The Journal of the Oceanological Society of Korea
Vol. 7, No. 2, p. 59-73, December 1972

THE HEAVY MINERALS OF THE RECENT SEDIMENTS OF NORTH CAROLINA SOUNDS AND ESTUARIES IN U. S. A.

Byong-Kwon Park
Department of Earth Science, Korean Military Academy

ABSTRACT

The heavy minerals of a barred estuarine and lagoonal sediments along the North Carolina coast have been studied with more than one hundred samples. Currents, salinity, and *p*H exhibit well-developed gradients from the upstream parts of the estuaries on the west toward the open ocean on the east. Twenty-four heavy minerals were identified in sediments of the study area. However, less than half of these occur frequently and the remainder exist only in minor quantities or trace amounts. Heavy minerals usually comprise less than 1% of the sample but vary from sample to sample. The maximum amount of heavy minerals in sediments of sounds and estuaries is 2.4% and in sediments of Outer Banks is 16.7%. Opaque minerals range from 10 to 85% of the total heavy mineral assemblage. Garnet and sillimanite are relatively more abundant in the eastern part than the western part in the area. Garnet is more abundant in the northern part than the southern part, whereas sillimanite is more abundant in the southern part than the northern part, because the garnet source is in the northern part and one of the sillimanite source is in the southern part in the study area.

The results of heavy mineral study indicate that the source of sediments is the Blue Ridge and Piedmont crystalline complex, and Coastal Plain formations. Some portions of sediments are transported from the Atlantic Ocean by the landward currents. They further indicate that the sediments of the Atlantic coast in the study area are transported mainly from the northern part to southern part by longshore littoral currents, and some portions of sediments are transported from the southern part to the northern part by the Gulf Stream.

INTRODUCTION

This heavy mineral study is a part of the work describing the mineralogy of recent sediments of North Carolina sounds and estuaries and investigating the regional relationshpis between the mineralogy of these sediments and their environments of deposition.

The sediments now accumulating in the North Carolina sounds and estuaries are contributed by several rivers and are trapped by the landward circulation of water along the bottoms of the North Carolina sounds and estuaries. These sediments can be placed in several main depositional environments such as bay away from inlet, bay near inlet, bay near river, inlet, lagoon away from inlet, lagoon near inlet, and barrier islands.

Most previous workers concerning the sediments and depositional environments in the North Carolina sounds and estuaries deal with small parts of the area. Therefore, the work was undertaken to investigate regional compositional relationships. More than one hundred samples were analyzed for clay minerals, heavy minerals, and light minerals by the coarse fraction analysis method of Shepard and Moore (1954).

GEOLOGIC AND GEOGRAPHIC SETTING

General Statement

The study area consists of Pamlico River es-

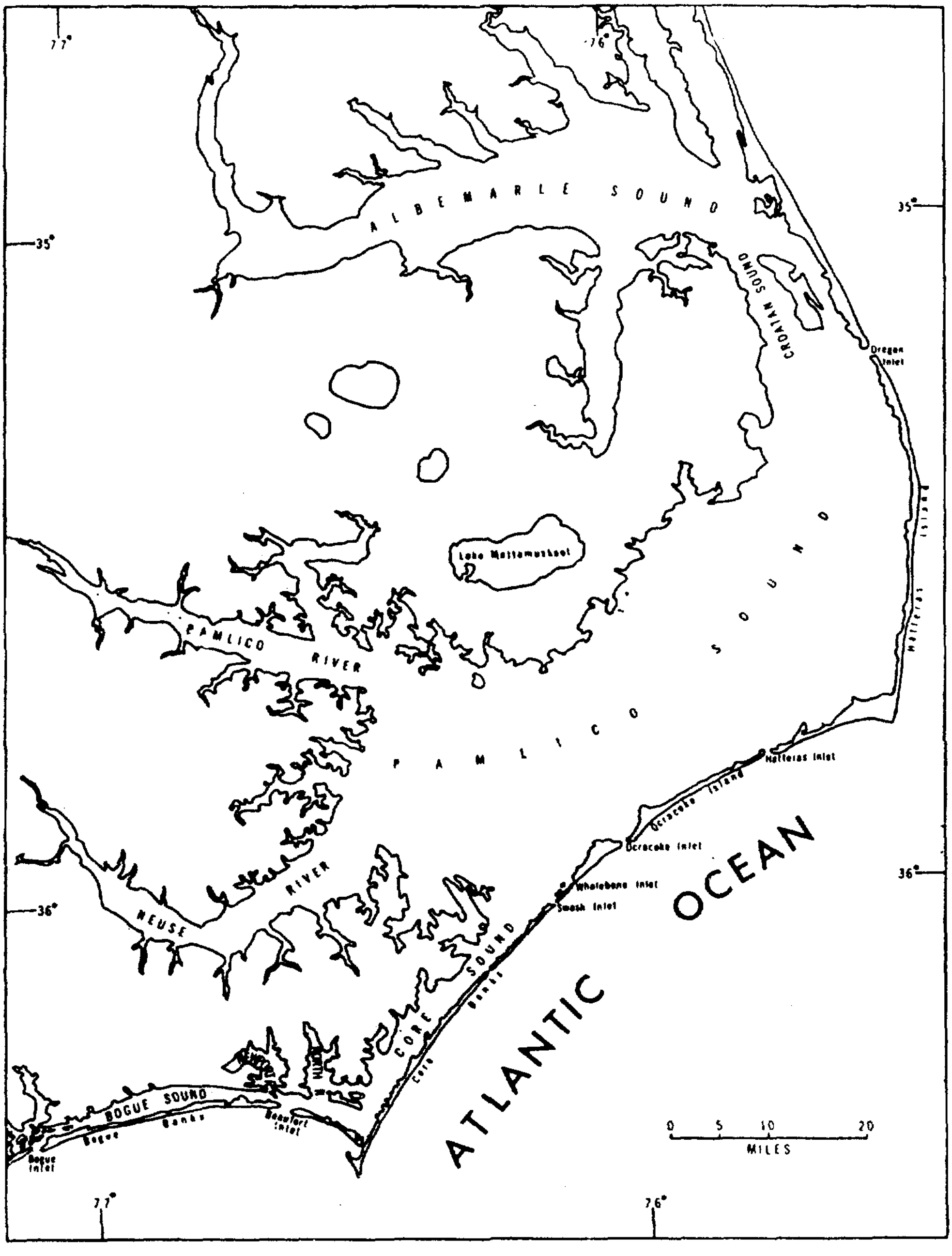

Fig. 1. Index map of the North Carolina coast.

tuary, Neuse River estuary, North River estuary, Newport River estuary, Albemarle Sound, Pamlico Sound, Core Sound, Bogue Sound, and Outer Banks (Fig. 1). The area is an estuarine lagoonal complex created by the submergence of former river valleys and shorelines and modified by the formation of barrier islands, the Outer Banks. Oregon Inlet, Hatteras Inlet, Ocracoke Inlet, Swash Inlet, Drum Inlet, Barden Inlet, Beaufort Inlet, Bogue Inlet, and other small inlets cut through the Outer Banks.

