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GRAIN SIZE RECONNAISSANCE OF THE VIRGINIA-NORTH CAROLINA INNER SHELF: ANALYSIS BY SETTLING TECHNIQUE

by

Robert Bailey Sanford, Jr.

Submitted to the Institute of Oceanography of Old Dominion University in partial fulfillment of the requirements for the degree of Master of Science.

This project was conducted under Coastal Engineering Research Center contract DACW 72-69-0016. Certain phases of the field work were supported by the Marine Geology and hydrology branch of the U.S. Geological Survey.

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Mr. R. N. Parker

July, 1970

ACKNOWLEDGMENTS

Funds for this study were generously provided by the Coastal Engineering Research Center contract DACW 72-69-C-0016, and by the U.S. Geological Survey. I am deeply indebted to Dr. Donald J. P. Swift who directed me in all phases of this study. I wish to thank Dr. John C. Ludwick, Dr. David Duane, and Dr. John Schlee for their valuable counsel, Mr. Robert D. Martin for his valuable help in calibrating the Rapid Sediment Analyzer, and Mr. Charles E. Dill who undertook much of the fieldwork.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

The 2-fold purpose of this study is to calibrate a Rapid Sediment Analyzer and to use it to aid in the determination of the genesis of sediment on the inner continental shelf between Cape Henry and Cape Hatteras. Rapid Sediment Analyzer calibration was conducted by comparison of sieving and settling results of similar sands.

The study area was divided into sediment provinces by both a qualitative procedure (grain size and topography) and a quantitatively procedure (factor-vector analysis). Qualitative provinces are beach and surf, upper shore face, lower shore face, sea floor, and terminal shoals. The berm fines from each terminal cape toward the centrally located False Cape with an anomalous, coarse sector in the area of Nags Head. This berm pattern is thought to be partly inherited from the Pleistocene substrate and partly due to the modern hydraulic regime.

Seaward of the breakers the shore face fines southward probably through increased winnowing of fines as wave height increases. In general, the wave-driven fractionation processes on the shore face are very efficient since all measured parameters vary systematically with depth.

On the sea floor a south and centrally located coarse sand is thought to be an unburied Pleistocene deposition. From Cape Henry to False Cape, the sea floor is coarse and well sorted and is probably due to a former hydraulic regime and land mass.

The northern terminal shoal off Cape Henry consists of medium-grained sand, and the southern terminal shoal (Diamond Shoals) consists of fine, well-sorted sand. In both cases the modern hydraulic regime is considered to be the cause of deposition.

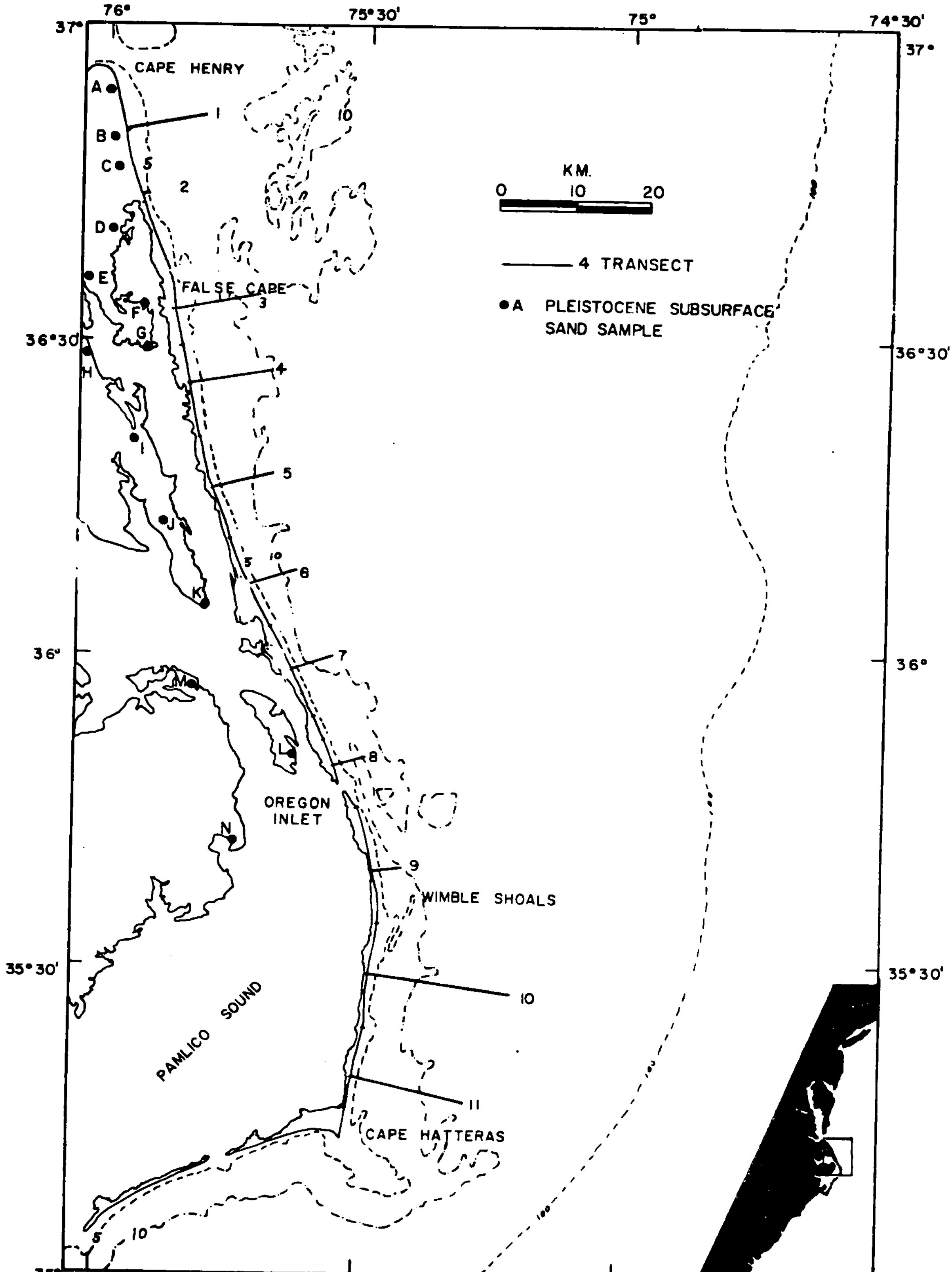
INTRODUCTION

Purpose of Study

The purpose of this study is to investigate the genesis of sediment on the inner continental shelf of Virginia and Northern North Carolina.

The generally accepted model of Holocene continental shelf sedimentation is that of Emery (1967, 1968). This model describes the continental shelves as having been exposed to subaerial (fluvial) sedimentation during the Wisconsin low stand of the sea. As the ice caps melted, sealevel rose across the Atlantic continental shelf from about 15,000 years ago to the present. The returning sea reworked the continental shelf bottom to form a Holocene transgressive sand sheet. The following characteristics are believed to indicate the relict nature of this sand sheet: coarse and/or of heterogeneous size, iron-staining, solution pitting (Emery, 1968), and anomalous fossils such as elephants teeth (Whitmore, *et al.*, 1967), and oyster shells (Merrill, *et al.*, 1965). The bottom on the shore face, landward of the relict sand, is believed to consist of seaward-fining modern sand in equilibrium with the present-day

Figure 1. Transects along which profiles and sediment samples have been collected.


76°
75° 30'
75°
74° 30'
37°
CAPE HENRY
A
B
C
D
E
F
G
H
I
J
K
L
M
N
FALSE CAPE
36° 30'
36°
35° 30'
35°
OREGON INLET
WIMBLE SHOALS
PAMLICO SOUND
CAPE HATTERAS
KM.
0 10 20
4 TRANSECT
A PLEISTOCENE SUBSURFACE SAND SAMPLE
1
2
3
4
5
6
7
8
9
10
11
100

hydraulic regime.

This study attempts to determine if the relict and modern sand facies really exist on the inner continental shelf as postulated and to determine their genesis on the basis of a regional grain-size reconnaissance.

Location of Study

The study area chosen was the Cape Henry to Cape Hatteras shoreline and 25 km seaward (Fig. 1). This area was accessible and is also representative of the Middle Atlantic Bight, in that it contains an adjacent bay mouth, a mainland stretch of beach, a spit - barrier island system, and an offshore ridge and swale topography.

Approach

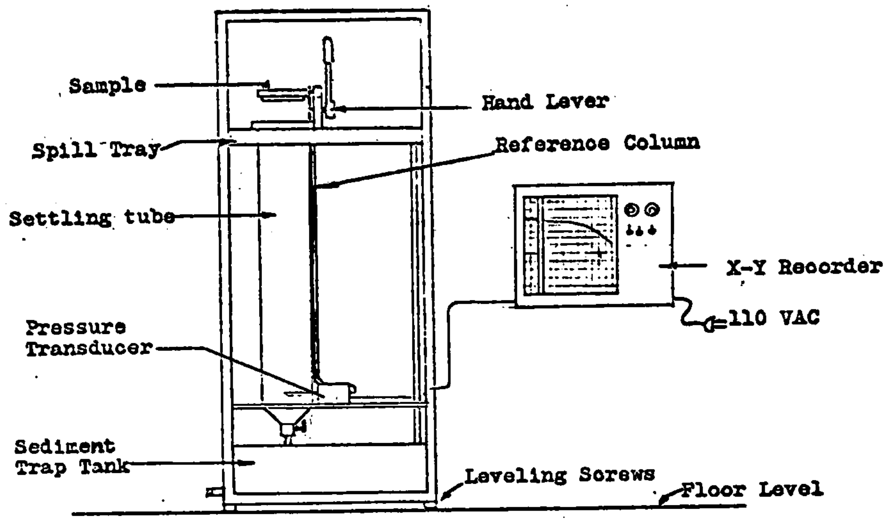
FIELD METHODS

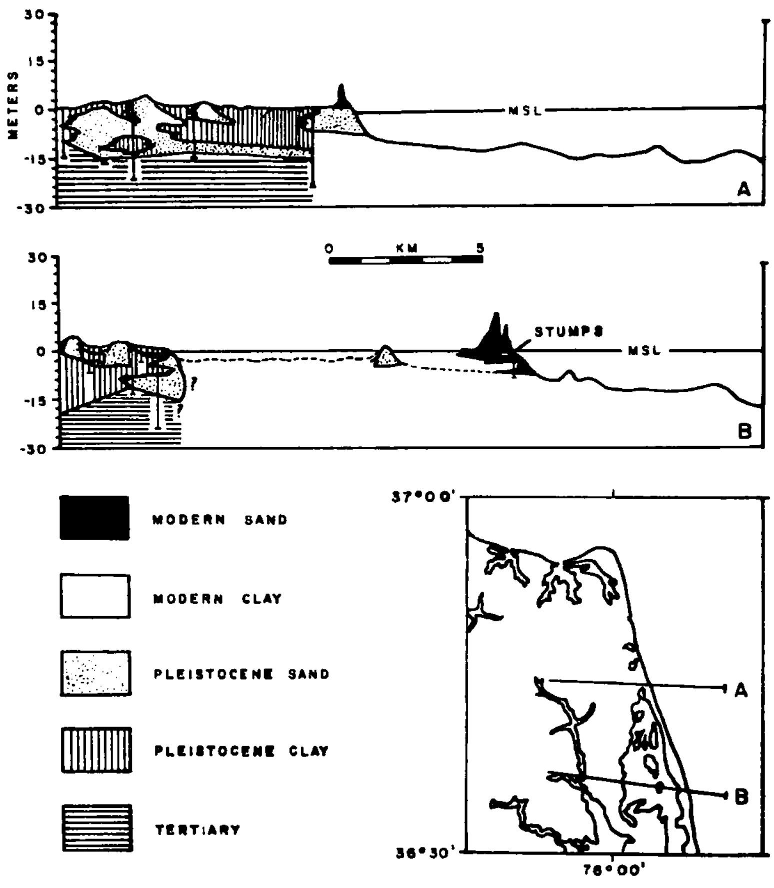
Sample net.--Sediment specimens of approximately liter size were collected from a series of transects (Fig. 1). Eleven transects, normal to shore were sampled every 20 km from Cape Henry to Cape Hatteras. The beach berm was sampled every 5 km.

Sampling of the transects began at the berm and extended seaward at 2 m depth increments until horizontal distance increments became as large as 1 km. The 1 km

Figure 2. (Above) Woods Hole type Rapid Sediment Analyzer (Benthos Corp.).

Figure 3. (Below) Transects through the Virginia and North Carolina coasts, from Oaks, 1964.


Sample
Hand Lever
Spill Tray
Reference Column
Settling tube
X-Y Recorder
110 VAC
Pressure Transducer
Sediment Trap Tank
Leveling Screws
Floor Level


30
15
0
-15
-30
METERS
MSL
A
0 KM 5
STUMPS
MSL
B
MODERN SAND
MODERN CLAY
PLEISTOCENE SAND
PLEISTOCENE CLAY
TERTIARY
37°00'
36°30'
76°00'
A
B

sampling increment was then continued until 2 consecutive coarse sand samples of the type generally considered "relict" had been collected. If an acceptable sample had not been obtained after 4 such intervals of 1 km, the interval was increased exponentially (2 km, 4 km, etc.). If the desired type of sediment was not obtained after a total distance from shore of 25 km, the transect was discontinued.

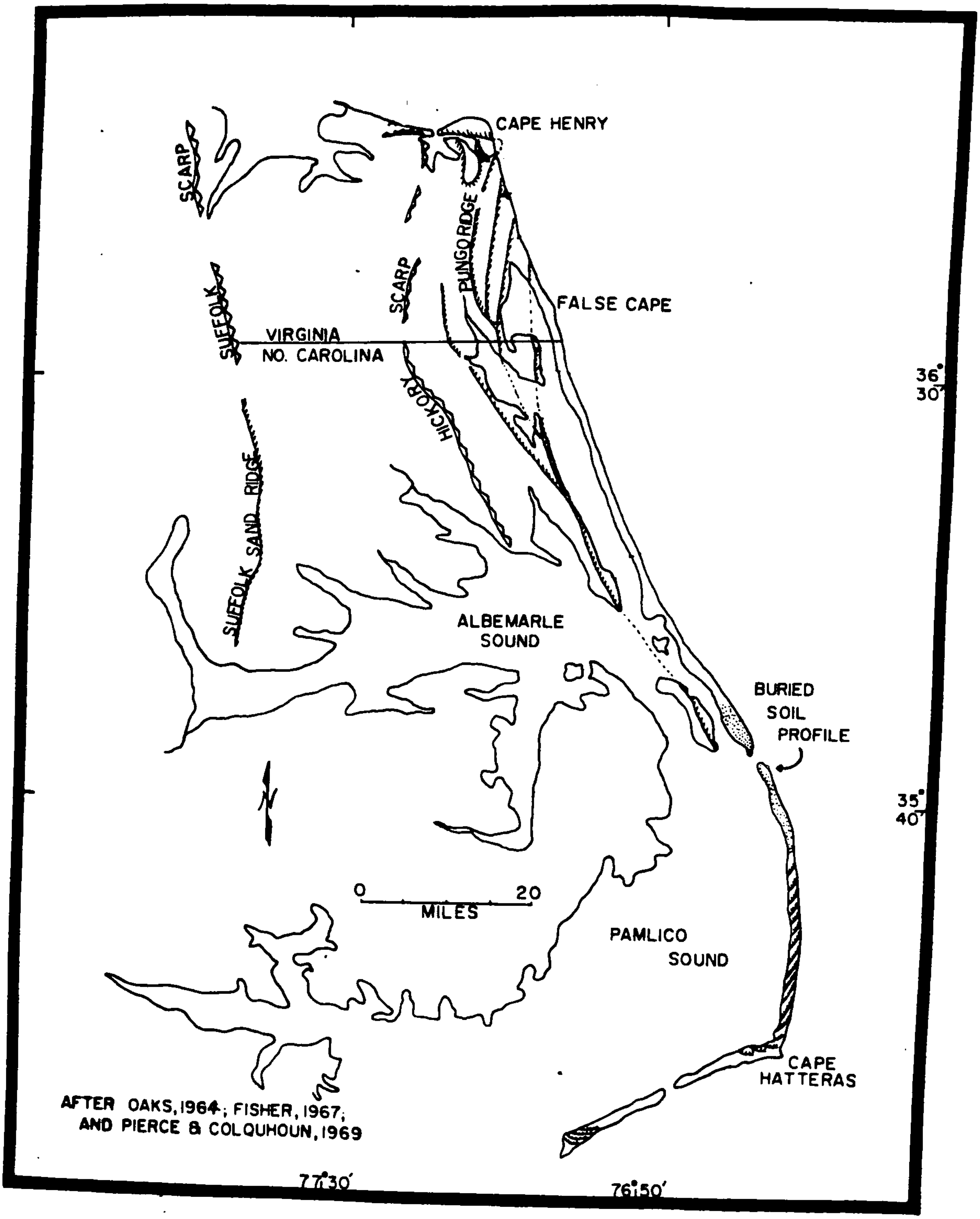
Offshore specimens were obtained by Shipek sampler from the R/V Albatross, a 65 ft. coastal trawler. Specimens, however, at the initial 2 m depth were obtained by diver, and those from the berm were obtained by hand from a beach buggy. Berm specimens were collected in a 10 cm diameter stove pipe sunk 7 cm into the sand.

Navigation.--Transect intervals (Fig. 1) were initially determined by vehicle odometer measurement of locations previously selected by map. Individual stations within the transects were determined by radar, bathymetry (Raytheon Depth Sounder), horizontal sextant angles, and dead reckoning.

LABORATORY METHODS

The laboratory procedure consisted of Rapid Sediment Analyzer (Fig. 2) determinations of the grain-size distribu-

Figure 4. Quaternary framework of the Virginia-North Carolina coast.


CAPE HENRY
SCARP
PUNGO RIDGE
SCARP
SUFFOLK
FALSE CAPE
VIRGINIA
NO. CAROLINA
HICKORY
SUFFOLK SAND RIDGE
ALBEMARLE
SOUND
BURIED
SOIL
PROFILE
N
0
20
MILES
PAMLICO
SOUND
CAPE
HATTERAS
AFTER OAKS, 1964; FISHER, 1967;
AND PIERCE & COLQUHOUN, 1969
36° 30'
35° 40'
77°30'
76°50'

tions of specimens from each major transect and all berm stations. The Rapid Sediment Analyzer was used because it is a relatively behavioristic method of analysis, and because it is much more rapid in operation than sieving. The analysis procedure is discussed fully in the section on Rapid Sediment Analyzer calibration. The settling method of grain size determination is behavioristic in that within limits it makes use of the same hydraulic processes as those encountered in nature.

