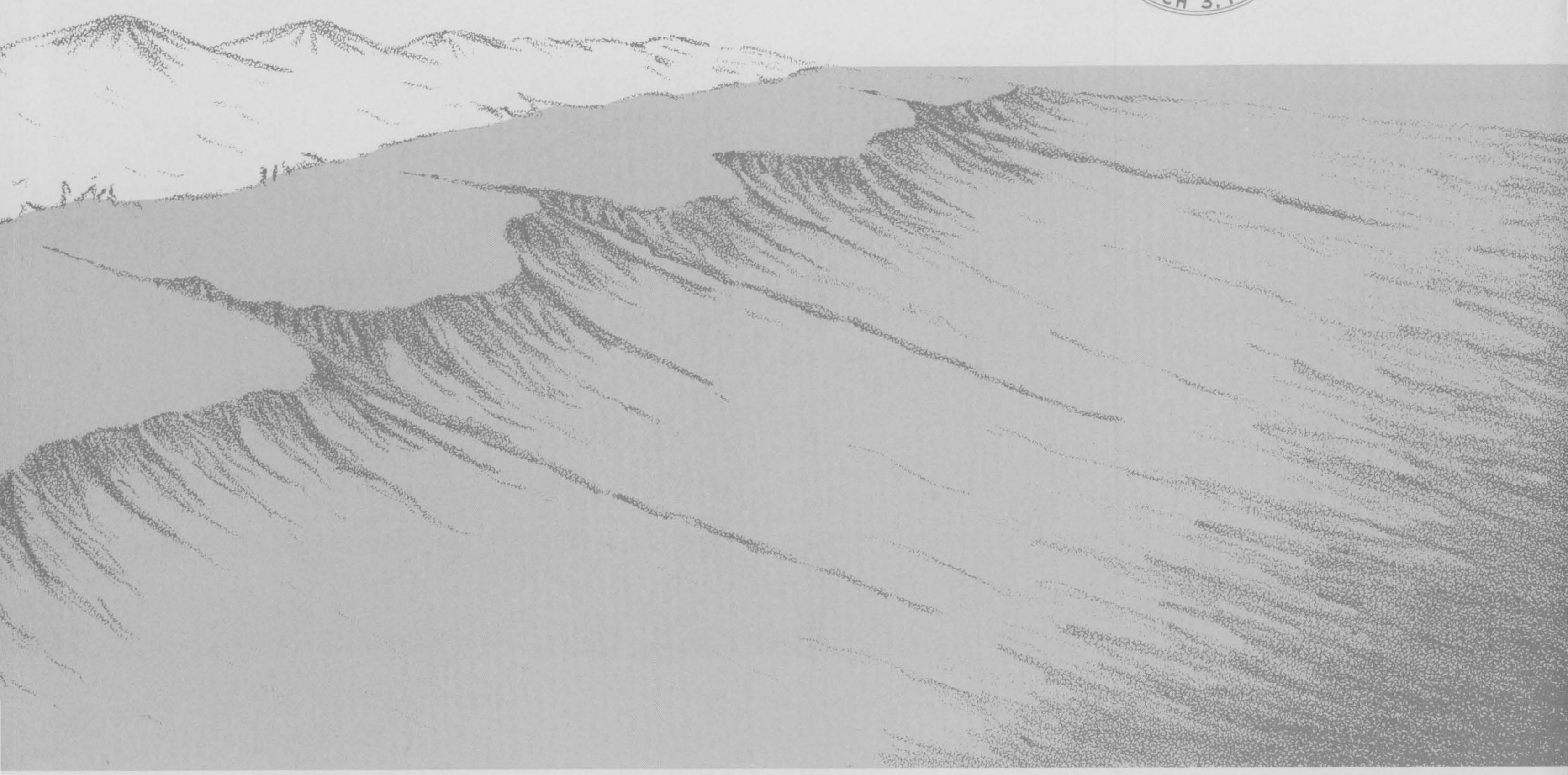
Atlantic Continental Shelf and Slope of the United States



Petrology of the Sand Fraction of Sediments, Northern New Jersey to Southern Florida

GEOLOGICAL SURVEY PROFESSIONAL PAPER 529-J

Atlantic Continental Shelf and Slope of the United States— Petrology of the Sand Fraction of Sediments, Northern New Jersey to Southern Florida

By JOHN D. MILLIMAN

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Description of the surface sediments on the continental margin from northern New Jersey to southern Florida

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By JOHN D. MILLIMAN, Woods Hole Oceanographic Institution

ABSTRACT

Surface sediments on the continental margin from northern New Jersey to southern Florida can be divided into different sediment types on the basis of their texture and composition. Most of the continental shelf north of Cape Hatteras is covered with a relict low-carbonate felspathic sand. Shelf sediments south of Cape Hatteras are characterized by relatively high carbonate and low feldspar contents, the result of warm coastal waters and southern river sedimentation. Carbonate components include mollusks, coralline algae, barnacles, and oolite. Sediments immediately adjacent to large Piedmont rivers, however, tend to have relatively low carbonate and relatively high feldspar contents.

The continental slope north of Cape Hatteras is dominated by silts and clays. The sand fraction of these sediments generally contains moderate amounts of carbonate and large amounts of feldspar. The insoluble fraction of the carbonate-rich sands on the northern Florida-Hatteras Slope are dominated by glauconitic casts, probably derived from nearby middle Tertiary outcrops. The carbonate-rich muds off Florida and southern Georgia are less glauconitic, but they do contain arkosic sands that probably also were derived from underlying middle Tertiary formations. The Blake Plateau is characterized by highly carbonate-rich sands. Apparently, little or no terrigenous sediment has accumulated in this area since at least the middle Tertiary.

The most impressive characteristic of the sediments of the continental margin is that most are relic or residual. The fine-grained nearshore sediments probably represent the only modern (posttransgressional) sediments on the shelf. The lack of modern sedimentation on the shelf is probably due to the trapping of river-borne detritus in estuaries and the winnowing of fine-grained shelf sediments by currents and waves. The presence of residual sediments and outcrops illustrates that much of the southeastern shelf, Florida-Hatteras Slope and Blake Plateau, have accumulated only slight sediment cover since the Tertiary. The erosive influence of the Florida Current must be considered a key factor.

INTRODUCTION

Continental margins separating the continents from the deep ocean basins consist of three physiographic provinces, the continental shelf, the continental slope, and the continental rise. Emery (1966) has estimated the area of the shelf and slope of the Atlantic continental margin of the United States (including the Blake Plateau) at more than 660,000 square kilometers. In 1962 the U.S. Geological Survey and the Woods Hole Oceanographic Institution undertook a cooperative investigation of the Atlantic continental margin (Emery and Schlee, 1963). A major part of the program involved the collection and analysis of sediment samples from the shelf and slope. The petrology of the sand fraction of the sediment on the margin between northern New Jersey and southern Florida is the topic of this paper.

A large number of workers have investigated the sediments on the east coast continental margin. Most of these studies were limited to estuaries or nearshore environments in rather confined areas. Many of these studies are mentioned by Uchupi (1963), Gorsline (1963), Emery (1966), and Schopf (1968).

Several studies have encompassed large parts of the margin. The earliest and, in terms of total samples, the most complete, was by Pourtales (1870, 1872), who studied more than 9,000 bottom samples collected by lead-line soundings of the U.S. Coast Survey. Pourtales was able to define most of the major petrographic provinces on the shelf, and he recognized areas of rock outcrop, different ecologic boundaries, and the relation between sediment type and water temperature and depth. As Schopf (1968) points out, Pourtales missed only two major shelf features, the seaward coarsening of shelf sands and the presence of the manganese and phosphate deposits of the Blake Plateau. Considering that most samples were obtained on the end of a sounding lead, his work portrayed shelf sediments with astonishing accuracy. Shepard and Cohee (1936) illustrated the dominance of relict shelf sediments from Block Island to Delaware Bay. The first 20th century study of sediments from the entire east coast shelf and upper slope was that by H. C. Stetson (1938). His study was based on 13 sam-

[1] Contribution 2423 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.

pling traverses spaced from Boston to Cape Canaveral (now Cape Kennedy) and emphasized the relict nature of the shelf sediments, including relict calcareous deposits, such as oolite, on the outer shelf south of Cape Hatteras. In the mid-1950's some 210 sediment samples were collected on a 76-sample station grid from Cape Hatteras to West Palm Beach by the U.S. Fish and Wildlife Service. Regional trends in textural, mineralogical, and chemical properties were reported by Gorsline (1963) and Goodell (1967), but apparently little petrographic analysis was performed on these samples.

GEOLOGY AND GEOMORPHOLOGY OF THE ATLANTIC CONTINENTAL MARGIN

The regional structure of the continental margin has been discussed by Murray (1961), Maher (1965), Joint Oceanographic Institutions' Deep Earth Sampling Program (1965), Uchupi and Emery (1967), and Uchupi (1970), and therefore need be mentioned here only briefly. Crystalline pre-Mesozoic rocks dip gently east from the Appalachian Mountains and underlie the Coastal Plain, the shelf, and the continental slope. Younger strata thicken considerably seaward. The basement is warped into a series of northeast and northwest trends, with the greatest sediment thicknesses along the outer edge of the shelf in the Chesapeake-Delaware (Salisbury) Embayment, the Savannah (Southeast Georgia) Embayment, and the South Florida Embayment. Between these troughs are broad warps, the Cape Fear and Ocala (Peninsular) arches. Tertiary sediment thicknesses range from more than 1,200 meters along the shelf break near the Savannah and Delaware Embayments, to less than 80 m on the Cape Fear arch. Tertiary sediments thicken to greater than 1,200 m south of Palm Beach, Fla.

The coastal area from northern New Jersey to southern Florida lies within the Coastal Plain province. This province is characterized by low relief, generally less than 30 m, and has regional slopes similar to those of the continental shelf, 0.4–1 m per kilometer. The province is bounded to the west by the Fall Line of the Piedmont province and ranges in width from more than 300 km in northern Florida to less than 50 km in northern New Jersey. North of Long Island the Coastal Plain is submerged (pl. 1).

Middle Tertiary and Quaternary sediments on the Coastal Plain consist mainly of sand and silt and local deposits of gravel. Much of the sediment is heavily iron stained, and calcium carbonate content increases markedly south of Cape Hatteras and towards the coast (LeGrand, 1961). Paleontologic studies of the various formations show the reworking and incorporation of older deposits throughout much of the Tertiary and Quaternary (Cooke, 1936; Richards, 1945), in part caused by numerous regressions and transgressions (DuBar and Solliday, 1963).

The coastline between New Jersey and Cape Lookout is deeply embayed by estuaries and bounded by barrier beaches and islands, and marshes (pl. 1). Fenneman (1938; cf. Murray, 1961) termed this area the "embayed section of the Coastal Plain." South of Cape Lookout the embayed estuaries disappear, and the barrier beaches and bars are replaced by barrier islands and marshes (Murray, 1961). Three cusplike bays, Raleigh, Onslow, and Long, defined by Capes Hatteras, Lookout, Fear, and Romain, dominate the Carolina coastline.

The continental shelf off the Middle and Southeastern United States is uniform in slope (0.4–1 m per km), and is generally considered to be a submerged counterpart of the Coastal Plain. The width of the shelf and the depth of the shelf break decrease south of New Jersey. Off New Jersey the shelf is about 150 km wide and extends to a depth of about 160 m. Off Cape Hatteras the shelf is 23 km wide and extends only to a depth of 40 m (Uchupi, 1968). To the south the shelf again widens, reaching more than 130 km off central Georgia, but the shelf break remains shallow, less than 60 m. Along the Florida coast the shelf narrows considerably, from 40 km at Cape Kennedy to less than 3 km at Key West. The shelf break off southern Florida occurs at a depth less than 10 m (Uchupi, 1968).

A series of sand ridges lie along the entire east coast shelf. Relief of these features is generally less than 5 m. Shepard (1963) and Sanders (1962) suggest that ridges off Virginia are relict barrier beaches or beach dunes. Uchupi (1968) thought that they in part are being formed by present-day storm activity. Biohermal and reeflike mounds protrude above the outer edge of the shelf and upper part of the Florida-Hatteras Slope, between Cape Hatteras and Key West (Menzies and others, 1966; Zarudski and Uchupi, 1968; Macintyre and Milliman, 1968). In addition, a discontinuous series of rocky banks protrude 1–5 m above the nearshore bottom of Onslow Bay and Long Bay, and along the entire Florida coast.

The outer shelf and continental slope between

Cape Hatteras and northern New Jersey is cut by several submarine canyons. Wilmington and Baltimore Canyons lie seaward of Delaware Bay, and Washington and Norfolk Canyons lie off Chesapeake Bay. The existence of a canyon seaward of Cape Hatteras has been debated (Rona and others, 1967; Pratt, R. M., 1967), but recent bathymetric studies by Newton and Pilkey (1969) indicate that the canyon consists of many branches.

The continental slope from New Jersey to Cape Hatteras occupies depths from the continental shelf break to the continental rise, which begins at about 2,000 m. Slopes average between 2° and 5°. Canyons and irregular features, some of which are thought to be massive slumps (Uchupi and Emery, 1967), occur along the base of the slope.

The slope off the Southeastern United States is interrupted by the Blake Plateau, a relatively flat hard-surfaced topographic feature. This plateau extends from depths of about 350–1,000 m, with slopes as gentle as 10′. It is separated from the continental shelf by the Florida-Hatteras Slope. Seaward of the plateau is the continental slope, known in this area as the Blake Escarpment. The southern extension of the plateau, between the Bahamas and Florida, is called the Straits of Florida. Although the Blake Plateau is generally flat, the inner margin is marked by numerous coral ridges (Stetson, T. R., and others, 1962; Milliman and others, 1967) and depressions (Stetson, T. R., and others, 1969).

HYDROLOGY

The land adjacent to the middle and southeastern Atlantic shelf is drained by more than a dozen major rivers that originate in the Piedmont province (pl. 1). Many smaller rivers and streams flow almost exclusively through the Coastal Plain. Because Piedmont and Coastal Plain rivers do not drain high altitudes or cold climates, runoff generally corresponds directly to precipitation. Major runoff is in the spring months, although, occasionally, summer and fall storms will cause flooding.

Rivers north of Cape Hatteras have high runoff, but they do not carry much suspended load (table 1, this report; Meade, 1969a). According to Dole and Stabler's (1909) data, more than 40 percent of the suspended material for the entire east coast is carried by the major South Carolina and Georgia rivers, the Pee Dee, Santee, Savannah, and Altamaha. This load in part reflects the greater availability of highly weathered Piedmont soils in the south; most northern source areas were stripped by Pleistocene glaciation (Meade, 1969a).

TABLE 1.—*Discharge of water and suspended sediment by major east coast rivers*

[Suspended load data after Dole and Stabler (1909). The large suspended sediment for the Ogeechee quoted by Dole and Stabler is not supported by subsequent studies (R. H. Meade, oral commun. 1969)]

River	Water discharge (m^3/sec)	Suspended-sediment discharge (thousands of tons per year)
Delaware	564	721
Susquehanna	1,141	960
Potomac	388	1,358
James	284	988
Chowan	131	400
Roanoke	244	2,490
Tar	133	349
Neuse	161	444
Cape Fear	268	226
Pee Dee	432	1,630
Santee	529	3,445
Savannah	291	2,575
Ogeechee	65	1,156
Altamaha	344	3,030

OCEANOGRAPHY

Iselin (1936) recognized three water masses in the Atlantic Ocean off the Eastern United States, the coastal waters, the slope water, and the central water (or Sargasso water). The coastal waters, with salinities less than 35 ‰, have been further classified into the Virginian and Carolinan waters (Bumpus and Pierce, 1955). The former typifies coastal water found north of Cape Hatteras and is characterized by relatively low salinities, due to river runoff, and great seasonal temperature variations (fig. 1). The Carolinan water, which is restricted to south of Cape Hatteras, is generally more saline because of lower river runoff and the inflow of the Florida Current; mixing with the Florida Current results in high temperatures and rather low seasonal temperature ranges (fig. 1).

A general knowledge of the shelf circulation has been derived from surface drift-bottle and seabed-drifter studies (Bumpus, 1955; Bumpus and Pierce, 1955; Harrison and others, 1967; Gray and Cerame-Vivas, 1963; D. F. Bumpus, oral commun., 1968). Between New Jersey and Cape Hatteras, in the Virginian province, the dominant bottom drift on the inner and middle shelf is to the south and landward (fig. 2). Most seabed drifters, released as much as 100 km offshore from Chesapeake Bay, were recovered within the bay or south of Cape Hatteras (Harrison and others, 1967). The effects of the southerly drift also can be seen in the general trend of spits and sandbars. Outer shelf currents are not well known, but the infrequency of recovery of offshore drifters suggests that the net transport is offshore (D. F. Bumpus, oral commun., 1968).

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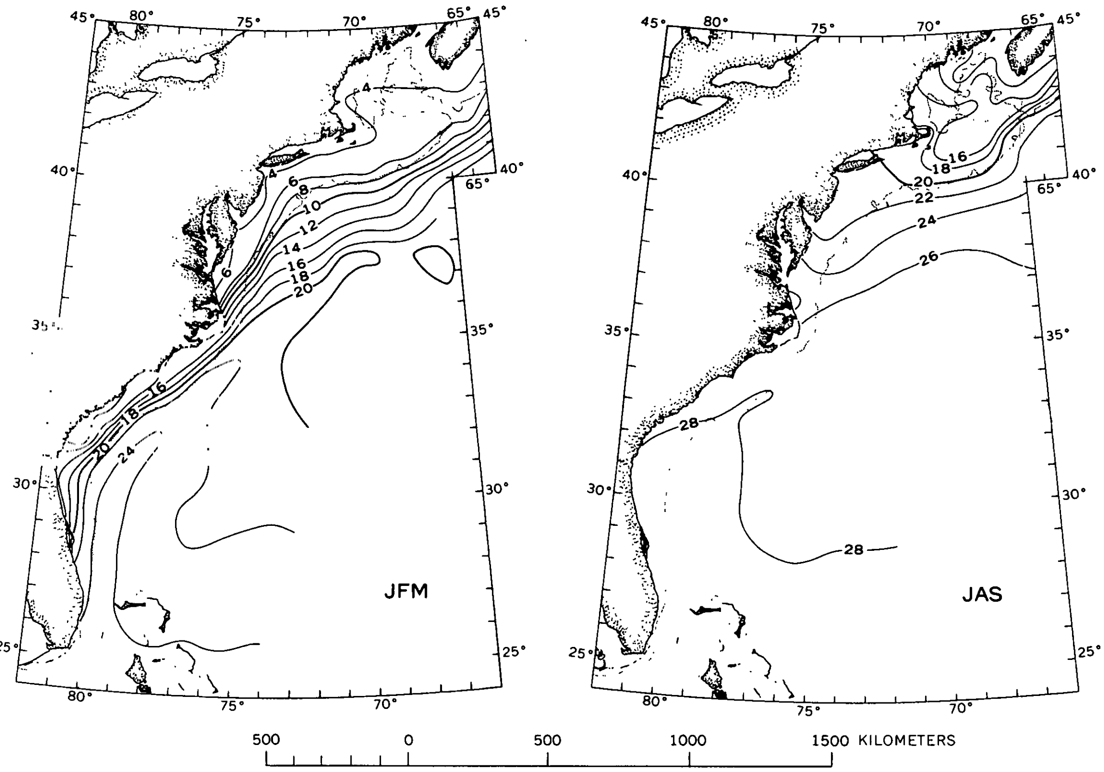


FIGURE 1.—Isotherms of winter (JFM) and summer (JAS) seasons for surface waters, in degrees Celsius (centigrade), off the Atlantic coast. From Emery (1966).

Virginian water flows south into Raleigh Bay, but significant transport is generally limited to the winter months when northerly winds are blowing (Steffanson and Atkinson, 1967). As a result of this southern transport, nearshore fauna and flora show mixed Virginian and Carolinan assemblages as far south as Onslow Bay (Cerame-Vivas and Gray, 1966).

Between Cape Hatteras and the shelf off Georgia, circulation is mainly in large-scale eddies caused by the interaction of the north-flowing Florida Current and the south-flowing nearshore water (fig. 2). The net flow south of Georgia has not been thoroughly studied, but the southerly trend of headlands and spits, and the transport of Georgia river sands as far south as Miami (see below) suggest the obvious direction of net transport.

The offshore waters south of Cape Hatteras are dominated by the Florida Current. Occasionally the current will meander onto the shelf, but generally it remains seaward of the shelf break. Surface currents average more than 200 cm/sec and bottom currents can reach velocities greater than 100 cm/sec. The existence of a southward flowing undercurrent along the Florida-Hatteras Slope has been observed (Milliman and others, 1967), but apparently this current is ephemeral and does not contribute to any significant southern transport.

ACKNOWLEDGMENTS

This study was part of the general investigation of the east coast continental shelf, slope, and upper rise undertaken by the Woods Hole Oceanographic Institution and the U.S. Geological Survey, under the direction of K. O. Emery. The author expresses thanks to all his colleagues at Woods Hole who aided in analyses, data reduction, and discussions; in particular, J. S. Schlee, R. H. Meade, D. A. Ross, C. D. Hollister, and Elazar Uchupi for critical reading of the manuscript, and F. T. Manheim and J. C. Hathaway for helpful discussion. O. H. Pilkey, of Duke University; V. A. Zullo, of the Marine Biological Laboratory, Woods Hole; R. K. S. Lee, of the Canadian Museum of Natural History; and E. T. Degens and W. G. Deuser, of Woods Hole, provided the author with valuable analyses and identifications.

METHODS

Most Woods Hole-U.S. Geological Survey sediment samples were collected with a Campbell grab, which samples a bottom area of 0.6 square meters (Emery, 1966). Other estuarine, shelf, and slope samples were taken with Smith-McIntyre and Van Veen grabs. Some Blake Plateau samples were collected by chain-bag and pipe dredges. A 10-mile (18 km) sample grid was followed throughout most of the study area (fig. 3). Beach samples were collected by J. M. Zeigler, presently at the University of Puerto Rico.

Silt- and clay-sized material was removed by washing through a 62-micron sieve. The petrography of the coarser sand and gravel material was studied as two distinct fractions, the carbonates and the noncarbonates.

