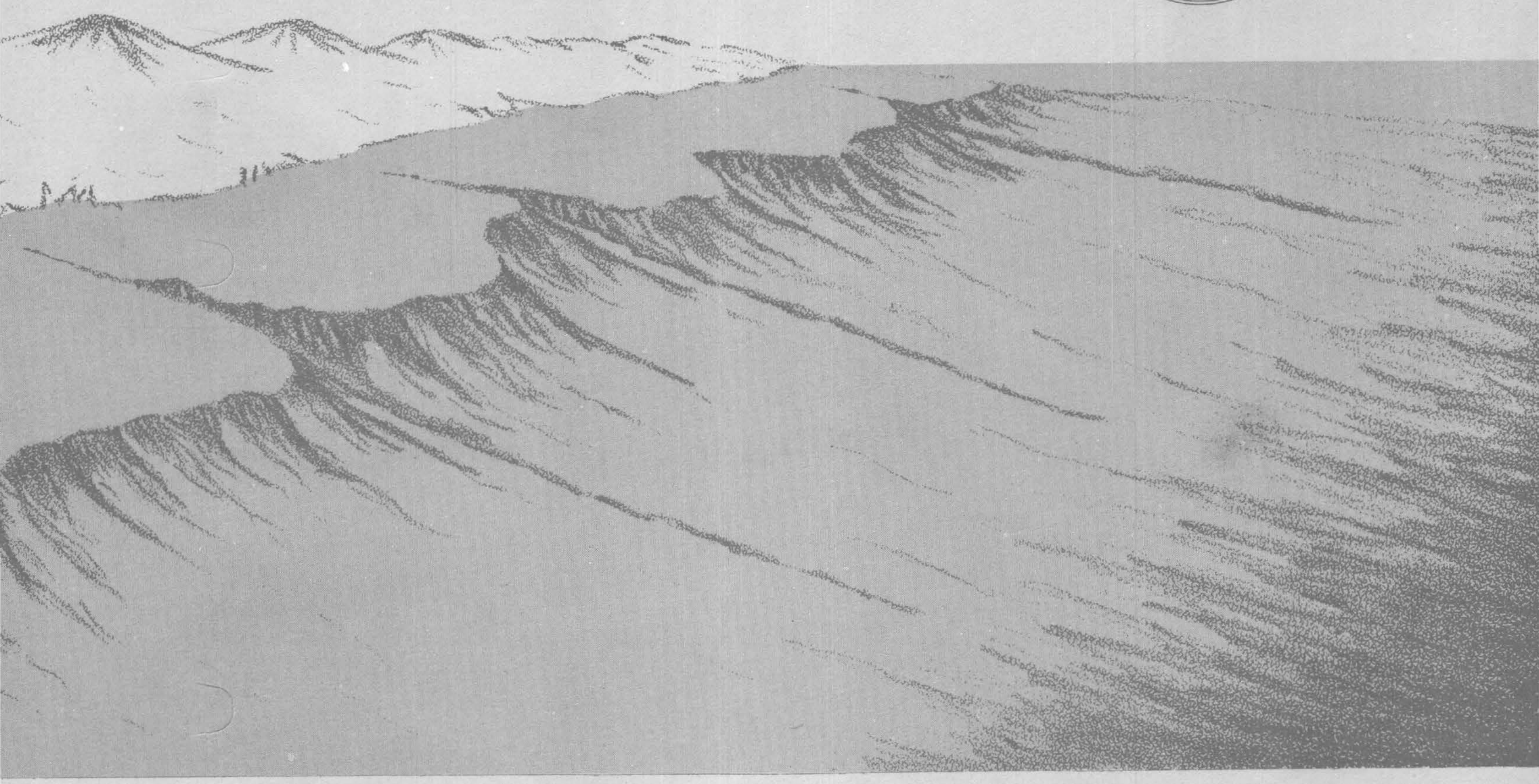
Atlantic Continental Shelf and Slope of the United States



Texture of Surface Sediments from New Jersey to Southern Florida

GEOLOGICAL SURVEY PROFESSIONAL PAPER 529-M

Atlantic Continental Shelf and Slope of the United States—Texture of Surface Sediments from New Jersey to Southern Florida

By CHARLES D. HOLLISTER

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An interpretation of textural parameters of sediment from the continental shelf and slope and the Blake Plateau and their relationship to modern patterns of oceanic circulation

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ATLANTIC CONTINENTAL SHELF AND SLOPE OF THE UNITED STATES—TEXTURE OF SURFACE SEDIMENTS FROM NEW JERSEY TO SOUTHERN FLORIDA[1]

By CHARLES D. HOLLISTER, Woods Hole Oceanographic Institution

ABSTRACT

A study of more than 800 bottom-sediment samples collected from the continental margin between New Jersey and Florida shows that sand covers almost the entire continental shelf. The sand is mainly unimodal, is well sorted, and has a symmetrical grain-size distribution curve. Mean grain size generally increases toward the shelf break. Shelf sands containing an appreciable amount of calcium carbonate on the continental shelf south of Cape Hatteras are texturally similar to the sands consisting mainly of quartz and feldspar north of Cape Hatteras, and thus it appears that composition does not influence grain-size distribution. The continental slope off the Carolinas is covered by sand; north of there, the slope is covered by clayey and sandy silt. The upper continental rise is veneered by silty clay.

Certain distinctive patterns of textural parameters appear to correlate with patterns of ocean-bottom circulation. The continental slope off Florida is covered by poorly sorted clay and silt deposited beneath the Gulf Stream Counter Current. Most fine-grained sediment is removed directly beneath the Gulf Stream. The silty sand near the southern margin of the Blake Plateau may be winnowed pelagic ooze transported from the eastern Blake Plateau by the westward-flowing Antilles Current. These two major current systems appear to control sediment texture on the Blake Plateau.

INTRODUCTION

What are the relations between textural parameters and the environment of deposition? Can one establish correlations between a known environment and the texture of surficial sediments that could be useful to sedimentologists working in ancient marine sediments where the environment has to be inferred? This report, concerned with patterns of bottom-sediment texture, is designed as an attempt to answer these questions.

Throughout this study the sediment textures, like those of other continental margins, are assumed to bear a close relation to the associated bottom relief, the underlying geology, sea-level fluctuations, and the distribution and nature of ocean-bottom currents.

In the study area (fig. 1) the continental shelf ranges in width from less than 5 kilometers off southern Florida to nearly 150 km off central Florida and New Jersey (Veatch and Smith, 1939; Heezen and others, 1959; Jordan, 1952; Uchupi, 1968). The shelf is smooth (relief less than 50 meters and has a seaward gradient of less than 1:1,000.

An abrupt increase in slope from about 1:1,000 to about 1:10 occurs at the "shelf break" marking the seaward limit of the continental shelf and the beginning of the relatively steep continental slope where gradients range from 1:40 to 1:6. The depth of the shelf break generally ranges from 10 m off Miami to 120 m off Norfolk. In the study area it generally lies between 40 to 70 m (Uchupi, 1968). Submarine canyons that slice through the continental slope north of Cape Hatteras are generally less than 15 km wide and the largest are about 300 to 500 m deep (Heezen and others, 1959; Rona and others, 1967).

The continental slope off Florida, along the western limit of the Blake Plateau, is about 75 m to about 750 m deep. An abrupt decrease in slope from 1:40 to 1:1,000 marks the boundary with the Blake Plateau which lies between 750 and 1,100 m below sea level. This major physiographic feature of the continental margin extends about 300 km seaward from the Florida continental slope. The seaward limit of the Blake Plateau is marked by an abrupt increase in slope at a depth of about 1,000 m. This is the top of the precipitous Blake-Bahama Escarpment whose face plunges to a depth of about 5,000 m. Very little unconsolidated sediment has accumulated on this current-swept scarp (Heezen and Sheridan, 1966). This feature marks the seaward limit of the study area east of Florida.

Various submarine features such as sinuous ridges, sand waves, benches, and terraces found on the continental slope are inferred to be remnants of former stands of sea level. The continental shelf

[1] Contribution 2566 of the Woods Hole Oceanographic Institution, based on work done under a program conducted jointly by the U.S. Geological Survey and the Woods Hole Oceanographic Institution and financed by the U.S. Geological Survey.

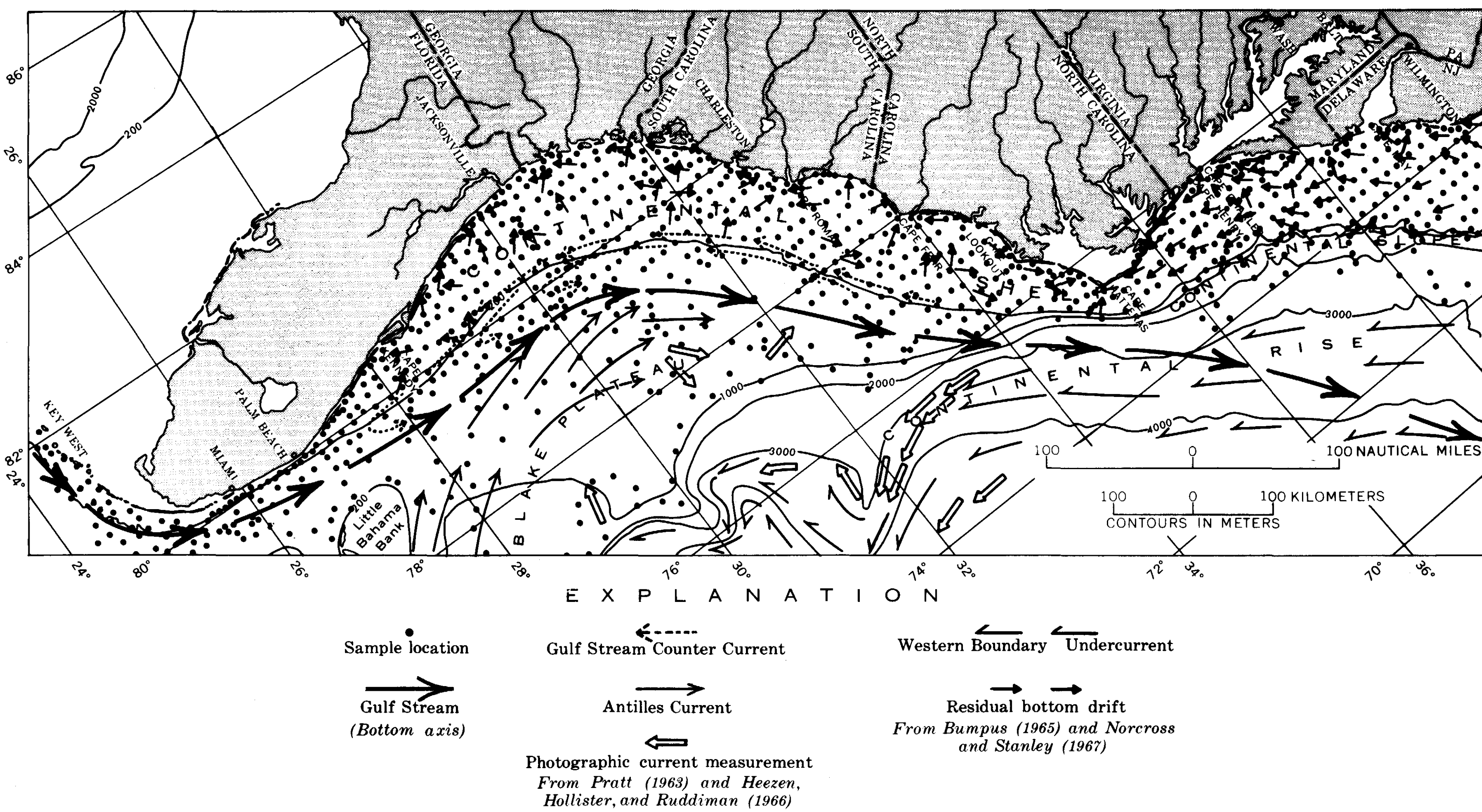


FIGURE 1.—Continental margin from New Jersey to southern Florida showing sample localities and bottom currents. The area is south of the region of glaciation. Textures of surface samples taken north of the area shown in this figure are given by Schlee (1973).

contains many fossils in the surficial sediment that also provide evidence of a former low stand of sea level such as teeth of mammoths (Whitmore and others, 1967), broken oyster shells (Merrill and others, 1965), and peat (Emery and others, 1967). Between North Carolina and Florida, oolites and unrecrystallized algal rocks (Milliman, 1972) were deposited in shallow lagoons during the last regression and transgression of the sea 9,000 to 28,000 years ago. The previous high stand of sea level, which approximates the present beach position, occurred during the last interglacial stage, or approximately 30,000 to 35,000 years ago. The effects of regression and transgression over that part of the continental shelf under consideration here may influence the observed textural patterns presented later in this report.