Regional Setting

LATE QUATERNARY STRATIGRAPHY

Pleistocene "basement."--The sand ridge and mud flat complex of the Sandbridge Formation deposited by a retreating marginal sea of probable late Pleistocene age immediately underlies the Holocene beach and lagoonal deposits of the Virginian Coast. (Oaks and Coch, 1963; Oaks, 1964; see Figure 3 and 4 this paper). A scuba dive in a swale off of False Cape revealed 15 cm of coarse, shelly sand overlaying a stiff clay tentatively correlated with the Sandbridge Formation (D. Swift, personal communication).

The Holocene Sand Sheet.--In 3 instances cores taken with a hydraulic coring system in the northern part of the study area appear to have nearly penetrated to this surface. They consist of 20 cm to 1 m of sand that appears to fine upward. In 2 cases there is a coarse shelly gravel at the bases of the cores and in the third case a coarse coquina (D. Swift, personal communication).

The thickness of the basal layer is unknown since it was sufficiently coarse to stop the corer. Large clay fragments presumably eroded from the Sandbridge Formation were found near the base of 2 of the cores. The sequence cored is presumably the Holocene transgressive sand sheet. Powers and Kinsman (1953, p. 229) have reported recovering 37 similar cores up to 1 m long just to the north of this study area off the mouth of Chesapeake Bay.

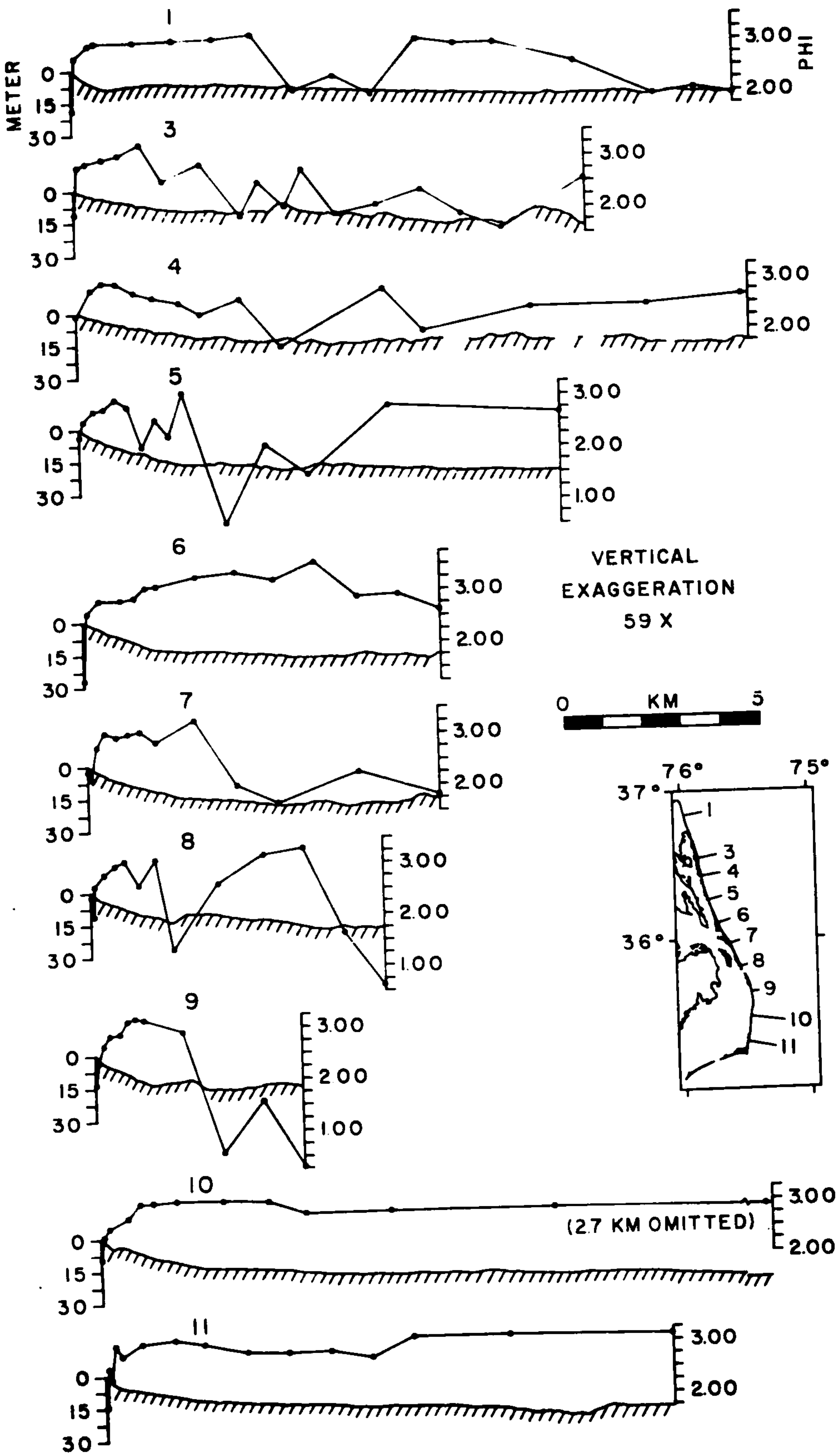
Geomorphology.--The shoreline of the study area (Fig. 1 and 4) consists of a mainland beach sector (Cape Henry to Sandbridge), a spit (Currituck Spit), and a barrier island (Hatteras Island).

Currituck Spit may be either a coast-parallel, distally prograding spit (Fisher, 1965, 1967; Pierce and Colquhoun, personal communication) or a detached mainland beach (Hoyt, 1967). Probably a headland existed formerly in the vicinity of Oregon Inlet. Fisher (personal communication) refers to such a formation as Bodie Island Headland. Pierce and Colquhoun (personal communication) have found buried soil profiles on Currituck Spit and Hatteras Island in the vicinity of this hypothetical headland. Fisher (1965, 1967) has found consecutive, parallel, relict beach ridges trending diagonally across the barrier along practically the entire length of Hatteras Island. He interprets this as indicating the original formation of Hatteras Island as a southerly prograding spit from the hypothetical Bodie Island Headland. Such diagonal beach ridges are absent on Currituck Spit.

The shoreline of the entire area probably dates from the late Holocene reduction in rate of sea level rise when most modern barrier systems were initiated (Curray, 1964, p. 181). According to Curray this reduction occurred between 7,000 and 4,000 years ago.

Historical records show that with few exceptions the entire ocean shoreline from Cape Henry to the North Carolina line (vicinity of False Cape) has exhibited continuous recession since the earliest surveys of record in 1858 (J. Felton, unpublished manuscript, Norfolk Corps of Engineers). More recently Langfelder et al.(1968, pp. 73-80)

Figure 5. Bathymetry and modal diameter of transects.

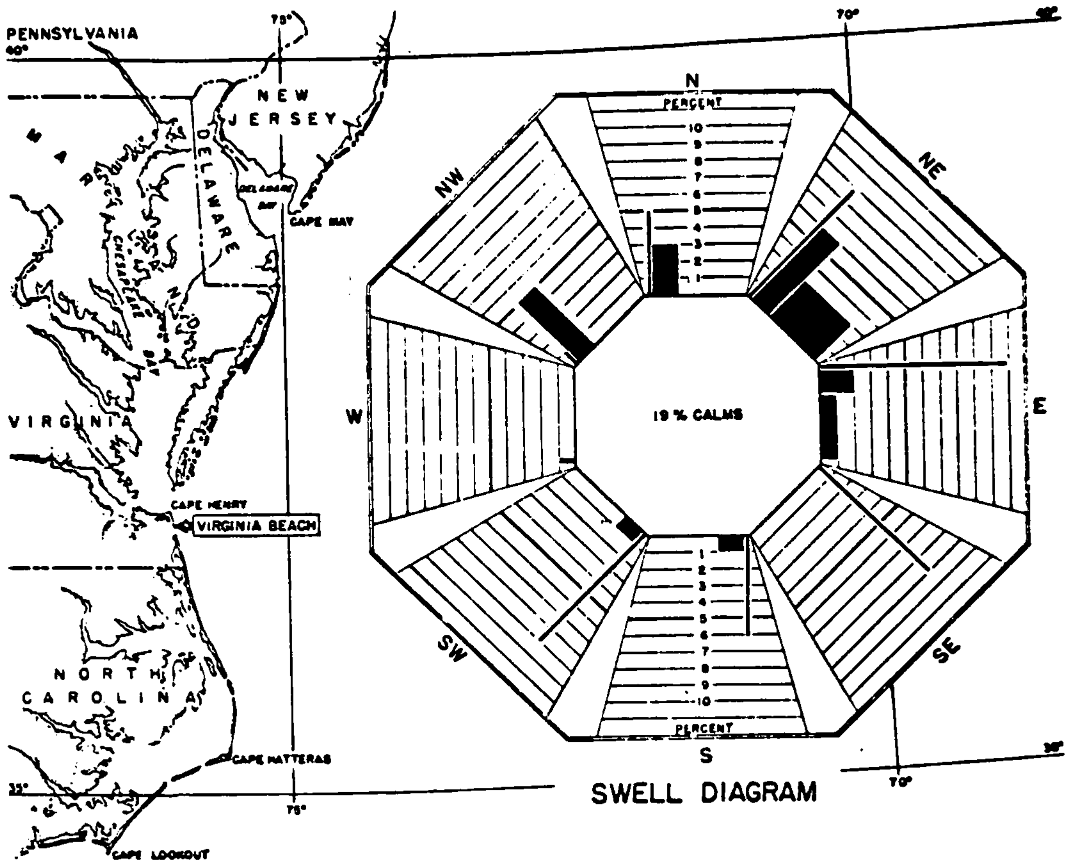

METER
PHI
1
3
4
5
6
7
8
9
10
11
0
15
30
3.00
2.00
1.00
VERTICAL
EXAGGERATION
59 X
0 KM 5
76°
75°
37°
36°
(2.7 KM OMITTED)

has demonstrated, by means of photogrammetric and wave refraction methods, that erosion is dominant along the entire ocean shoreline of North Carolina.

In the submarine province of the study area, the bottom profiles (Fig. 5) indicate that at most transects 2 well-defined geomorphic provinces are present. The nearly planar shore face has a gradient of 8 m/km down to an approximate water depth of 14 m. Seaward of the shore face an undulating shelf floor slopes seaward at 1 m/km. Such sharply angulated profiles seem to be characteristic of eroding shorelines (Zenkovich, 1967, p. 205).

The sea floor exhibits a ridge and swale topography with relief up to 7 m (Uchupi, 1968, p. C17; see C& GS chart 1109). At False Cape and Wimble Shoals, ridge systems associated with this topography tie to the shore face at depths of 5 to 15 meters. These ridges parallel the beach ridges of the Sandbridge Formation and have been considered relict beach ridges (Sanders, 1963). More likely, however, they are formed and maintained by the modern hydraulic regime. They have moved inland since 1922 (Avignone, personal communication), and the shore face has cut deeply into the Sandbridge Formation (Oaks, 1964, Fig. 25). Presumably this has resulted in the destruction of any Pleistocene relief.

Figure 6. Swell diagram.



IN THE SWELL DIAGRAM THE LENGTH OF THE BAR DENOTES THE PERCENT OF THE TIME THAT SWELLS OF EACH TYPE HAVE BEEN MOVING FROM OR NEAR THE GIVEN DIRECTION. THE FIGURE IN THE CENTER OF THE DIAGRAM INDICATES THE PERCENT OF CALMS.

LOW SWELLS (1–6 FEET)
MEDIUM SWELLS (6–12 FEET)
HIGH SWELLS (OVER 12 FEET)

WIDTH OF BARS HAVE BEEN WEIGHTED IN PROPORTION TO THE SWELL HEIGHT SQUARED.

THE SWELL DIAGRAM SHOWN ABOVE APPLIES TO THAT PORTION OF THE ATLANTIC OCEAN BETWEEN LATITUDE 35° AND 39° NORTH AND FROM THE SHORE EASTWARD TO THE 70 TH MERIDIAN WEST.

VIRGINIA BEACH, VIRGINIA
BEACH EROSION AND HURRICANE STUDY

SWELL DIAGRAM

U.S. ARMY ENGINEER DISTRICT, NORFOLK FEB 1967

DRAWN: M.R.H.
CHECKED: A.R.P.
REVIEWED: C.O.M.
FILE:

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Hydrography

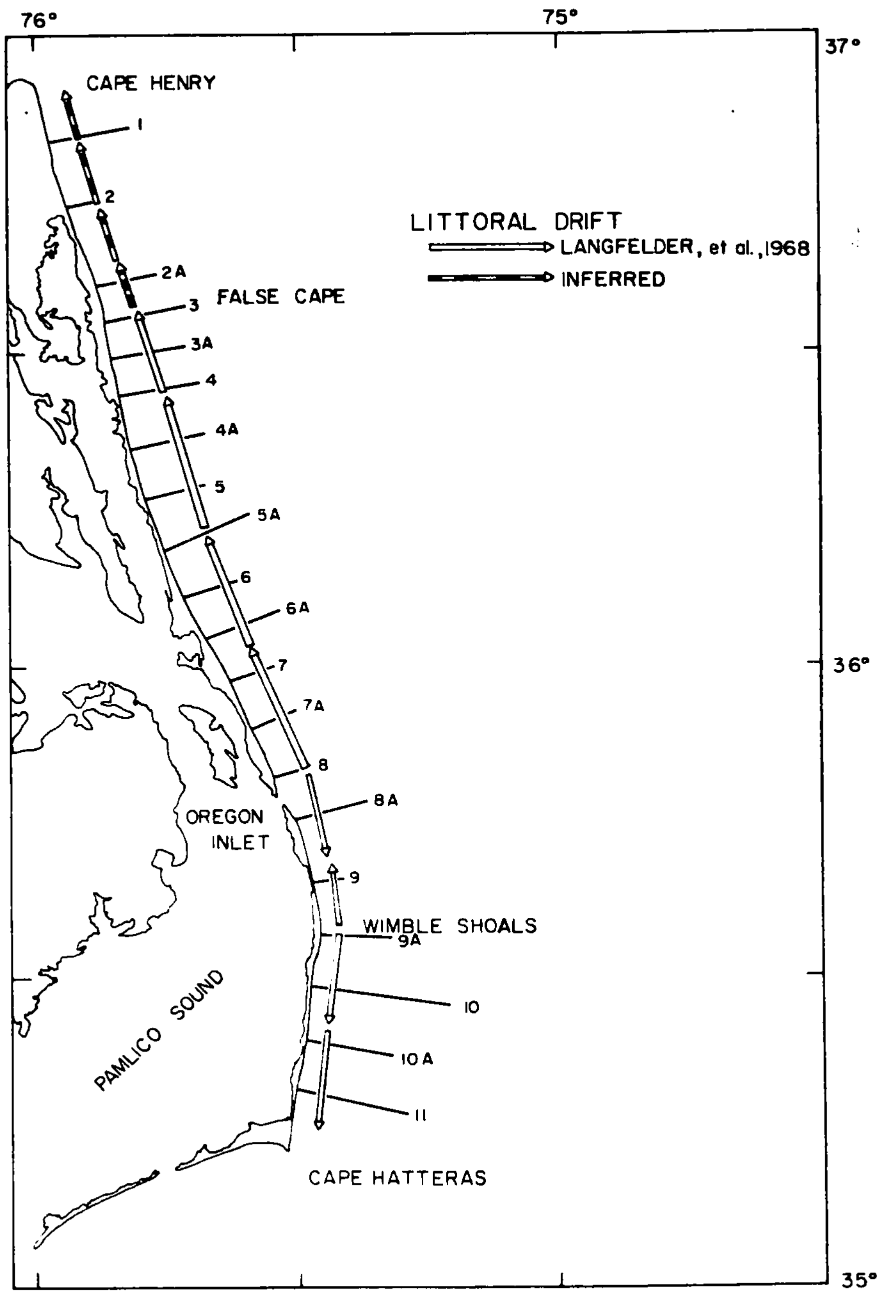
WAVES

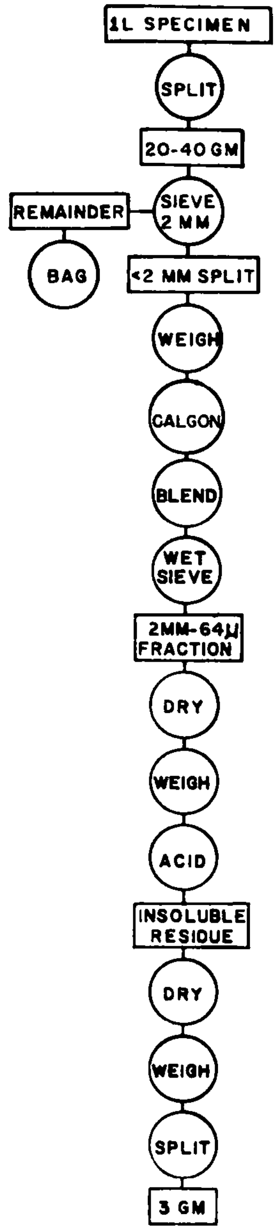
Swells reaching the coast between Cape Henry and Cape Hatteras are predominantly from the southeastern quadrant during the summer and the northeastern quadrant during the winter (Fig. 6). On an annual basis, however, swells are predominantly from the northeast. Of them, 9 percent are 1 to 6 ft. high, 6 percent are 6 to 12 ft. high, and 3 percent are over 12 ft. Calm prevails 19 percent of the time (Beach Erosion and Hurricane Study, U. S. Army Corps of Engineers Norfolk District, Unpublished Report). The data from which the swell diagram was made were obtained from ships operating between shore and an average distance of 5° (540 km) offshore.

In the vicinity of the entrance to Chesapeake Bay, for all seasons, the swells are predominantly from the east-northeast. The most frequently recorded wave height is 0.75 m. Calm or swells of less than 15 cm in height prevails 31.7 percent of the time (Coastal Engineering Research Center, Tech. Memo. No. 55).