In the drainage basin of the rivers is a great variety of rock types that includes Precambrian gneiss and schist; Paleozoic gneiss and schist, metavolcanics, metasediments, and granite; Triassic conglomerate, sandstone, and mudstone; and Cenozoic gravel, sand, clay, and limestone. The mainland shore is composed of Quaternary sediments except for local bluffs in the western part of the study area where the Miocene Yorktown Formation and Eocene Castle Hayne Limestone border the study area.

Hydrography

Currents

Currents are the major factor in controlling the distribution of sediment sizes with the coarsest grained sediments occuring where the currents are the most rapid and the finest sediments where the currents are slow. Currents in the sounds and estuaries are produced by wind, river discharge, evaporation and rainfall over the sound and estuarine water, and tides. Coriolis's force tends to deflect currents to the right in the northern hemisphere but has little effect in shallow waters of these sounds and estuaries.

Tidal currents are negligible in the study area except at the inlets. The sounds are too small to have an appreciable tide generated within, and the tidal currents in the study area come from the ocean by way of the inlets. Such tidal effects are rapidly damped with distance from these inlets, but they are significant at the inlets. Tidal mean range is 1.8 feet at Oregon Inlet, 2.0 feet at Hatteras Inlet, 1.9 feet at Ocracoke Inlet, 2.5 feet at Beaufort Inlet, and 2.2 feet at Bogue Inlet (Marshall, 1951). Tidal exchange at the inlets of Pamlico Sound would produce a rise and fall of approximately 2 inches over the entire sound (Woods, 1967).

Evaporation and rainfall over the study area are a relatively minor factor. Seasonal highs and lows in river discharge directly affect currents in the sounds and estuaries and generally cause the greatest seaward flow to occur in the early spring. Currents resulting from runoff and the rivers in Pamlico Sound are calculated by Roelofs and Bumpus (1953) to average about 0.2 inch per second. Wind is, in general, the greatest current-producing force in the study area. According to the U. S. Coast and Geodetic Survey (1936) the wind can change water level about 2 feet above and below normal in the open sounds. Funnelling of this water may produce current velocities of 2.3 f.p.s. in squall, but currents average between 0.3 and 0.9 f.p.s. in Pamlico Sound (Roelofs and Bumpus, 1953). According to Hjulström (1939) a velocity of 2.3 f.p.s. and 0.3 to 0.9 f.p.s. can move material up to 9mm and 3.5mm in diameter, respectively. Minimum current velocity is zero and maximum current velocity range from 0.3 to 5 f.p.s. in Bogu Sound (Brett, 1963). According to Hjulström (1939) a velocity of 0.3 to 5 f.p.s. can move material of 1 to 20 mm in diameter. The water level of the northern Albemarle Sound is raised by as much as 12 inches in 24 hours by southeasterly winds (Pels, 1967).

In addition to the above currents the landward currents produced by tides and density differences between fresh and saline waters are effective in transporting and redistributing sediments in the study area. Mixing of fresh and saline waters occurs at the interface, so that a continuous upstream flow of saline water may occur at the bottom to replace that lost by mixing.

Temperature

Water temperature of the North Carolina sounds and estuaries correspond closely to the air temperature through the year but are usually slightly lower than air temperature (Marshall, 1951). The correlation coefficient between water temperature and air temperature is 0.972 (Roelofs and Bumpus, 1953). Air temperature is highest during June, July, and August, and lower during winter months averaging about 77°F and 47°F, respectively. Bottom water temperature is usually less than one degree colder than surface water temperature (Pels 1967). There is little that is distinctive about the distribution of temperatures except that the highest or lowest temperatures occur in the shallow areas. Constant wind agitation of the water prevents any appreciable thermal stratification in the study area.

Salinity

The salinity of Albemarle Sound is the lowest in the study area. In the western part of Albemarle Sound the Salinity is always less than 1‰ and increases steadily eastward up to 15‰ in summer and 4‰ in spring. In Pamlico River and Neuse River estuaries the salinity increases gradually from fresh water in upstream areas to about one-third to one-half that of normal sea water at the mouths. The salinity in Pamlico Sound increases seaward gradually from about 10‰ in the mainland side to about 26‰ near the Outer Banks, and rises quickly to 32‰ in Ocracoke Inlet. Core Sound becomes progressively less saline from south to north and the salinity ranged from 25‰ at the northern part of Cedar Island to 35‰ at Beaufort Inlet. The salinity in North River and Newport River estuaries is relatively high since there are no large fresh water tributaries entering the estuaries. The maximum salinity is about 33‰. Bogue Sound maintains an estimated mean annual salinity of 31 to 33‰, somewhat less than the nearshore ocean salinity which fluctuates slightly about 34‰.

In general, the bottom waters are slightly more saline than the surface waters, but frequently this stratification is destroyed by vertical mixing. However some stratification of fresh water over saline water is to be expected even in the shallow North Carolina sounds and estuaries. Since warm water is less dense than cold and since there is a tendency for the surface to be heated during warm periods, temperature condition may supplement the salinity stratification.

***p*H**

Griffin and Ingram (1955) summarized data from earlier works and reported that the *p*H values are 6.5 at the upstream end and 8.15 at the downstream end of Neuse River estuary. Johnson (1959) reported that the *p*H values are 7.9 at the upstream end, 8.4 at the downstream end of Newport River estuary, and 8.6 at the Beaufort Inlet. Grossman (1961) reported that a general change from acidic condition at the upstream end of Pamlico River estuary and Neuse River estuary to neutrality on the ocean side of Ocracoke Inlet in Pamlico Sound. Duane (1962) stated that the acidic conditions of the estuaries are produced by the organic acid, notably tannic and gallic, in the surronding low-lying swamps at the upstream of Pamlico River and Neuse River estuaries. Duane (1962) further stated that the distribution of micro-organisms is indicative of acidic conditions in the estuaries. Arenaceous forams compose almost the entire fauna of the acidic estuaries, and calcareous forams and molluscan fragments are very rare, and ostracods almost nonexistant. However calcareous organisms and molluscan fragments show a seaward increase in abundance, in the direction of decreasing acidity.

