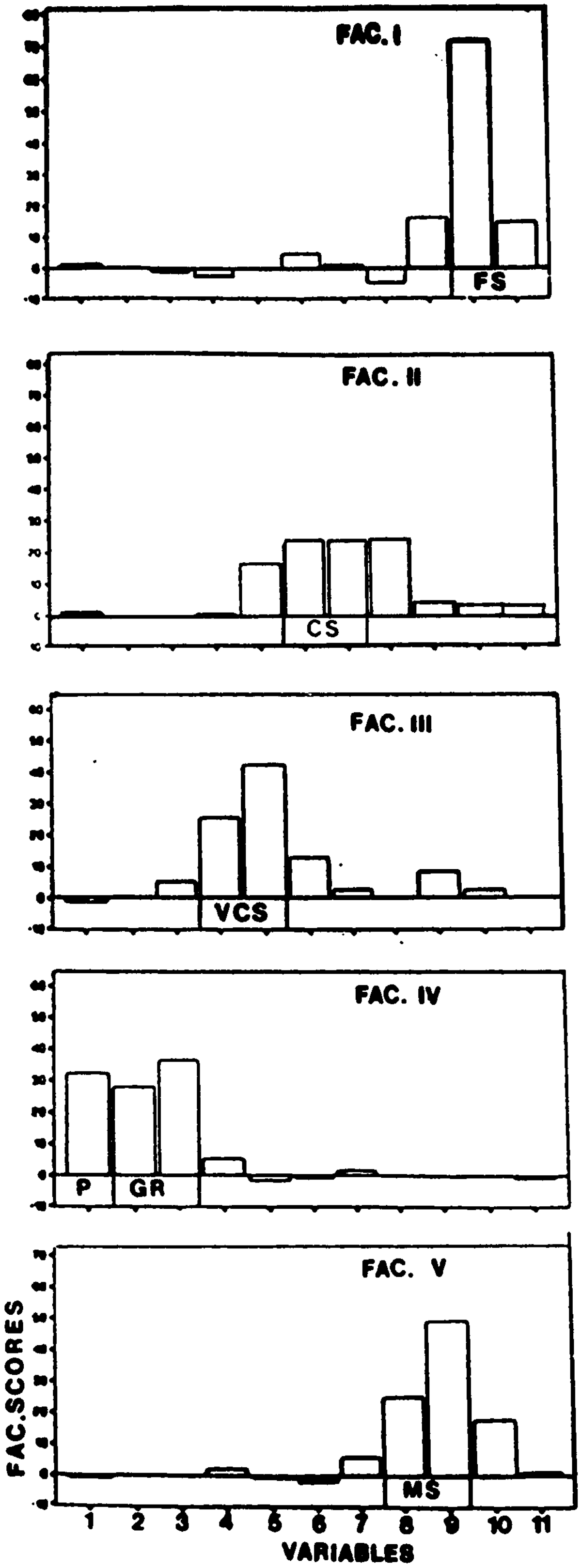

FAC. I
FS
FAC. II
CS
FAC. III
VCS
FAC. IV
P
GR
FAC. V
MS
FAC.SCORES
1
2
3
4
5
6
7
8
9
10
11
VARIABLES

Table 2. Composition scores of reference factor axes. (Duck and Whalehead beach data set)

Composition scores of reference Factor axes

PHI CLASS	VAR	AXIS	I	II	III	IV	V
-3.5/-2.0	1		1.3951	1.1791	-1.3813	32.3055	-0.9110
-2.0/-1.5	2		0.3807	-0.4519	0.7343	27.9965	0.2463
-1.5/-1.0	3		-1.2045	-0.7430	5.4069	36.5604	0.0685
-1.0/-0.5	4		-2.5503	0.9144	25.6256	5.3646	2.1672
-0.5/ 0.0	5		0.1555	16.5831	42.3986	-1.6823	-0.6837
0.0/ 0.5	6		4.8384	23.8449	12.9582	-0.8991	-1.8033
0.5/ 1.0	7		1.1384	23.7129	2.7841	1.4868	6.1788
1.0/ 1.5	8		-4.9547	24.1815	0.1851	-0.1099	25.6158
1.5/ 2.0	9		16.1043	4.2892	8.4606	-0.3068	49.6999
2.0/ 2.5	10		69.9642	3.4201	2.5912	0.1812	18.0647
2.5/ 3.5	11		14.7330	3.0697	0.2365	-0.8968	1.3568

5.1.1 End member samples

Composition loadings of extreme normalized samples defined as end-members are listed in **Table 3**. The loading values for each end-member are not 1.00 because in order to obtain positive loadings and scores a iterative procedure described by Full et al. (1981) which generates a new oblique solution was used. Histograms, cumulative frequency curves and textural parameters determined for these end-members are given in **Figure 8**. Sample **P193,** located on the backshore at Whalehead beach, was chosen as the extreme end-member representing Factor I. The histogram of this sample illustrates that it is composed of 86.64% fine and very fine sand. The sample is very well sorted and has a symmetrical distribution basically characterizing a unimodal fine sand.

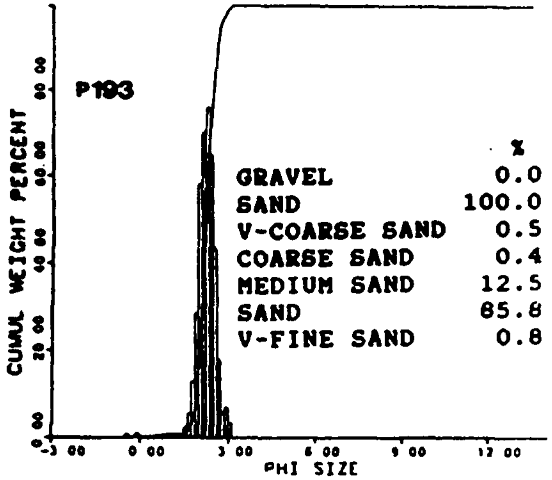
Sample **DP43**, located on the backshore at Duck beach, represents Factor II being mainly composed of coarse sand (52.58%), medium sand (28.28%) and very coarse sand (15%). The gravel fraction is absent and fine sand is negligible.

Factor III is represented by sample **DS22** located at the lower foreshore at Duck. Almost 70% of this sample is composed of very coarse sand. A small percentage of coarse, medium and fine sand is also present. The primary mode yields a characteristically moderately sorted sediment sample. The tendency for a fine grain-size fraction (3 phi) gives a fine skewed distribution to the sample.

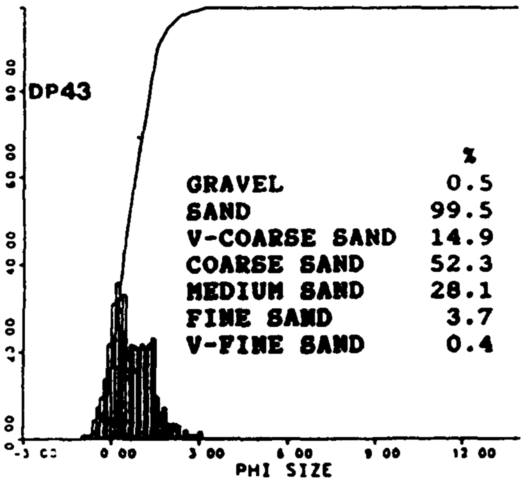
Table 3. Communalities and loadings of extreme normalized samples selected as population end-members.

END-MEMBER	COMMUNALITY	1	2	3	4	5
P193	1.0000	0.9517	0.0308	0.2863	-0.0127	0.0264
DP43	1.0000	-0.1318	0.9680	-0.0240	-0.0759	-0.1980
DS22	1.0000	-0.0799	0.0970	0.9911	0.0278	-0.0347
WS27	1.0000	0.1986	-0.0178	-0.0228	0.9795	-0.0164
P31	1.0000	-0.0838	0.2690	-0.1517	-0.0581	0.9456

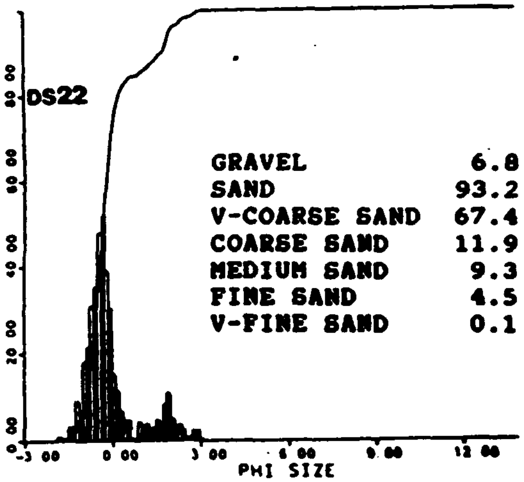
Figure 8. Histograms, cumulative frequency plots and grain-size percentages of sediment samples determined as end-members in the pilot study.



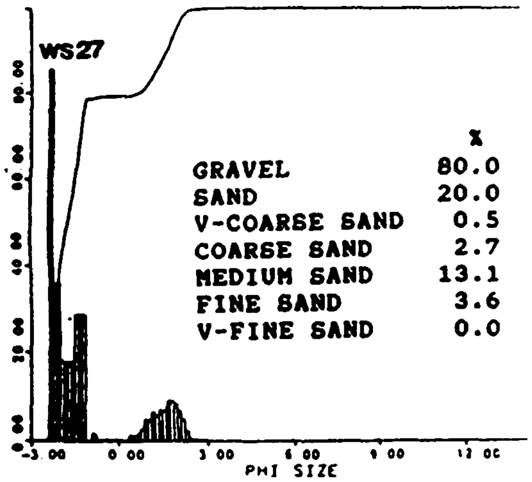
	%
GRAVEL	0.0
SAND	100.0
V-COARSE SAND	0.5
COARSE SAND	0.4
MEDIUM SAND	12.5
SAND	85.8
V-FINE SAND	0.8



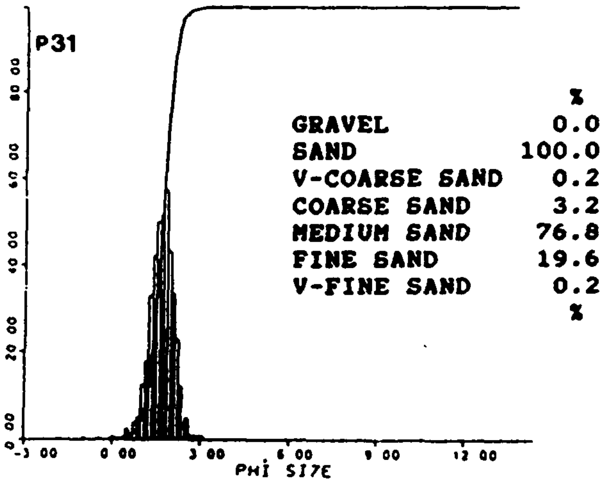
	%
GRAVEL	0.5
SAND	99.5
V-COARSE SAND	14.9
COARSE SAND	52.3
MEDIUM SAND	28.1
FINE SAND	3.7
V-FINE SAND	0.4



GRAVEL	6.8
SAND	93.2
V-COARSE SAND	67.4
COARSE SAND	11.9
MEDIUM SAND	9.3
FINE SAND	4.5
V-FINE SAND	0.1



	%
GRAVEL	80.0
SAND	20.0
V-COARSE SAND	0.5
COARSE SAND	2.7
MEDIUM SAND	13.1
FINE SAND	3.6
V-FINE SAND	0.0



	%
GRAVEL	0.0
SAND	100.0
V-COARSE SAND	0.2
COARSE SAND	3.2
MEDIUM SAND	76.8
FINE SAND	19.6
V-FINE SAND	0.2

%

Factor IV's end-member is represented by sample **WS27**. This sample is mainly composed of gravel (80%). The sample was collected from the step at Whalehead beach.

Sample **P31** located on the dune toe at Whalehead beach was selected as the end-member representing Factor V. This sample is basically composed of medium (76.84%) and fine sand (19.75%).

5.2. Relationship between samples and Factors

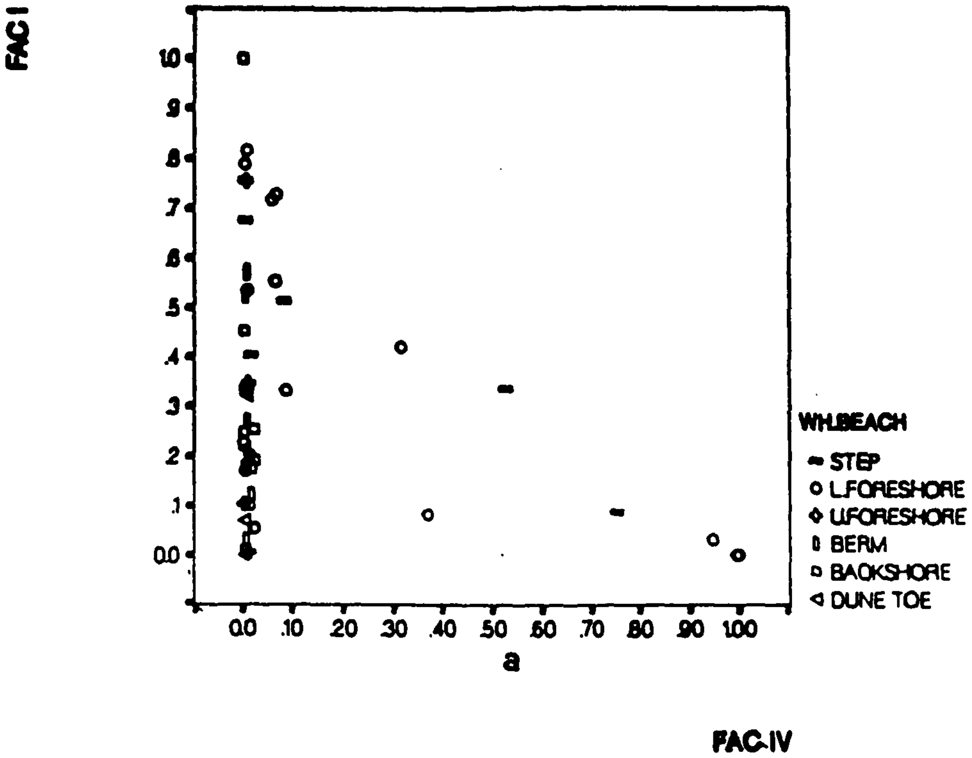
Figures 9 to 10 show the results of plotting the factor loading for Whalehead beach on two axes at a time. Coordinates of plotted data points were taken from the rows of the oblique projection matrix. Each factor axis coincides with a sample which represents an end-member object. Each sediment sample is plotted as a symbol representing its position across the beach. Negative values were reversed for plotting purposes. Whenever factor axis one, four and five are displayed, the end-members representing that factor axis are located at 1.0 value. The more expressive results for this beach can be visualized in **Figure 9(b)** Most of the samples can be explained by the two factors which represent medium and fine sand (Factors I and V). Samples located at zero represent the third end-member located on the lower foreshore which is composed of a unimodal gravel population. As indicated, the definition of a particular sub-environment based on grain-size factors across Whale Head is not evident. With the exception of samples from the dune toe and backshore which are associated with Factor V, the other beach zones do not show any link to a particular factor axes. The lower foreshore is equally represented by the two of the factor axis. As shown in the remaining plots (appendix A), most of the samples have very little relationship with factor axes two and three.

Plots of factor loadings for Duck beach display a different pattern from Whalehead beach (**Figures 11 to 12**). The association of samples from particular zones to factors is more clearly defined. **Figure 11(a)** shows that the backshore samples are well characterized by Factor II (coarse sand). According to the patterns shown in **Figure 11(b)** the upper foreshore appears to be best represented by Factor III (very coarse sand). The lower foreshore can be characterized by both Factors I and V (**Figure 12(b)**.

Figure 9. Plots of factor loadings on the oblique factor axes.

9(a) Loadings on the oblique factor axes I and IV

9(b) Loadings on the oblique factor axes I and V


FAC I
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0.0
0.0
.10
.20
.30
.40
.50
.60
.70
.80
.90
1.00
a
FAC IV
WH.BEACH
▬ STEP
○ L.FORESHORE
◆ U.FORESHORE
▯ BERM
▫ BACKSHORE
◁ DUNE TOE

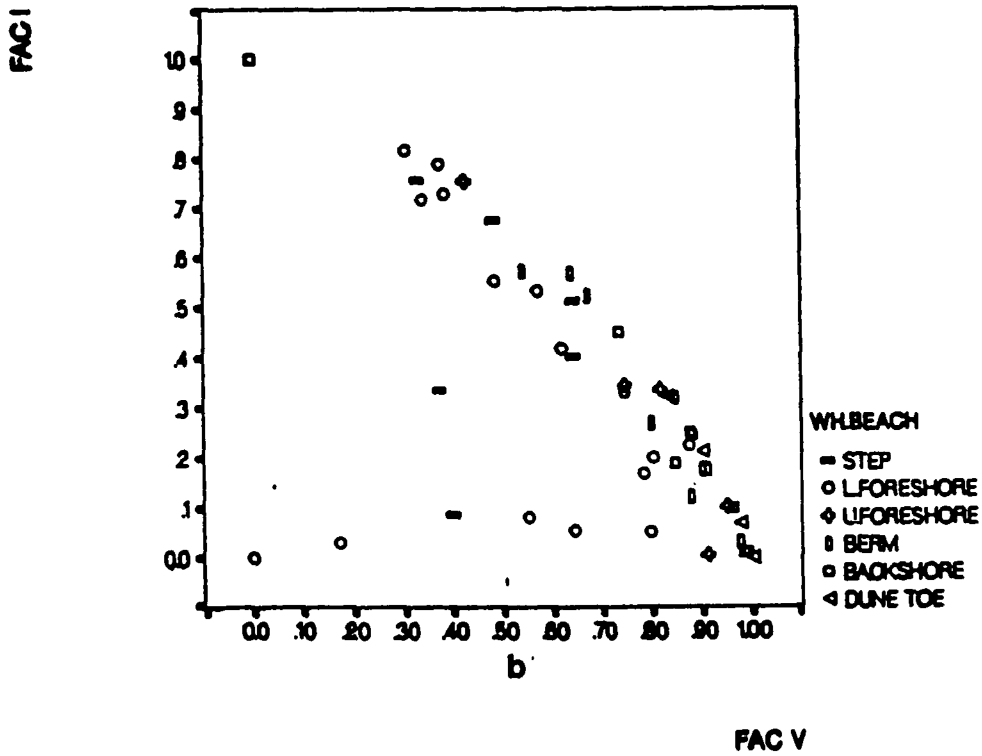
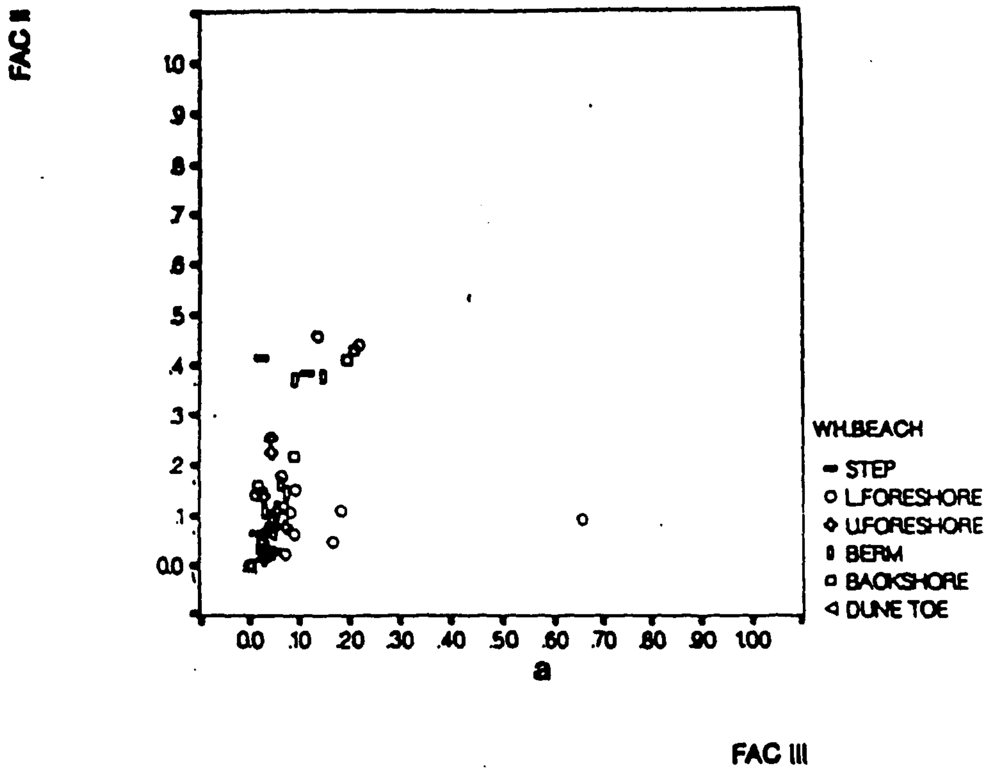

FAC I
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0.0
0.0
.10
.20
.30
.40
.50
.60
.70
.80
.90
1.00
b
FAC V
WH.BEACH
▬ STEP
○ L.FORESHORE
◆ U.FORESHORE
▯ BERM
▫ BACKSHORE
◁ DUNE TOE

Figure 10. Plots of factor loadings on the oblique factor axes.

10(a) Loadings on the oblique factor axes II and III

10(b) Loadings on the oblique factor axes II and IV


FAC II
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0.0
0.0 .10 .20 .30 .40 .50 .60 .70 .80 .90 1.00
a
FAC III
WH.BEACH
STEP
L.FOESHORE
U.FORESHORE
BERM
BACKSHORE
DUNE TOE

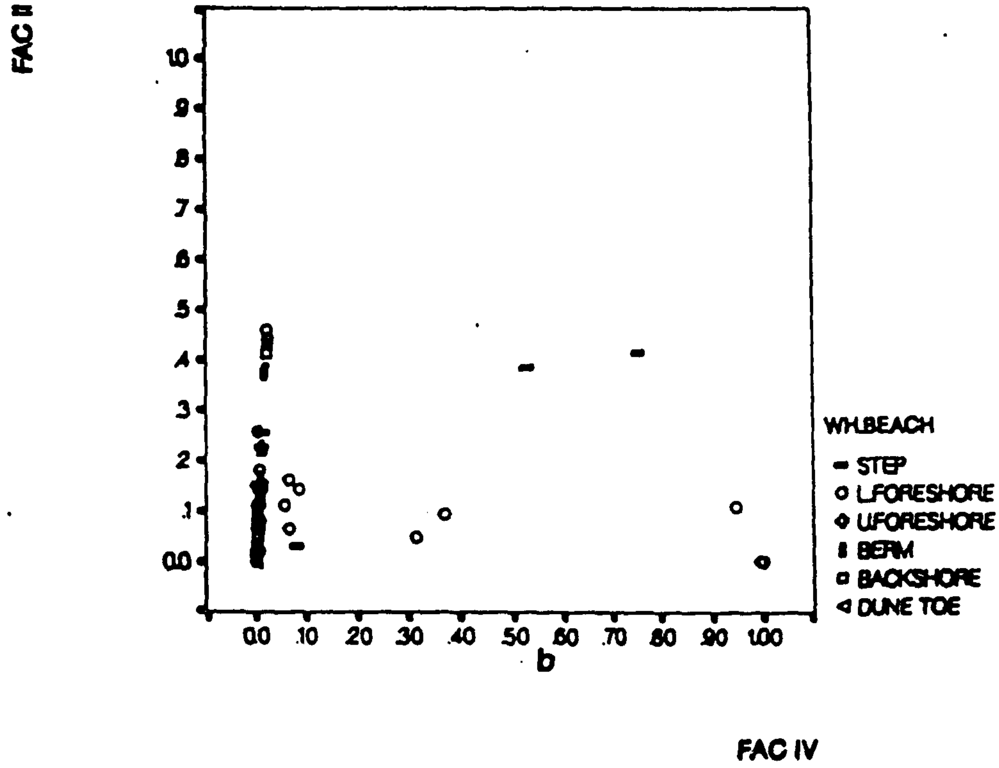
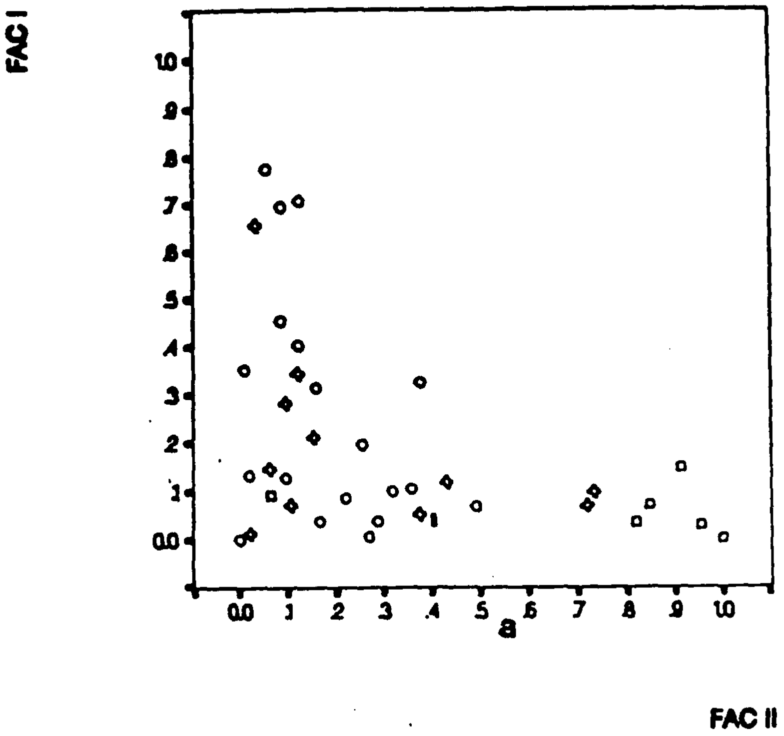

FAC II
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0.0
0.0 .10 .20 .30 .40 .50 .60 .70 .80 .90 1.00
b
FAC IV
WH.BEACH
STEP
L.FORESHORE
U.FORESHORE
BERM
BACKSHORE
DUNE TOE

Figure 11. Plots of factor loadings on the oblique factor axes

11(a) Loadings on the oblique axes I and II

11(b)Loading on the oblique axes I and III


FAC I
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0.0
0.0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
a
FAC II

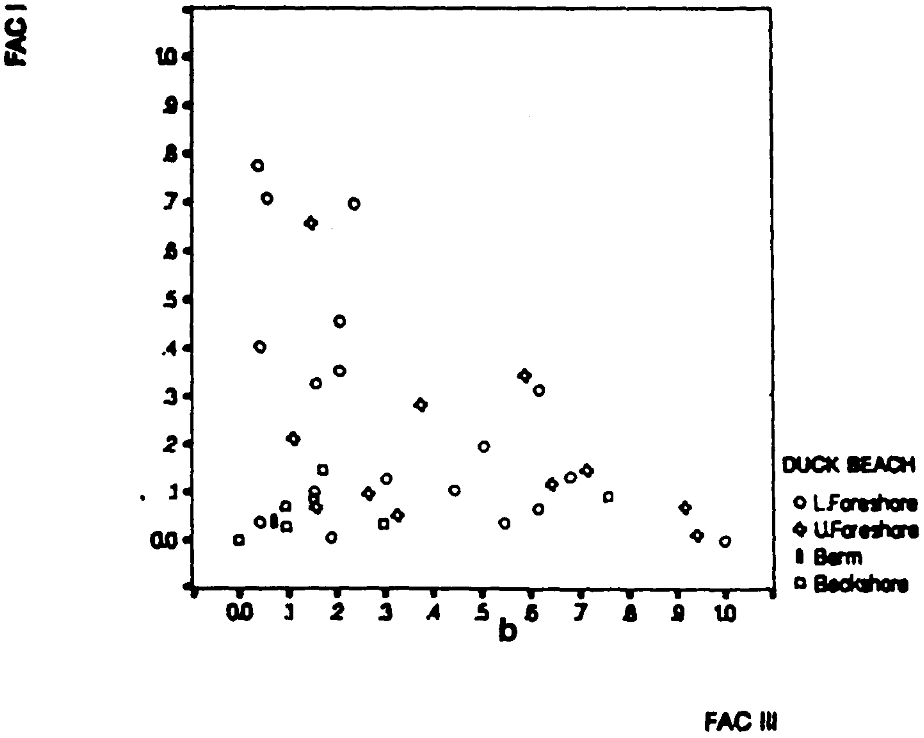
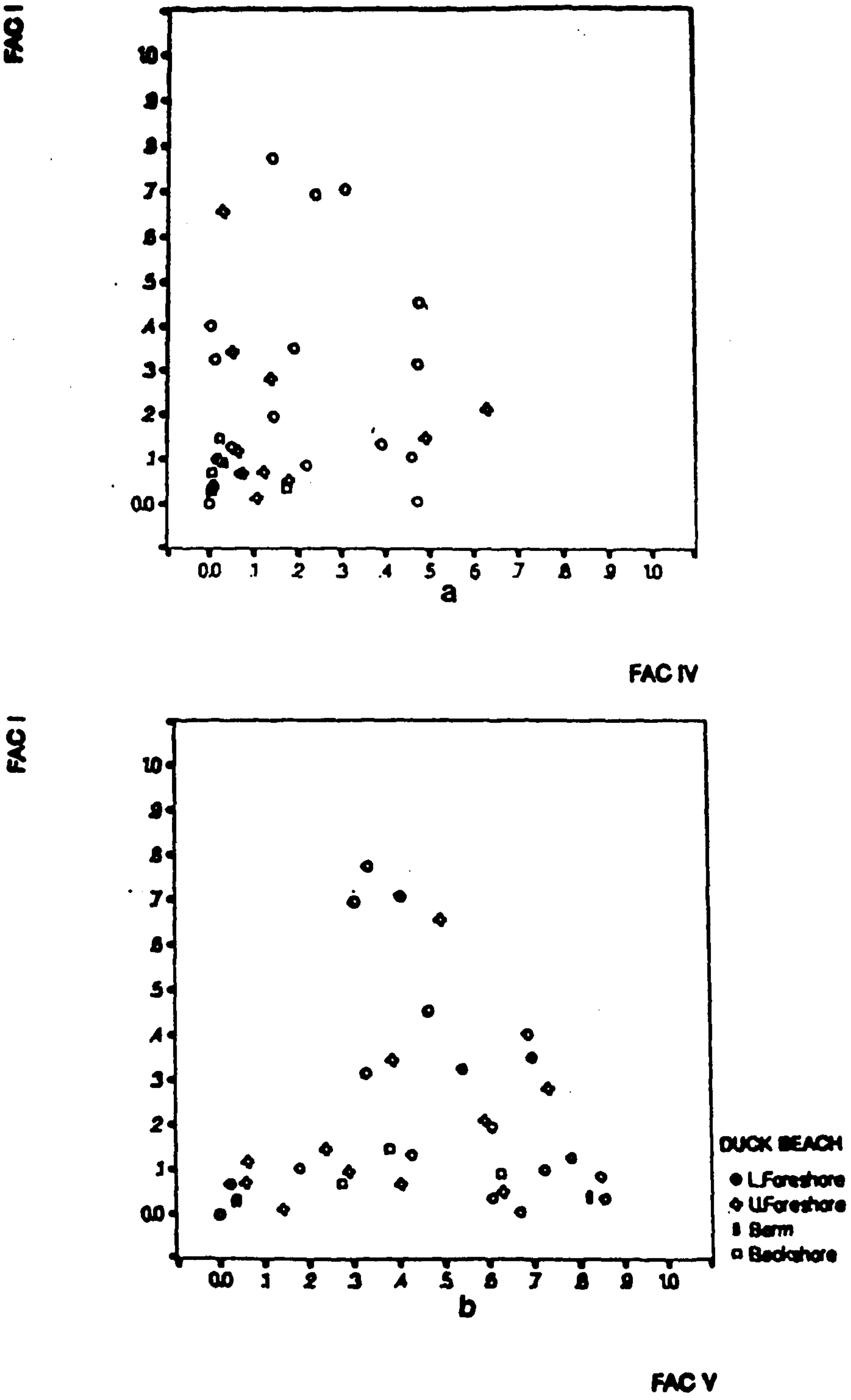

FAC I
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0.0
0.0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
b
FAC III
DUCK BEACH
○ L.Foreshore
◇ U.Foreshore
▮ Berm
□ Backshore

Figure 12. Duck beach. Plot of factor loadings on the oblique factor axes.

12(a) Loadings on the oblique axes I and IV

12(b) Loadings on the oblique axes I and V

FAC I
0.0
1
2
3
4
5
6
7
8
9
1.0
0.0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
a
FAC IV
FAC I
b
FAC V
DUCK BEACH
● L.Foreshore
◇ U.Foreshore
▮ Berm
□ Backshore

5.3 Spatial distribution of sediment factor groups

Using the oblique projection matrix, all the sediment samples can be grouped according to the principal axes on which they have the highest loading. In doing this, spatial patterns may emerge which can provide some clues to the sediment distribution.

Figure 13(a) shows that despite the reduced number of samples, there is a differentiation of sediment factor groups across the beach at Duck. Factor II, represented by coarse sand, is mostly limited to the backshore. The fine sand fraction represented by Factor I occurs mainly on the lower foreshore. Factors III and V, representing very coarse sand and medium sand respectively are present from the lower to the upper foreshore and are almost absent at the backshore. Factor IV shows a low occurrence at Duck, being only represented by one sample.

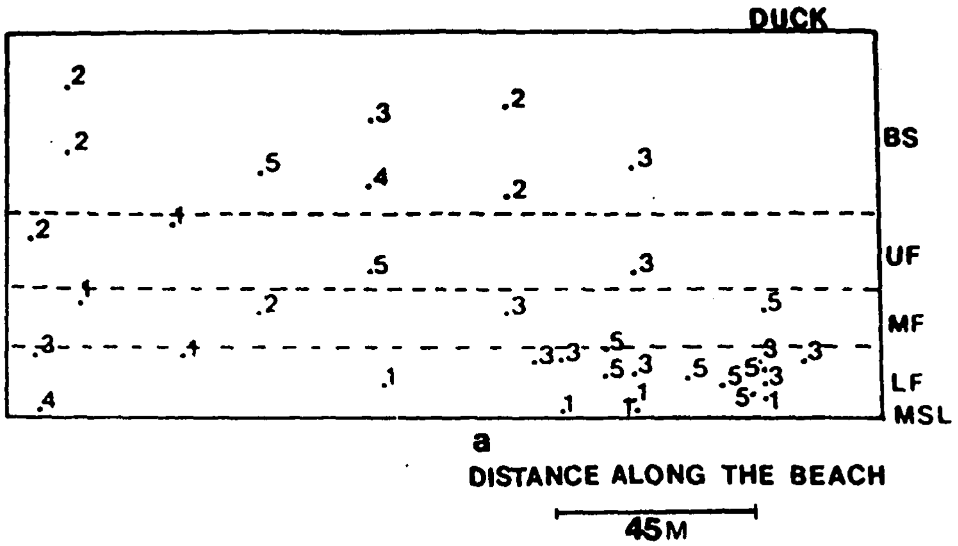
Figure 13(b) shows that differentiation of sediment factor groups at Whalehead is almost non-existent. Factor V, representing medium sand, predominates across the beach. Factors II and III which represent coarse and very coarse sand are insignificant at Whalehead. Factor IV is restricted to the lower foreshore. The unimodal fine sand, representing Factor I, occurs between the lower and upper foreshore.

A better way to demonstrate the grain-size uniformity by factor is show in **Figure 14**. Here, sediment factor groups obtained by factor analysis are plotted according to variable combinations representing proportions of gravel to very coarse sand, coarse sand to medium sand and fine to very fine sand. Positions of end-members and cluster patterns illustrate the factor group characteristics obtained by factor analysis.