Seismic reflection profiles along the continental shelf and slope between Cape Hatteras and Miami (Uchupi and Emery, 1967) suggest that the upper kilometer of Quaternary and Tertiary sedimentary rocks have prograded as much as 50 km seaward over flat-lying surfaces that form the Blake Plateau (fig. 2). Data from dredges and borings (Pratt and Heezen, 1964; Heezen and Sheridan, 1966; Joint Oceanographic Institutions' Deep Earth Sampling Program, 1965) show that the Blake Plateau is underlain by strata of Cretaceous to Miocene age. Nearly flat lying Miocene to Pliocene sedimentary rocks lie beneath the unconsolidated Quaternary sediments covering most of the continental shelf.

Reflection profiles across the continental slope north of Cape Hatteras (Ewing and others, 1963; Uchupi and Emery, 1967; Knott and Hoskins, 1968) have shown that the gentler parts are mantled by conformable strata and that the steeper parts are mantled by gently seaward-dipping strata. Slumps, turbidity currents, and ocean-bottom circulation apparently remove much of the unconsolidated sediment from the slope before significant thicknesses can accumulate; however, the presence of prograded sediment suggests that on some parts of the continental slope turbidity currents, and slumps have been inactive.

Many recent studies (Heezen and others, 1966; Jones and others, 1970; Hollister and Heezen, 1972) have shown that ocean-bottom circulation plays an important role in marine sedimentation and thus, before proceeding into the discussion of sediment texture, a brief review of circulation patterns pertinent to this study area is presented (fig. 3).

Oceanographers (Iselin, 1936) in the early 1930's established that the comparatively fresh "coastal water" is, in summer, thermally stratified; however, in winter, the water is uniform from top to bottom, showing evidence of being completely stirred by the frequent and violent gales. Tidal-current velocities on the order of 10 centimeters per second may be superimposed on the more vigorous wind-driven circulation. A study by Bumpus (1965, 1969) has shown residual bottom currents on the continental shelf to be irregular in direction, but with a distinct inshore component between Cape Hatteras and southern Florida (fig. 1); however, between Cape Hatteras and northern New Jersey, residual drift is predominantly in a north to south direction, subparallel to the coastline. Near the entrance to Delaware Bay and Chesapeake Bay the residual current is directed inward toward the estuaries. Velocities of residual bottom currents off Florida are probably on the order of 25 to 50 cm/sec (fig. 4).

The Gulf Stream is a high velocity (as much as 300 cm/sec), narrow (less than 300 km) northeasterly-flowing western boundary current between the warmer Sargasso Sea and the colder slope water (Iselin, 1936; Stommel, 1958). The deeper water (greater than 500 m) of the Gulf Stream is apparently a mixture of Antarctic intermediate water and North Atlantic deep water. A strong influx of Sargasso Sea water towards the northward-moving Gulf Stream has been inferred in the area just north of the Little Bahama Banks (fig. 3); this current has been called the Antilles Current (Wust, 1924). Measured near-bottom current velocities beneath the Gulf Stream approach 15 cm/sec (Pratt, 1963a) and velocities exceeding 30 cm/sec have recently been observed from submersibles (fig. 5). Hydrographic profiles show that the axis of maximum current velocity lying at 100-m water depth is 10 km east of the Gulf Stream surface axis, and in deeper water the bottom-current maximum lies as far as 30–50 km east of the surface axis (F. C. Fuglister, oral commun., 1970). These profiles also suggest that the horizontal density gradient associated with the Gulf Stream may persist to the bottom in depths of more than 4,500 m along the continental rise of northeastern United States, Nova Scotia, and the Grand Banks (Fuglister, 1960). In addition, direct measurements (Knauss, 1965) of northerly-flowing bottom currents (velocities of 7–14 cm/sec at a depth of 3,580 m) beneath the Gulf Stream on the continental rise north of Cape Hatteras show that currents associated with the Gulf Stream may at times reach the sea floor in abyssal depths.

At the seaward limit of the relatively fresh (salinity less than 35 ‰) coastal water lies the slope water (Iselin, 1936). This distinctive water mass ranges in width from less than 15 km off Florida to about 80 km off Chesapeake Bay. The upper 200 m is a mixing zone of coastal water and Gulf Stream water, and in this zone seasonal changes in temperature and salinity are large. Slope water lying just above the continental slope in the region south of Cape Hatteras may flow as a poorly developed countercurrent parallel to but in the opposite direction as the northerly-flowing Gulf Stream (Stommel, 1965). The current systems mentioned above may be, at least partly, responsible for bottom-sediment textures.

The first detailed study of the sea-floor surface sediment off the eastern United States was presented by Pourtales (1872). He noted that most of the continental shelf off northeastern United States was covered by quartzose sand and that calcareous sediments prevailed on the shelf south of Cape Hatteras and on the Blake Plateau.

During the 1880's, the U.S. Coast and Geodetic Survey steamer, *Blake*, under the command of Alexander Agassiz, recovered samples from the continental shelf that were later studied and reported on by Murray (1885). Murray added little to the knowledge already gained by Pourtales except that the area beneath the Gulf Stream was found to be devoid of significant sediment accumulation. Later Agassiz (1888) and Weber (1902) recognized the importance of the Gulf Stream as an agent of submarine transportation and erosion.

In the 1930's, S. A. Tyler (1934) took 111 surface-sediment samples along the continental shelf off the eastern United States aboard *Lydonia*, the U.S. Coast and Geodetic Survey ship. Heavy-mineral and carbonate-mineral data were published in the form of tables, but no maps were drawn and regional patterns were not discussed.

One of the earliest textural analyses of continental shelf sediments, including sediments from the area under consideration here, was made by Stetson (1938, 1939). Samples were collected at 1.5- to 3-km intervals along eight traverses across the continental shelf and onto the upper part of the continental slope. Results of this classic work showed that on the open continental shelf a combination of wave-induced and tidal currents have sorted the bottom deposits in depths less than 50 to 70 m. He noted further that wave action must be an efficient sorting process along the entire shelf during winter storms.

Bottom-sediment samples were collected between Cape Hatteras and southern Florida by the U.S. Fish and Wildlife Service aboard the MV *Gill*. These samples were analyzed chemically and texturally and the data were used to outline sediment type, carbonate constituents, and the distribution of organic carbon and heavy minerals (Gorsline, 1963).

A number of more detailed studies dealing mainly with chemical composition or the biogenic composition of certain accumulations were published in the 1960's (Pilkey, 1964; Milliman and others, 1968; Giles and Pilkey, 1965).

The present textural study deals with nearly 1,000 samples taken during a program initiated by the U.S. Geological Survey in 1963. Most samples were obtained, aboard the RV *Gosnold*, by use of a Smith-MacIntyre grab, Van Veen type sampler, Campbell grab, and a pipe dredge. A modified Woods Hole settling tube (Ziegler and others, 1960) was used to determine sediment grain size (Schlee, 1966). Material coarser than sand was sieved at 1-phi intervals and clays were analyzed by the standard pipet method. Textural parameters were computed with a program developed by Schlee and Webster (1967). Detailed discussions of each statistical parameter are presented by Schlee (1973) and thus will not be repeated here. Statistical measures are the moment-measure type given by Krumbein and Pettijohn (1938).

ACKNOWLEDGMENTS

The writer is particularly indebted to K. O. Emery and J. D. Milliman, Woods Hole Oceanographic Institution, and John Schlee, U.S. Geological Survey, for continued help and criticism during this study. Many valuable suggestions concerning this manuscript were generously provided by Gilbert Corwin, U.S. Geological Survey.

SEDIMENT TEXTURE

Textural components of samples from the study area have been plotted on a ternary diagram (fig. 6). The majority of samples (297 out of 320) from the continental shelf consists of more than 90 percent sand and thus cannot be shown on the diagram. The remaining samples from this area contain a gravel component and are plotted within fields on the left side of the diagram by substituting "gravel" for "clay" at the top of the diagram. This also applies to 10 samples containing gravel from the Blake Plateau. Clay, silt, clayey sand, and sandy clay are not found in the study area.

The areal distribution of the general textural types plotted in figure 6 is shown on plate 1. The continental shelf and most of the Blake Plateau are covered with sand, whereas just landward of the Gulf Stream near the base of the continental slope off Florida and beneath the Gulf Stream Counter Cur-