Figure 7. (Left) Longshore drift on the Cape Henry-Cape Hatteras coast.

Figure 8. (Right) Flow chart for sample preparation.





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LITTORAL DRIFT

The littoral drift (Fig. 7), is primarily northward between Cape Henry and Cape Hatteras (Longfelder, et al., 1968, p. 80; Bunch, 1969, p. 13). Apparently the preponderance of light swells which are from a southerly and easterly direction have the deciding effect in the direction of drift. In addition, just south of Cape Henry, Harrison, et al. (1964) have noted a clockwise eddy. Such an eddy would contribute to the northerly littoral flow in this portion of the study area.

TIDES

The tides along this outer coast are semidiurnal, and mean tidal range varies from 2.0 feet at Oregon Inlet to 3.6 feet at False Cape, Currituck Beach Light, Cape Hatteras, and Hatteras Inlet. Table I presents tidal amplitudes and tidal currents at various locations along the outer coast from Cape Henry to Cape Hatteras.

SEMI-PERMANENT CURRENTS

Nontidal water motion in the portion of the continental shelf involved in this study is the net result of many variables.

Table I. Various tidal values at selected locations in the test area.

Location	Tidal Range (ft) Mean	Tidal Range (ft) Spring	Maximum Currents: Flood Direction (deg)	Flood Ave. Vel. (kt)	Ebb Direction (deg)	Ebb Ave. Vel. (kt)
Virginia Beach	3.4	4.1	355	1.1	165	0.3
False Cape	3.6	4.3				
Currituck Beach Light	3.6	4.3				
Kitty Hawk (Ocean)	3.2	3.8				
Oregon Inlet	2.0	2.4				
Cape Hatteras	3.6	4.3				
Hatteras Inlet	3.6	4.3	305	2.1	150	2.0

Surface currents.--Harrison *et al.*, (1967) defined an inshore surface eddy system just south of Cape Hatteras. This eddy is due to the combination of an inflow of surface waters toward the mouth of Chesapeake Bay together with part of the bay outflow. Miller (1952) found what appeared to be a strong flow of surface water from offshore which impinged on the beaches near Currituck Beach Light. South of Oregon Inlet there was a strong flow in a southerly direction close to shore.

Density-driven circulation.--Biglow and Sears (1935) allude to indrafts of high salinity bottom water onto the shelf as indicated by salinity profiles taken across the shelf. This bottom water flows landward to replace that entrained by the seaward moving surface diluted by river runoff. Recovery of seabed drifters (Harrison, *et al.*, 1967) released off the Chesapeake Bight indicated shoreward drift of bottom water which was oriented, at times, toward Chesapeake Bay though generally in a southwesterly direction.

RAPID SEDIMENT ANALYZER CALIBRATION

Introduction

RAPID SEDIMENT ANALYZER--DEFINITION

The Rapid Sediment Analyzer (RSA) is an instrument which can be used to determine the range of fall velocities of samples of sand. (Zeigler *et al.*, 1960; Schlee, 1966) (Fig. 1). The differential fall velocities of the various sized grains of a sediment distribution may then be converted to grain sizes. This system measures these fall velocities by means of pressure changes produced in a water column due to the settling of sediment through a specific distance (100 cm).

REASONS FOR USING THE RSA

The two most important factors favoring the use of the RSA over sieves are the increased speed with which the RSA can conduct analysis (Emery, 1938, p. 105) and the fact that it is a behavioristic method. (Sengupta and Veenstra, 1968, p. 63). The sieving procedure lacks both of these qualities. According to Schlee (1966, p. 407), a steady worker can conduct from 40 to 89 analyses per day if the samples are weighed and ready. I was able to do approximately 50 per day with samples weighed and ready. Sieving, on the other hand, is conducted at the much slower rate of 20 to 25 per day. As for the greater suitability of the determination of grain size based on settling velocity compared to sieving, this settling approach is behavioristic, taking into consideration factors such as particle density, concentration, water temperature, shape and roundness which determine size segregation in nature (Sengupta and Veenstra, 1968, p. 33; Schlee, 1966, p. 407; Ziegler et al., 1960, p. 495). Sieve determined diameters are based on intermediate grain diameters (Sahu, 1965, p. 750), or some function of intermediate diameter as determined by shape (Ludwick and Henderson, 1968).

RSA Description

DESCRIPTION OF DEVICE

The RSA used for this study, was purchased from Benthos Inc., of Falmouth, Mass. It consists (Fig. 2) primarily of a vertical, transparent, plastic tube 12.7 cm in diameter and slightly over 1 meter in length which is filled with water. A sandy sediment sample weighing between 2 gm. and 10 gm. is quickly and uniformly released at the surface of the water column by a mechanism operated by a hand lever. Near the bottom of the settling tube and 100 cm below the surface of the water is an electrical, pressure transducer. This transducer has water inlets on both sides and compares the water pressure of the settling tube with that of a water-filled reference column of the same height but to which no sediment has been added.

With the release of sediment into the settling tube, a pressure increase is registered by the transducer. As grains of different size settle past the transducer port (large particles first and small ones last) pressure as sensed by the transducer is reduced by a proportional amount.

The signal from the transducer operates an XY recorder so that a settling curve is drawn with voltage as the ordinate and time as the abscissa. This curve is a function of grain size distribution.

LIMITATIONS

Behavioristic Limitation.--The Rapid Sediment Analyzer provides a behavioristic measurement of sand size frequency distributions. This behavior, however, is that of suspended load, while most natural sands have accumulated mainly as traction load. Unfortunately no satisfactory conversion exists between the characteristics of suspended and traction sediment (Briggs and Middleton, 1965, p. 13; Brush, 1965, p. 24). Nevertheless, size analysis by settling does better lend itself to the assessment of transportational qualities of the sediment than does sieve analysis (Kuenen, 1968, p. 829). However, sieving is by custom the standard procedure for determining grain size distribution, and settling results are difficult to compare with it.

Truncation of the Distribution.--Particle size suitable for size determination by settling is almost entirely confined to the sand range as indicated by the following limits: 62μ to 2mm (Schlee, 1966, p. 406), 40μ lower limit (Ziegler *et al.*, 1960, p. 492), 50u lower limit (Kuenen, 1968, p. 817), and 62μ to 1mm (Poole *et al.*, 1951, pp. 7, 8). (This is because larger particles settle too rapidly for accurate analysis, and smaller particles settle too slowly). Therefore, the settling distributions of many specimens are necessarily truncated on one or both ends.

Role of Shape in Grain Size Determination.--Sengupta and Veenstra (1968) found shape to be very important in grain size determinations. Diameters determined by sieving and settling compared much more favorably for well rounded grains than for elongate grains. The grain's intermediate diameter or some function of it, is measured in sieving while the long diameter controls settling determinations. Apparently, an elongate grain will frequently bounce upright and therefore pass through a sieve opening whose oblique measure is close to the grain's intermediate diameter. When settling, however, this same grain assumes a horizontal or oblique configuration thereby allowing the long diameter to control descent rate and resulting diameter determination.

Poole (1957, p. 460) found that usually settling diameter was coarser than sieve diameter. His explanation for this was the fact that the diagonal width of the sieve mesh allows larger than expected grain sizes to pass. The grains are evaluated, however, at their normal sieve sizes. Ludwick and Henderson (1968) have pointed out that the value of this error will vary with the grain's departure from sphericity. Sengupta and Veenstra (1968, p. 34) state that grains with intermediate diameters of 1.4 times the normal sieve opening can pass through. However, cumulative curves plotted from sieving and settling data by Schlee (1966, Table 2) of 5 Cape Cod beach sands show coarser sieve distributions than settling distributions of the same specimens in 3 of the cases.

Water-Sediment Interaction.--According to Kuenen (1963, pp. 317, 330), two aspects of water-sediment interaction that may have an adverse effect on grain-size analysis are settling conviction and hindered settling. Settling conviction is the irregular, upward or downward movement within the settling tube of clouds of sediment of varying densities formed by differential dispersion of sediment. The heavier clouds and their entrained water will sink at a greater speed than the fall velocity of individual grains. As a result of this, lighter clouds are forced to rise. A marginal case of settling convection is the "vertical density current" of Bradley (1965) in which plankton or volcanic ash introduced close to the surface of a lake reached the bottom rapidly in high density suspension clouds. Such a vertical tubidity current develops during RSA analysis, and may result in sedimentation diameters systematically coarser than equivalent sieve diameters.

Hindered settling is manifested by particles that settle 6 diameters or less from each other (Kuenen, 1963, p. 317). Retardation of their settling occurs because of the upward flow of water around neighboring grains (McNown and Lin, 1952).

Hindered settling occurs in all settling suspensions. Settling conviction occurs only in differentially dispersed suspensions, where its effects are dominant over hindered settling, resulting in increased fall velocities.

Ludwick (personal communication, 1969) has noted that a turbulent effect was produced on a dye particle stream of potassium permanganate when a particle of sand settled past it at a distance of 2 particle diameters or less. From this he concluded that water-sediment interaction does not occur unless the particles are falling at 2 diameters or less apart. Ideally, therefore, sediment introduced into the RSA should be in sufficiently small quantity such that the grains will settle at least 2 diameters from each other. This has not been possible during this study due to the sensitivity threshold of the recorder.

Interaction of Size Classes.--Schlee (1966, p. 409) found that fall time of a sediment within a single class is longer when this class is the finest class of a multiple class system than when it falls alone and even longer than when the class is the coarser part of a multiple class system. Cooke (1969, p. 781) has noted that in a grain size mixture smaller particles are entrained by the larger particles and accelerated downward by as much as 15 percent over their normal fall velocities.

Sediment-Cylinder Interaction.--Wall effect (Krumbein and Pettijohn, 1938, pp. 98, 99) is the resistance experienced by a particle which is settling near and parallel to a wall. This concept was further elaborated by Arnold (1911) who found that settling velocity according to Stokes' law is not appreciably effected until the radius of the particle equals 10% of the radius of the settling cylinder. Since viscosity of the settling fluid is involved here, and particles whose velocities conform to the impact formula are even less effected by fluid viscosities than are those whose velocities conform to Stokes' law, one would assume that wall effect would be even less of a problem in the larger grain size range concerned with in this study (settling tube 127 mm in diameter, grains 0.84 mm to 62µ in diameter).

Miscellaneous General Limitations.--Smooth particles fall faster than rough ones (Ziegler et al., 1960, p. 495), reproducibility of settling distribution is poorer for the coarse than for the fine end of a settling distribution (Poole *et al.*, 1951, p. 1), increased temperature causes decreased viscosity and increased settling velocity (McNown and Lin, 1952, p.411), well sorted sand settles more rapidly than poorly sorted sand (Schlee, 1966, p. 403).

Limitations Specific to the Equipment Used.--The pressure transducer (Fig. 2) incorporated in the RSA used in this project had a hysteresis[1] of ± 0.1% of full pressure excursion. Due to attempts to increase the sensitivity of the RSA in order to analyze smaller than recommended sediment samples, hysteresis was increased to ± 2%. Therefore, the pressure differential signal sent from the transducer to the XY recorder lags behind the actual effect of the transducer differential pressure to the extent of 2%.

On occasions, the settling curves produced by the XY recorder did not return to the base line. Out of 205 samples run, 32% remained above, 2% fell below, and 66% returned to the base line. There are 3 explanations for these variations: transducer drift, hysteresis, and slow-settling silt and clay. Drift test curves were run . . .

---

[1] Hysteresis is the lagging of a physical effect on a body behind the cause of the effect.

immediately before and after every analysis and the indicated drift error thereby compensated for. Hysteresis and silt and clay errors were compensated by adjusting the height of the curves' base lines to 40 point on the settling curves.

Comparison of Sieve and Settling Methods.--Several of the writers cited above (Sengupta and Veenstra, 1968, p. 97; Schlee, 1966, p. 403) have concluded that the conversion of settling time to sedimentation diameter[2] and comparison with the corresponding sieve diameter[3] is often unsatisfactory in the case of natural sands because variations of fall velocity due to water-sediment interaction, shape, specific gravity, and other systematic errors cannot be satisfactorally taken into account. For this reason, they feel that comparison between these 2 types of determinations should not be made, and settling velocity should instead be

---

[2]Sedimentation diameter is the diameter of a sphere of the same specific gravity and the same terminal, uniform settling velocity as the given particle in the same sedimentation fluid (St. Anthony Fally Hydraulic Laboratory, 1957, p. 11).

[3]Sieve diameter is the length of the side of the smallest square opening through which the given particle will pass (St. Anthony Falls Hydraulic Laboratory, 1957, p. 11).

used as a new grain parameter. I have, however, attempted such a comparison between analyses of samples via calibrated sieves and a Ro-Top, and analysis of the same samples in the RSA. My results, presented on following pages, show that the comparison is indeed difficult.

Sieve Calibration

Sieve calibration was conducted with a microscope calibrated by stage micrometer. The microscope's 10X micrometer oculor scale was found to equal 14.5u per division with the 10X objective and 57.14u per division with the 40mm objective. On all but 2 of the 21 quarter Ø sieves used in this study (-1.0 Ø to 4.0Ø), 100 microscopic measurements of mesh widths were made (-1.0Ø and -0.75Ø sieves had too few mesh to permit 100 measurements). This consisted of the measurement of perpendicular distances between the edges of parallel, adjacent wires. In this way a row of warp and a row of shoot interspaces were measured approximately across the center of each sieve. Table II shows the means and standard deviations of warp and shoot interspaces for each of the sieves. In view of these findings the sieves were considered to be acceptable.

Table II. Means and standard deviations of distances between warp and filling wires of each of the quarter phi sieves between -1.00 phi and +4.00 phi.

		Warp		Shoot	
Nominal size (mm)	Phi size	x̄(mm)	σ(mm)	x̄(mm)	σ(mm)
2.00	-1.00	2.04	.07	2.02	.02
1.651	- .75	1.69	.03	1.69	.03
1.41	- .50	1.42	.02	1.40	.03
1.19	- .25	1.23	.01	1.18	.02
1.00	- .00	1.02	.02	1.00	.03
Linear size (M)		x̄(μ)	σ(μ)	x̄(μ)	σ(μ)
841	+ .25	843.56	20.66	855.27	27.22
707	+ .50	696.34	46.56	725.39	32.50
595	+ .75	592.80	10.52	605.38	20.74
500	+1.00	503.06	14.03	499.62	9.43
420	+1.25	423.12	8.57	415.87	16.01
350	+1.50	351.56	7.28	355.31	9.92
297	+1.75	296.79	10.29	309.33	9.01
250	+2.00	250.76	4.62	250.36	6.15
177	+2.25	179.12	5.14	180.13	3.49
210	+2.50	211.74	9.52	214.24	4.36
149	+2.75	150.79	5.62	151.16	4.42
125	+3.00	126.21	6.87	132.07	2.78
105	+3.25	107.85	4.23	110.26	6.03
88	+3.50	91.21	2.66	91.45	5.22
74	+3.75	77.72	4.09	77.84	3.66
62	+4.00	61.64	4.60	65.92	5.39

RSA Calibration Against Sieves

CALIBRATION SPECIMEN SELECTION

For the purpose of RSA calibration I chose a specimen of each of the 3 basic sediment types found in the study area. These were: 1) beach sands which were coarse and moderately sorted, 2) nearshore sands which were fine and well sorted, and 3) offshore sands which were coarse and poorly sorted. The particular type specimens selected were as follows: 1-Beach-1 (beach), 1-G-1 (nearshore) and 1-0-3 (offshore).

CALIBRATION SPECIMEN PREPARATION

Specimen preparation consisted of several steps (Fig. [illegible]) designed to record for each specimen sample total initial weight, weight of fraction less than 4 Ø, weight of carbonate fraction, and weight of silt and clay fraction. Splits were conducted by means of sample splitter. Weighing was conducted by triple beam balance. Dispersion of silt and clay was effected by treatment with 4% sodium hexametaphosphate for approximately 18 hours. Stirring was conducted by electric blender for 2 min. prior to wet sieving. Decalcification was conducted by 3.7% HCl treatment until all CO_2 formation ceased. Drying was conducted in an electric, laboratory oven at 100°C for approximately 24 hours.

SIEVE ANALYSIS OF CALIBRATION SPECIMENS

From each of the 3 above-mentioned calibration specimens, 5 splits of approximately 30 gm each were obtained. Splits were then sieved at 1/4 Ø intervals from -0.75 to 4 for 15 min. on either a Soil Test or Ro-Tap sieve shaker. Initial sievings were conducted on the Soil Test sieve shaker, but mechanical failure necessitated completion on the Ro-Tap. Fractions were then weighed to 3 decimal places on a Mettler balance.

In order to compare the Soil Test shaker used with the more standard Ro-Tap, splits of the same sample were used, and the results compared. The comparison of size distribution means of 3 sand splits sieved on both shakers is seen in Table III. The following comparison procedure was used: 3 splits of a fine grained sand from the lower shore face were sieved at 0.5 Ø intervals from 0.0 Ø to 4 Ø on each shaker for varying periods of time (30 min., 20 min., 15 min., and 10 min.) and the resulting size distributions compared statistically by Student's t method. The probability that the 2 shakers produce the same results was found to be 43%. Since any value over 20% indicates insignificant differences (Folk, 1963, p. 62), the 2 shakers were considered to produce the same sieving results (personal communication, Dill, 1969).

Table III. Comparison of Ø size distribution means obtained by sieving on Ro-Top and Soil Test shakers (Dill, personal communication, 1969).