The carbonate components were studied by two methods. Sediments low in carbonate generally contain only a few easily recognizable carbonate constituents, such as mollusks, echinoids, and Foraminifera. Hence, these organisms generally could be identified with a standard binocular microscope. Many carbonate-rich shelf sediments south of Cape Hatteras contain components such as oolite, pellets, barnacle plates, and encrusted fragments that require thin sectioning for identification. Accordingly, these sediments were impregnated with polyester resin, thin sectioned, and the carbonate components identified under refracted light, using a petrographic microscope. Criteria for recognition of most carbonate grains are given by Ginsburg (1956) and Purdy (1963). One to three hundred point counts were made.

Following identification of the carbonates, the sample was digested in dilute hydrochloric acid, and the percent of the carbonate fraction computed by weight loss. The samples were then sieved and the 125μ- to 250μ-sized fraction was separated and mounted on a glass slide with Caedex mounting medium. The reason for separating the noncarbonate grains will be explained in a subsequent section. Visual estimates were made of the percent of iron-stained grains, and then the mounted grains were stained for potassium and sodium feldspar using the sodium bichromate-eosin B method of Hayes and Klugman (1959). Potassium feldspar grains stain orange, sodium feldspar turns pink, and quartz grains remain colorless. Occasionally, glauconite grains pick up either the pink or orange stain, but they usually can be recognized by their shape, granular texture, and dark undercoating. Unstained glauconite is recognized by the polylobate and pelletal shapes and light green to black colors. Phosphate grains are generally amber in color. Questionable grains were tested with nitric acid and ammonium nitrite, a treatment that turns the phosphatic grains yellow.

Heavy minerals were noted but not identified. D. A. Ross is studying the heavy minerals in this area. The noncarbonate fraction was not studied in samples in which it consisted of less than 5 percent of the total sample.

RESULTS

SEDIMENT TEXTURE

SIZE

Size analyses of the sediments were made by J. R. Frothingham, J. S. Schlee, C. R. Hayes, A. Weston, and the author. The following discussion deals only with the distribution of the various size classes and modal sizes. The texture of these sediments is being studied by C. D. Hollister.

Most sediments on the shelf are composed entirely of sand and gravel (fig. 4; pl. 2*A*). The principal modal class is medium-fine sand (125μ to 500μ); (fig. 4; pl. 2*C*). This sediment also dominates large parts of the northern Florida-Hatteras Slope and the Blake Plateau. Coarse sand (500μ to $2,000\mu$) is the second most abundant size grade on the shelf (pl. 2*B*). Most large concentrations occur in several zones off Delaware and Chesapeake Bays, off Capes Fear and Romain, and on the outer shelf of northern Florida. In these areas, gravel (coarser than $2,000\mu$) is a visible component (pl. 2*A*). North of Cape Hatteras, gravel occurs seaward of Delaware and Chesapeake Bays, suggesting possible relict stream deposits (Schlee, 1964). Coarse sand and gravel also are significant in the Straits of Florida and in the inner parts of the Blake Plateau.

Very fine sand (62μ to 125μ) and silt and clay (finer than 62μ) are present in small amounts (average, less than 5 percent) on the shelf (pl. 2*D, E*). These fine sediments, however, are prominent in nearshore areas, such as off Chesapeake and Delaware Bays, Albemarle Sound, and almost the entire nearshore area between Cape Hatteras and Cape Kennedy. Silt and clay are dominant in the slope sediments north of Cape Hatteras and on the Florida-Hatteras Slope seaward of central Florida, where they make up more than 75 percent of the sediment.

SEDIMENT COLOR

Many detrital grains on the shelf are stained with iron oxide, giving the sediments colors ranging from rust brown to light yellow. The occurrence of

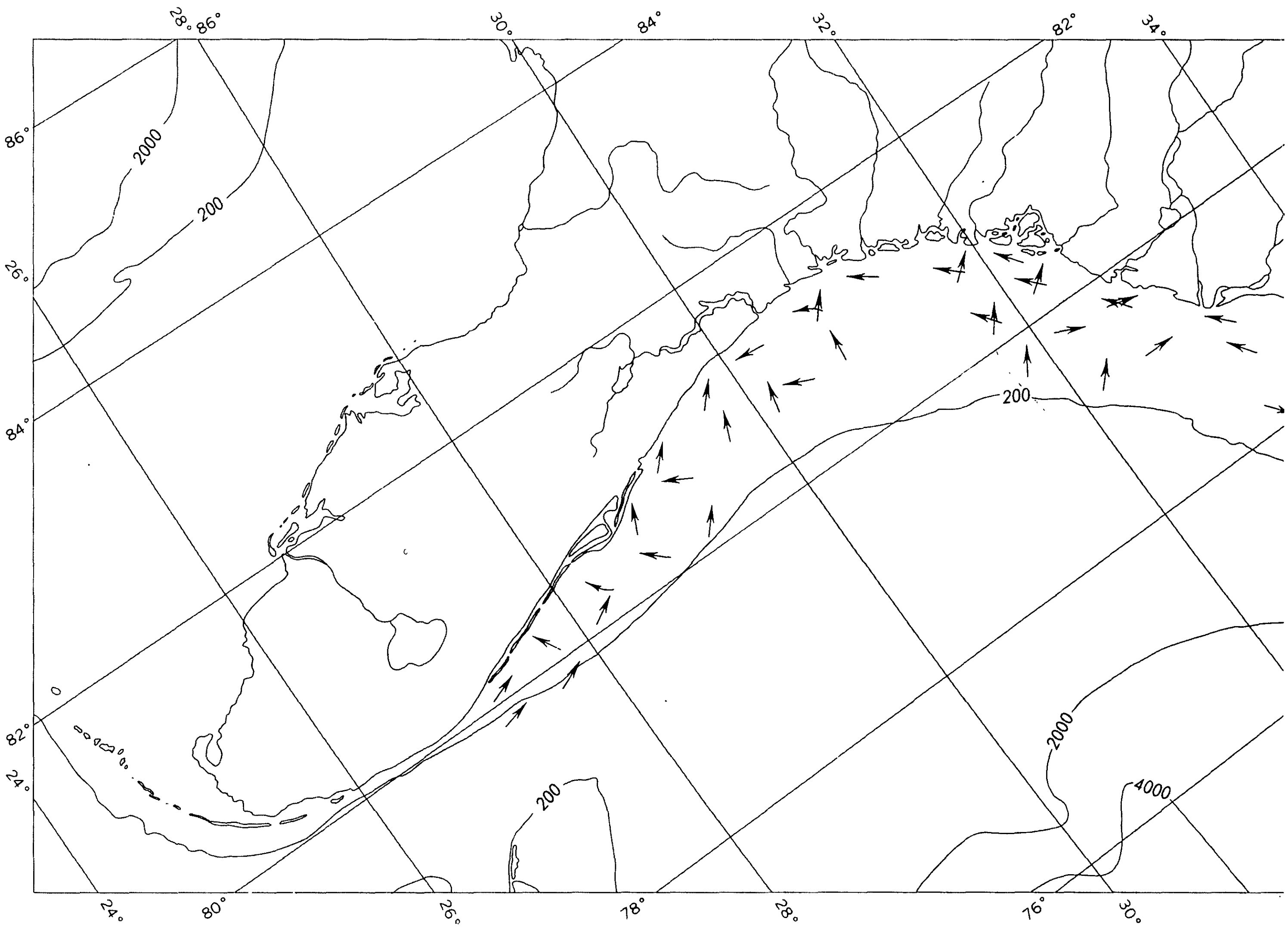


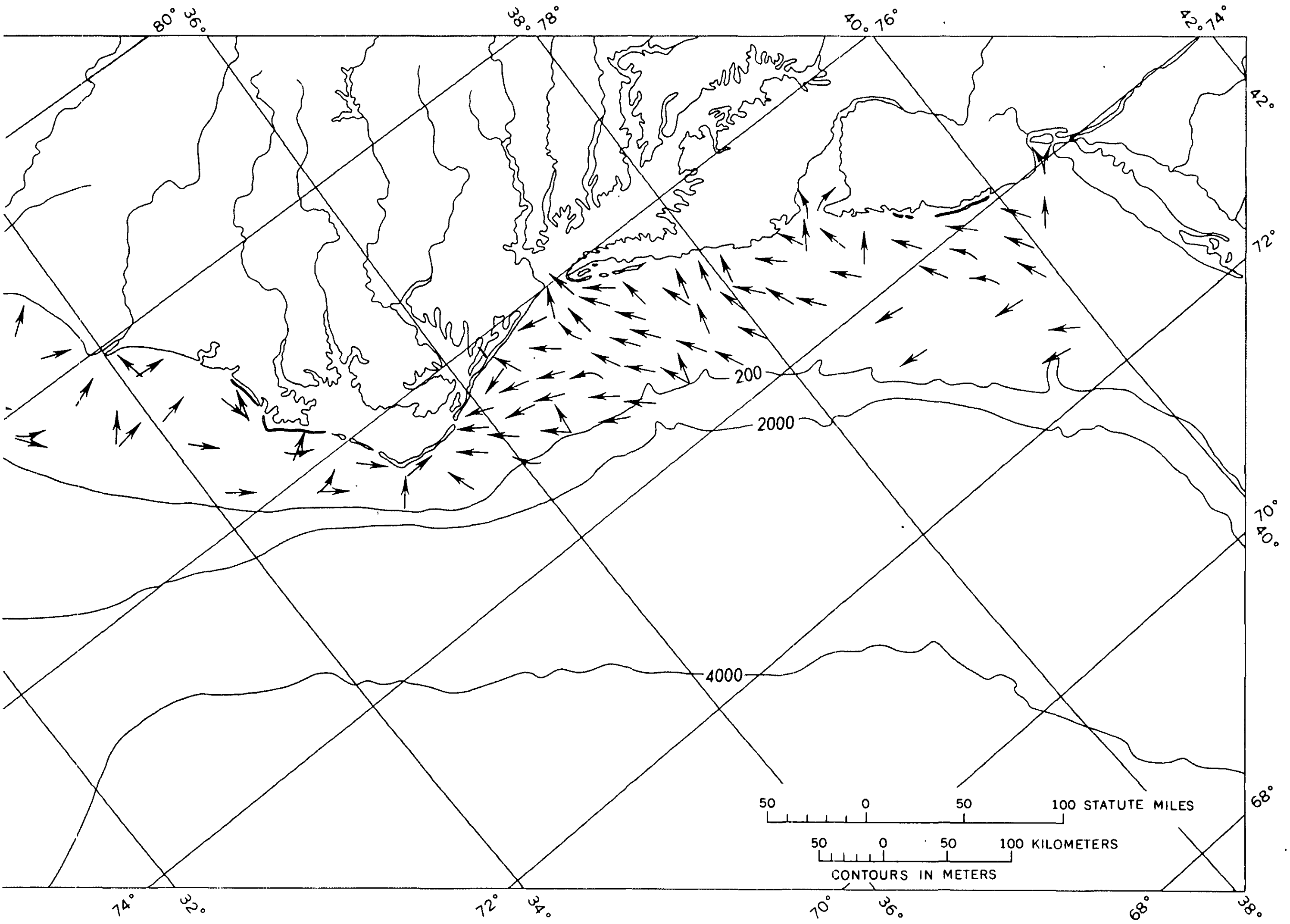
FIGURE 2.—Map showing near-bottom currents and

staining and the degree of coating decreases markedly with decreasing grain size. Most fine grains have thin coatings, or are only stained in cracks and pits. To avoid this size-dependency factor, the 125μ- to 250μ-sized fraction of each sample was used for visual color estimates. All grains with reasonable traces of stain were classified as iron stained.

Iron staining is limited mainly to the continental shelf sediments north of Cape Romain (fig. 5). Most sediments in this area contain more than 15 percent stained grains within the 125μ- to 250μ-sized fraction. The most highly stained sediments (those with more than 50 percent staining) are off southern New Jersey, Delaware, and Onslow Bay. Sediments south of Cape Romain are much less iron stained; few sediments contain more than a few percent stained grains, and in none does the staining account for more than 20 percent.

Estuarine sediments commonly contain fewer stained grains than those on the shelf. Duane (1962) showed that the sediments in outer Pamlico Sound are stained and suggested their derivation from offshore areas. The sands in Delaware Bay near Wilmington are heavily coated with a dark iron oxide. Since these seems to be no upstream or downstream source for such sediment, the source is probably local, perhaps industrial pollution.

Although some shelf sediments are derived from iron-stained Coastal Plain and Piedmont formations, iron-oxide coatings were probably removed during transport. Rather, the iron staining probably reflects the subaerial Pleistocene shelf, in which



drift off the Middle and Southern Atlantic States.

aerate, organic-rich conditions existed (Dunbar and Rodgers, 1957). Removal of such stains requires brief exposure of anoxic, reducing conditions, such as those found in coastal swamps. During the transgression of Holocene sea level, such reducing swamp conditions existed across the shelf, as evidenced by the blackened and gray shells and ooids in the shelf sediments (Doyle, 1967). Thus, the lack of iron-stained sediments in the area south of Cape Romain may reflect the low energy, swampy environment during the last transgression, an environment similar to present-day coastal conditions in this area.

THE CARBONATE FRACTION

CARBONATE CONTENT

North of Cape Hatteras most shelf sediments contain less than 5 percent carbonate (fig. 6). The only exception is a mollusk bank near Cape Charles, where carbonate values are as high as 40 percent. Slope sediments off Maryland and Delaware contain more carbonate than the sediments on the slope seaward of Delaware and Chesapeake Bays. These low-carbonate areas might be related to high rates of terrigenous sedimentation during glacially lowered sea level.

The carbonate content of sediments increases markedly on the outer shelf south of Cape Hatteras and on the middle and inner shelf south of Cape Lookout. This sharp demarcation coincides with the transition from northern temperate waters to southern semitropical waters at Cape Hatteras (fig. 1). The band of low-carbonate sediments in inner Raleigh Bay is probably related to periodic intrusion of northern waters into the nearshore areas

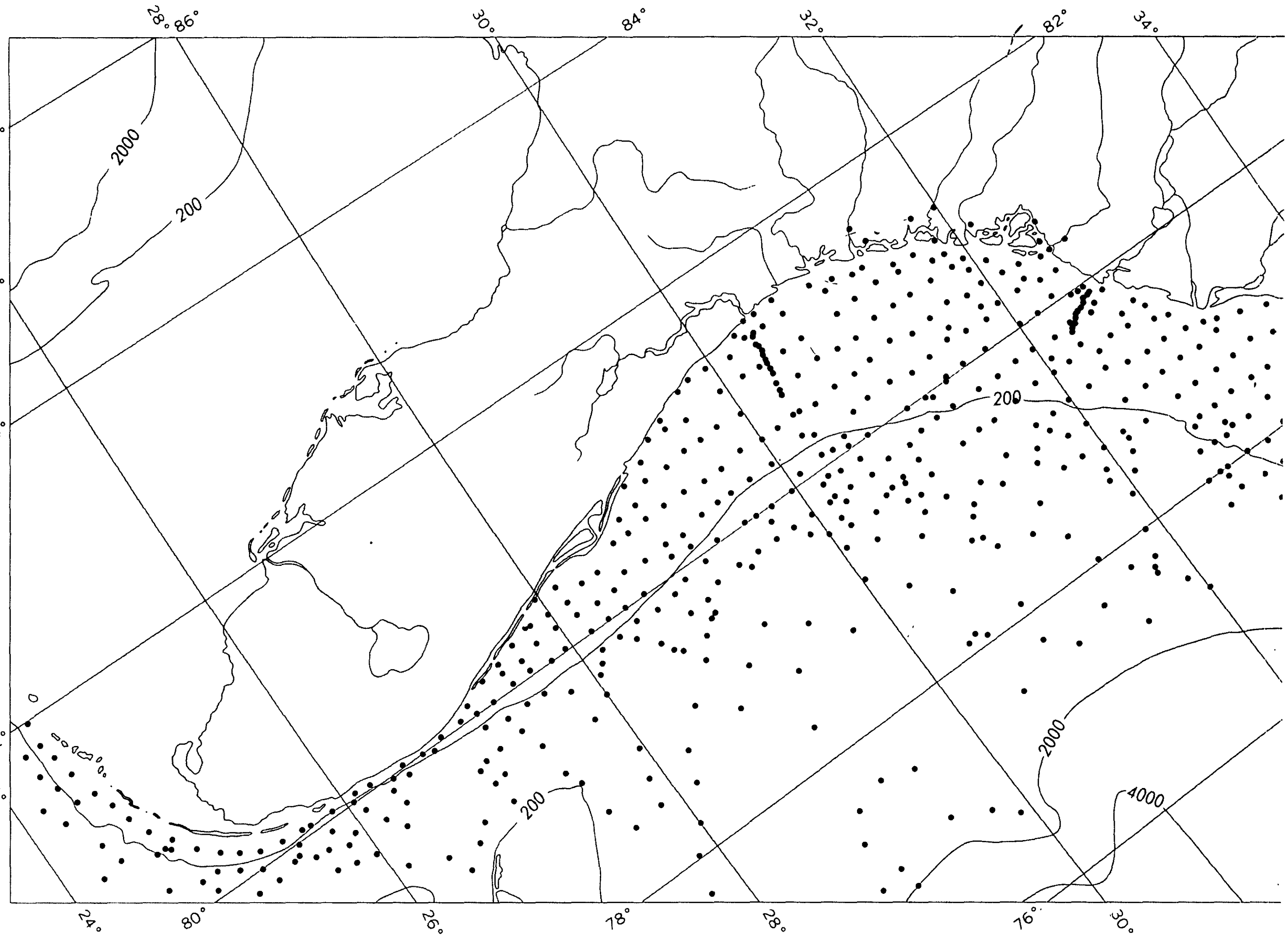


FIGURE 3.—Map showing the sediment-sampling pattern

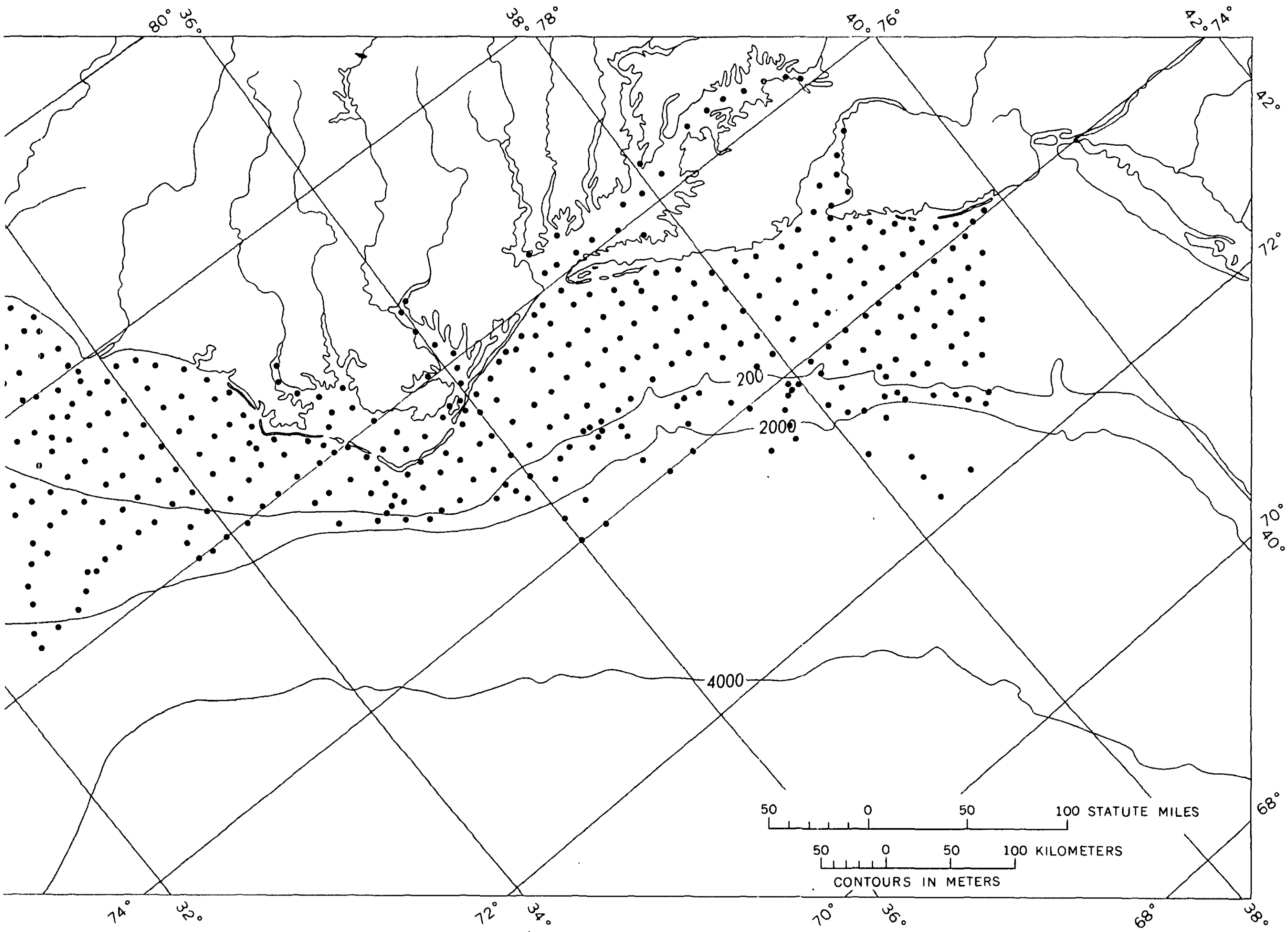
south of Cape Hatteras, which apparently discourages the growth of tropical carbonate-secreting organisms (Cerame-Vivas and Gray, 1966).

Dilution of carbonate content of shelf sands south of Cape Lookout is influenced by the contribution of detrital material from Piedmont rivers. Because of low river inflow, Onslow Bay sediments contain relatively high carbonate concentrations (averaging about 35 percent). In contrast, Piedmont rivers between Cape Fear and northern Florida have effectively diluted the carbonates with detrital sediments; carbonate values average less than 20 percent. Carbonate content increases to the south on the Florida shelf, as the influence of Georgia rivers decreases. At Cape Kennedy, most shelf sands contain more than 25 percent carbonate, and south of Palm Beach, most values are greater than 75 percent (fig. 6).