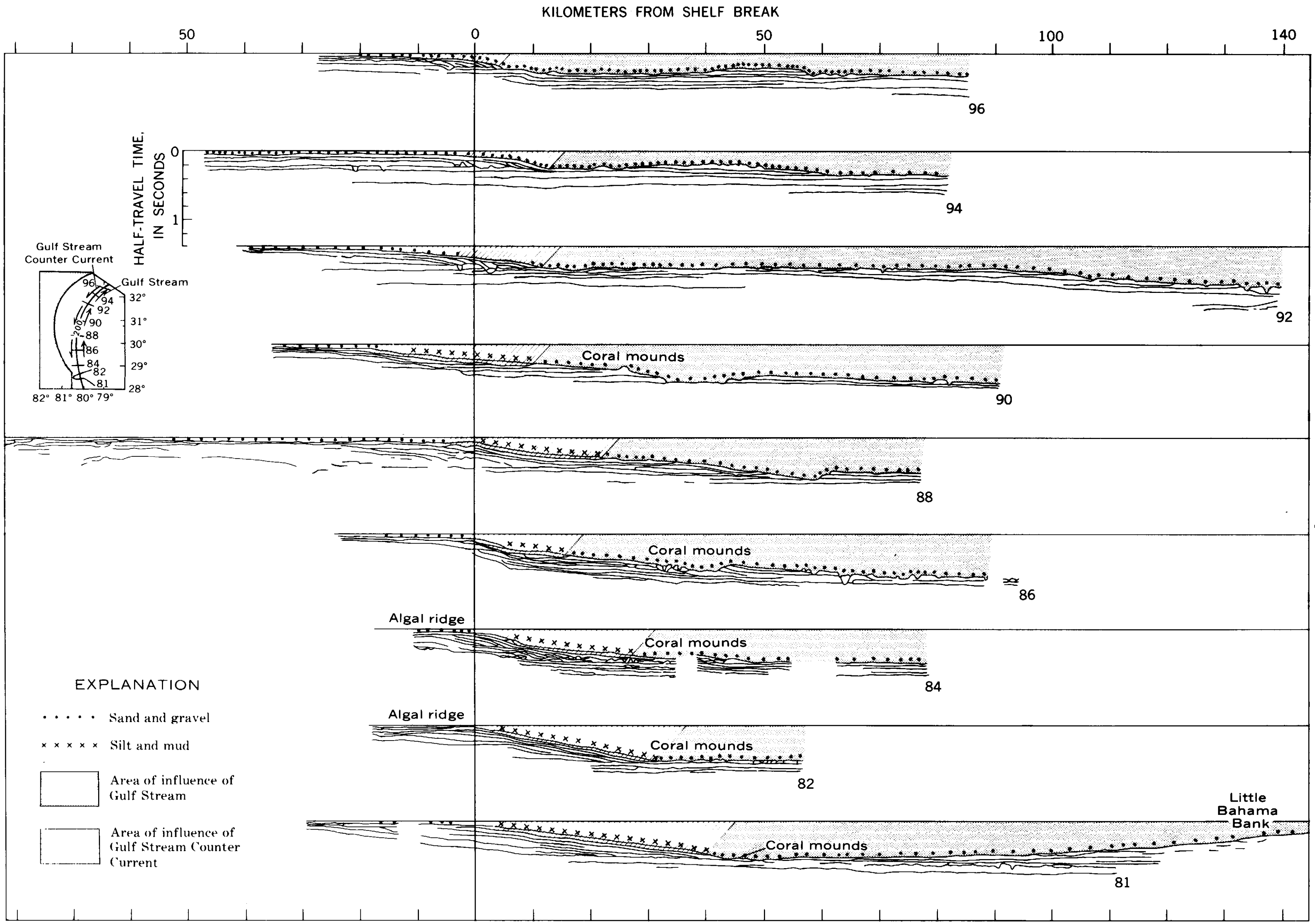
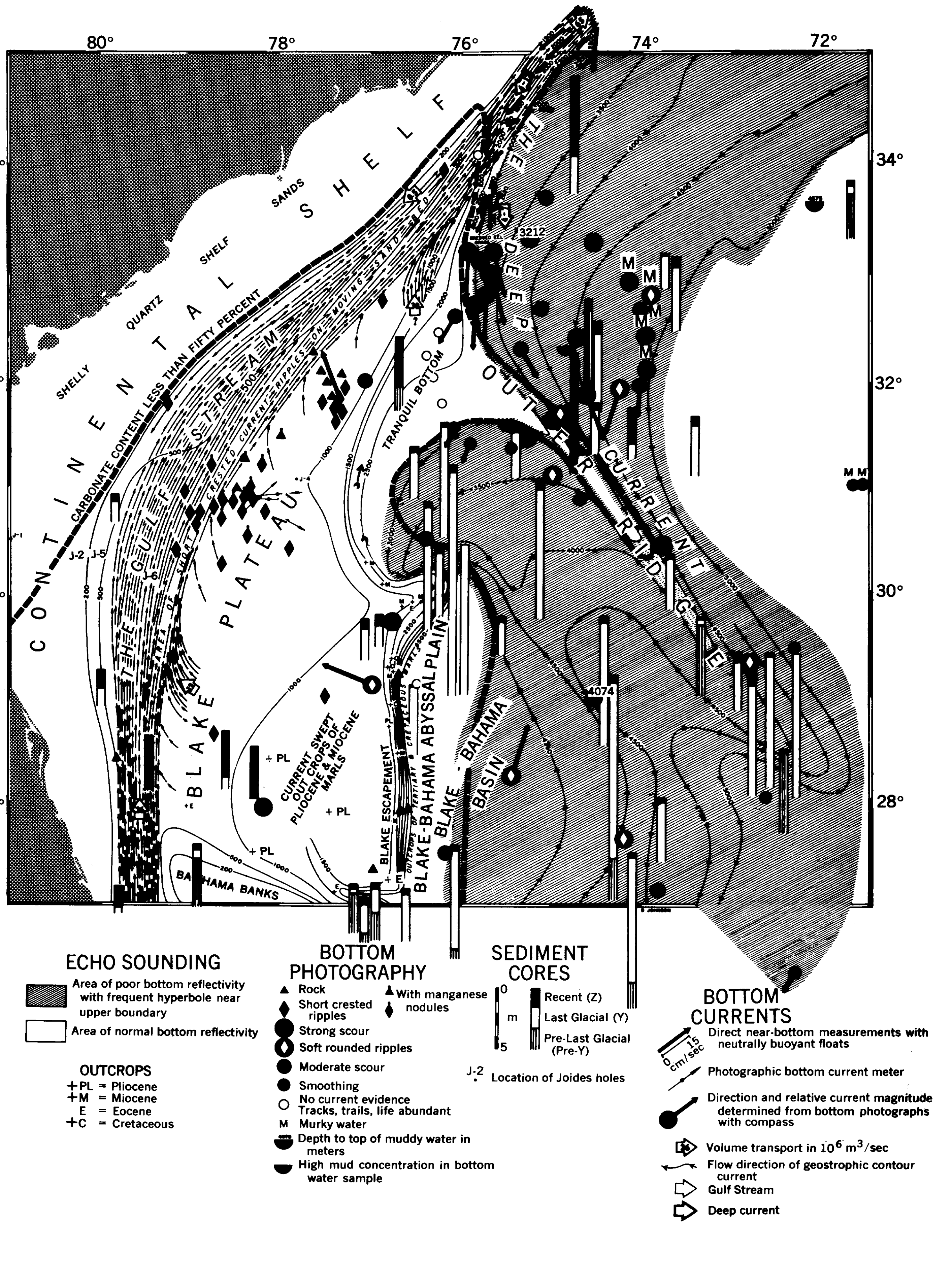


FIGURE 2.—Schematic sections of bottom currents and subbottom reflecting horizons along the continental slope off Florida. The southward-flowing Gulf Stream Counter Current in the slope water inshore of the Gulf Stream may be responsible for deposition of the anomalously fine grained sediment blanketing the sea floor in this region. Modified from Uchupi and Emory (1967).


80°
78°
76°
74°
72°
34°
32°
30°
28°
CONTINENTAL SHELF
SHELLY QUARTZ SHELF SANDS
CARBONATE CONTENT LESS THAN FIFTY PERCENT
THE GULF STREAM
CRESTED CURRENT RIPPLES ON MOVING SAND
AREA OF SHORT
BLAKE PLATEAU
TRANQUIL BOTTOM
THE DEEP OUTER CURRENT RIDGE
BLAKE-BAHAMA ABYSSAL PLAIN
BLAKE-BAHAMA BASIN
BLAKE ESCAPEMENT
CURRENT SWEPT OUT CROPS OF PLIOCENE & MIOCENE MARLS
BAHAMA BANKS
3212
4074
+ PL
J-2
J-5
J-6
ECHO SOUNDING
Area of poor bottom reflectivity with frequent hyperbole near upper boundary
Area of normal bottom reflectivity
OUTCROPS
+PL = Pliocene
+M = Miocene
E = Eocene
+C = Cretaceous
BOTTOM PHOTOGRAPHY
Rock
With manganese nodules
Short crested ripples
Strong scour
Soft rounded ripples
Moderate scour
Smoothing
No current evidence Tracks, trails, life abundant
M Murky water
Depth to top of muddy water in meters
High mud concentration in bottom water sample
SEDIMENT CORES
0
m
5
Recent (Z)
Last Glacial (Y)
Pre-Last Glacial (Pre-Y)
J-2 Location of Joides holes
BOTTOM CURRENTS
0 cm/sec 15
Direct near-bottom measurements with neutrally buoyant floats
Photographic bottom current meter
Direction and relative current magnitude determined from bottom photographs with compass
Volume transport in 10^6 m^3/sec
Flow direction of geostrophic contour current
Gulf Stream
Deep current

rent, is an anomalous deposit of clayey silt. Sediments from the continental slope north of Cape Hatteras are either clayey silt and silty clay or a mixture of sand, silt, and clay. Sediment on the upper continental rise is principally silty clay.

The areal distribution and percentage of gravel, sand, silt, and clay in surface sediment on the continental margin from New Jersey to southern Florida are shown on plate 1. All samples of sandy gravel and gravelly sand and all available sediments in which the amount of gravel exceeds 10 percent were obtained principally in the region of the Gulf Stream from the continental shelf off the Carolina coast and from the northern Blake Plateau. Gravel from the continental shelf is probably derived from outcrops of older sediment (Milliman, 1972). On the Blake Plateau, gravel is more abundant. Here it is composed of coral fragments and calcareous crusts coated with manganese oxide and phosphate minerals.

A linear band of gravel (principally coral fragments) lies below the Gulf Stream. In contrast to the material on the northern Blake Plateau, sediment from the continental slope north of Cape Hatteras contains 20 to 80 percent sand; silt makes up about 20 to 40 percent of these sediments; and the amount of clay may reach as much as 40 percent. Sediment from the continental rise contains less than 20 percent sand, generally 40 to 60 percent silt, and 40 to 60 percent clay. Sediment on the southern Blake Plateau contains little coarse material. The sand component is less than 60 percent, silt content may reach 60 percent, and clay forms less than 30 percent.

Sand dominates on the continental shelf and percentages fall off abruptly with depth down the continental slope and onto the continental rise, where clay predominates. Exceptions to this pattern occur on the sandy continental slope off the Carolinas and in the fine-grained accumulation lying beneath the Gulf Stream Counter Current. Silt dominates the sediment on the continental slope beneath the Gulf Stream Counter Current and the Antilles Current and it forms a significant contribution to the sediments along most of the continental slope. Clay-sized sediment is extremely rare on the continental shelf but it occurs in elongate deposits near the Gulf Stream Counter Current and Antilles Current. It is a dominant component of continental rise sediments.

Grain-size distribution curves of certain sediments show two or more maxima separated by saddles. This polymodal configuration may indicate that there is more than one population of grains in a sample. Most of the continental shelf sands, regardless of composition, are unimodal (pl. 2). Thus either the sediment originates from a single well-sorted source or more likely the sediment has been thoroughly sorted since and (or) during deposition. The fine-grained deposits of parts of the continental slope and rise are generally bimodal, reflecting an admixture of pelagic silt- and sand-sized foraminifers with terrigenous organic-rich clay. Two (and locally three) modes are common in the coarse sediments found on the Blake Plateau and Straits of Florida and in some samples along the landward margins of the Gulf Stream axis where poorly sorted debris eroded from proximal outcrops may constitute a significant fraction of the unconsolidated sediment.

The principal grain size on the continental shelf is sand (0.062–2.0 mm). A few shelf samples off the Carolinas and some from the northwestern part of the Blake Plateau have a dominant gravel mode (pl. 2).

The linear accumulation of fine sediment on the continental slope off Florida has a modal size of silt. The principal mode of sediment beneath the Gulf Stream Counter Current is silt. Silt is also the principal mode in the hemipelagic silty clay on the continental slope and upper continental rise north of Cape Hatteras. In the region off Cape Hatteras, the sands of the continental shelf are finer grained on the central parts of the shelf and become coarser near the shelf break (pl. 1); a pattern noted earlier by Stetson (1938).

The mean grain size is thought to be determined by the environment of deposition and the size and composition of the source material (for example, Curray, 1960). However, composition does not appear to affect the average grain size of the samples studied. The sediments north of Cape Hatteras are principally terrigenous, and those to the south contain significant amounts of biogenic material; yet

FIGURE 3.—Bottom currents, microphysiography, and sediment cores on the continental margin south of Cape Hatteras (from Heezen and Hollister, 1971). Note the increase of Gulf Stream transport from 26 million cubic meters of water per second near the Bahama Banks to 65 million m^3/sec off Cape Hatteras. The Antilles Current near lat 29° N., long 79° W. adds about 12 million m^3/sec to this flow. A weak (0.5 million cm^3/sec) Gulf Stream Counter Current flows south along the edge of the continental shelf off the Carolinas. Relatively low rates of accumulation can be inferred from the cores east of the Bahama Banks; however, beneath the Antilles Current and beneath the Gulf Stream Counter Current (along the Florida-Hatteras slope) 2 to 4 m of recent pelagic ooze has accumulated.

FIGURE 4.—Concave-up and concave-down attitudes of mollusk shells (10 cm in diameter) on the rippled oolitic sand on the current-swept continental shelf off northern Florida (lat 29°50′ N.; long 80°31′ W.). Photograph taken at a depth of 29 m.

the mean and median grain size of this principally unimodal material is virtually the same along the entire shelf (that is, sand). The continental shelf and much of the Blake Plateau is covered with sand. Silt- and clay-sized material predominates in the regions beneath the Gulf Stream Counter Current and Antilles Current, in the deeper parts of the Florida Straits, on the continental slope north of Cape Hatteras, and on the continental rise. The continental slope off the Carolinas, unlike most other continental slopes, is covered with sand.