		Ø Mean	
Time (min)	Split	Ro-Top	Soil Test
30	1	3.43	3.42
30	2	3.35	3.38
30	3	3.39	3.38
20	1	3.40	3.38
20	2	3.42	3.41
20	3	3.38	3.37
15	1	3.37	3.40
15	2	3.38	3.40
15	3	3.33	3.40
10	1	3.38	3.40
10	2	3.40	3.37
10	3	3.37	3.40

RSA ANALYSES OF CALIBRATION SPECIMENS

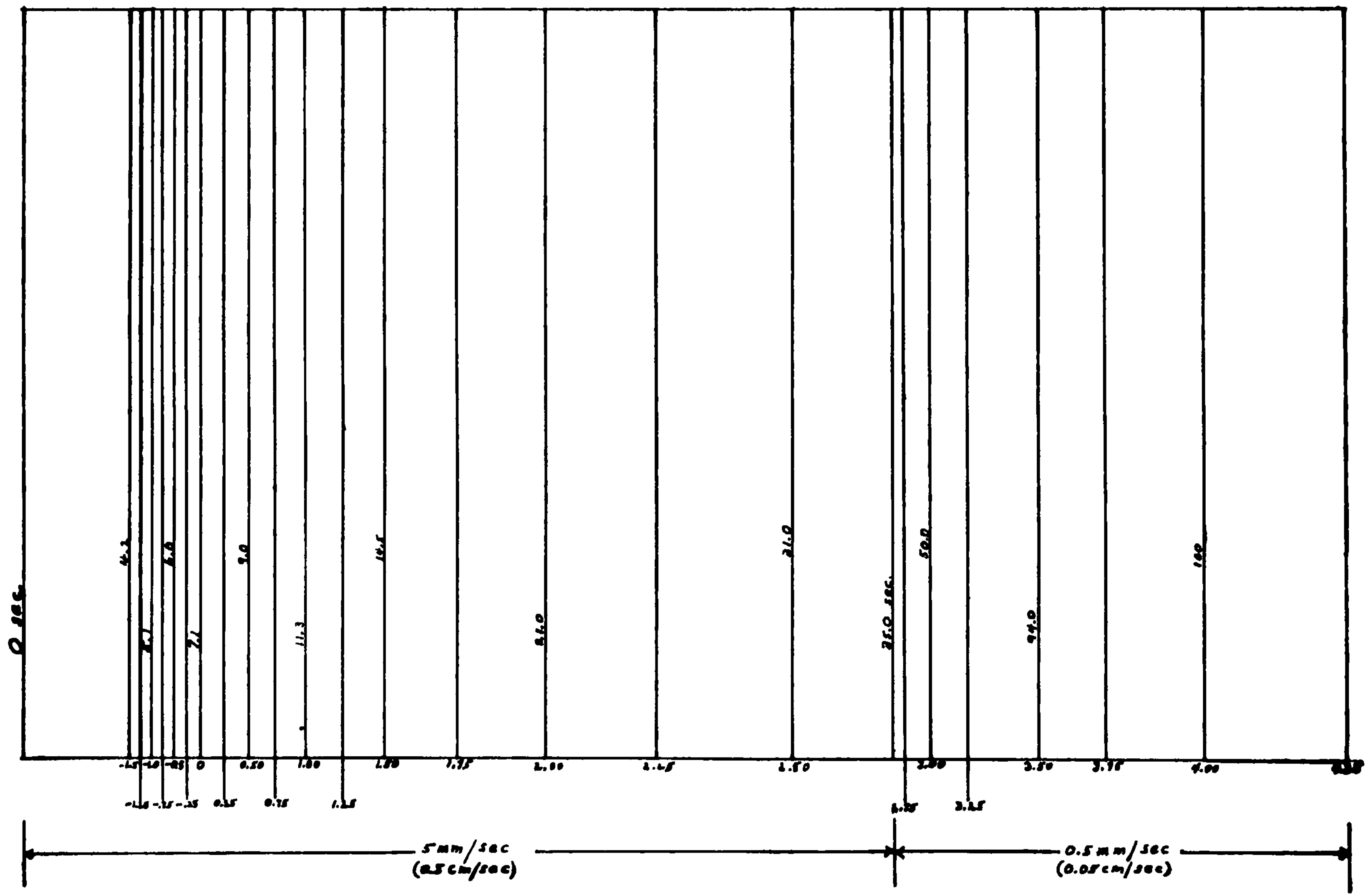
RSA splits of 3 gm were made from each of the reconstituted sieve samples (beach, nearshore, and offshore). Sample size of 3 gm was selected because it produced adequate settling curve elevation yet remained at the low end of the RSA manufacturer's recommended sample size range of 2 gm to 10 gm. In each case the sediment samples were dispersed by hand as widely and evenly as possible on the introduction mechanism (Fig. 2) in an attempt to keep vertical density currents (Bradley, 1965) to a minimum.

In order to eliminate any settling differences due to temperature fluctuations, settling tube water was maintained at 22.3°C to 22.5°C for all analyses.

INTERPRETATION OF RSA CURVES

The overlay method by Schlee (1966) was chosen to evaluate RSA size distribution curves. This method consists of placing over the settling curve a transparent, time-size overlay upon which is drawn, at intervals along the abscissa, vertical lines whose positions are functions of the fall times of particles of various sizes and therefore

Figure 9. Modified Schlee overlay.



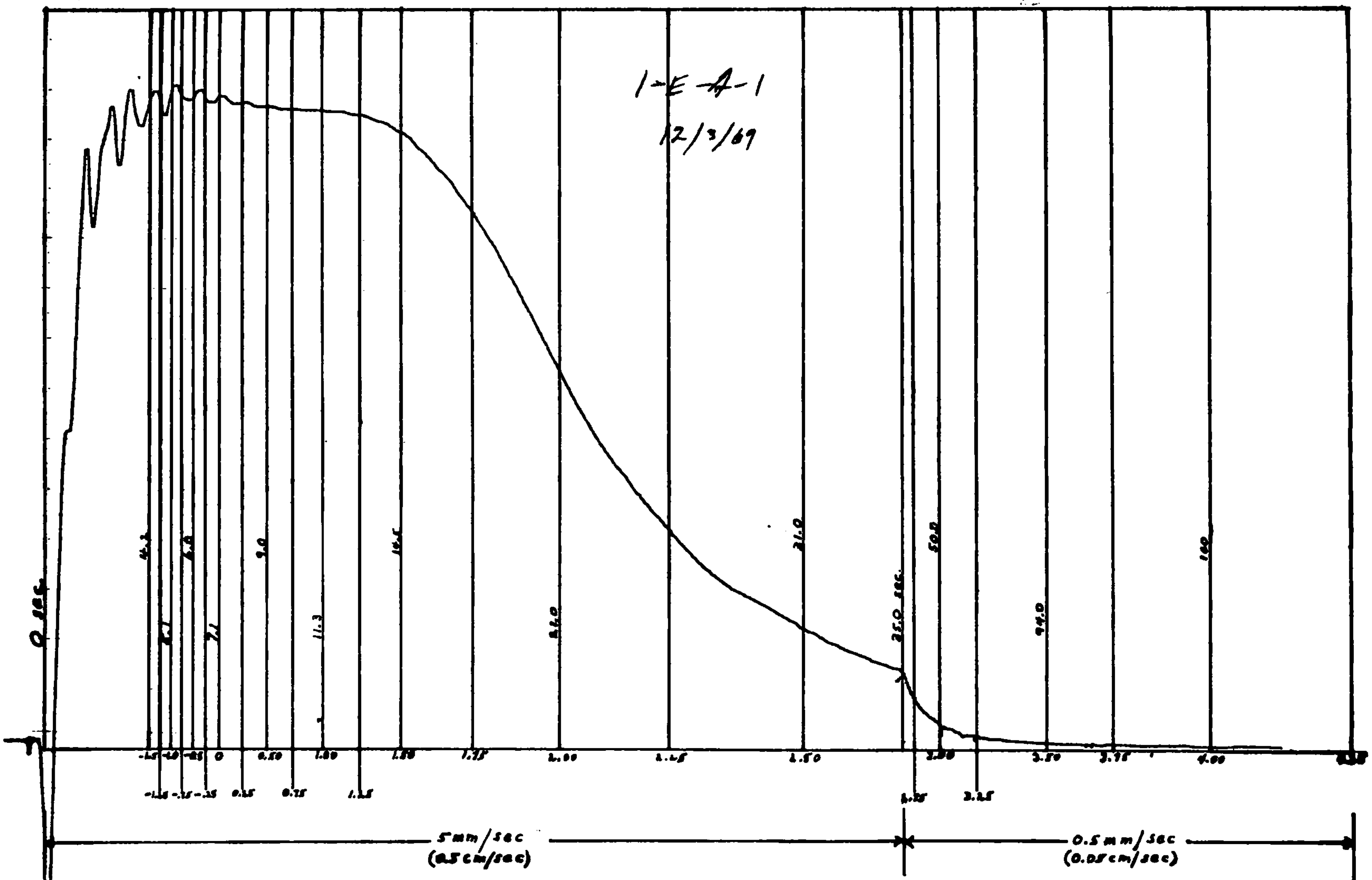
Size – Time overlay
(Modified from Sohico, 1966)

representative of their Ø sizes.

Schlee determined fall velocities of various phi sizes by first sieving naturally occurring sand specimens and then dropping them through the RSA. By knowing the sieved weight percentage, the fall times and therefore velocities of the major size classes of the sediment types were read from the settling curves. Schlee's fall velocities were used in this study, but the actual locations of the Ø lines had to be modified slightly to conform to my different time base speeds as well as the need for quarter Ø measurements (Fig. 9).

The overlay modification was based on experimentation with the various time base speeds available on my instrument and the 3 basic types of sediment in this study. It was found most practical to operate the recorder time base at 0.5 cm/sec for 35 sec and thereafter at 0.05 cm/sec during the recording of settling curves. The locations of the vertical Ø lines on the modified overlay had to conform to these velocities. The new locations of these lines were determined by multiplying the settling times on Schlee's overlay by my base speeds. The quarter Ø intervals were determined mathematically by taking the square root of the products of the millimeter distance from the zero point

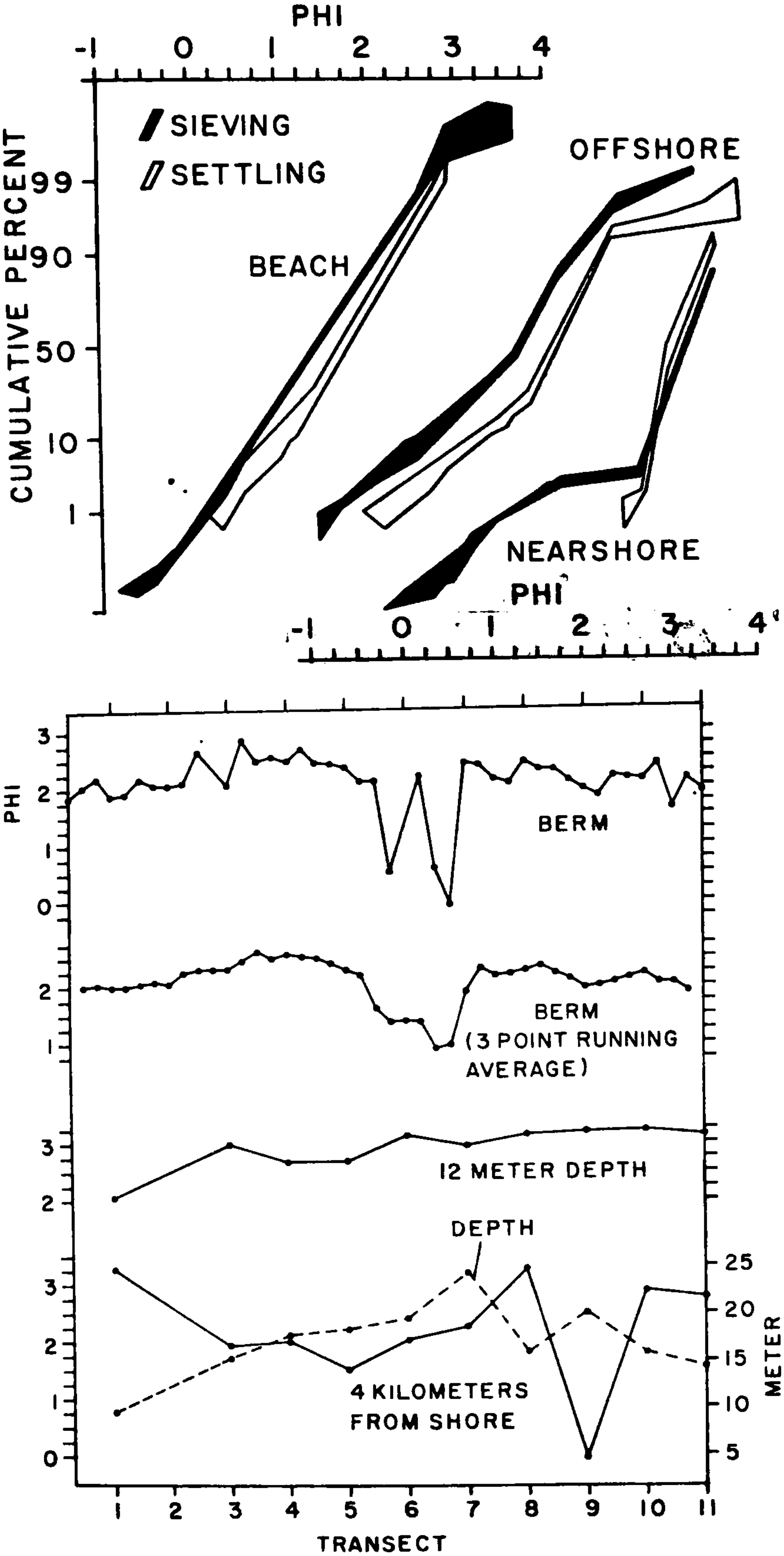
Figure 10. Typical Rapid Sediment Analyzer settling curve with modified Schlee overlay superimposed.



Size – Time overlay
(Modified from Schlee, 1966)

Figure 11. (Above) Envelopes of sieving and settling calibration curves.

Figure 12. (Below) Longitudinal profiles of modal diameter at berm, 12 m depth, and 4 km from shore.


PHI
-1
0
1
2
3
4
SIEVING
SETTLING
CUMULATIVE PERCENT
99
90
50
10
1
BEACH
OFFSHORE
NEARSHORE
PHI
PHI
BERM
BERM
(3 POINT RUNNING
AVERAGE)
12 METER DEPTH
DEPTH
4 KILOMETERS
FROM SHORE
METER
25
20
15
10
5
TRANSECT
1
2
3
4
5
6
7
8
9
10
11

to the respective Ø boundaries. A typical settling curve with the modified overlay in the proper position for analysis is shown in Figure 10. Cumulative percentages are read off the curve at the junction of the curve and the vertical Ø size lines by a Gerber variable scale which divides the maximum deflected distance of the recorder pen into 100 equal parts. The cumulative percents of each Ø size is thereby determined by counting the number of scale increments from the curve's base line to these junctions.

STATISTICAL EVALUATION

Various statistical parameters of the calibration specimens were computed in order to make quantitative comparisons (Table IV). Mean, median, standard deviation, skewness, and kurtosis were determined for sieve and settling data by the graphic method of Folk (1963, p. 45-46) with values obtained from the average cumulative curve values in Figure 11. Modes were determined by the method of Spiegel (1961, p. 47-48).

As seen in Table IV, the 2 coarse sands (beach and offshore) have coarser means by sieve analysis than by RSA. The reverse is true with the fine sand specimen (nearshore). This sieving versus settling relationship is graphically illustrated in Figure 11 where both methods of size analysis produce cumulative curves with similar slopes but displaced horizontally from each other.

Table IV. Statistical information on calibration specimens.

	Beach (coarse, moderately sorted)		Nearshore (fine, well sorted)		Offshore (coarse, poorly sorted)	
	sieve size distribution	RSA size distribution	sieve size distribution	RSA size distribution	sieve size distribution	RSA size distribution
mode	1.41 1.79	1.70	3.27	2.99	1.70	2.02
mean	1.41	1.73	3.33	3.20	1.30	1.71
std. dev.	0.55	0.52	0.28	0.24	0.65	0.52
median	1.42	1.72	3.31	3.13	1.43	1.82
skewness	+0.01	-0.02	+0.12	+0.38	-0.27	-0.27
kurtosis	0.99	1.22	1.07	0.89	1.18	1.42

Comparison of Sieving and Settling Results

The differences in size distribution obtained by sieving and settling analysis are particularly noted by comparing the test specimens' sieving and settling cumulative curve envelopes (Fig. 11). It will readily be seen that the curve slopes in each specimen's couplet is similar. The major difference, however, lies in the fact that each specimen's respective set of curve envelopes are displaced laterally one from the other. Such a variation in size distribution by the 2 methods is probably inherent in the Schlee (1966) method of interpretation of the RSA curve as used in this study. Various other potential influences, however were investigated.

A microscopic count (30X) of mica and heavy minerals was conducted on every sieve fraction of each specimen, and averages were obtained (Table V). A split of each sieve size was placed on a glass slide, and both quartz and heavy mineral particles were counted in 3 widely spaced microscope fields. Fields were selected which contained approximately 100 gm each. An ocular with cross hairs dividing the field into quadrants was used to facilitate counting. The flat, low density mica grains settle more slowly than quartz of the same sieve size. Size analysis of a sample containing

Table V. Comparison of mica and heavy mineral content of the 3 calibration specimens.

	Beach (1-A-1)		Nearshore (1-G-1)		Offshore (1-0-3)	
	mica(%)	heavies(%)	mica(%)	heavies(%)	mica(%)	heavies(%)
-0.75						
-0.50						
-0.75						
0.00						
0.25						
0.50						
0.75	0	0	1	5	3	3
1.00	0	0	1	5	2	2
1.25	0	1.0	1	6	1	4
1.50	0	3.0	5	3	5	5
1.75	0	7.0	6	5	7	10
2.00	0	4.0	5	8	2	2
2.25	0	8.0	3	9	10	1
2.50	0	5.0	1	10	8	10
2.75	0	7	10	10	12	10
3.00	1	10	11	14	11	6
3.25	2	5	9	18	9	5
3.50	2	5	8	23	8	11
3.75	2	10	5	20	10	9
4.00	0	10	9	20	15	13
Average	0.5	5.7	5.4	11.1	7.4	6.5

mica, therefore, would be expected to result in a finer settling distribution than a sieving distribution. Heavy mineral grains due to their high density produce the opposite effect (Emery, 1938, p. 111). The highest average mica content (7.4%) is seen to be in the offshore specimen and the highest heavy mineral content (11.1%) is in the nearshore specimen. The beach specimen contains the lowest quantities of both mica and heavies. No precise statement can be made as to the extent to which these 2 extreme grain type effect their respective distribution and cumulative curves. It is, however, interesting to note that the highest content of heavy minerals is found in the only specimen (nearshore) whose settling curve is coarser than its companion sieve curve.