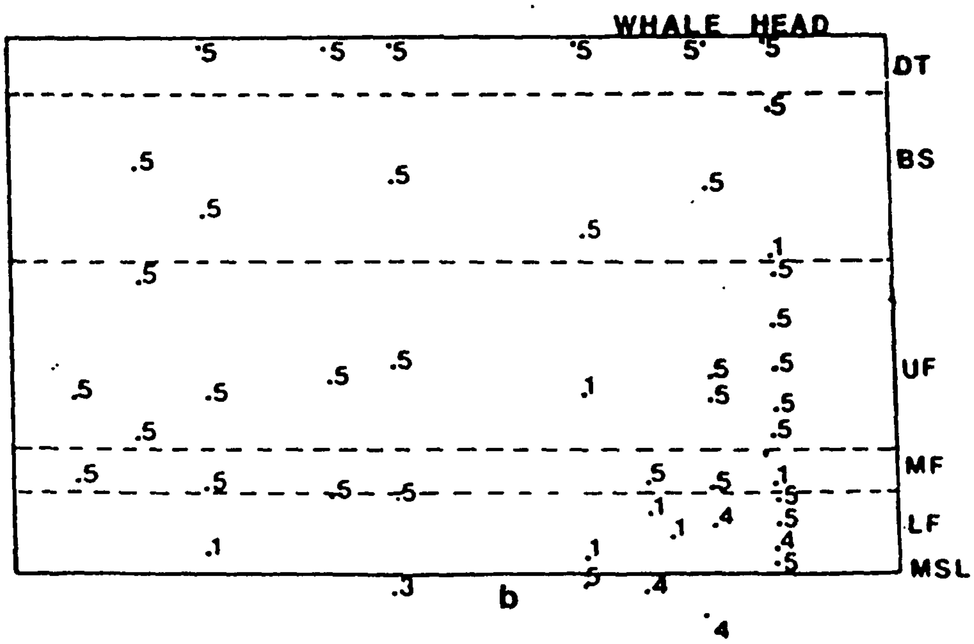
Figure 13. Spatial distribution of sediment factor groups according the oblique factor axes.

13(a) Spatial distribution of sediment factor groups for Duck.

13(b) Spatial distribution of sediment factor groups for Whalehead

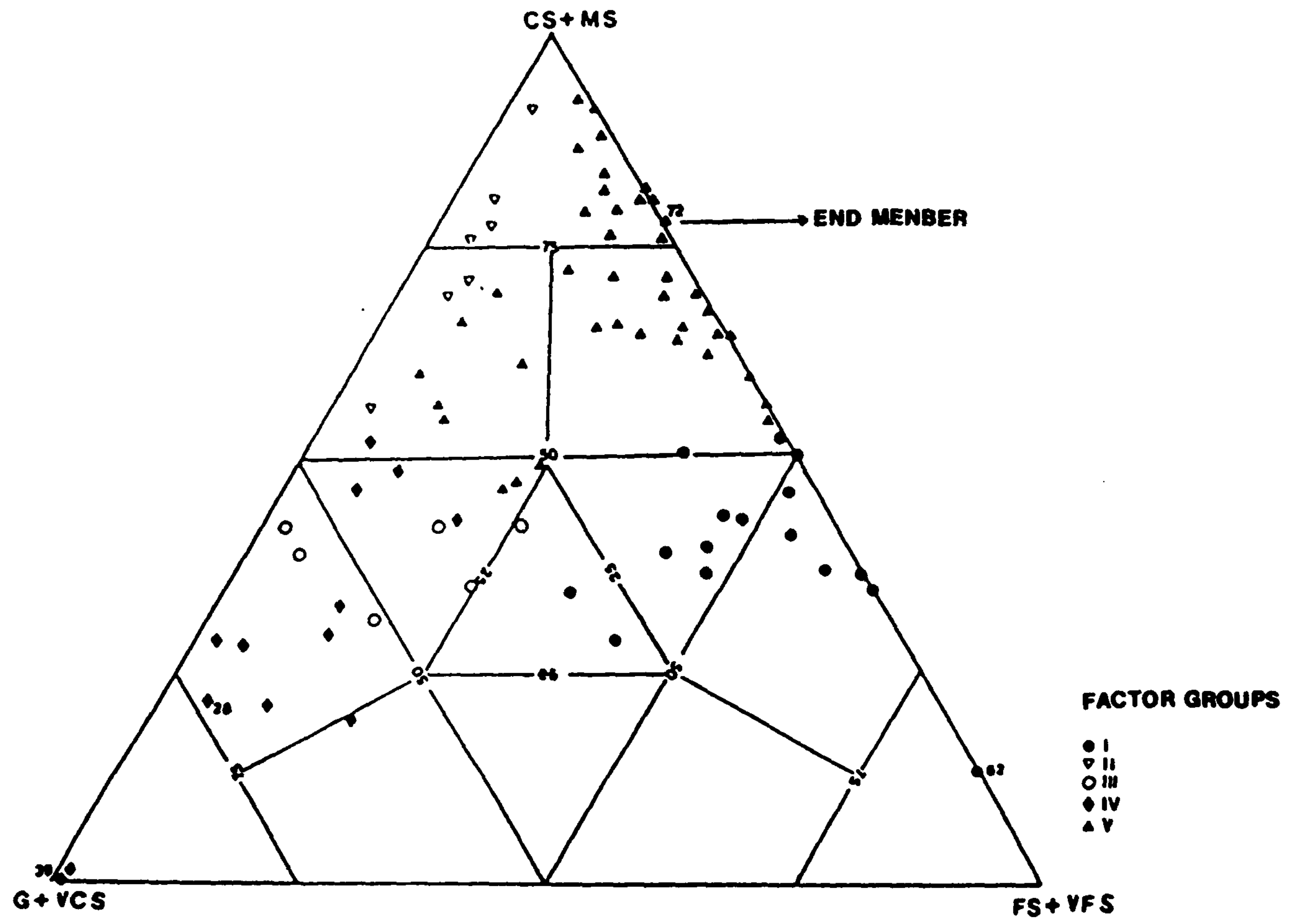

DUCK
BS
UF
MF
LF
MSL
DISTANCE ALONG THE BEACH
45M

a


WHALE HEAD
DT
BS
UF
MF
LF
MSL

b

Figure 14. Ternary diagram displaying the factor groups according the percentages of: Gravel+very coarse sand; coarse sand+medium sand and fine sand+very fine sand.



CS+MS
72
END MENBER
75
50
25
50
25
50
75
28
30
62
G+VCS
FS+VFS
FACTOR GROUPS
● I
▽ II
○ III
◆ IV
▲ V

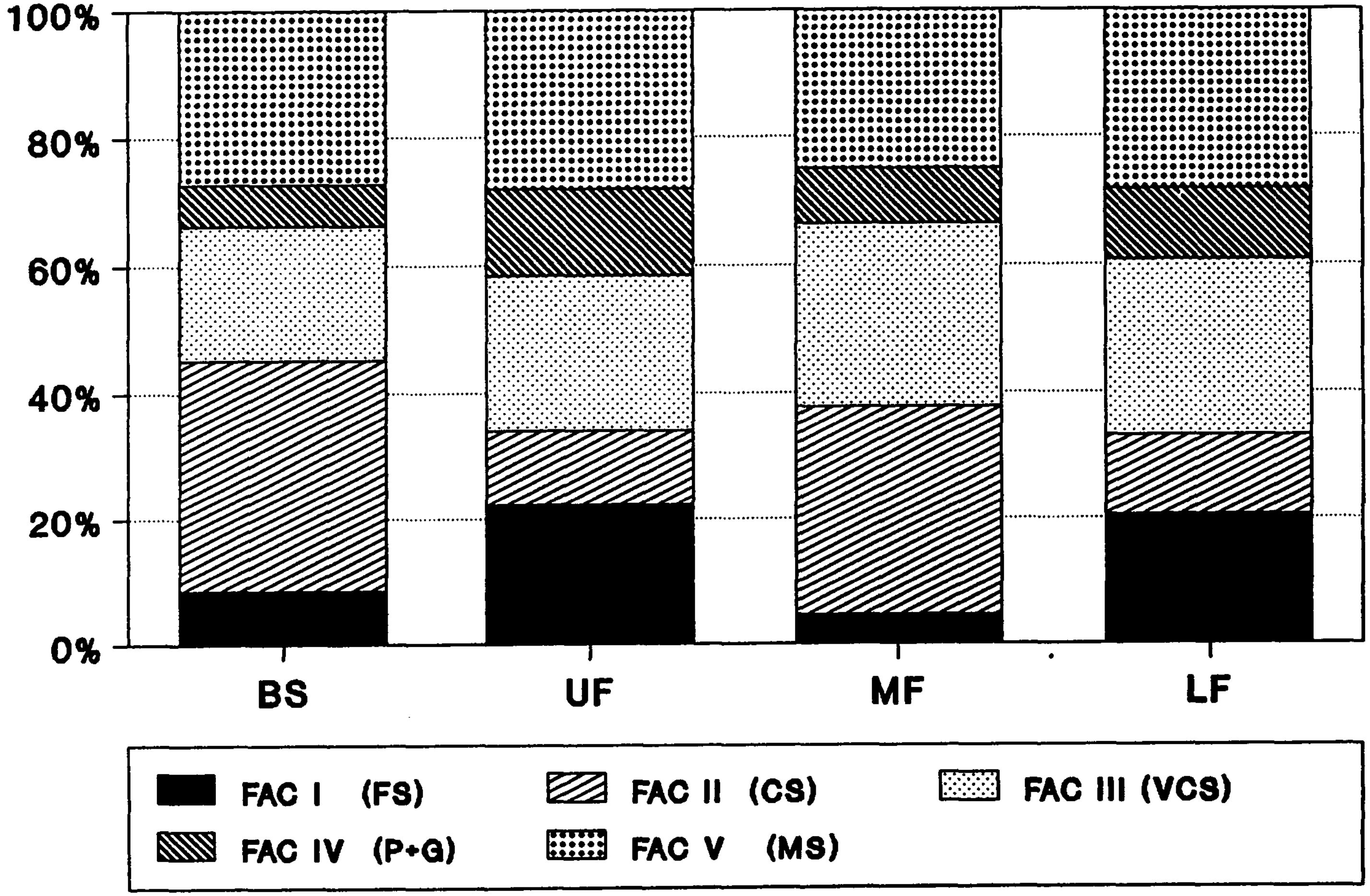
5.4. Average percentage of factors across the beach

Based on the composition loading matrix (which expresses the factor loadings as true percentages of each object on the factor axis) and the samples'location, it is possible to calculate the average percentage of each factor across the different zones of the beach.

Figure 15 represents Duck beach. As can be visualized, the highest and lowest percentage of Factors II (coarse sand) and I (fine sand) occur respectively on the backshore and middle foreshore. Average percentage of Factor III (very coarse sand) shows a slight decrease towards the backshore. Factor V's average percentage remains the same across the beach. The average percentage of Factor IV is highest on the upper and lower foreshore.

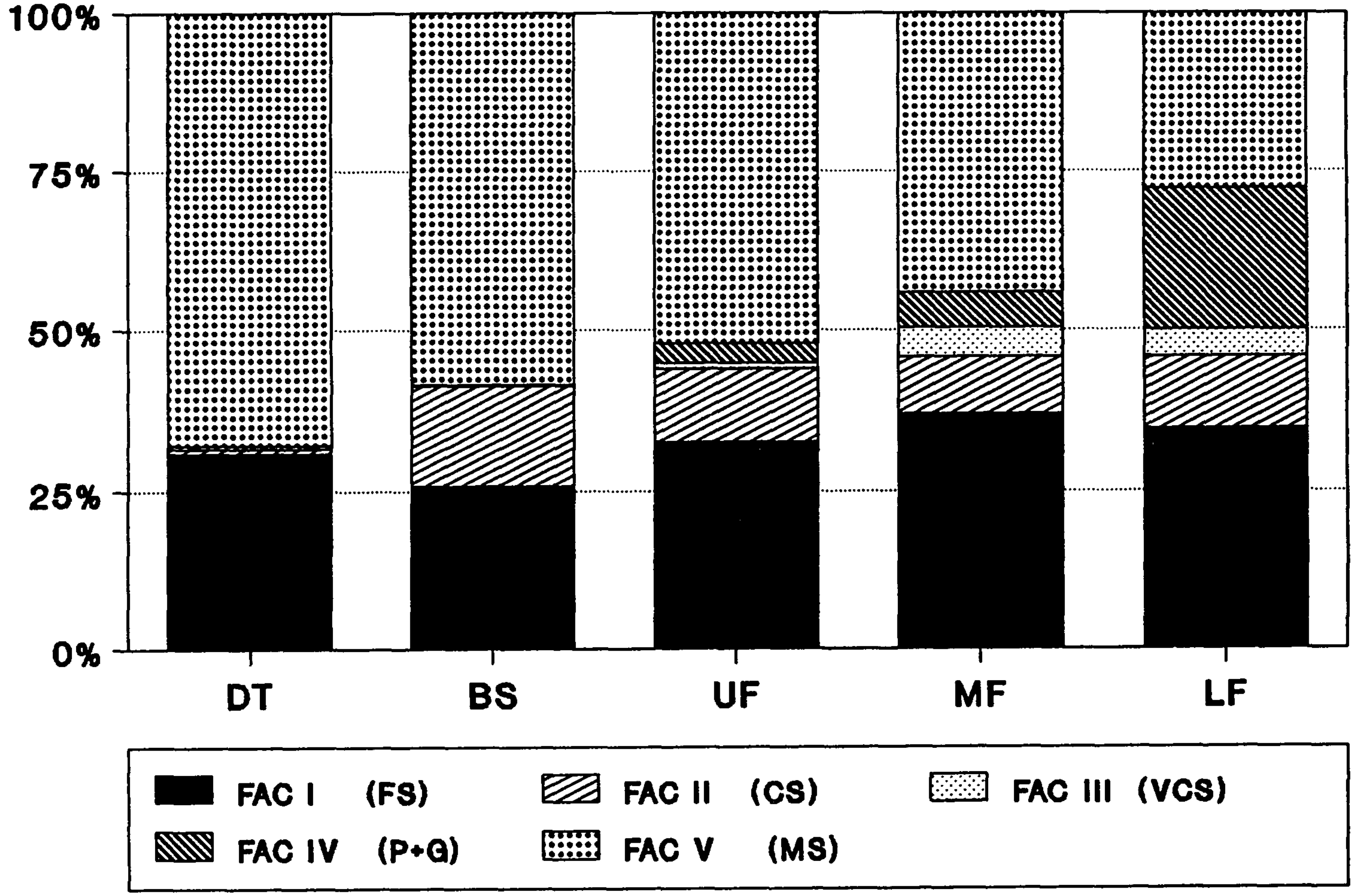
Figure 16 displays the patterns observed for Whalehead beach. The highest and lowest average percentage for Factors II and I are associated with the backshore. Average percentage for Factor III is almost negligible and only appears on the lower and middle foreshore. Factor IV's average percentage displays the highest values at the lower foreshore, decreasing toward the dune toe. Unlike the findings at Duck, average percentage for Factor V (medium sand) decreases toward the lower foreshore.

Figure 15. Duck beach. Average percentage of factor loadings across the beach


100%
80%
60%
40%
20%
0%
BS
UF
MF
LF
■ FAC I (FS)
▨ FAC II (CS)
░ FAC III (VCS)
▧ FAC IV (P+G)
▦ FAC V (MS)

DUCK, NC.

Figure 16. Whalehead beach. Average percentage of factor loadings across the beach



WHALE HEAD, N.C.

5.5 Factor Groups grain-size characteristics

Tables 4 and 5 list the mean and standard deviation percentage values of gravel, very coarse, coarse, medium, fine and very fine sand, as well as the statistical parameters calculated from the moment measures associated with each group obtained by the highest loading on the factor axis. The number of samples, their percent corresponding to each factor, and the location across the beach, is also given.

At Whalehead (**Table 4**), 68% of the total number of samples collected were associated with Factor V, representing the medium sand factor. Twenty percent of the samples collected were associated with Factor I, the fine sand factor. There are no samples corresponding to Factor II (gravel fraction) at Whalehead. Only one sample (2%) is associated with Factor III (very coarse sand).

In contrast, the Duck samples are more evenly distributed among the different factor groups.

In order to attempt to observe relationships between factor groups and their position across the beach, the percentages of total samples found at any given location for each factor group was also calculated. As shown in **Table 5**. for Duck beach, Factor groups I IV and V are found almost totally at the lower foreshore. Factor group II dominates in the backshore, but is found in the upper foreshore. Factor group III is equally represented by the upper and lower foreshore.

Table 4. Whalehead beach. Mean and standard deviation of sediment factor groups. G - gravel; VCS- very coarse sand; CS- coarse sand; MS- medium sand; FS- fine sand; VFS- very fine sand; M- mean; Std- standard deviation; Slk- skewness; Kurt- kurtosis; N- number of samples; T- total; S- step; LF- lower foreshore; UF- upper foreshore; B- berm; BS- backshore; D- dune toe.

Whale Head beach

GROUP	%G	%VCS	%CS	%MS	%FS	%VFS	M	STD.	SLK	KURT	N	%T	%S	%LF	%UF	%B	%BS	%D
ONE																		
MEAN	2.10	3.24	5.23	33.01	55.29	0.95	1.85	0.71	-1.29	4.95	10	20	20	50	10	10	10	-
STD	2.53	3.98	3.63	8.69	12.85	0.90	0.27	0.31	0.67	1.83								
TWO	NO SAMPLES																	
THREE	ONE SAMPLE																	
MEAN	25.00	29.64	6.66	26.47	11.14	1.27	0.24	1.47	0.10	1.69	1	2		100				
FOUR																		
MEAN	61.10	4.25	8.30	17.02	9.16	0.17	-0.89	1.09	0.05	1.93	5	10	40	60	-	-	-	- -
STD	35.68	4.06	8.28	16.05	11.65	0.25	0.84	0.66	0.74	0.68								
FIVE																		
MEAN	1.88	2.54	9.61	60.47	25.05	0.47	1.58	0.62	-1.03	5.80	34	68	6	26	12.5	20.60	20.60	14.70
STD	4.38	3.91	6.68	11.62	11.01	0.61	0.26		0.60	2.45								

Table 5. Duck beach. Mean and standard deviation of sediment factor groups. G- gravel; VCS- very coarse sand; CS- coarse sand; MS- medium sand; FS- fine sand; VFS- very fine sand; M- mean; STD- standard deviation; SK- skewness; K- kurtosis; N- number of samples; T- total number of samples; S- step; LF- lower foreshore; UF- upper foreshore; B- berm; BS- backshore; D- dune toe.

Duck beach

GROUP	%G	%VCS	%CS	%MS	%FS	%VFS	M	STD	SK	K	N	%T	%S	%LF	%UF	%B	%BS	%D
ONE																		
MEAN	1.61	5.63	5.40	29.83	42.49	0.53	1.19	1.47	-1.31	3.81	4	11	-	75	25	-	-	-
STD	9.84	5.05	3.85	5.56	4.91	0.70	0.34	0.56										
TWO																		
MEAN	3.37	18.25	41.23	33.01	3.81	0.31	0.70	0.79	0.11	2.89	7	19	-	-	29		71	-
STD	4.77	6.61	7.71	8.74	0.88	0.31	0.20	0.12	0.38	0.30								
THREE																		
MEAN	12.32	43.39	13.46	20.68	9.61	0.48	0.24	1.13	0.57	2.55	10	27	-	40	50	10	-	-
STD	12.97	13.48	9.70	9.12	6.99	0.53	0.41	0.27	0.53	1.01								
FOUR																		
MEAN	37.16	11.69	9.83	25.25	15.91	0.15	0.11	1.66	-0.26	1.58	3	8	-	75	25	0	0	-
STD	10.26	10.38	9.23	5.55	9.17	0.13	0.36	0.10	0.27	0.34								
FIVE																		
MEAN	8.36	14.27	16.28	45.60	16.08	0.16	0.99	1.06	-0.63	2.53	13	35	-	77	15	8		
STD	8.57	8.05	5.67	8.54	7.25	0.22	0.37	0.29	0.33	0.61								

At Whalehead, Factor groups I,III and IV comprise the lower foreshore, Factor group V represents different areas, but is best represented at the lower foreshore, berm, backshore and dune toe.

It is striking that the factor groups are very well differentiated according to the weight percent in each granulometric class. In other words, they reflect the composition of the factor scores matrix, as well as the end members composition.

Analysis of the factor groups obtained by Q-mode factor analysis using Visher's (1969) method can provide additional insight into environmental separation, and thus support the applicability of Q-mode factor analysis for such studies. According to Visher, natural samples are composed of several straight line segments with each segment representing a log-normal sub-population corresponding to a different mode of sediment transport.

Figure 17(a), shows the log-probability plots of the five end-member sediment samples. Marked differences between the number of segments, truncation points, segment slopes and the degree of mixing are evident for these end-members.

Factor group I end-member, represented by sample **P193** is located on the backshore at Whalehead. It displays a very well sorted population consisting of 70% (of total weight) fine sand and 25% medium sand. Both traction and suspension populations are minimal. The break between the traction and saltation populations occurs at 1.5 phi. **Figure 17(b)** shows that most of the samples in Factor group I have between 3 and 7 segments. The log-normal population which characterizes this factor group as fine sand is defined by the 1.5 and the 2.56 phi truncation points. More than 50% of the sample weight falls within this interval. Important subpopulations are also defined by the -2.75 to -1 and the -1 to 1.5 phi grain size intervals which correspond respectively to gravel and mixtures of very coarse, coarse and medium sand. As the plot indicates, the coarse fraction is more poorly sorted than the fine fraction. Generally (**Table 4** and 5), samples classified under Factor group I are associated with the lower foreshore.

Sample **DP43** represents Factor group II and is located on the backshore at Duck beach. This sample is composed of seven moderate to well sorted segments. The first truncation point occurs at 0.35 phi (coarse sand); 48% of the sample weight is included under this point. A 1.10 phi break, which corresponds to the beginning of the medium sand class, includes 28.5% of the total sample weight. **Figure 18(a)** illustrates all the samples related to Factor group II. The number of segments vary between four and nine. Major populations are related to the -0.1 to 1.15 phi interval (coarse sand). Additional important populations are represented by medium and very coarse sand intervals.

Factor group III is represented by sample **DS22** which is predominantly composed of a well sorted, very coarse sand population. The next segment in terms of weight percent is represented by a poorly sorted, coarse and medium sand corresponding to 10% of the total weight. An additional 10% is represented by a relatively well sorted, medium and fine sand population.

The plots of all the samples related to factor group III are shown in **Figure 18(b)**. The number of segments varies from five to eight. Common characteristics related to this factor group are: the high representation of the well sorted very coarse population and the presence of a well sorted medium to fine sand population which is separated from the very coarse sand by a poorly sorted coarse sand. Although Factor group III represents samples from the lower and upper foreshore, berm samples are also incorporated in this factor group. Even though truncation points are similar, upper foreshore samples appear to have a higher percentage of gravel, very coarse and coarse sand as compared to lower foreshore samples. Berm samples are predominantly gravel, very coarse and medium sand.

Sample **WS27** located on the lower foreshore at Whalehead beach is the end-member representing Factor group IV sediments. This sample is composed of a well sorted population of pebbles and an extremely well sorted, granule and very coarse sand population. The number of segments of the samples included in this factor group **(Figure 19(a)** vary from two to six. In all of them, the major population is defined by the -2.75 phi to -1.25 phi interval which corresponds to the pebble and granule size fraction range. The second most important sediment population is defined by the 1.5-2 to 3.0 phi breaks.

The Factor group V end member is represented by sample **P31**, located on the dune toe at Whalehead beach. Approximately 98% of the total weight of this sample is included between the 0.75 and 2.5 phi interval. Most of the samples related to this factor group **(Figure 19(b))** show a well sorted, medium sand population comprising on the average, more than 50% of the total sample weight. A coarse tail composed of granule and very coarse sand also occurs in many of the samples. Plots representing factor group V are very similar to plots representing factor group I except that the well sorted segment in factor group V is shifted one granulometric class to the left.

5.6 Factor groups and the moment measures

According to **Tables 4 and 5**, statistical measures based on the moment measures for both beaches do not reflect the real grain-size values corresponding to each factor group. This is especially true for the mean statistic. Only Factor Groups V and II, associated with Whalehead beach and Duck beach respectively, are well defined by the mean statistical values. Both of these factor groups represent samples with tendency toward unimodality. As the bimodal characteristics of the different factor groups increase, measures such as the mean can lead to erroneous conclusions about the group characteristics. Even after samples have been grouped by Q-mode, subtle differences existing between distinct populations are not well defined by traditional standard statistics such as mean and mode.

Figure 17. Log-probability plots.

(a) Log-probability plots of the five end-member sediment samples.

(b) Log-probability plots of Factor group I sediment samples.

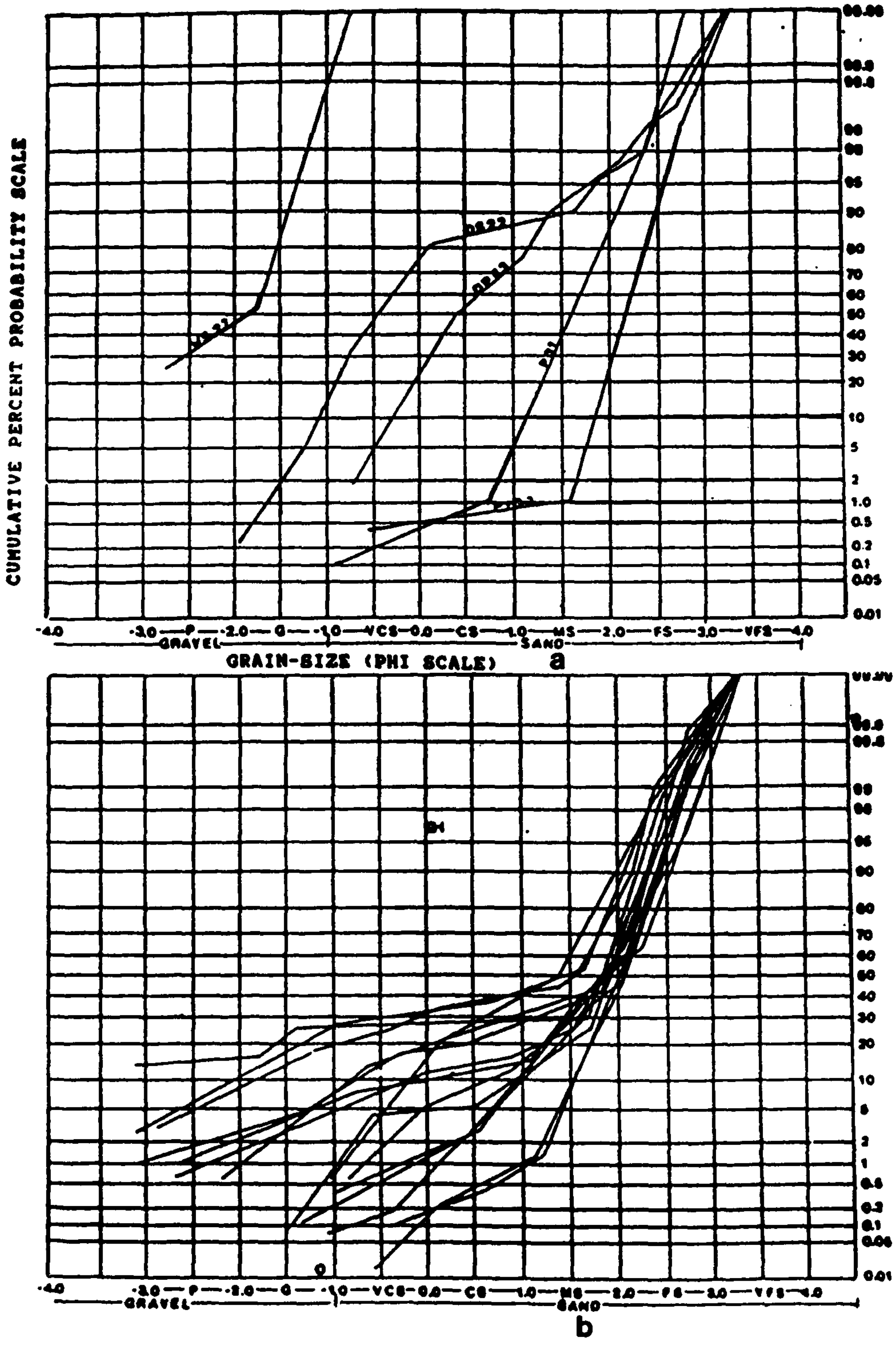
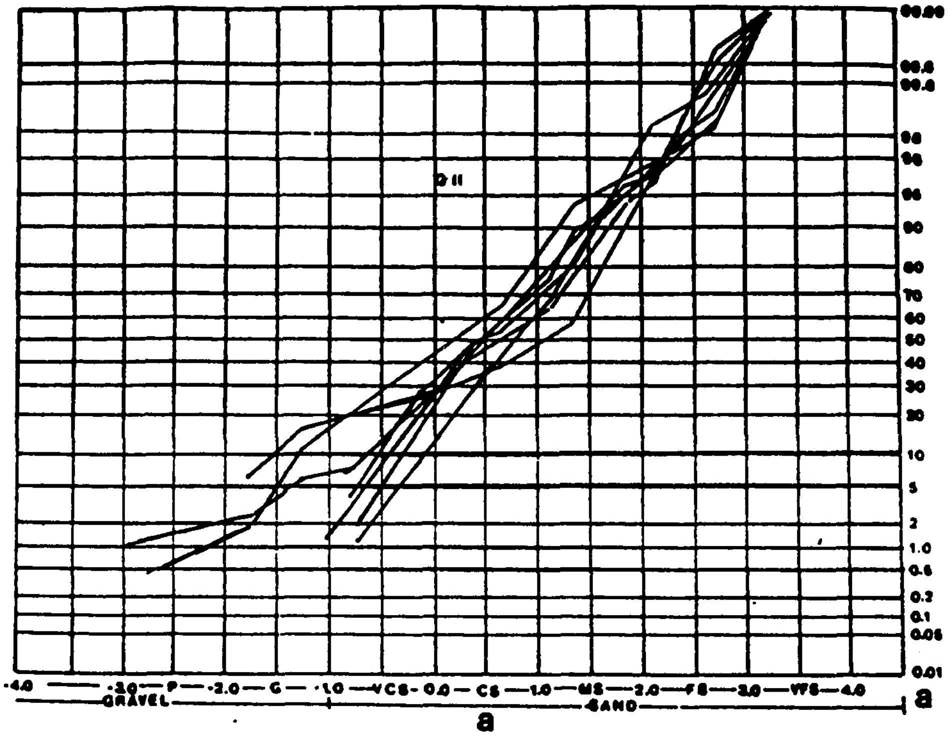

CUMULATIVE PERCENT PROBABILITY SCALE
99.99
99.9
99.8
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1.0
0.5
0.2
0.1
0.05
0.01
DB22
P11
-4.0
-3.0
P
-2.0
G
-1.0
VCS
0.0
CS
1.0
MS
2.0
FS
3.0
VFS
4.0
GRAVEL
SAND
GRAIN-SIZE (PHI SCALE)
a
b

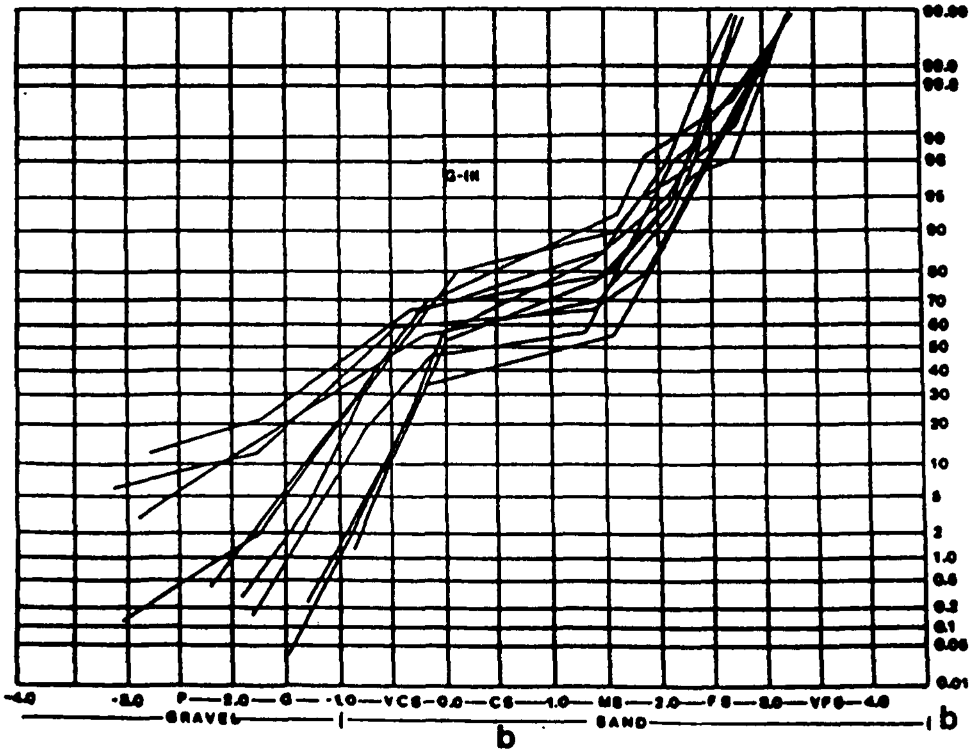
Figure 18. Log-probability plots

(a) Log-probability of Factor group II sediment samples.

(b) Log-probability plots of Factor group III sediment samples.


D II
99.99
99.9
99.8
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1.0
0.5
0.2
0.1
0.05
0.01
-4.0
-3.0
P
-2.0
G
-1.0
VCS
0.0
CS
1.0
MS
2.0
FS
3.0
VFS
4.0
GRAVEL
SAND
a

a

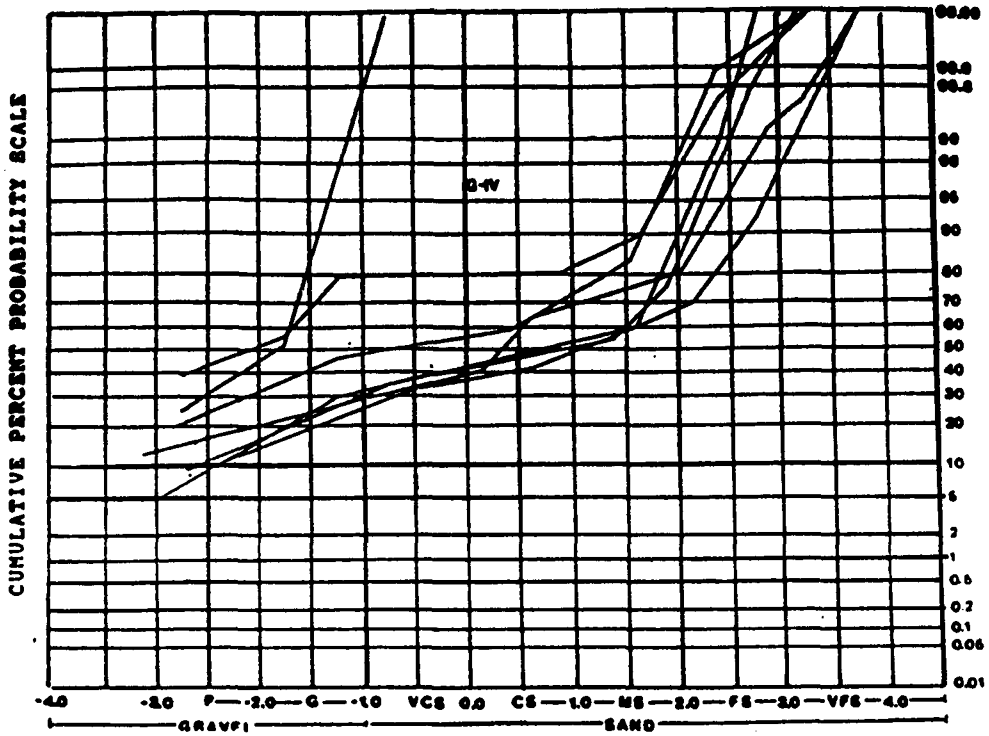

D-III
99.99
99.9
99.8
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1.0
0.5
0.2
0.1
0.05
0.01
-4.0
-3.0
P
-2.0
G
-1.0
VCS
0.0
CS
1.0
MS
2.0
FS
3.0
VFS
4.0
GRAVEL
SAND
b

b

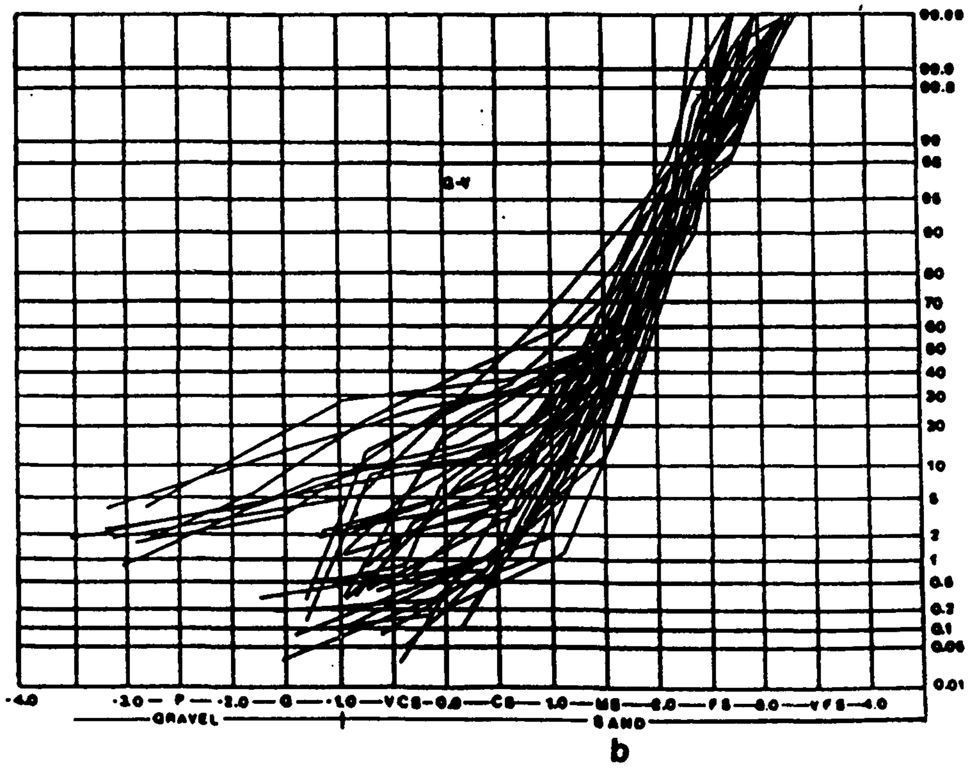
Figure 19. Log-probability plots

(a) Log-probability plots of Factor group IV sediment samples

(b) Log probability plots of Factor group V sediment samples


CUMULATIVE PERCENT PROBABILITY SCALE
G-IV
99.99
99.9
99.8
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
0.1
0.05
0.01
-4.0
-3.0
P
-2.0
G
-1.0
VCS
0.0
CS
1.0
MS
2.0
FS
3.0
VFS
4.0
GRAVEL
SAND
GRAIN-SIZE (PHI SCALE)

a


G-V
99.99
99.9
99.8
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
0.1
0.05
0.01
-4.0
-3.0
P
-2.0
G
-1.0
VCS
0.0
CS
1.0
MS
2.0
FS
3.0
VFS
4.0
GRAVEL
SAND

b

6. DISCUSSION OF THE PILOT STUDY

6.1 Beach zonation

Factor group separation based on the oblique solution proved to be a useful manner to classify sediments according to common grain-size attributes. Homogeneity within factor groups is supported by the log-probability plots. Particularly at Duck beach, there is a reasonable link between factor groups and specific zones along the beach profile.