Surface samples from the entire continental shelf, whether in the area covered with terrigenous material north of Cape Hatteras or in an area having a large admixture of organic debris south of Cape Hatteras, are typically well sorted (pl. 1). Beyond the

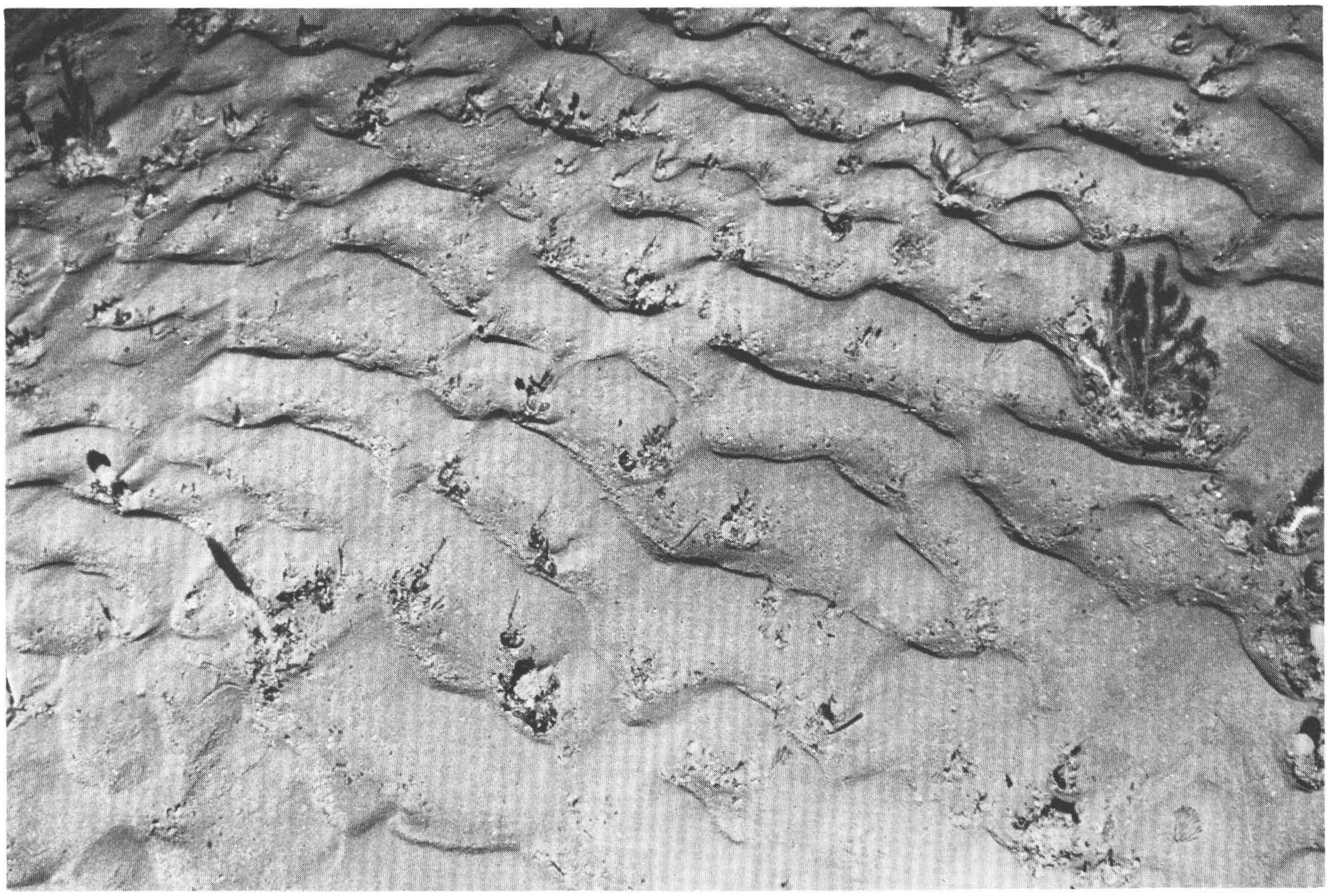


FIGURE 5.—Short-crested ripples (wavelength about 15 cm) in sand beneath the Gulf Stream (west-central Blake Plateau, lat 30°52′ N.; long 78°41′ W., at a depth of 828 m). Velocities required to form these ripples are of the order of 20 to 30 cm/sec (Hollister and Heezen, 1972; Heezen and Hollister, 1971).

edge of the shelf north of Cape Hatteras, surface sediments become more poorly sorted where mean grain size decreases into the silt range. Most of the continental slope and continental rise are covered with this poorly sorted mixture of hemipelagic silt and clay. Just landward of the axis of the Gulf Stream, on the continental slope off Florida, the sorting of the silts and clays is extremely poor.

Skewness values of sediments from the continental margin are generally unlike previous statistical measures in that they lack patterns of distinctive values characteristic of sedimentological provinces (pl. 2). The majority of sediments on the continental shelf and continental rise have size-frequency curves that are symmetrical, indicating little or no unusual admixture of fine material. Some samples from within the tongue of fine-grained and poorly sorted sediment just landward of the Gulf Stream show a slight tendency towards having a coarse admixture, which may reflect a small addition of coarse material from local outcrops or from the gravel-covered region beneath the Gulf Stream axis. Nevertheless, skewness is absent in most sample curves.

The degree of peakedness of the grain-size distribution curves, kurtosis, is thought to be a measure of the equalness in mixture of two populations of different grain size. A subequal mixture of two dominant populations generally yields a saddle, or flat-topped (platykurtic) grain-size distribution curve. A peaked (leptokurtic) shape is thought to represent a mixture of one predominant and one very subordinate population. Kurtosis values are believed by some to be too insensitive to yield meaningful information concerning sediment genesis or environment of deposition, and this criticism is thought to be especially valid if the values are obtained through the use of a settling tube such as the one used in this study (Folk, 1966).

Most of the continental shelf sands show low values of kurtosis (pl. 1); thus, their frequency-distribution curves are very close to having a normal bell shape. Samples having platykurtic curves predominate except on the Blake Plateau where samples

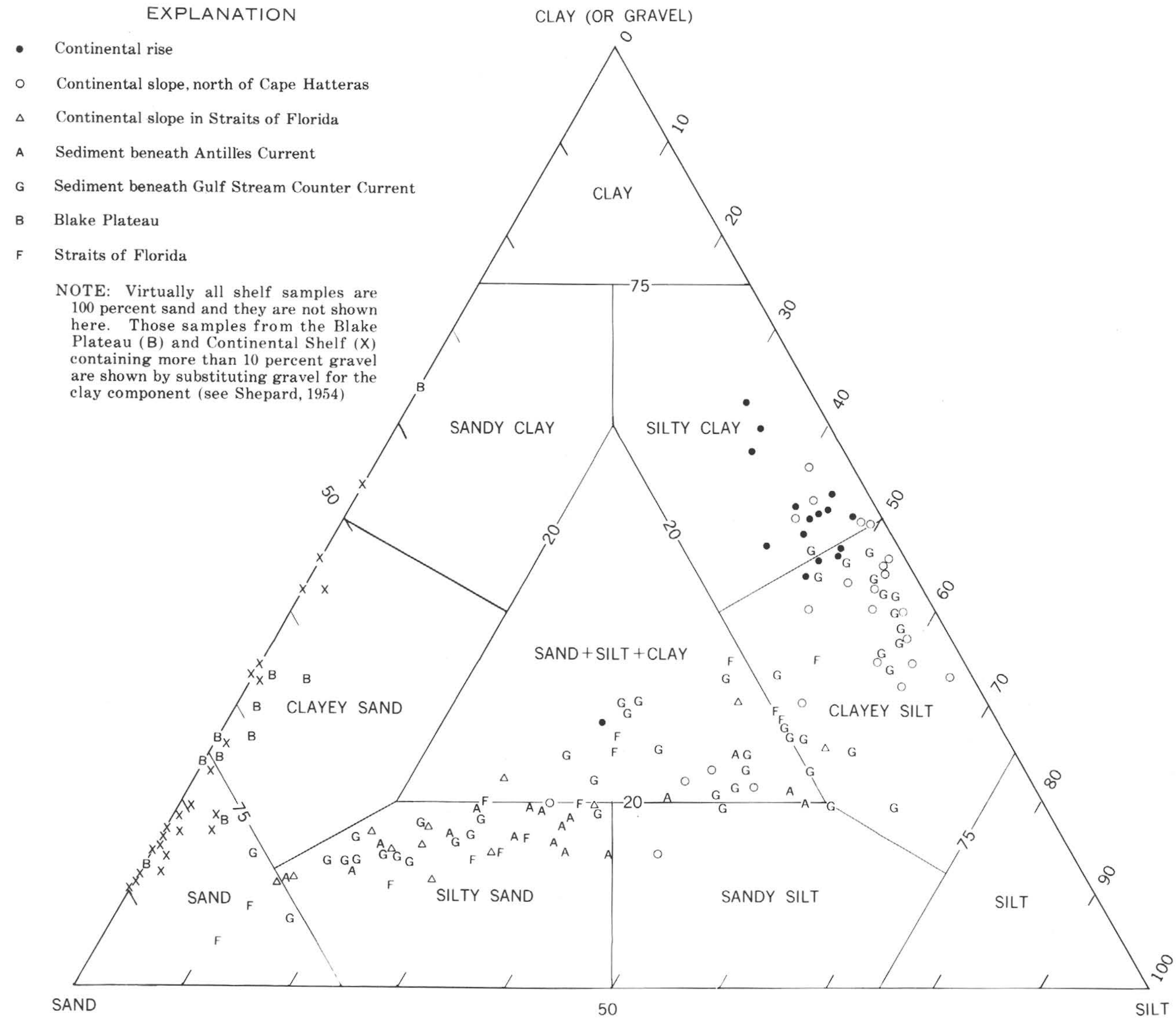


FIGURE 6.—Ternary plot of clay-silt-sand or gravel-silt-sand components of continental margin surficial sediment off southeastern United States. Field limits are adapted from Shepard (1954).

having leptokurtic curves are found in linear zones. Patterns of kurtosis are linear in areas influenced by the Gulf Stream (or its countercurrent) and more random on the continental shelf. The fine-grained, poorly sorted silt found landward of the axis of the Gulf Stream is characterized by symmetrical to slightly saddle-shaped frequency curves.

The areal distribution patterns of textural parameters and statistical measures shown on plate 1 indicate that the study area can be divided into "sedimentological provinces" which may reflect present and perhaps past environments of deposition. These provinces, with the surface-sediment characteristics, are as follows:

1. Continental shelf, the continental slope off Florida, and the northeast part of the Blake Plateau: well-sorted sand or gravelly sand showing a tendency towards coarsely skewed grain-size distribution curves.
2. Continental slope (north of Cape Hatteras) and upper continental rise: poorly sorted clayey silt to silty clay having symmetrical grain-size distribution curves.
3. Regions associated with major ocean-current patterns (western and southern margins of the Blake Plateau) : very poorly sorted clayey silt to silty sand having fine-skewed grain-size distribution curves.

In order to test the uniqueness of these sedimentological provinces, statistical parameters were plotted against each other in the forms of scatter diagrams to determine if samples from a given province fall within a restricted field and to establish which, if any, combinations of statistical parameters could be used to differentiate sediments taken from different environments.

SCATTER DIAGRAMS OF GRAIN-SIZE PARAMETERS

For this study, samples were labeled according to their textural similarities discussed in the previous section. That is, (1) continental shelf and Blake Plateau, (2) continental slope and continental rise, and (3) sediment associated with the two major currents flowing through the area—the Gulf Stream and the Antilles Current. These sediment groupings determined from an examination of aerial distribution of textures appear to possess distinguishable characteristics, and their statistical relationships will be discussed in the above order.

The well-sorted sand-sized particles found on the surface of the continental shelf as well as on most of the Blake Plateau (except the extreme southern and western margins) are texturally hard to differentiate from each other even though these two areas have undergone very different environmental histories. For example, the shelf has experienced transgression and regression during the Pleistocene, and the plateau has remained submerged during this time. Scatter plots of mean grain size versus standard deviation (fig. 7), skewness (fig. 8) and kurtosis (fig. 9), skewness versus standard deviation (fig. 10), and kurtosis versus standard deviation (fig. 11) show that samples from the Blake Plateau and continental shelf can be texturally distinguished from samples of the other two provinces. However, no set of values can be used to distinguish shelf from plateau sediment.

Size-frequency curves of both shelf and plateau sediments resemble those characteristic of river deposits (figs. 7, 8, 10). This observation reflects, perhaps, a similarity of two dynamic environments—both influenced by relatively strong bottom-current flow. Some standard deviation and mean grain-size values of shelf deposits are the same as those reported from beaches, whereas only a few plateau samples have this tendency (fig. 7).

Values of standard deviation plotted against mean grain size or skewness (figs. 7 and 10) and mean grain size versus skewness (fig. 8) provide the best criteria for the differentiation of shelf and Blake Plateau sediments from the other two marine provinces. Kurtosis and skewness values (fig. 12), the least reliable of all the statistical parameters, show a good deal of overlap from province to province.