Table VI which shows percentage variation between nominal[4] and measured sieve screen openings indicates that 17 of the 21 calibrated sieves (81%) have warp and shoot interspaces 0.2% to 6.3% larger than their respective nominal screen sizes. Brackets to the right indicate the sieve size ranges included in 2 standard deviations of each calibration

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[4]The nominal opening is the rated sieve opening (Poole, 1957, p. 461).

Table VI. Percent variation between nominal and measured sieve screen openings with sieve size ranges indicated by brackets and average percent variations in parenthesis.

Ø	Nominal sieve size	%variations from nominal screen size: warp	%variations from nominal screen size: shoot	Sieve size ranges included in 2 standard deviations
-1.00	2.00mm	2.0	1.0	
-0.75	1.65mm	2.4	2.4	
-0.50	1.41mm	0.7	-0.7	
-0.25	1.19mm	3.4	-0.8	
0.00	1.00mm	2.0	0.0	
0.25	841µ	0.3	1.7	off shore begins
0.50	707µ	-1.5	2.6	beach begins
0.75	595µ	-0.4	1.7	
1.00	500µ	1.8	-2.1	
1.25	420µ	0.7	-1.0	beach (+1.1%); off shore (+1.1%)
1.50	350µ	3.3	4.4	
1.75	297µ	-0.1	4.2	
2.00	250µ	0.3	0.3	
2.25	177µ	1.2	1.8	off shore ends
2.50	210µ	0.8	2.0	beach ends
2.75	149µ	1.2	1.4	
3.00	125µ	1.0	1.0	near shore begins
3.25	105µ	2.7	5.0	
3.50	88µ	3.6	3.9	near shore (+3.4%)
3.75	74µ	5.0	5.2	
4.00	62µ	-0.2	6.3	near shore ends

specimen's average sieve distribution. Average percent variations from nominal screen sizes are in parentheses beside the respective brackets: beach, 1.1% larger; nearshore, 3.4% larger; and offshore, 1.1% larger. These sieve size increases over those indicated by the manufacturer would all be expected to promote coarser settling distributions than sieve distributions. As with the heavy mineral counts above, the extreme value (3.4% larger) involves the nearshore specimen which is the only one of the 3 calibration specimens showing a settling distribution coarser than its companion sieve distribution.

Settling convection and hindered settling (Kuenen, 1968) play roles in this conflicting sieving versus settling situation. Settling convection with its tendency to increase settling velocity, particularly with fine, well sorted sediments (Kuenen, 1968, p. 317) would explain to some extent the coarse settling distribution of the nearshore specimen (Fig. 11) compared to its sieving distribution. It does not explain, however, the reverse relationship of the sieving versus settling distributions in the beach and offshore specimens. Possibly my modification of Schlee's overlay (Fig. 9, 10) over compensates for the expected coarsing effect on size distribution of settling over sieving

(Poole, 1957; Schlee, 1966).

On the basis of computations by the writer, the particles of offshore specimen (coarsest mean grain size by sieve as seen in Table IV) will initially fall, if regularly spaced, at a distance apart of 3.5 average grain diameters. The particles of the nearshore specimen with the finest mean grain size by sieve would fall at a distance apart of 0.1 diameter. The distance between falling particles of the beach specimen would be between those of the nearshore and offshore specimens at 3.2 diameters. Water-sediment interaction is possible, therefore, in all 3 calibration specimens if Kuenen's criterion of 5 diameters apart or less is adhered to.

Since sieves allow the passage of particles whose intermediate diameters are 40 percent larger than the nominal sieve size, all 3 calibration specimens would be expected to show coarser settling than sieving curves. Again, only the nearshore specimen reflects such an occurrence.

In addition to the above mentioned influences on grain settling velocity there is a possibility that a consistent variation in grain shape exists among these calibration specimens. Such variations could have a considerable effect on settling velocities and hence apparent settling distributions (Ziegler et al., 1960, p. 495; Sengupta and Veenstra, 1968, p. 33; Schlee, 1966, p. 407). Due to the extensive nature of a shape determination, this analysis was not undertaken.

Table VII. Confidence limits.

	Beach specimen		Nearshore specimen		Offshore specimen	
	Sieve	RSA	Sieve	RSA	Sieve	RSA
M_ϕ	1.41	1.73	3.33	3.20	1.30	1.73
O_ϕ	0.55	0.52	0.28	0.24	.65	.52
N	19	13	17	7	20	18
V	30		22		36	
t	1.59		1.03		2.17	
$t_{.975}$	±2.75		±2.07			
$t_{.99}$					±2.44	

The means of the sieve and settling size distributions of each of the 3 calibration specimens were compared by the 2-tailed Student's t test (Table VII). No significant difference could be found between the respective sieve and settling distributions of the beach and nearshore specimens at the 95% level of significance and the offshore specimen at the 99% level of significance.

RESULTS

General

All results are based on RSA grain size distribution determinations of 205 sediment specimens obtained from the sample net from Cape Henry to Cape Hatteras (Fig.1).

In this chapter, the relationship of grain size to topography is described, and samples have been relegated to various provinces by 2 different procedures. A qualitative procedure is based on grain size and topography and a quantitative procedure is based on factor vector analysis. Further examination of the sediment types has been conducted by means of scatter plots of various statistical parameters keyed to factor vector analysis.

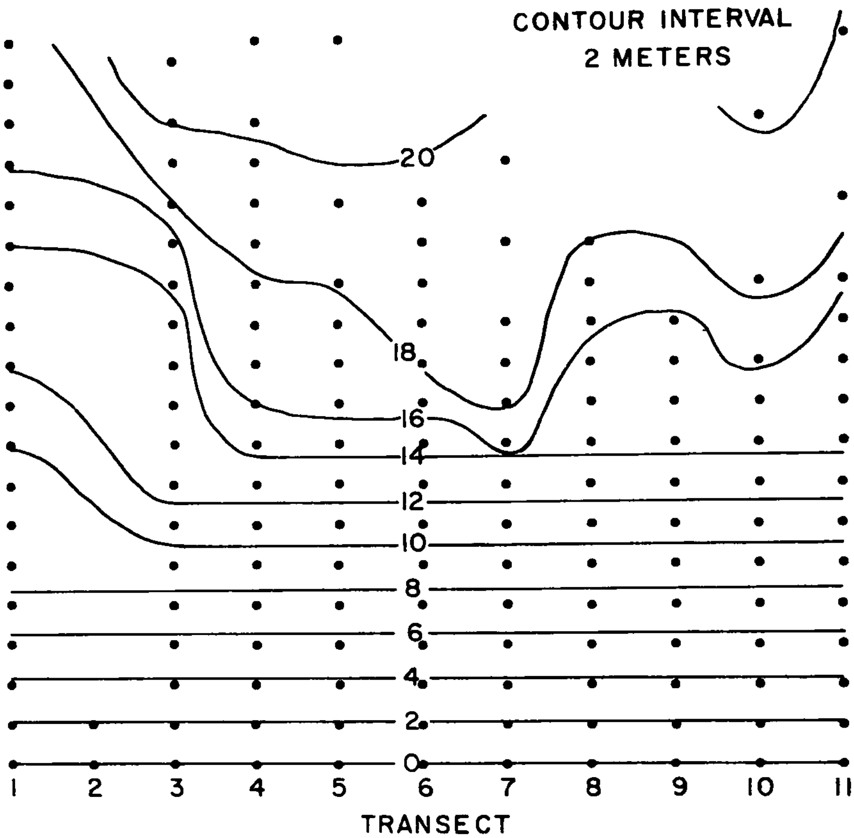
Qualitative Evaluation of Sediment Types

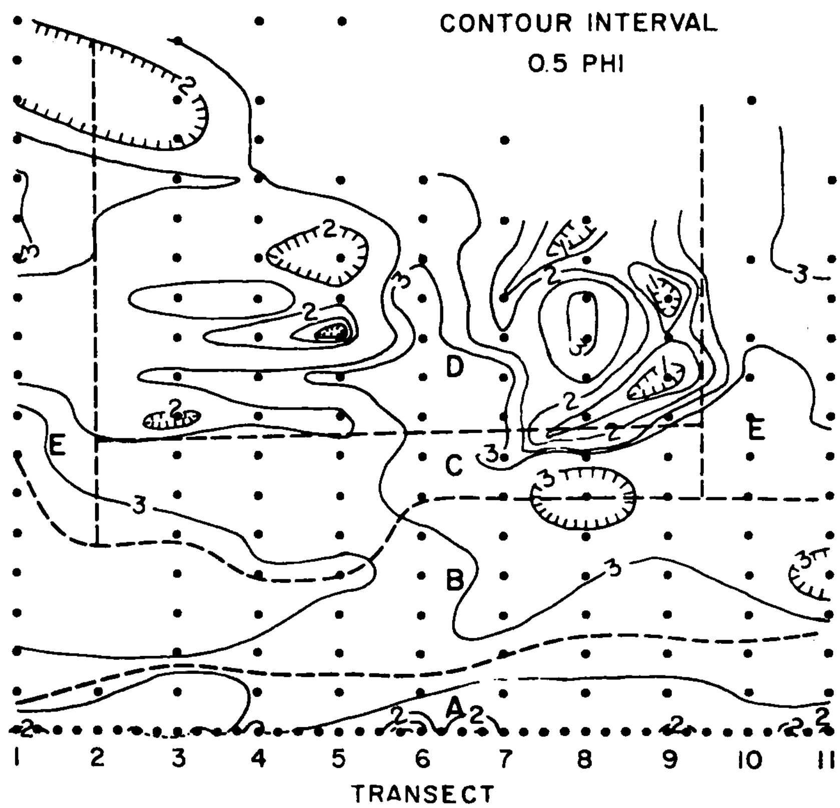
DATA

Modal diameter vs. bathymetry.--The relationship between modal diameter and bathymetry is seen in Figure 5. Modal diameter was selected for this comparison because it is considered to be most representative of sediment size: it is unaffected by truncation in the laboratory due to

Figure 13. (Above) Topographic map of study area (Y distance between stations within transects are exaggerated compared to X distances).

Figure 14. (Below) Modal diameter isopleth map.


CONTOUR INTERVAL
2 METERS
20
18
16
14
12
10
8
6
4
2
0
1 2 3 4 5 6 7 8 9 10 11
TRANSECT


CONTOUR INTERVAL
0.5 PHI
A
B
C
D
E
E
1 2 3 4 5 6 7 8 9 10 11
TRANSECT

RSA limitations, and it is sensitive to the history of bed-load transport.

Longitudinal modal diameter profiles.--The 4 longitudinal profiles in Figure 12 are size distribution modes of specimens along the berm, 12 m depth, and 4 km distance from shore. The berm profile is plotted with original values and also in a 3 point running average to eliminate small scale variations.

Regional overview.--This consists of a topographic map (Fig. 13) and a modal diameter map (Fig. 14). The Y distance between stations within the transects in both figures are exaggerated compared to the X distance between transects. This distortion of physical fact is conducted to present a clearer picture of grain size variation in the highly elongate study area.

SUBJECTIVE ASSESSMENT OF AREAL DATA

The consideration of diagrams cited suggests that the data may be grouped into a series of sediment provinces on the basis of grain size and topography (Fig. 13, 14) as follows:

A. Coarse sand of beach and surf zone.

B. Fine, seaward fining sand of upper shoreface..

C. Heterogeneous sands of lower shoreface.

D. Heterogeneous sands of the sea floor.

E. Fine sand of terminal shoals.

Factor-vector Analysis of Sediment Types

TECHNIQUE

Factor-vector analysis was used to assess the data quantitatively. This procedure is a statistical approach which defines each sample, of up to 21 quarter phi weight percents, as a vector in a 21 dimensional space (Imbrie and Van Andel, 1964; Klovan, 1966). The procedure takes all possible combinations of vectors 2 at a time and assesses the degree of parallelism. Every vector then is resolved into components on four orthogonal axes; thus each sample is described in terms of 4 hypothetical end numbers. Since an infinite number of 4-fold axial sets may be defined for the system, a varimax procedure is used to determine which set of theoretical end numbers (axes) result in the least amount of mixing (lowest entropy).

Factor loading values may range from -1 to +1. Samples were assigned to 4 factorial classes on the basis of which of the sample's four factor loadings had an absolute

Figure 15. (Above) Cumulative curve envelopes for the 4 factorial sediment classes.

Figure 16. (Below) Scatter plot of modal grain size vs. depth of sediment on the shoreface.

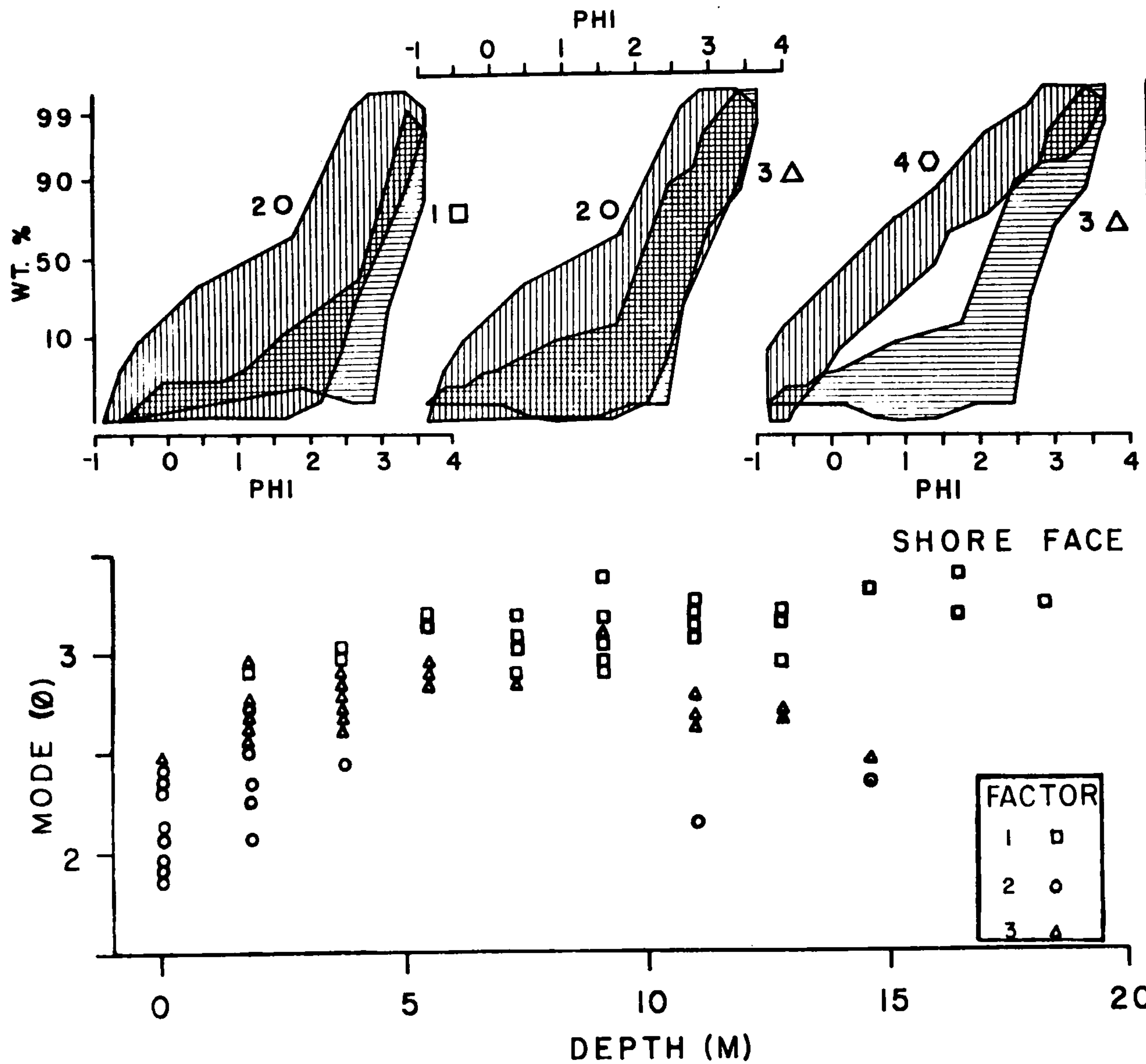

PHI
WT. %
99
90
50
10
2 ○
1 □
3 △
4 ○
SHORE FACE
MODE (Ø)
DEPTH (M)
FACTOR
1 □
2 ○
3 △

Figure 17. Scatter plot of mean grain size vs. skewness of sand on shoreface.

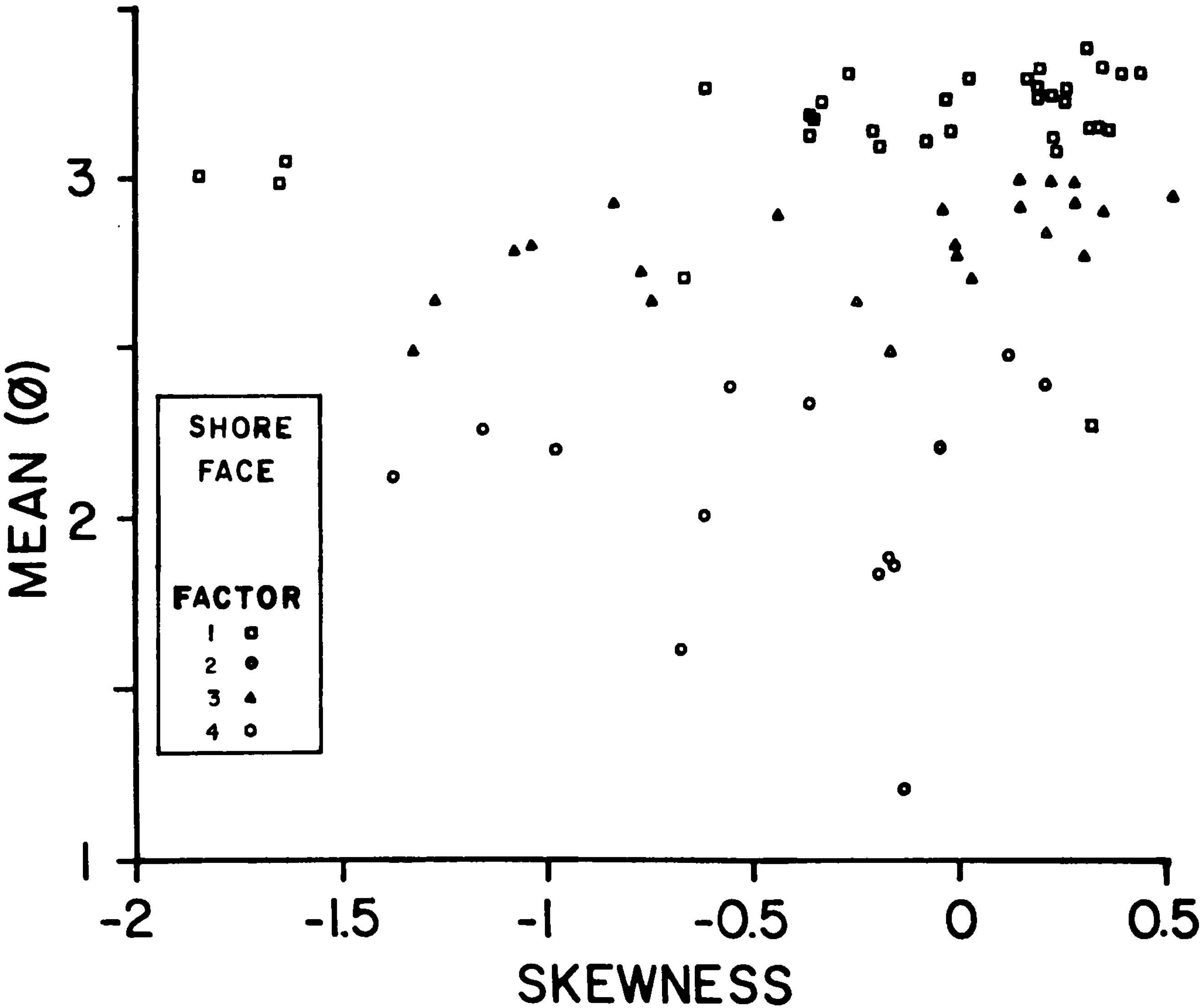

MEAN (Ø)
3
2
1
-2
-1.5
-1
-0.5
0
0.5
SKEWNESS
SHORE FACE
FACTOR
1
2
3
4

Figure 18. Scatter plot of sample detph vs. percent fine on shoreface.