The sand fraction on the Florida-Hatteras Slope generally contains 50–75 percent carbonate north of Cape Romain, and 50–95 percent, to the south. Most of the sediments on the Blake Plateau contain more than 95 percent carbonate; the only exceptions are local patches of phosphate and manganese nodules.

CARBONATE COMPONENTS

Terrigenous sediments can be considered dilutants of a potential carbonate environment (Chave, 1967). Therefore, low-carbonate sediments can be treated as pure carbonates that have been diluted with noncarbonate particles. Although the total carbonate content within a sediment facies can vary, the carbonate components may remain constant rel-



off the Middle and Southern Atlantic States.

ative to one another (Milliman and others, 1968). In the present study the percentages of the various carbonate components have been determined relative to other carbonate components, and therefore cannot be considered as absolute abundances.

Mollusks

The major skeletal contributors to shelf carbonates are mollusks, mainly as infaunal filter-feeding pelecypods. Greatest concentrations are nearshore, and lowest are on the shelf edge. Slope sediments rarely contain more than 5 percent molluscan debris (pl. 3*A*).

North of Cape Hatteras about half of the shelf samples studied contain more than 75 percent mollusk fragments in the carbonate fraction. South of the cape the percentage of mollusks is inversely related to the carbonate content. Mollusks average about 70 percent of the carbonate fraction in those sands with less than 10 percent carbonate, but only 25 percent in sands with more than 85 percent carbonate (fig. 7). This trend is caused by the increased sedimentary influence of algae, barnacles, and oolite in the carbonate-rich southern sediments.

Many mollusks in the shelf sediments are relict in that they lived in shallow water during lower stands of sea level. Many of these relict shells are blackened and fragmented (Doyle, 1967; Estes, 1967). Blackwelder (in Milliman, and others, 1968) reported that mollusks on the North Carolina shelf show two shallow-water asemblages, a "0–20 meter" and an "inlet and intertidal" assemblage. Not all mollusks, however, are relict; many mollusks live in the nearshore environment, and large quanti-

FIGURE 4.—Map showing distribution of modal-size classes in

ties of scallops are being harvested from the middle and outer shelf off North Carolina and Florida.

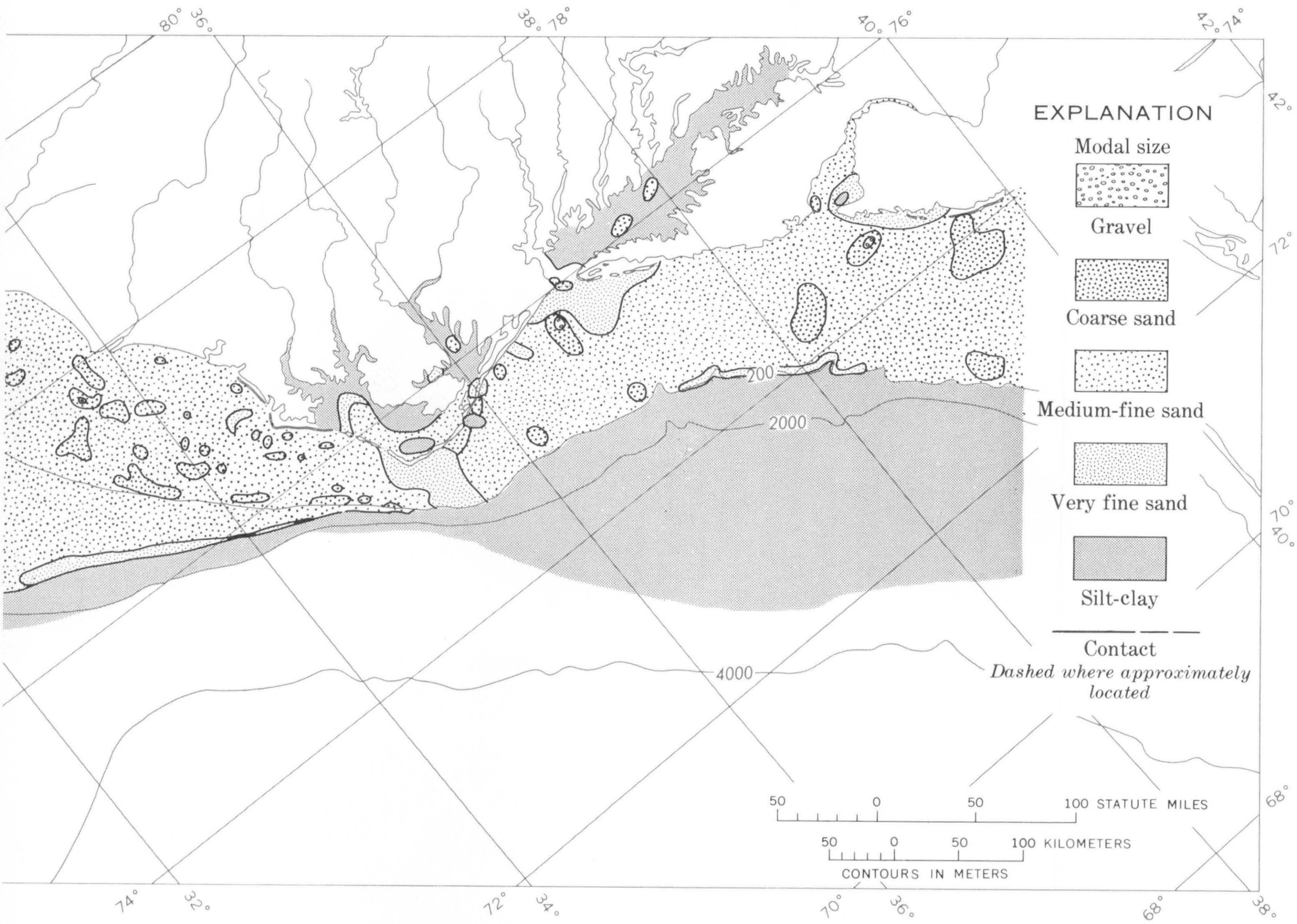
Echinoids

In most shelf sediments the majority of echinoid fragments are plates from the body tests. Upper slope sediments and shelf sediments south of Palm Beach contain numerous echinoid spines. Highest echinoid concentrations are in shelf sediments north of Cape May (pl. 3*B*). Concentrations reach more than 75 percent of the carbonate fraction. Abundant populations of sand dollars (*Echinarchinus parma*) (fig. 8) probably have contributed most of this debris. Between Cape May and Cape Lookout, echinoid fragments are less abundant, but generally constitute more than 10 percent of the carbonate fraction. Relatively high concentrations occur in Long Bay and seaward from Cape Romain.

Coralline Algae

Coralline algae, belonging to the phylum Rhodophyta (red algae), contribute significantly large quantities of carbonate to the shelf sediments south of Cape Hatteras (pl. 3*C*). Encrusting algae are important constituents on the Florida-Hatteras Slope and on the outer shelf, from Cape Hatteras to Cape Kennedy, but less abundant in the offshore areas adjacent to the South Carolina and Georgia Piedmont rivers. R. K. S. Lee (written commun., 1968) found that the dominant massive genera are *Lithothamnion* and *Lithophyllum.* The lack of reproductive structures and the fragmentary nature of the specimens did not permit a more complete identification.

Branching coralline algae are an important sedimentary constituent in sediments landward of the



surface sediment off the Middle and Southern Atlantic States.

encrusting algae. They are also found in local areas in the inner shelf. Milliman, Pilkey, and Blackwelder (1968) found that in Onslow Bay more than 60 percent of the carbonate fraction of several samples was composed of branching corallines, mainly *Neogoniolithon* sp., probably *N. strictum* (Foslie) Setchell et Mason (R. K. S. Lee, written commun., 1968). The green chlorophyll color of many specimens (fig. 9*A*) suggests that these branching corallines are presently living on the shelf, probably on the rock outcrops that line the inner shelf bottom (Milliman and others, 1968). The encrusting and branching algae on the outer shelf and upper slope are probably derived from the algae ridge system that lines the outer shelf and upper slope in this area (Menzies and others, 1966; Macintyre and Milliman, 1969).

Encrusting and branching algae are also found in shelf sediments south of Palm Beach. Algal content often exceeds 25 percent, and is derived from coral reef biota that live in this area (see below).

Cirripedia

Other than mollusk fragments, barnacle plates are probably the most important organic component in the shelf sediments south of Cape Hatteras. They are common on the outer shelf from Cape Hatteras to Florida and dominate the sediments along the entire inner and middle Florida shelf (pl. 3*D*).

Although specific barnacle identification was impossible because of a lack of the opercular valves, V. A. Zullo (oral commun., 1967) felt that most specimens might be *Balanus calidus* Pilsbry, a common species on the outer shelf off South Carolina (Zullo,

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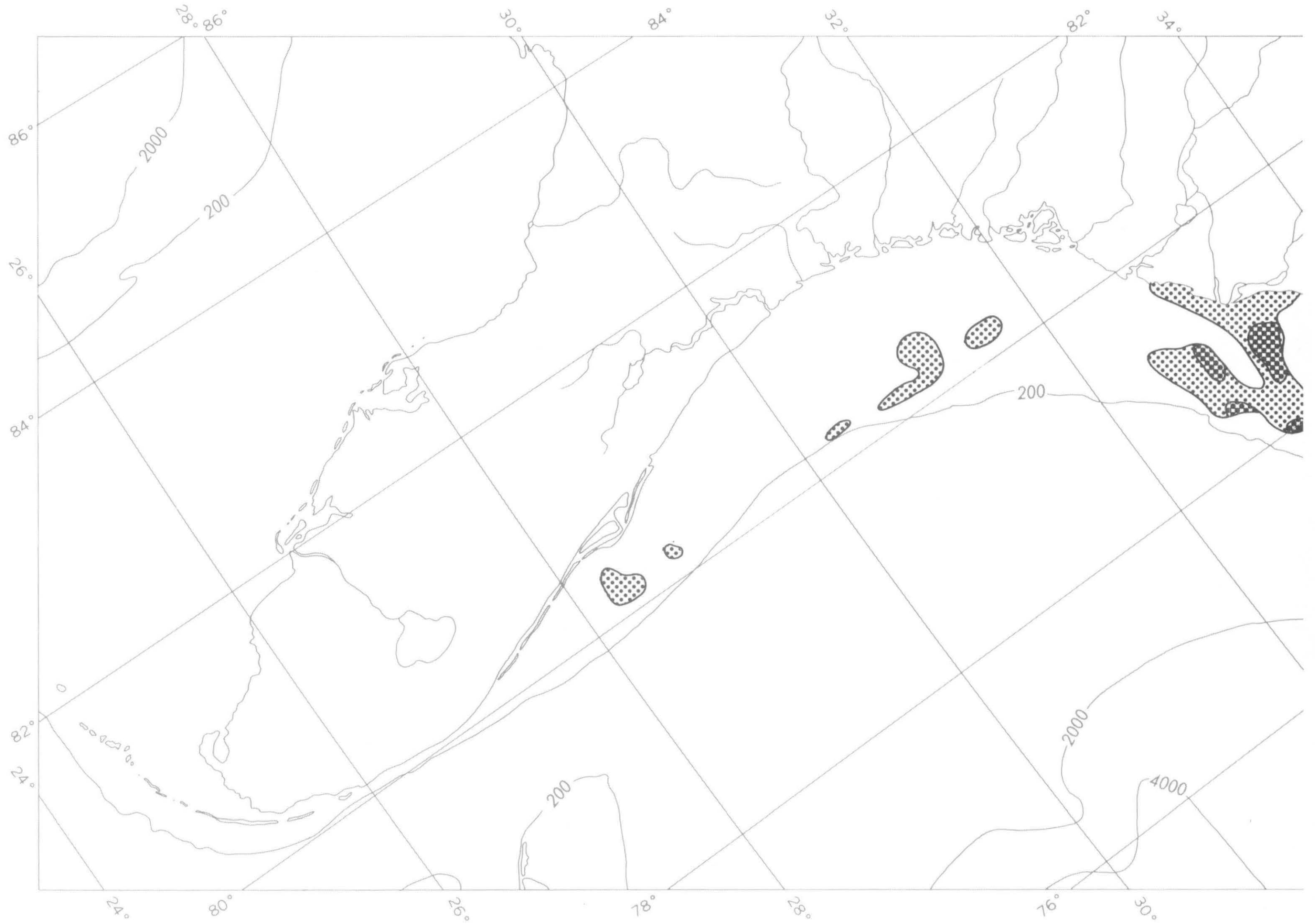


FIGURE 5.—Map showing distribution of iron-stained surface sediment within

1966). *B. calidus* and *B. amphitrite* have been found actively encrusting modern scallop shells in 30–40 m depths in Raleigh Bay (Wells, H. W., and others, 1964) and are growing on numerous other hard substrates (fig. 9*B*).

Halimeda

Fragments of the green algae *Halimeda* are found in shelf sediments south of Palm Beach, Fla. (pl. 3*E*). These sediments contain more than 90 percent carbonate, of which *Halimeda* contributes an average of 16 percent. Because of rapid alteration, *Halimeda* loses its identity more rapidly than other fragments, suggesting that its content may be greater than petrographically determined.

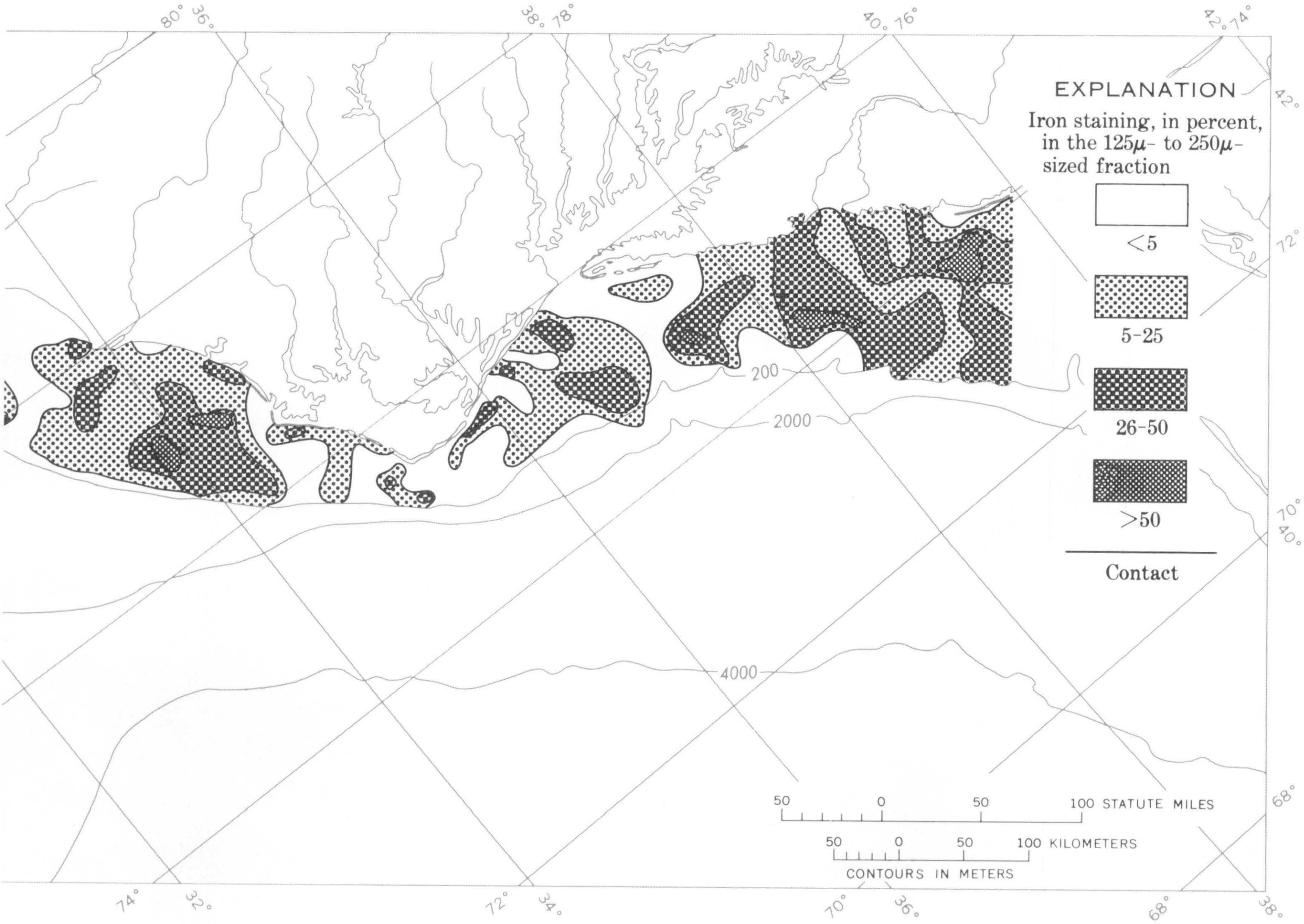
Coral

Coral fragments contribute only small quantities to most shelf sands and gravels. In sediments south of Palm Beach, apparently the northern limit for tropical coral reefs, coral averages about 12 percent of the carbonate fraction (pl. 4*A*).

Coral is a major component in sediments, primarily the gravel fraction, on the inner Blake Plateau, and is probably derived from nearby coral mounds that form topographic edges and banks (Stetson, T. R., and others, 1962; Milliman and others, 1967).

Bryozoans and Serpulids

Bryozoans and serpulids contribute relatively small amounts of carbonate to the shelf sediments (pl. 4*B*, *C*). Chave (1967) noted that bryozoans are a major contributor to nontropical shelf sediments. Although such a trend is true in other shelf areas, concentrations on the east coast shelf seldom exceed 10 percent, and those on the north of Cape Hatteras are much smaller.



the 125μ- to 250μ-sized fraction off the Middle and Southern Atlantic States.

Serpulids follow a similar distribution to the bryozoans. Except for one sample off New Jersey, all serpulid-rich sediments are found south of Cape Hatteras. Generally, concentrations are less than 10 percent, except locally on the outer shelf off North Carolina (Milliman and others, 1968). There is considerable overlap between the bryozoan- and serpulid-rich sediments, especially off Cape Romain.

Benthonic Foraminifera

Outer shelf and upper slope carbonates generally contain 5–10 percent benthonic Foraminifera (pl. 4*C*). Types include species of *Bolivina, Quinqueloculina,* and *Cibicides.* Parker (1948) found that *Q. seminilum* is the dominant species in depths of 15–90 m off Maryland and Delaware, and *Robulus, Marginella, Pulvinulinella,* and *Cassidulina* are prominent in deeper water. In most cases these forms are indicative of present-day deposition of neretic depths, and mark the transition from shelf to deep-sea environments.

Relatively high concentrations of foraminifers are also present in the carbonate fractions directly off Delaware and Chesapeake Bays. Prominent types include *Elphidium* and *Quinqueloculina.* Sediments within these foraminifer-rich bands, however, seldom contain more than 2 percent carbonate, so that the absolute abundance of Foraminifera is small.

South of Cape Hatteras the benthonic Foraminifera are dominated by miliolids and amphistigerinids. In southern Florida, soritids and peneroplids are also common. Many of these forms are probably relict; similar shallow-water forms have been noted

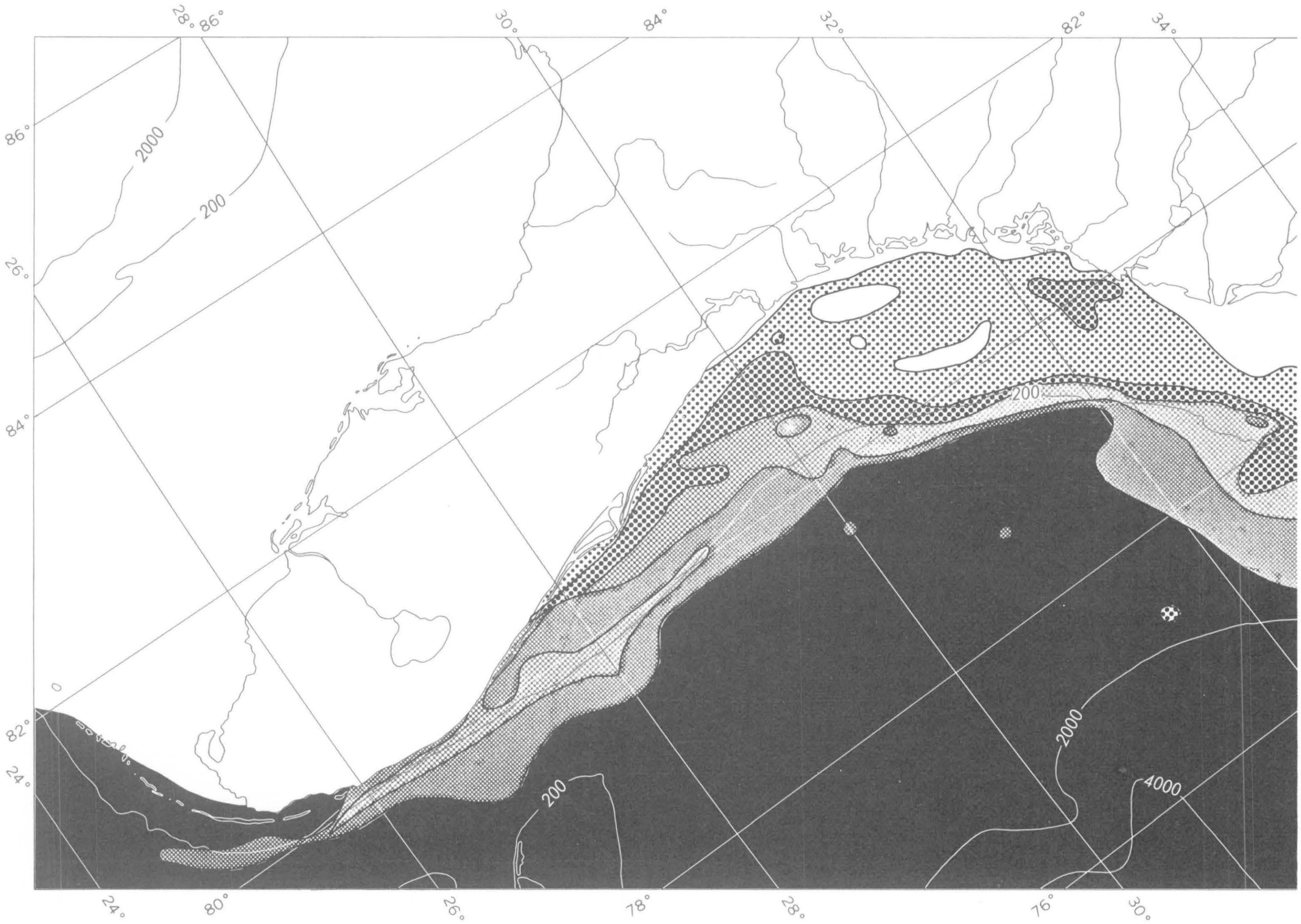


FIGURE 6.—Map showing distribution of calcium carbonate in the sand-sized

in relict shelf sediments in the Gulf of Mexico (Ludwick and Walton, 1957; Walton, 1964).