The poorly sorted clayey silt to silty clay found on the surface of the continental slope and upper continental rise can also be distinguished from sediment of the other two provinces of the study area. Mean grain size plotted against standard deviation (fig. 7), and skewness (fig. 8) as well as kurtosis plotted against standard deviation (fig. 11), reveal the best distinction. Some overlap occurs on the other statistical plots. None of the relationships determined for samples from the slope or upper rise coincide with values found in the literature for beach, river, or dune environments.

As noted above, kurtosis values plotted against either mean grain size or skewness show considerable overlap with values from other provinces and thus cannot be considered a reliable province indicator. Nevertheless, sediments from the slope and rise appear to have rounded (platykurtic) frequency-distribution curves suggesting that they may contain unequal mixtures of two distinct size populations which may be a result of the mixing of pelagic and terrigenous components to form the well-known hemipelagic muds.

Clearly the most striking textural pattern to emerge from this study is the linear distribution of very poorly sorted clayey silt to silty sand that appears to be associated with the oceanic currents: the Gulf Stream Counter Current and the Antilles Current.

The sediment beneath the Gulf Stream Counter Current on the lower part of the continental slope off Florida (figs. 2 and 3) and the sediment on the southern and southwestern parts of the Blake Plateau have textural peculiarities that serve to separate these areas from the other two sedimentary provinces discussed above. All the scatter diagrams with the exception of the plot of kurtosis versus mean grain size (fig. 9) or skewness (fig. 12) serve to separate these current-deposited(?) sediments from either the principally pelagic sediment of the continental slope and rise or the more winnowed (and better sorted) sediment from the dynamic environment of the continental shelf or Blake Plateau. Interestingly, values plotted on the kurtosis-skewness diagram show a unique linear trend (fig. 12) of increasing kurtosis with increasing skewness. In other words, as the grain-size distribution curves become more peaked, they also tend to be more skewed towards the fine grains. Apparently as the unequalness of size population decreases, the sedi-

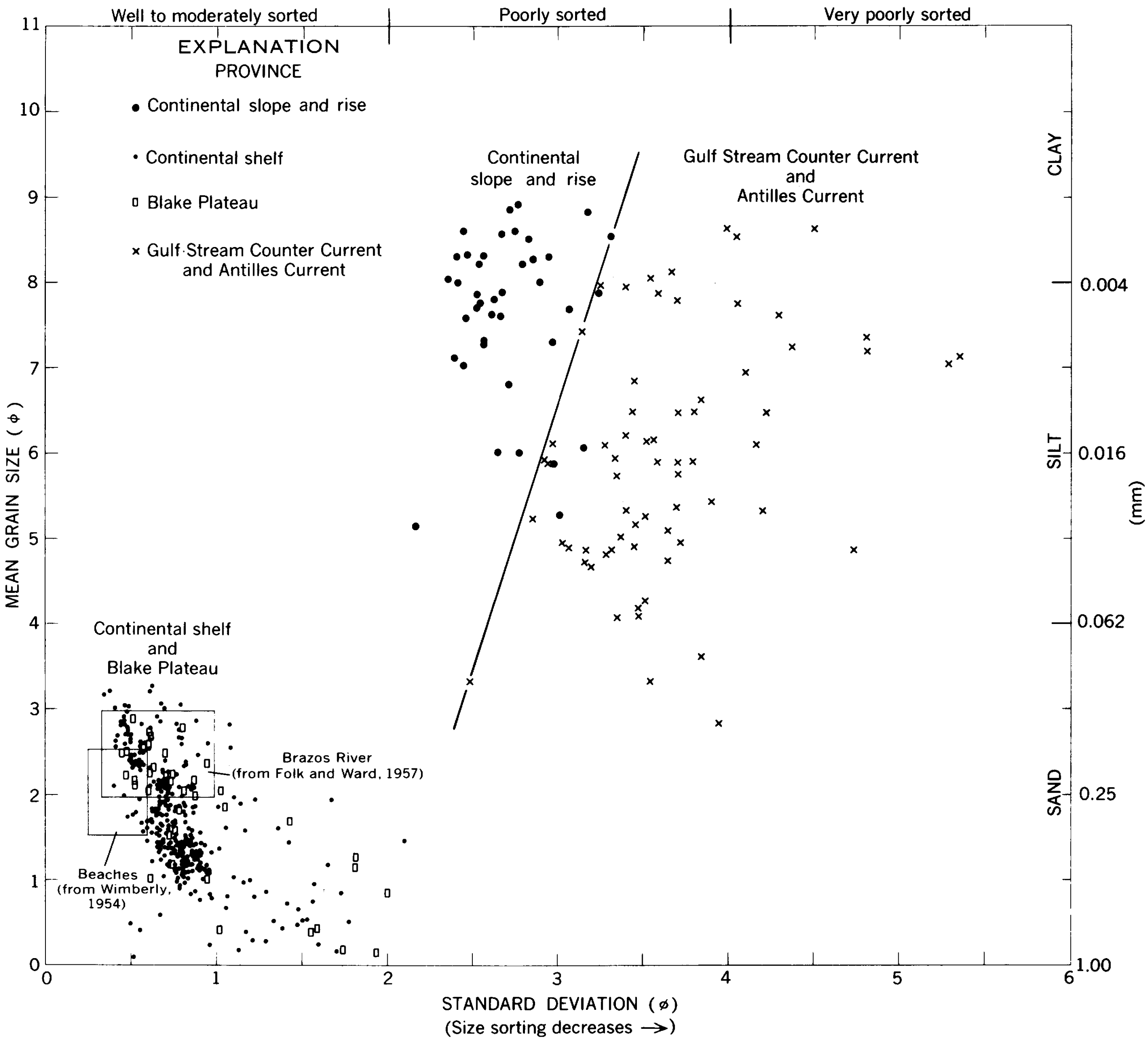


FIGURE 7.—Mean grain size versus standard deviation of surface sediments on the continental margin from New Jersey to southern Florida. Continental shelf sediments fall in a small field characterized by good sorting and coarse mean grain size. Finer sizes tend to be more poorly sorted. Note the textural similarity of river, Blake Plateau, and continental shelf sediments.

ment contains increasing amount of coarser material. This might suggest that the currents tend to intermix varying amounts of coarser material into an originally well-sorted finer grained material.

A comparison of the continental slope and rise material with the sediment described above suggests that in an environment only slightly affected by bottom currents and in moderately deep water (greater than 200 m) sediments are characteristically poorly sorted and have a fine mean grain size. Slope and rise sediment is composed principally of very fine, organic-rich, hemipelagic clay intermixed with sand- and silt-size foraminifers. This material can be distinguished from the even more poorly sorted sediments found beneath the Antilles Current and beneath the Gulf Stream Counter Current. Standard deviation values apparently distinguish those sam-

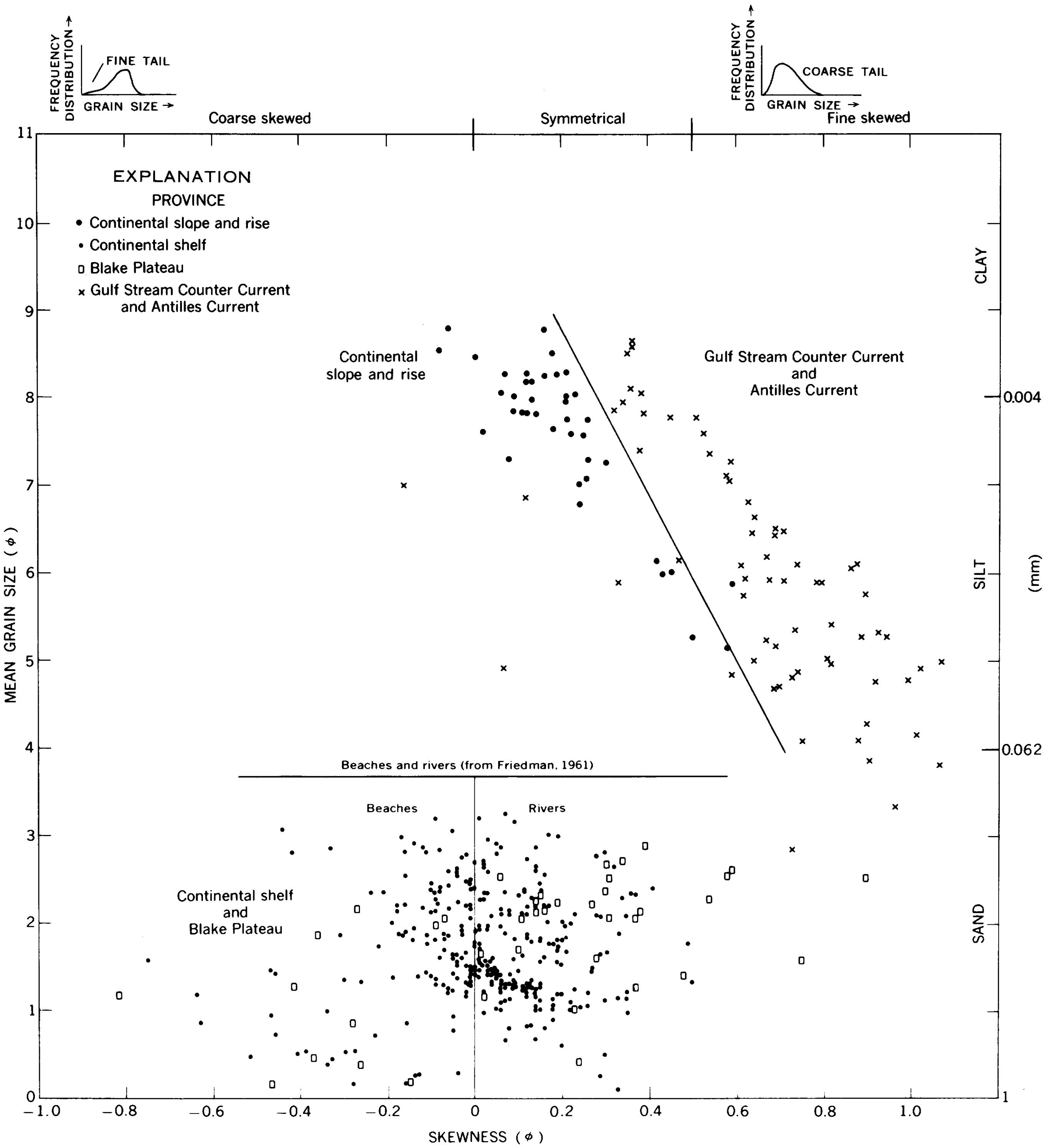


FIGURE 8.—Mean grain size versus skewness of surface sediments on the continental margin from New Jersey to southern Florida. The coarser more poorly sorted sediments tend to be fine skewed whereas the coarser well-sorted material tends to have a symmetrical grain-size distribution curve. Note the textural similarity of river sediments and some continental shelf and Blake Plateau sediments.

ples which are deposited in relatively shallow water and in an area affected by relatively fast bottom currents from those deposited in the more tranquil environs of the upper continental rise and slope.