Topography

The land surrounding the study area is generally flat and swamp. Near the western edge, however, there is a relatively rapid elevation to about 25 feet. This is the boundary between Pamlico and Chowan terraces. There are many bluffs on the shoreline and several large sand dunes in Nags Head on the Outer Banks. Nest of the shoreline of the study area is bordered by sandy beaches. Other shorelines are bordered by marshes.

The center of Albemarle Sound is a wide

central basin which ranges in depth from 12 to 24 feet. Albemarle Sound is bordered with a gently dipping shelf, ranging in depth from 0 to 6 feet, and the shelf is separated from deeper center by a relatively steeply dipping slope which separates the two. In the main channel of Pamlico River and Neuse River estuaries the water increases in depth from about 24 feet at the entrance into Pamlico Sound. The bottom topography of Pamlico Sound is also generally flat. Pamlico Sound is divided into two wide central basins separated by sand shoal. The floors of the central parts of these basins are uniformly 18 to 24 feet deep. The sand shoal has only 3 to 12 feet of water over it, depending on the proximity to land. Several deltaic shoals extend soundward from the inlets. Much of the shoal areas on the sound side of the barrier bar are probably relict inlet deltas. Most of Newport River and North River estuaries are less than 6 feet at mean low tide. There are several channels with depth of 18 feet near the estuary mouths. Core Sound and Bogue Sound are shallow with slightly undulatory bottoms. The mean depth of Core Sound and Bogue Sound is not more than 3 to 4 feet and the maximum depths are about 12 feet. The depth of inlets are less than 3 feet except for Ocracoke Inlet and Beaufort Inlet. Ocracoke Inlet ranges in depth from 2 feet near the barrier islands to 45 feet in the channel. Beaufort Inlet is about 2 to 3 feet except for the dredged navigation channel which is more than 30 feet deep. There are several inlets which are open only during hurricanes.

SAMPLING AND ANALYTICAL METHODS

Sampling

Most of the samples studied came from the modern sediment collection in the Department of Geology, University of North Carolina at Chapel Hill. Most of these had been in storage for a few years, and so samples were dry when received. This storage and drying did not appear to affect the mineral properties investigated here. Additional samples were collected using a Peterson-type dredge by the present writer in Albemarle Sound and along the Outer Banks.

From these samples more than one hundred samples which represent the environments and other environmental factors were selected for the present study (Fig. 2).

Laboratory Methods

General Statement

The procedure for preparing samples for clay mineral, coarse fraction, and heavy mineral analyses in as follows:

Dry and weigh 50.0 gm split of bulk sample.

Soak in de-mineralized water overnight and decant or siphon clear liquid. Repeat until the filtrate no longer give a positive test for the chloride ion.

Separate sand fraction from clay and silt fraction for coarse fraction analysis by wet sieving.

Isolate the $<2\mu$ clay fraction for clay mineral analysis by centrifuging.

Weigh the coarse fraction of each sample and subtract the amount of coarse fraction from 50.0 gm to get the amount of silt and clay fraction.

Separate approximately 300 grains for coarse fraction analysis with a microsplitter.

Separate heavy minerals from all sample of coarse fraction of each sample with the tetrabromoethane (s.g.=2.96) after coarse fraction analysis.

Heavy Mineral Analysis

Heavy minerals separated with tetrabromoethane were washed with acetone and dried at 40°C. Heavy minerals were weighed to obtain the ratio between heavy fraction and light fraction, and percentage of heavy mineral of each sample. Heavy mineral microsplit of approximately 1000 grains were mounted on slide with Lakeside 70 cement (n=1.540).