Factor III, very coarse sand, dominates the upper foreshore,lower foreshore and the berm at Duck. Very coarse sand is deposited on the foreshore and the berm by swash processes during periods of very high water, such as spring tides. The positive skewness of this factor group probably results from the presence of a medium to fine sand fraction. The presence of these sediments could be the result of the prevailing but weak offshore south to southwest wind that transports sediments to the upper foreshore and berm. This fact should be considered because these zones can be subjected to long periods of subaerial exposure. It is possible that the coarse sediment on the lower foreshore is deposited on the upper foreshore and landward during storms or high wave energy seasons. These coarse layers, or storm deposits, display bimodal characteristics. The presence of Factor group III on the lower foreshore is probably related to the backwash regime which concentrates both coarse and fine grain sediments. The fine fraction is not lost to the dune field because it is in constant movement and permanently wet.

At Duck beach, Factor group IV (characterized by pebbles and granules) is best associated with the step and the upper foreshore. Most of the samples as shown by the log probability plots are extremely poorly sorted. This factor group displays unimodal coarse, as well as bimodal, characteristics. At Whalehead beach, Factor group IV, characterized by pebbles and granules, is confined to the lower foreshore and step. Since the uprush current is unlikely to have energy to transport these sediments farther up the beach, Factor group IV sediments are not associated with higher zones. It is well known that many beaches have a concentration of coarse-grained material near the backwash breaker zone (Bascom, 1964) . According to Taira and Scholle (1979), this sediment forms step-like deposits whose upper surface is the continuation of the beach face and whose outer face is at the angle of repose.

Factor group II sediments are dominated by coarse and medium sand. The presence of coarse sand, small amounts of gravel and very coarse sand indicate storm contributions. Although composed of several log-normal sub-populations, most display moderate to well sorted symmetric grain-size distributions. The negligible amounts of fine sand and very fine sand could be due to aeolian processes winnowing out these size fractions.

According to the data set, Factor group I includes samples which best represent the lower and upper foreshore at Duck.

However, this factor group shows high values for all the zones across Whalehead beach.

Factor group V is well represented on all the sub-environments for both locations. However, with the exception of the lower foreshore at Duck, the highest values are found at Whalehead beach.

It is difficult to link Factor groups I and V with specific beach processes when they are well represented everywhere across the beach.

Although truncation points on log-probability plots for sediment factor groups do represent boundaries between specific granulometric classes it is difficult to associate these sub-populations with specific modes of sediment transport. However, in the presented data set, the characteristic foreshore plot described by Visher (1969) and Kolmer (1966) appears to be best identified in Factor groups III and I. In particular, Factor group III is very similar to distributions described by Visher as foreshore sediments composed of terrigenous gravel displaying a high percentage of material in the rolling sub-population.

In summary, even though the log probability plots of sediment factor groups previously defined by Q-mode factor analysis are distinct, only three major sub-environments are clearly defined: 1) The backshore (plots of Factor group II). 2) The general foreshore (upper and lower) which can include the berm and 3) the step (plots of Factor group IV).

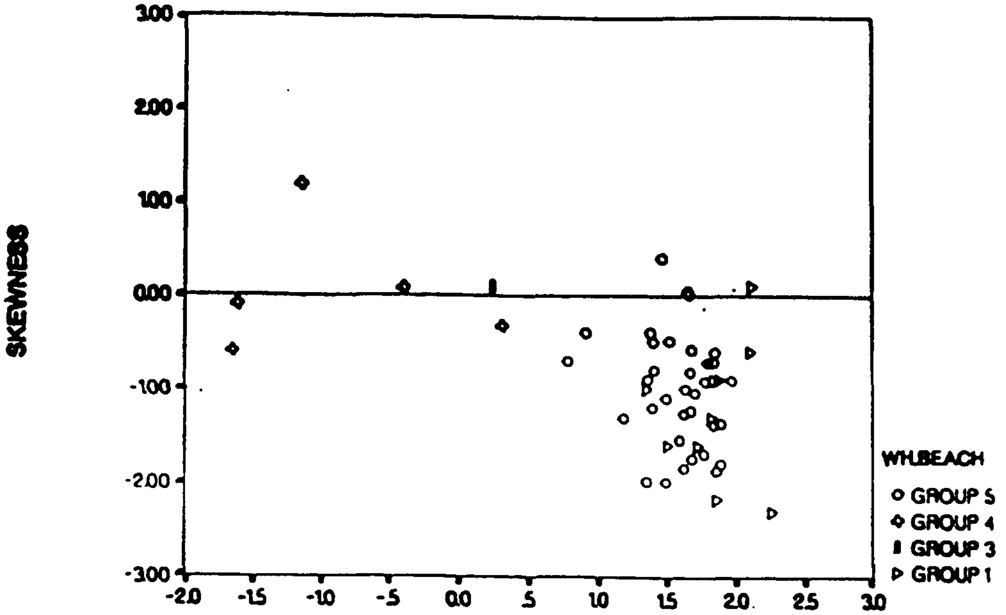
6.2 Factor Analysis versus standard statistics

As was shown in **Tables 4** and 5 the mean obtained by standard statistical methods does not adequately represent the factor group characteristics. In **Figures 20 to 25,** the moment measures are displayed separately for both beaches in the form of bivariate plots. Based on the mean and standard deviation it is difficult to separate Factor group I from V at Whalehead beach **(Figure 20(b))**. Skewness is thought to be one of the most sensitive environmental indicators (Greenwood, 1969; Friedman, 1963). Mason and Folk (1958) found that bivariate plots of skewness and kurtosis are the best means of distinguishing environments in a barrier island. According to Mason and Folk (1958), differences between environments on barrier islands are reflected only in the tails of the grain-size curves; and skewness and kurtosis are specifically aimed at measuring these properties. According to Greenwood (1969), the range of skewness values for the foreshore and backshore make this parameter useful for separating environments of deposition. Greenwood states that backshore sands exhibit very low negative skewness values and their distributions are nearly symmetrical. The foreshore deposits have a tendency to be negatively skewed or very coarse. **Figures 22(b) and 24(b)** displays bivariate plots of skewness versus kurtosis for Duck and Whalehead beach, respectively. Factor group II, characterizing the backshore at Duck shows low positive values. Factor group III which characterizes the lower foreshore at Duck shows strong positively skewed values. These anomalous values are probably due to the bimodal characteristics displayed by Factor group III. The standard statistical parameters probably are best applied to unimodal distributions.

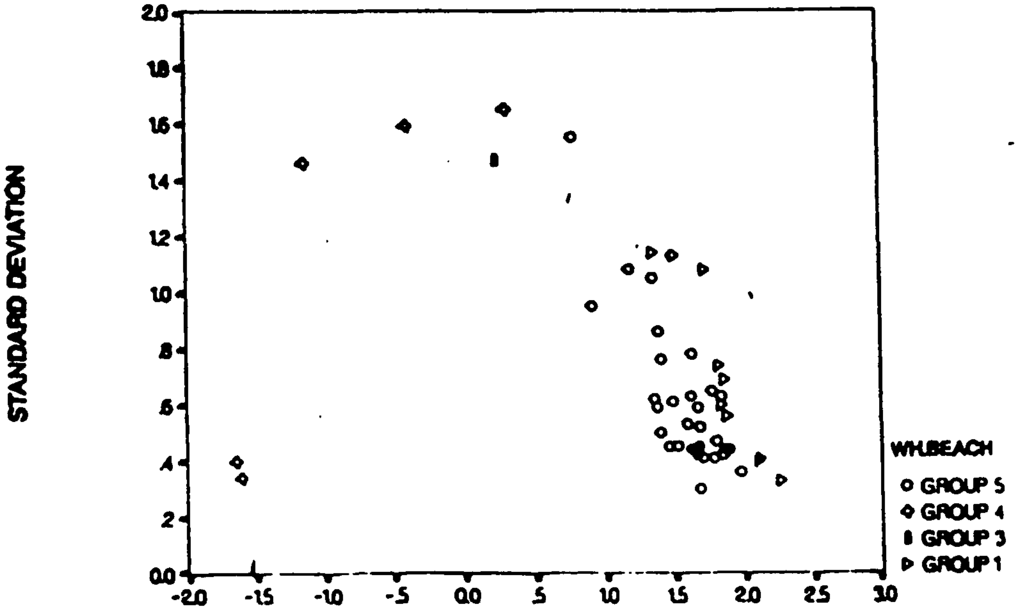
Figure 20. Plot of the moment measures for Whalehead beach.

(a) Mean versus skewness

(b) Mean versus standard deviation


SKEWNESS
3.00
2.00
1.00
0.00
-1.00
-2.00
-3.00
-2.0
-1.5
-1.0
-.5
0.0
.5
1.0
1.5
2.0
2.5
3.0
WH.BEACH
○ GROUP 5
◇ GROUP 4
▮ GROUP 3
▷ GROUP 1

a


STANDARD DEVIATION
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0.0
-2.0
-1.5
-1.0
-.5
0.0
.5
1.0
1.5
2.0
2.5
3.0
WH.BEACH
○ GROUP 5
◇ GROUP 4
▮ GROUP 3
▷ GROUP 1

b

MEAN

Figure 21. Plot of the moment measures for Whalehead beach.

(a) Standard deviation versus skewness

(b) Mean versus kurtosis.

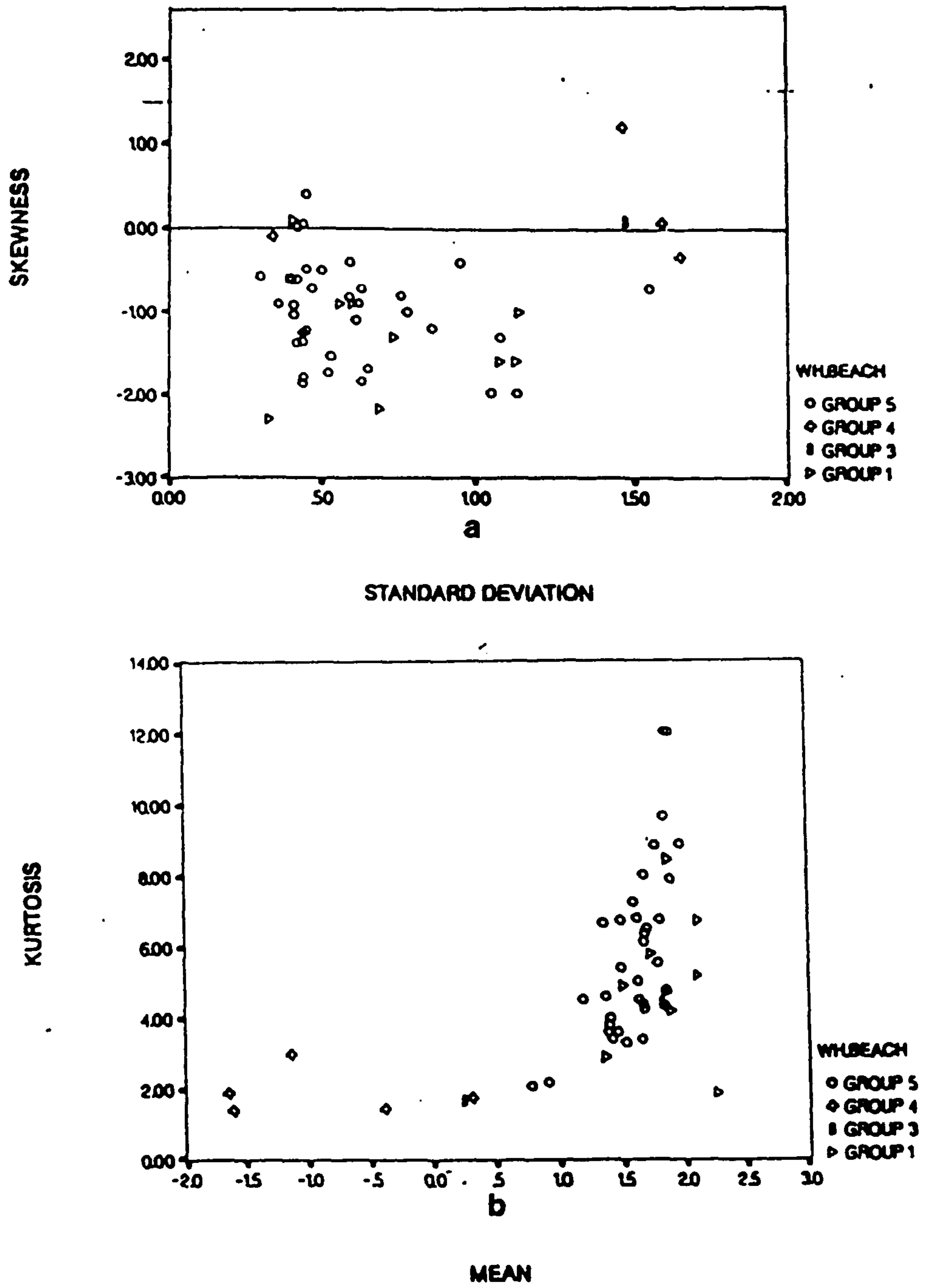
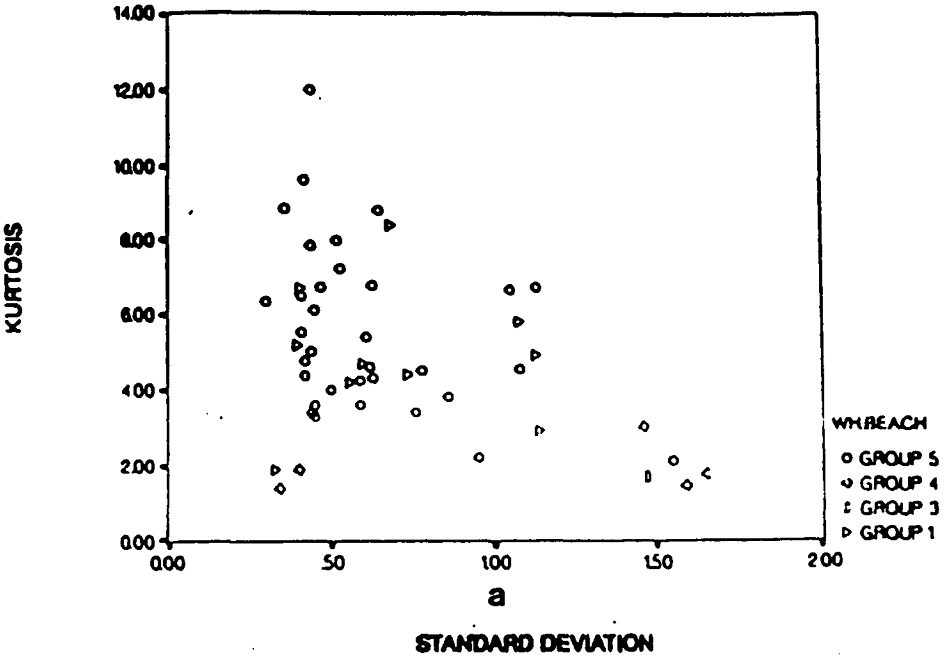

SKEWNESS
2.00
1.00
0.00
-1.00
-2.00
-3.00
0.00
.50
1.00
1.50
2.00
WH.BEACH
GROUP 5
GROUP 4
GROUP 3
GROUP 1
a
STANDARD DEVIATION
KURTOSIS
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
-2.0
-1.5
-1.0
-.5
0.0
.5
1.0
1.5
2.0
2.5
3.0
WH.BEACH
GROUP 5
GROUP 4
GROUP 3
GROUP 1
b
MEAN

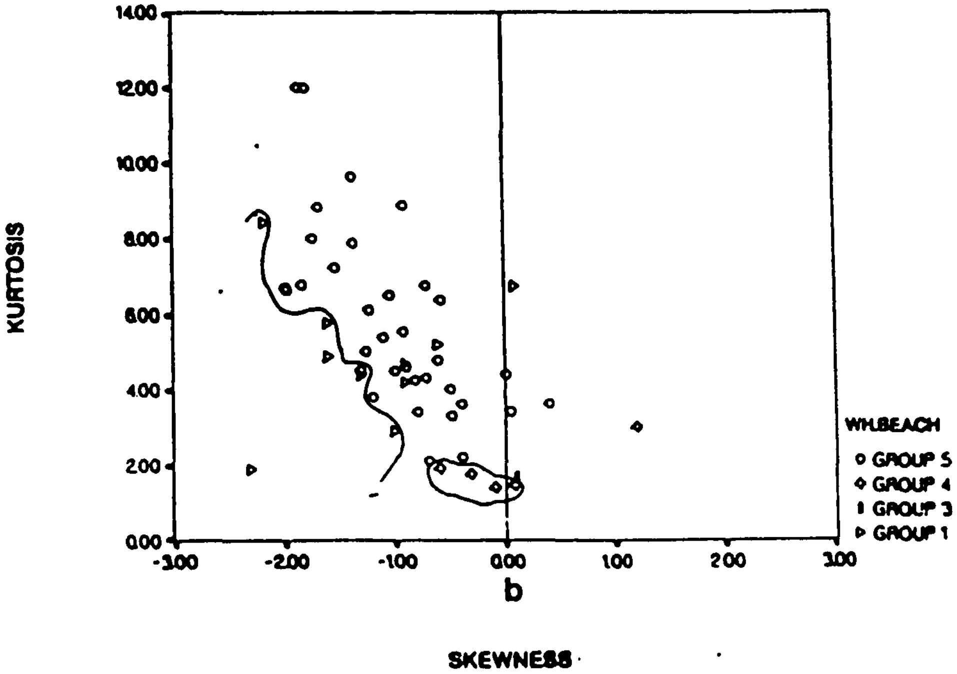
Figure 22. Plot of the moment measures for Whalehead beach

(a) Standard deviation versus kurtosis

(b) Skewness versus kurtosis


KURTOSIS
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
0.00
.50
1.00
1.50
2.00
STANDARD DEVIATION
WH.BEACH
GROUP 5
GROUP 4
GROUP 3
GROUP 1

a

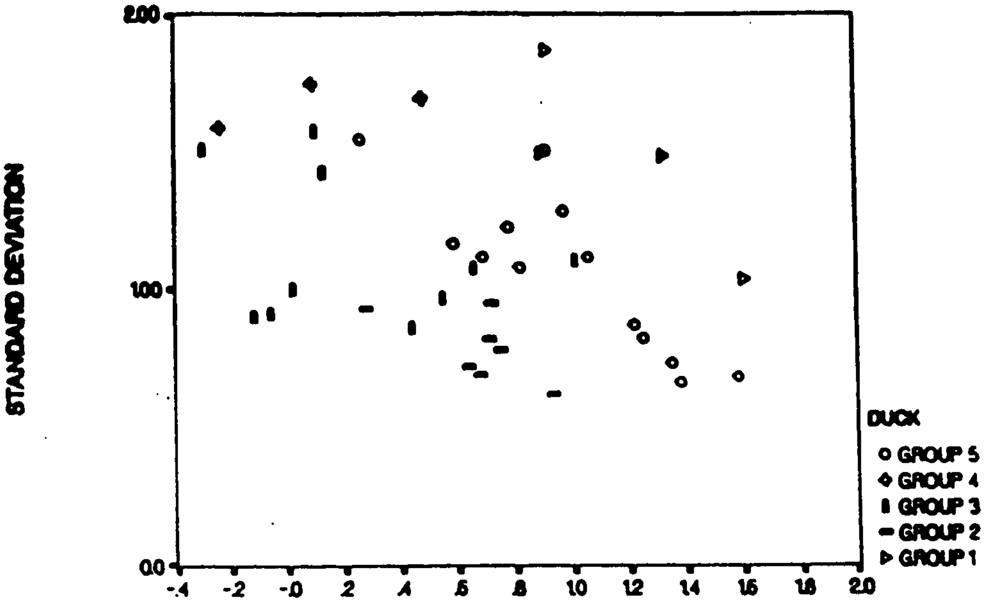

KURTOSIS
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
-3.00
-2.00
-1.00
0.00
1.00
2.00
3.00
SKEWNESS
WH.BEACH
GROUP 5
GROUP 4
GROUP 3
GROUP 1

b

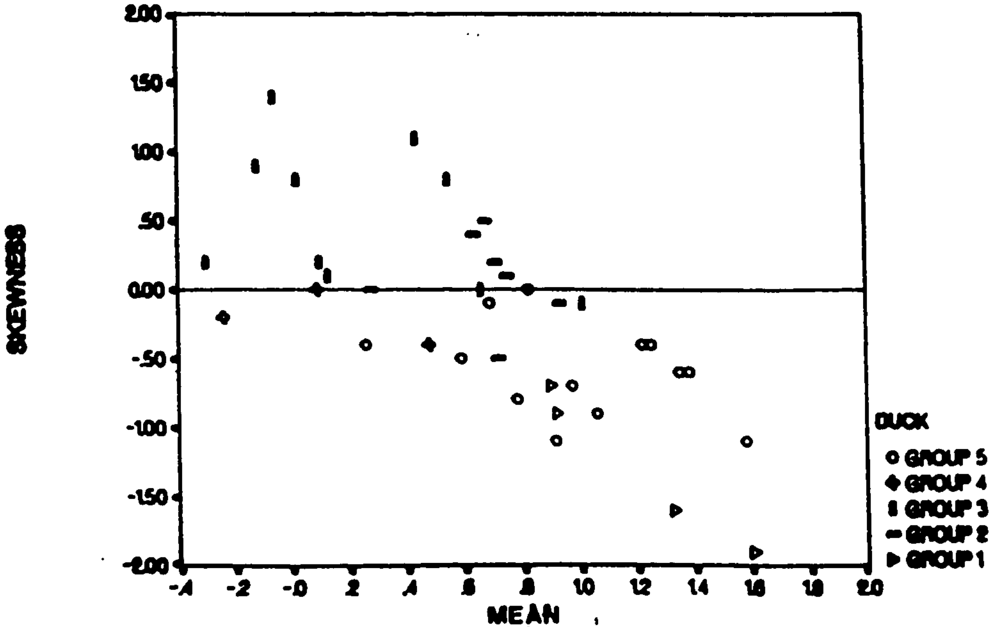
Figure 23. Plot of the moment measures for Duck beach

(a) Mean versus standard deviation

(b) Mean versus skewness


STANDARD DEVIATION
2.00
1.00
0.0
-.4
-.2
-.0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
DUCK
○ GROUP 5
◇ GROUP 4
▮ GROUP 3
▬ GROUP 2
▷ GROUP 1
MEAN

a

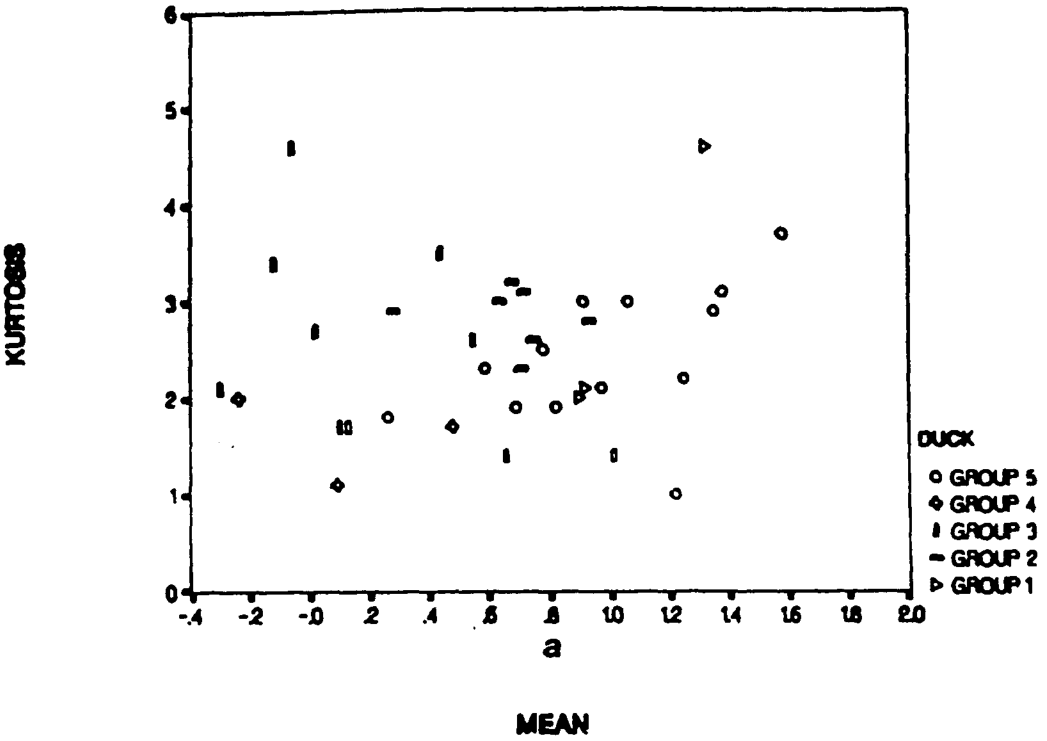

SKEWNESS
2.00
1.50
1.00
.50
0.00
-.50
-1.00
-1.50
-2.00
-.4
-.2
-.0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
MEAN
DUCK
○ GROUP 5
◆ GROUP 4
▮ GROUP 3
▬ GROUP 2
▶ GROUP 1

b

Figure 24. Plot of the moment measures for Duck beach

(a) Mean versus kurtosis

(b) Skewness versus kurtosis


KURTOSIS
6
5
4
3
2
1
0
-.4
-.2
-.0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
a
MEAN
DUCK
○ GROUP 5
◊ GROUP 4
▮ GROUP 3
▬ GROUP 2
▷ GROUP 1

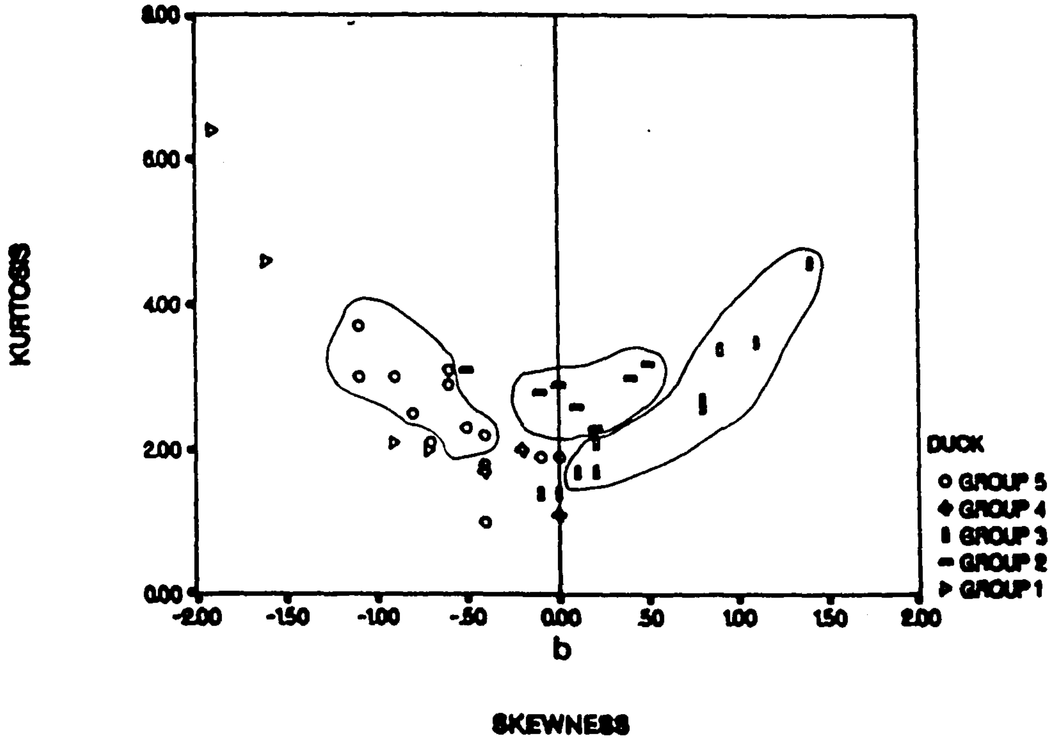
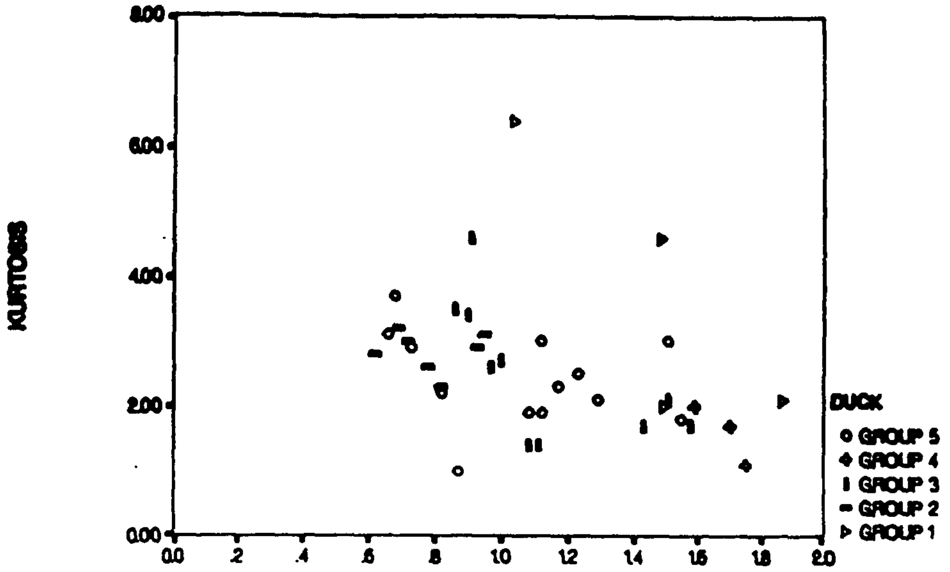

KURTOSIS
8.00
6.00
4.00
2.00
0.00
-2.00
-1.50
-1.00
-.50
0.00
.50
1.00
1.50
2.00
b
SKEWNESS
DUCK
○ GROUP 5
◆ GROUP 4
▮ GROUP 3
▬ GROUP 2
▶ GROUP 1

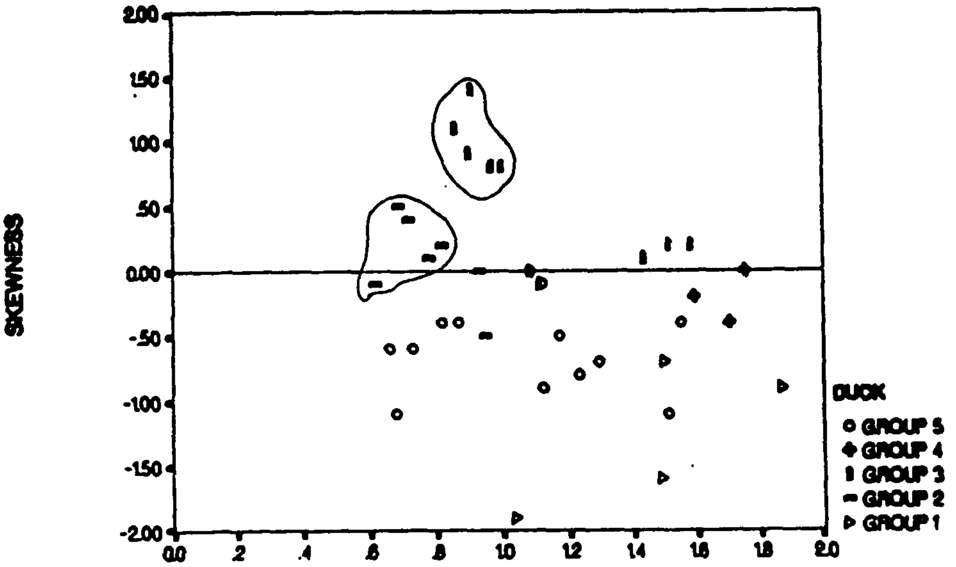
Figure 25. Plot of the moment measures for Duck beach

(a) Standard deviation versus kurtosis

(b) Standard deviation versus skewness


8.00
6.00
4.00
2.00
0.00
KURTOSIS
0.0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
DUCK
GROUP 5
GROUP 4
GROUP 3
GROUP 2
GROUP 1
STANDARD DEVIATION

a


2.00
1.50
1.00
.50
0.00
-.50
-1.00
-1.50
-2.00
SKEWNESS
0.0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
DUCK
GROUP 5
GROUP 4
GROUP 3
GROUP 2
GROUP 1
STANDARD DEVIATION

b

6.3 Differences in the spatial sediment distributions among Duck and Whalehead beach

The spatial distribution of the factor groups, as well as the average percentage of factor by zone as calculated based on the composition loading matrix, indicates that beaches composed of a highly variable grain-size range display both greater sedimentological variability and more distinct zonations than beaches composed of a small grain-size range. Plots of factor loadings and groups at Duck beach indicate that the backshore is well characterized by Factor II (coarse sand) **(Figure 13(a))**. Factor I (fine sand) in both beaches is more representative of the lower foreshore. The trends suggest that the characteristic zonations observed are due to the availability of particular grain-size assemblages and to the predominance of specific processes acting on specific zones.