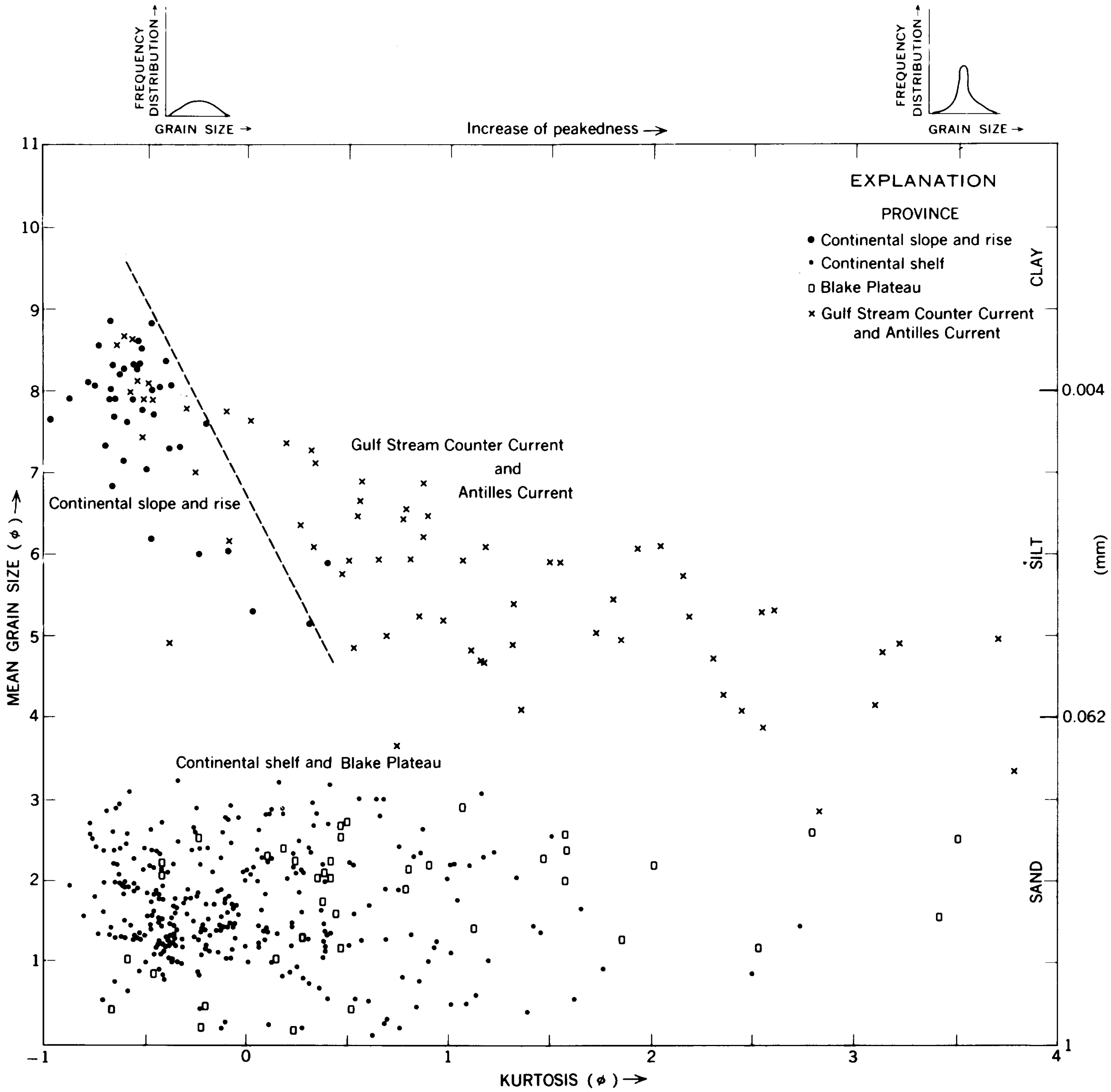


FIGURE 9.—Mean grain size versus kurtosis of surficial sediments on the continental margin from New Jersey to southern Florida.

DISCUSSION

Principal origins of continental margin sediments (Emery, 1952) are detrital, residual, organic, and authigenic. Detrital refers to sediment carried by streams and rivers to the shelf. Though rivers may have provided sediment to the emerged continental shelf during the Pleistocene, at the present time very little sand is transported onto the shelf by runoff. Most is trapped in the drowned river valleys or estuaries, though an occasional flood may eject fine-grained sediment onto the open shelf (Meade, 1969; Folger, 1972). Thus at the present time, modern detrital sediment is probably not an important sand source for the continental shelf; the sediment that does escape from the estuaries appears to be transported parallel to the coastline and subsequently de-

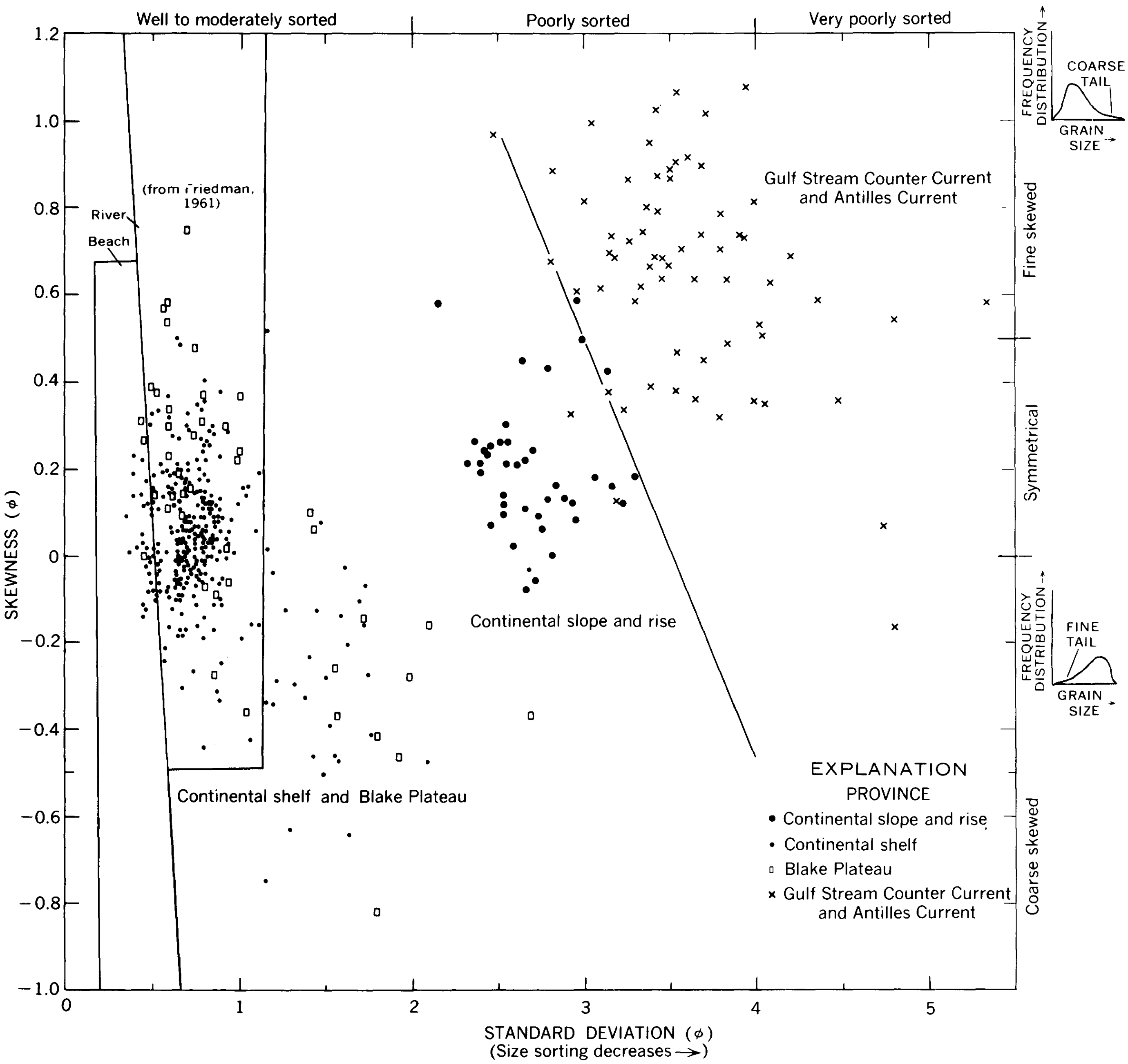


FIGURE 10.—Skewness versus standard deviation of surficial sediments from the continental margin between New Jersey and southern Florida. The poorly-sorted current deposits tend to have grain-size distribution curves that have coarse tails. This effect might result from a combination of pelagic and bottom-transported sediment. Note the textural similarity of river sediments and continental shelf sediments.

posited as bars in the nearshore area. Post-Pleistocene silty sediment does constitute a significant fraction of the silt-sized material found in continental slope sediments and thus silt periodically must be carried across the shelf.

Residual sediments, which have a rather limited transportation history, result from the in situ weathering of rocks or other sediments. Residual sediment may be forming at the present time in areas of outcrops on the continental shelf and the Blake Plateau (Milliman, 1972), and the distribution of gravel shown on plate 1 probably reflects the distribution of outcrops.

Organic constituents such as the tests of Foraminifera, shell fragments, and coral debris make up a large proportion of the samples of hemipelagic clay

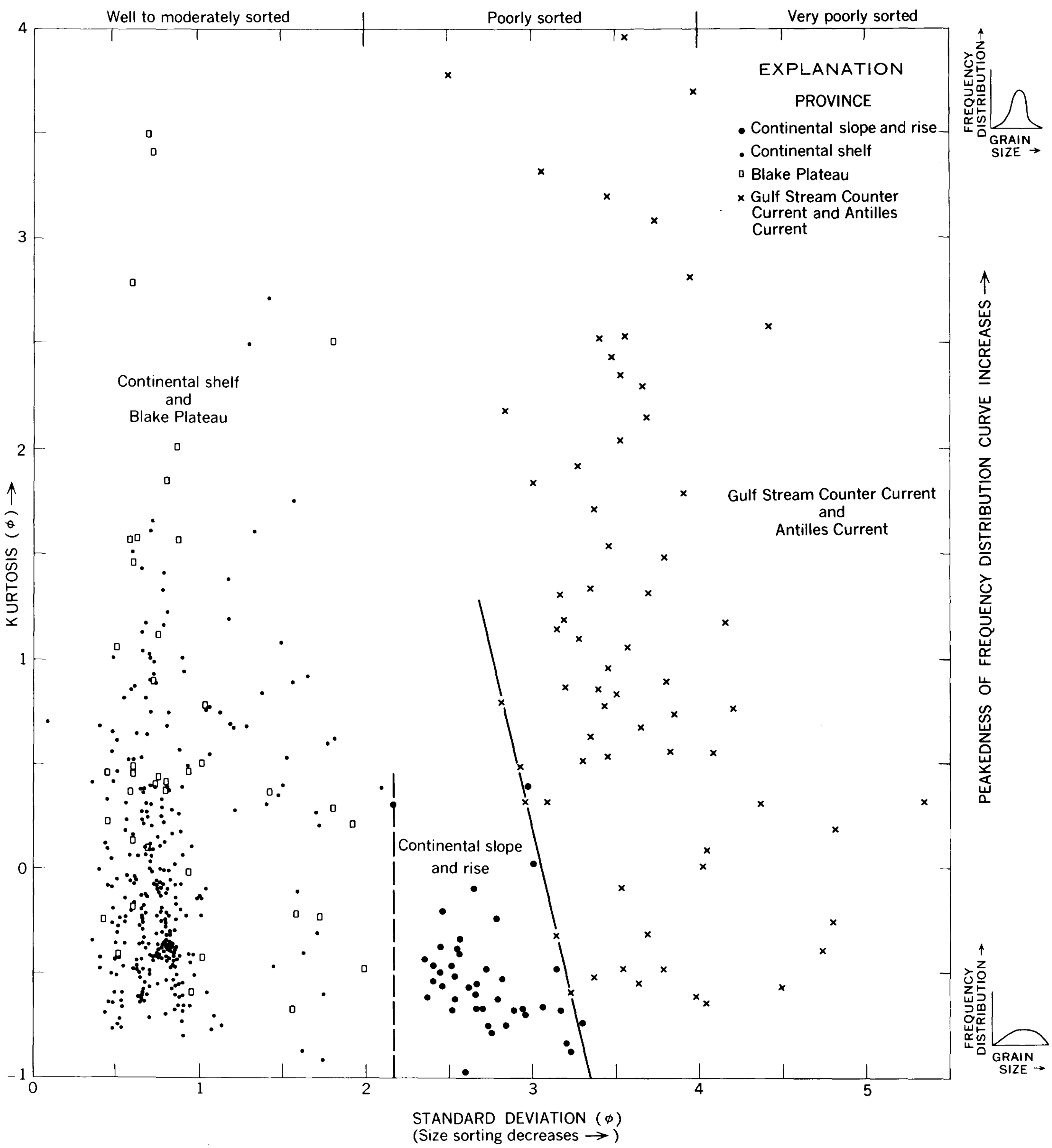


FIGURE 11.—Kurtosis versus standard deviation of surficial sediments from the continental margin between New Jersey and southern Florida. Continental shelf sediments are well sorted, whereas sediments deposited beneath the Antilles Current and the Gulf Stream Counter Current have the poorest sorting.

from continental rise and slope and from the shelf south of Georgia, where nearly tropical conditions prevail.