Planktonic Foraminifera

An estimated 90 percent of the carbonate sand fraction in slope sediments is composed of planktonic Foraminifera (pl. 4*D*). Relative concentrations are slightly lower within the Blake Plateau, where coral and pteropods also contribute noticeable amounts.

Pteropods

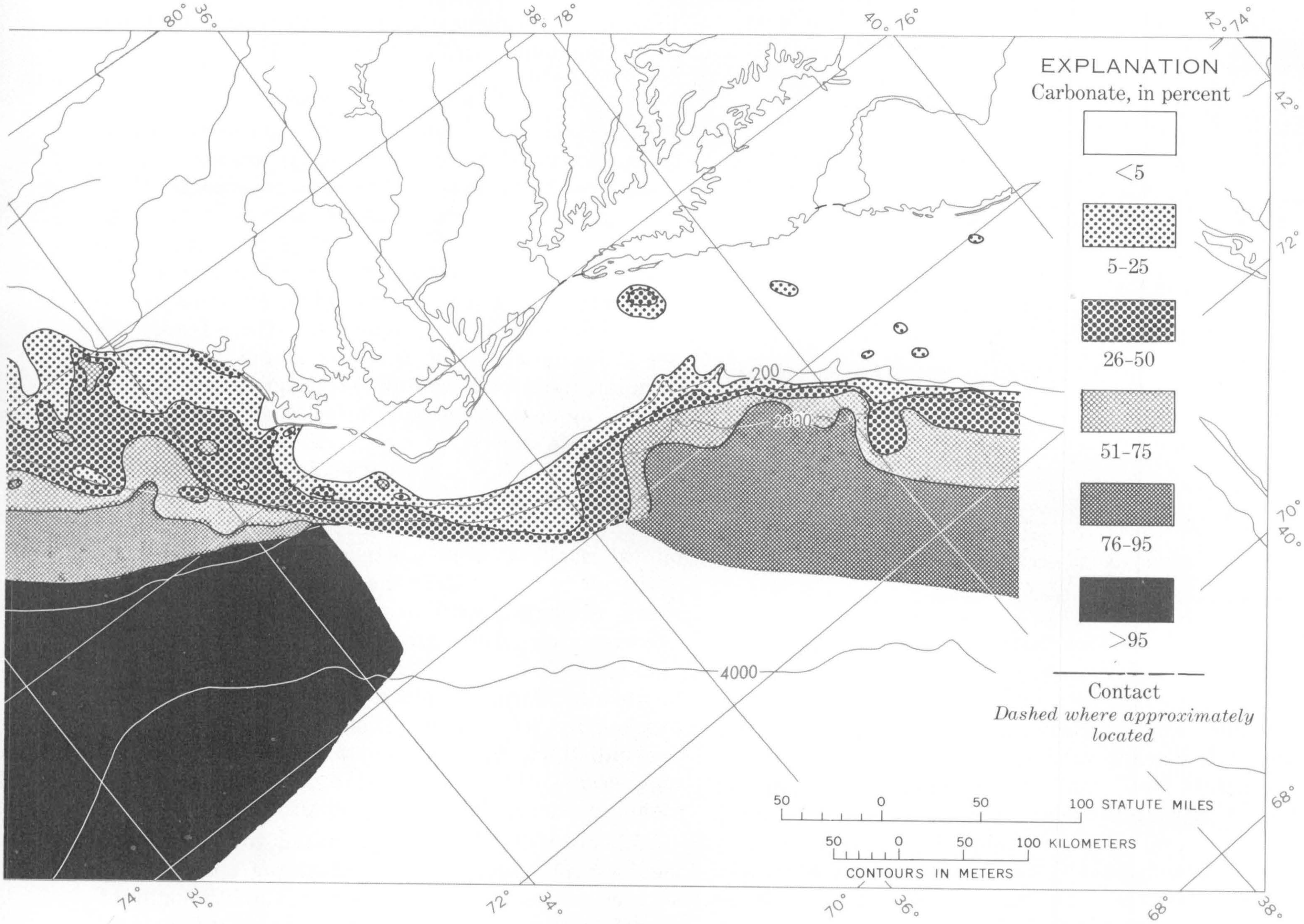
Pteropods are a common to minor component in the Blake Plateau sediments. Concentrations on the inner plateau commonly range from 10 to 25 percent, although, locally, they may reach more than 50 percent (pl. 4*E*).

Miscellaneous Skeletal Components

Ostracodes, decapods (crab carapaces), and calcareous spicules contribute trace amounts to the shelf carbonates. Fish otoliths are present in slope sediment. In no sample do any of these components compose more than 1 percent of the carbonate fraction, and the combined total generally averages much less than 1 percent.

Encrusted and Reworked Skeletal Fragments

In shelf sediments containing more than about 20 percent carbonate, a significant amount of the skeletal grains are encrusted or reworked. Boring organisms have destroyed the original structures of some grains, whereas other grains have been encrusted with algae, or micritic rims, or have been completely altered to micrite. In most sediments these altered fragments constitute 5–10 percent of



fraction of surface sediment off the Middle and Southern Atlantic States.

the carbonate fraction, but in some areas, such as Onslow Bay and the shelf near Jacksonville, Fla., the reworked fragments form more than 25 percent of the carbonate fraction, and are suspected to have been derived from nearby outcrops (pl. 5*A*).

Oolite

An ooid is defined by Newell, Purdy, and Imbrie (1960) as a grain that has one or more regular lamella formed around a nucleus, and whose constituent crystals show a systematic orientation with respect to the grain surface. Oolite (a deposit of ooids) is a prominent sedimentary component on the shelf south of Cape Hatteras (pl. 5*B*). These oolite deposits were first reported by H. C. Stetson (1938). Gorsline (1963) denied their presence, apparently mistaking them for phosphate pellets. Oolite in Onslow Bay and off Florida occurs in sediments relatively high in carbonate (averaging 50 and 72 percent, respectively). Oolite sediments off South Carolina and Georgia contain less carbonate, an average of 23 percent.

Most ooids are between 0.2 and 0.4 mm in diameter, and are yellow to black; generally, the outer laminae are darkest, and the center lightest (fig. 9*D*). The reason for these abnormally dark colors is probably related to the high iron content, ranging from 0.4 to 1.3 percent (Terlecky, 1967). Other than this high iron content, the ooids are apparently unaltered. Selected ooids studied contain between 85 and 95 percent aragonite; the remainder of the carbonate is magnesian calcite. Strontium averages about 1 percent (Terlecky, 1967), which agrees closely with modern Bahamian oolite (Kahle, 1965; Milliman, 1967).

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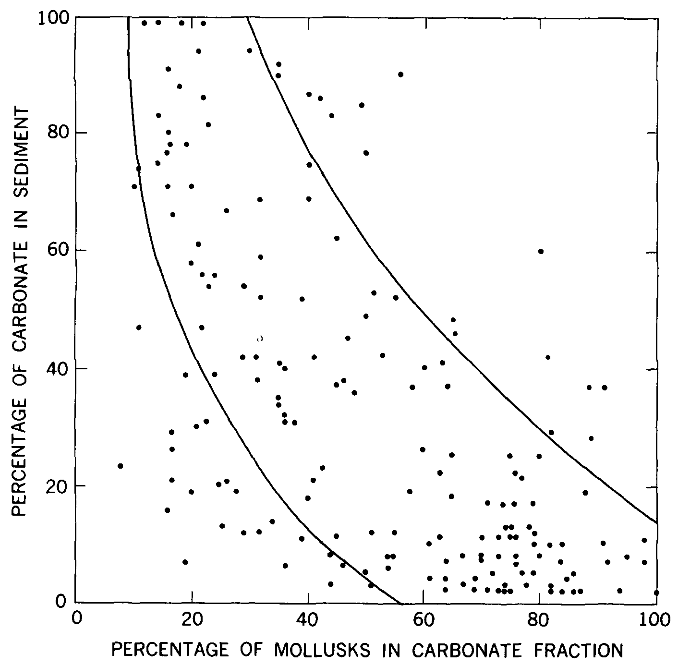


FIGURE 7.—Relation of mollusk content to carbonate content in the sand-sized fraction of shelf sediments south of Cape Hatteras. Curved lines envelop most values.

Ooids found off North Carolina have both carbonate and noncarbonate nuclei. The average nucleus represents the inner 40 percent (by diameter) of the ooids (Milliman and others, 1968). The South Carolina and Georgia ooids have predominantly quartz grains nuclei, which account for the inner 50–70 percent of the diameter. The shelf ooids off Florida are superficial, with only one or two coatings around a pelletoid or skeletal carbonate nucleus.

Pelletoids

Pelletoids are ellipsoidal to spheroidal grains that have a cryptocrystalline texture. Some grains have the internal consistency of fecal pellets, but many, especially those on the shelf off Florida, have been recrystallized, so that identification of the original texture is difficult. Some of these pelletoids may be ooids with random crystal orientation (Rusnak, 1960), reworked ooids, or recrystallized fecal pellets, (Illing, 1954).

Pelletoid distribution coincides closely with that of the oolite (pl. 5*C*). Sediments in the oolite areas of North Carolina, Georgia, and Florida commonly contain 5–20 percent pelletoids, but rarely more. It should be remembered, however, that many of the superficial Florida ooids have pelletoid nuclei, so that in total volume the pelletoids in this area are more abundant than shown on plate 5*C*.

Lithoclasts and Rock Outcrops

Lithoclasts are angular or rounded aggregations of grains cemented by a calcareous matrix and are considered to be clastic limestone fragments. Four basic types of lithoclasts are recognized on the continental shelf south of Cape Hatteras: quartzose, coquina, oolitic, and algal. Quartzose fragments (fig. 10*A*) are rich in quartz, with minor amounts of biogenic debris (commonly mollusks); these fragments are generally cemented with low-magnesium calcite. Coquina limestones contain large quantities of biogenic fragments, especially pelecypods, cemented by a carbonate matrix of either calcite or magnesian calcite (fig. 10 *B, C*). Barnacles, bryozoans, coralline algae, and oolite are sometimes present in these limestones. Two distinct oolitic lithoclasts are found on the shelf. One is a dense limestone, cemented with calcite (fig. 10*D*); the other is a porous limestone, cemented with aragonite (fig. 10*E*). Algal lithoclasts (fig. 10*F*) are composed of mollusks, barnacles, coral, Foraminifera, and algal fragments, cemented by coralline algae. Some algal limestones are heavily recrystallized, and the algal structures are indistinct, but they contain the same general magnesian calcite composition as unrecrystallized algal limestones (Macintyre and Milliman, 1971).

Lithoclast distribution is limited to a few sediment samples south of Cape Hatteras (pl. 5*D*). To supplement these distribution data, the lithologies of rocks dredged by Duke University (Menzies and others, 1966; Macintyre and Milliman, 1969, 1970; Milliman and others, 1968) and the U.S. Fish and Wildlife Service also were studied. The dredged rocks represent the same lithologies as the lithoclasts in the sediment samples, and together they give a fairly informative picture of the distribution of the various rock types on the shelf (pl. 6*A*).

Quartz-rich limestones mainly occur in Onslow Bay and along the inner shelf off Florida. In Onslow Bay the fragments are associated with phosphate and middle Tertiary fossils, including shark's teeth (fig. 10*G*), and probably were derived from middle Tertiary shelf outcrops which form a discontinuous band of banks across the entire middle of Onslow Bay (Radcliffe, 1914). Roberts and Pierce (1967) associate the outcrops with the Yorktown Formation (upper Miocene), whereas Pearse and Williams (1951) equated the outcrops near the New River (pl. 1) with the Trent Marl.

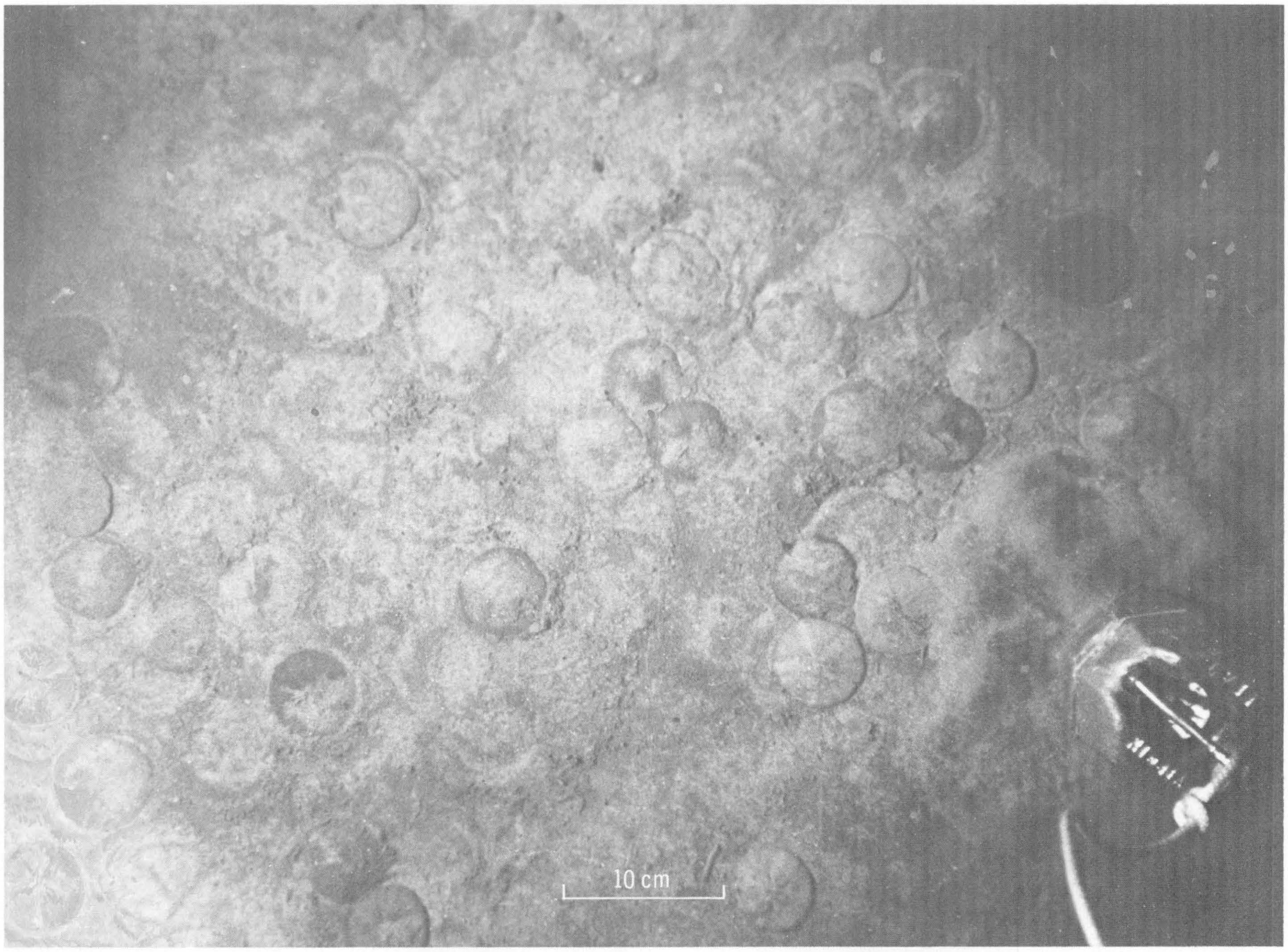


FIGURE 8.—Underwater photograph of *Echinarchinus parma* populations on the shelf off southern New Jersey. Station G 1343, water depth of 35 m. From Emery and others (1965).

The quartzose limestones off Florida are distinctively smooth but irregularly shaped (fig. 11). Some fragments contain large mollusk shells, but coquina is rare. Similar rock types are found in the Pleistocene (Sangamon?) limestone of the Anastasia Formation which stretches along the Florida coast, from Palm Beach to Jacksonville. This limestone has been thought to occur offshore and to form the substrate for marine encrustation (Multer and Milliman, 1967).

Dense coquina, cemented with low-magnesian calcite, occurs discontinuously along the inner shelf. Richards (1936), H. W. Wells and H. G. Richards (1962), and DuBar and Johnson (1964) have reported numerous nearshore coquina outcrops. Goode and associates (1888) found rocky shoals along the entire inner shelf from Cape Romain to northern Florida. R. C. Allen [2] has dredged and cored similar rocks from the shelf off northern Florida. Stratigraphic studies (Richards, 1936; H. W. Wells and H. G. Richards, 1962; DuBar and Johnson, 1964) suggest that these coquina outcrops are Pleistocene in age. DuBar and Johnson (1964) suggest a Sangamon age for the "Coquina" limestone that lines the beaches and nearshore areas of South Carolina and North Carolina. As already mentioned, the Anastasia limestone probably crops out offshore farther south. Thus, the inner shelf from central Florida to Cape Hatteras apparently is lined with Pleistocene outcrops, probably of Sangamon age.

Coquina present on the outer shelf of Onslow Bay is cemented with magnesian calcite. Preliminary studies of these fragments indicate that they are

[2] R. C. Allen, 1967, Florida SF cable route survey: Bell Telephone Laboratories, Chester, N.J., unpub. report, 45 p.

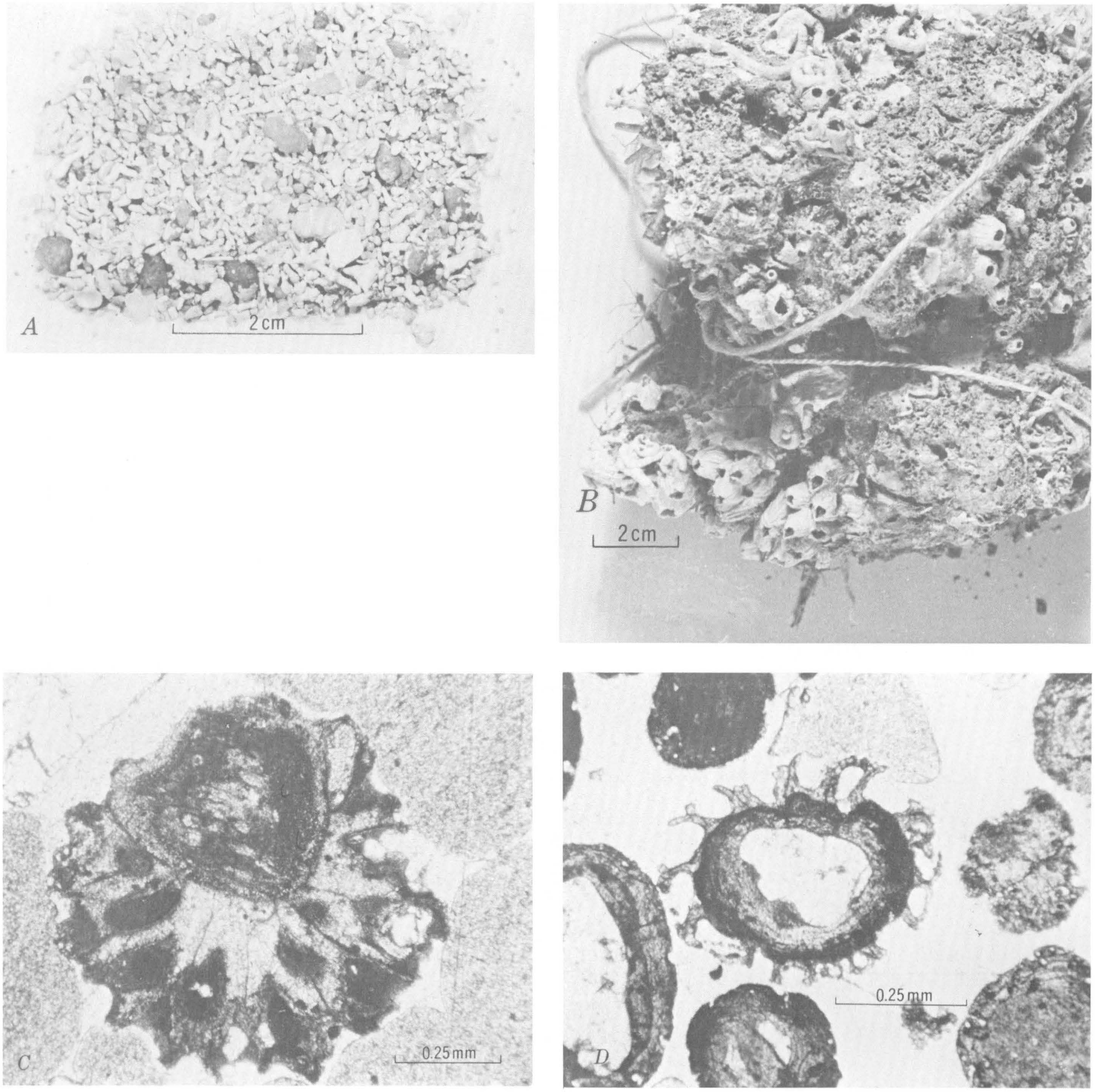


FIGURE 9.—Carbonate components of the sand-sized fraction. *A*, Photomicrograph of branching coralline algae from Onslow Bay, North Carolina. *B*, Barnacles encrusting an oolitic rock fragment. Sample was dredged from the central Florida shelf from a depth of 45 m, by the U.S. Fish and Wildlife Service. *C*, Photomicrograph (plane-polarized light) of the bryozoan *Discoporella* sp. which is a common component in the gravel and sand fractions of many sediments. *D*, Photomicrograph (plane-polarized light) of shelf ooids. Note that the dark color is generally restricted to their outer laminae.

fragments of beachrock, lithified during the last low stand of sea level (Macintyre and Milliman, 1970, 1971).