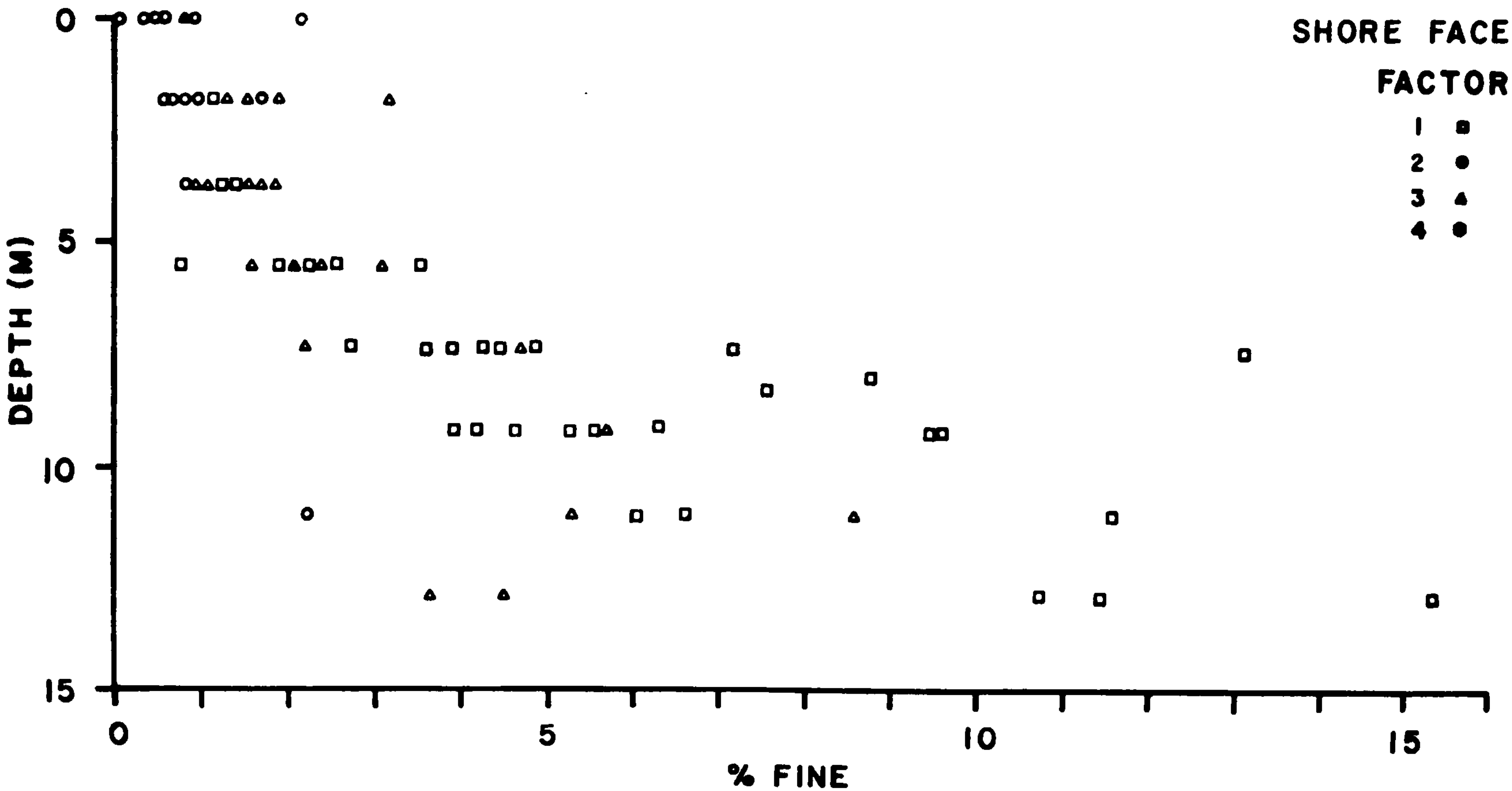
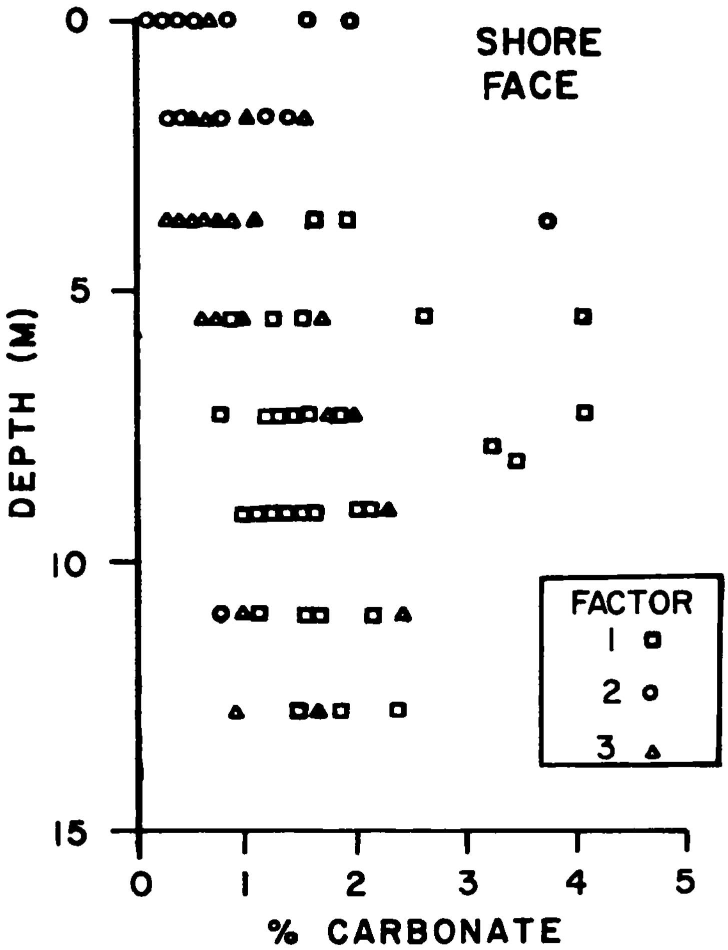

SHORE FACE
FACTOR
1
2
3
4
DEPTH (M)
0
5
10
15
0
5
10
15
% FINE

Figure 19. (Above) Scatter plot of sample depth vs. percent carbonate on shoreface.

Figure 20. (Below) Scatter plot of mean grain size vs. standard deviation of sand on shoreface.


SHORE FACE
DEPTH (M)
% CARBONATE
FACTOR
1
2
3
0
5
10
15
0
1
2
3
4
5

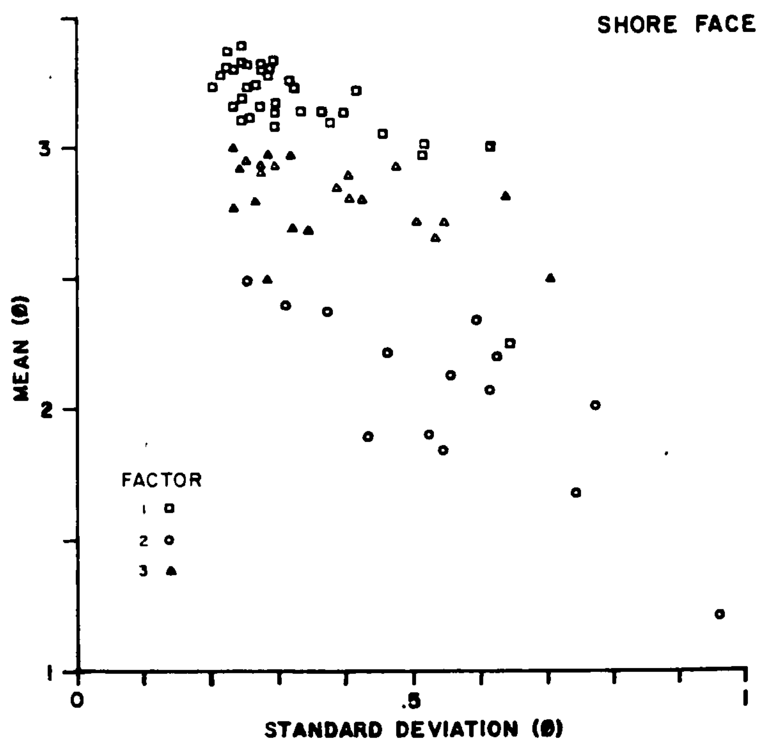

SHORE FACE
MEAN (Ø)
STANDARD DEVIATION (Ø)
FACTOR
1
2
3
0
.5
1
2
3

Figure 21. Scatter plot of mean grain size vs. skewness of sand on sea floor.

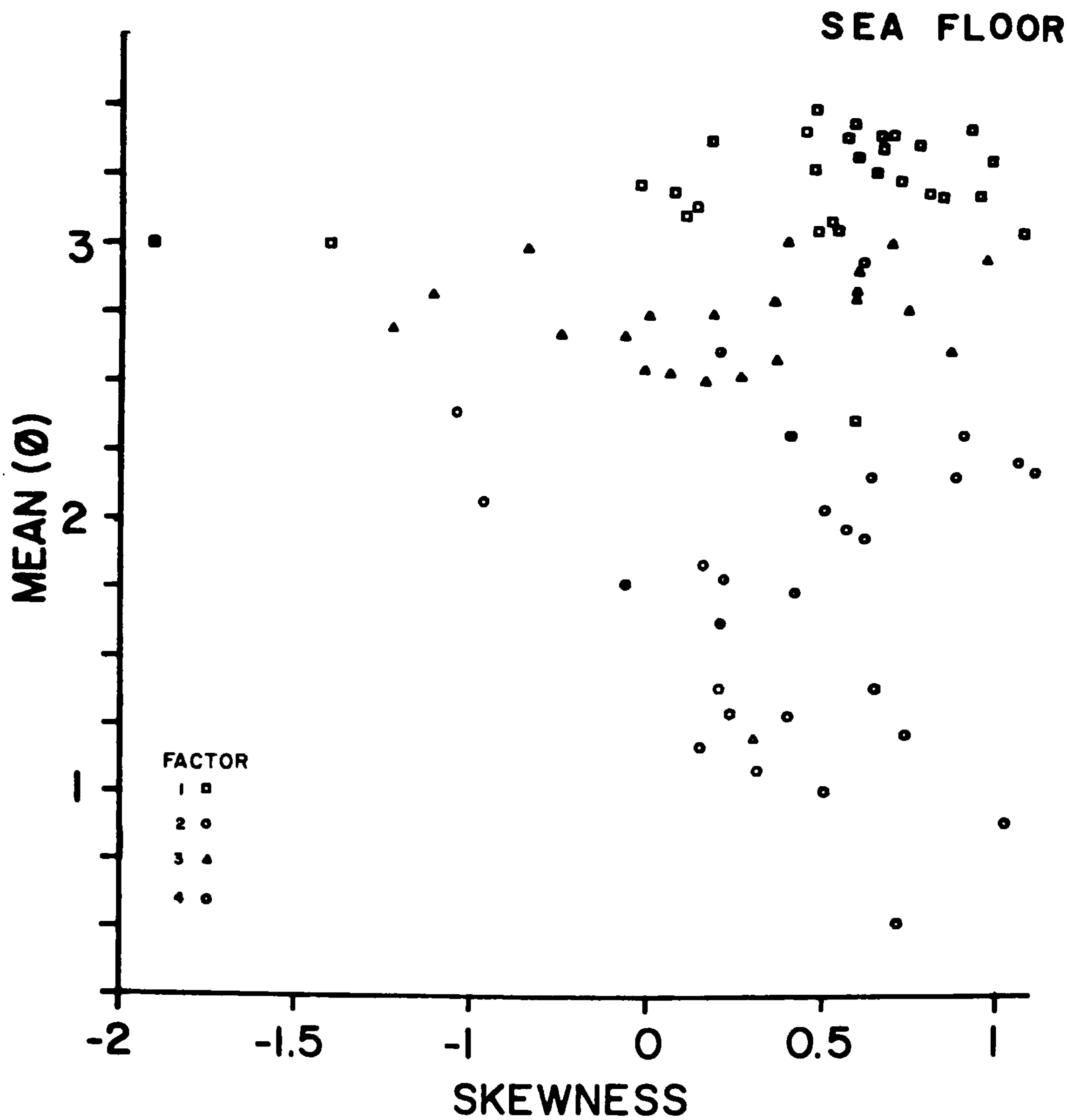

SEA FLOOR
MEAN (Ø)
SKEWNESS
FACTOR
1
2
3
4
-2
-1.5
-1
0
0.5
1

Figure 22. Scatter plot of mean grain size vs. standard deviation on sea floor (circled points come from topographic highs).