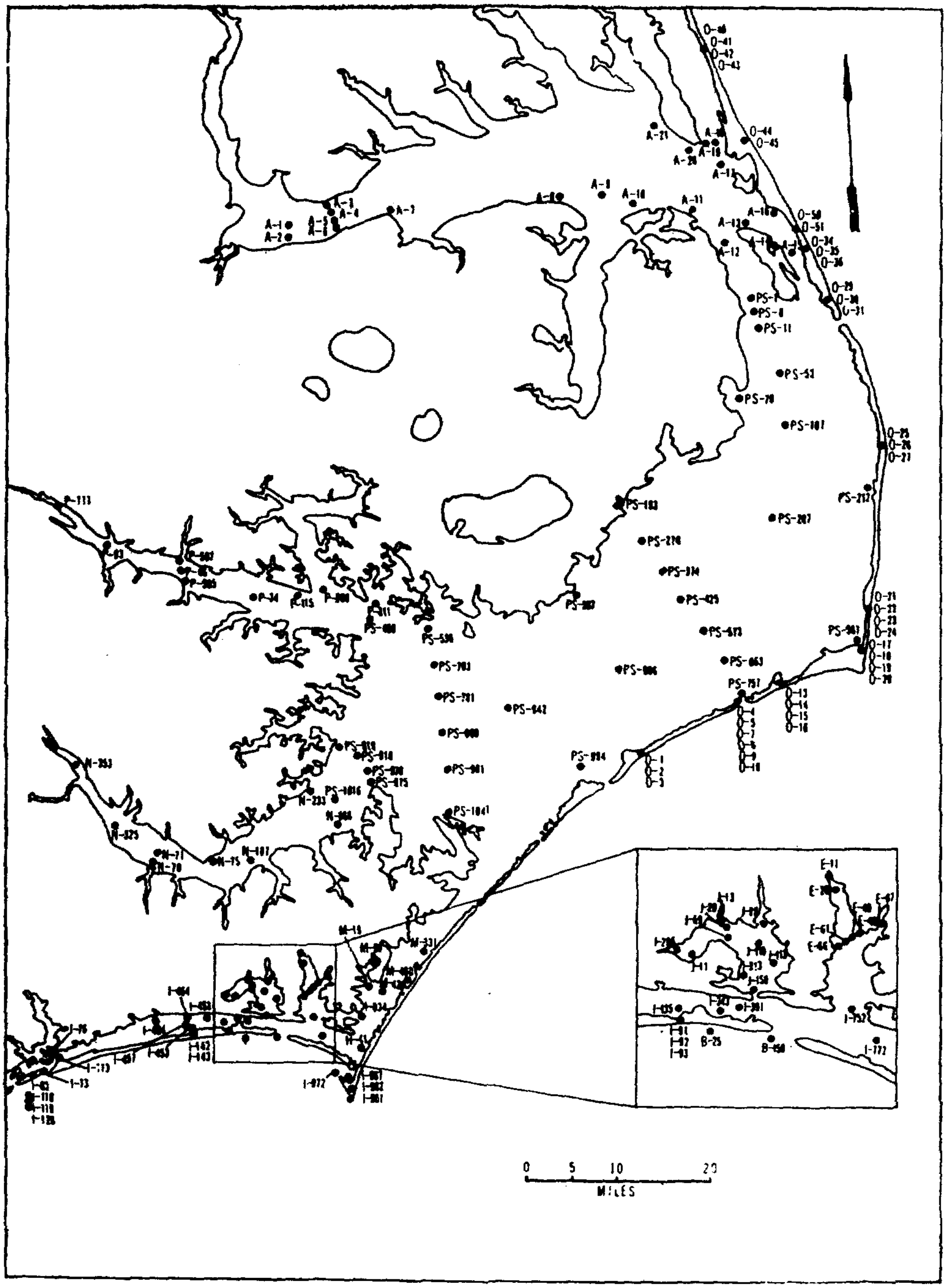

Fig. 2. Sample location map in the study area.

All sample slides were examined under a petrographic microscope and grain counts were made with a mechanical point counter. A count of 400 grains spread evenly over the slide was done. This count was thought to be more than adequate for the type of study involved.

HEAVY MINERAL ANALYSIS

Analytical Results

Mineralogy

Twenty-four heavy minerals were identified in sediments of the study area. However, less than half of these occur frequenlty and the remainder exist only in minor quantities or trace amounts. Heavy minerals usually comprise less than 1% of the sample but vary from sample to sample. The maximum amount of heavy minerals in sediments of sounds and estuaries in the study area is 2.4% and in sediments of Outer Banks is 16.7%.

Opaque minerals, mostly ilmenite, magnetite, and leucoxene, range from 10 to 85% of the total heavy mineral assemblage. Quantitatively important heavy minerals are garnet, epidote, hornblende, augite, staurolite, kyanite, sillimanite, tourmaline, zircon, hypersthene, and rutile. Other heavy minerals that occur in trace amounts are andalusite, apatite, chloritoid, collophane glaucophane, monazite, olivine, titanite, and zoisite.

The following minerals were identified in the samples studied.

Andalusite: Rare. Colorless, subrounded to rounded grains. Faint colorless to pink pleochroism.

Apatite: Rare. Colorless, small, well-rounded to egg-shaped grains.

Augite: Common. Yellowish green, green to blackish green, rounded prismatic grains. Recognized by cleavage and extinction angles.

Chloritoid: Rare. Blue to bluish-green black, flaky grains. Identification is uncertain.

Collophane: Rare. White to reddish brown, grey, wellrounded grains. Numerous inclusions grouped centrally. Isotropic.

Epidote: Common. Greenish-yellow, angular to rounded grains. Same color under crossed nicols as in ordinary light. Greenish-yellow to colorless pleochroism.

Garnet: Common to abundant. Colorless to pale-pink, subangular to well-rounded grains showing percussion scars or possible etching patterns. Inclusions common. Isotropic.

Glaucophane: Rare. Colorless to pale-blue, subrounded coarse grains. Colorless to dark blue pleochroism. Isotropic.

Hornblende: Common to abundant. Green, subangular to subrounded elongated grains. Yellowish green to green pleochroism. Cleavage is evident.

Hypersthene: Rare to common. Grey-green, subrounded to rounded, elongated grains. Parallel extinction. Green to pink pleochroism.

Ilmenite: Abundant. Opaque, subrounded to well-rounded grains. Iron-black color and purple-grey in reflected light. Partial alternation to leucoxene observed sometimes.

Kyanite: Common. Colorless, subangular to subrounded, prismatic grains. Conspicuous cross cleavage associated step-like changes in order of interference color.

Leucoxene: Common. Opaque, rounded grains. White to brown in reflected light. A rough pitted surface is characteristic. Sometimes a core of unaltered ilmenite is observed.

Magnetite: Common. Opaque, subangular to rounded grains. Bluish black in reflected light. Crystal facets noted on some grains. Separated by hand magnet.

Monazite: Rare. Light yellow to greenish yellow, subrounded to rounded grains. Same color under crossed nicols as in ordinary light. Weak pleochroism.

Olivine: Rare. Yellowish green to green, subrounded to rounded grains. Much fractured, showing traces of decomposition.

Pyrite: Rare. Opaque, subangular to rounded globular or sometimes minute crystal aggregates. Pale brass-yellow in reflected light.

Rutile: Rare. Red to reddish brown, subangular to subrounded grains. Inclusions are abundant. Same color under crossed nicols as in ordinary light. Deep red-brown varieties are nearly opaque.

Sillimanite: Common. Colorless to pale shades of grey, subangular to subrounded prismatic grains. Marked by longitudinal splitting and striations parallel to length.

Staurolite: Common. Reddish brown to straw-yellow, subangular to subrounded grains. Marked by hackly fracture and haphazard boundaries. Colorless to golden yellow pleochroism. Inclusions are numerous.

Titanite: Very rare. Brownish yellow, diamond-shaped grains. Same color under crossed nicols as in ordinary light. No complete extinction in white color. Colorless to yellow weak pleochroism.

Tourmaline: Common. Brown, greenish brown, brownish black, subangular to subrounded prismatic grains. Rare cleavage and wellmarked striations. Strong pleochroism.

Zircon: Common. Colorless but some pink varieties. Some grains show euhedral forms. Commonly prisms with pyramid terminations. Commonly small grains. Red-shaped inclusions are abundant. Well defined zoning.

Zoisite: Very rare. Colorless to shades of brown, subrounded grains. Abnormal ultra-blue interference colors.