On Duck beach, the gradation in grain-size observed from the backshore to the upper foreshore is in agreement with previous studies describing these environments (Fox et al, 1963; Greenwood, 1966; Bascom, 1951). However, the presence of Factor group I sediments (fine sand) at the lower foreshore is unusual. The absence of fine sands in the backshore, berm and upper foreshore at Duck is thought to be due to the proximity of these zones to a source of coarse sediments. The original sediment factor groups, which were probably represented by Factors I and V, have been replaced by Factor groups II, III and IV. Aeolian and wave processes (swash and backwash) have removed Factor group I sediments and deposited them in dune fields or transported them offshore. Cross-shore grain size distributions at Duck as described by Birkemeier (1985) support this observation. Bimodal samples with a gravel to coarse sand mode are practically restricted to the subaerial beach. Seaward of this zone the sediments become fine and unimodal. Apparently coarse material remains on the foreshore and is transported between the berm and step or the first trough of the longshore bar according to the cyclicity described by Sonu (1972). Finer sediment is subject to transport between the beach and the nearshore area. This observation is also supported in the nearshore hydrodynamic models based on non-linear wave theory as proposed by Cornaglia (1898) in Komar (1976). These studies recognize the asymmetry of the wave orbital motions with a strong onshore velocity versus a weaker offshore velocity with a longer duration. The result is a net shoreward transport of coarser sediment. More recently, Richmond and Sallenger (1984) compared changes in foreshore texture with computed values of onshore transported material based on current measurements from the inner surf-zone and Bagnold's total-load sediment transport model to the data collected during the Duck 82 experiment. According to them, although the mechanisms of sediment transport and deposition on the foreshore differ from those in the nearshore, the sediment moving onshore through the inner surf zone should be and indicator of the material deposited on the foreshore. Their results showed that sediment coarser than 0.4mm (medium sand) can be expected to move landward. Sediments finner than 0.4mm were predicted to move offshore. According to Richmond and Sallenger (1984) such results are in agreement with previous theoretical (Bowen, 1980) and field (Murray,

1967) studies which have shown the possibility of different size classes of sediment be transported in opposite direction under oscillatory flow. As waves shoal, oscillatory water velocities become asymmetric with a strong and short landward flow followed by an slower and longer seaward return flow. Due to the higher peak flow, the landward directed current is able to transport coarser material than the seaward current (Richmond and Sallenger, 1984). They also point out that the seaward migration of the bar was presumably due to the result of offshore transport of medium and fine sands, which is in agreement with previous nearshore sediment data obtained by Birkemeier et al. (1985). According to Birkemeier (personal communication) the offshore limit for the occurrence of coarse sediments generally coincides with the first nearshore trough.

6.4 Inferences about geologic evolution of the study beaches

The absence of Factor groups II and III, as well as the low representation of Factor group IV sediments, at Whalehead suggests that factor groups I and V were the two original sediment types present on the ancient beach of this barrier island system. The proximity to relict Pleistocene deposits serving as the sediment source, the process of shoreface retreat which erodes and distributes the sediment and geological time have been responsible for the actual differences between Duck and Whalehead in terms of sediment composition and associated beach morphology. Vibracores and drill holes from the beach and nearshore area at Duck analysed by Field (1973), and presented in Birkemeier (1985) indicate that the beach is underlain by more than 15 m of sand at the modern shoreline. Sediments vary from coarse sand with gravel layers to dense, poorly graded well sorted fine sand. Well graded sand with gravel and poorly graded sand with occasional gravel horizons appear in cores located offshore in 6 m of water. Based on the same cores, Field et al.(1979) suggest that the upper portion of the barrier in this area represents a prograding spit sequence in the ancestral Albemarle River channel.

Wright et al.(1985) related the six commonly occurring beach states (dissipative, longshore bar-through, rhythmic bar and beach, transverse bar and rip, low-tide terrace, and reflective) with the parameter $\Omega = Hb/Ws\ T$ in which Hb is breaker height, Ws is mean sediment fall velocity and T is wave period, as being the most significant dimensionless index for examining the behavior of beach profiles. Data analysed by Wright and Short (1984) showed that when $\Omega < 1$ the beach will remain in the reflective extreme; when $\Omega > 6$ the beach will remain fully dissipative. For $1 < \Omega > 6$, the beach state tends to be intermediate. **Table 6** displays a time series of breaker height, wave period and sediment settling velocity using the mean, the modal coarse and the modal fine grain-size. Wave data at both beaches were obtained by applying a numerical model of wave transformation by shoaling, refraction and frictional dissipation developed by Green (1987). At Duck, the sediments vary between unimodal coarse, bimodal and unimodal fine. Sediments at Whalehead vary from unimodal fine to bimodal; with unimodal distributions being more frequent. As can be seen from this table, the range of Ω

for both beaches can be highly variable according to the sediment settling velocity used. The occurrence of coarse sediments at Duck contributes to the low Ω values for this beach. The fact that differences in wave height and period between the two beaches is minimal indicates that grain-size is the most important parameter determining morphologic differences between them.

Table 6. Time series of breaker height, wave period, sediment fall velocity and the Ω parameter obtained for Duck and Whale Head beach. Hb = breaker height; T= wave period; Ω= Hb/T.Ws; W= sediment fall velocity; W mean = sediment settling velocity using the mean grain-size; Wcm= sediment settling velocity using the coarse mode grain-size; Wfm= sediment settling velocity using the fine mode grain-size.

WHALE HEAD

DAY	Hb(cm)	T(s)	W(cm/s)			Ω			FORESHORE SEDIMENT CHARACTERISTICS
			MEAN	CM	FM	MEAN	CM	FM	
9-19-87	80	8.5	4.31	7.41	2.86	2.15	1.25	3.25	Bimodal
9-20-87	93	8.1	4.31	-	-	2.66		-	Unimodal Fine
9-21-87	83	8.7	4.31	14.58	2.86	2.21	0.65	3.33	Bimodal
9-22-87	65	9.2	4.31	6.24	2.56	1.63	1.13	2.75	Bimodal
9-23-87	52	5.4	4.31	-	-	2.23	-	-	Unimodal Fine
9-24-87	40	9.4	3.18	-	-	1.33	-	-	Unimodal Fine
9-25-87	49	3.9	3.91	-	-	3.32	-	-	Unimodal Fine
9-26-87	75	9.9	3.91	-	-	1.94	-	-	Unimodal Fine
9-27-87	43	7.8	3.92	12.96	2.56	1.41	0.42	2.15	Bimodal
9-28-87	41	6.9	3.91	-	-	1.52	-	-	Bimodal
9-30-87	69	7.6	4.31	15.60	2.56	2.10	0.58	2.71	Bimodal
10-02-87	53	8.1	4.75	12.69	2.29	1.38	0.51	2.63	Bimodal
10-03-87	49	8.2	3.18	-	-	1.87	-	-	Unimodal
10-06-87	84	14.7	3.91	-	-	1.46	-	-	Unimodal
10-07-87	87	11.0	4.75	6.24	2.56	1.66	1.26	3.06	Bimodal
10-08-87	71	10.0	4.31	6.24	3.18	1.64	1.13	2.22	Bimodal
10-09-87	77	8.9	3.53	-	-	2.44	-	-	Unimodal
10-10-87	54	10.4	3.53	6.24	2.86	1.46	0.83	1.81	Bimodal
10-16-87	111	9.9	3.18	-	-	3.52	-	-	Unimodal

DUCK, N.C.

DAY	Hb(cm)	T(s)	W(cm/s)			Ω			FORESHORE SEDIMENT CHARACTERISTICS
			MEAN	CM	FM	MEAN	CM	FM	
9-19-87	91	8.5				2.25	0.78	3.16	Bimodal
9-20-87	93	8.0	4.75	13.62	3.53	1.70	1.14	3.64	Bimodal
9-21-87	95	8.8	6.81	10.19	3.18	0.98	0.69	3.77	Bimodal
9-22-87	75	9.2	10.98	15.60	2.86	0.69	0.56	2.85	Bimodal
9-23-87	60	7.6	11.82	14.58	2.86	1.16	0.54	2.01	Bimodal
9-24-87	42	9.1	6.81	14.58	3.91	0.48	0.39	1.06	Bimodal
9-25-87	68	4.7	9.43	11.82	4.31	2.12	1.31	4.54	Bimodal
9-26-87	86	9.5	6.81	10.98	3.18	1.58	1.12	3.16	Bimodal
9-27-87	45	7.8	5.71	8.04	2.86	1.81	-	-	Unimodal Fine
9-28-87	59	6.7	3.18	-	-	2.34	-	-	Unimodal Fine
9-29-87	58	6.5	5.71	11.82	3.18	1.01	0.75	2.80	Bimodal
9-30-87	77	7.8	5.21	9.43	2.86	1.89	1.04	3.44	Bimodal
10-02-87	71	8.4	6.24	12.69	3.91	1.35	0.66	2.15	Bimodal
10-03-87	59	7.9	4.75	8.04	2.86	1.57	0.92	2.60	Bimodal
10-06-87	80	8.4	8.04	15.60	2.86	1.18	0.61	3.47	Bimodal
10-07-87	87	10.2	5.21	12.69	2.86	1.63	0.67	2.98	Bimodal
10-08-87	74	7.6	3.91	12.69	2.86	2.49	0.76	3.40	Bimodal
10-09-87	71	8.8	1.61	-	-	5.00	-	-	Unimodal Fine
10-10-87	67	13.3	3.91			1.28	-	-	Unimodal
16-10-87	124	10.0	6.24	11.82	4.31	1.98	1.05	2.88	Bimodal

7. GENERAL STUDY : DUCK AND COQUINA BEACH

Introduction

In order to consolidate the results found in the pilot study and verify the alongshore variation of the sediment groups defined by Q-mode factor analysis, a more complete data set was needed. In addition to better define the cross-shore zonation boundaries, this data set would have to include a time series of beach profiles and associated sediment characteristics to investigate seasonal variability. Sample collection was provided by the Coastal Engineering Research Center's (CERC's) Field Research Facility, located at Duck, North Carolina.

7.1. Data description

As part of a study conducted by the CERC Beach Evaluation Program (BEP), from May of 1974 to January 1977, a series of 915 sediment samples were collected at quarterly intervals from 14 beach normal transects located between Duck and Oregon inlet (Birkemeier et al, 1975) **(Figure 26)**. Samples were collected from the landward side of the dune, the dune crest, the dune toe, the backshore, the berm, the foreshore and the step. The elevation of each sample station was determined by level and rod techniques.

In contrast to the sampling technique used in the pilot study, where the 15 cm of sediment was sampled, BEP's sediment data represent the top first centimeter. Major differences in sediment analysis techniques between this data set and that used in the pilot study can account for the exclusion of the gravel fraction and the inclusion of minor amounts of shell fragments in the BEP data.

Splits of the original samples were analyzed on the CERC Rapid Sediment Analyzer (RSA). Weight percents at 0.50 phi class intervals in the sand fraction (-1 to 4 phi), and the standard statistics graphics moment measures were obtained from the CERC's RSA output program.

7.2. Data Collection

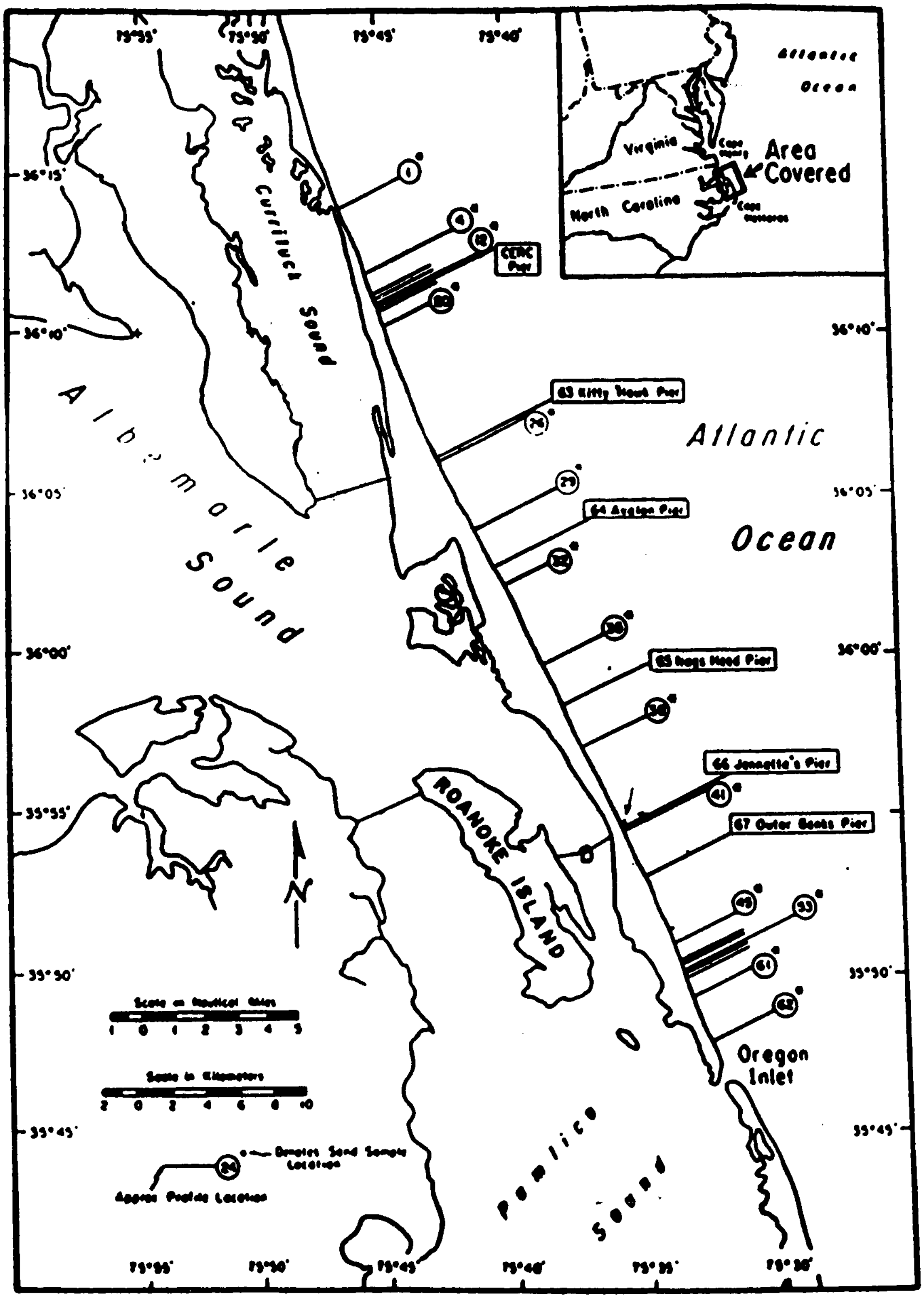
Field observations of the region sampled by the BEP clearly depict the beaches of Duck and Coquina as opposite extremes with regard to sediment texture and general morphology. These two sites were chosen to verify the validity of the pilot study.

A time series of 27 sediment sample profiles, (17 from Duck at profile 20 and 10 from Coquina beach at profile 53) representing different seasons from 1974 to 1978 were randomly selected from the original data set. The number of sample points in each profile varied between 5 and 10. These profiles provided 178 sediment samples collected from the landward side of the dune to the beach step.

The original matrix for this study then consisted of 178 rows by 10 variables. This matrix was then analyzed through a Q-mode factor analysis program.

An additional 350 sediment samples from the beaches located between Duck and Coquina were used to determine the alongshore variability of the sediment factor groups defined by the study of these two extreme beaches.

Figure 26. Location of sand sample profile lines. From Birkemeier et al. (1985)



75°55'
75°50'
75°45'
75°40'
75°35'
75°30'
36°15'
36°10'
36°05'
36°00'
35°55'
35°50'
35°45'
Atlantic Ocean
Virginia
North Carolina
Area Covered
Currituck Sound
Albemarle Sound
ROANOKE ISLAND
Pamlico Sound
Atlantic
Ocean
Oregon Inlet
CERC Pier
63 Kitty Hawk Pier
64 Avalon Pier
65 Nags Head Pier
66 Jennette's Pier
67 Outer Banks Pier
1
4
29
41
53
61
62
N
Scale in Nautical Miles
1 0 1 2 3 4 5
Scale in Kilometers
2 0 2 4 6 8 10
24
Denotes Sand Sample Location
Approx Profile Location

8. RESULTS

8.1. The Factor Solution

The best solution was attained using five factors. **Table 7** lists the calculated eigenvalues for the general 178 x 10 matrix explained by the first seven factors. The individual and cumulative variance of factors before and after the varimax rotation are also provided. It can be seen that after the rotation, most of the variance is explained by Factors I and III. In addition, there is a more even distribution in the variance, with Factors IV and II being approximately equal. The varimax factor loading matrix obtained with the first five principal factors indicates that most samples have communality values higher than 0.99. Only 6 of the 178 samples have a communality value less than 0.9. However, these values are all higher than 0.7; the critical value normally chosen as a cut-off for sample elimination.

The composition scores of reference axis matrix is indicated in **Figure 27 and Table 8**. It can be observed that factor I is mostly dominated by variables 5 and 6 (medium sand). Factor axis II is predominantly composed of variables 3 and 4 which characterizes the coarse sand interval. Factor III displays subtle bimodal characteristics. The primary mode is constituted by coarse and medium sand. The secondary mode is primarily composed of fine sand grains (variables 7 and 8). Variables 6 through 9 (upper portion of medium sand to very fine sand) describe factor axis IV. Factor V, the coarsest factor, is mostly represented by variables 1 and 2 (very coarse sand).

Table 7. Eigenvalues of the 178x10 sediment data matrix for the Duck and Coquina beach data set, explained by the first seven factors, along with the individual and cummulative sums of squares before and after the rotation.

NUM	EIGENVALUE	%INDIVIDUAL SUM OF SQUARES	CUMULATIVE SUM OF SQUARES	%INDIVIDUAL SUM OF SQUARES AFTER ROTATION	CUMULATIVE SUM OF SQUARES AFTER ROTATION
I	123.873108	73.11	73.11	39.086	39.08
II	23.340515	13.04	86.15	15.034	54.12
III	11.134426	6.22	92.37	24.058	78.18
IV	5.322152	2.97	95.35	15.933	94.11
V	4.107711	2.29	97.64	3.530	97.64
VI	2.291609	1.28	98.92		
VII	1.0371766	0.58	99.50		

Figure 27. Histogram of the composition scores of reference factor axes for the Duck and Coquina beach data set. Ms = medium sand; CS= coarse sand; FS= fine sand; VFS= very fine sand; VCS= very coarse sand.

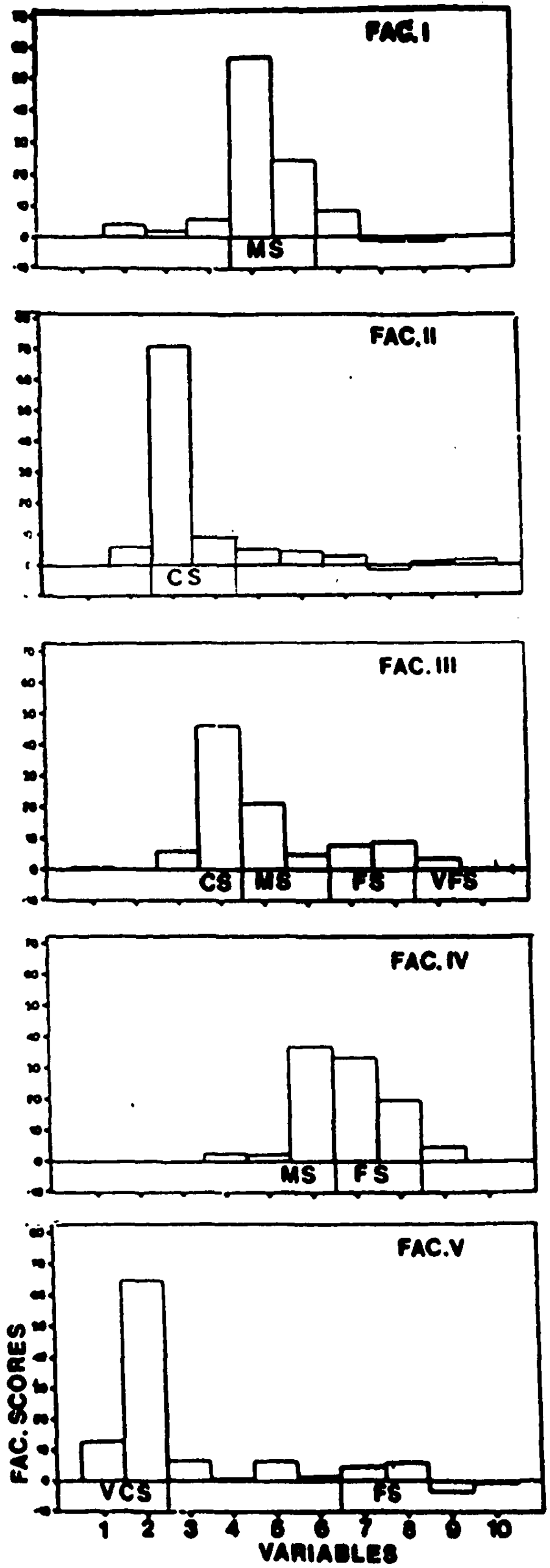

FAC. I
MS
FAC. II
CS
FAC. III
CS
MS
FS
VFS
FAC. IV
MS
FS
FAC. V
VCS
FS
FAC. SCORES
1
2
3
4
5
6
7
8
9
10
VARIABLES

Table 8. Duck and Coquina beach data set. Composition scores of reference factor axes.

Composition scores of reference Factor axes

PHI CLASS	VAR AXIS	I	II	III	IV	V
-1.0/0.50	1	0.5279	-0.2340	0.9138	-0.0402	12.8687
-0.50/0.0	2	4.2430	6.1681	0.0720	0.2525	54.9114
0.0/0.50	3	2.2142	71.1455	5.8757	-0.3969	6.7651
0.50/1.0	4	6.1328	9.2337	46.1686	2.7006	0.9865
1.0/1.5	5	56.4695	5.2930	21.2678	2.2587	6.6873
1.5/2.0	6	24.3485	4.5546	4.8968	36.9295	1.6065
2.0/2.5	7	8.5160	3.0929	7.9165	33.4694	4.7773
2.5/3.0	8	-1.2489	-1.8734	8.9547	19.8704	6.0592
3.0/3.5	9	-1.3511	1.1529	3.5568	4.7718	-3.5817
3.5/4.0	10	0.1481	1.4667	0.3773	0.1842	-1.0804

8.1.2. End member samples

Table 9 displays the end-member samples obtained by the oblique solution. All the diagonal elements of this table have high loadings indicating that a good explanation was achieved by the five factor solution. Histograms and graphical statistical parameters are given in **Figure 28**.

Sample **1774**, located on the upper foreshore at Coquina beach, was determined to be the extreme end-member representing Factor I.

The grain size parameters show that this sample consists of a moderately well sorted, strongly skewed medium sand. End-member II is sample **5747D** which is located on the lower foreshore at Duck. According to the histogram and statistical parameters, this sample is an extremely fine skewed, leptokurtic, well sorted coarse sand.

Factor III's end-member sample is represented by sample **178RD**. This sample was collected from the backshore at Duck and is classified as an extremely leptokurtic, fine skewed, moderately sorted coarse sand.

Sample **Q7752** from the dune crest at Coquina beach is the Factor IV end-member. According to the textural parameters derived from the graphic measures, this sample is predominantly composed of a very leptokurtic, near symmetrical, moderately to well sorted medium sand. Analysis of the sample histogram however, shows that the sample is composed mainly of fine sand.

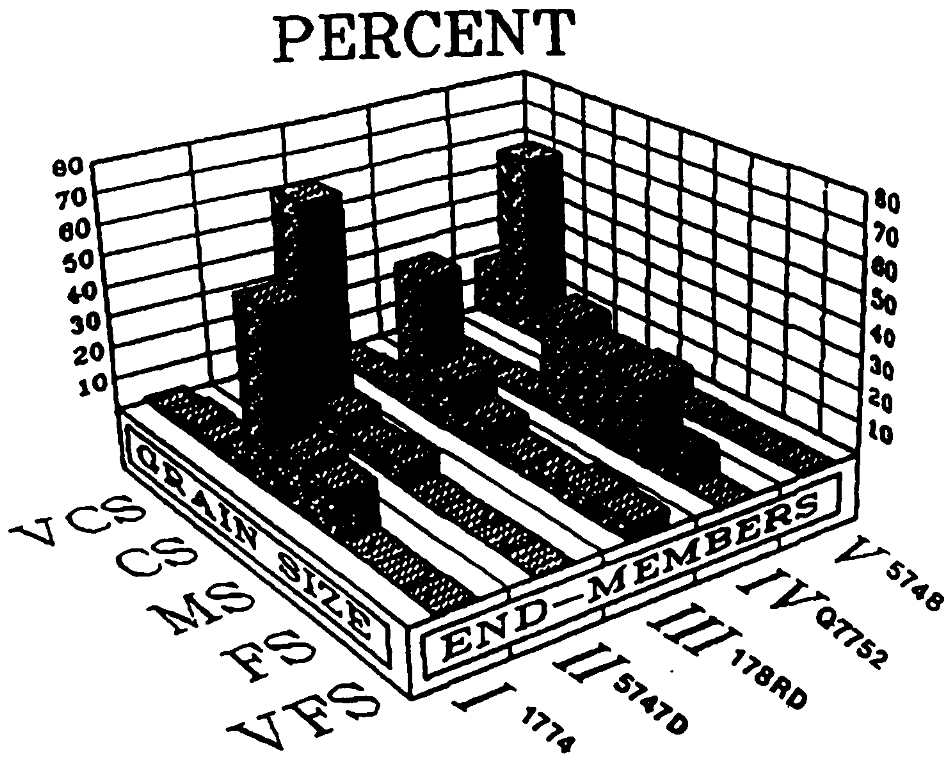
Sample 5748 located on the lower foreshore at Coquina Beach illustrates the coarsest sediments found in these beaches. Analysis of the histogram and graphical measures indicates that it is a very leptokurtic, fine skewed, moderately well sorted sand.

Table 9. Duck and Coquina beach. Communalities and loadings of extreme normalized samples selected as population end-members.

Communalities and loadings of extreme normalized samples selected as population end-members (Duck and Coquina beach)

END-MEMBER	COMMUNALITY	1	2	3	4	5
1774	0.9952	0.9474	0.0450	0.2992	-0.0721	0.0298
5747D	0.9967	-0.0507	0.9778	0.0117	-0.0524	-0.1877
178RD	0.9985	-0.0620	0.1188	0.9882	0.0471	0.0422
7752	0.9988	0.3435	0.0754	0.0894	0.9300	0.0470
5748	0.9937	-0.0135	0.2824	-0.0606	-0.0295	0.9535

Figure 28. Histograms and grain-size statistics parameters of sediment samples determined as end-members for the Duck and Coquina beach data set.



sample	mean	std.dev.	skw.	kurt.
1774	1.35	0.59	-0.87	5.07
5747D	0.41	0.47	1.62	5.49
178RD	0.86	0.95	1.19	3.38
Q7752	1.74	0.52	-0.09	2.68
5748	-0.06	0.69	1.84	35.16

8.2 Relationship between samples and factors

Loadings of the oblique projection matrix for both Duck and Coquina beach, were plotted on two principal axes at a time according to the approach used in the pilot study.

Figures 29 to 31, display the relationships observed at Duck. Obvious groups and patterns exist between samples and factors.

The best defined cluster is shown in samples located at the landward side of the dune which have high loadings on Factor IV (the finest grain-size factor) (**Figure 30(a)**).

Samples from the lower foreshore have high loadings on Factor II (coarse sand) (**Figure 29(a)**). Dune crest samples are equally composed of Factors I and III (**Figure 29(b)**); these samples appear to be best characterized by Factor III (**Figure 29(b)**). Samples which display high loadings on Factor V are mainly from the step (**Figure 30(b)**).

Plots of the factor loadings for Coquina beach (**Figure 31**) shows that all the samples are equally influenced by Factors I and IV (**Figure 31(a)**).

Figure 29. Plots of factor loadings on the oblique factor axes for Duck beach.

(a) Loadings on the oblique factor axes I and II

(b) Loadings on the oblique factor axes I and III

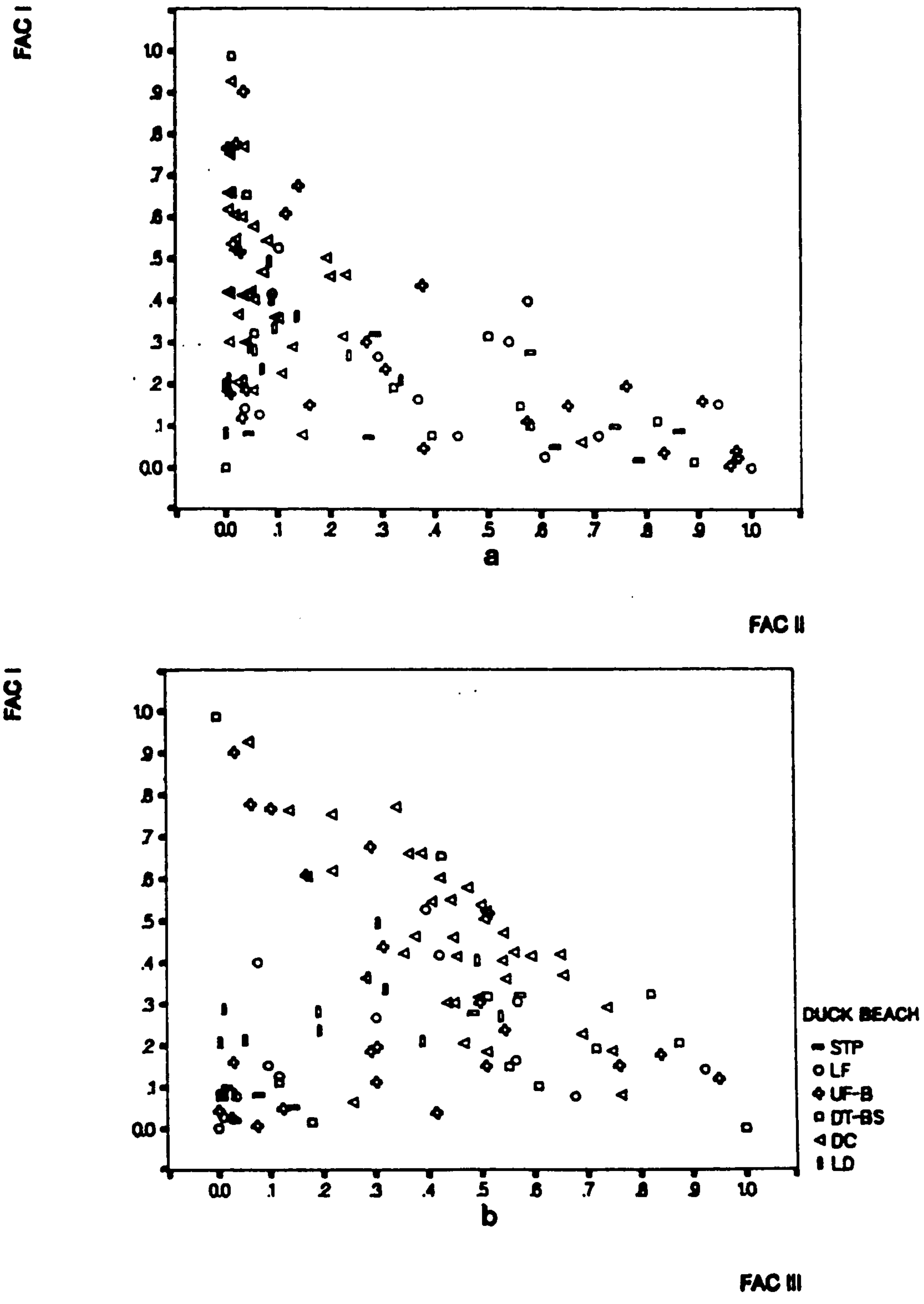
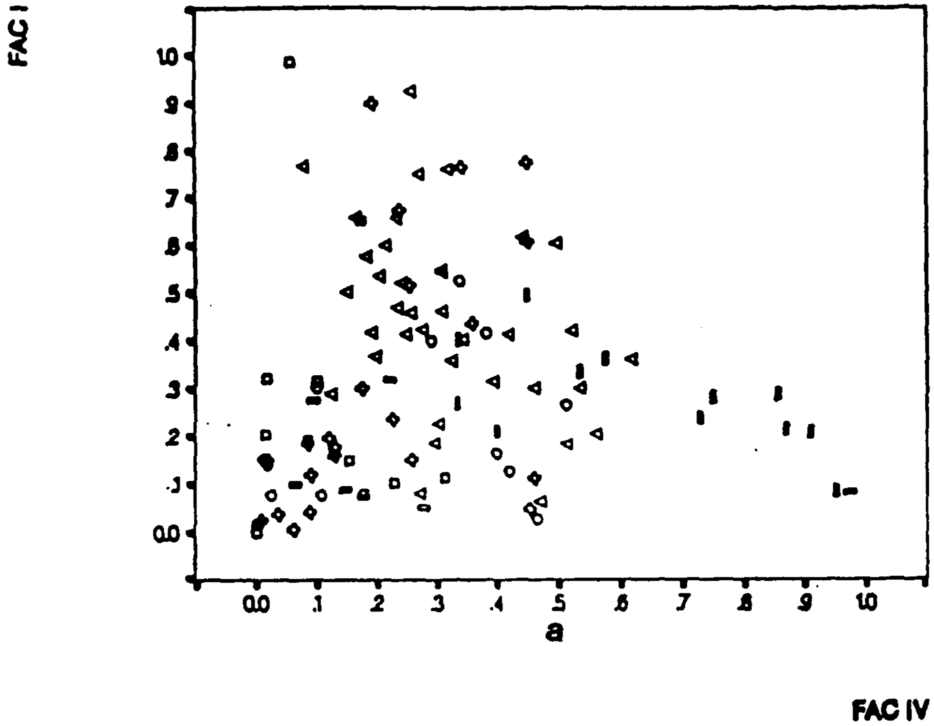

FAC I
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0.0
0.0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
a
FAC II
FAC I
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0.0
0.0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
b
FAC III
DUCK BEACH
▬ STP
○ LF
◇ UF-B
□ DT-BS
◁ DC
▮ LD

Figure 30. Plot of factor loadings on the oblique factor axes for Duck beach.