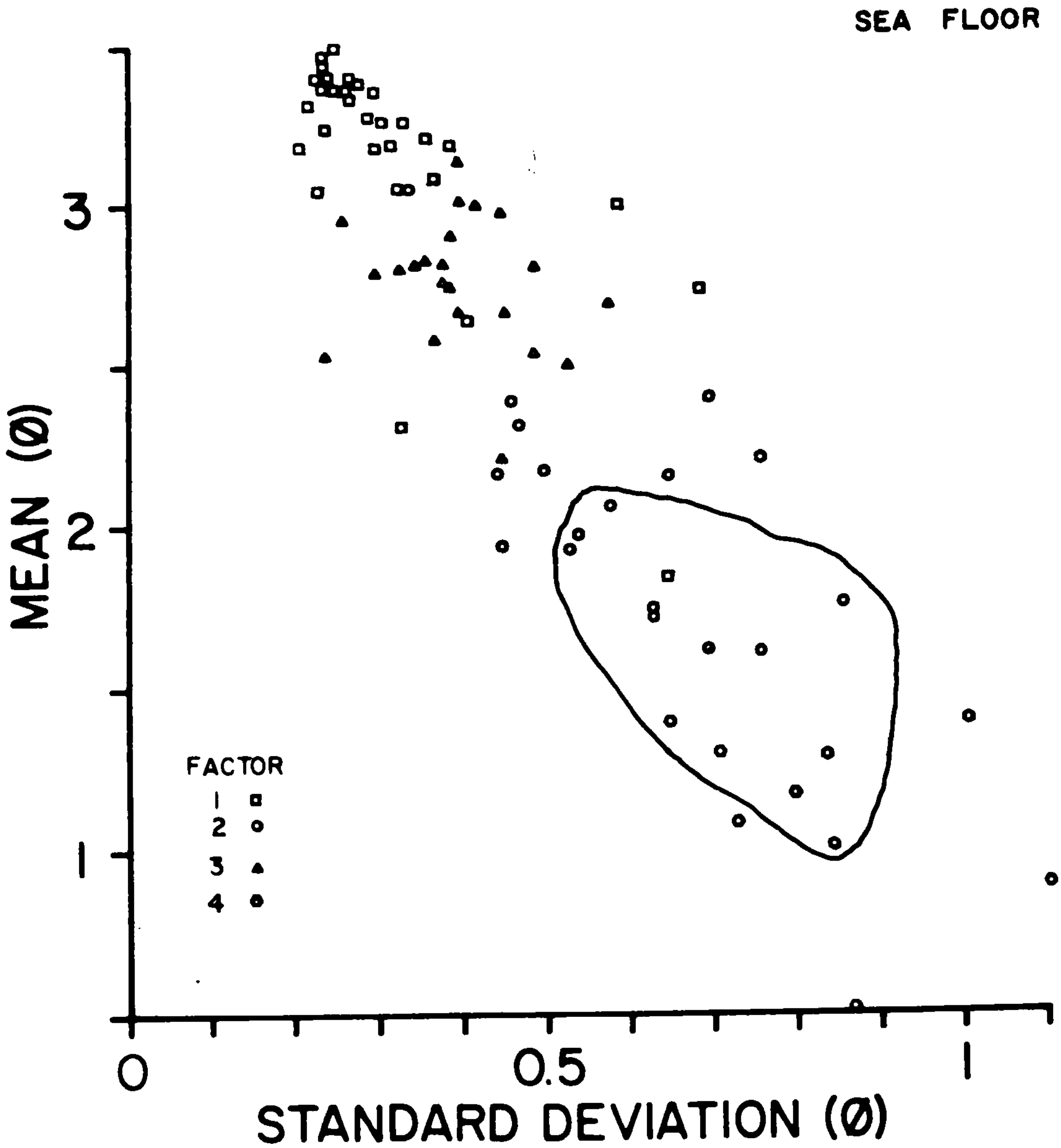
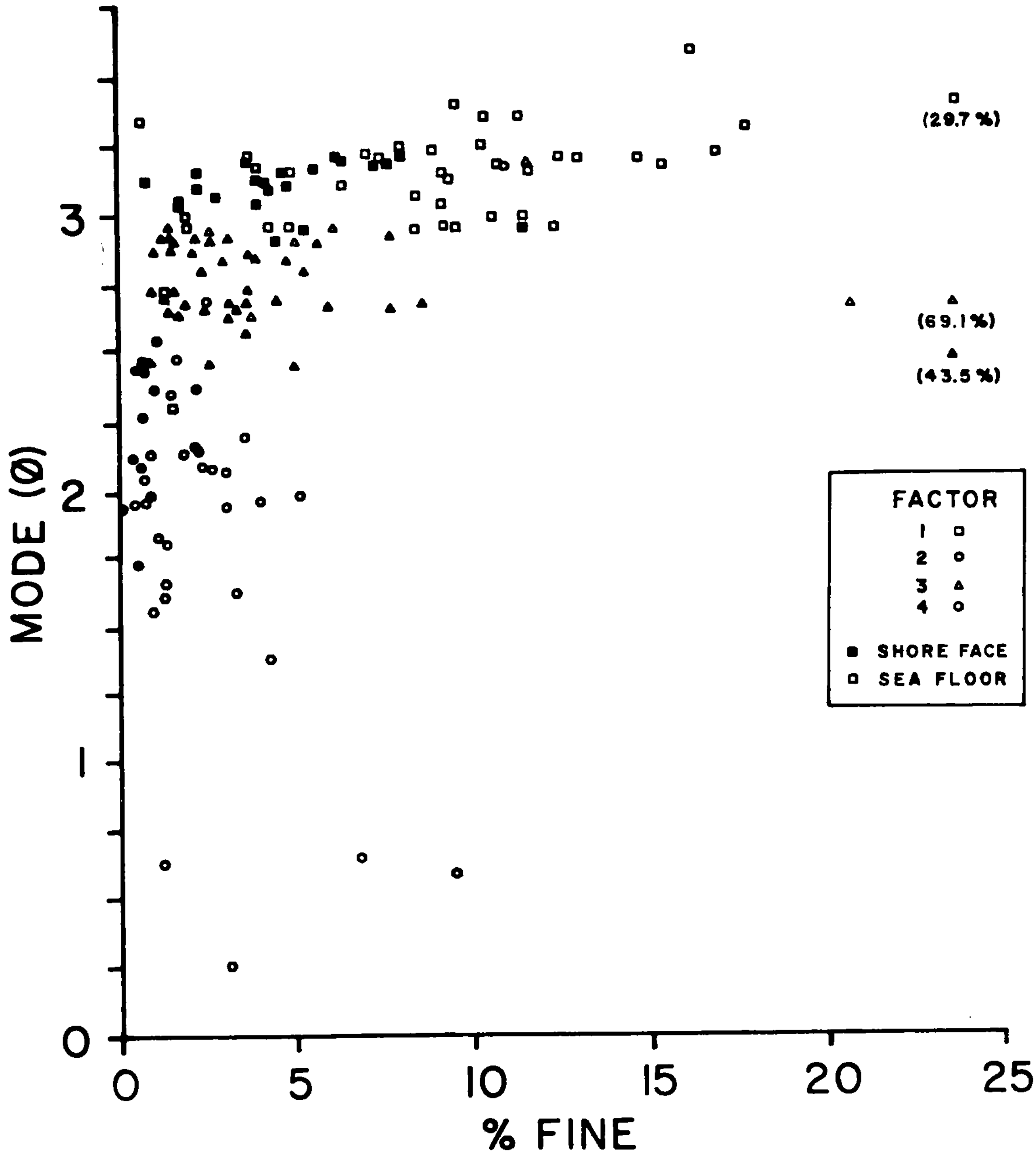
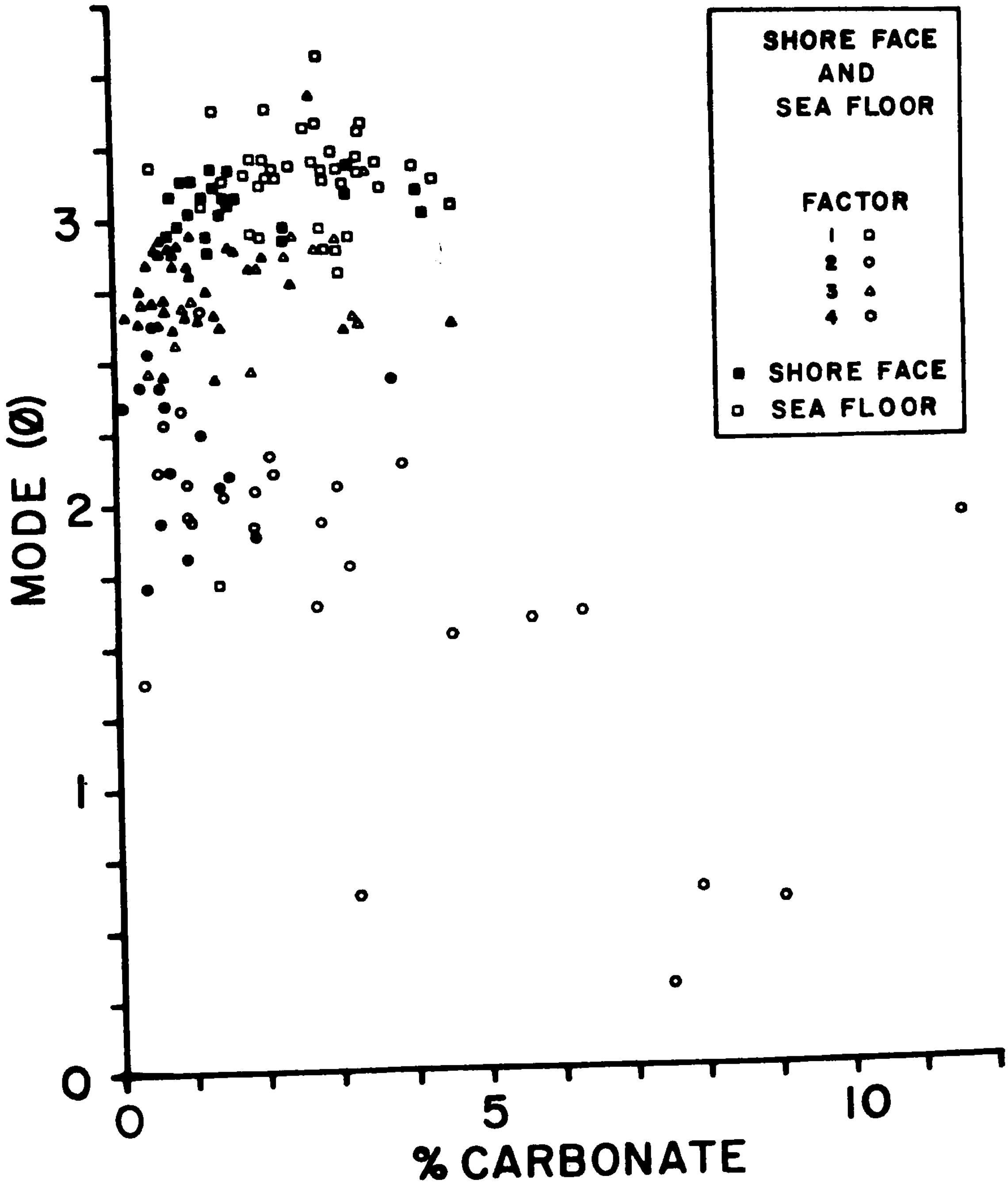

SEA FLOOR
MEAN (Ø)
3
2
1
FACTOR
1
2
3
4
0
0.5
1
STANDARD DEVIATION (Ø)

Figure 23. Scatter plot of modal grain size diameter vs. percent fines for the entire study area.



MODE (Ø)
% FINE
0
1
2
3
0
5
10
15
20
25
(29.7 %)
(69.1 %)
(43.5 %)
FACTOR
1
2
3
4
SHORE FACE
SEA FLOOR

Figure 24. Scatter plot of modal grain size vs. percent carbonate for the entire study area.


SHORE FACE
AND
SEA FLOOR
FACTOR
1
2
3
4
SHORE FACE
SEA FLOOR
MODE (Ø)
0
1
2
3
0
5
10
% CARBONATE

value in excess of 0.5. The values were not normalized because the program used did not provide for this transformation. Hence a factor loading of 0.5 for a given theoretical end member does not necessarily mean that the end member comprises 50 percent of the sample.

NATURE AND DISTRIBUTION OF FACTOR SEDIMENT TYPES

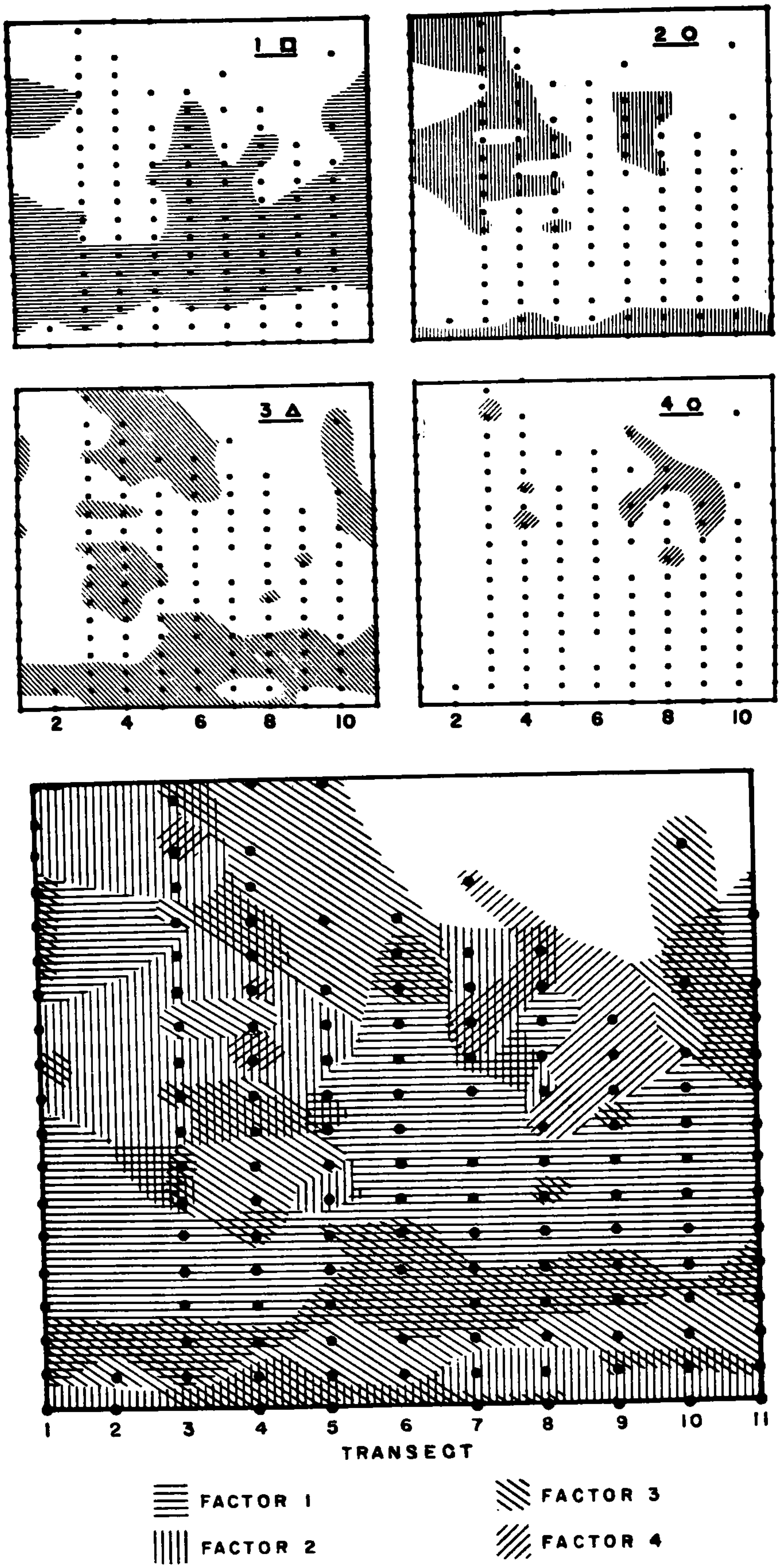
Cumulative curves.--Cumulative curve envelopes for the 4 factorial sediment classes are seen in Figure 15. Factor members and their corresponding symbols are shown in this figure. The same factor symbols are also used in other figures pertaining to factor-vector analysis.

Scatter plots.--Phi moment parameters and other petrographic parameters associated with the factor sediment types are presented in the following scatter plots: sediment types for the shoreface (Fig. 16-20), sediment types of the sea floor (Fig. 21, 22), and figures combining both areas (Fig. 23, 24).

Factor 1.--The three elongate segments of the cumulative curve envelope for factor 1 sands indicate 3 lognormal subpopulations: a coarse subpopulation laid down by rolling, a subpopulation deposited by saltation,

Figure 25. (Above) Distribution of individual factor sediment types.

Figure 26. (Below) Composite map of sediment factor types.


1 □
2 ○
3 △
4 ○
2
4
6
8
10
1
2
3
4
5
6
7
8
9
10
11
TRANSECT
FACTOR 1
FACTOR 2
FACTOR 3
FACTOR 4

and a fine subpopulation deposited from suspension (Visher, 1969). The suspension load in this and other factor envelopes are not evident because lines indicative of these loads are almost vertical--almost as well sorted as saltation load.

Sediments in this factor group are the finest of the factor sediments and have a mode of 2.33 to 3.57. They occur mainly on the lower shoreface and on Diamond Shoals (Fig. 25, 26), are well sorted, fine-skewed, and are relatively rich in fines and carbonate material (Table VIII).

Factor 2.--Sediments with this endmember consist of 3 lognormal subpopulations produced by rolling, saltation, and, to a very slight extent, suspension (Visher, 1969). These specimens are fine to medium grained and are found on the berm, in the surf zone, and on portions of the sea floor and Cape Henry Shoal (Fig. 25, 26). Their modes are 1.71 Ø to 2.69 Ø, they are moderately well sorted, and most of them are fine-skewed. They contain a moderate amount of carbonate and fines (Table VIII).

Factor 3.--These sediments are composed of rolling and saltation populations and exceedingly small suspension populations (Vesher, 1969). They are found on the berm,

Table VIII. Ranges of parameters found in factor-vector scatter plots.

	Factors			
Parameters	1	2	3	4
mode (Ø)	2.88 to 3.57	1.71 to 2.69	2.42 to 2.97	0.25 to 1.64
standard deviation (Ø)	0.21 -- 0.61	0.25 -- 0.86	0.23 -- 0.70	0.65 -- 1.10
mean (Ø)	1.83 to 3.48	1.20 to 2.47	2.20 to 2.97	0.05 to 1.39
skewness	-1.91 to 0.54	-1.38 to 0.57	-1.33 to 0.52	-0.35 to 0.52
percent fine	0.6 -- 17.6	0.0 -- 5.1	0.8 -- 8.6	0.8 -- 9.5
percent carbonate	0.5 -- 4.5	0.1 -- 3.8	0.1 -- 4.5	0.3 -- 9.0
Traction load:				
Ave. range (Ø)	0.63 to 2.32	0.16 to 1.43	0.85 to 1.47	-0.85 to 1.30
Ave. wt. %	1	25	5	59
Saltation load:				
Ave. range (Ø)	2.32 to 2.62	1.43 to 2.42	1.47 to 2.53	1.30 to 2.02
Ave. wt. %	11	57	47	29
Suspension load:				
Ave. range (Ø)	3.62 to 3.99	2.42 to 3.51	2.53 to 3.82	2.02 to 3.26
Ave. wt. %	88	18	48	12

in the surf zone, upper shoreface, and in various small deposits on the lower shoreface, sea floor and Diamond Shoals (Fig. 25, 26). Their grain sizes vary from fine to very fine with a modal diameter of 2.42 Ø to 2.97 Ø. They are well sorted, and most are postively skewed. They contain moderate amounts of carbonate and fines (Table VIII).

Factor 4.--This endmember consists primarily of a rolling subpopulation, a moderate saltating subpopulation, and an extremely small suspension subpopulation (Visher, 1969). Factor 4 sands are the coarsest of the 4 factor types and with a modal grain diameter of 0.25 Ø to 1.64 Ø. It is found in small patches on the sea floor (Fig. 25, 26), is moderately well sorted, is positively skewed, and is moderately rich in carbonate and fines (Table VIII).

CONCLUSIONS

Regional Sediment Distribution

SHOREFACE

The genesis of the Currituck Spit-Hatteras Island complex (Fig. 1) is a perplexing problem, and the scant coring reports and geomorphic data available (Fisher, 1967) personal communication; Pierce and Colquhoun, personal communication; Swift, personal communication) do not give a definitive answer. See discussion on page 8 of this report.