Oolitic limestones occur exclusively within deposits presently containing unlithified oolite. The oolitic lithoclasts in Onslow Bay are dense and cemented with low-magnesian calcite, suggesting that they were cemented by meteoric water during the last low stand of sea level (Milliman and others, 1968; see below). Oolitic limestone forms distinctive ridges, 5–15 m high that parallel much of the outer shelf off Florida (Macintyre and Milliman, 1969, 1970). These limestones are porous and are cemented by rims of aragonite (Macintyre and Milliman, 1970, 1971). Carbon-14 dates suggest deposition and lithification during the Holocene transgression (Macintyre and Milliman, 1970, unpub. data).

Algal limestones occur along the outer shelf and upper Florida-Hatteras Slope, in depths between 50 and 120 m. Off North Carolina these lithoclasts have been dredged from topographic highs termed algal ridges (Menzies and others, 1966; Zarudzki and Uchupi, 1968; Macintyre and Milliman, 1969, 1970). Dates for the unrecrystallized lithoclasts indicate deposition during the Wisconsin regression and Holocene transgression. One recrystallized rock, dredged from about 80 m, was dated at 26,250+900, –800 years B.P., suggesting that the algae lived during a prior lower stand of sea level and was recrystallized subaqueously (Macintyre and Milliman, 1970). Other algal rocks are found in the coral-reef environment south of Palm Beach, Fla.

A fifth limestone type, found only on the Blake Plateau, is composed of pelagic Foraminifera and pteropods, and is cemented with magnesian calcite. Lithification was probably subaqueous (Milliman, 1966; Fischer and Garrison, 1967; F. T. Manheim and R. M. Pratt, unpub. data).

CARBONATE ASSEMBLAGES

Sediments were classified into various assemblages on the basis of dominant carbonate components. Components constituting significant percentages (usually more than 20 percent) of the carbonate fraction define each assemblage. This type of classification has ecologic significance because it defines carbonate environments.

The most widespread carbonate assemblage on the shelf is the mollusk assemblage (pl. 7). Sediments of this assemblage contain relatively low amounts of calcium carbonate (3 percent north of Cape Hatteras and 12 percent to the south) and are dominated overwhelmingly by molluscan debris, principally the shells of infaunal pelecypods (table 2). These sediments occupy most of the shelf north of Cape Hatteras and most of the inner and middle shelf between Cape Hatteras and northern Florida. This assemblage decreases in importance offshore and to the south.

The echinoid-mollusk assemblage occurs in low-carbonate sediments that average 2 percent carbonate north of Cape Hatteras, and 5 percent, to the south. Echinoid plates contribute about one-half of the carbonate fraction, although southern sediments average somewhat less. Sediments characterized by this assemblage occur on the shelf off New Jersey and several smaller areas off Delaware, Maryland, and Pamlico Sound, and on the nearshore region of Long Bay.

TABLE 2.—*Carbonate assemblages on the continental margin, with average percentage of carbonate and diagnostic components*

[Tr., trace]

Carbonate assemblage	Average (and range) of $CaCO_3$ (percent)	Diagnostic components with average (and range) of each, in percent
Mollusk:		
North of Cape Hatteras	3 (Tr.–47)	Mollusk, 83 (64–100).
South of Cape Hatteras	12 (2–60)	Mollusk, 73 (46–98).
Echinoid-mollusk:		
North of Cape Hatteras	2 (Tr.–6)	Echinoid, 49 (20–100); mollusk, 43 (0–80).
South of Cape Hatteras	5 (2–13)	Echinoid, 30 (19–49); mollusk, 54 (39–73).
Benthonic Foraminifera-mollusk	2 (1–3)	Benthonic Foraminifera 42 (20–68); mollusk, 43 (14–69).
Barnacle-mollusk	55 (6–97)	Barnacle, 37 (20–53); mollusk, 47 (23–68).
Barnacle-coralline algae	61 (26–97)	Barnacle, 27 (5–55); coralline algae, 19 (8–43).
Oolite-pelletoid:		
Onslow Bay	50 (39–58)	Oolite, 26 (10–56); pelletoid, 11 (7–14).
South Carolina and Georgia	23 (12–39)	Oolite, 23 (0–35); pelletoid, 18 (12–24).
Florida	72 (45–94)	Oolite, 33 (11–56); pelletoid, 12 (11–56).
Coral reef	94 (80–99)	Coral, 13 (10–18); *Halimeda*, 17 (12–33); coralline algae, 25 (16–34).
Limestone outcrops	---------	Abundance of carbonate lithoclasts in sediment, especially gravel fraction.
Planktonic Foraminifera:		
North of Cape Hatteras	33 (3–90)	Planktonic Foraminifera greater than 90 percent.
South of Cape Hatteras	87 (54–99)	Do.
Glauconitic Foraminifera	52 (29–77)	Do.
Planktonic Foraminifera-pteropod	96 (88–99)	Planktonic Foraminifera, 70 (65–80); pteropod, 25 (15–55).
Planktonic Foraminifera-coral	90 (85–99)	Planktonic Foraminifera, 70 (65–80); coral, 25 (15–90).

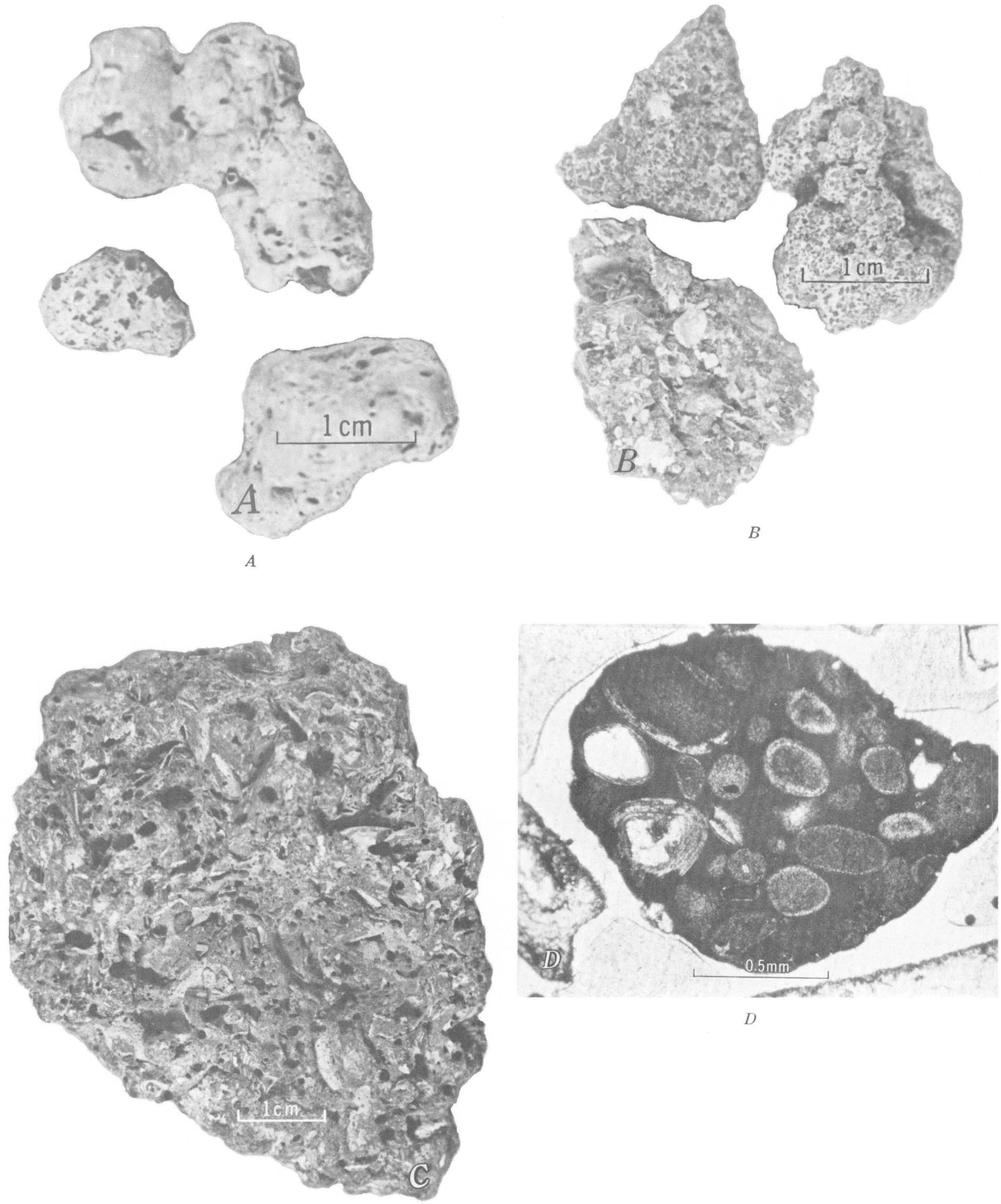
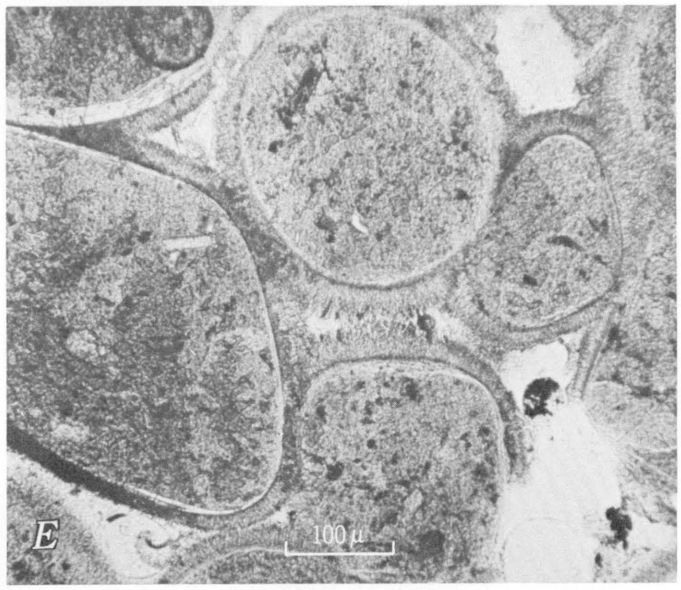


FIGURE 10.—Photomicrographs of lithoclasts. *A*, Quartzose lithoclasts; cement is low-magnesium calcite. *B*, Coquina lithoclast; cement is low-magnesium calcite. *C*, Section of coquina limestone dredged by I. G. Macintyre, Duke University. Cement is magnesium calcite. *D*, Thin section of oolitic lithoclast with low-magnesium calcite cement (plane-polarized

E



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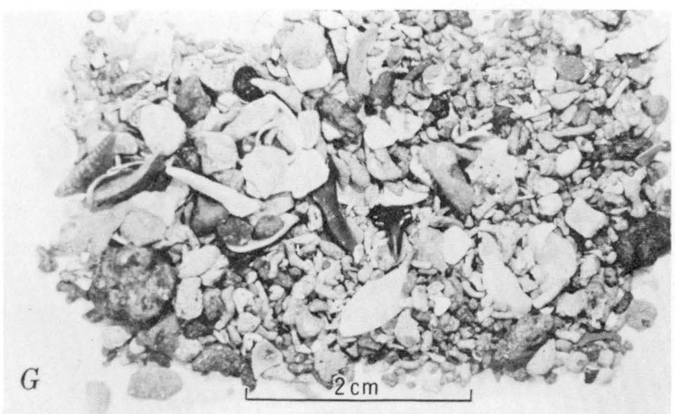

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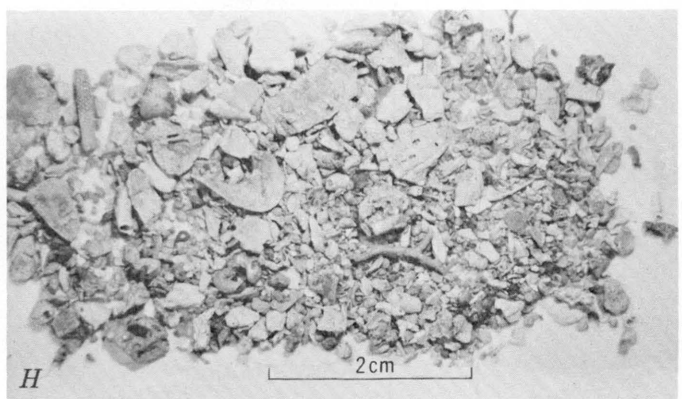

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light). *E*, Thin section of oolitic lithoclast with aragonitic cement (plane-polarized light). *F*, Algal limestone. *G*, Typical sediment from the Frying Pan Shoals phosphate outcrop in Onslow Bay. Note the Miocene shark's teeth in center of photograph. *H*, Algal-barnacle sediment.

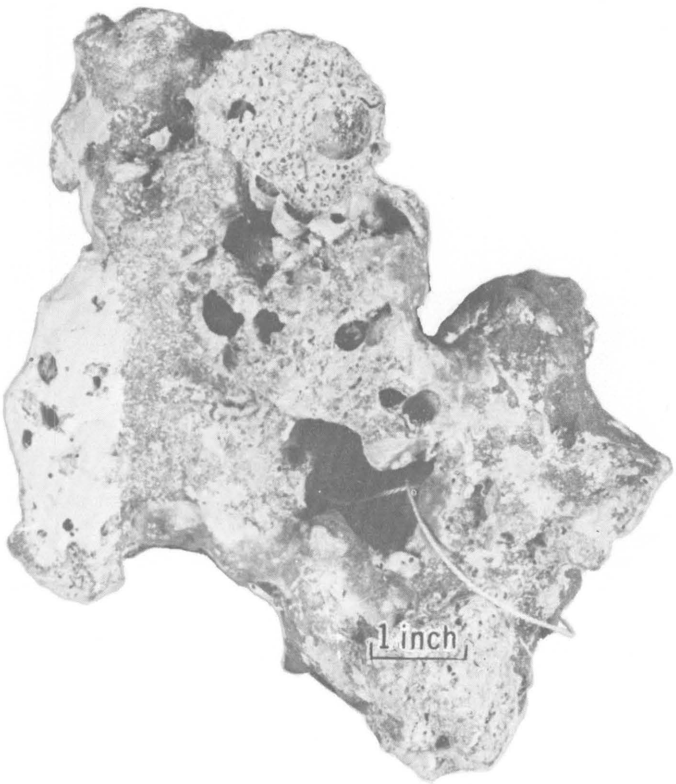


FIGURE 11.—Quartzose limestone fragment dredged from the Florida shelf by the U.S. Fish and Wildlife Service.

The benthonic Foraminifera-mollusk assemblage represents the third most abundant carbonate shelf assemblage north of Cape Hatteras. Sediments of this assemblage are characterized by extremely low carbonate contents, averaging about 2 percent (table 2). Foraminifera (mainly benthonic) and mollusks are present in about equal amounts. The assemblage is found mainly in very fine sands off Delaware and Chesapeake Bays.

The increased carbonate content in shelf sediments south of Cape Hatteras is reflected in the increased diversity of carbonate components contributing to the various assemblages (pl. 7). The barnacle-coralline algae assemblage characterizes relatively carbonate-rich sediments on the outer shelf and upper Florida-Hatteras Slope off the Carolinas (fig. 10*H*). These sediments apparently are derived from an algal ridge system that borders the upper slope and outer shelf edge. Carbon-14 dates plus petrographic studies indicate that this ridge system was actively growing during the last glacial regression and transgression (Menzies and others, 1966; Macintyre and Milliman, 1969, 1970). Apparently, ridge building ended when sea level was high enough to limit the growth of the hermatypic coralline algae. Similar ridge systems have been reported in other areas of the world, and ages of the algae recovered from these ridges agree closely with those off the east coast (Stetson, H. C., 1953; Ludwick and Walton, 1957; Nota, 1958; Koldewijn, 1958; Matthews, 1963; Allen, 1964; Williams, 1963; Harding, 1964; VanAndel and Veevers, 1967; McMaster and LeChance, 1969).

The barnacles probably represent a more recent addition to the sediment. Ross and others (1964), Wells, H. W., and others (1964), and Zullo (1966) all report active barnacle growth on the shelf off the Southeastern United States. The algal ridge system no doubt provided an excellent substrate for attachment. Swift currents in the area are probably also beneficial for barnacle growth. A similar origin is offered for the barnacle-mollusk assemblage off Florida. Average carbonate content of sediment in this assemblage is similar to the barnacle-coralline algae assemblage (table 2), but barnacles are more abundant (averaging 37 percent) and algae are practically absent. Apparently, barnacles are actively growing on the Anastasia limestone and oolitic outcrops exposed on the shelf off Florida (fig. 9*B*).

Although limestone outcrops are common over much of the shelf, they seldom dominate as a source of sediments. Most of the carbonates having large amounts of lithoclasts are nearshore in Onslow Bay and off Cape Romain. However, as mentioned in the preceding paragraphs, the large amounts of barnacles off Florida and the branching coralline algae off North Carolina, together with the many dredged limestones reported, suggest that outcrops are most important in providing substrate for marine organisms.

The oolite-pelletoid assemblage occurs on the middle and outer shelf south of Cape Hatteras. Oolite-pelletoid sediments in Onslow Bay average 50 percent carbonate and lie leeward of the barnacle-coralline algae assemblage. The South Carolina–Georgia oolite contains only about 23 percent of carbonate (owing to dilution by sediment from Piedmont rivers), whereas the Florida oolite assemblage averages about 72 percent carbonate. These southern oolitic sediments are on the outer shelf and rarely are bordered by the algal ridge.

Present-day oolite forms in warm or supersaline shallow marine waters (Rusnak, 1960; Newell and others, 1960). Modern oolites range in age from 300 to 700 years, although their inner laminae are often more than 2,000 years old, and their outer laminae are contemporaneous (Newell and Rigby, 1957; Martin and Ginsburg, 1966). Carbon-14 dates for northern oolites range from 22,000 to 29,000 years old, whereas the Florida oolites are generally much younger, mostly less than 15,000 years (Terlecky, 1967; Pilkey and others, 1966; Milliman and Emery, 1968). Assuming that ooids are in isotopic equilibrium with their depositional environment (Lowenstam and Epstein, 1957), the δO^{18} values for North Carolina and Florida oolite samples (+1.84 to +2.01 ‰; table 3) suggest either an environment of low temperatures (at present-day salinities) or high salinities (at present-day temperatures). Since ooids generally require warm temperatures in which to form, a supersaline lagoonal environment, such as Laguna Madre (Rusnak, 1960) might be envisioned, although this would require a climate more arid than present. Such lagoons might have formed behind offshore bars during regression and behind coastal dunes during transgression.

TABLE 3.—*Stable carbon and oxygen isotopes in continental shelf oolites (relative to the Chicago PDB standard)*

[Determinations by E. T. Degens and W. G. Deuser, Woods Hole Oceanographic Institution]

Sample	δO^{18} (‰)	δC^{13} (‰)
1534 (Florida)	+1.89	+4.10
1806 (Onslow Bay)	+1.84	+3.52
1847 (Onslow Bay)	+2.01	+4.77
1847 (inner ½)	+1.96	+4.68
Average Bahamian oolite (after Lowenstam and Epstein, 1957)	−0.1	+5.0

Coral reef sediments are characterized by high carbonate content (greater than 94 percent) and the presence of *Halimeda*, coralline algae, and hermatypic coral, and are restricted to sediments south of Palm Beach. North of this area, winter temperatures are lower than 20°C (Emery, 1966), the approximate lower tolerance limit of most reef corals (Wells, J. W., 1957). Similar concentrations of *Halimeda*, coralline algae, and coral are found in the forereef sediments in the Florida Keys (Ginsburg, 1956).

Continental slope sediments are dominated by planktonic Foraminifera, and three distinct subassemblages can be recognized. North of Cape Hatteras the sediments are relatively low in carbonate, averaging 33 percent. The glauconitic assemblage on the Florida-Hatteras Slope from Cape Lookout to Georgia contains somewhat more carbonate (52 percent), and the southern slope and the Blake Plateau planktonic foraminiferal sediments average 87 percent carbonate.

Two other deep-water assemblages can be recognized; a planktonic Foraminifera-pteropod assemblage scattered over the Blake Plateau, and a planktonic Foraminifera–coral assemblage on the inner Blake Plateau and the Florida Straits. The gravel fraction generally consists of coral, and the finer sediments consist of Foraminifera. These coral-rich sediments coincide with coral banks that have been reported in the area (Stetson, T. R., and others, 1962; Milliman and others, 1967).

THE NONCARBONATE FRACTION

SIZE DEPENDENCY OF NONCARBONATE COMPOSITION

Most carbonate particles are products of their environments, and, as such, can influence sediment size. In contrast, terrigenous components that are transported to their site of deposition are dependent upon both sediment size and density. In turn, the composition of a terrigenous sediment is dependent upon the relative ability of components to resist comminution and thus also upon particle size. For example, the ratio of feldspar to quartz changes markedly with grain size, the less stable feldspar increasing with decreasing size (Martens, 1931; Russell, 1935); fig. 12, this report). Therefore, different sizes of the same sediment may show different compositions, whereas similar sizes of different sediments may show similar compositions. To delineate this size effect, the same size fraction from each sediment sample was studied. The 2–3 phi (125μ to 250μ) size was chosen because it is present in all sized sediments.

NONCARBONATE COMPONENTS

Quartz and Feldspar

Quartz and feldspar generally constitute more than 95 percent of the insoluble residue on the continental shelf (pl. 8*A*). Dilution by mica and siliceous organic debris lowers the amount of quartz and feldspar on the slope north of Cape Hatteras. South of the cape, quartz and feldspar proportions are decreased by the abundance of glauconite.