(a) Loadings on the oblique factor axes I and IV

(b) Loadings on the oblique factor axes one I and V


FAC I
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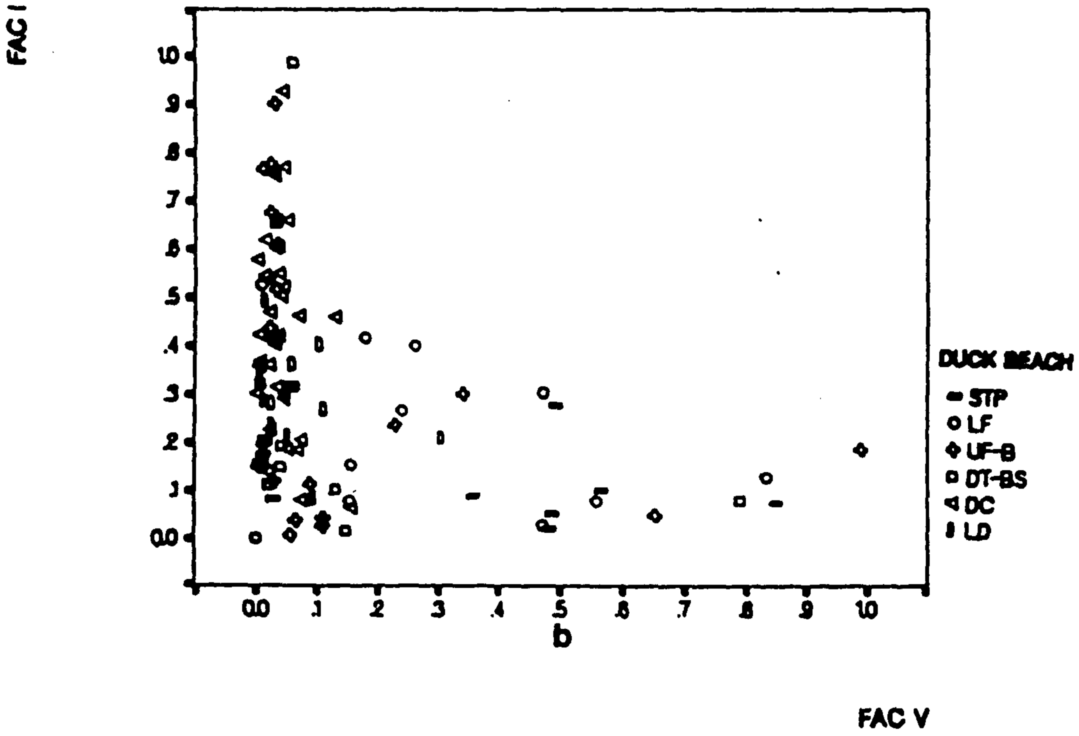
.8
.9
1.0
FAC IV

a


FAC I
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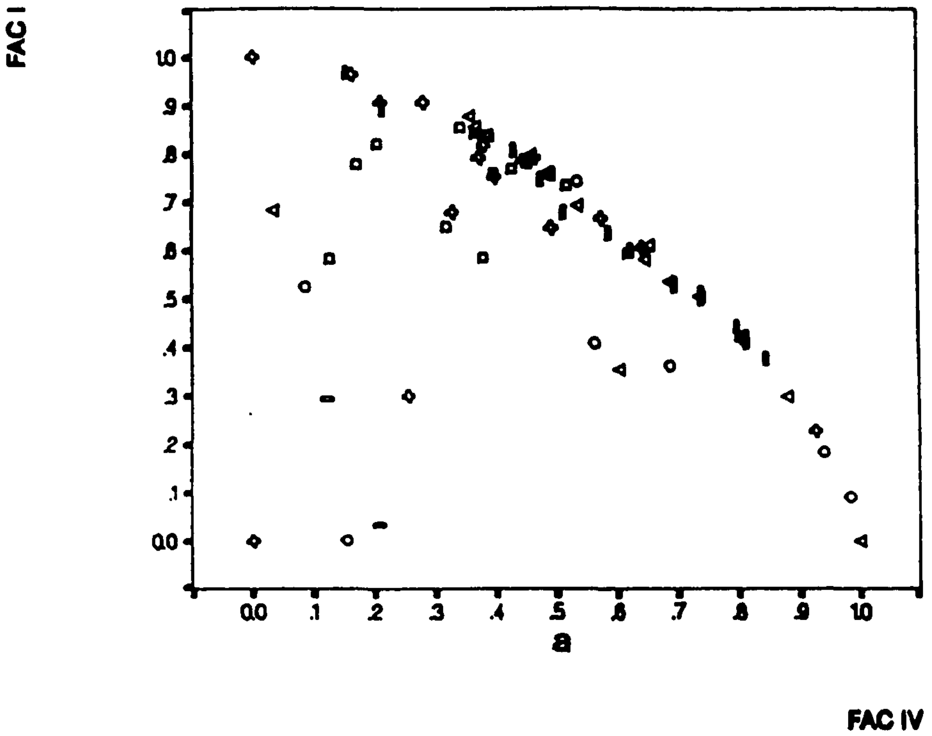
.5
.6
.7
.8
.9
1.0
FAC V
DUCK BEACH
- STP
○ LF
◇ UF-B
□ DT-BS
◁ DC
▮ LD

b

Figure 31. Plot of factor loadings on the oblique factor axes for Coquina beach.

(a) Loadings on the oblique factor axes I and IV

(b) Loadings on the oblique factor axes I and V


FAC I
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0.0
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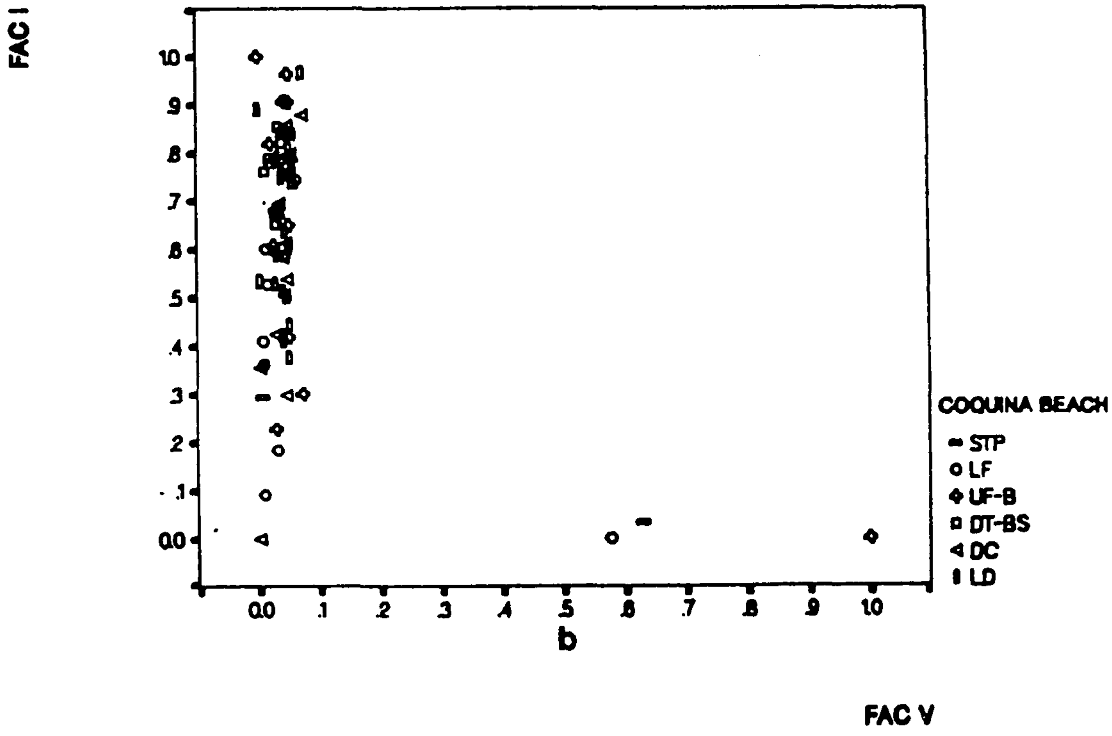
.5
.6
.7
.8
.9
1.0
a
FAC IV


FAC I
1.0
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.2
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0.0
0.0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
b
FAC V
COQUINA BEACH
▬ STP
○ LF
◇ UF-B
□ DT-BS
◁ DC
▮ LD

8.3. Cross-Shore temporal distribution of sediment factor groups

Samples classified into factor groups according to the highest loadings on a particular factor axis show that spatial trends exists through time in both beaches. These trends, are in agreement with the results reported in the previous section (section 8.2). At Duck beach (**Figure 32**), Factor group IV sediments are mainly present on the landward side of the dunes. Factor groups III and I, although occurring in all the sub-environments, best represent the dune crest zone. Factor group II sediments occur mainly at the step and the lower and upper foreshore. The lower portion of the backshore appears to be the landward limit for Factor group II sediments. Few samples are associated with Factor group V sediments, whose landward limit is defined by the upper foreshore.

At Coquina beach (**Figure 33**), subtle patterns do exist but are not obvious. These patterns were not clear in the previous section (section 8.2), but the temporal distributions here allow them to be discriminated. Although factor group IV sediments are present in all the cross-shore sub-environments, they are more frequently associated with the landward side of the dunes and the dune crest. Factor groups III and V sediments are rare and restricted to the lower and upper foreshore.

Figure 32. Cross-shore temporal distribution of sediment factor groups for Duck beach.

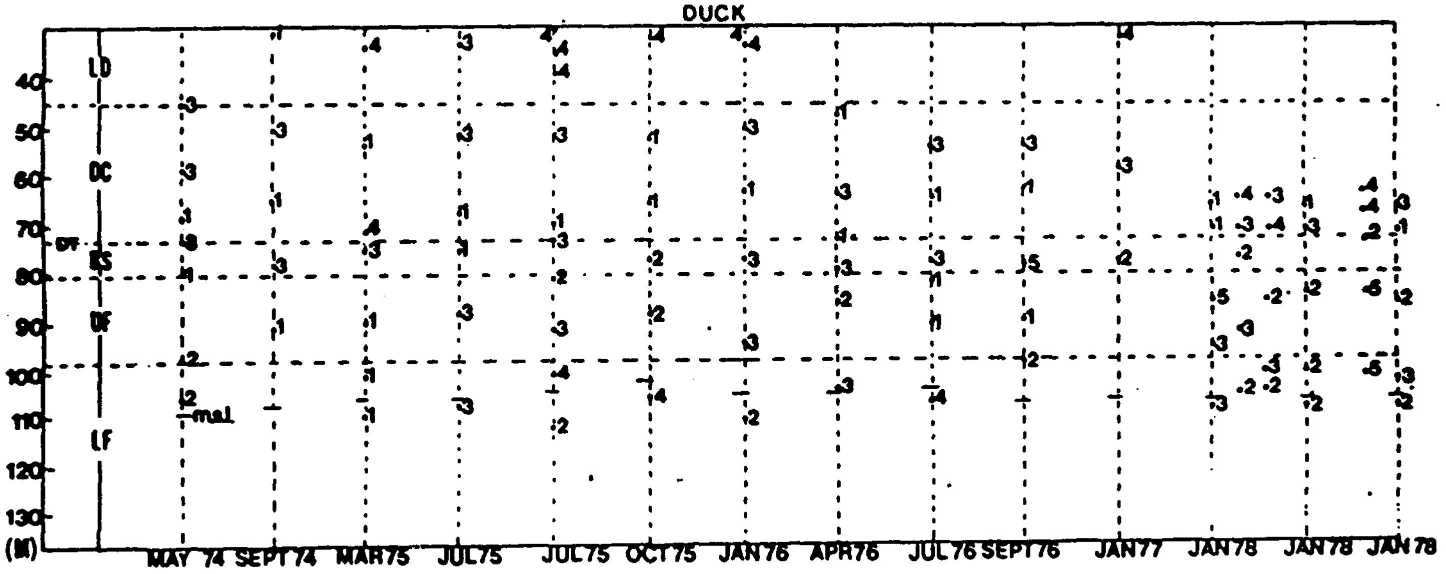
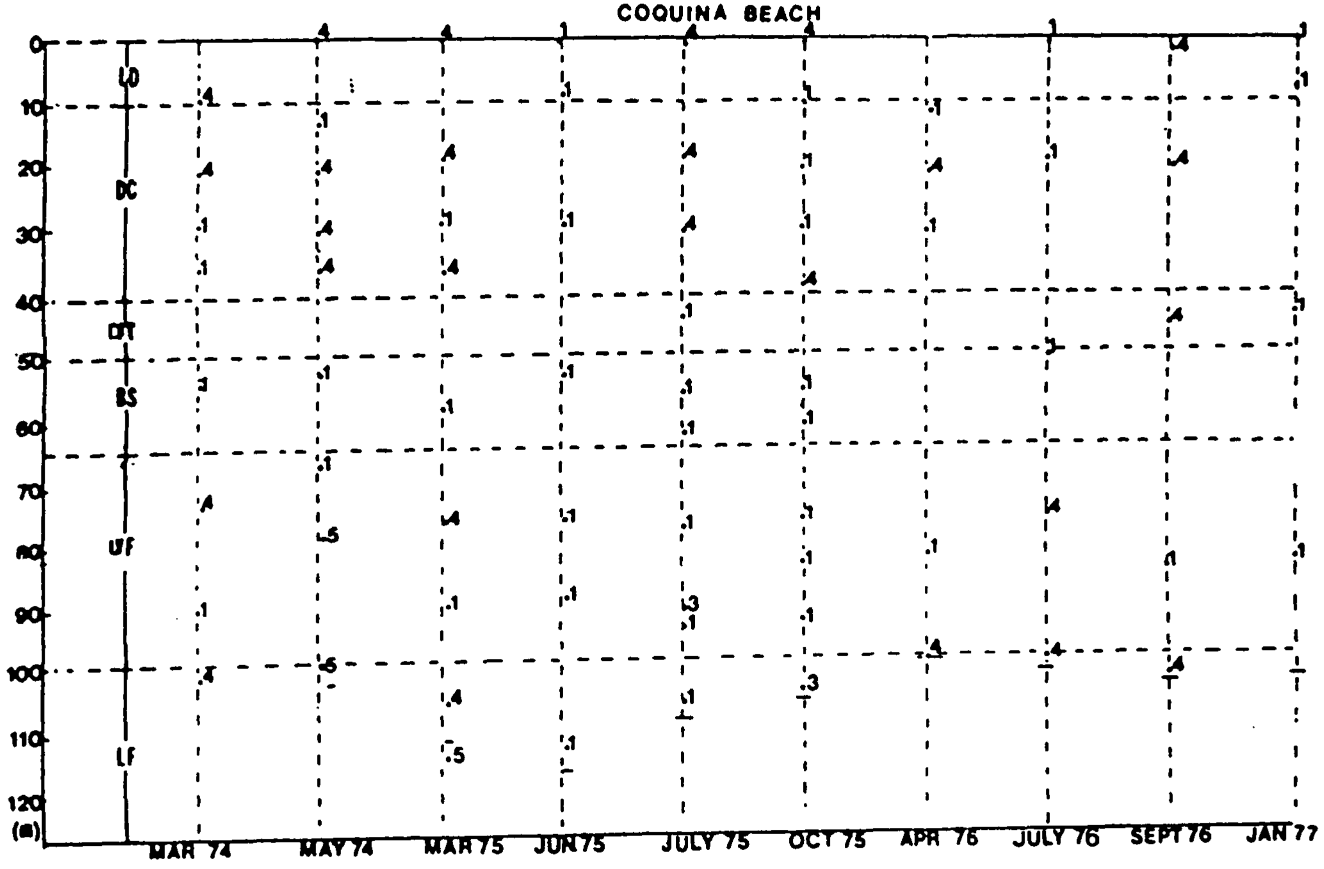

DUCK
40
50
60
70
80
90
100
110
120
130
(M)
LD
DC
DT
KS
DF
LF
mal
MAY 74
SEPT74
MAR75
JUL75
JUL75
OCT75
JAN76
APR76
JUL76
SEPT76
JAN77
JAN78
JAN78
JAN78

Figure 33. Cross-shore temporal distribution trends of sediment factor groups for Coquina beach.

COQUINA BEACH



8.4. Average percentage of factor across the beach

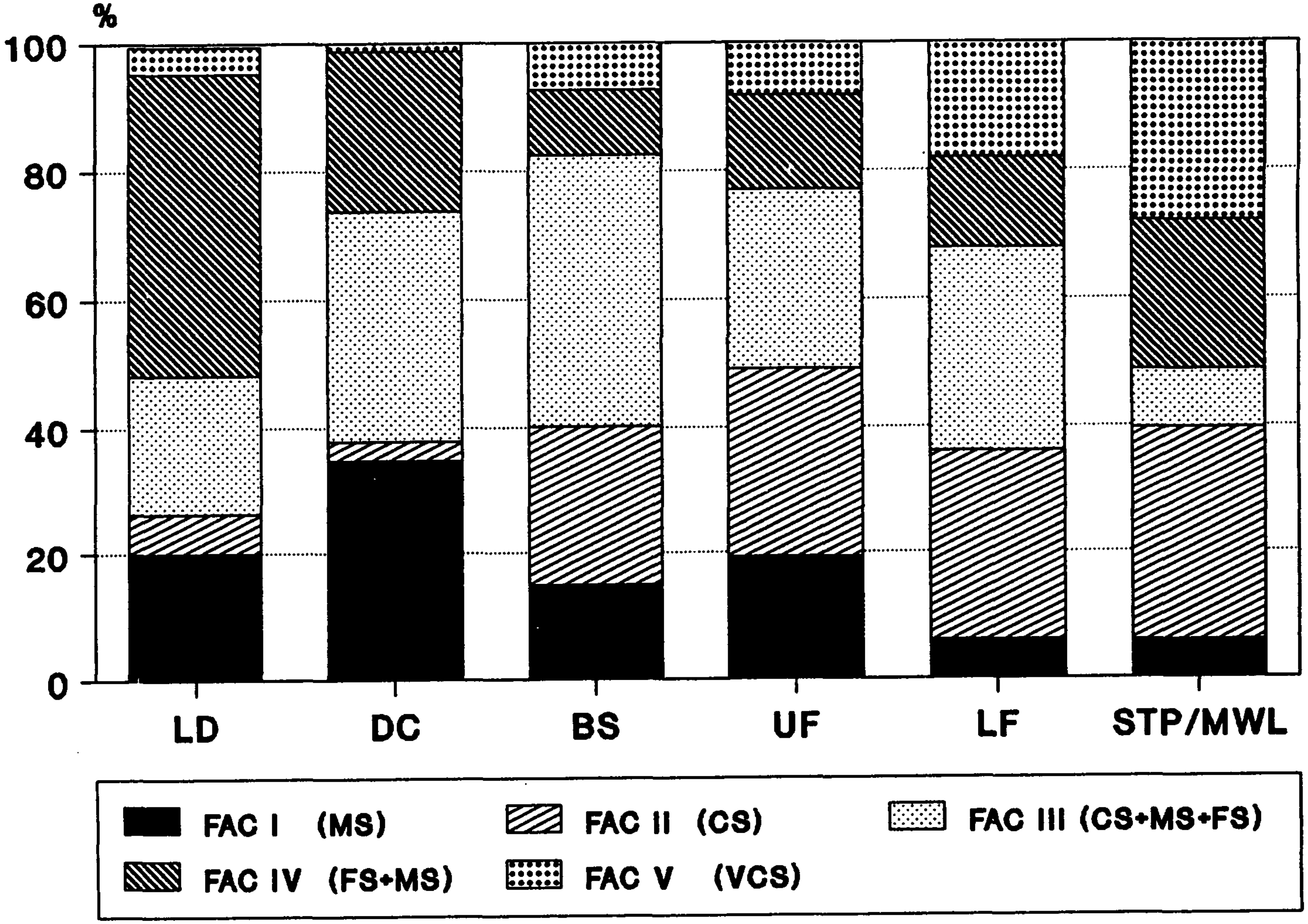
8.4.1.Duck Beach

Figure 34 display trends already seen in the cross-shore temporal distribution of sediment factor groups. The highest percentage on factor I is associated with the dune crest zone. Although the highest percentage values on factor III is linked with the backshore, excluding the step high percentages on this factor occurs in all the other zones. High values on factor II occurs from the step to the backshore area. Factor IV's highest and lowest average percentage are respectively associated with the landward side of the dune and backshore zones. Factor V shows high values at the step and in general decreases toward the dune area.

8.4.2. Coquina Beach

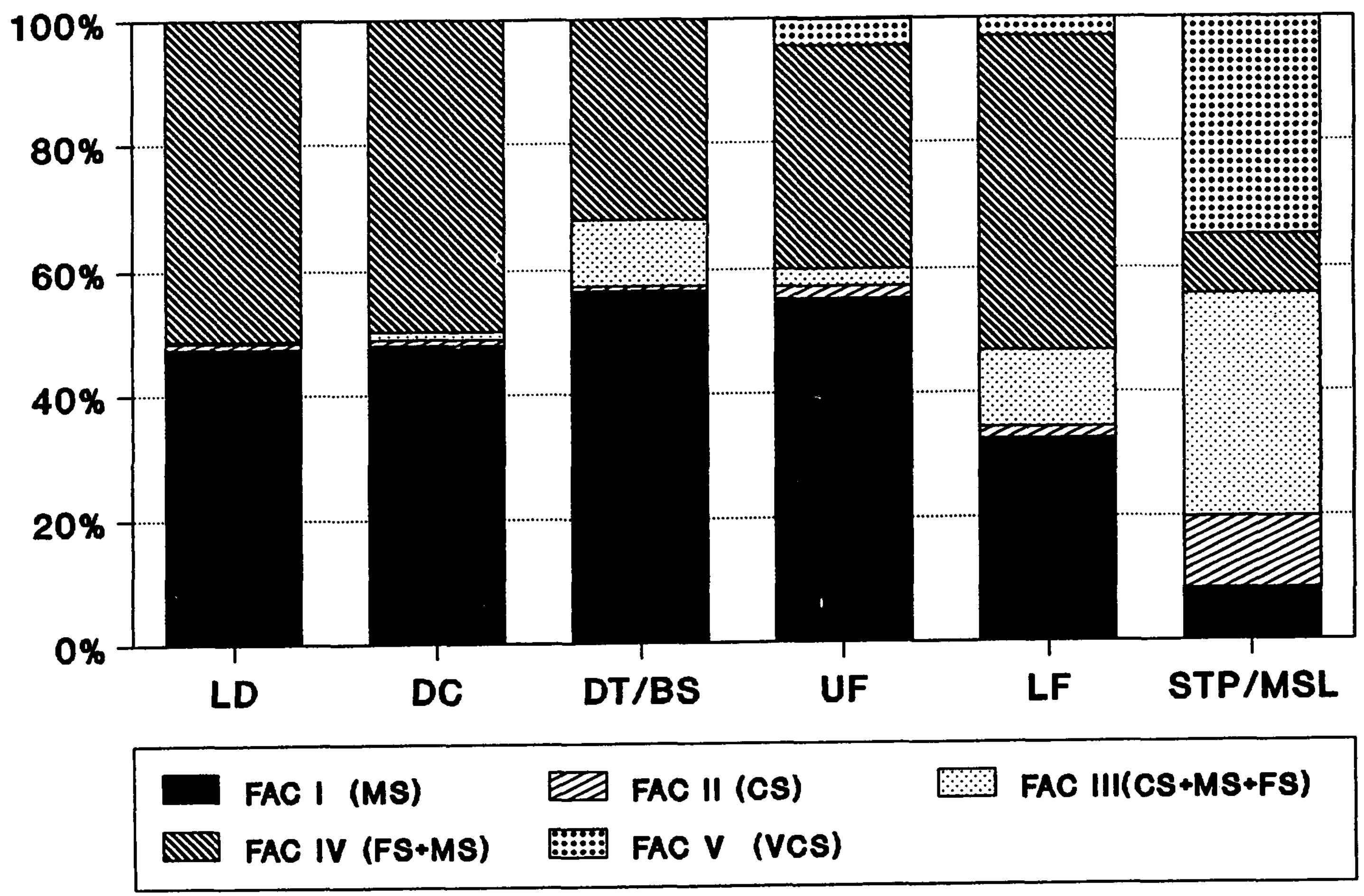
As shown in **Figures 35** the continuously high percentage values for Factors I and IV across the beach make it difficult to discern sediment distribution trends. Factor III shows some affinity towards a selective distribution in the step, lower foreshore and backshore. High percentage values on factor V are restricted to the step zone. It is important to notice that low values for Factor IV are associated with the step and dune toe/backshore areas.

Figure 34. Cross-shore average percentage of loadings on the oblique factor axes for Duck beach.


%
100
80
60
40
20
0
LD
DC
BS
UF
LF
STP/MWL
FAC I (MS)
FAC II (CS)
FAC III (CS+MS+FS)
FAC IV (FS+MS)
FAC V (VCS)

DUCK, NC.

Figure 35. Cross-shore average percentage of loadings on the oblique factor axes for Coquina beach.



COQUINA BEACH, N.C.

8.5. Factor groups grain-size characteristics

Factor groups of sediment samples classified according the highest loadings on the factor axis of the oblique solution, give us more information about textural differences existing between Duck and Coquina beach. They also allow us to draw some inferences about the different zones within a beach.

8.5.1. Duck Beach

Table 10, representing Duck Beach, shows that 33.65% of the samples are best related to Factor group III. Almost an equal number of samples are associated with Factor groups I and II, 25% and 15% respectively. Factor group IV sediments make up 15.38% of the total number of samples. Only 4.82% of the total samples are classified under Factor group V.

The percent of occurrence of each factor group in each sub-environment suggests some cross-shore distribution. Factor I and IV are usually associated with sediments from the dune crest and the landward side of the dune, respectively. Sediments best represented by factor II mainly appear in the upper foreshore/berm and step/mean water level zones. Factor group III sediments, while represented in several zones, are strongly associated with the dune crest area. Factor group V sediments are found at the step/mean sea level/mean water level and upper foreshore/berm zones.

Table 10. Duck beach. Mean and standard deviation of sediment factors groups. VCS- very coarse sand; CS- coarse sand; MS- medium sand; FS- fine sand; VFS- very fine sand; STD.DEV.- standard deviation; STP/MWL- step/mean water level; LF- lower foreshore; UF/B- upper foreshore-berm; DT/BS- dune toe-backshore; DC- dune crest; LD- landward side of the dune.

Duck beach-general study

GROUP	%VCS	%CS	%MS	%FS	%VFS	MEAN	STD.DEV.	SKEWNESS	KURTOSIS	NUMBER	%TOTAL	%STP/MWL	%LF	%UF/B	%DT/BS	%DC	%LD
ONE																	
MEAN	1.50	19.50	54.00	23.00	2.00	1.50	0.68	0.09	2.91	26	25.00	-	4	23	7	62	4
STD.DEV.	1.81	6.47	11.21	6.18	4.39	0.11	0.13	0.45	0.62								
TWO																	
MEAN	15.21	55.71	16.48	10.91	1.69	0.75	0.80	0.91	3.03	22	21.15	36.36	4.54	40.90	19.23	-	-
STD.DEV.	12.39	14.60	9.12	10.40	4.51	0.32	0.24	0.54	1.22								
THREE																	
MEAN	5.05	37.20	36.42	18.69	2.55	1.25	0.76	0.20	2.53	35	33.65	2.86	14.30	17.14	17.14	42.85	5.71
STD.DEV	7.17	12.87	10.31	9.95	4.89	0.32	0.15	0.40	0.61								
FOUR																	
MEAN	3.60	14.56	39.37	37.92	4,53	1.75	0.80	-0.47	3.13	16	15.38	6.25	6.25	-	-	31.25	56.25
STD.DEV.	4.15	6.22	4.96	8.59	5.52	0.24	0.12	0.56	1.60								
FIVE																	
MEAN	40.98	33.85	10.42	11.84	2.89	0.56	0.92	0.83	2.24	5	4.82	40	-	40	20	-	-
STD.DEV	24.47	18.56	9.41	11.50	6.48	0.43	0.32	0.44	0.84								

8.5.2. Coquina beach

Table 11 shows that nearly 94% of the total samples representing Coquina beach are best associated with factors I and IV. Factor I, the most dominant, is equally represented in zones between the upper foreshore and the landward side of the dunes. Factor IV, the second most important factor (35.62%), appears to equally characterize the dune crest and landward side of the dune sub-environments. Factor group II samples are not represented on Coquina Beach. Sediments associated with Factor III and V are negligible and only occur between the step/mean water level and the upper foreshore/berm zones.

For both beaches, factor groups mean grain size values based on the standard statistics only agree with Factor groups I and II. The fact that the other factor groups show a tendency towards bimodality, strengthens the idea that standard statistical measures are most useful when applied to unimodal distributions. **Figure 36(a)** includes the log-probability plots of the five end-member sediment samples, as well as plots of samples randomly selected within each sediment factor group (**Figures 36(b) to 38(b)**).

Factor group I samples (**Figure 36(b)**) are mainly composed of five straight line segments. Well defined truncation points occur at 0, 1 and 1.5 phi. The very coarse sand fraction extends to the second percentile and is well sorted. The coarse sand segment

Table 11. Coquina beach. Mean and standard deviation of sediment factor groups. VCS- very coarse sand; CS- coarse sand; MS- medium sand; FS- fine sand; VFS- very fine sand; STP/MWL- step-mean water level; LF- lower foreshore; UF/B- upper foreshore-berm; DT/BS- dune toe-backshore; DC- dune crest; LD- landward side of the dune.

Coquina beach

GROUP	%VCS	%CS	%MS	%FS	%VFS	MEAN	STD.DEV.	SKEWNESS	KURTOSIS	NUMBER	%TOTAL	%STP/MHL	%LF	%UF/B	%DT/BS	%DC	%LD
ONE																	
MEAN	1.02	8.19	66.55	23.07	1.19	1.62	0.54	-0.19	3.83	42	57.53	0	4.76	28.57	26.19	21.42	19.04
STD.DEV.	1.13	8.07	7.58	6.66	2.79	0.13	0.06	0.43	1.02								
TWO	NO SAMPLES																
THREE																	
MEAN	2.00	37.69	45.52	14.78	0.00	1.23	0.63	0.20	2.85	2	2.74	50	50				
STD.DEV.	0.27	5.18	8.36	3.46	-	0.01	0.06	0.40	0.50								
FOUR																	
MEAN	0.72	4.61	58.36	34.14	2.11	1.82	0.55	-0.11	3.71	26	35.62	7.70	11.54	11.54	3.85	30.76	34.61
STD.DEV.	0.97	5.89	6.99	5.84	6.84	0.13	0.11	0.59	1.66								
FIVE																	
MEAN	48.46	28.01	15.45	8.08	0.00	-0.37	0.85	1.07	3.25	3	4.11	33.33	33.33	33.33	-	-	-
STD.DEV.	26.48	17.20	32.80	6.87	0.00	0.37	0.15	0.67	1.66								

extends to the 15th percentile and is poorly sorted. The medium sand fraction, which dominates the sand population in this group, extends to the 80th percentile and is broken in two segments with different degrees of sorting. The fine and very fine sand fractions generally comprise 10% of the total sample and are extremely well sorted.

Factor group II sediment plots (**Figure 37(a)**) can generally be broken into three segments. The coarsest break is located between 0 and 0.5 phi (coarse sand) and ranges from the 10th to the 80th percentile. The middle segment ranges from 0.5 to 2.5 phi and is poorly sorted. It is composed of a mixture of coarse and medium sand. The last segment range from 1.5 to 3.0 phi and is extremely well sorted.

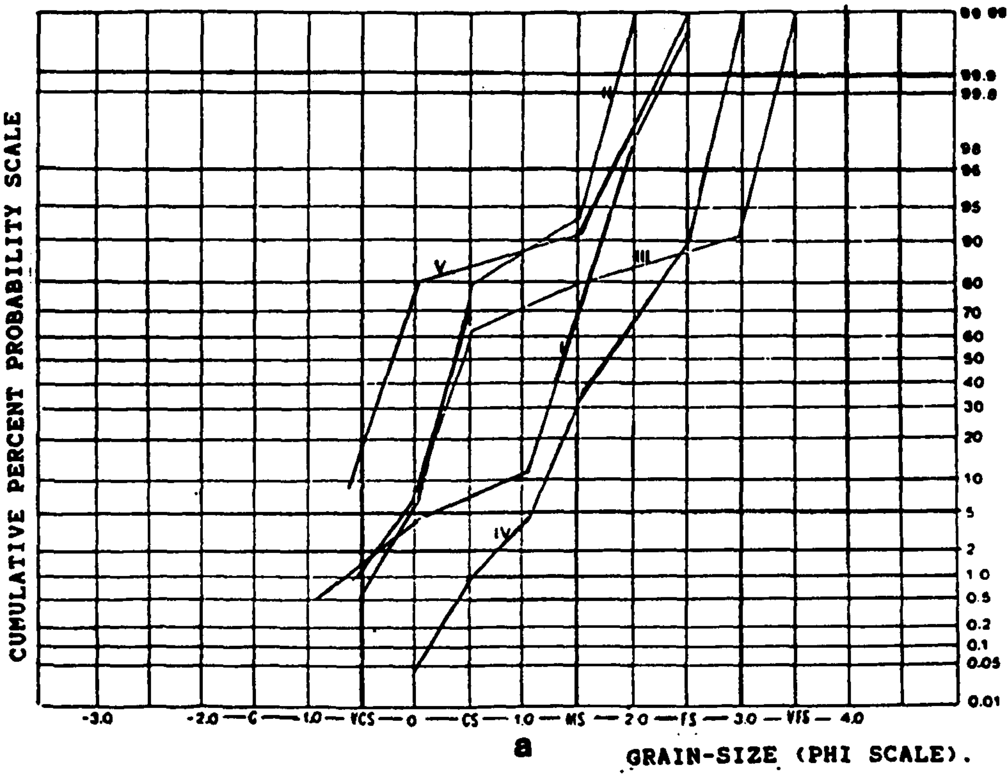
Curves of Factor group III (**Figure 37(b)**) indicate an increase in the number of segments as seen in the previous factor groups. Major differences include an increase in the fine fraction, shown by the last segment. Major breaks occur at 0.5 and 1.5 phi points and 2 to 2.5 phi interval. Segments representing the coarsest and finest fractions are better sorted than the intermediate segments which represent medium sand.

Factor group IV sediments (**Figure 38(a)**) display an extremely well sorted tail of fine sediments occurring between 2.5 and 3.5 phi (fine sand to very fine sand). The middle fraction is moderately sorted and includes the 0.5 to 2.5 phi intervals. A very

Figure 36. Log-probability plots of the Duck and Coquina beach data set.

(a) Log-probability plots of the five end-member sediment samples

(b) Log probability plots of factor group I sediment samples


CUMULATIVE PERCENT PROBABILITY SCALE
GRAIN-SIZE (PHI SCALE).
-3.0
-2.0 — G — 1.0 — VCS — 0 — CS — 1.0 — MS — 2.0 — FS — 3.0 — VFS — 4.0
99.99
99.9
99.8
98
96
95
90
80
70
60
50
40
30
20
10
5
2
1.0
0.5
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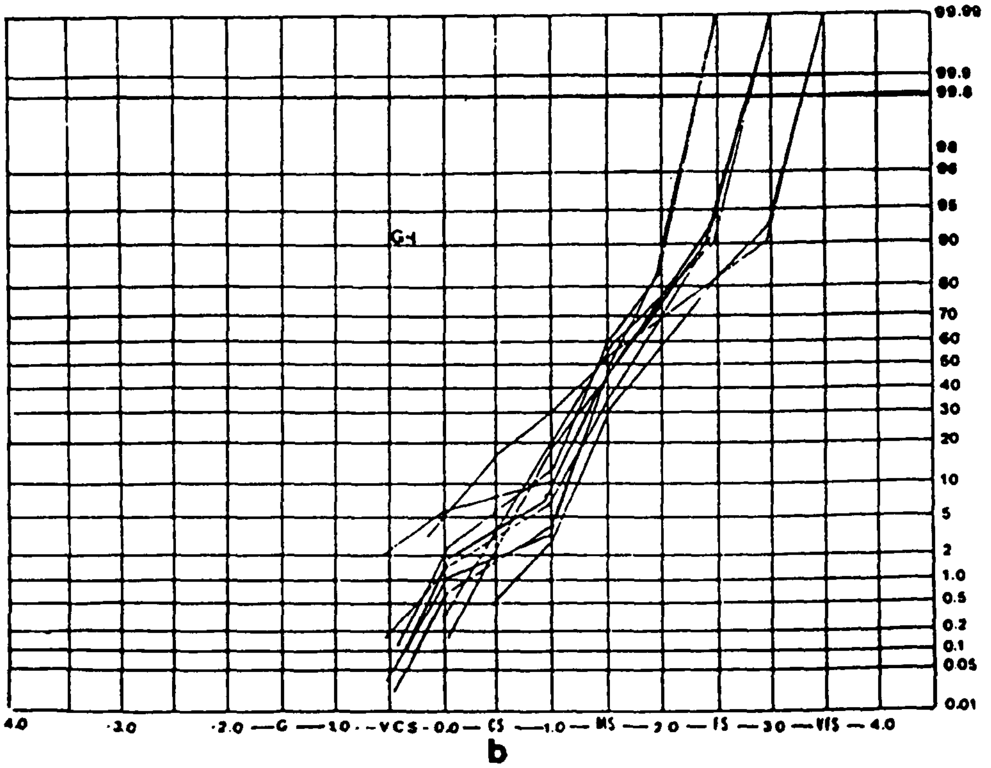
0.1
0.05
0.01
V
II
III
I
IV

a

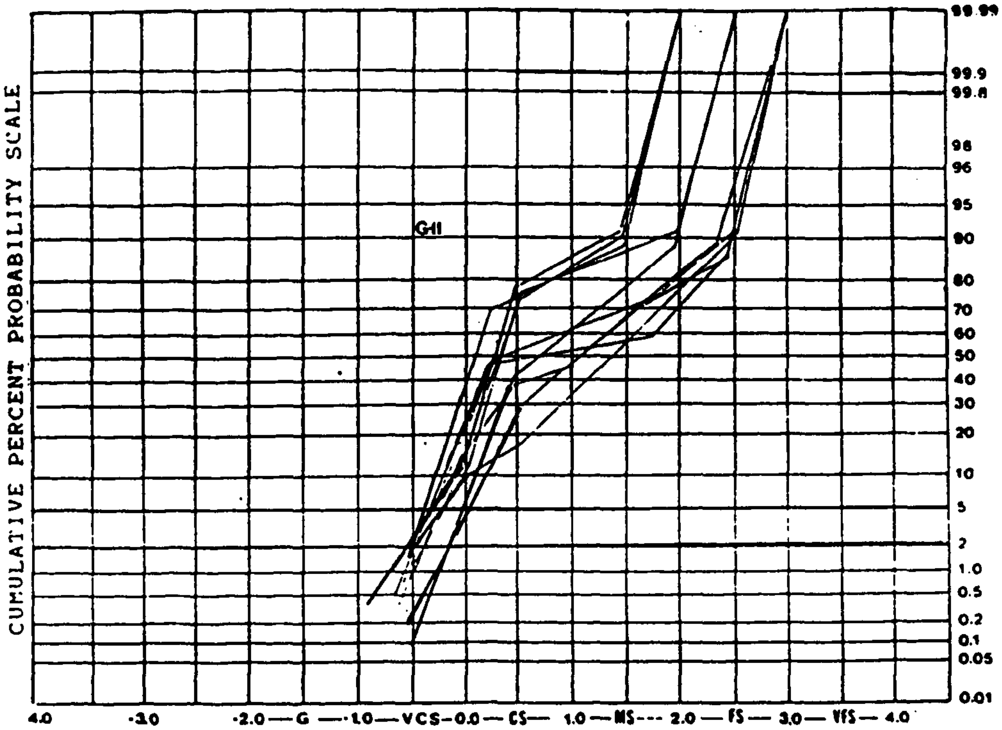

4.0
3.0
2.0 — G — 1.0 — VCS - 0.0 — CS — 1.0 — MS — 2.0 — FS — 3.0 — VFS — 4.0
99.99
99.9
99.8
98
96
95
90
80
70
60
50
40
30
20
10
5
2
1.0
0.5
0.2
0.1
0.05
0.01
G-1

b

Figure 37. Log-probability plots of Duck and Coquina beach data set.