Authigenic material, which includes manganese oxide, phosphorite, and glauconite, has been deposited locally owing to the chemical interaction of sea

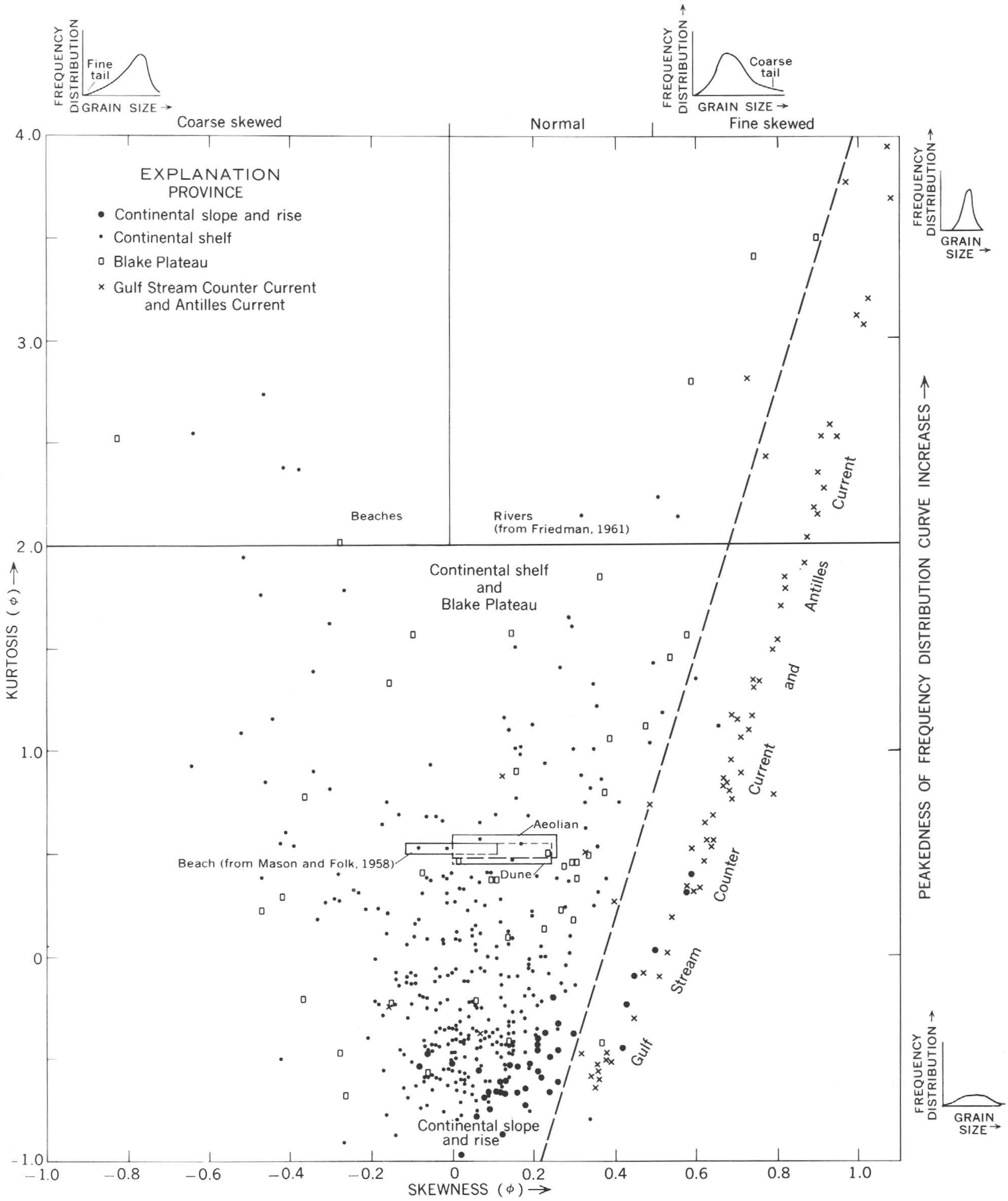


FIGURE 12.—Kurtosis versus skewness of surficial sediments from the continental margin between New Jersey and southern Florida. Note the linear trend of data from sediments deposited beneath the bottom currents—the Gulf Stream Counter Current and Antilles Current. Most continental shelf sediments have low skewness and kurtosis values. Note the very restricted range of skewness and kurtosis of aeolian, beach, and dune deposits, and the textural dissimilarity of samples from beaches and rivers and those from the continental margin.

water and bottom sediments. Glauconite is found locally on the continental slope, and manganese and phosphorite nodules and accretions are abundant in samples from the Blake Plateau (Pratt and MacFarlin, 1966; Milliman, 1972; and fig. 13).

The above sources provide the raw material for the accumulations mapped in this study; however, the textural patterns of surficial material suggest that some of this sediment has had a history of active transportation and thus it seems worthwhile to take a closer look at possible agents of transport.

A study of the physiography of the continental shelf has revealed many prominent sand swells or dunelike forms which have been interpreted by Sanders (1962) and Shepard (1963) as remnant beaches and dunes formed during a lower stand of sea level. If the sand swells were relict dunes or drifts built during former low stands of sea level they would probably have been destroyed by wave action during the last transgression. Uchupi (1968, p. C17) has suggested that the sand swells may be produced by high-velocity bottom currents (more than 100 cm/sec) generated during winter gales. These dunes appear to be alined approximately parallel to directions of residual drift reported by Bumpus (1969) and Norcross and Stanley (1967) Furthermore, if arrows are placed on the inshore end of the crest of each sand swell (fig. 14), the result is a pattern resembling that observed for directions of bottom drift (fig. 1). The strong southerly component of residual bottom drift north of Cape Hatteras has a distinct landward component in the region of estuaries. The sand-swell crests in this region also point towards the estuaries. South of Cape Hatteras the patterns show less regularity (partly because of the lack of measurements); however, many of the residual drift measurements indicate that transport is approximately parallel to the crest orientations. It is hypothesized here that the sand swells may be longitudinal dunes reflecting transport of shelf sediment in the present environment.

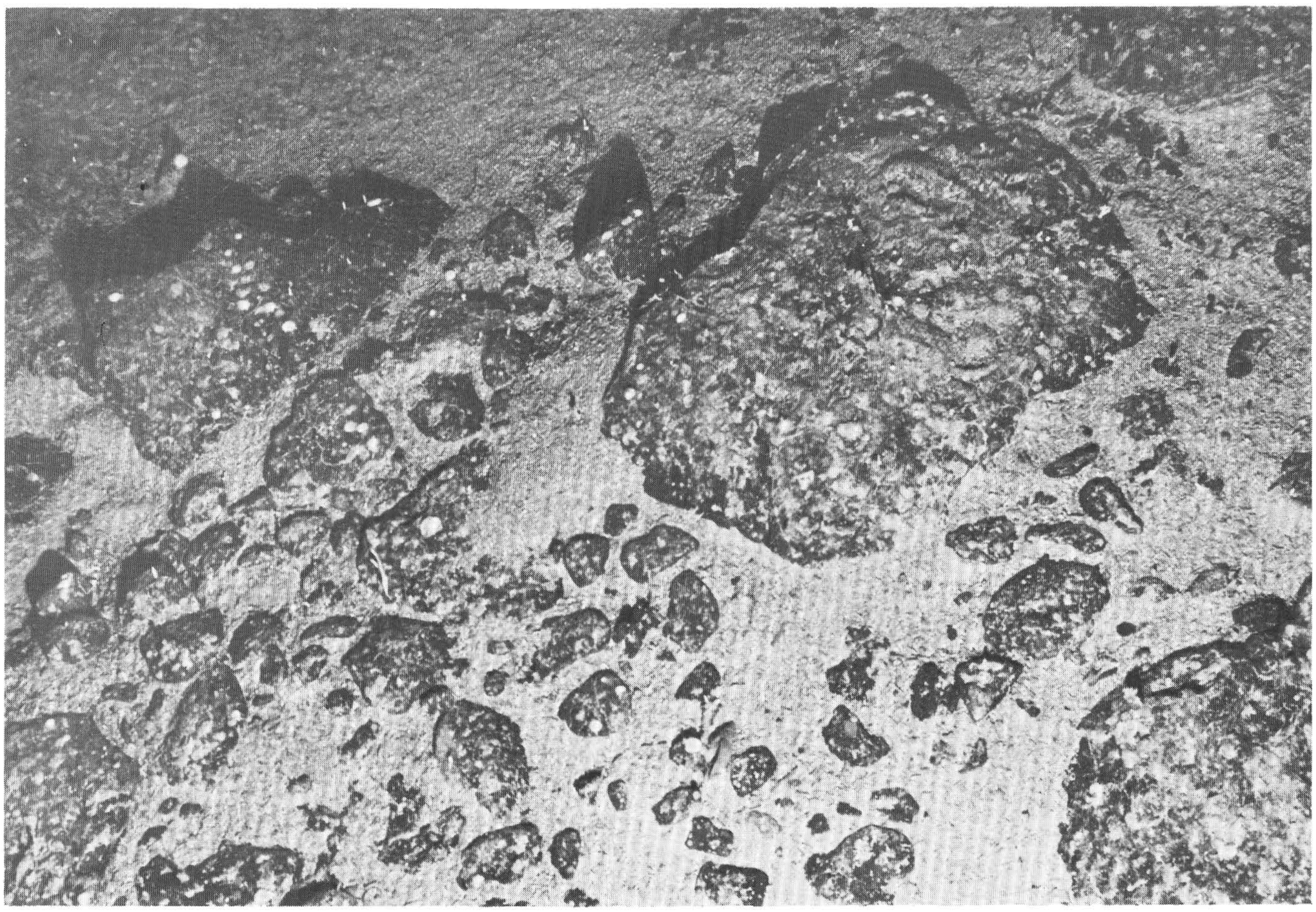


FIGURE 13.—Current-scoured manganese oxide and phosphorite encrusted slabs on the central Blake Plateau (lat 31°36′ N.; long 77°58′ W.) at a depth of 634 m. Light-colored calcareous sediment from this area is sand sized. The largest boulder is about 0.5 m across.