The ratio of feldspar to quartz and feldspar varies greatly with location (pl. 8*B*). Most shelf sediment is arkosic to subarkosic north of Cape Hatteras and orthoquartzitic to orthoquartzitic-subarkosic south of the cape. Tongues of arkosic sands extend across the shelf from both the Delaware and Chesapeake Bays. Although these two estuaries appear to be the obvious sources for the arkosic

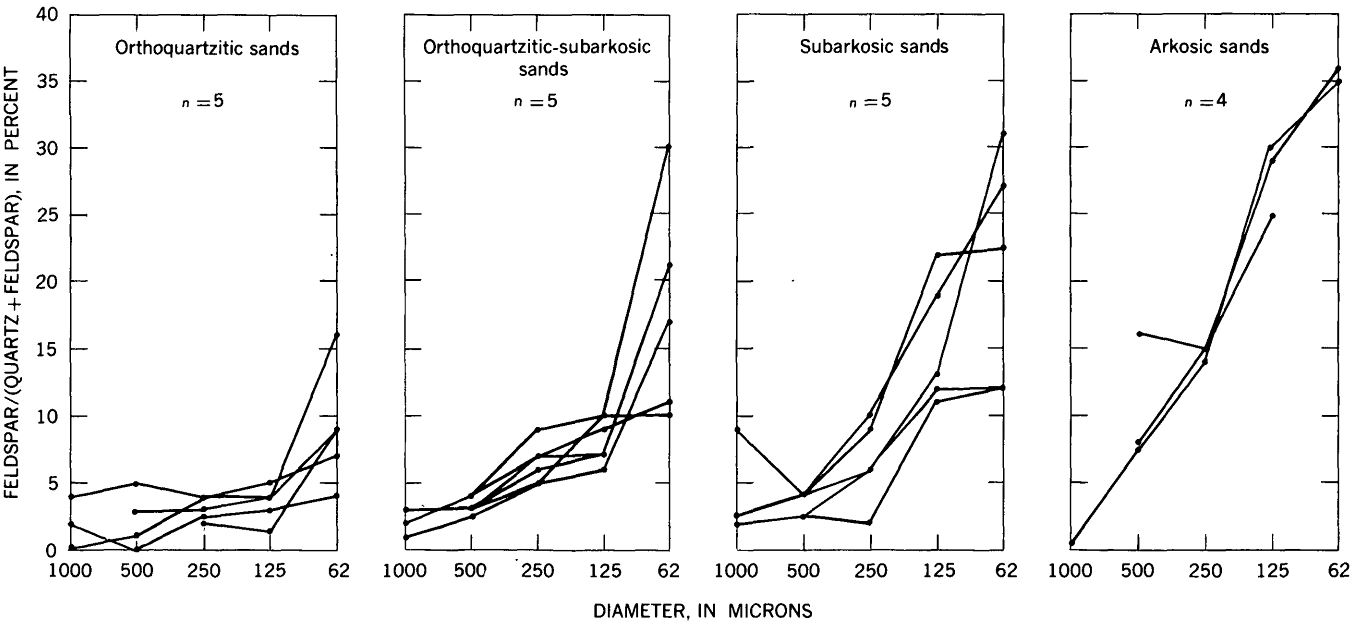


FIGURE 12.—Variation of the feldspar/quartz + feldspar ratio with grain size. Each of the four sediment types is defined on the basis of the $f/q+f$ ratio in the 125μ- to 250μ-sized fraction.

sediments, the age of the deposits is open to question (see discussion below). The rest of the sediment north of Cape Hatteras (and extending into the northern half of Raleigh Bay) is predominantly subarkosic, with an average feldspar content of 10–20 percent.

To the south the sands generally contain less than 10 percent feldspar. Two bands of subarkosic sands, however, extend seaward from Cape Lookout and Cape Fear, suggesting derivation from Bogue Sound and Cape Fear respectively. A large patch of orthoquartzitic sand occupies much of the Onslow Bay shelf; feldspar values commonly are less than 3 percent. Between Cape Romain and northern Florida, nearshore sand is subarkosic with feldspar values generally between 10 and 15 percent. This subarkosic band is widest off South Carolina and central Georgia and gradually decreases to the south, apparently disappearing at Cape Kennedy. This band of subarkosic sand corresponds rather closely to the band of turbid water observable between Capes Romain and Kennedy from the air (R. H. Meade, oral commun., 1969). The location and distribution of these sediments suggests that they have been derived from the nearby Piedmont rivers. Most of the middle and outer shelf sands south of Cape Romain contain less than 10 percent feldspar. South of Georgia the sediment becomes highly orthoquartzitic.

The difference between terrigenous shelf sediments north and south of Cape Hatteras probably reflects the different sources of the component particles. To the north, rivers drain predominantly Paleozoic formations, many of which have been metamorphosed, and erosion is largely mechanical. As a result, feldspar is a common sedimentary component. Southern rivers carry large quantities of highly weathered and lateritic Piedmont and Coastal Plain soils, resulting in relatively low feldspar content. Highly orthoquartzitic sediments may also be derived from local Coastal Plain outcrops, such as those in Onslow Bay. Differential abrasion during long-shore transport may explain the low feldspar content in the Florida shelf sands.

Slope sediments north of Cape Romain contain feldspar concentrations similar to those on the adjacent shelf, and basic trends are normal to the coastline. In contrast, shelf and slope feldspar ratios south of Cape Romain parallel the coast; this may be a result of the streamlining effect of the Florida Current.

Feldspar content on the upper slope off South Carolina and Georgia is greater than 15 percent, and off Florida it reaches 35 percent of the noncarbonate fraction. It is not likely that such highly feldspathic sands were derived from the Piedmont rivers that presently are contributing relatively feldspar-poor sediments. A northward transport by the Florida Current seems equally unlikely because southern sediments are dominantly carbonate. The most reasonable explanation is that the arkosic slope sands were derived from older strata that crop out on the slope. Hathaway, McFarlin, and Ross (1970) have shown that feldspar increases greatly relative to quartz in pre-Pliocene sediments cored during JOIDES[3] I off Jacksonville, Fla. Seismic evidence (Emery and Zarudzki, 1967) suggests that Miocene strata lie near the present Florida-Hatteras Slope surface, and thus could provide a possible source for the feldspathic sands.

The reader is cautioned that this discussion is based only on the 125μ- to 250μ-sized fraction. Because most shelf sediments are medium to coarse sand, and most slope sediments are mud, the distributions of quartz and feldspar shown on plate 8*A*, *B* do not accurately portray the character of the different sediments of the continental margin. If size were taken into account, most shelf sediments would appear more orthoquartzitic and the slope sediments more arkosic.

Glauconite

The term "glauconite" refers to green to black polylobate grains and casts, often composed of illite or illite-montmorillonite; no mineralogical definition is implied in its usage in this paper. Glauconite is common, although not abundant, on the outer shelf of the Southeastern United States, forming 1–5 percent of the noncarbonate fraction. On the upper Florida-Hatteras Slope south of Cape Hatteras, however, glauconite forms a dominant sediment type (pl. 8*C*); in those slope sediments containing more than 5 percent glauconite (within the noncarbonate fraction), the average concentration is about 45 percent.

Several classifications of glauconite have been proposed. Burst (1958) and W. L. Pratt (1963) used mineralogy, morphology, and color to distinguish the various types. Ehlmann, Hulings, and Glover (1963) based their classification of southeastern Atlantic grains on color (light, medium, and dark). The author used this latter scheme, and estimated the relative abundance of each color with a binocular microscope. In most samples, one color was clearly dominant, so that color trends were obvious (fig. 13).

Dark-colored glauconite grains are dark green to black and are mostly irregular and rounded lobes, often polished and sometimes cracked. Most grains are free of encasing organic tests, hence giving the sediments in which they abound a green to black color (fig. 15*G*, left). Some polished peletoidal grains look like replacements of ooids or fecal pellets; the more polylobate forms may be abraded foraminiferal casts, but most grains do not exhibit shapes suggestive of their origin. Abrasion, which undoubtedly was responsible for much of the rounding and polishing, apparently altered the original shapes.

[3] JOIDES, Joint Oceanographic Institutions' Deep-Earth Sampling Program.

Glauconitic sediments dominated by dark grains are concentrated on the upper Florida–Hatteras Slope, from Cape Fear to Charleston. Average water depth is about 280 m. These sediments tend to be free of silt and clay (averaging less than 8 percent finer than 62μ) and relatively low in calcium carbonate (46 percent within the sand fraction). The insoluble 125μ to 250μ-sized fraction contains an average of 69 percent glauconite (table 4).

TABLE *4*.—*Glauconite grain characteristics in glauconite-rich sediments south of Cape Hatteras*

[Ranges of values are in parentheses. Tr., trace]

Dominant glauconite color	Average			Average percent glauconite in—	
	Water depth (meters)	Percent $CaCO_3$	Percent silt and clay	Insoluble 125μ- to 250μ-sized fraction	Total 125μ- to 250μ-sized fraction
Dark	283 (117–499)	46 (29–70)	8 (Tr.–47)	69 (33–95)	37
Medium	360 (185–504)	68 (38–91)	11 (Tr.–82)	72 (46–97)	24
Light	402 (85–881)	80 (48–95)	26 (Tr.–97)	49 (2–98)	10

Black grains dominate glauconite north of Cape Hatteras. These sediments, however, contain relatively low amounts of glauconite, never more than 10 percent of the insoluble 125μ- to 250μ- sized fraction. The dark grains are mainly rounded pellets. Shelf sediments in several areas, such as off the Delaware, Chesapeake, and Pamlico estuaries, also contain small quantities of these grains.

Medium-colored glauconite is light olive to emerald green, is less rounded than the darker varieties, and is more polylobate, often having foraminiferal shapes. The lower degree of rounding is also reflected by the decreased polish and by the fact that surface cracks are more common than on darker grains. Because the grains are seldom encased by carbonate organisms, medium-colored glauconitic sediments have an obvious greenish color. These sediments lie in a near-continuous belt from Cape Lookout to northern Florida, in depths averaging 360 m. The sediments contain similar concentrations

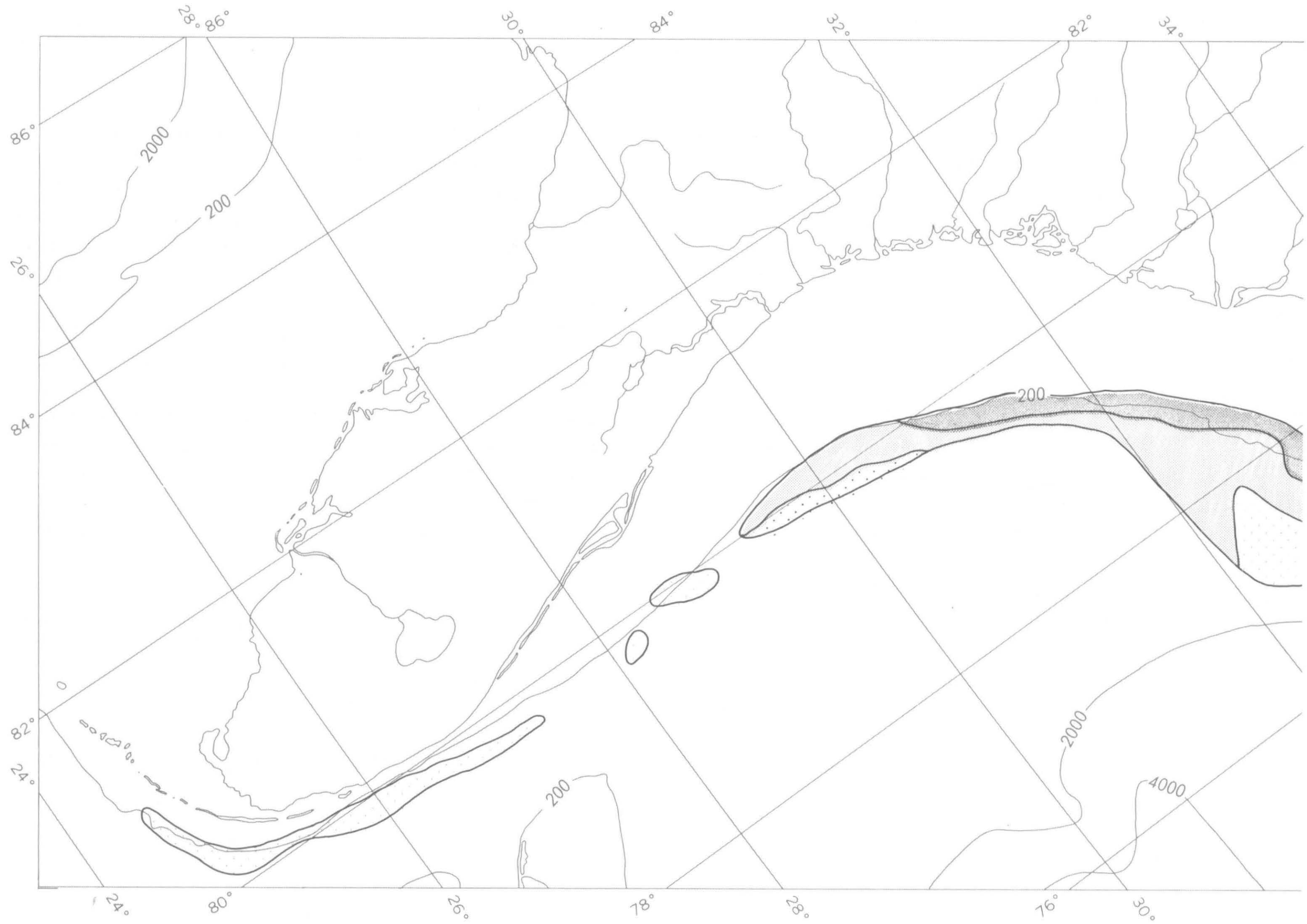


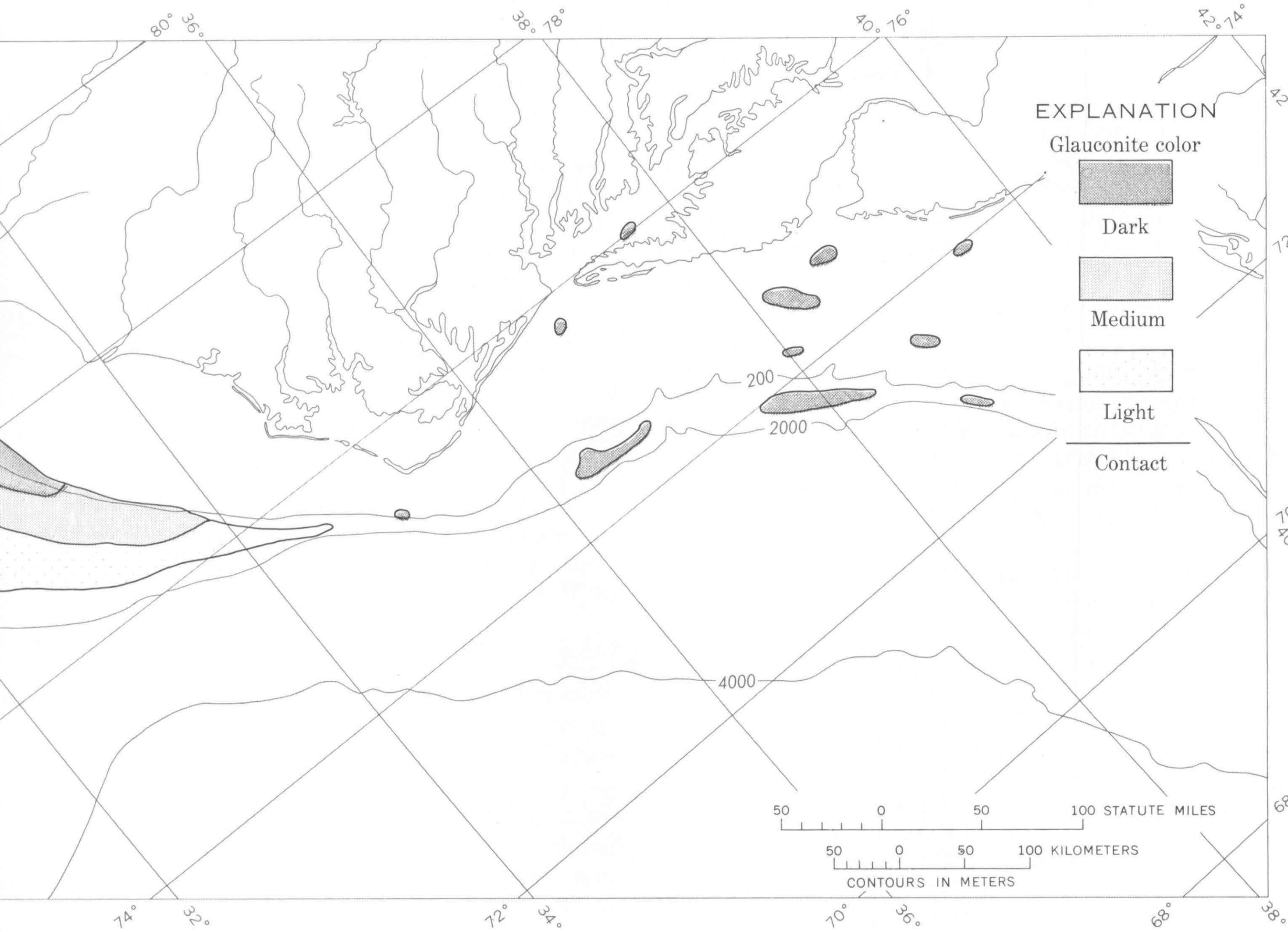
FIGURE 13.—Map showing distribution of dark-, medium-, and light-colored glauconitic

of silt and clay (11 percent) and glauconite (72 percent of the insoluble fraction) as the darker sediments, but, because of their greater carbonate content (68 percent), the medium-colored sediments actually contain appreciably less glauconite (table 4, col. 5).

Light-colored glauconite grains are greenish white and light green, with granular and dull surface textures. Rounding and abrasion apparently have not altered the original shapes significantly. Some light grains are internal casts of gastropods, pteropods, echinoids, and sponges, but most are polylobate casts of planktonic Foraminifera. W. A. Berggren (oral commun., 1968) identified the light glauconitic casts as Quaternary in age, on the basis of *Globorotalia truncatulinoides* casts. Most of these grains are still incorporated within their foraminiferal tests and become visible only after acid leaching.

Light-colored glauconite sediments dominate two areas. From Cape Hatteras to northern Florida, light glauconite is seaward of the dark and medium colors, at an average depth of 510 m. Off central and southern Florida, all glauconitic sediments are light (fig. 13); depth averages 280 m. Because of the high carbonate content, the actual amount of glauconite in these sediments is rather low (table 4).

Ehlmann, Hulings, and Glover (1963), Bell (1966), and Dill (1969) studied the mineralogy and chemistry of the Atlantic slope glauconite. Bell (1966) found the light grains to be composed of a mixed-layer silicate, probably montmorillonite-illite; the dark grains are illite with some chlorite. X-ray diffractograms of the dark grains have sharp peaks,



surface sediment (125μ- to 250μ-sized fraction) off the Middle and Southern Atlantic States.

indicating that the grains are composed of nonexpandable clays. The darker grains also contain more potassium and less water than the light grains; apparently, cracks in the darker grains formed during dehydration (Ehlmann and others, 1963). All these factors suggest that the darker grains are more mature and therefore probably older than the lighter grains.

Data presented in this paper support conclusions made by earlier workers. The muddy sediments in which light glauconite generally is found contain montmorillonite, illite, and kaolinite (J. C. Hathaway, oral commun., 1968), thereby providing an obvious source for the montmorillonite-illite mixtures found within the light-colored casts. Light grains are encased by Quaternary Foraminifera, such as *Globorotalia truncatulinoides*. In contrast, the rounded polished dark glauconitic sands south of Cape Hatteras are practically devoid of fine sediment, hence offering no immediate source for the clay within the casts. Moreover, the illite composition of the glauconite casts does not correspond with the composition of those sparse clays that are available within the sand (see above). These glauconitic sands probably were derived and winnowed from neighboring middle Tertiary glauconitic-phosphate outcrops that are prominent in the upper Florida-Hatteras Slope in the Cape Fear to Cape Romain area.

Black glauconite grains on the shelf and slope north of Cape Hatteras also probably come from older units. The Cretaceous and lower Tertiary sands of New Jersey offer an obvious source, and the glauconite on the shelf seems to be seaward of the estuaries that drain these glauconite-rich strata. Therefore, it seems possible that the glauconite on the shelf is detrital, transported by the rivers. Speculation on the source of the slope glauconite north of Cape Hatteras provides more difficulties. Seismic reflection profiles show that the slope has been accreting since the Teritary (Uchupi, 1970), suggesting that the glauconite-bearing strata are deeply buried. Slumping, submarine erosion, or land transport may have contributed to the glauconite present in modern sediments.

Phosphorite

Phosphorite contributes generally less than 1 percent of the insoluble fraction (125μ to 250μ), although, locally, it can be a common constituent, especially in phosphorite gravels (pl. 6*B*). Coarser phosphorite on the shelf south of Cape Hatteras is mainly black and amber pellets and scattered shark's teeth and phosphatic limestone fragments. Pevear and Pilkey (1966) noted that amber grains are slightly less abundant on the shelf and totally absent in estuaries; they suspect that the black color may be due to pyrite formation in the reducing estuarine environment.

Highest phosphorite concentrations on the shelf are found in a band across the middle of Onslow Bay, from Cape Fear to Cape Lookout. Luternauer and Pilkey (1967) found that the phosphorite on Frying Pan Shoals exceeds 14 percent of the total sediment, and that most of the sediments in the middle of Onslow Bay contain more than 3 percent. On a carbonate-free basis these values would be much higher. This phosphorite was probably derived from the middle Tertiary outcrops in this area (see above). Significant concentrations of phosphorite are found also in the sands of estuaries and nearshore areas of South Carolina, Georgia, and Florida (Pevear and Pilkey, 1966). Large angular phosphate fragments have been found in several South Carolina and Georgia estuaries, notably the Edisto, Savannah, and St. Mary's Rivers, which undoubtedly were derived from nearby Miocene outcrops (Malde, 1959; Herrick and Vorhis, 1963; Darby and Hoyt, 1964).

Abundant quantities of phosphatic rocks have been dredged from the Florida-Hatteras Slope and from the Blake Plateau. The slope rocks, with glauconitic foraminiferal casts, have freshly broken surfaces, thereby suggesting that they were dredged from outcrops. These phosphatic rocks are especially prominent on the slope seaward of Cape Romain but are also found from Cape Fear to northern Florida. Gorsline and Milligan (1963) have reported phosphatic bones, nodules, and conglomerates on Pourtales Terrace south of the Florida Keys. Fossil evidence (Gorsline and Milligan, 1963; F. T. Manheim and R. M. Pratt, unpub. data) suggests a middle Tertiary age for these phosphates.