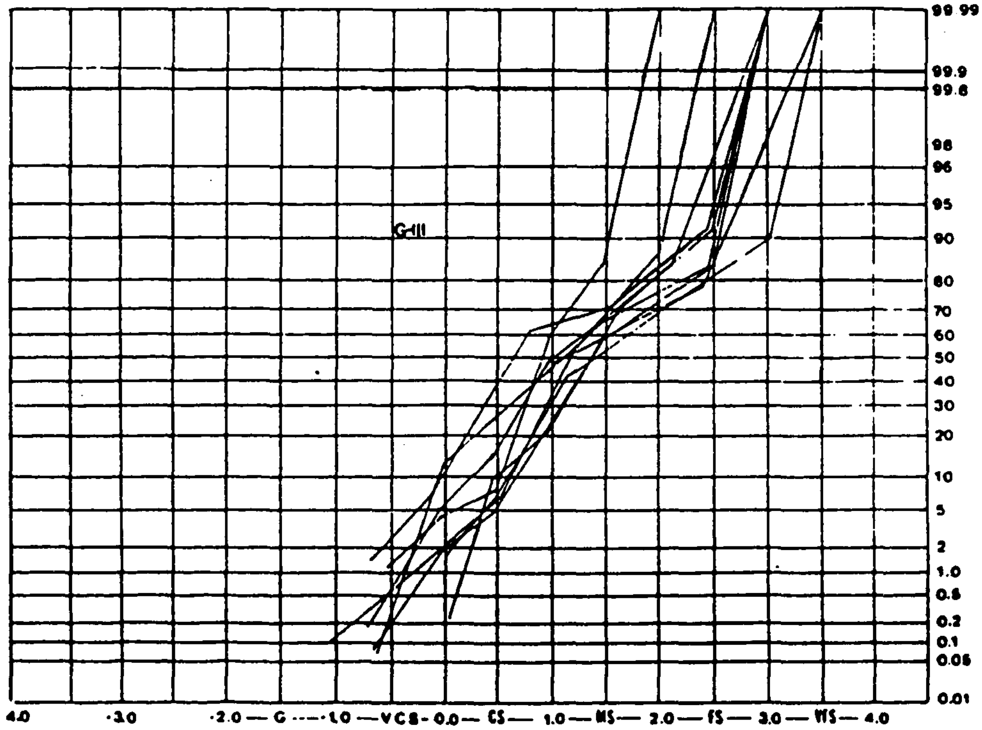
(a) Log-probability plots of factor group II sediment samples

(b) Log-probability plots of factor group III sediment samples



a

GRAIN-SIZE (PHI SCALE)

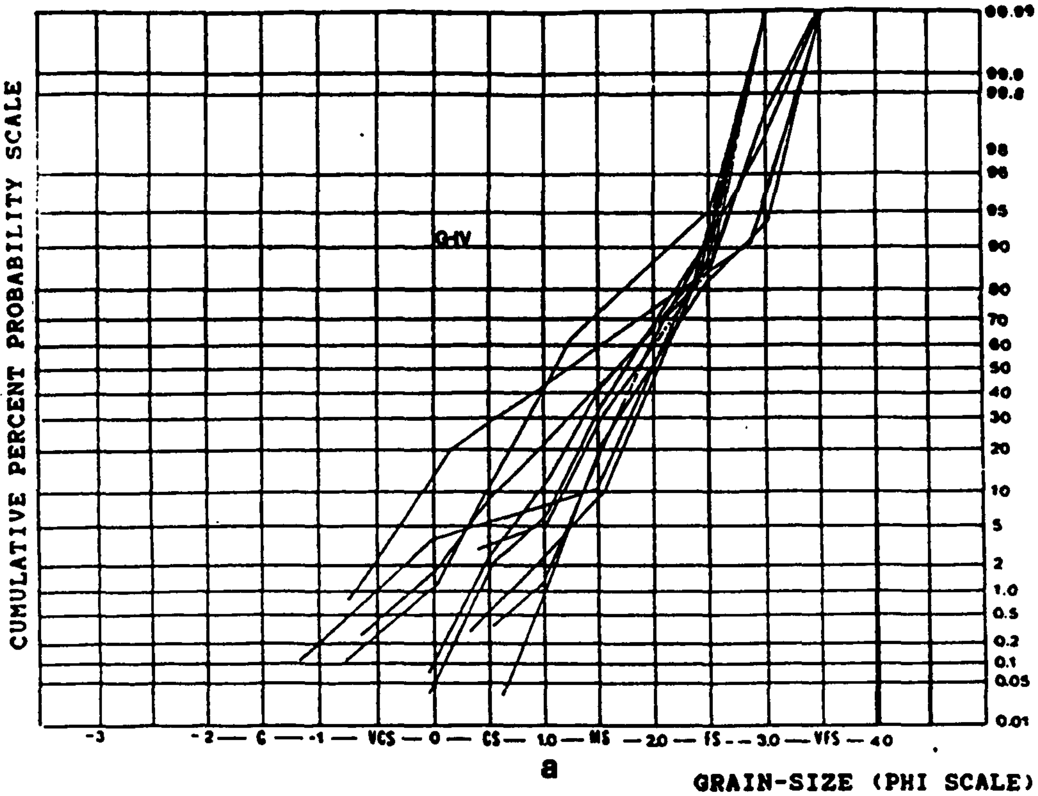


b

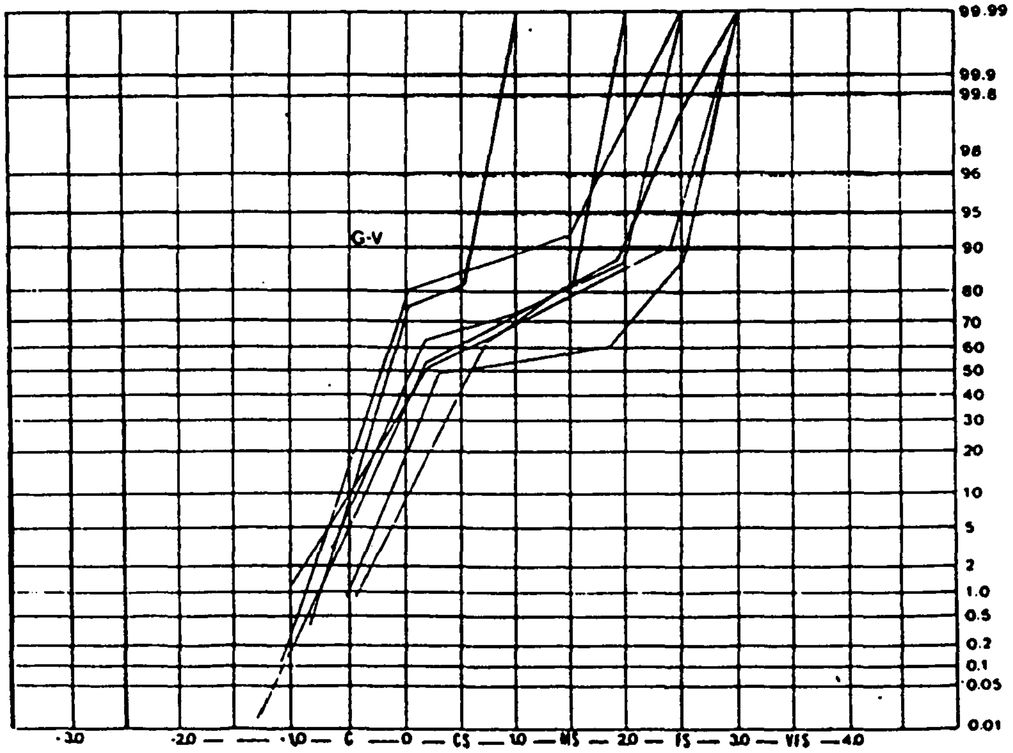
Figure 38. Log-probability plots of Duck and Coquina data set.

(a) Log-probability plots of factor group IV sediment samples

(b) Log-probability plots of factor group V sediment samples.


CUMULATIVE PERCENT PROBABILITY SCALE
G-IV
99.99
99.9
99.8
98
96
95
90
80
70
60
50
40
30
20
10
5
2
1.0
0.5
0.2
0.1
0.05
0.01
-3
-2 — C — -1 — VCS — 0 — CS — 1.0 — MS — 2.0 — FS — 3.0 — VFS — 4.0
GRAIN-SIZE (PHI SCALE)

a


G-V
99.99
99.9
99.8
98
96
95
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80
70
60
50
40
30
20
10
5
2
1.0
0.5
0.2
0.1
0.05
0.01
-3.0
-2.0 — — -1.0 — C — 0 — CS — 1.0 — MS — 2.0 — FS — 3.0 — VFS — 4.0

b

small tail of coarse sediments occurs between 0.5 and -1.0 phi.

Plots of samples associated with Factor group V (**Figure 38(b)**) show that most of the samples are composed of an extremely well sorted, very coarse sand population. The first important phi break occurs between the 0 and 0.5 phi interval. Following this break, there is a poorly sorted segment which is confined to the 1.5 and 2.0 phi break. The third segment is composed of an extremely well sorted, medium to fine sand.

8.6. Factor Groups and the standard statistics

Standard statistical measurements from the factor groups are plotted separately for each beach in the form of scattergrams.

8.6.1. Coquina beach

Figures 39 to 40 show that in addition to the mean, the only parameter which exhibits some environmental sensitivity is the standard deviation (**Figure 39(a)**). The finest sediments represented by factor group IV display the best sorting and a slight tendency toward negative skewness. It is important to remember that factor group IV sediments at both, Coquina and Duck Beach are strongly associated with the landward side of the dune and dune crest.

8.6.2. Duck beach

Figure 41(a), demonstrates that at Duck the best sorting occurs in factor group I sediments which are strongly associated with the dune crest zone.

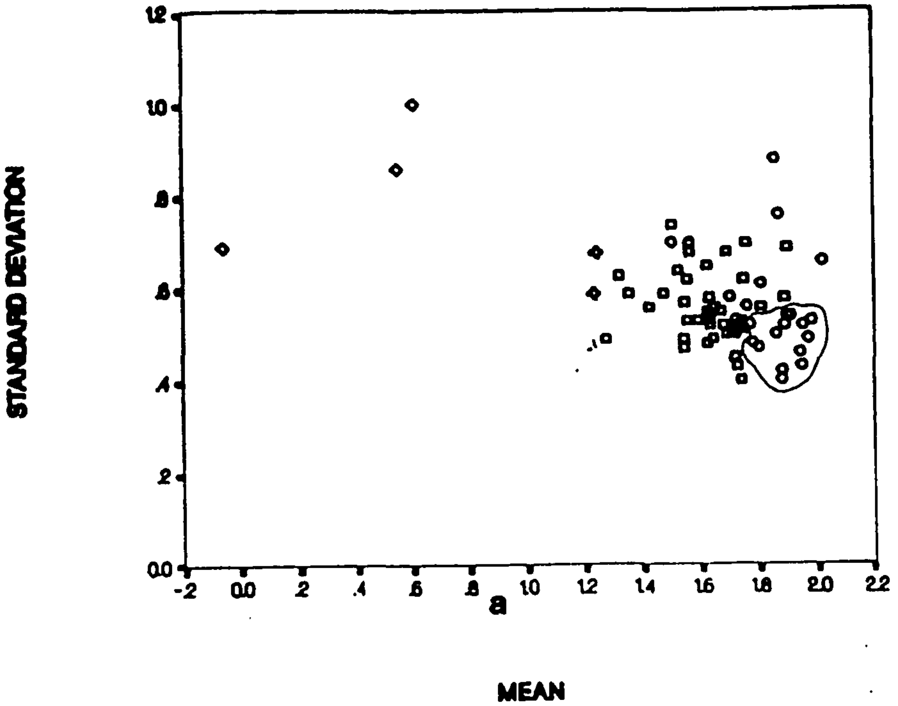
In **Figure 41(b)** factor group II, associated with the step/mean sea level and the upper foreshore and berm, displays unusual trends for sediments located in these zones. Factor group II sediments are coarse and display strong positive skewness. This is the opposite of what has been previously described for this zone. However, factor groups I and IV, which are respectively associated with the dune crest, and the landward side of the dune, display low negative values which are in agreement with the general trend for this area.

Positive skewness shown in upper foreshore and berm sediments at Duck is introduced by small amounts of fine sediments which were not winnowed from this area. Negative skewness from a small coarse fraction (**Table 10**) is associated with the landward side of dunes and could be due to the occasional introduction of coarse material by storms. Factor group III, representing the dune crest area, exhibits symmetrical tendencies.

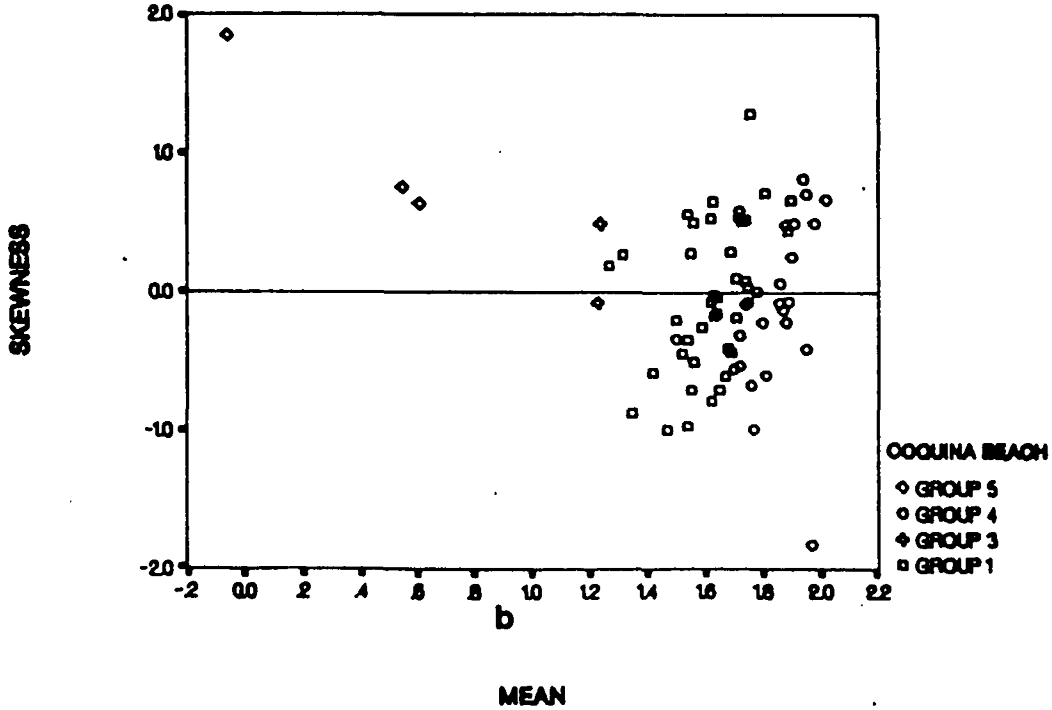
Figure 39. Plot of the moment measures for Coquina beach

(a) Mean versus standard deviation

(b) Mean versus skewness


STANDARD DEVIATION
1.2
1.0
.8
.6
.4
.2
0.0
-.2
0.0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
MEAN

a

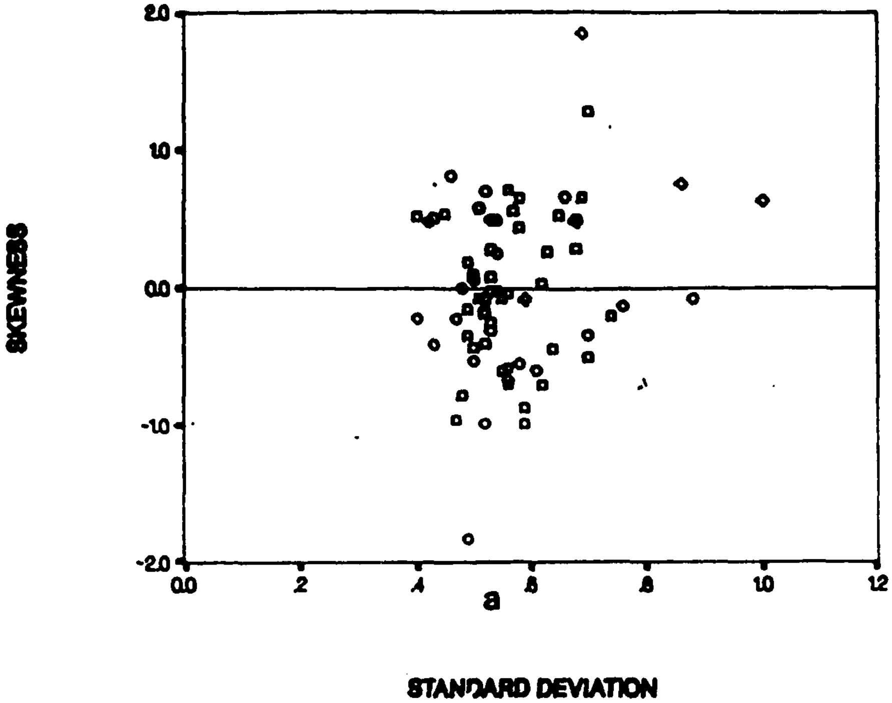

SKEWNESS
2.0
1.0
0.0
-1.0
-2.0
-.2
0.0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
MEAN
COQUINA BEACH
◇ GROUP 5
○ GROUP 4
✧ GROUP 3
□ GROUP 1

b

Figure 40. Plot of the moment measures for Coquina beach

(a) Standard deviation versus skewness

(b) Standard deviation versus kurtosis


SKEWNESS
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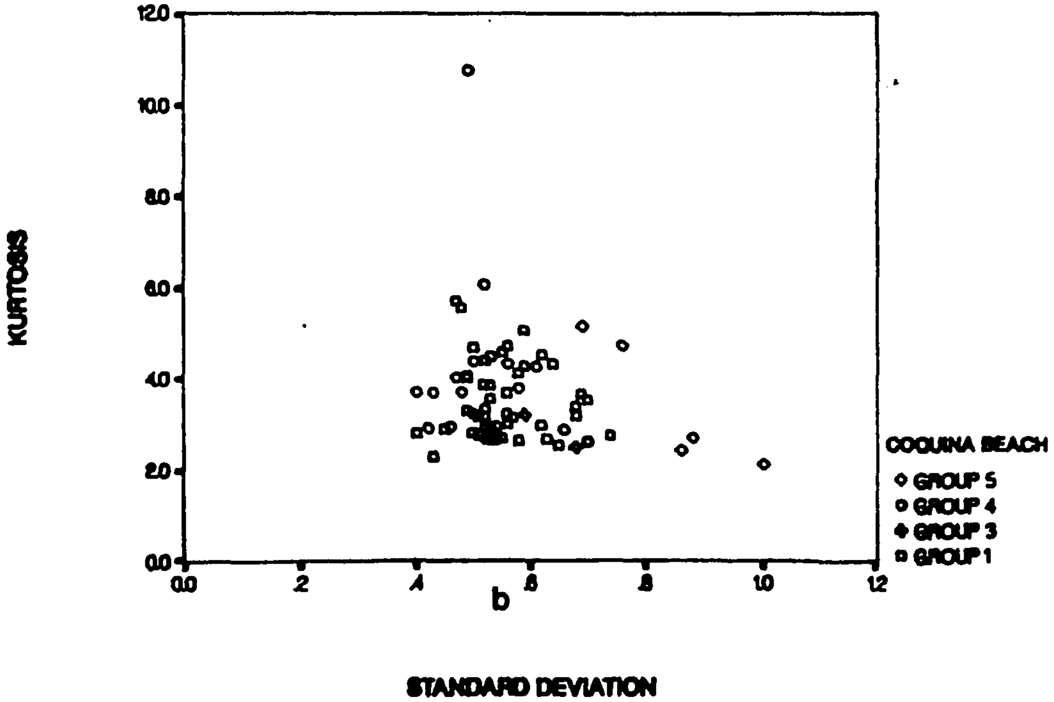
1.0
0.0
-1.0
-2.0
0.0
.2
.4
.6
.8
1.0
1.2
a
STANDARD DEVIATION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4.0
2.0
0.0
0.0
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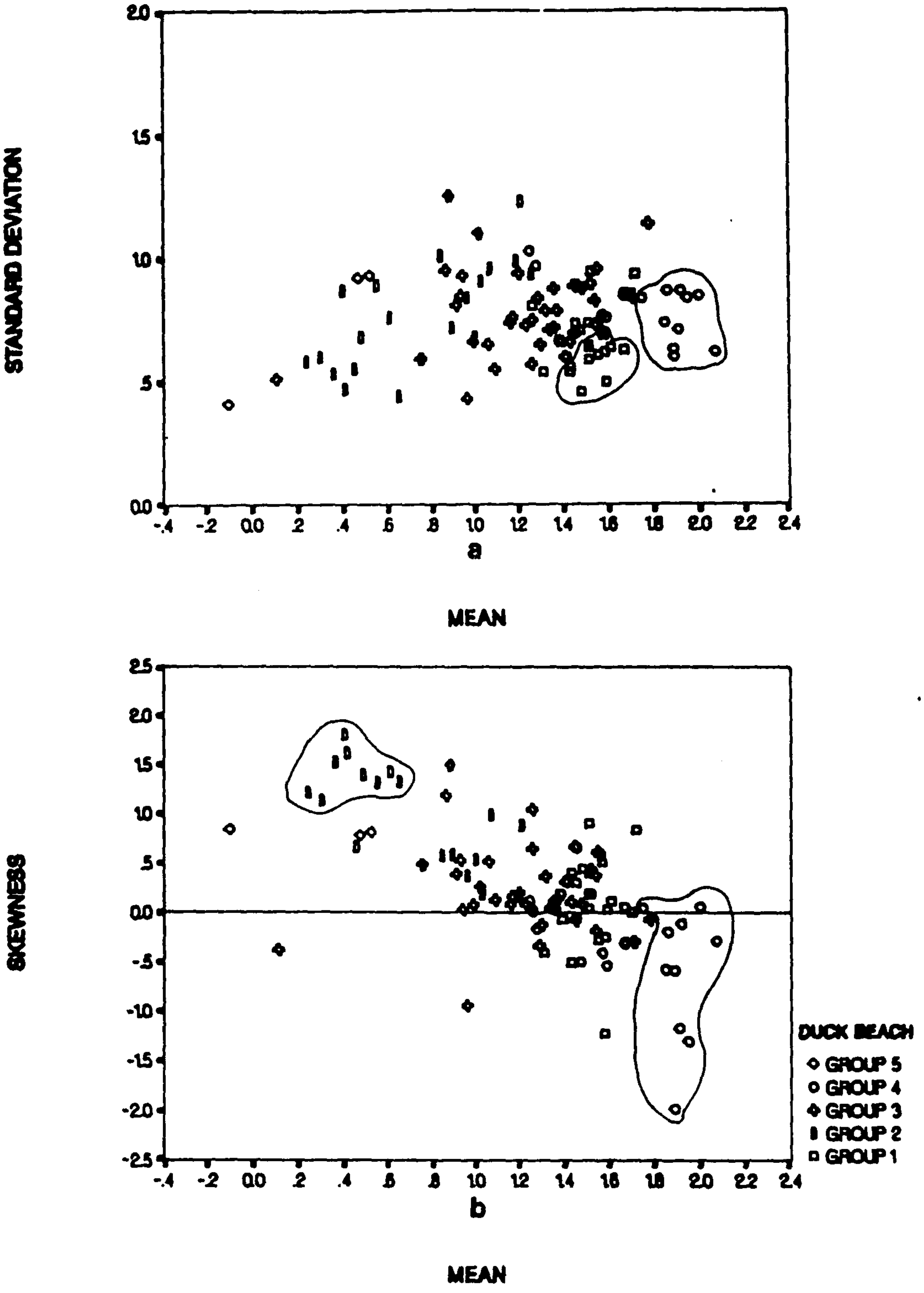
.4
.6
.8
1.0
1.2
b
STANDARD DEVIATION
COQUINA BEACH
◇ GROUP 5
○ GROUP 4
◆ GROUP 3
□ GROUP 1

Figure 41. Plot of the moment measures for Duck beach

(a) Mean versus standard deviation

(b) Mean versus skewness

STANDARD DEVIATION
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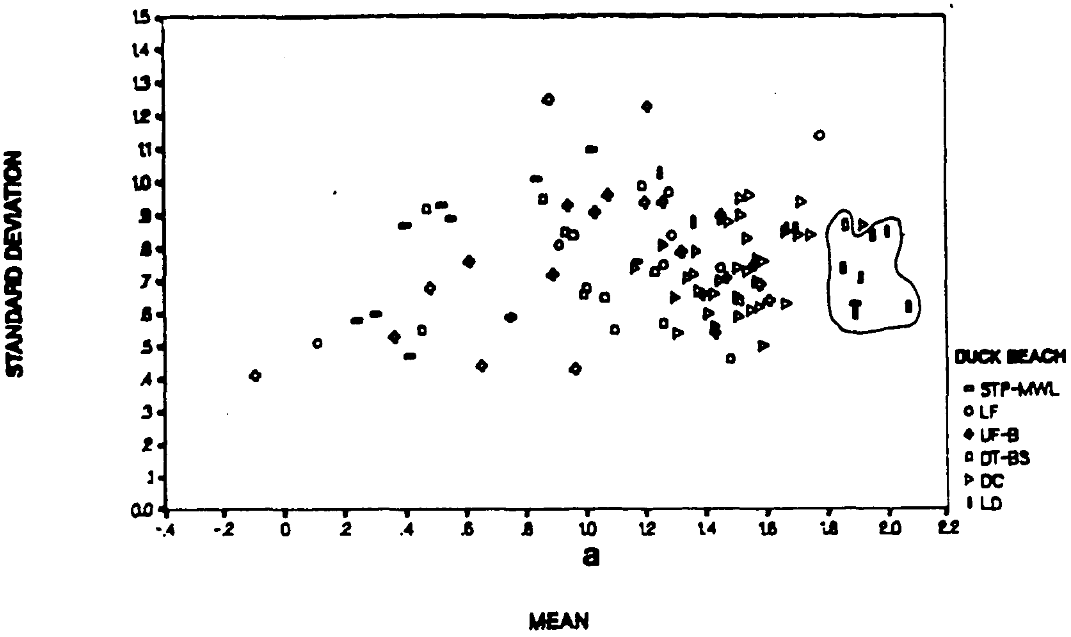
1.0
.5
0.0
-.4
-.2
0.0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
a
MEAN
SKEWNESS
2.5
2.0
1.5
1.0
.5
0.0
-.5
-1.0
-1.5
-2.0
-2.5
-.4
-.2
0.0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
b
MEAN
DUCK BEACH
◇ GROUP 5
○ GROUP 4
◆ GROUP 3
▮ GROUP 2
□ GROUP 1

Figure 42. Plot of the moment measures for Duck beach without previous separation by Q-mode factor analysis.

(a) Mean versus standard deviation

(b) Mean versus skewness


STANDARD DEVIATION
MEAN
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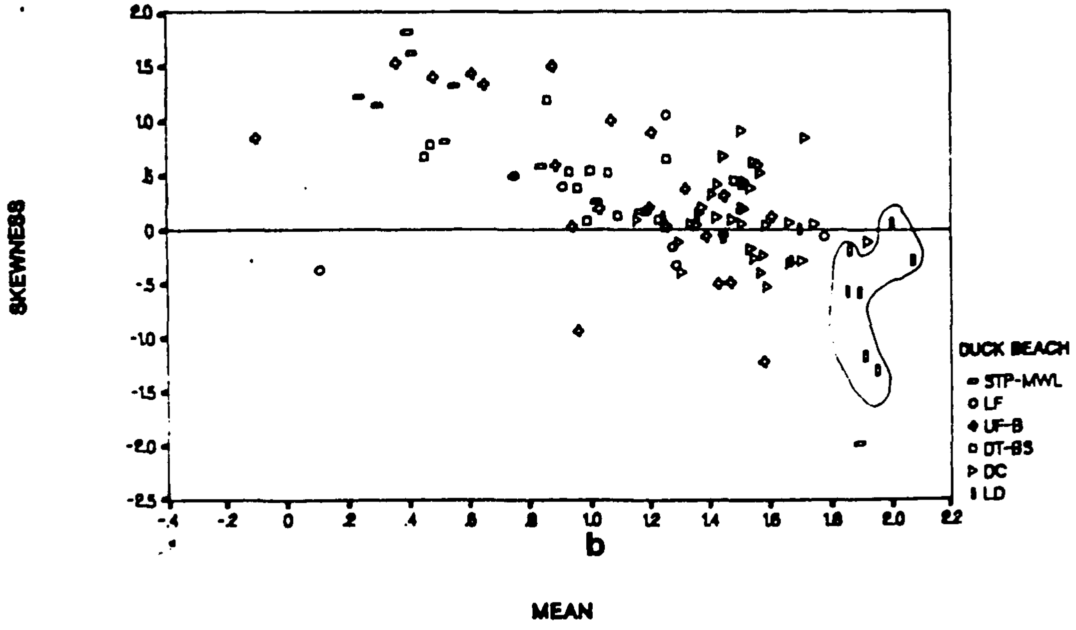
1.4
1.3
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0.0
-.4
-.2
0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
DUCK BEACH
STP-MWL
LF
UF-B
DT-BS
DC
LD

a


SKEWNESS
MEAN
2.0
1.5
1.0
.5
0
-.5
-1.0
-1.5
-2.0
-2.5
-.4
-.2
0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
DUCK BEACH
STP-MWL
LF
UF-B
DT-BS
DC
LD

b

9. DISCUSSION OF THE GENERAL STUDY: DUCK AND COQUINA BEACH

9.1 Comparisons between the factors obtained in both studies

Compositional similarities among the factors are evident when both studies are compared. Factor II (coarse sand) is analogous in both data sets. Factors I (fine sand), III (very coarse sand) and V (medium sand) in the pilot study are similar to Factors IV, V and I respectively in the general study. With exception of the differences associated with the very coarse and fine fractions, Factor III in the second study, resembles Factor one in the first study. Factor IV (pebble + gravel) is unique to the pilot study. It should be noticed that composition similarities do not mean that the factors characterize the same sub-environments at both beaches.

The absence of sediment Groups II (coarse sand + very coarse sand) and III (coarse + fine sand + medium sand) and the low representation of Group V at Coquina beach, appears to corroborate earlier suggestions that fine and medium sand where the native sediments present on this area of Currituck spit.

9.2 Separation of sub-environments

Differentiation of sub-environments based on the distribution of the sediment factor groups is more pronounced at Duck than at Coquina beach. Coquina Beach, exhibits some spatial distribution of sediment groups, while Whalehead Beach shows practically no differentiation (**Figure 13(b)**).
The fact that differentiation occurs at Coquina Beach is probably due to the sampling scheme used in the general study which included more cross-shore sub-environments.

The distinction between sub-environments using Q-mode factor analysis appears to be confirmed by the log-probability plots of specific groups, particularly at Duck . Plots of Factor groups I,III and IV sediments which are associated with the landward side of the dune and dune crest, are both characterized by several well sorted segments which appears to be typical of dune environments. Plots of Factor group II sediments (which were associated with the backshore (**Figure 18(a)**) in the pilot study display similar characteristics to these aeolian deposits. It is difficult to distinguish between dune and backshore zones based on the plots. However, differences can be observed when we look at the proportion of fine sand as well as the statistical parameters obtained by the groups previously determined by Q-mode factor analysis. Dune crest at Duck Beach, characterized by Factor group III sediments, displays subtle bimodal characteristics. A major difference among the plots described above and the plots of Factor group III, is the presence of a low slope for the medium sand interval segment in Factor group

III, indicating that this size class interval is poorly sorted. The occurrence of bimodal sands in dune environments has been previously reported in the literature. Bimodal sands composed of coarse and fine sand associated with aeolian megaripples present on crest of barchan dunes were described by Taira and Scholle (1979). Dune toe/backshore deposits also appear to be characterized by factor group III sediments.

Log probability plots associated with factor groups II and V appears to be typical of upper foreshore/berm, lower foreshore and step/mean water level deposits. However, plots related to the step/mean sea level deposits display a higher percentage of coarse sediments. Factor group II plots are very similar to factor group III plots in the pilot study which are also best characterized by the upper foreshore/berm zone.

9.3. Factor groups versus standard statistics

The same parameters which allow us to draw some inferences about sub-environments in the pilot study also appear to be applicable in the general study. Best sorting values at Duck and Coquina beach are associated with the landward side of the dune and the dune crest respectively. Even with the large fluctuations of grain size in the area between the mean water level and upper foreshore, no relationship between grain size and standard deviation was found there.

Skewness values for dune sediments at Coquina beach are not in agreement with values reported by other authors in similar environments. Here, dune samples exhibited a very low negative skewness. As observed in the pilot study, positive values of skewness associated with lower and upper foreshore deposits at Duck do not follow the general patterns predicted for wave-lain deposits. Andrews and Van der Lingen (1969), studying coarse beaches at New Zealand found similar trends and concluded that skewness is not necessarily an environmentally sensitive measure.

However, the differentiation of sub-environments based on the standard statistical parameters, can display some meaning when the sediments were previously grouped based on the Q-mode technique. Such statements can be supported when plots of the statistical parameters of the sediment factor groups (group statistics) are compared with analogous scattergrams obtained without previous grouping (parameters and locations) as displayed by **Figures 42(a) and 42(b)**. For these plots the best sorted sediments, represented by Factor groups I and IV and characterizing the dune crest, are impossible to separate without the Q-mode method.

Using a similar approach (Q-mode and comparisons of graphical measures), Beall (1970) was able to explain overlapping environmental occurrences in the small fluvial-deltaic system of the Colorado River, Texas. The same approach was used by Dal Cin (1976) in order to determine beach erosion and accretion from grain-size data.

10. ALONG-COAST DISTRIBUTION OF SEDIMENT GROUPS

In accordance with the factor model concept defined in equation 11 (page 47), the varimax factor score matrix obtained with the general study was used to map into the previously determined factor space 350 new sediment samples located across the sub-environments from north of Duck beach and Oregon inlet (**figure 26**).

10.1 Results

Excluding four samples which displayed communality values ranging from 0.8 to 0.9, all samples showed values higher than 0.9 indicating that the new samples can be explained by the five factor model.

10.2 Cross-Shore and Along-Coast Average Factor Loadings for Individual Factors

Table 12 and **figure 43** display the average factor loading values for each factor (which indicates grain size composition) across all the sub-environments of the 14 studied beaches. Some trends are obvious.