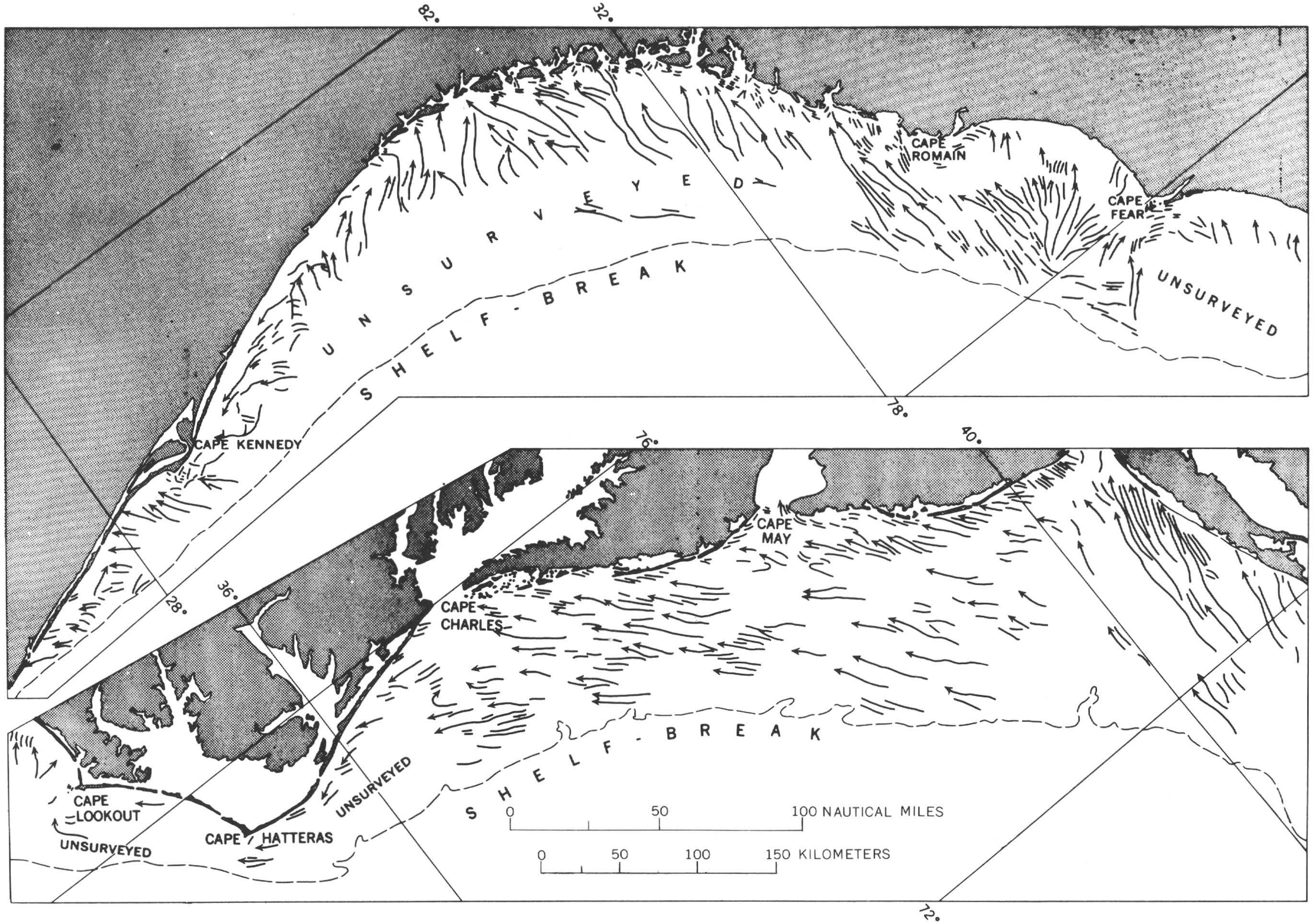


FIGURE 14.—Sand-swell crests on the continental shelf from New Jersey to southern Florida. Arrows placed on the inshore end of the sand-swell crests mapped by Uchupi (1969) resemble residual bottom drift directions (fig. 1) determined by Bumpus (1965, 1969) and Norcross and Stanley (1967). This correlation suggests that the sand swells are alined parallel to the bottom current. The transport of bottom sediment may follow these drift directions.

Along the base of the continental slope off Florida, just beneath the Gulf Stream Counter Current, a deposit of clayey silt occurs. The sorting of this sediment is extremely poor and grain-size distribution curves are skewed towards the fine grains. The principal mode is coarse silt. Textural parameters of this sediment are not apparently affected by water depth alone (figs. 15–17). The clayey silt is adjacent to the Gulf Stream, one of the strongest currents known to exist in water more than 200 m deep and it lies beneath a much less well-defined Gulf Stream Counter Current where southerly flowing bottom currents are relatively weak (10–20 cm/sec) and cannot at present erode clayey silt.

Bottom-drift measurements (Bumpus, 1969) indicating a predominantly shoreward drift along the continental shelf in this area (fig. 1) appear to eliminate the possibility that this deposit is formed from seaward-migrating continental debris. Alternately, this material might be derived from bottom-current erosion of underlying sediments (Milliman, 1972). In support of this conclusion. Hathaway (1972) noted that the clay mineralogy of samples recovered from the JOIDES bore holes in this area is virtually uniform from the surface to the underlying Oligocene limestone. However, the abundant planktonic Foraminifera found in samples from this area are Holocene, not Tertiary, in age (T. Gibson, oral commun., 1969). Furthermore, the process of erosion by bottom currents would not account for the fine-grained texture of the deposit nor for its progradation as seen on reflection profiles (Uchupi, 1969; and fig. 2).

Moore and Gorsline (1960) suggested that this band of clayey silt may represent material lying behind or downcurrent, with respect to the Gulf Stream, of the channel sill now forming the northern terminus of the Straits of Florida, and thus they infer that this accumulation is a giant leeside deposit with its source to the south. Such a deposit would, however, form directly behind the sill, rather than upslope, or to the west, against the continental slope.

An alternative suggestion proposed here is that a southerly flowing cold (6°–7°C) Gulf Stream Counter Current (with its source north of Cape Hatteras) impinges on the inshore edge of the northerly flowing Gulf Stream and forms an area of "slack" water probably characterized by slowly revolving southerly directed eddies. Sediment from northerly sources caught in this southerly flowing current system would be deposited on the Florida-Hatteras slope as a thin veneer of fine-grained material built since the last sea-level transgression.

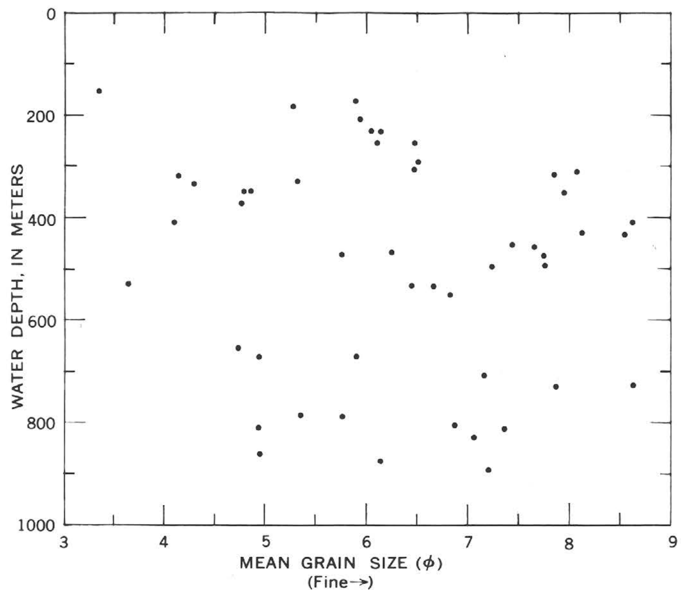


FIGURE 15.—Depth of water versus mean grain size for sediment beneath the Gulf Stream Counter Current. No obvious correlation exists between depth of water and sediment size in these deposits.

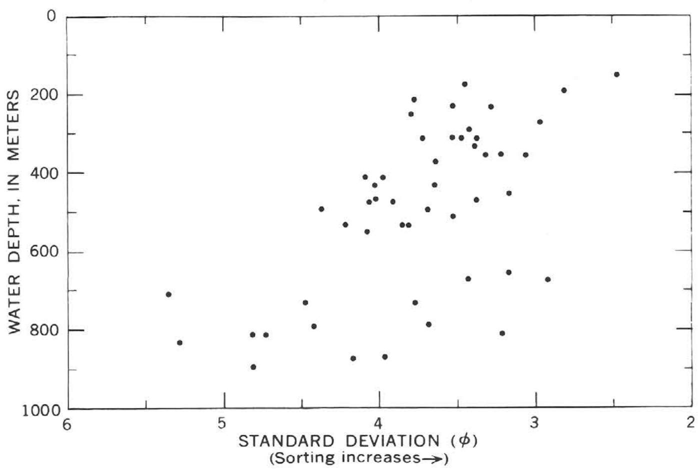


FIGURE 16.—Depth of water versus standard deviation for sediment beneath the Gulf Stream Counter Current. A very poor correlation exists between a decrease in sorting with increasing depth of water.

Hydrographic data from the numerous cruises of the MV *T. N. Gill* (Anderson and others, 1956–1960) show that water in the area just inshore of the Gulf Stream has a very low oxygen content characteristic of quasi-stagnant conditions and is relatively rich in nitrogen. Thus the sediment should be high in organic material and comparatively enriched in nitrogen.

The areal pattern of sorting (pl. 2) shows that the winnowing effect of the Gulf Stream proper can

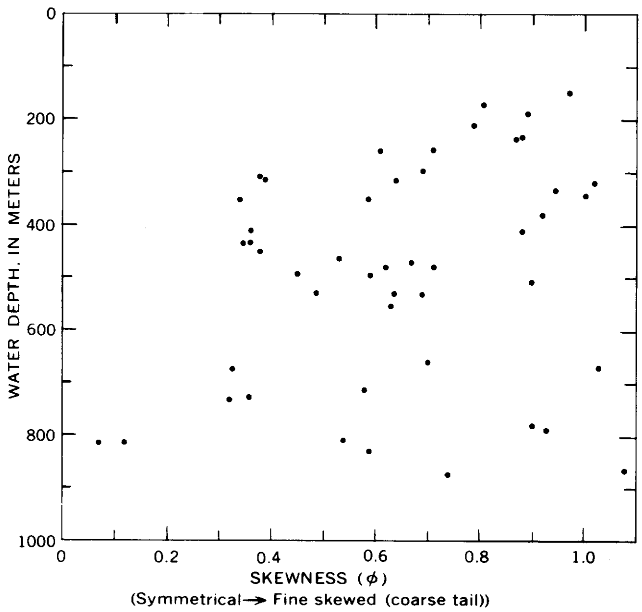


FIGURE 17.—Depth of water versus skewness for sediment beneath the Gulf Stream Counter Current. No apparent correlation exists.

be traced from the Florida Keys to the region south of Cape Hatteras. In fact, on the continental rise east of Cape Hatteras, a poorly developed tongue of coarser carbonate material lies near the Gulf Stream axis, perhaps reflecting the continuing work of this vigorous current as it leaves the Blake Plateau and flows across the continental rise.

Surface sediment on the southern part of the Blake Plateau has many of the textural characteristics of the sediment accumulation beneath the Gulf Stream Counter Current. The mean grain size of this "Antilles Current sediment" is coarse silt (0.062–0.016 mm). This material is poorly sorted and tends to be skewed towards the fine grains. The sediment is generally bimodal; the principal mode is fine sand or coarse silt. Gravel is absent. This deposit may represent pelagic carbonate ooze transported shoreward from the open Blake Plateau to its present location by the westerly flowing Antilles Current (Wüst, 1924).

Sediment from the northern part of the Blake Plateau is similar in textural characteristics to sediment covering the continental shelf. It is principally well sorted sand or gravel with nearly symmetrical grain-size distribution curves. The material differs only slightly from sediments of the continental shelf by having relatively peaked and bimodal grain-size distribution curves and by containing a higher percentage of gravel-sized coralline debris.

Gravel, which is a dominant mode in some samples from the central Blake Plateau, principally consists of nodules and pebbles of manganese oxide and phosphorite (fig. 13) in addition to some coral fragments (Milliman, 1972). The little fine-grained sediment being deposited there now is pelagic foraminiferal ooze; however, most of the finer sizes have been winnowed away, leaving a residual lag accumulation (Pratt, 1963b; Pratt and MacFarlin, 1966).

The Blake Plateau was not exposed during the Pleistocene, and thus its environmental history stands in marked contrast to that of the continental shelf. The observed similarity, however, seen in textural parameters between these two very different regions by itself suggests that there may be few remaining sedimentological characteristics of the continental shelf which can be considered at all related to its previously emerged conditions.

CONCLUSIONS

Three major sedimentary provinces on the continental margin off southeastern United States are distinguished by textural parameters of surface sediment. The provinces and their characteristic sediment texture are as follows:

1. Continental shelf and northeastern part of the Blake Plateau: well-sorted sand or gravelly sand; grain-size distribution curves tend to be skewed towards the coarse grains.
2. Continental slope and upper continental rise: poorly sorted clayey silt to silty clay with symmetrical grain-size distribution curves.
3. The area beneath the Gulf Stream Counter Current and the Antilles Current: very poorly sorted clayey silt to silty sand with grain-size distribution curves that are skewed towards the fine grains.

Bottom currents on the continental margin play a major role in governing textural parameters. Bottom currents have reworked sediments on the continental shelf and Blake Plateau in such a fashion that many of the surface samples from these two distinct physiographic and mineralogic provinces are texturally similar. The continental slope off Florida is covered by a prograding accumulation of poorly sorted clayey silt deposited beneath the southerly flowing Gulf Stream Counter Current. A distinctive accumulation of silty sand on the southern margin of the Blake Plateau is winnowed pelagic ooze transported from the eastern Blake Plateau by the Antilles Current. Well-sorted sand-sized sediment is found beneath the axis of the Gulf Stream in the Straits of Florida and on the Blake Plateau. North of the Blake Plateau, where the Gulf Stream touches the bottom in deeper water, a marked increase in silt and sand is found.

The clayey, hemipelagic silt found on the continental slope north of Cape Hatteras was deposited beneath the sluggish, southerly moving slope water. The silty clay on the upper continental rise off Maryland and New Jersey accumulates in the relatively tranquil regions between the slope water and the deeper but more vigorous southerly flowing Western Boundary Undercurrent.

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