Phosphatic rocks also cover much of the present-day surface of the Blake Plateau off South Carolina and in the Straits of Florida off southern Florida. R. M. Pratt and P. F. McFarlin (1966) classified the Blake authigenic deposits into phosphate nodules, manganese nodules, and manganese slabs; however, even the manganese deposits contain appreciable, even dominant, amounts of phosphate. Apparently, these rocks represent several generations of reworking and cementing of phosphatic gravels derived from nearsurface middle Tertiary outcrops. The complex petrology, mineralogy, chemistry, and history of these deposits is being studied by F. T. Manheim and R. M. Pratt (unpub. data).

Rock Fragments

The 125μ- to 250μ-sized fraction seldom contains more than a few percent rock fragments. Weathering is particularly effective in decomposition of rock fragments in these finer sized fractions; hence, their contribution is slight. The coarser fractions north of Cape Hatteras and seaward of the southern Piedmont rivers, however, do contain appreciable amounts of rock fragments.

Mica

Sediment in every major river and estuary contains mica. Mica flakes, however, are almost totally absent in shelf sediments. The only areas where mica occurs in more than trace amounts is seaward of Delaware and Chesapeake Bays, and in a few isolated nearshore patches along the southeastern coast (pl. 8*D*). Doyle, Cleary, and Pilkey (1969) report that the outer shelf of Long Bay contains the richest concentrations on the southeastern shelf, although concentrations seldom reach one-half percent. Slope sediments commonly contain mica concentrations between 1 and 10 percent of the insoluble 125μ- to 250μ-sized fraction; off Cape May, mica values are greater than 25 percent. Mica is almost totally lacking in the glauconitic sands on the Florida-Hatteras Slope, but it is present in the glauconitic muds off central Florida and Georgia.

Because it is hydraulically equivalent to finer spherical grains, mica generally is associated with fine-grained sediments. The presence of mica, therefore, can be used as one indication of fine sediment accumulation. On the shelf such areas are mostly limited to the nearshore, near large estuaries.

Siliceous Biologic Remains

Spicules, probably derived from sponges, are present in the Florida-Hatteras Slope sediments (pl. 8*E*). They are most common in sediments with high carbonate content; those sediments with more than 3 percent spicules in the insoluble fraction contain about 90 percent carbonate. Spicules in a sample seaward off the Florida Keys makeup 90 percent of the insoluble fraction. In most other samples, spicules are less than 5 percent.

Radiolarians are in greatest abundance on the middle and lower continental slope off Delaware, where they reach as much as 40 percent of the insoluble 125μ to 250μ-sized fraction (pl. 8*F*). Slope sediments south of Cape Hatteras also contain radiolarians, but do not exceed 5 percent. Sediments containing appreciable amounts of radiolarians are generally high in carbonate; those sediments containing more than 1 percent, average 82 percent carbonate.

Diatoms are present in trace amounts in many slope samples. In none of the samples studied, however, did they form more than 1 percent of the insoluble fraction.

The high carbonate content associated with sediments containing siliceous tests and spicules suggests that present-day detrital sedimentation is relatively unimportant. Thus, the contribution of pelagic (radiolarians and diatoms) and benthonic (sponges) siliceous tests are relatively great compared to detrital minerals.

Miscellaneous Noncarbonate Components

Cellulose fibers and plant material are found only in estuarine sediments, especially in Upper Chesapeake Bay. These particular estuarine sediments are also associated with large quantities of coal (Ryan, 1953). North of Annapolis the 125μ- to 250μ-sized fraction generally contains more than 75 percent coal and plant debris. The coal comes from anthracite mining activities along the Susquehanna (Meade, 1969b) and probably from the dumpings of barges that transport coal for use in this area. Sediments in the Potomac River and Tangier Sound also contain a significant amount of plant material. The only other areas with significant amounts of plant material are in the southern Georgia estuaries, notably Ogeechee and St. Marys Rivers.

Some river sediments also contain trace amounts of fine-grained silt and clay bound into pelletal shapes and assumed to be of fecal origin. Most abundant concentrations are found in the Ogeechee River, in which the 125μ- to 250μ-sized fraction contains about 1 percent fecal pellets.

BEACH SANDS

Thirty-two beach samples collected by John M. Zeigler were analyzed. Beach sands characteristically contain very low carbonate concentrations north of Cape Kennedy (fig. 14). Only in Raleigh Bay and in northern Florida does the carbonate exceed 10 percent. South of Palm Beach the carbonate increases markedly and reaches nearly 100 percent in the Florida Keys. Mollusks contribute most of the beach carbonate, although some oolite is present near Palm Beach. The Florida Keys sediment is derived from nearshore reefs and is composed chiefly of coral, *Halimeda,* and coralline algae.

Most of the beach sands north of Cape Hatteras are subarkosic to arkosic. Sands are dominantly quartzose-arkosic south to Georgia and quartzose further south. The fact that these sediments are slightly less felspathic than the nearshore shelf sands indicates a greater maturity. This may be related to greater reworking, perhaps through longshore transport.

DISCUSSION

SEDIMENT TYPES AND THEIR DISTRIBUTION

The sediments on the Middle and Southern Atlantic continental margin can be classified on the basis of various textural and compositional properties. The most diagnostic parameters are size, percent carbonate, and feldspar content; but carbonate assemblages and glauconite content are also important. The nine sediment types are given in table 5 and shown on plate 9*A*.

1. On the shelf very fine sands and muds are found close to shore and adjacent to major estuaries (pl. 9*A*; fig. 15*A*). These sediments contain very little calcium carbonate (less than 2 percent), and are arkosic off Chesapeake and Delaware Bays and subarkosic to the south. The nearshore sands south of Cape Hatteras extend no more than 20 km offshore. Although the 18-km sampling grid (together with the shallow depth) limited nearshore sampling, studies by O. H. Pilkey (Pilkey and Frankenburg, 1964; O. H. Pilkey, oral commun., 1968) show that this belt is more or less continuous along much of the southeastern coastline.

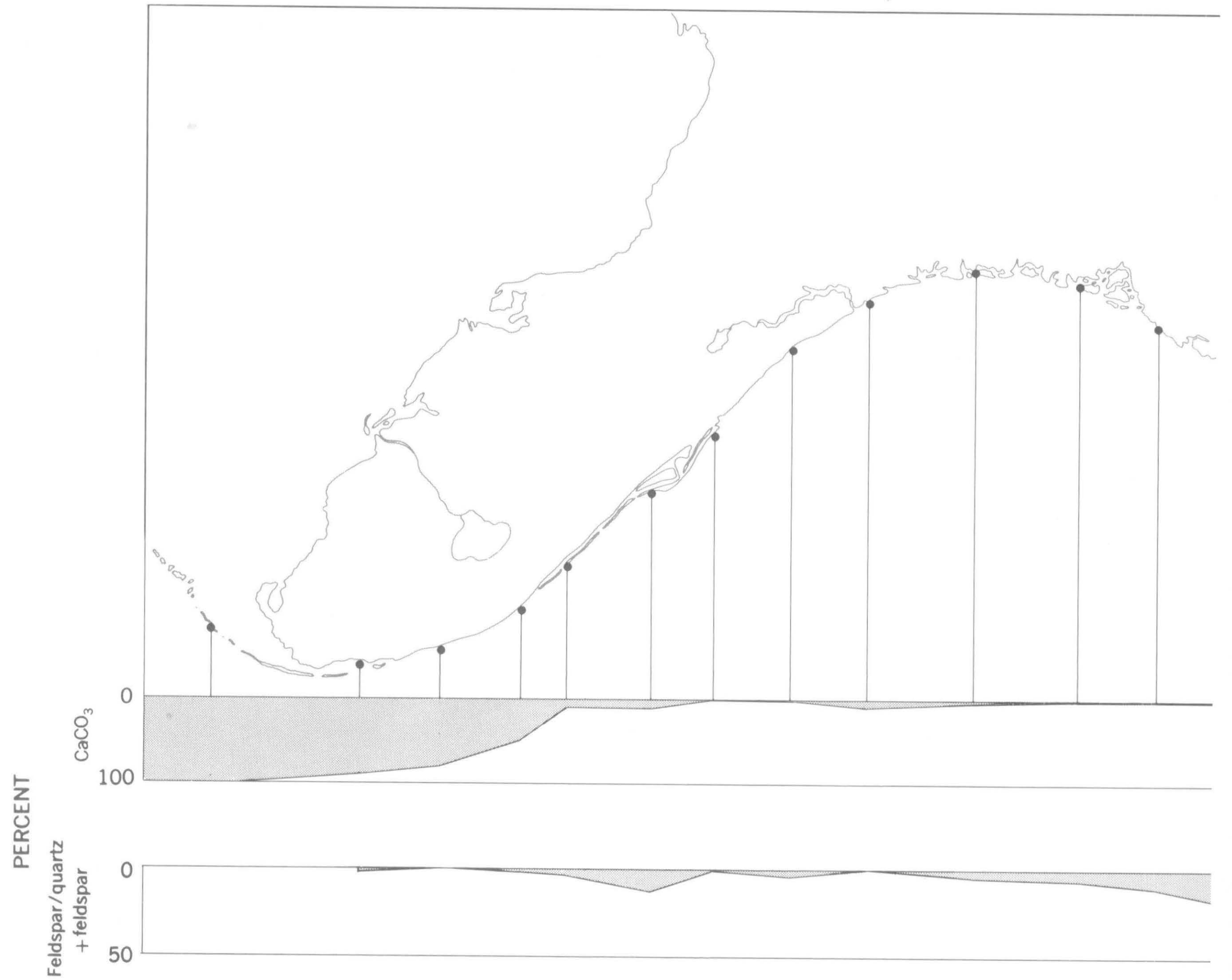
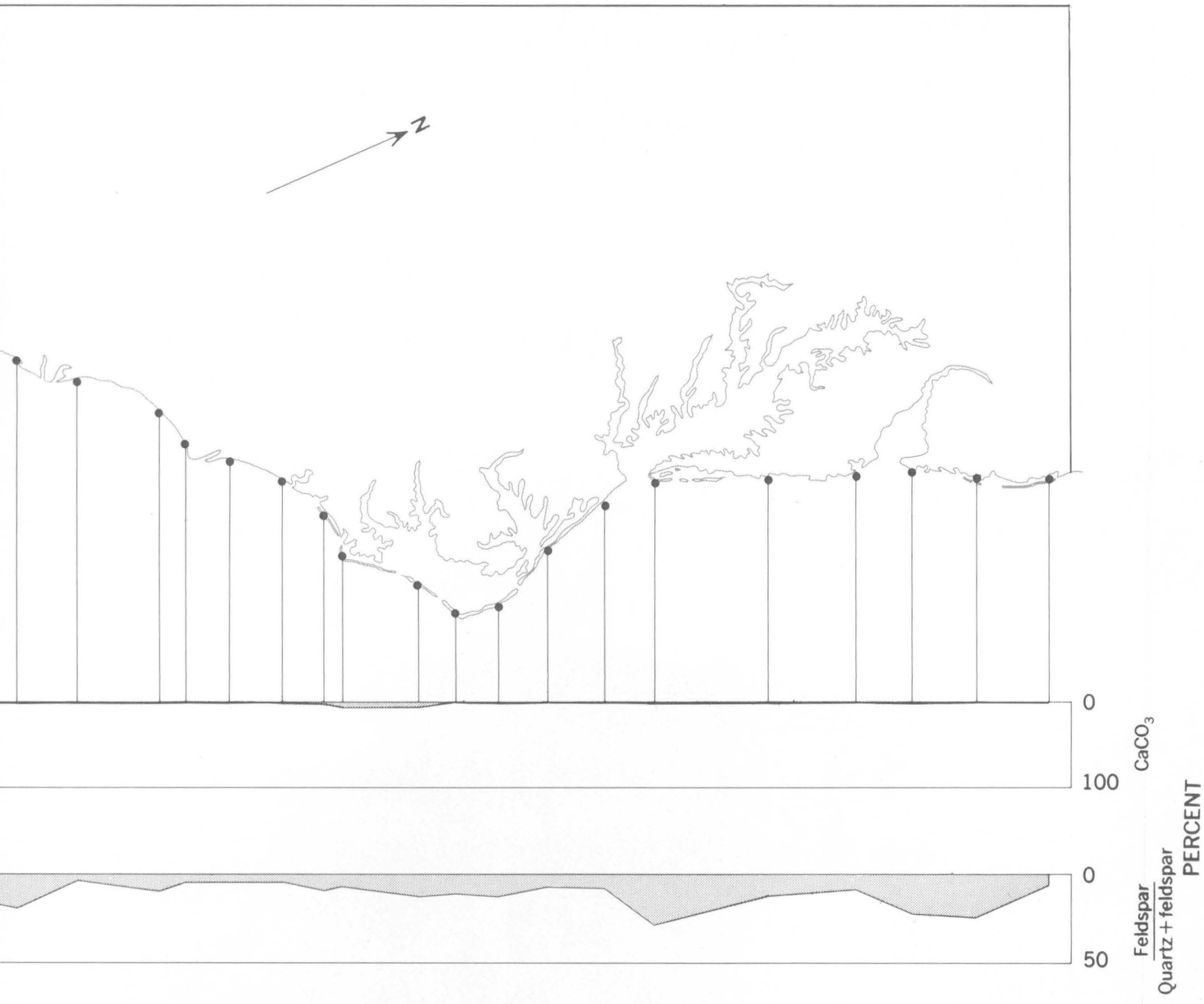


FIGURE 14.—Map showing distribution of calcium carbonate and the feldspar/quartz

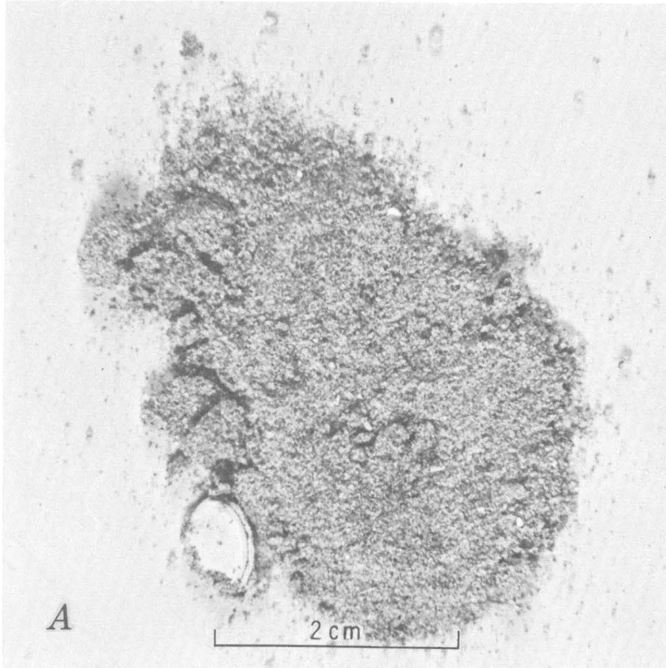
TABLE 5.—*Distinguishing characteristics of the sediment types on the continental margin*

Sediment type	Location	Sediment texture	Color	Noncarbonate components	Percent carbonate	Carbonate assemblages
1. Subarkosic to arkosic, very fine sands.	Nearshore and off estuaries.	Very fine sands and muds.	Clear	Arkosic (north of Cape Hatteras), subarkosic to south.	<2	Mollusk; benthonic Foraminifera-mollusk.
2. Low-carbonate subarkosic-arkosic sands.	Shelf north of Cape Hatteras.	Medium to coarse sands.	Iron stained	Subarkosic to arkosic	<5	Mollusk; echinoid-mollusk.
3. Moderately low carbonate, orthoquartzitic sands.	Inner and middle shelf south of Cape Hatteras.	do	Iron stained north of Cape Romain.	Orthoquartzitic-subarkosic; some subarkosic and orthoquarzitic.	<25	Mollusk; lithoclasts.
4. Moderately high carbonate, orthoquartzitic sands.	Middle and outer shelf, Onslow Bay to central Florida.	do	Iron stained in Onslow Bay; clear in Florida.	Mainly orthoquartzitic	25–75	Oolite-pelletoid; mollusk; barnacle-coralline algae; barnacle-mollusk; lithoclast.
5. High-carbonate orthoquartzitic sands.	Southern Florida shelf	do	Clear	Orthoquartzitic	>75	Oolite-pelletoid; coral reef; barnacle-mollusk.
6. Subarkosic to arkosic muds.	Slope north of Cape Hatteras.	Silt and clay	do	Subarkosic to arkosic	5–95	Pelagic Foraminifera.
7. Glauconitic sands	Slope between Cape Hatteras and northern Florida.	Medium sand and gravel.	Green to black	Glauconite; orthoquartzitic-subarkosic off North Carolina; subarkosic to arkosic to the south.	25–95	Glauconitic Foraminifera; pelagic Foraminifera.
8. High-carbonate muds.	Slope off Florida	Silt and clay	Clear	Subarkosic and arkosic; glauconite.	50–95	Foraminifera; glauconitic Foraminifera.
9. Very high carbonate sands.	Blake Plateau and Straits of Florida.	Medium sand; mud; coarse sand and gravel.	Clear to orange	Some phosphate and glauconite.	>95	Planktonic Foraminifera; Foraminifera-pteropod.



+ feldspar ratio in beach sands along the middle and southeastern Atlantic coast.

2. Most of the shelf sediments north of Cape Hatteras are medium to coarse iron-stained sands, subarkosic (in the 125μ- to 250μ-sized fraction) and low in carbonate (fig. 15*B*). The mollusk and echinoid-mollusk assemblages dominate the carbonate fraction. This sediment type extends south of Cape Hatteras and occupies the inner part of Raleigh Bay.
3. Medium to coarse orthoquartzitic-subarkosic sands cover much of the shelf south of Cape Hatteras (pl. 9*A*; fig. 15*C*). These sands contain less than 25 percent carbonate, and are characterized by mollusks, plus some lithoclasts. North of Cape Romain the sands are heavily iron stained; to the south most sands are relatively clear. This sediment type occupies most of the shelf off Georgia, the middle and inner shelf off South Carolina, the inner shelf off Onslow Bay and off northern Florida, and the outer part of Raleigh Bay.
4. Orthoquartzic sands cover much of the shelf off Onslow Bay and central Florida, and also the outer shelf off South Carolina and Georgia. These sediments are relatively high in carbonate (25–75 percent) and are characterized by oolite-pelletoid, barnacle-coralline algae, and barnacle-mollusk assemblages (fig. 15*D*).
5. The shelf off southern Florida contains high-carbonate (greater than 75 percent) orthoquartzitic sands. Carbonate components are dominated by the oolite-pelletoid, barnacle-mollusk, and (south of Palm Beach) the coral reef assemblages (fig. 15*E*). The nearshore and beach sediments in southern Florida, however,



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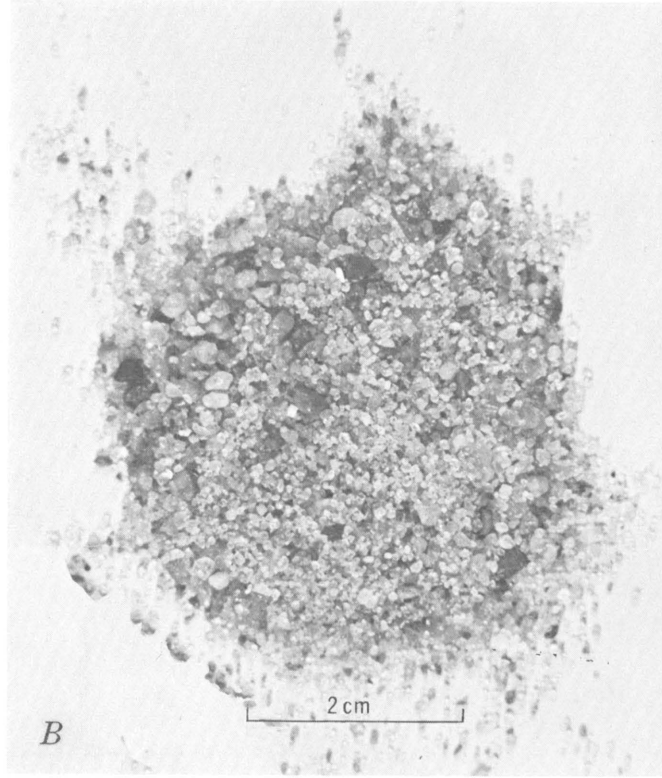

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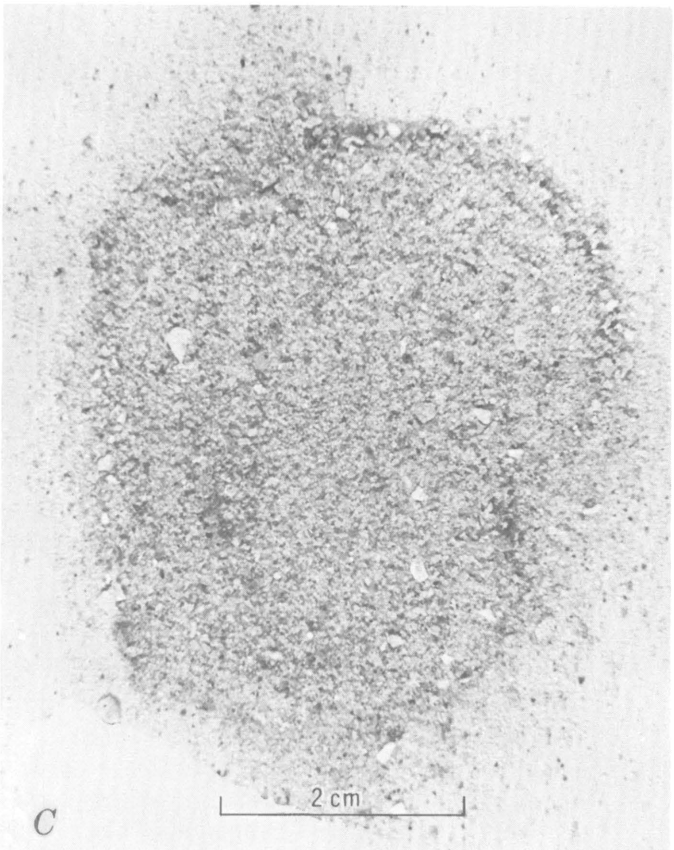