Factor I consists almost entirely of medium sand and displays the lowest values at Duck (P-12/3.3 miles) and south of the Avalon pier (P-32/11.83 miles). South of P-32, the factor loading value for factor I increases reaching a maximum value at Coquina beach (P-53/26 miles).

Factor II is extremely rich in coarse sand and has the highest loading values at Duck, south of Avalon pier (P-32) and south of Nags Head (P-38/18.36 miles).

Factor III is rich in coarse sand but also contains a reasonable amount of medium and fine sand. Its highest loadings occur close to Duck (north and south), as well as between P-32 and P-38.

Factor IV is composed of approximately equal proportions of medium and fine sand. With the exception of Duck, where it displays anomalously high values, and at P-32 where a small decrease is shown, its general tendency is to increase toward Coquina beach.

Factor V, which is almost totally composed of very coarse sand, displays high values at Duck (P-12), Kitty Hawk (P-26/8.46 miles), and south of Nags Head (P-38).

An interesting feature is that all the factors display a bimodal distribution along the coast. Excluding the area north of Duck, Factors I and IV vary together from Duck to Coquina Beach. Factors III and IV do not covary, therefore when one factor increases, the other decreases. Between P-20 (4 miles) and P-32 Factors II and V vary in opposite directions. Outside of these boundaries, they are in phase.

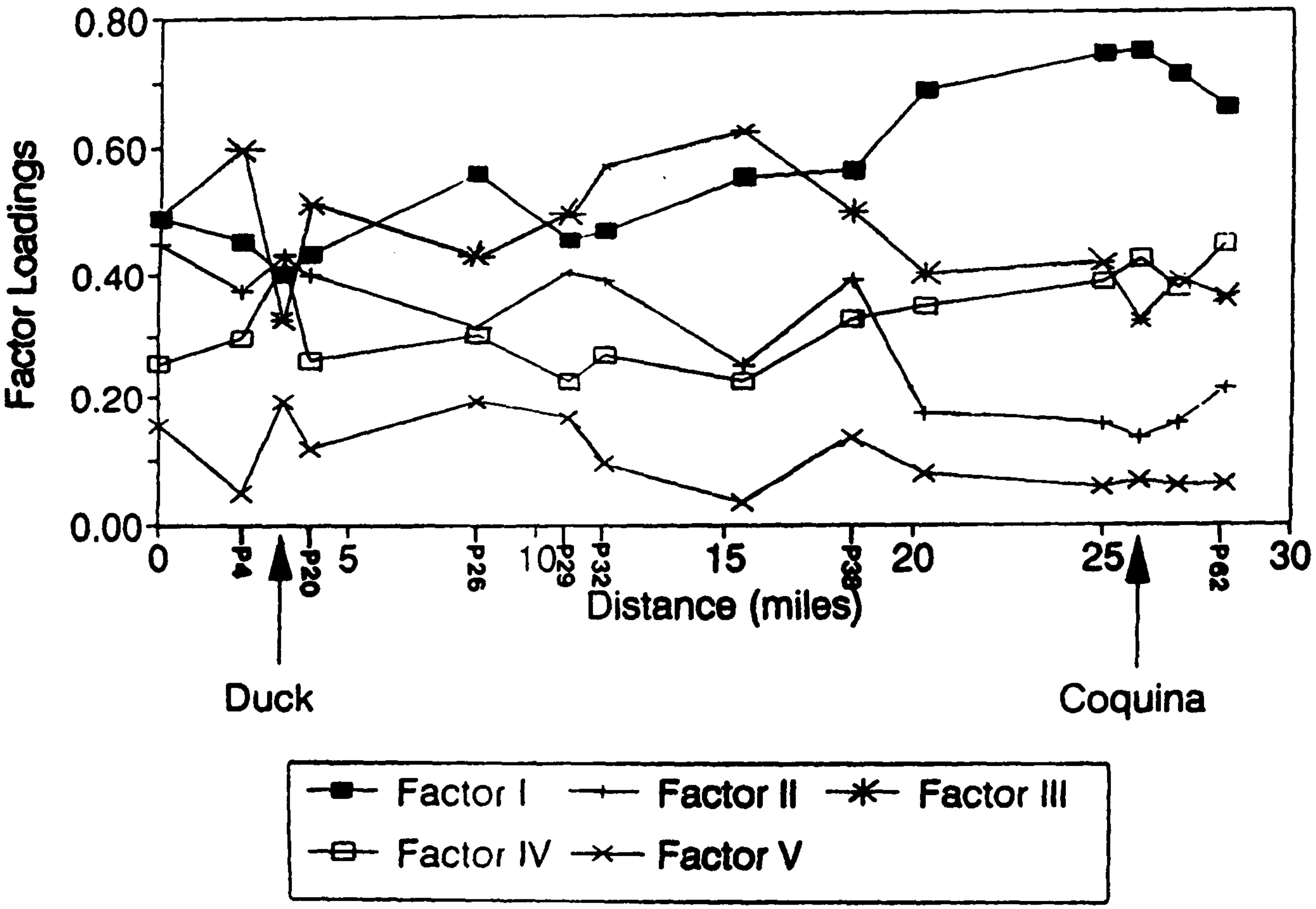
Data analysis suggests that several inputs of coarse sand

Table 12. Along-coast and cross-shore average factor loadings by factor of 14 beaches located between Duck and Oregon Inlet.

Average Factor Loadings

Distance (miles)	Factor I	Factor II	Factor III	Factor IV	Factor V
0.00	0.490	0.450	0.495	0.254	0.154
2.20	0.453	0.373	0.596	0.297	0.050
3.30	0.401	0.431	0.325	0.422	0.193
4.00	0.433	0.399	0.512	0.260	0.117
8.46	0.557	0.314	0.429	0.301	0.191
10.86	0.453	0.401	0.491	0.223	0.165
11.83	0.467	0.390	0.566	0.267	0.095
15.48	0.550	0.250	0.617	0.224	0.035
18.36	0.557	0.388	0.495	0.323	0.132
20.28	0.680	0.171	0.397	0.345	0.079
25.00	0.735	0.155	0.413	0.382	0.059
26.00	0.741	0.132	0.320	0.420	0.066
27.00	0.704	0.156	0.387	0.371	0.061
28.26	0.651	0.211	0.357	0.442	0.063

Figure 43. Cross-shore and along coast average factor loadings for individual factors


Factor Loadings
0.80
0.60
0.40
0.20
0.00
0
5
10
15
20
25
30
P4
P20
P26
P29
P32
P38
P62
Distance (miles)
Duck
Coquina
Factor I
Factor II
Factor III
Factor IV
Factor V

may exist along this barrier island strip. The southern limit of the coarse sediment influence appears to be located at P-38, just south of Nags Head. More evidences can be provided by analyzing separately the along-coast average loadings values of both, the same factor in different sub-environment and different factors in the same sub-environment.

10.3 Cross-Shore and Along-coast average factor loading value for specific beach zones

Figures 44 to 48 display tables and three-dimentional plots of the along-coast average factor loading value for each factor according to each zone across the beach. The values were obtained from the factor loading matrix of each location and represent the average of all the samples of that matrix associated with a particular sub-environment.

10.3.1 Factor I

As is shown in **Figure 44**, South of P-38, high loadings of Factor I are present across the beach. North of station P-38 higher values are more commonly associated with the landward side of the dune and dune crest. In general, factor loading values are lower for stations North of P-38 than at stations South of P-38.

10.3.2 Factor II

Figure 45 shows that Factor II is nearly absent south of P-38 (south of Nags Head.) South of P-53 (Coquina Beach) few significant loadings appear between the berm and mean sea level. North of P-38 high values, mainly associated with the step and lower foreshore, are evident. High loadings of Factor II appear to be limited to the zones between the step and the dune-toe backshore area. Loadings values associated with the landward side of the dunes are low. Yet it is possible to discern peaks of this factor in this zone.

10.3.3 Factor III

High significant loadings of Factor III are present north of P-38, (**Figure 46**) where, excluding the step/mean water level area, the values show little variation. South of this area while homogeneity exists, values associated with the upper foreshore/berm area are slightly higher. Excluding few points, the loading values in all sub-environments increase toward the area located between P-29 (10.86 miles) and P-38.

10.3.4 Factor IV

As is evident from **Figure 47**, the lowest loadings for Factor IV are linked to the area located between **P-32 and P-38**. Outside of these region, Factor IV increases. Highest values are more commonly associated with either the dune zone or the mean step/mean water level.

10.3.5. Factor V

Factor V's highest values are associated with the step and lower foreshore **(Figure 48)**. The lowest values are found on beaches located between P-38 and P-53 (Coquina beach) where there is no evidence of significant loadings beyond the lower foreshore. North of P-38, loadings are found from the step to the upper foreshore/berm zone.

The values listed on the tables, as well as the three dimensional plots, demonstrate that the highest values for both Factors II and V occur from the step/mean water level to dune toe/backshore zones. These zones were found to have very low loadings for Factors I and IV.

Figure 44. Factor I. Cross-shore and along-coast average factor loadings values for specific beach zones.

FACTOR I

LOCATION	Distance(miles)	PROFILE	LD	DC	DT/BS	UF/B	LF	STP/MSL
CAFFEYS INLET	0	1	0.6326	0.7427	0.2997	0.5469	0.4553	0.2134
	2.2	4	0.3759	0.5756	0.4091	0.3090	0.6546	0.3217
CERC	3.3	12	0.4090	0.3493	0.5437	0.4608	0.2475	0.3212
	4.0	20	0.5362	0.6081	0.3439	0.5499	0.0265	0.3172
KITTY HAWK	8.46	26	0.6390	0.5708	0.6910	0.5150	0.4649	0.1396
	10.86	29	0.7646	0.7925	0.3902	0.2354	0.1844	0.4137
S.AVALON PIER	11.83	32	0.3320	0.7058	0.4251	0.4940	0.4516	0.1681
	15.48	35	0.7119	0.7656	0.4679	0.4477	0.1651	0.4948
S.NAGS HEAD	18.36	38	0.6246	0.6619	0.5719	0.5767	0.3440	0.1573
JENNETS PIER	20.28	41	0.8045	0.6496	0.7620	0.6634	0.5188	0.5271
	25.00	45	0.6544	0.7592	0.7488	0.7406	0.5965	0.6948
COQUINA	26.00	53	0.6537	0.7858	0.8377	0.7652	0.8166	0.4998
	27.00	61	0.7684	0.7730	0.6603	0.6809	0.5775	0.5270
OREGON INLET CAMPGROUND	28.26	62	0.8203	0.6462	0.6359	0.5772	0.5906	0.4957

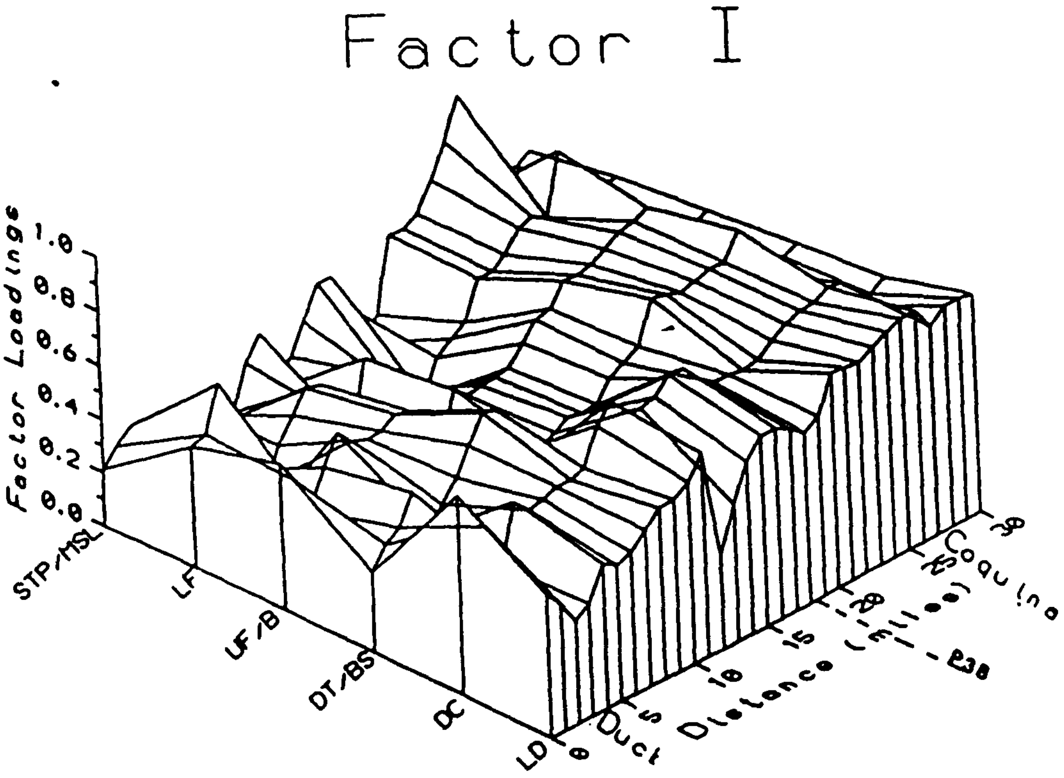


Figure 45. Factor II. Cross-shore and along-coast factor loading value for specific beach zones.

FACTOR II

LOCATION	Dist.(miles)	PROFILE	LD	DC	DT/BS	UF/B	LF	STP/MSL
CAFFEYS INLET	0	1	0.3884	0.1589	0.6907	0.4604	0.4767	0.6858
	2.2	4	0.4147	0.1840	0.4503	0.5432	0.3327	0.5867
CERC	3.3	12	0.3127	0.3918	0.4265	0.4139	0.6487	0.7817
	4.0	20	0.2075	0.2141	0.6187	0.5274	0.6128	0.3880
KITTY HAWK	8.46	26	0.2600	0.3205	0.2293	0.2737	0.4022	0.6862
	10.86	29	0.1041	0.0900	0.2913	0.2626	0.5674	0.4673
	11.83	32	0.3825	0.1352	0.4882	0.3861	0.3458	0.8606
	15.48	35	0.1072	0.0900	0.2913	0.2626	0.5674	0.4673
	18.36	36	0.3421	0.2607	0.2824	0.3733	0.7331	0.8202
JENNETES PIER	20.28	41	0.1450	0.2419	0.1642	0.1119	0.2116	0.1195
	25.00	45	0.0830	0.1058	0.1334	0.1752	0.2731	0.1040
COQUINA	26.00	53	0.0750	0.1298	0.1017	0.1577	0.1173	0.0962
	27.00	61	0.0922	0.0983	0.1349	0.1379	0.3227	0.3517
	28.26	62	0.1036	0.0945	0.2586	0.3591	0.3047	0.0782

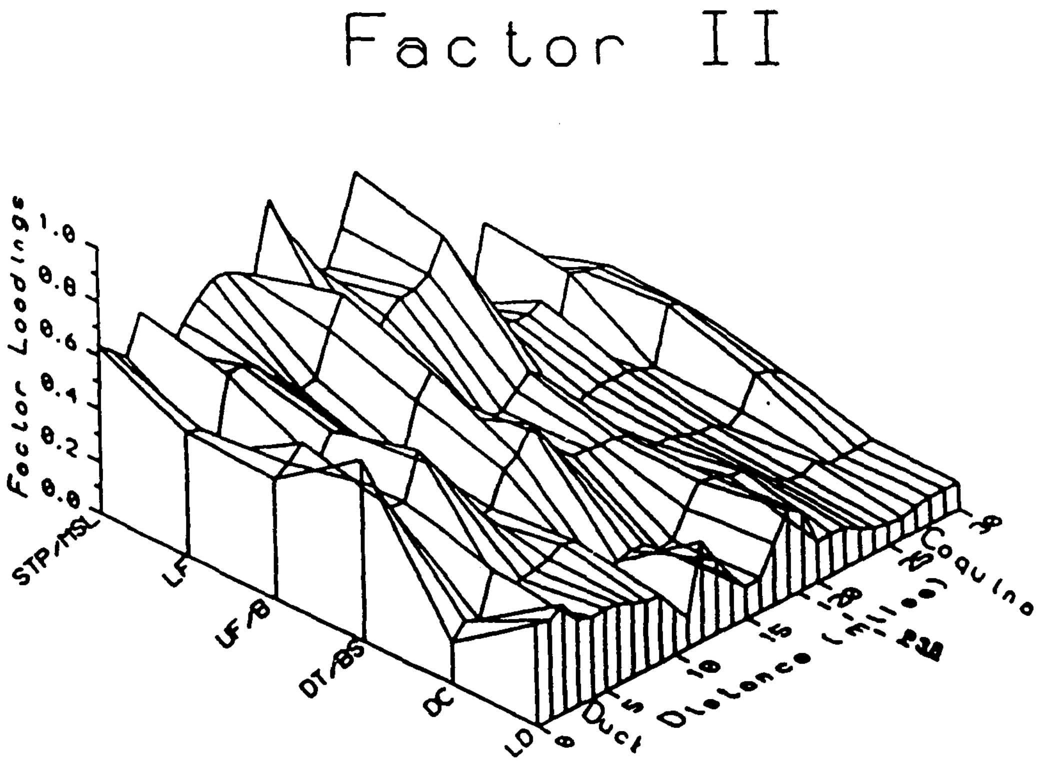


Figure 46. Factor III. Cross-shore and along-coast factor loading values for specific beach zones.

FACTOR III

LOCATION	Dist.(miles)	PROFILE	LD	DC	DT/BS	UF/B	LF	STP/MSL
CAFFEYS INLET	0	1	0.6508	0.5102	0.4193	0.5668	0.4645	0.2876
	2.2	4	0.6189	0.7219	0.6745	0.6448	0.3264	0.8000
CERC	3.3	12	0.2371	0.3229	0.3608	0.4276	0.2419	0.2817
	4.0	20	0.3605	0.6504	0.4828	0.3055	0.4765	0.0791
KITTY HAWK	8.46	26	0.5185	0.2276	0.4937	0.4108	0.5438	0.2966
	10.86	29	0.5965	0.2543	0.5366	0.6364	0.5113	0.1948
S.AVALON PIER	11.83	32	0.7983	0.5495	0.1943	0.5806	0.4349	0.2663
	15.48	35	0.6150	0.5576	0.7149	0.6409	0.5866	0.5334
S.NAGS HEAD	18.36	38	0.5195	0.5005	0.5706	0.5114	0.3266	0.3111
JENNETS PIER	20.28	41	0.3987	0.3048	0.4174	0.5398	0.3827	0.1015
	25.00	45	0.3294	0.2689	0.4997	0.4531	0.5349	0.2668
COQUINA	26.00	53	0.2725	0.3689	0.4177	0.3699	0.3019	0.1148
	27.00	61	0.2229	0.3129	0.5984	0.4078	0.3904	0.6866
OREGON INLET	28.26	62	0.3173	0.1511	0.4407	0.4239	0.3411	0.1050

Factor III

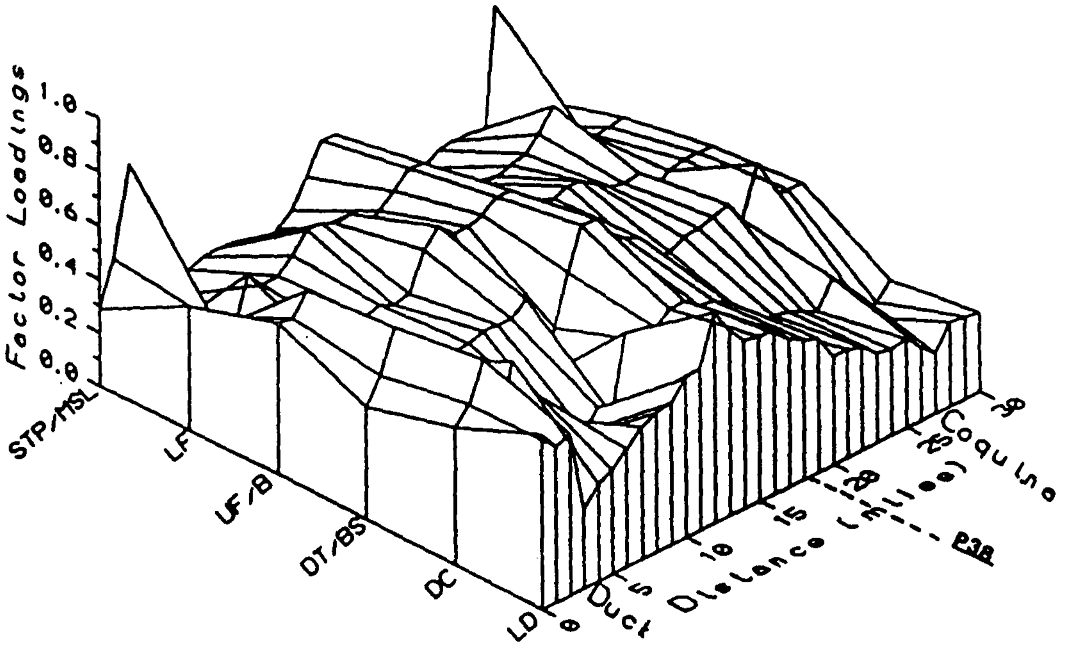


Figure 47. Factor IV. Cross-shore and along-coast factor loading values for specific beach zones.

FACTOR IV

LOCATION	Distance (miles)	PROFILE	LD	DC	DT/BS	UF/B	LF	STP/MSL
CAFFEYS INLET	0	1	0.2597	0.3563	0.2212	0.3066	0.2001	0.1060
	2.2	4	0.4046	0.2544	0.2168	0.1160	0.3580	0.4180
CERC	3.3	12	0.6379	0.4673	0.3641	0.3771	0.1242	0.3087
	4.0	20	0.6196	0.2564	0.1217	0.0443	0.0235	0.5036
KITTY HAWK	6.46	26	0.3544	0.4484	0.3035	0.2563	0.1669	0.1656
	10.86	29	0.1784	0.4770	0.1760	0.1885	0.0856	0.3109
S.AVALON PIER	11.83	32	0.2330	0.3952	0.1843	0.2925	0.2586	0.1687
	15.48	35	0.2669	0.1485	0.1901	0.2531	0.2168	0.2676
S.NAGS HEAD	18.36	38	0.2873	0.3520	0.3596	0.3331	0.2724	0.2373
JENNETS PIER	20.28	41	0.3539	0.3691	0.3673	0.2531	0.2794	0.7920
	25.00	45	0.3410	0.5545	0.2937	0.3240	0.3242	0.3186
COQUINA	26.00	53	0.4052	0.4212	0.2858	0.3415	0.4162	0.8315
	27.00	61	0.5767	0.3622	0.2243	0.4415	0.3830	0.2379
OREGON INLET CAMPGROUND	28.26	62	0.4483	0.6700	0.3866	0.3641	0.3241	0.8493

Factor IV

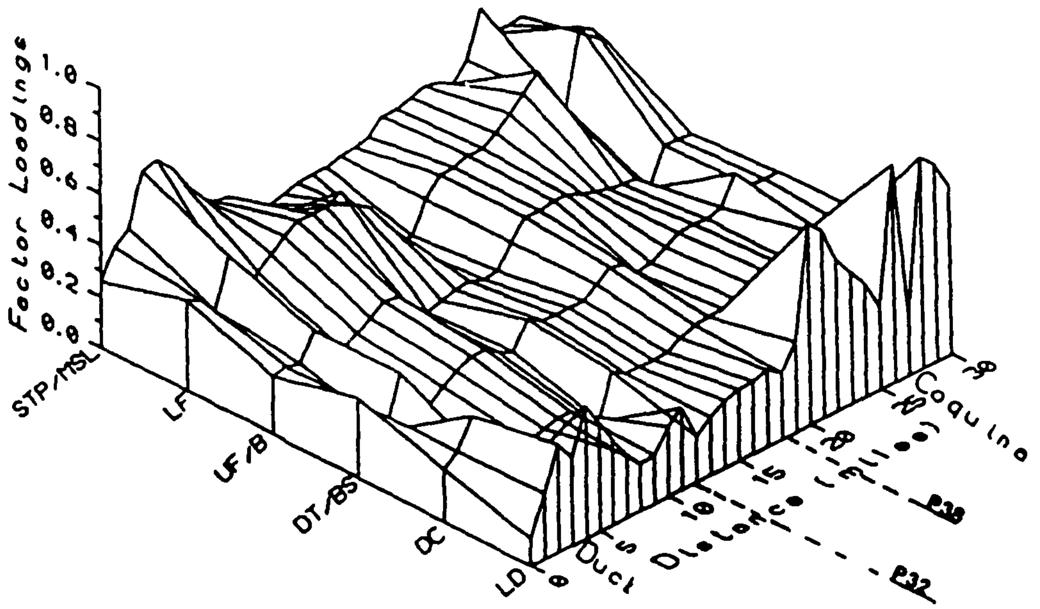
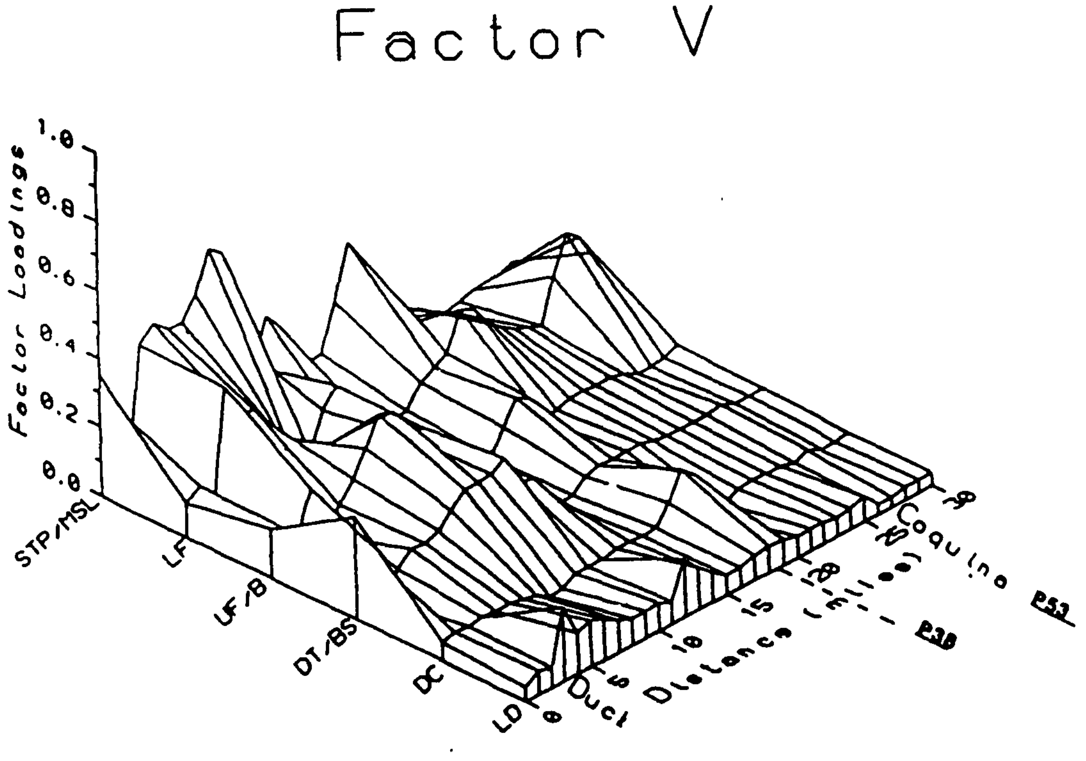


Figure 48. Factor V. Cross-shore and along-coast factor loading values for specific beach zones.

FACTOR V

LOCATION	Distance (miles)	PROFILE	LD	DC	DT/BS	UF/B	LF	STEP/MSL
CAFFEYS INLET	0	1	0.0248	0.0554	0.3015	0.1452	0.1008	0.3522
	2.2	4	0.0523	0.0576	0.0137	0.0790	0.0544	0.0138
CERC	3.3	12	0.2475	0.0646	0.0691	0.2309	0.4339	0.4260
	4.0	20	0.1175	0.0604	0.1233	0.0443	0.2667	0.4182
KITTY HAWK	8.46	26	0.0738	0.0153	0.2185	0.3238	0.0342	0.5815
	10.86	29	0.0602	0.0435	0.2446	0.2139	0.2174	0.1464
S.AVALON PIER	11.83	32	0.1697	0.0455	0.1454	0.0658	0.0385	0.2756
	15.48	35	0.0533	0.0477	0.0218	0.0058	0.0229	0.0610
S.NAGS HEAD	18.36	38	0.0771	0.1929	0.0741	0.1562	0.1173	0.3842
JENNETS PIER	20.28	41	0.0618	0.0043	0.0752	0.0421	0.2527	0.0519
	25.00	45	0.0732	0.0440	0.0537	0.0666	0.0899	0.0173
COQUINA	26.00	53	0.0308	0.0321	0.0543	0.0545	0.0830	0.0249
	27.00	61	0.0288	0.0473	0.0640	0.0343	0.1963	0.0368
OREGON INLET CAMPGROUND	28.26	62	0.0375	0.0260	0.0438	0.0331	0.3205	0.0397



10.4 Along-coast average loadings of different factors in the same environment

Figures 49 to 54, display along-coast average loadings of all the factors in each environment. In the same manner as the previous section, average values were also extracted from the factor loadings matrix of each location.

10.4.1 Landward side of the dune

According to **Figure 49**, Factors I and III best describe the landward side of the dune everywhere along the coast except at Duck and South of Coquina Beach where Factor IV shows significant loadings. Loadings on Factor III for this zone, decrease south of P-38. The absence of high loadings on Factor III south of this point appears to be linked with the low representation of Factors II and V which display some significance north of P-38. As already shown in previous diagrams, with the exception of some areas which could indicate possible overwash deposits, Factors II and V are not represented in these sub-environment.

10.4.2 Dune crest

As shown in **Figure 50**, the same inferences drawn for the above sub-environment are also valid for the dune crest zone. Major differences between these two zones are: a southerly increase in the loadings of Factor I south of P-38, and the higher homogeneity on Factor I loadings displayed by the dune crest zone.

10.4.3. Dune toe/backshore

The factor loading distributions associated with this zone are similar to previous observations related to areas under the influence of the coarse sediments. **Figure 51** shows that north of 18.36 miles, dune toe/backshore deposits display high loadings on Factor II. South of this point, deposits only display significant loadings on Factors I and III. North of P-38, loadings on Factor II are considerably higher.

10.4.4 Upper foreshore/berm

As can be seen in **Figure 52**, north of P-38 the highest values are related to Factors II and III. South of **P-38**, maximum loadings are best associated with Factor I which also displays significant values south of Duck. Loadings on Factor II and on Factor V are not indicated south of 18.36 miles.

10.4.5 Lower foreshore

The lower foreshore as demonstrated by **Figure 53** displays basically the same trends already described for the upper foreshore/berm zone. Major differences are related to the presence of high loadings on Factor II in the lower foreshore.

10.4.6 Step/mean water level

Major differences related to the loading values associated with the Factors I, II IV and V are obvious (**Figure 54**). Factor II, excluding a few points, is the most important factor north of P-38. Factor V also presents significant loadings related to this area. South of P-38, this zone is characterized by high loadings on Factors I and IV.

Figure 49. Along-coast average loadings on the factor axes for the landward side of the dune

LANDWARD SIDE OF THE DUNE

LOCATION	Distance (miles)	PROFILE	FACTOR I	FACTOR II	FACTOR III	FACTOR IV	FACTOR V
CAFFEYS INLET	0	1	0.5326	0.3884	0.6508	0.2587	0.0429
	2.2	4	0.3759	0.4147	0.6169	0.4046	0.0523
CERC	3.3	12	0.4090	0.3127	0.2371	0.6379	0.2475
	4.0	20	0.5362	0.2075	0.3605	0.6196	0.1175
KITTY HAWK	8.46	26	0.6390	0.2600	0.5185	0.3544	0.0738
	10.86	29	0.7648	0.1041	0.5965	0.1764	0.0602
S.AVALON PIER	11.83	32	0.3320	0.3825	0.7893	0.2330	0.1697
	15.48	35	0.7119	0.1072	0.6150	0.2669	0.0533
S.NAGS HEAD	18.36	38	0.6446	0.3421	0.5195	0.2873	0.0771
JENNETS PIER	20.28	41	0.8045	0.1450	0.3987	0.3539	0.0618
	25.00	45	0.8544	0.0830	0.3294	0.3410	0.0732
COQUINA	26.00	53	0.8537	0.0750	0.2725	0.4052	0.0308
	27.00	61	0.7684	0.0922	0.2229	0.5767	0.0288
OREGON INLET CAMPGROUND	28.26	62	0.8203	0.1036	0.3173	0.4483	0.0375

LD

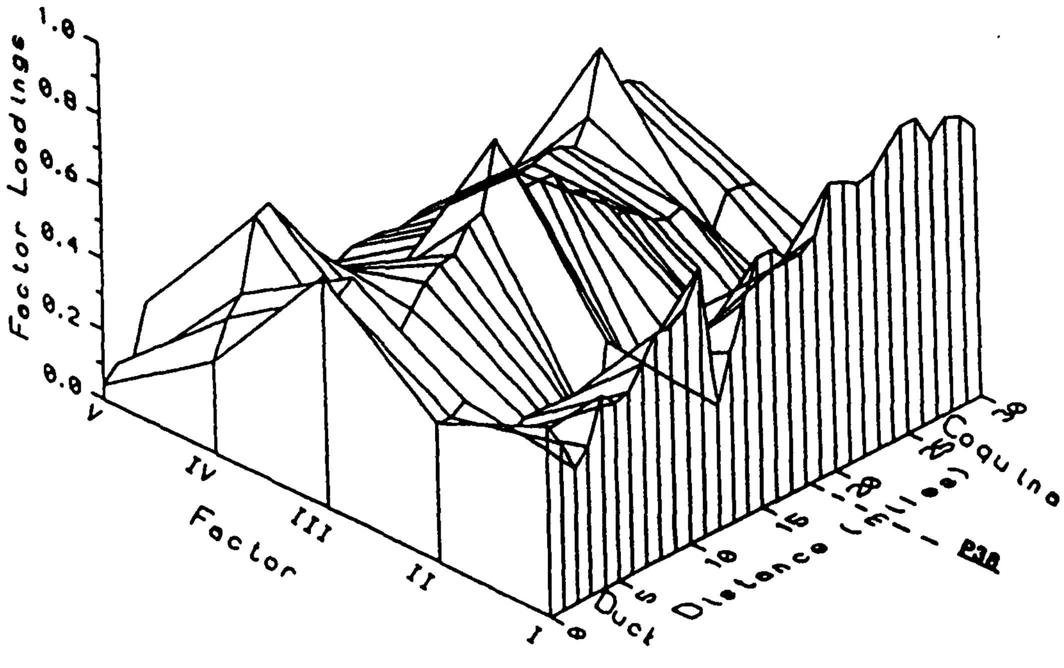


Figure 50. Along-coast average loadings on the factor axes for the dune crest area.