Distribution

The most common non-opaque heavy minerals in each sound and estuary in the study area are shown in Table 1 to illustrate more clearly the geographic trends in heavy mineral abundance. Except for garnet and sillimanite the heavy minerals present in the sediments in the study area have no well-defined trends because of the lack of differences in different source areas. Figures 3 and 4 show the geographic trends of garnet and sillimanite in the study area. In sediments of sounds and estuaries garnet ranges from less than 1% to more than 7%, and on the Outer Banks garnet ranges about 20% in the northern part to about 10% in the southern part. The average percentage of sillimanite in sediments of each sound and estuary ranges from 2.3% to 8.9% in the study area. In general, the geographic trends of garnet and sillimanite show a seaward increase in sounds and estuaries, and a southward decrease in garnet and a southward slight increase in sillimanite. The seaward increase in garnet starts at the downstream ends of Pamlico River estuary, Neuse

Table 1. The Average of Number Percentages of the Most Common Non-opaque Heavy Minerals in Each Sound and Estuary in the Study Area.

Heavy Mineral	Western Albemarle Sound	Eastern Albemarle Sound	Pamlico River Estuary	Neuse River Estuary	Northern Pamlico Sound	Southern Pamlico Sound	North River Estuary	Newport River Estuary
Opaque	19.0	37.6	47.6	52.5	33.8	45.7	48.0	36.1
Amphiboles & Pyroxene	40.3	26.2	19.2	13.0	28.6	19.1	14.0	26.6
Garnet	0.7	7.4	1.4	1.3	10.4	4.6	3.4	4.0
Epidote	14.0	5.6	8.0	6.4	5.9	6.6	7.0	5.7
Zircon	1.7	2.4	1.1	1.4	1.5	2.2	2.0	2.9
Staurolite	7.7	3.9	4.9	6.1	3.9	4.4	7.4	4.6
Tourmaline	1.3	2.7	1.3	1.9	2.6	1.8	2.2	3.1
Sillimanite	2.3	3.7	5.7	5.1	4.3	6.8	7.4	6.6
Kyanite	2.7	1.9	1.4	2.3	1.5	1.9	1.6	2.4
Hypersthene	1.0	1.6	0.6	0.4	1.5	0.9	0.8	1.7
Rutile	0	0.5	1.4	2.0	1.2	1.6	1.6	1.3
Others	9.3	6.4	7.3	7.4	4.7	4.5	4.6	5.3

Table 1. Continued.

Heavy Mineral	Core Sound	Bogue Sound	Northern* Outer Banks	Southern** Outer Banks
Opaque	30.1	30.2	36.9	40.7
Amphiboles & Pyroxene	29.7	30.2	16.0	14.9
Garnet	7.1	6.1	19.8	9.9
Epidote	5.7	7.7	5.4	3.9
Zircon	1.6	1.3	2.6	1.4
Staurolite	5.7	5.2	3.8	6.9
Tourmaline	2.6	2.7	2.2	3.4
Sillimanite	8.1	6.8	2.3	8.9
Kyanite	2.0	1.9	1.8	2.3
Hypersthene	1.7	1.2	2.8	1.0
Rutile	1.3	1.2	1.2	1.7
Others	4.3	5.5	4.1	5.1

* Northern Outer Banks belongs to garnet zone of Guy(1964).

** Southern Outer Banks belongs to transition zone of Guy (1964).

River estuary, and the eastern part of Albemarle Sound. In North River and Newport River estuaries the seaward increase in garnet begin at the entrance of the estuaries. The seaward increase in sillimanite is not significant within each estuary and sound. However, the average of sillimanite in each sound and estuary shows an increase from low saline to high saline water sounds and estuaries. Thus the distributional trends of garnet and sillimanite would aid in determination of the provenance and limit of landward transport of the sand size sediments in the study area.

Councill (1956) studied heavy minerals in three samples along Neuse River estuary. His results, in general, are consistent with the results of the present study in Neuse River estuary except that he found small amount of topaz and relatively high amount of rutile. But the present study did not find topaz and but found small amount of rutile and trace amounts of glaucophane and pyrite. Duane (1962) studied heavy mineral in Pamlico River estuary, Neuse River estuary, the southern part of Pamlico Sound, and Core Sound. His results are consistent with the present study results. Pilkey (1963) studied heavy minerals of the U. S. south Atlantic continental shelf and slope and concluded the following; "two heavy mineral provinces have been outlined in the area a low-epidote province (0-10%) and a high-epidote province (10-20%), and the boundary between the two is a northwest southeast line extending from Cape Fear, North Carolina." His results off the North Carolina coast generally are consistent with the heavy mineral results of the present study along the Outer Bank except for the amounts of zircon. His data show 5 to 10% zircon, whereas this study shows about 2% zircon in the southern Outer Banks.

Guy (1964) studied the heavy minerals of beach sands along Outer Banks and divided the North Carolina coast into a garnet zone (Corella to Ocracoke Inlet), a transition zone (Ocracoke Inlet to Bogue Inlet), and a staurolite-zircon zone (Bogue Inlet to Sunset Beach) based on the non-opaque heavy minerals present in the beach sands and their relative amounts. The Outer Banks of the study area belongs to the garnet zone and transition zone of Guy (1964). According to Guy (1964) the garnet zone shows a southward decrease in garnet, and the transition zone shows a southward slight decrease in garnet and slight increase in staurolite and zircon, and the staurolite-zircon zone shows a southward increase in staurolite and zircon, and significant increase in kyanite, sillimanite, and tourmaline. In general, the present study results are consistent with the results of Guy (1964). However, the present study found glaucophane and pyrite in trace amounts which he did not find.