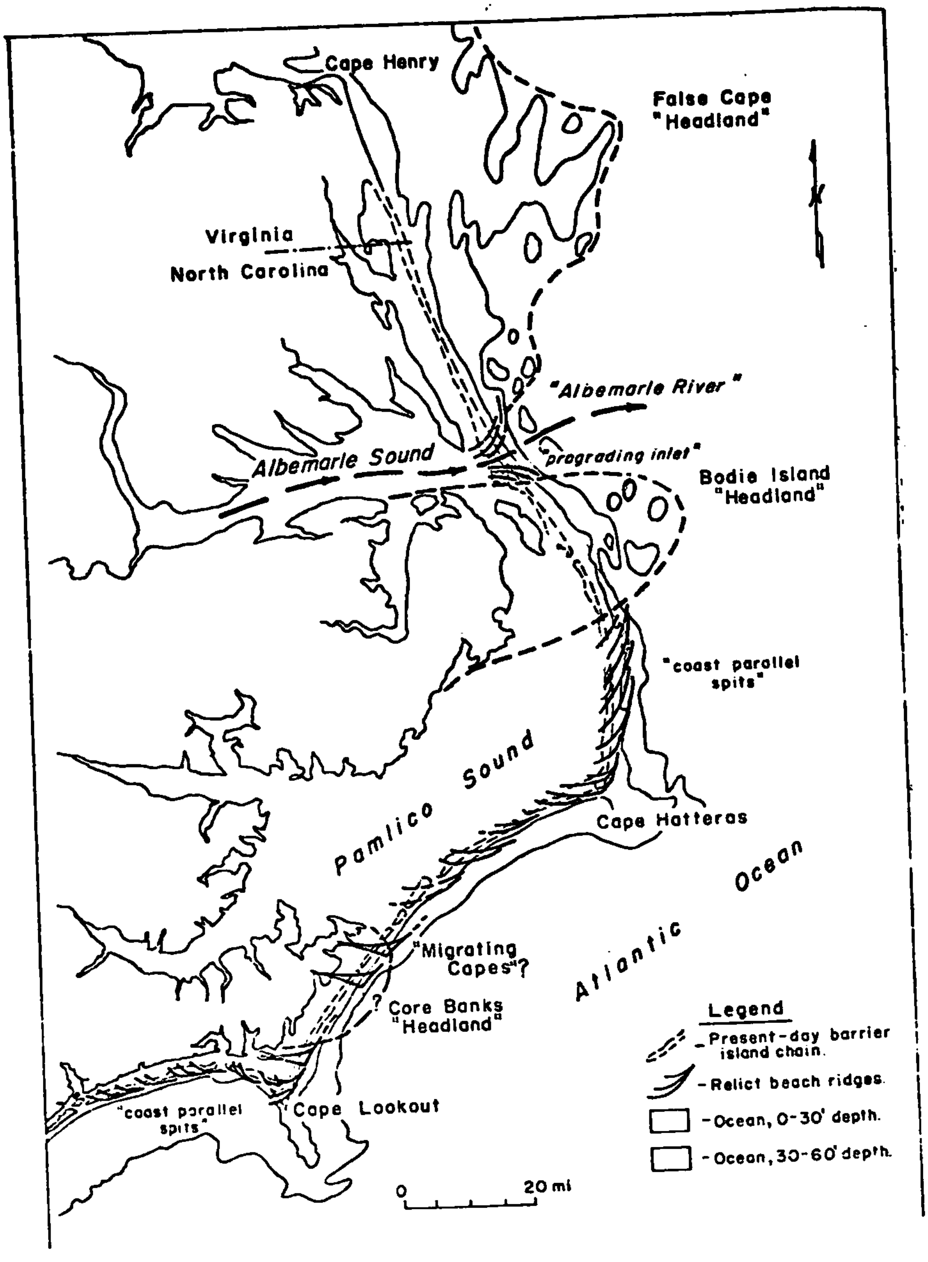
Lack of cores and radiocarbon dates precludes a definitive statement on the origin of Currituck spit, but the grain size data presented in this study plus information of past and present littoral drift directions permit some informed speculation. The northward divergence of beach ridges in the Sandbridge formation (Fig. 4) has lead Oaks to postulate northward littoral drift on the Virginia coast during the Sandbridge time. Langfelder *et al*. (1968) have assessed wave refraction patterns on the modern coast and concluded that there is a major node in the vicinity of Oregon Inlet. Drift north of the inlet is north toward the Virginia border (Fig. 7). Since shoals occur on the south sides of shipwrecks and groins on the Virginia coast, this trend appears to continue to Cape Henry. Langfelder et al. (1968) consider the drift south of Oregon Inlet to be generally south (Fig. 7).

Analysis of modal diameter on the berm between Cape Henry and Cape Hatteras reveals a regional trend of fining from both capes toward transect 3 (Fig. 12). The regional trend is interrupted by a strong coarse anomaly in the vicinity of transects 5, 6, and 7. The factor map (Fig. 26) shows that the regional trend results from an admixture of the relatively fine factor 3 sand to the coarse factor 2 beach sands in the central stations (transects 3-8). This factor map fails to reveal the coarse anomaly presumably because the coarse material is lumped with the factor 2 component.

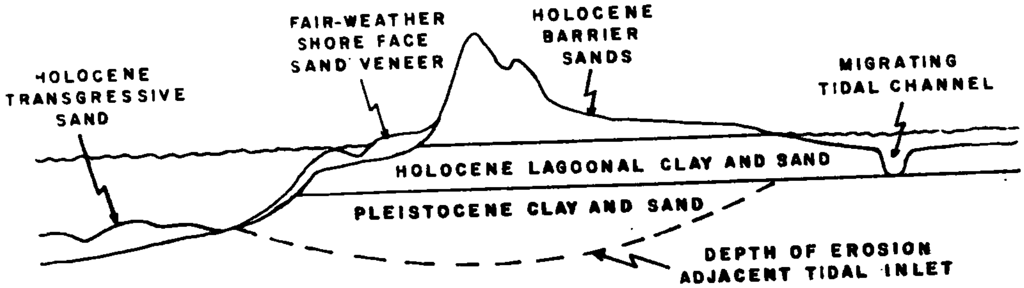
The pattern of the seaward fining sands of the shoreface lacks the symmetry of the beach sand pattern. At 12 meters the shoreface sand fines steadily to the south (Fig. 12). The factor map (Fig. 25, 26) shows that the factor 2 band of upper shoreface and the fact 1 band of the lower shoreface broaden to the south. The factor 1 band also

Figure 27. (Above) Hypothetical Albemarle River system from Fisher, unpublished diagram by J. Fisher, Univ. Rhode Island.

Figure 28. (Below) Conceptual diagram illustrating sediment fractionation model developed by this study.



Cape Henry
False Cape "Headland"
Virginia
North Carolina
"Albemarle River"
Albemarle Sound
"prograding inlet"
Bodie Island "Headland"
"coast parallel spits"
Pamlico Sound
Cape Hatteras
Atlantic Ocean
"Migrating Capes"?
? Core Banks "Headland"
Cape Lookout
"coast parallel spits"
Legend
- Present-day barrier island chain.
- Relict beach ridges.
- Ocean, 0-30' depth.
- Ocean, 30-60' depth.
0 20 mi



HOLOCENE TRANSGRESSIVE SAND
FAIR-WEATHER SHORE FACE SAND VENEER
HOLOCENE BARRIER SANDS
MIGRATING TIDAL CHANNEL
HOLOCENE LAGOONAL CLAY AND SAND
PLEISTOCENE CLAY AND SAND
DEPTH OF EROSION ADJACENT TIDAL INLET

reveals an anomaly in the vicinity of transects 5, 6, and 7. Here the anomaly is a geographic one. A tongue of fine factor 1 sand protruds seaward into what appears to be a low area (Fig. 25, 26).

It is possible to suggest a model for coastal sedimentation that accounts for these facts, though it is not necessarily a unique solution. The model interprets the distribution of sediment on the North Carolina-Virginia coast as the response of a Pleistocene substrate to the modern hydraulic regime. The key is the anomalous sediment pattern in the vicinity of transects 5, 6, and 7. Fisher (1967) has interpreted the beach ridge pattern of this portion of Currituck Spit as indicative of a former Albermarle Inlet, originally the site of a late Pleistocene and early Holocene Albemarle River (Fig. 27). Presumably the plug of coarse sand now blocking the former inlet was surf-excavated from the underlying coarse channel sands. The seaward protruding tongue of fine sand filling the offshore swale may be the old river valley partly filled by fine sand winnowed from the shoreface and adjacent highs.

The next more difficult part of the complex shoreface sediment pattern to unravel is the southward fining of the shoreface sands seaward of the breakers. Since these seaward-fining sands of the zone of shoaling waves are believed to be winnowed from the surf, it seems reasonable to suggest that they coarsen southward in response to increasing input of wave energy. This suggestion is consistant with geography. Wave refraction would cause wave height to increase from the head of the Chesapeake Bight towards its southern terminus at Cape Hatteras (Tanner, 1961).

The most difficult portion of the shoreface grain size pattern to interpret is the regional trend of the berm modal diameter. The increase of modal diameter from transect 3 to Cape Hatteras parallels the trend at 12 m and could likewise reflect increasing wave heights. The reversal north of transect 3 may reflect the increasing exposure of Pleistocene substrate on the shoreface as the mainland beach is approached and increasing contamination with coarse Pleistocene sand.

The coarsening of berm sand toward the north and south could be alternatively explained as a consequence of progressive extraction of fines from the beach by wave action as the sand is moved north and south from the Oregon Inlet node. The asymmetry of the Nags Head anomaly is consistent with this interpretation, since the coarse sands appear to be smeared out to the south. These 2 suggested mechanisms of coarsening of the beach north along Currituck Spit are not mutually exclusive.

SEA FLOOR

The sea floor in the Cape Henry to False Cape area (transects 1-3) consists of coarse, shelly, well-sorted type 2 sand with admixtures of other factors (Fig. 25, 26). Another study (Holliday, in preparation) shows general increases of sea floor grain size from False Cape toward Cape Henry. This trend, however, stops short of the medium-grained sand of Cape Henry Shoal.

The explanation of this sediment pattern is speculative. The Susquehanna River during lower sea level may have supplied coarse sand. The proximity of the modern mouth of Chesapeake Bay may result in intensified tidal currents.

In the south-central sea-floor portion of the study area, between transects 7 and 10, one sees an area of coarse, poorly sorted, shelly, factor 4 sediment (Fig. 25, Table VIII). This coarse sediment may be not-yet-buried Albermarle Flood Plain. If this coarse area is of fluvial origin, its high shell content (up to 10 percent) indicates heavy reworking by marine processes.

The southern sector of the study area (transects 10 and 11) is the north flank of Diamond Shoals. Here the fine factor 1 and 3 sands extend the length of the transects. Apparently the shoal is a terminus for littoral drift from Oregon Inlet on the north and Hatteras Inlet on the south (Tanner, 1960, p. 263; El Ashury and Wanless, 1968; Langfelder, et al., 1968, Fig. 3.14).

Sediment fractionation of a Retreating Shoreface

UPPER SHOREFACE SEDIMENT FRACTIONATION

Mechanics of fractionation.--Sediment fractionation of the upper shoreface by wave action is well known. Storm waves in particular strip retreating unconsolidated coasts down to the older Holocene back-barrier deposit or to the Pleistocene substrate (Harrison and Wagoner, 1964, Fig. 2). Following this, long period, flat, fair-weather swells fractionate the material thus released from the substrate. Within the surf zone, landward movement of the coarse fraction is caused by asymmetric wave surge and mass transport currents. Shoreward crestal surge of these fairweather waves is stronger than the following seaward trough surge. Hence, coarser sand is moved shoreward (Inman and Nasu, 1956). Also, the mass transport profile for fairweather swells indicates landward movement at the sea floor (Longuet-Higgins, 1963).

Fine sand is transported seaward of the surf zone by the sheet-like, mid-depth return flow of the mass transport profile, or by localized rip currents (Inman and Nasu, 1956). Further fractionation results from interaction between oscillatory wave surge and the wave-generated sea floor ripples (Kuelegan, 1948). As crestal surge passes over the ripples, it transports coarse material shoreward, and finer sand is suspended and trapped in the horizontal eddies generated in the troughs. These eddies rise and then the seaward surge of the wave trough sweeps this entrained, fine sand seaward. Thus sand settling in the zone of shoaling waves seaward of the breaker is divided into a coarse, landward moving bed load and a fine, seaward moving, intermittently suspended load.

In addition to these mechanisms, the null line mechanism originally set forth by Cornaglia (Munch-Petersen, 1950) and recently treated by Johnson and Eagleson (1966) has also been suggested for sediment fractionation on the shoreface. According to this postulate, successively deeper isobaths have successively finer grain sizes in equilibrium with opposing forces of asymetric wave surge and downslope gravity components. However, the validity and significance of this mechanism has been questioned by some coastal oceanographers (See discussion in Swift, 1969, 1970).

Results of fractionation.--Whatever the hydraulic mechanism for fractionation of shore-face sediments, it is very efficient. All measured parameters vary systematically with depth down the shoreface (Fig. 5, 16, 18, 19). Mode decreases exponentially due probably to ripple fractionation (Fig. 16). Percent fines (Fig. 18) increases exponentially and may, to some extent, be due to settling lag, scour lag, and other hydraulic mechanisms as postulated by Postma (1967) for tidal flats. Seaward increase in fines may be also due to lagoonal mud outcropping immediately beneath the sand (Fig. 28) and a slower rate of sand deposition with distance from shore. This gives animals more of a chance to work mud into the sand. In addition, turbid outflow of adjacent tidal inlets is frequently trapped in the near shore zone. Note the nearshore turbidity visible in the frontispiece.

Percent carbonate increases down the shore face (Fig. 19). This is probably due to a slower rate of sand input relative to production of shell material relative to biological productivity and consists primarily of fragile particles of razor clams (Solen virides Say).

LOWER SHORE-FACE SEDIMENT FRACTIONATION

Modal diameter vs. depth.--The lower shore face sediment grain size goes through a minimum and then becomes, coarser (Fig. 5). This is possibly due to the fact that the fine, modern sand blanket has become so thin that it is contaminated by Pleistocene substrate found below lagoon muds (Fig. 28). Also the lower shoreface is subject to a different hydraulic regime than the upper shoreface. Probably only the surge of steep-sided storm waves is effective at these depths, and such an intermittent effect would not be expected to fractionate the sediment to nearly the extent seen on the upper shoreface.

Ridge and swale topography.--The submarine sand ridge systems of Wimble Shoals and False Cape tie to the lower shoreface. The False Cape system has migrated landward since 1922 (Swift, et al.) hence it appears to be hydraulic in origin. Large scale, longitudinal bedforms of this sort have been ascribed to helical flow cells

(Houbolt, 1968). It seems doubtful that the tide currents of this area are significantly intense to mold such features. They may instead be responses to coast-parallel, storm-surge currents. Such a regime may also be responsible, to an extent, for the coarser sands of the lower shoreface. Further analysis of the nearshore ridge systems are beyond the scope of this report.

Sediment Fractionation of the Sea Floor

RECONNAISSANCE SAMPLE INTERVAL

Reconnaissance sample interval is generally wider than the wave length of the sea floor textural variations. Therefore, the sea floor sectors of the study area appears to be a nearly random distribution of factor 2, 3, and 4 sands. However, where known ridges are sampled, crests are always coarse, factor 2 and 4 sands, and swales are usually fine, factor 1 or 3 sands (Fig. 22).

FRACTIONATION MODEL FOR SEA FLOOR SEDIMENT

Houbolt (1968) describes sand ridges in the North Sea built by special flow cells in the tidal currents. These flow cells result in a coarse lag in the troughs and medium sand up on the ridges (crests). If ridge and swale topography of the study area's sea floor sector is the result of spiral flow during storm surge, then the grain-size distribution after a storm might resemble that described by Houbolt (1968). During fair weather, wave surge might winnow fines out of the crests and return them to adjacent swales. This would result in ridges of homogeneous medium grained sand and swales of fine sand with coarse lag horizons. The observed pattern is consistent with this model, but coring would be needed to verify the proposed interbedding of the swales.

A Model for Sediment Fractionation of a Retreating Coast Line

ORIGIN OF HOLOCENE TRANSGRESSIVE FACIES

The Johnsonian model; the sea floor as a wave-cut terrace.--A critical relationship that has not yet been discussed is the origin of both the sea floor sediment and the sand blanket of the shoreface and their relationship to each other. Johnson (1919) suggested that during a rise in sea level over a shelf with a low sediment input an abrasion platform would form with its seaward edge 100 fathoms below sea level. This platform would gently slope up in a shoreward direction for some indefinite distance to a point where the gradually dampened waves would lose their ability to erode the shore any further.

Curray's model; discontinuous coastal retreat.--With sufficient sediment supply, a barrier may grow for a while and thereby keep pace with the rising sea level. Eventually, however, the enlarged estuary or lagoon behind it formed by the rise of the sea will trap too much of the river-derived sediment. The barrier is then overtopped and the lagoon becomes an open sound (Curray, 1964).

Dillon's model; continuous coastal retreat.--Dillon (1970), through a study of a barrier beach-lagoon system in Rhode Island, developed a barrier erosion model in which, with a rising sealevel, a barrier with a low sand supply retreats more or less continuously by a process of shore-face erosion and storm washover.

This model is in distinction to that developed for a barrier with a high initial sediment supply (Curray, 1964); such a barrier is able to stabilize and grow upwards. Dillon, however, offers an alternative explanation as to the eventual cause of foundering of a well-nourished barrier. It is

Dillon's belief that as the water deepens, and the area of the barrier's shoreface increases, more and more sediment is needed to maintain its top at sea level; ultimately it is overstepped.

Dillon's scheme seems more applicable to the Carolina-Virginia coast. River sand is trapped far inland at the heads of estuaries; evidence cited in previous pages suggests that barrier is largely fed by its own substrate. Oaks' profiles (Fig. 3) suggest that the shoreface cuts through the Holocene marginal facies to the Pleistocene.

Bruun's theory; shore-face erosion and sea floor aggradation.--Bruun has suggested a rise in sea level results in erosion of the shoreface and an equal-volumn aggradation of adjacent sea floor (Bruun, 1954; Harris, 1954, p. 17; Swartz, 1965, 1967, 1968). Bruun's hypothisis is supported by the work of Moody (1964) who cites such an equal volume transfer between the barrier and the off shore area between Indian River Inlet and Bethany Beach, Delaware. Harris' 4 year study of the Long Branch, New Jersey dredge dumping site shows that during this period there was erosion of the shoreface and concomitant aggradation of the adjacent sea floor.

SEDIMENT FRACTIONATION MODEL DEVELOPED BY THIS STUDY

The model adopts the principles set forth by Dillon (1970) and Bruun (1954) which are pertinent to sediment-starved barriers of the Middle Atlantic Bight.

It recognizes a two-fold structure as characteristic of the sediment-starved class of barriers (Fig. 28). A constructional superstructure retreats in cyclic. tank-tread fashion by storm erosion, storm washover, burial and reemergence at the beach. The substructure consists of the shoreface carved into older Holocene materials and into the subadjacent Pleistocene. Sediment released from this surface by storm erosion is moved mainly seaward under the impetus of steep-sided storm waves. The Holocene transgressive sand sheet would be thus formed in accordance with Bruun's theory. While this model satisfactorily accounts for the grain size distribution reported in this study, it is not necessarily a unique solution. A program of sea floor coring and monitoring of the hydraulic regime would be required to substantiate it.

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