DUNE CREST

LOCATION	Distance(miles)	PROFILE	FACTOR I	FACTOR II	FACTOR III	FACTOR IV	FACTOR V
CAFFEYS INLET	0	1	0.7427	0.1599	0.5102	0.3563	0.0554
	2.2	4	0.5758	0.1840	0.7219	0.2544	0.0576
CERC	3.3	12	0.3493	0.3918	0.3229	0.4837	0.0646
	4.0	20	0.6081	0.2141	0.6504	0.2564	0.0604
KITTY HAWK	8.46	26	0.5708	0.3205	0.2276	0.4494	0.0153
	10.86	29	0.7925	0.0968	0.2543	0.4770	0.0435
S.AVALON PIER	11.83	32	0.7058	0.1352	0.5495	0.3952	0.0455
	15.48	35	0.7856	0.0900	0.5576	0.1485	0.0477
S.NAGS HEAD	18.36	38	0.6619	0.2807	0.5005	0.3520	0.1928
JENNETS PIER	20.28	41	0.6496	0.2419	0.3048	0.3691	0.0043
	25.00	45	0.7592	0.1058	0.2689	0.5545	0.0440
COQUINA	26.00	53	0.7858	0.1298	0.3689	0.4212	0.0321
	27.00	61	0.7730	0.0983	0.3129	0.3622	0.0473
OREGON INLENT CAMPGROUND	28.26	62	0.6462	0.0945	0.1511	0.6700	0.0260

DC

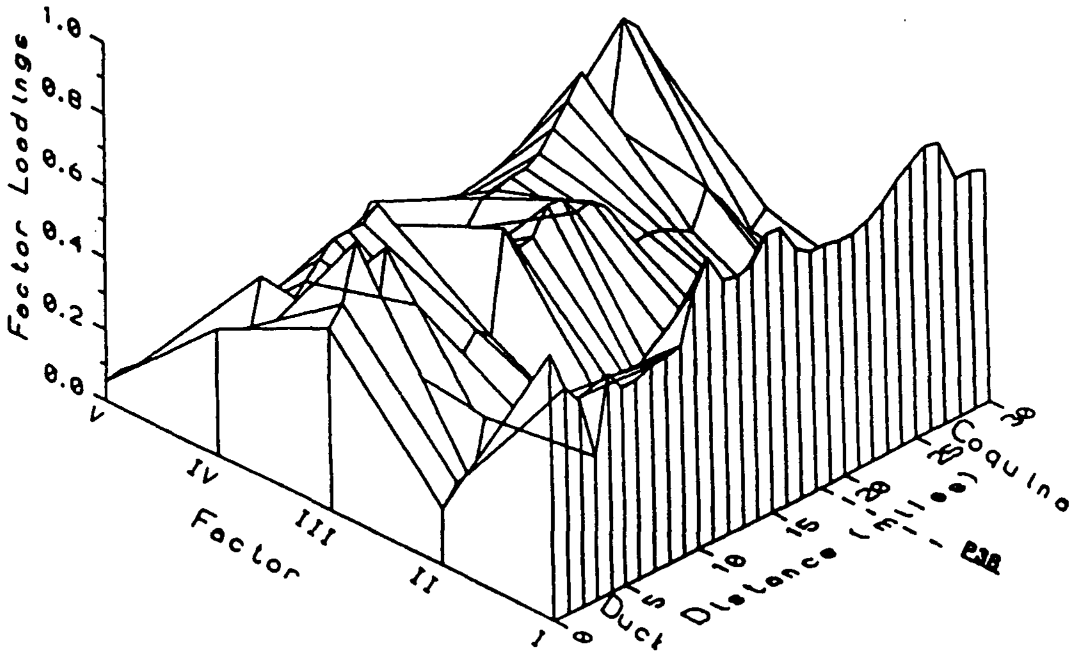


Figure 51. Along-coast average loadings on the factor axes for the dune toe-backshore area.

DUNE TOE/BACKSHORE

LOCATION	Distance(miles)	PROFILE	FACTOR I	FACTOR II	FACTOR III	FACTOR IV	FACTOR V
CAFFEYS INLET	0	1	0.2997	0.6906	0.4183	0.2214	0.3015
	2.2	4	0.4091	0.4503	0.6745	0.2169	0.0137
CERC	3.3	12	0.5437	0.4285	0.3806	0.3541	0.0891
	4.0	20	0.3436	0.6187	0.4826	0.1217	0.1233
KITTY HAWK	6.46	26	0.6910	0.2293	0.4937	0.3055	0.2185
	10.86	29	0.3902	0.4046	0.5368	0.1760	0.2448
S.AVALON PIER	11.63	32	0.4251	0.4982	0.1943	0.1943	0.1454
	15.46	35	0.4679	0.2913	0.7149	0.1901	0.0218
S.NAGS HEAD	18.36	38	0.5719	0.2824	0.5706	0.3596	0.0741
JENNETS PIER	20.28	41	0.7620	0.1642	0.4174	0.3673	0.0752
	25.00	45	0.7486	0.1334	0.4997	0.2937	0.0537
COQUINA	26.00	53	0.8377	0.1017	0.4177	0.2858	0.0543
	27.00	61	0.6603	0.1349	0.5984	0.2243	0.0640
OREGON INLET CAMPGROUND	28.26	62	0.6359	0.2586	0.4407	0.3686	0.0438

DT-BS

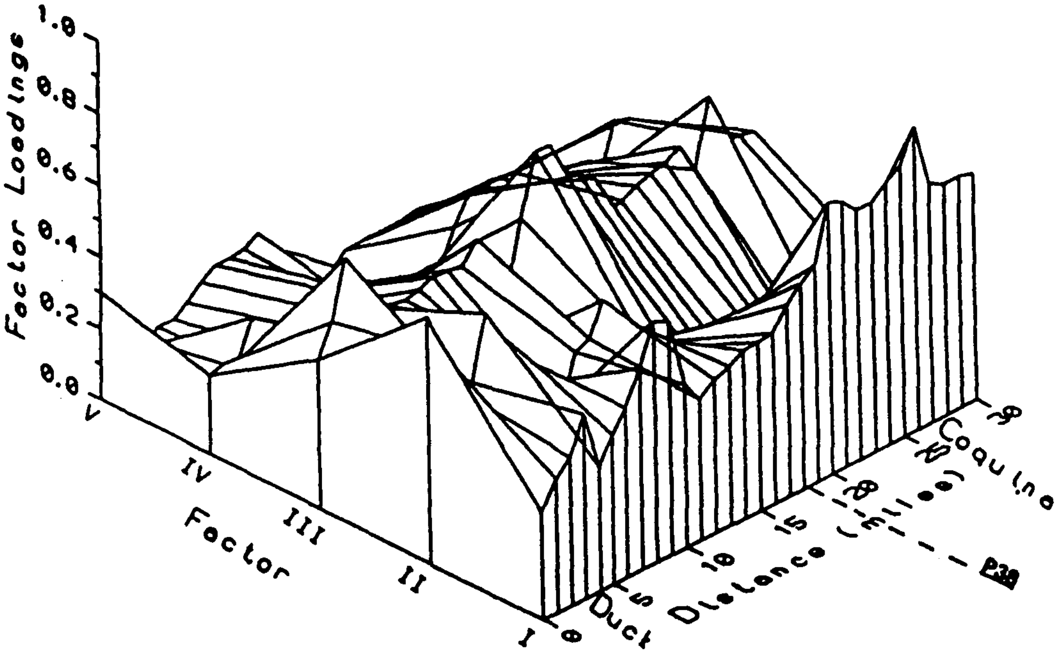


Figure 52. Along-coast average loadings on the factor axes for the upper foreshore-berm area.

U.FORESHORE/BERM

LOCATION	Distance(miles)	PROFILE	FACTOR I	FACTOR II	FACTOR III	FACTOR IV	FACTOR V
CAFFEYS INLET	0	1	0.5489	0.4604	0.5666	0.3068	0.1452
	2.2	4	0.3090	0.5432	0.6446	0.1180	0.0780
CERC	3.3	12	0.4606	0.4139	0.4276	0.3771	0.2309
	4.0	20	0.5499	0.5274	0.3055	0.0443	0.0443
KITTY HAWK	8.46	26	0.5150	0.2737	0.4106	0.2583	0.3238
	10.86	28	0.2354	0.5665	0.6364	0.1695	0.2139
S.AVALON PIER	11.83	32	0.4940	0.3661	0.5606	0.2925	0.0656
	15.46	35	0.4477	0.2628	0.6409	0.2531	0.0058
S.NAGS HEAD	18.36	38	0.5767	0.3733	0.5114	0.3331	0.1562
JENNETS PIER	20.28	41	0.6634	0.1119	0.5398	0.2531	0.0421
	25.00	45	0.7406	0.1752	0.4531	0.3240	0.0666
COQUINA	26.00	53	0.7652	0.1677	0.3699	0.3415	0.0545
	27.00	61	0.6609	0.1379	0.4078	0.4415	0.0343
OREGON INLET CAMPGROUND	28.26	62	0.5772	0.3591	0.4329	0.3641	0.0331

UF - B

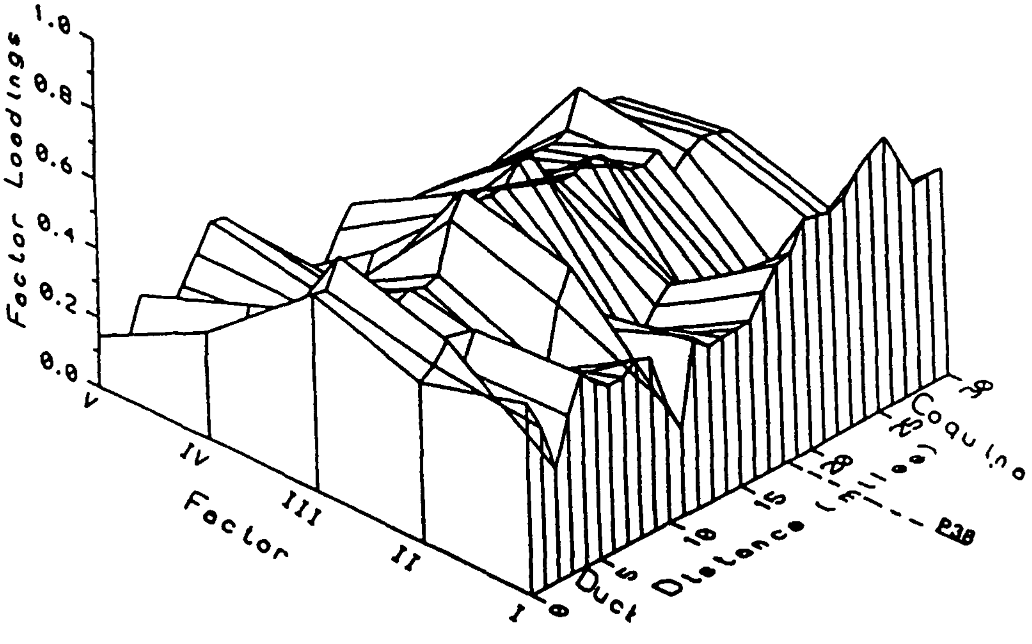


Figure 53. Along-coast average loadings on the factor axes for the lower foreshore.

LOWER FORESHORE

LOCATION	Distance(miles)	PROFILE	FACTOR I	FACTOR II	FACTOR III	FACTOR IV	FACTOR V
CAFFEYS INLET	0	1	0.4553	0.4767	0.4645	0.2001	0.1009
	2.2	4	0.6549	0.3327	0.3264	0.3590	0.0544
CERC	3.3	12	0.2475	0.6487	0.2419	0.1242	0.4339
	4.0	20	0.0265	0.6128	0.4765	0.0235	0.2667
KITTY HAWK	8.46	26	0.4649	0.4022	0.5438	0.1869	0.0342
	10.86	29	0.1884	0.6960	0.5153	0.0856	0.2174
S.AVALON PIER	11.83	32	0.4516	0.3458	0.4349	0.2586	0.0385
	15.46	35	0.1651	0.5674	0.5866	0.2168	0.0229
S.NAGS HEAD	18.36	38	0.3440	0.7331	0.3268	0.2724	0.1173
JENNETS PIER	20.28	41	0.5188	0.2116	0.3827	0.2794	0.2527
	25.00	45	0.5965	0.2731	0.5349	0.3242	0.0899
COQUINA	26 00	53	0 8166	0.1173	0.3019	0.4163	0.0730
	27 00	61	0.5775	0.3227	0.3904	0.3830	0.1963
OREGON INLET CAMPGROUND	28.26	62	0 5906	0.3047	0.3411	0.3241	0.3205

LF

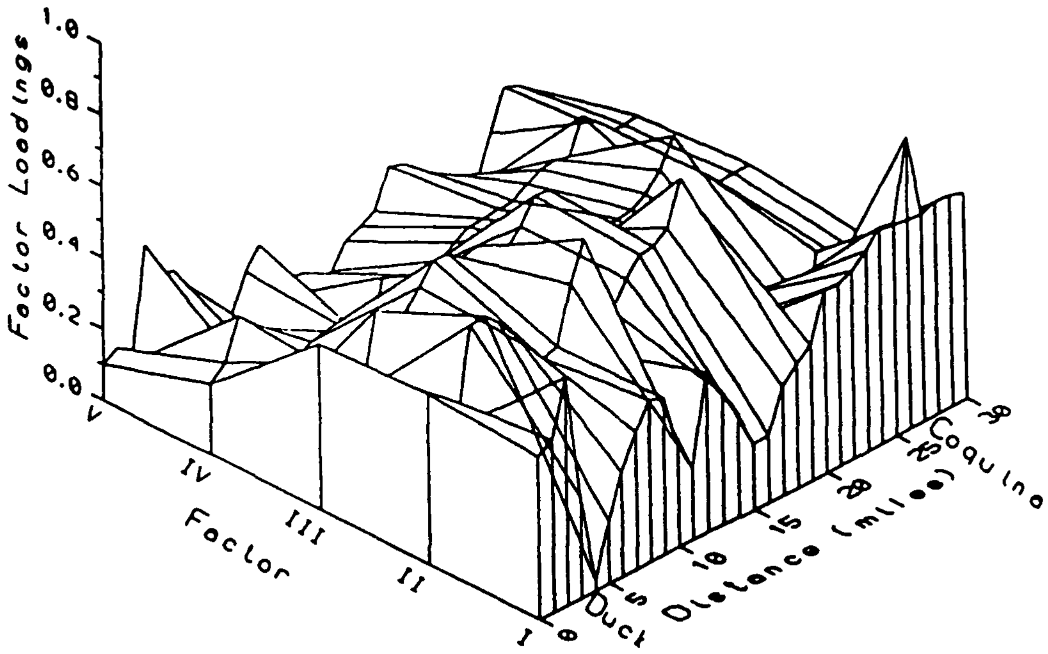
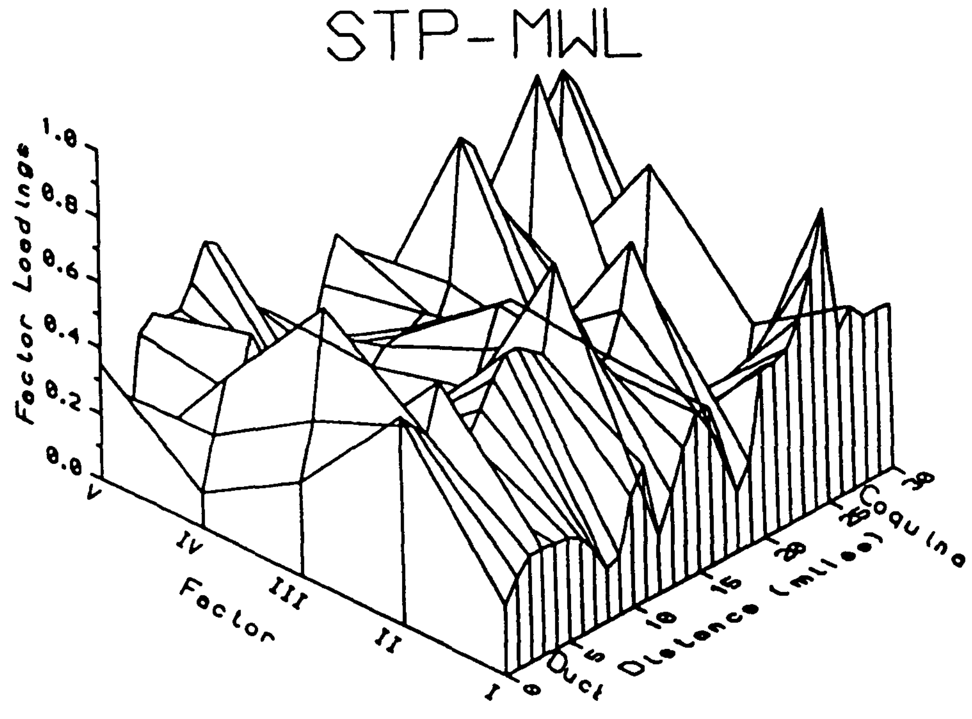


Figure 54. Along-coast average loadings on the factor axes for the step-mean water level zone.

STEP/MWL

LOCATION	Distance(miles)	PROFILE	FACTOR I	FACTOR II	FACTOR III	FACTOR IV	FACTOR V
CAFFEYS INLET	0	1	0.2134	0.6359	0.2876	0.1069	0.3522
	2.2	4	0.3217	0.5337	0.6000	0.4180	0.0138
CERC	3.3	12	0.3212	0.7317	0.2817	0.3097	0.4260
	4.0	20	0.3172	0.3390	0.0791	0.5036	0.4192
KITTY HAWK	6.46	26	0.1396	0.6662	0.2966	0.1656	0.5615
	10.86	29	0.4137	0.5874	0.1946	0.3109	0.1464
S.AVALON PIER	11.63	32	0.1681	0.8606	0.2663	0.1687	0.2756
	15.46	35	0.484	0.4673	0.5334	0.2678	0.0610
S.NAGS HEAD	18.36	38	0.1573	0.8202	0.3111	0.2373	0.3842
JENNETS PIER	20.28	41	0.5271	0.1195	0.1015	0.7920	0.0519
	25.00	45	0/8948	0.1040	0.2668	0.3186	0.0173
COQUINA	26.00	53	0.4998	0.0962	0.1146	0.8315	0.0249
	27.00	61	0.5527	0.3517	0.6666	0.2379	0.0368
OREGON INLET CAMPGROUND	28.26	62	0.4957	0.0792	0.1050	0.8493	0.0397



11. DISCUSSION OF THE ALONG-COAST RESULTS

The distribution of factor loadings values supports the results found in the general study, which demonstrated the association between factor groups and sub-environments. However, the introduction of a more representative data set also shows alongshore variations in the previously defined relationships. Such is the case for the landward side of the dune zone at Duck, which in the previous study was best characterized by factor IV. The along-coast study shows that besides factor IV, factors I and III also display high loadings in this sub-environment. Results for this sub-environment obtained for Coquina Beach in the general study are confirmed by the along-coast data set.

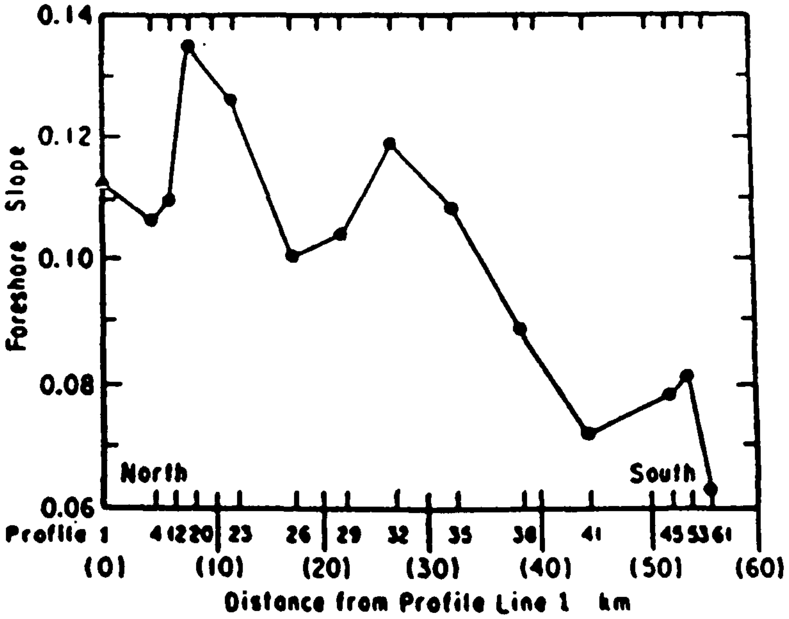
The previous results obtained for the dune crest and dune toe/backshore sub-environments at Duck and Coquina Beaches also show alongshore continuity. However, the new data set also provides some information related to the presence of significant loadings in factor III on fine beaches.

The along-coast study also shows that high loadings in factors II and III and significant loadings in factor I are found in the lower foreshore of beaches dominated by coarse sediments. The foreshore for fine beaches in the study area display high loadings in factor I although factors III and IV also display reasonable values. With exception of high loadings associated with factor V, the trends displayed by the alongshore data set corroborate those obtained by the general study.

As is shown by the along-coast distribution of factor loadings, there is an accentuated difference among sediment factor groups and their distribution in the study area. North of Profile 38, which is located just south of Nags Head, high loadings on factors II and V are clear. Major loadings are located near Duck in proximity of Avalon Pier (profile 32) and at profile 38, close to Nags Head Pier. The manifestation of these coarse factors can be identified throughout all the sub-environments. These relict sediments introduced to the sedimentary system appear to be replacing the original sediments, probably represented by factor I (medium sand) and Factor IV. These localized inputs are corroborated by the alongshore variation in average foreshore slope as is demonstrated by **Figure** 55 from Birkemeier et al. (1985), where steep foreshore slopes are found in areas with coarse sediments.

Based on the study of the nearshore sediment distribution between Cape Henry and Cape Hatteras, Swift (1970) attributed the occurrence of these discontinuous coarse sediments to a local source of gravel excavated from the former Albemarle river channel. Shideler and Swift (1972) analyzed seismic evidence from the middle shelf that suggested that this channel may have trended eastward along the coastal plain near the former mouth of Albemarle Sound during the late Tertiary or early Pleistocene. Farrel (1977) analyzed the detailed bathymetry of this area indicating the presence of a relict channel in the vicinity. Goldsmith (1977) found evidence of a coarse area concentrated between Caffey's inlet (located 5 miles north of Duck) and Duck. Birkemeier and others

Figure 55. Alongshore variation in average foreshore slope. From Bierkemeier et al. (1985)


0.14
0.12
0.10
0.08
0.06
Foreshore Slope
North
South
Profile 1
4
12
20
23
26
29
32
35
38
41
45
53
61
(0)
(10)
(20)
(30)
(40)
(50)
(60)
Distance from Profile Line 1 km

(1985), indicate a decrease in sand size from north to south of the Army Corps of Engineers pier (CERC) at Duck.

Riggs and O'Connor (1974), through detailed acoustic sub-bottom profiling adjacent to Roanoke Island, found evidence of extensive channel systems that transect the area at right angles to the coastline. One branch of this channel, which extends beneath Roanoke Island and has been interpreted as fluvial or tidal, is directly related to a gravelly sand unit which occurs between -2.5 and -6 m in depth within the area. Some well defined burried channels whose southern limits coincide with the limit of the coarse anomalies found in our study area were also mapped. This channel was the only one recorded by sub-bottom profiling that could be traced seaward of the barrier island chain **(Figure 56)**.

Although a offshore source has been postulated for these coarse deposits, it is suggested here that the occurrence of several ephemeral inlets as demonstrated by Fisher (1977) and Everts and al. (1983) may have contributed to the presence of coarse sediments in this area. The southern limit of the coarse deposits is located approximately at 36° 00 South and coincides with the limit of ancient ephemeral inlets in the area as described by Everts et al. (1977).

Riggs and O'Connor (1974), mapping the surface sediment distribution adjacent to Roanoke Island, found that relict sediments composed of medium, coarse and gravelly sands are the main sediments exposed along the deeper channels of Croatan Sound (just behind

Roanoke Island), as well as in the eroding beach of Roanoke Island (**Figure 57**). According to Riggs and O'Connor (1974), significant development of relict sediments can occur within the estuarine complex itself.

Figure 56. Map showing the distribution of relict sub-bottom channels through Croatan Sound, Roanoke Island and Roanoke Sound, North Carolina. The channels are based upon 500 miles of seismic surveys. From Riggs and O'Connor (1974).

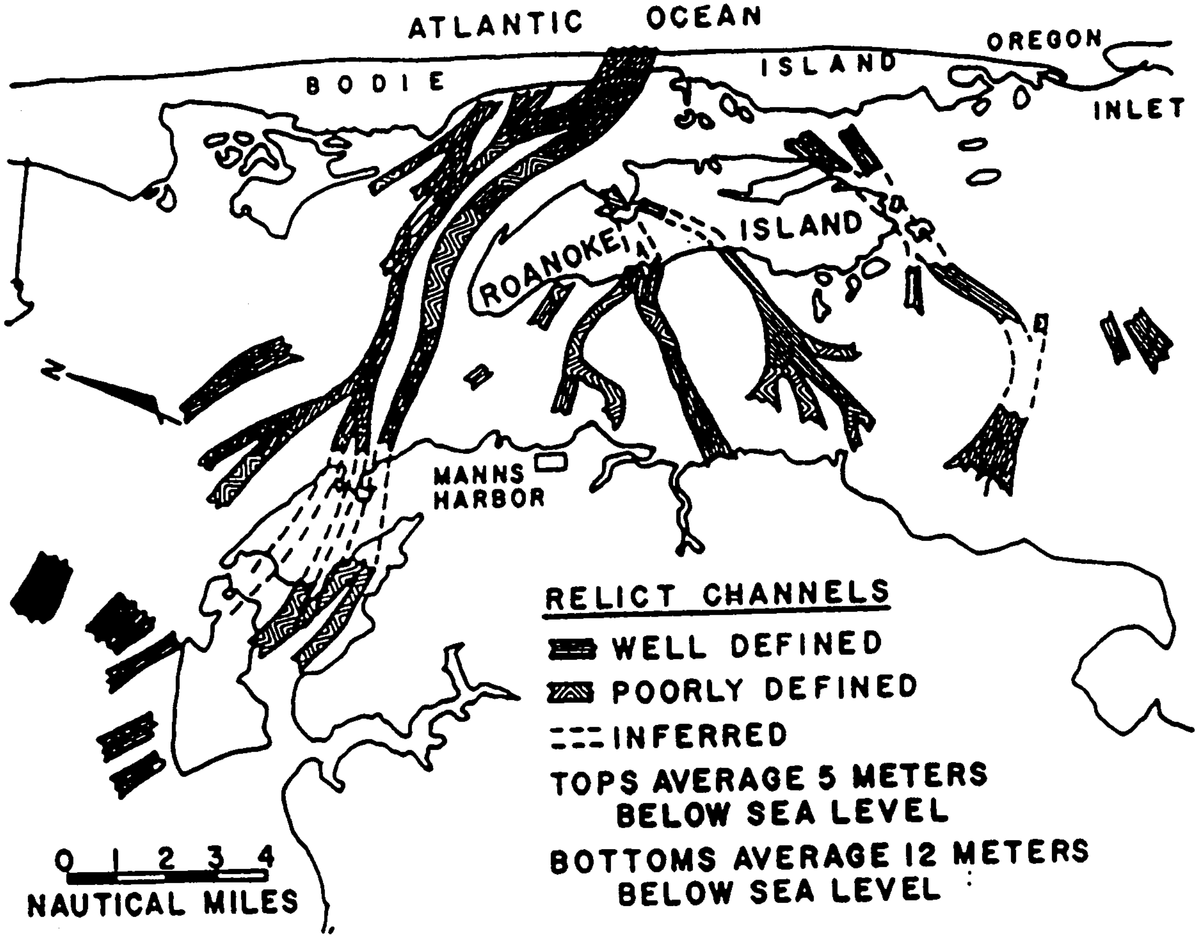
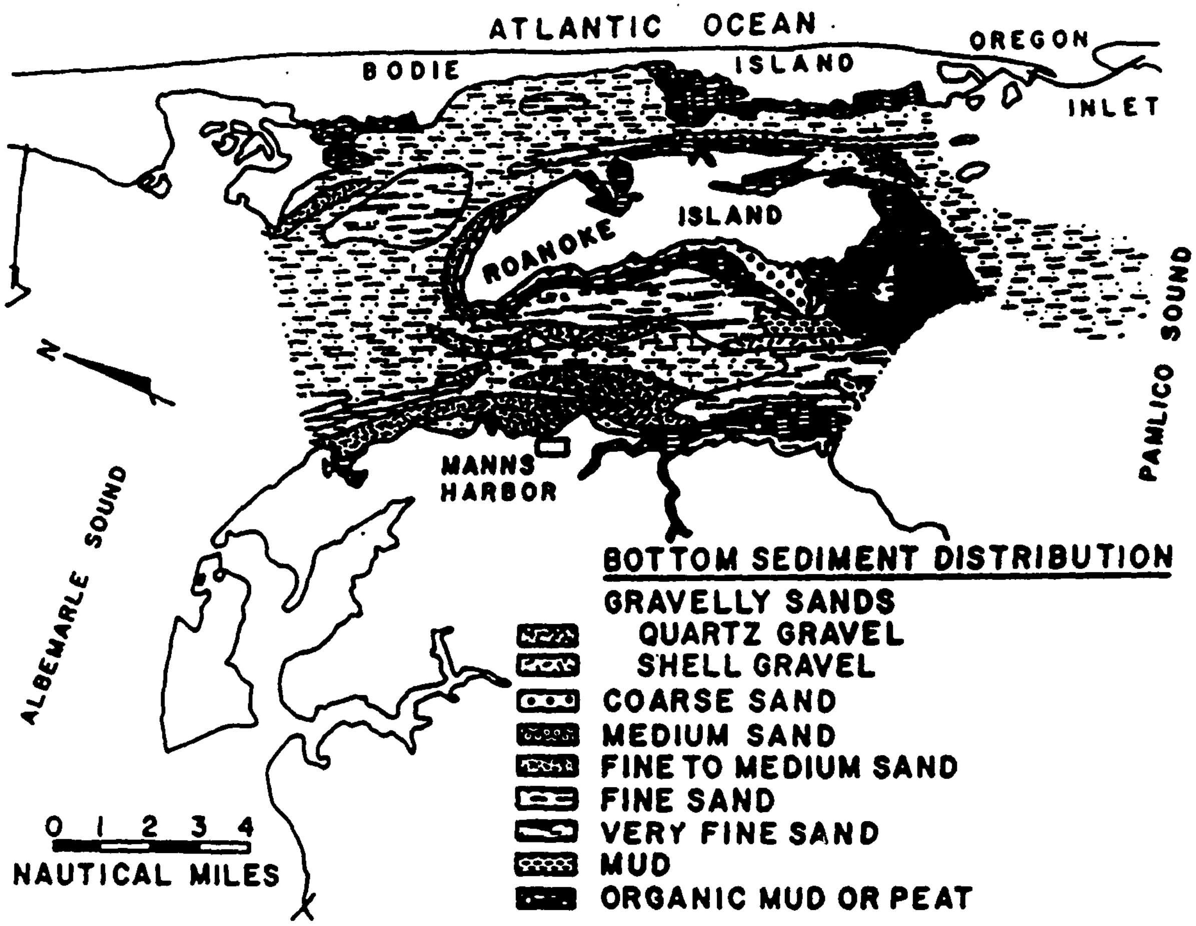

ATLANTIC OCEAN
BODIE ISLAND
OREGON INLET
ROANOKE ISLAND
MANNS HARBOR
N
RELICT CHANNELS
WELL DEFINED
POORLY DEFINED
INFERRED
TOPS AVERAGE 5 METERS BELOW SEA LEVEL
BOTTOMS AVERAGE 12 METERS BELOW SEA LEVEL
0 1 2 3 4
NAUTICAL MILES

Figure 57. Map of estuarine surface sediment distribution in the proximities of Roanoke Island, North Carolina. From Riggs and O'Connor, (1974)


ATLANTIC OCEAN
OREGON
INLET
BODIE
ISLAND
ROANOKE
ISLAND
PAMLICO SOUND
ALBEMARLE SOUND
MANNS
HARBOR
N
0 1 2 3 4
NAUTICAL MILES
BOTTOM SEDIMENT DISTRIBUTION
GRAVELLY SANDS
QUARTZ GRAVEL
SHELL GRAVEL
COARSE SAND
MEDIUM SAND
FINE TO MEDIUM SAND
FINE SAND
VERY FINE SAND
MUD
ORGANIC MUD OR PEAT

12. CONCLUSIONS

- The pilot study (Duck and Whalehead beach) demonstrates that Q-mode factor analysis has condensed the relationship among the grain-size characteristics of 87 surficial sediment samples collected over a period of one year. Based on this analysis, all the samples can be related to a five end-member distribution. These five factors explain 97.36% of the total variance in the grain-size data set (gravel to very fine sand). Independently, Factor I accounts for 33.76% of the variability in the sediment data set. Factor V accounts for 31.15%, Factor III 15.12%, Factor II 10.01% and Factor IV 7.32%. These five groups are characterized by: I) very well sorted coarse to medium sand, II) moderately well sorted, coarse to medium sand, III) poorly sorted very coarse sand displaying a bimodal distribution, IV) poorly sorted gravel, and V) well sorted medium sand.

- The general study indicates that when only the sand fraction is considered, all 178 sediment samples collected from the landward side of the dune to the mean water level at Duck and Coquina beach can be related to a five end-member distribution. These end-members exhibit unique textural distributions. The other samples can be regarded as combinations of these five unique samples. Although the general study did not include a gravel fraction, the factors obtained from both studies (pilot and general) were similar.

- These five factors, which explain 97.64% of the variance, proved to be both effective in explaining the data set variability when the addition of 300 hundred new sediment samples from intermediate zones were introduced, and well defined by the Q-mode factor model.

- Although textural differentiation occurs within major environmental categories, sub-environmental separation on the basis of factor analysis in the study area appears to be more effective than the use of summary statistics.

-The inverse relationship between coarse and fine sediments at the backshore of bimodal beaches suggests that a replacement process is taking place. Fine sediments will be dislocated shoreward to areas where they will be exposed to energy conditions that result in their depletion in the subaerial beach.

- Q-mode factor analysis demonstrated that, on a long-term basis, a general trend in the surficial distribution of sediments in the study area exists. Particularly at beaches which are rich in coarse sediments, the association of sediment factor groups with specific cross-shore beach zones (dunes to step) reflects a textural differentiation produced by the energy level associated with the mechanism of sediment transport inherent to each zone. With only the support of the log-probability plots, it is very difficult to quantify the significance of specific sediment transport processes (traction, saltation and suspension) in zones between the step and the dune toe. The plots derived here do not coincide with the typical plots described in the literature for these particular sub-environments. However the log-probability plots provide signatures which characterize some of these zones. In this way, Factor II in the pilot study as well Factors I, III and IV in the general study are associated with environments where aeolian processes are the predominant transporting agent. Differences between these sub-environments (specially the landward side of the dune and dune crest) can be discerned by careful inspection of the log-probability curve. The foreshore and the step are best represented by Factors II and V.

- The combination of Q-mode factor analysis and log-probability plots proved to be a useful tool for interpreting sedimentary processes. These tools can be used to interpret depositional processes of ancient sand bodies.

- By using the Q-mode factor model approach, a relatively large area of Currituck Spit was "mapped" in terms of the surficial sediment distribution. The pattern observed represents an average of the sedimentary processes occurring under both fair weather and storm conditions. This distribution as described by the factors provide a more accurate and realistic picture than maps produced using standard statistical parameters.

-The along-coast gradients observed in the factor loading plots indicate that there are several sources of coarse sediments between Duck and Oregon Inlet. Sedimentologic, stratigraphic, and seismic data collected offshore and landward of the barrier substantiate these findings. Particularly, the southern limit of the coarse anomalies south of (P-38) correspond to the southern limit of a paleochannel which is continuous on the adjacent inner shelf. These facts demonstrate that beach evolution in this part of Currituck Spit was partially influenced by the availability of coarse sand from the paleodrainage of the Albermarle river. Localized sources of coarse sediments are responsible for the general morphological differences (width and steepness) of the beaches in the studied area.

- The fact that coarse Factors (specially very coarse sand) are less represented across all the beach profile at Whalehead than at Duck and almost negligible at Coquina beach, lead us to make the following observations:

a) Assuming an offshore source for the coarse clastics, these sediments introduced to the beach system over recent geological time, have replaced, in some locations (where the coarse anomalies are more pronounced), the medium and fine sand native to the beach at the time the barrier was formed. Although the influence of these coarse sediments can be observed across the entire beach profile, the replacement process occurs from the step to the backshore.

If the above is true, the facts imply a process of beach evolution from a wide beach with a flat beach face towards a narrow beach with a steep beach face. Since a fine grained beach tends to be broad and flat and a coarse beach tends to be steep and narrow, Duck Beach in the past, therefore, would have a configuration similar to the present Whalehead and Coquina beaches.

This also implies that very fine, fine and medium sand can be lost from these coarse beaches. The system has probably been losing fine and medium sands offshore.

b) The assumption that the coarse sediments were present when the barrier was formed, implies that they represent a lag deposit (product of hydraulic sorting). In this case both beaches evolved differently simply by the fact of the availability of coarse material.

The fact that: factor II (coarse sand) in the pilot study display some importance from the backshore to the lower foreshore and factor III (very coarse sand) also appears in small amounts at the middle and lower foreshore at Whalehead, and factors II and V (respectively coarse and very coarse sand) are significant in the lower foreshore and step of Coquina beach, lead us to choose the first assumption as the most reasonable one.

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