The differences between the previous works and present study may result from the different samples used. The present study used samples which came from beach, dune, and berm, and Guy (1964) used only beach sand samples, and

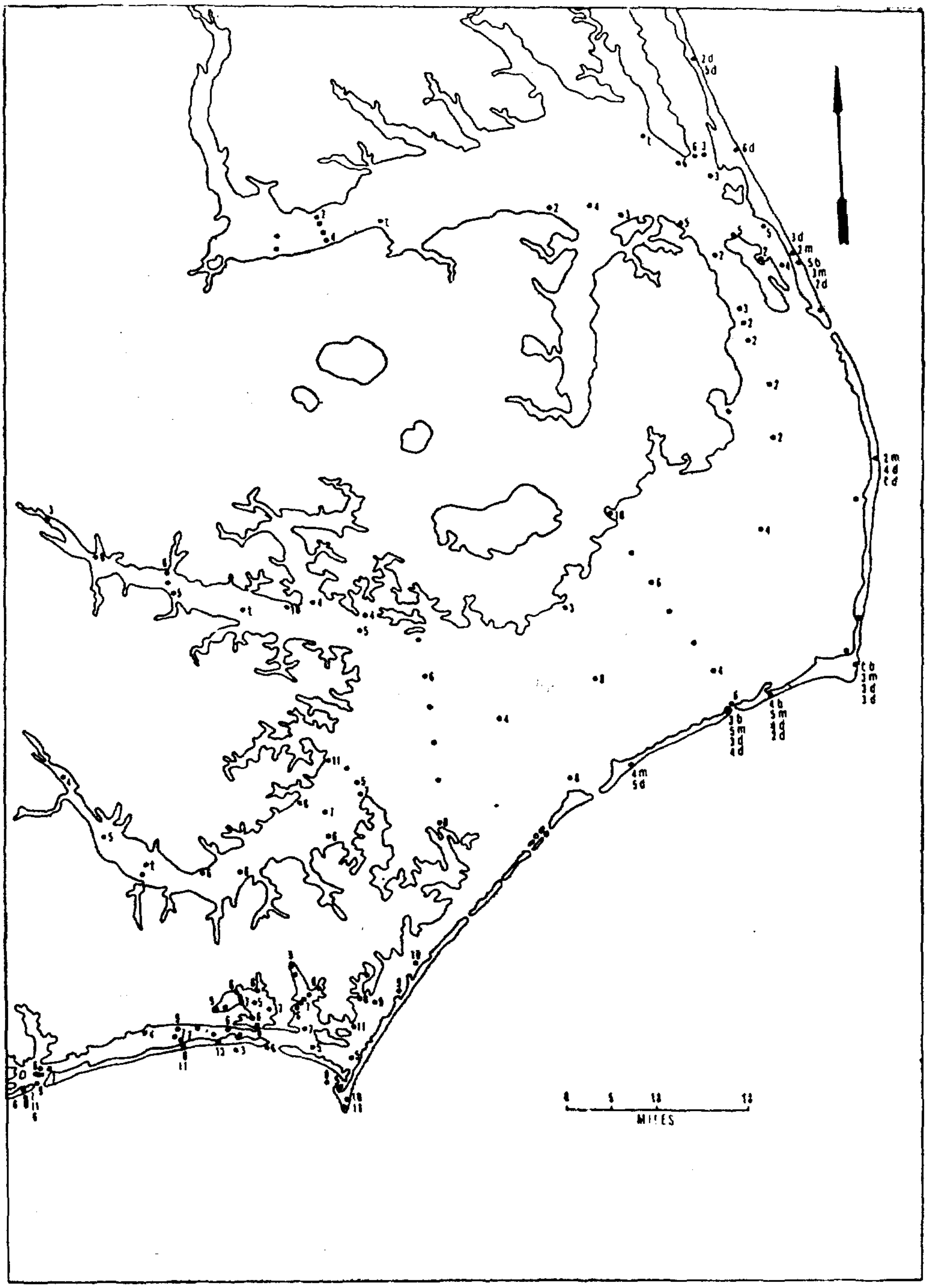

Fig. 3. Map of percent garnet in sediments of the study area. Symbols are: t-less than 1%; b-beach sample; m-berm sample; d-dune sample.

Pilkey (1963) used the bottom samples of continental shelf and slope.

Interpretation of Results

Primary sources of the heavy minerals of the sediments in the study area are the Blue Ridge and Piedmont crystalline complex, and the At-