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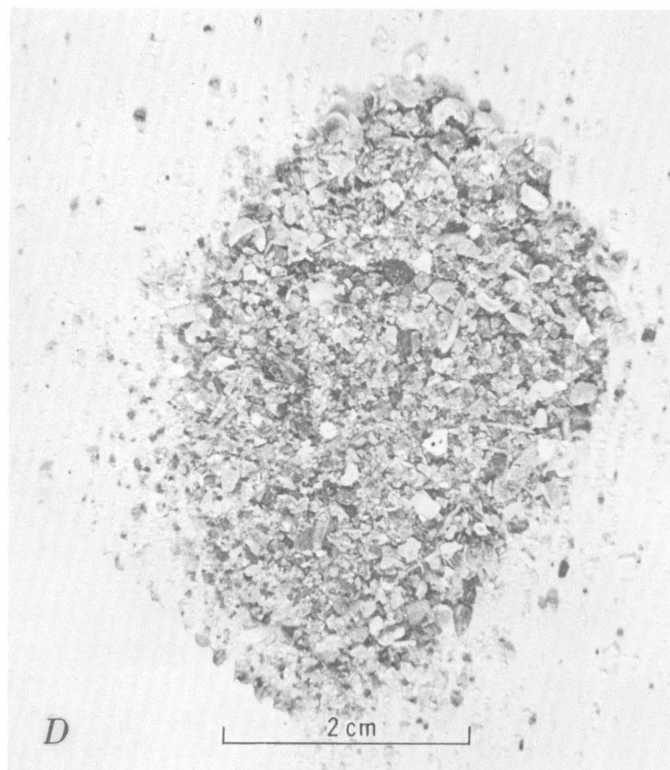
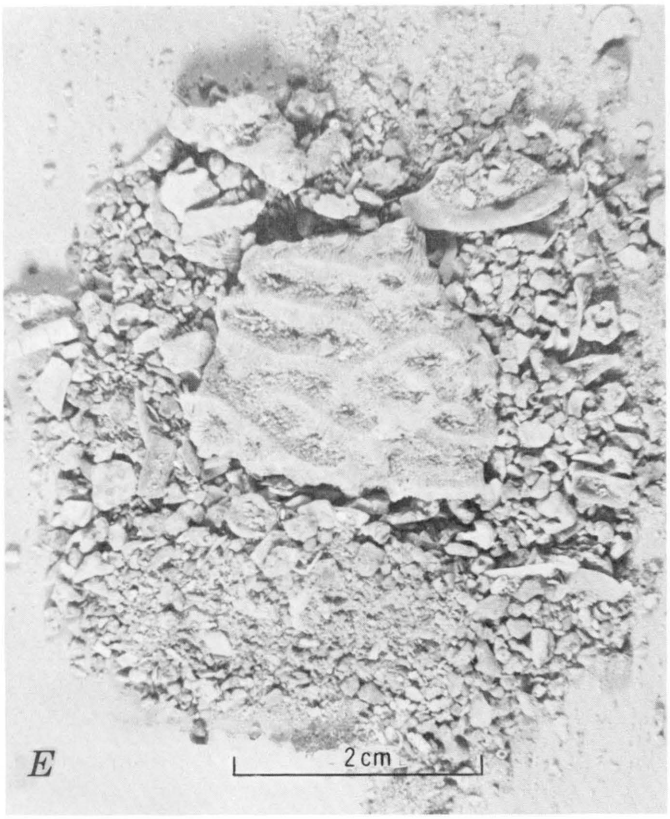


D

FIGURE 15.—Photomicrographs of sediment types 1-8. *A*, Sediment type 1, very fine low-carbonate sand. *B*, Sediment type 2, medium to coarse iron-stained subarkosic sand. *C*, Sediment type 3, medium to coarse orthoquartzitic to subarkosic sand. *D*, Sediment type 4, moderately high carbonate, orthoquartzitic sand. This particular sediment contains an oolite-pelletoid carbonate assemblage. *E*, Sediment type 5, high carbonate orthoquartzitic sand. This particular sediment from



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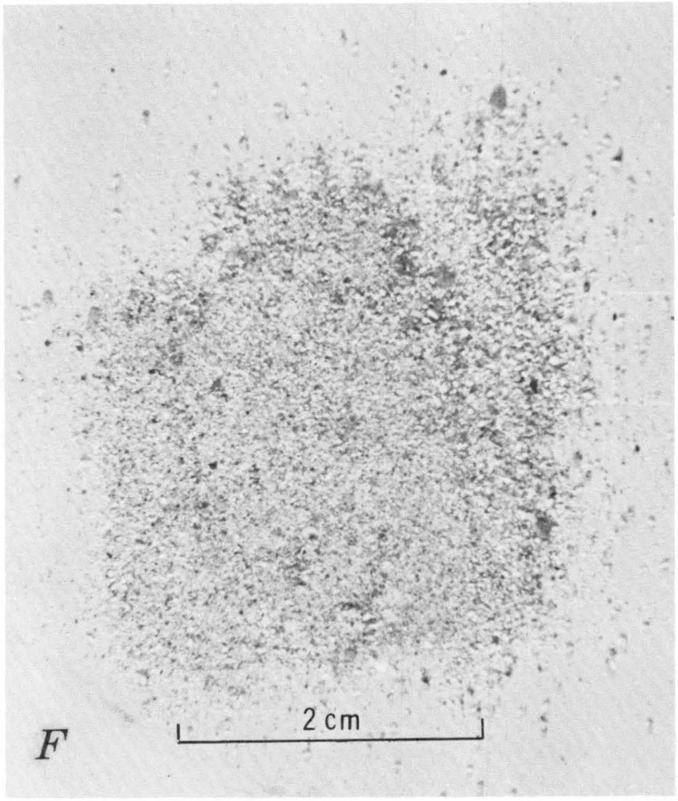

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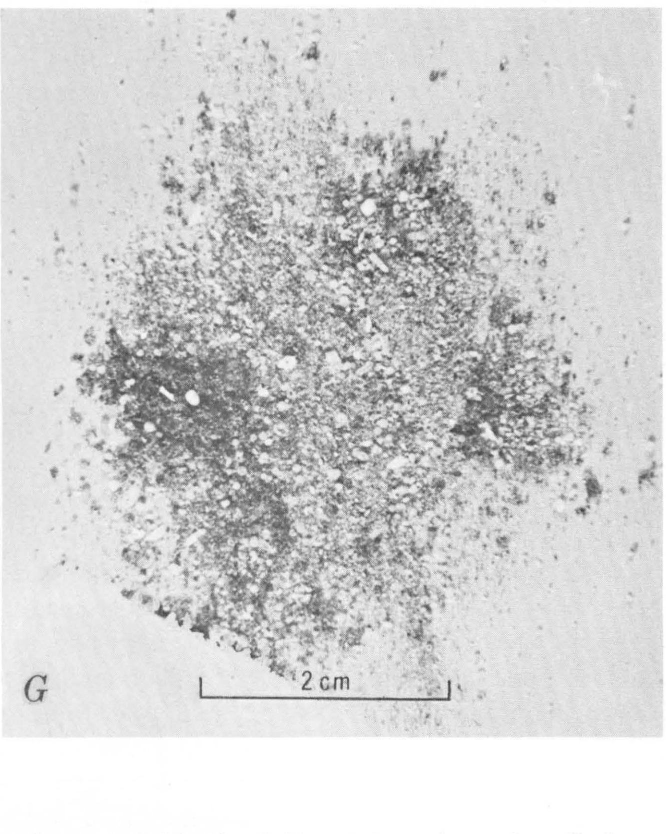

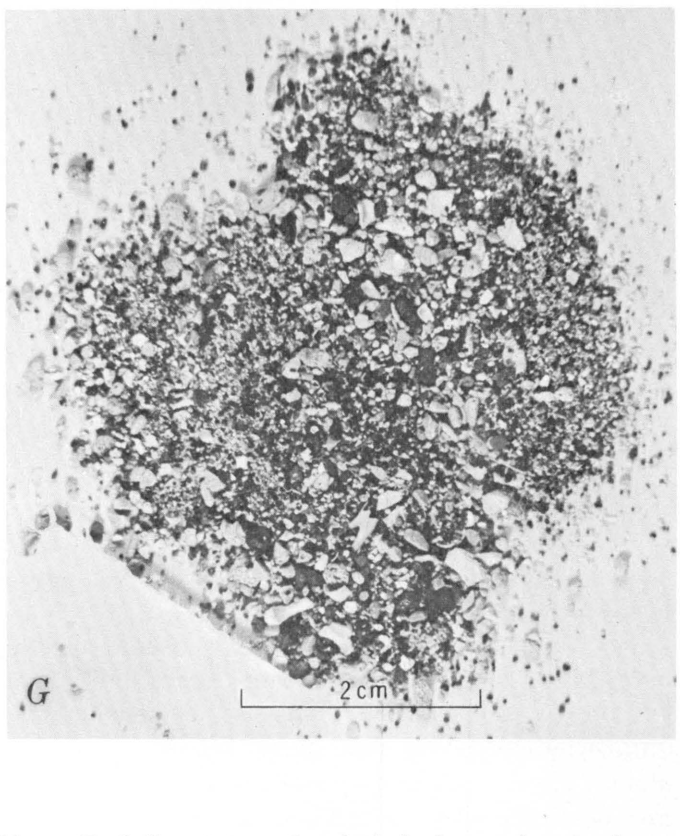

G

the central Florida shelf contains a barnacle-mollusk assemblage. *F*, Sediment type 6, relatively low carbonate slope mud. This particular photomicrograph shows only the sand part of the sediment. *G*, Sediment types 7 and 8, glauconitic slope sand (right) and mud (left).

contain much less carbonate (about 5–50 percent north of Miami) and therefore should probably be classified as sediment type 4.

6. The continental slope north of Cape Hatteras is covered with silts and clays. The 125μ- to 250μ-sized fraction is arkosic to subarkosic. Carbonate content in the sand fraction is widely variable but generally is less than 95 percent. Planktonic Foraminifera makeup most of the carbonate organisms (fig. 15*F*).
7. Green to black glauconitic sands dominate the Florida-Hatteras Slope between Raleigh Bay and northern Florida (fig. 15*G*, right). The sands off Onslow Bay are orthoquartzitic-subarkosic; to the south the sands are subarkosic to arkosic.
8. Carbonate-rich muds cover most of the Florida-Hatteras Slope off central and southern Florida. Planktonic Foraminifera are the major carbonate contributors (fig. 15*G*, left), although shallow-water debris is present on the upper slope. Sands are arkosic off central Florida and become progressively less felspathic to the south. Glauconite is a dominant insoluble component, especially off southern Florida.
9. The Straits of Florida and the Blake Plateau are covered with a wide variety of sediments, but most are carbonate-rich sands and gravel (fig. 16). Planktonic Foraminifera dominate the sediments, but deep-water coral and pteropods are also important. Phosphate is locally abundant, especially off South Carolina.

Special mention should be given to the distribution of rock outcrops on the shelf. Not only have they contributed sediment locally (as, for example, in Onslow Bay), but rock outcrops also provide substrate on which encrusting organisms, such as barnacles and coralline algae can attach. Moreover, their presence signifies areas of low sediment accumulation, which, in turn, gives some ideas about rates of sedimentation on the margin. Plate 9*B* shows the distribution of rock outcrops on the margin. All outcrops are south of Cape Hatteras. Pleistocene rocks extend along the entire inner shelf. Upper Pleistocene-Holocene limestones are found on the outer shelf. Off North Carolina, coralline algae, beachrock, and various bioclastic limestones prevail, whereas oolite dominates the Florida limestones. Miocene outcrops cover much of Onslow Bay and dominate most of the central Florida-Hatteras Slope and Blake Plateau. Numerous phosphorite

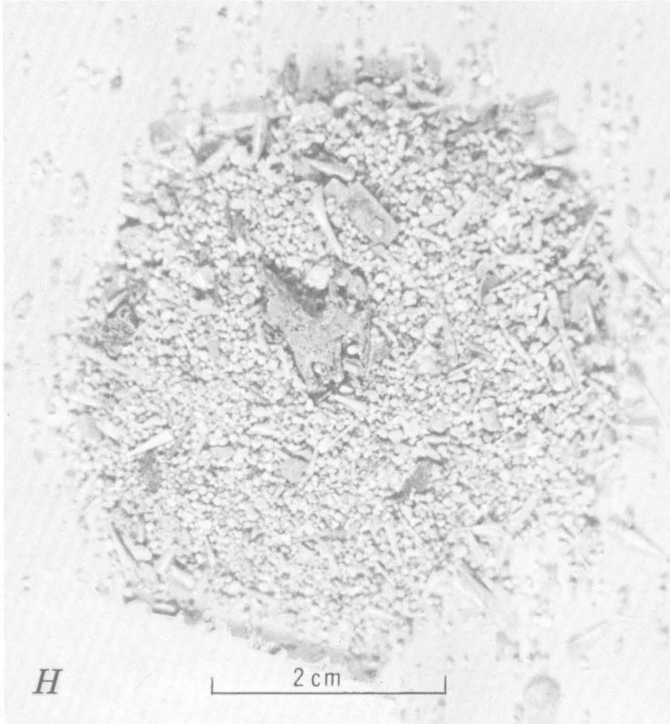

FIGURE 16.—Photomicrograph of sediment type 9, Blake Plateau sand containing phosphatic pebbles.

outcrops are found on the Florida-Hatteras Slope and Pourtales Terrace off southern Florida. These phosphatic limestones contain abundant concentrations of glauconite-filled Foraminifera.

SOURCE AND HISTORY OF SURFICIAL SEDIMENTS ON THE CONTINENTAL MARGIN

The surficial sediments on the central and southeastern Atlantic continental margin have had three dominant sources: rivers, carbonate precipitation, and authigenic processes. Terrigenous sediments eroded from subaqueous outcrops can be considered as being originally fluvial. Fluvial sediments that cover the shelf and slope north of Cape Lookout are subarkosic with arkosic patches off major estuaries, and probably were derived from northern rivers. Sediments between Cape Fear and northern Florida are less felspathic, implying derivation from southern Piedmont rivers (see above). The subtropical to tropical waters south of Cape Hatteras have provided a favorable environment for carbonate deposition. Dominant carbonates include skeletons of mollusks, coralline algae, barnacles, Foraminifera, and oolite. The absolute carbonate content, however, depends upon the influx of detrital material. Authigenic components, namely, glauconite, are dominant in sediments on the Florida-Hatteras Slope. Phosphorite is a common constituent on the slope off Cape Romain and in various areas on the inner Blake Plateau off South Carolina and Florida.

These sedimentary components represent several ages and modes of deposition: modern, relict, and residual (Emery, 1952, 1960) (pl. 9*C*). Residual sediments have been weathered from underwater outcrops, and are considered to be the oldest surficial sediments on the margin. Paleontologic evidence, together with stratigraphic correlation with onshore deposits, suggests that the outcrops and quartzose sediments in Onslow Bay represent seaward extensions of the middle Tertiary Coastal Plain formations. Middle Tertiary outcrops and residual sediments also cover much of the Florida-Hatteras Slope and Blake Plateau. The glauconite found in this area is largely residual. The Blake Plateau deposits are also middle Tertiary in age (F. T. Manheim and R. M. Pratt, unpub. data). The presence of these residual sediments and the lack of detrital components suggest that fluvial material from the southeastern rivers has not accumulated on the Blake Plateau nor on large parts of the Florida-Hatteras Slope. No doubt the Florida Current has effectively precluded deposition in much of this area (Pratt, R. M., 1966).

Relict sediments, which are defined as having been deposited during lower stands of Pleistocene sea level (Emery, 1952, 1960), are generally medium to coarse iron-stained sands (although not all relict sediments are iron stained) that contain subaerial and shallow-water fossils, such as elephant teeth (Whitmore and others, 1967), fresh- and salt-water peat (Emery and others, 1967), oysters (Merrill and others, 1965), coralline algae, oolite, beachrock, and coral reef debris. Carbon-14 dates indicate that most of the carbonate fossils were deposited during the last 5–30 thousands years (Milliman and Emery, 1968), suggesting deposition during the Würm regression and transgression. From fossil evidence, most of these relict sediments were probably deposited in littoral and sublittoral environments. At present, these sediments are in both textural and compositional disequilibrium with the present-day shelf environment. As Curray (1965) states, these sediments have been separated from their "supply line."

Modern shelf sediments are unstained fine sands and muds that coincide in character with sediment type 1, shown in figure 15*A*. Generally, the modern sediment band is less than 20 km wide and is marked by a rather abrupt seaward boundary with the coarser relict sediments (Pilkey and Frankenburg, 1964). Some shelf carbonates, such as Foraminifera, barnacles, and some mollusks and echinoids, are probably recent additions to the shelf sediment. Carbonate accretion also has accounted for a significant accumulation of recent shallow-water sediments in southern Florida (Hoffmeister and Multer, 1968).

From the dominance of relict sediments and the lack of mica and fine sediments, one can conclude that little modern sediment is accumulating on the continental shelf. Numerous workers have suggested that most fluvial sediment is being trapped within estuaries and that little is escaping to the shelf (Meade, 1969a, and references therein). In fact, seabed drifters and sedimentologic studies suggest that shelf sediments may be transported shoreward into estuaries (Harrison and others, 1967; Pevear and Pilkey, 1966; Meade, 1969a).

Most current and transport data, however, have been derived during normal meteorologic and oceanographic conditions; although the net transport may be represented in these average conditions, the effect of cataclysmic events, such as storms and floods, has not been taken into account. Shallow-water turtle grass *(Thalassia)* has been recovered from the Blake Plateau (Menzies and others, 1967) and presumably was carried there by hurricane-induced currents. On the basis of the increased suspended matter concentrations in shelf waters after storms (Manheim and others, 1970) and of satellite photographs showing plumes of light-colored water near estuary mouths after major floods (R. E. Stevenson and Elazar Uchupi, oral commun., 1969) periodic cataclysms appear capable of transporting large quantities of sediment to the shelf and beyond. The fact that fine-grained modern sediments are not able to accumulate on the middle and outer shelf may reflect the activity of currents to prevent deposition or to winnow bottom deposits. Depending on current direction, the fine sediment may be transported landward or it may be carried seaward to the slope or deep sea. Thus, present-day currents may be able to preserve the disequilibrium nature of the relict shelf sediments.

The age of the very fine sands that extend seaward from Delaware Bay and Chesapeake Bay (pl. 2*B*, *E*) has not been determined (pl. 9). These sediments are finer, considerably more felspathic, more irregular in shape, and contain less iron staining than surrounding sediments. They tend to lie north of (and intermingle with) the gravels and sands that extend seaward from the estuaries (pl. 2*B*, *D*). Although the sediments probably were derived from the neighboring estuaries, their age is subject to debate. The fact that very fine sands extend seaward from estuaries and mix with coarser relict sediments would suggest a modern age. On the other hand, it is difficult to imagine significant offshore transport from either Delaware Bay or Chesapeake Bay; both estuaries probably are acting as large sediment traps. Even assuming that some sediment does exit during large floods or storms, bottom currents would probably tend to transport the sediment north or south, resulting in a distribution considerably different from the existing pattern. Without further data, including observations on sediment transport during and after storms, the age of these fine sediments cannot be accurately defined.

SUMMARY

The surficial sediments on the continental margin off the east coast of the United States represent a wide spectrum of compositions and ages. The waters north of Cape Hatteras are temperate, and the tributary rivers have contributed mostly mechanically weathered sediment. As a result, the shelf sediment tends to be low in carbonate (generally less than 5 percent) and high in feldspar; the 125μ- to 250μ-sized fraction is classified as arkosic to subarkosic.

The shelf and slope waters south of Cape Hatteras have been influenced strongly by the Florida Current. Organisms are subtropical to tropical, and the carbonate content tends to be much greater than in the northern temperate waters. In nearshore waters the carbonate has been diluted by the accumulation of relatively feldspar poor sediments, derived from southern rivers that drain the Piedmont and Coastal Plain. In shelf areas not adjacent to major rivers, terrigenous sediment has been derived from underlying outcrops (such as in Onslow Bay) or by longshore transport (such as on the shelf off Florida). Because of the low rate of terrigenous sedimentation in these areas, carbonate is dominant, often comprising more than 50 percent of the total sediment. Oolite, barnacles, and coralline algae are among the major contributors; south of Palm Beach, Fla., coral reefs have contributed much carbonate.

The slope north of Cape Hatteras contains fine sands and muds, with moderate amounts of carbonate. The felspathic detrital sands in the slope sediments apparently came from the northern rivers. The age of these sediments is not known, but their fine-grained texture and planktonic carbonate constituents suggest deposition in an environment similar to the present-day slope. The Florida-Hatteras Slope, on the other hand, is covered with sediment apparently derived from underlying formations. The glauconitic sands off South Carolina and North Carolina are thought to be middle Tertiary in age, and the arkosic sands and muds off Georgia and Florida possibly come from felspathic middle Tertiary formations that underlie the slope.

The Blake Plateau is covered with a planktonic foraminiferal sand. Coral gravel has been contributed from coral ridges that line the inner Blake Plateau off South Carolina. Middle Tertiary phosphorite covers extensive areas of the plateau and is indicative of the almost nonexistent rate of terrigenous sedimentation in this area.

Most surficial sediment on the continental margin has not been deposited in modern times. The only shelf sediment that appears to be modern (deposited after the last rise in sea level) is the fine sand and mud found in nearshore areas. The sandy texture and the presence of shallow-water and land fossils in most of the shelf sediment indicate deposition during the last regression and transgression of sea level. River material remains trapped within estuaries or bypasses the shelf and is deposited in deeper water. Apparently, the present-day current and wave regime on the shelf is sufficient to prevent deposition. Longshore currents have transported some nearshore material, notably low-carbonate felspathic sands south into Raleigh Bay and Georgia river sands southward along the Florida coast. On the basis of the rather definitive boundaries of most petrographic parameters (such as carbonate, phosphate, and feldspar), most of the shelf sediments do not appear to have undergone significant net transport since their deposition.

The middle Tertiary outcrops in Onslow Bay and the discontinuous Pleistocene(?) formations that mark much of the southeastern shelf illustrate that many shelf areas have received little or no sediment. Only a trace of terrigenous sediment has accumulated on the Blake Plateau since the middle Tertiary, resulting in the high-carbonate content and the abundance of middle Tertiary outcrops.

This would suggest that material escaping from the southeastern coastal estuaries must have been transported northwestward by the Florida Current. The width of the Coastal Plain in the Georgia area, however, may be the result of the seaward accretion of river sediments over the shelf, and may suggest that little terrigenous sediment has escaped the nearshore areas.

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