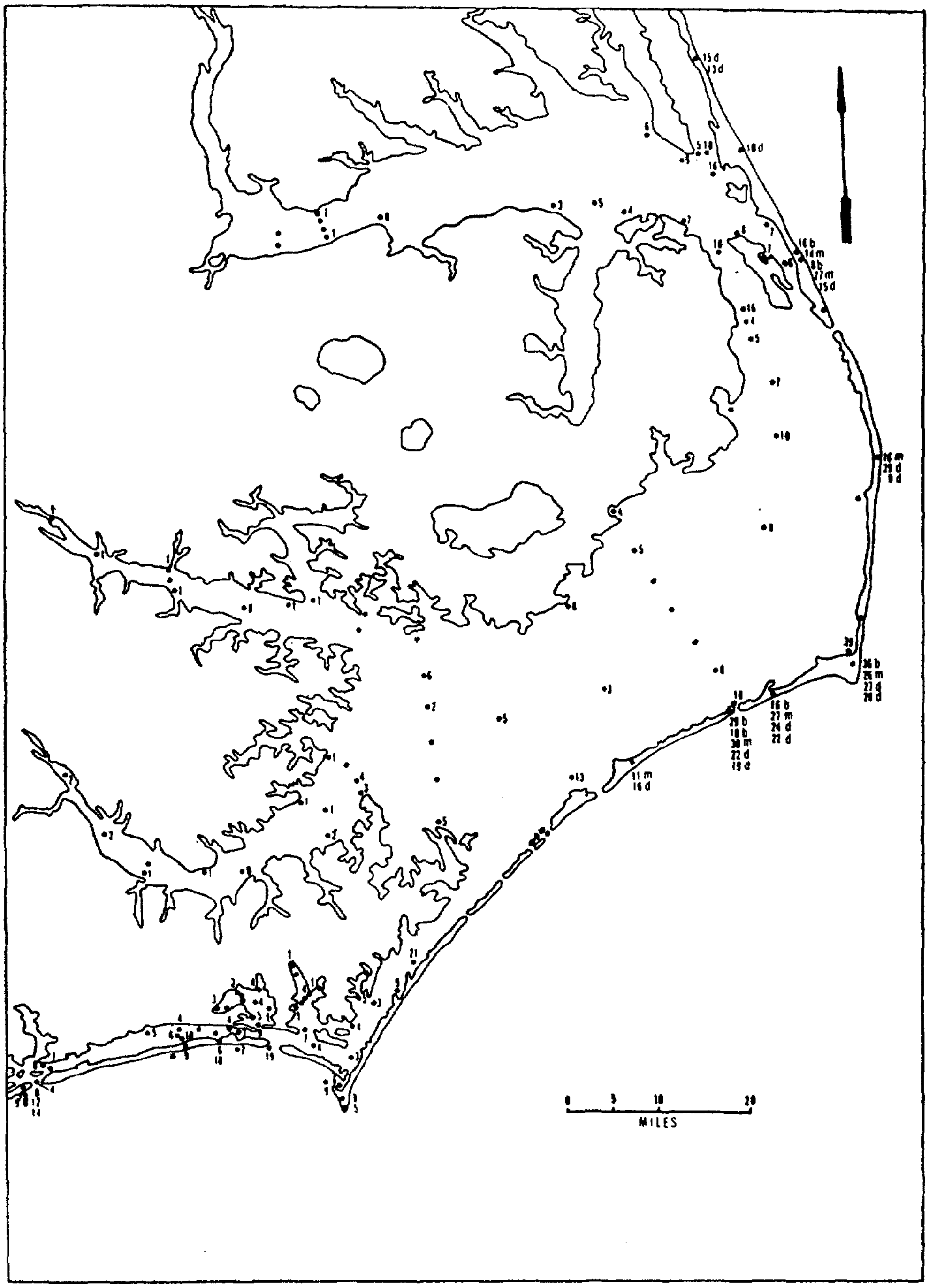

Fig. 4. Map of percent sillimanite in sediments of the study area. Symbols are; t-less than 1%; b-beach sample; m-berm sample; d-dune sample.

lantic Coastal Plain formations. The primary source of all heavy minerals in the Coastal Plain formations is also the crystalline complex. The crystalline complex consists of felsic and mafic intrusives, gneisses, schists, quartzite, marble, and meta-volcanics of Precambrian and Paleozoic ages. All of the major rivers draining into the study area carry sediments from similar source areas, and hence a wide quantitative variation in heavy mineral assemblages would not be expected.

Dryden and Dryden (1956) divided the Atlantic Coastal Plain into a northern and southern regions on the basis of heavy minerals. The North Carolina Coastal Plain is located between the northern and southern regions. They stated that in the northern and southern areas there is "full" suite, containing all of the common heavy minerals of the nearby crystalline rocks, and a "limited" suite, lacking garnet, epidote, chloritoid, and hornblende. In the northern region, a limited suite is found in the (generally) older, non-marine sediments, and a full suite in the rest of the Coastal Plain, Cretaceous to Pleistocene. In the southern region, a limited suite is found throughout the Coastal Plain sediments, marine and non-marine, except for low-lying Pleistocene and certain Recent deposit. Later they (1959) modified their original ideas somewhat and stated that, "a full suite should contain appreciable quantities (not just a trace) of two or more of the four minerals named above."

Duane (1962) found no chloritoid and an absence of or only trace amount of garnet from a bar in Trent River (tributary to Neuse River), the Pleistocene Pamlico Formation, and the Miocene Yorktown Formation. He described the heavy minerals of upstream sediments of Neuse River as limited suite and those of beach sediments of Outer Banks as full suite in the sense of Dryden and Dryden (1956). He further stated that the heavy minerals of open sounds as Pamlico Sound and Core Sound are a mixture of the limited and full suites.

The heavy minerals of the western Albemarle Sound, Pamlico River estuary, and Neuse River estuary contain very small amounts of garnet, whereas those of Outer Banks contain relatively abundant garnet. Therefore, the heavy mineral suite of the western Albemarle Sound, Pamlico River estuary, and Neuse River estuary are a limited suite, whereas that of Outer Banks is a full suite, and that of the eastern Albemarle Sound, Pamlico Sound, Core Sound, North River estuary, Newport River estuary, and Bogue Sound are a mixture of the limited and full suites in the sense of Dryden and Dryden (1956). However, most of the common heavy minerals occurring in each sound and estuary in the study area would be equivalent to what Dryden and Dryden (1959) referred to as a full suite because the appreciable quantities of hornblende and epidote (two of the four minerals) are present in the area.

Garnet and sillimanite show a seaward increase in the study area. In general, garnet decreases southward and sillimanite increases southward. The major source of garnet-rich sediments appear to the Chesapeake Bay and the southern Virginia coast. Ryan (1953) found the sediments of Chesapeake Bay to contain garnet in amount ranging up to 31%. The major source of sillimanite-rich sediments appear to be the South Carolina coast. Giles and Pilkey (1965) reported that the river, beach, and dune sediments of South Carolina contain an average of 16, 16, and 19% sillimanite, respectively. Neiheisal (1962) and Stone and Siegel (1969) found an average of 7% sillimanite in the sediments off the Georgia and South Carolina coasts.

Biedermann (1961) studied the heavy minerals of Stone Harbor of New Jersey and concluded that the main source of sediments of the lagoonal shoreline of the barrier islands was from the seaward direction. He further mentioned the follows: "sand is brought along the coast by the longshore currents and is sucked into the mouth of the inlet by the incoming tide. Once in the channel area, sand is carried by a strong current until it is deposited in the calm waters of the lagoons. The deposits so formed are called tidal delta." Duane (1962) concluded from the study of heavy minerals in the southern Pamlico Sound that sediment sources were either outside the sound region to the north with the sediment being shifted southward by littoral drift, or the sediment possibly came directly from the continental shelf due to wave action. Guy (1964) pointed out that a strong southward drift of littoral longshore currents from the Virginia coast apparently is the agent of transportation for the garnet-rich sediments in the North Carolina coast. These garnet-rich seadiments are transported into the sounds through inlets by the landward currents. The seward increase and southward decrease in garnet in the study area can be explained as a result of the above processes.

Pilkey (1963) reported the relatively high content of epidote (10 to 20%) in the southern part of the U. S. south Atlantic continental shelf and slope (from Cape Fear of North Carolina to the Florida coast). Guy (1964) found the relatively high content of epidote in the transition zone (the southern part of the present study area), and he also found the significant increase in sillimanite, kyanite, and tourmaline in the staurolite-zircon zone. According to Stefansson and Atkinson (1967) there is an indication of a counter-clockwise eddy currents in Onslow Bay and Raleigh Bay off the North Carolina coast. This current is produced by a deflection of the inner edge of the Gulf Stream as it approaches the shoals off the capes and from counter-clockwise eddies in the bays.

Therefore, the high content of epidote in the transition zone and the significant increase in sillimanite in the staurolite-zircon zone can be explained as a result of transportation by the Gulf Stream from the southern part where epidote-rich and sillimanite-rich sediments are present. Thus the seaward increase and southward increase in sillimanite in the study area also can be explained by the above processes.

The limit of the landward transport of sand size sediments from the ocean in the study area is apparently marked by the point of rapid change in garnet content. The seaward increase in garnet begins at the downstream ends of Pamlico River estuary, Neuse River estuary, and the eastern part of Albemarle Sound.

In summary, the main source of the sediments in the study area are the Blue Ridge and Piedmont crystalline complex, and the Atlantic Coastal Plain formations. These sediments are mixed with the sediments which are transported from the Virginia coast by the litteral longshore currents and from the South Carolina coast by the Gulf Stream to the North Carolina coast, and retransported into the sounds and estuaries in the study area by the landward currents. The landward transport of sand size sediments may reach the downstream ends of Pamlico River estuary, Neuse River estuary, and the eastern part of Albemarle Sound.

CONCLUSION

Factors of depositional environments such as currents, temperature, salinity, acidity, and depth of water are varying and exhibit well developed gradients through the study area from the estuaries on the west to the Atlantic coast on the east.

Twenty-four heavy minerals are present, but less than one half of these occur frequently. Heavy minerals comprise about less than 1% of the sample but vary from sample to sample, and range in amounts up to 2.4% in sound and estuarine sediments, and 16.7% in Outer Banks sediments. In general, only garnet and sillimanite show geographic trends. Garnet and sillimanite show a seaward increase in sounds and estuaries, and a southward decrease in garnet and southward increase in sillimanite. The distributional trends of garnet and sillimanite, and the results, of clay mineral study indicate that some portion of sediments in the study area are contributed from the Atlantic Ocean.

The main source of the sediments in the study area are the Blue Ridge and Piedmont crystalline complex and the Atlantic Coastal Plain formations. These sediments are mixed with the sediments which are transported from Virginia coast by the littoral longshore currents and from South Carolina coast by the Gulf Stream to the North Carolina coast, and retransported into the sounds and estuaries in the study area by the landward currents. The landward transport of sand size sediments may reach the downstream ends of Pamlico River estuary, Neuse River estuary, and the eastern part of Albemarle Sound.

REFERENCES

Biederman, E. W., Jr., 1961. How to analyze strand lines from heavy minerals, facies data. World Oil, **152**(5), 76-79.

Brett, C. E. 1963. Relationships between marine invertebrate in fauna distribution and sediment type distribution in Bogue Sound, North Carolina: unpublished Ph.D. dissertation, Univ. of N. C., Chapel Hill, N. C., 202 p.

Councill, R. J. 1956. Mineralogy and particle attributes of Neuse River (North Carolina) sands. unpublished M. S. thesis, Univ. of N. C., Chapel Hill, N. C., 40 p.

Dryden, L., and C. Dryden. 1956. Atlantic Coastal Plain heavy minerals: a speculation summary. 20th Internat. Geol. Cong., Mexico City, 18 p.

Dryden, L., and C. Dryden. 1959. Heavy minerals from the North Carolina Coastal Plain. Proc. Penn. Acad. Sci., **33**, 185-194.

Duane, D. B. 1962. Petrology of Recent bottom sediments of the western Pamlico Sound region, North Carolina. unpublished Ph.D. dissertation, Univ. of Kansas, Lawrence, Kansas, 108 p.

Griffin, G. M. and R. L. Ingram. 1955. Clay minerals of the Neuse River estuary. Jour. Sed. Petrology, **25**, 194-200.

Grossman, S. 1961. The ecology of the Rhizopodea and Ostracoda of the southern Pamlico Sound, North Carolina. unpublished Ph.D. dissertation, Univ. of Kansas, Lawrence, Kansas, 254 p.

Guy, S. C. 1964. A heavy mineral analysis of North Carolina beach sands. unpublished M. S. thesis, Univ. of N. C., Chapel Hill, N. C., 30 p.

Hjulström, F. 1939. Transportation of detritus by moving water, p. 5-31 *in* Trask, P. D., Editor, Recent marine sediments. Am. Assoc. Petroleum Geologists, Tulsa, Oklahoma, 736 p.

Johnson, F. K. 1959. The sediments of the Newport River estuary, Morehead City, North Carolina. unpublished M. S. thesis, Univ. of N. C., Chapel Hill, N. C., 36 p.

Marshall, N. 1951,. Hydrography of North Carolina marine waters, p. 1-76 *in* Tayler, H. F. and associates, Editors, Survey of marine fisheries of North Carolina. Chapel Hill, N. C., Univ. of N. C. Press, 555 p.

Neiheisal, J. 1962. Heavy-mineral investigation of Recent and Pleistocene sands of lower Coastal Plain of Georgia. Geol. Sec. America Bull., **73**, 365-374.

Pels, R. J. 1967. Sediments of Albemarle Sound, North Carolina. unpublished M. S. thesis, Univ. of N. C., Chapel Hill, N. C., 73 p.

Pilkey, O. H. 1963. Heavy minerals of the U. S. South Atlantic continental shelf and slope. Geol. Soc. America Bull., **74**, 641-648.

Roelefs, E. W. and D. F. Bumpus. 1953. The hydrography of Pamlico Sound. Bull. Marine Sci. of Gulf and Caribbean, **3**, 181-205.

Ryan, J. D. 1953. The sediments of Chesapeake Bay. Maryland Dept. of Geology, Mines and Water Resources, Bull. **12**, 120.

Shepard, F. P. and D. G. Moore. 1954. Sedimentary environments differentiated by coarse fraction studies. Am. Assoc. Petroleum Geologists Bull., **38**, 1792-1802.

Stefansson, U. and L. P. Atkinson. 1967. Physical and chemical properties of the shelf and slope waters off North Carolina. Duke Univ. Marine Lab., Beaufort, N. C., 230 p.

Stone, I. C. and F. R. Siegel. 1969. Distribution and provenance of minerals from continental shelf sediments off the South Carolina coast. Jour. Sed. Petrology, **39**, 276-296.

U. S. Coast and Geodetic Survey. 1936. U. S. Coast Pilot, Atlantic Coast, Section D, Cape Henry to Key West, 4th ed., Serial No. 582.

Woods, W. J. 1967. Hydrographic studies in the Pamlico Sound, p. 104-114 *in* Proceedings symposium on hydrology of the coastal waters of North Carolina. Water Resources Research Inst. of the Univ. of N. C., Report No. 5, Raleigh, N. C., 154 p.