SOURCE AND DISTRIBUTION OF SEDIMENTS AT BRUNSWICK HARBOR & VICINITY GEORGIA

by

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FOREWORD

The investigation reported herein embodies an integrated approach to an interpretation of sedimentation and hydrodynamics of a complex coastal harbor area containing many variables. In order to establish certain diagnostic minerals of value in analysis of sediment characteristics, research of the regional geology was conducted and sediments of rivers analyzed. These data appear in Appendix A to this report. A general understanding of energy levels and dynamic agencies operating along this section of coast was accomplished by use of wave refraction analysis and historic coastline studies; this background material appears as Appendix B.

The inter-relation of sediment and hydrodynamic agents reflects the source material causing active shoaling in Brunswick Harbor and augments prototype investigations conducted during the last several years by the U. S. Army Engineer District, Savannah. The use of diagnostic minerals as "natural tracers" appears most worthwhile and suggests a relatively inexpensive technique that could be of real benefit in future studies.

The work and study leading to preparation of this report, "Coastal Investigation of Brunswick Harbor and Vicinity, Georgia", was sponsored under a Secretary of the Army Research and Study Fellowship for a period of one year.

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Because of its application to the research and investigation program of the U. S. Army Coastal Engineering Research Center and a widespread interest in procedures for tracing movement of coastal sediments, this report with appendices is being published at this time in the CERC technical memorandum series.

This report is published under authority of Public Law 166, 79th Congress, approved July 31, 1945, as supplemented by Public Law 172, 88th Congress, approved November 7, 1963.

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SOURCE AND DISTRIBUTION OF SEDIMENTS AT BRUNSWICK HARBOR AND VICINITY, GEORGIA

by

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ABSTRACT

The distribution patterns of bottom sediment in Brunswick Harbor and vicinity, Georgia, reflect the long-term hydrodynamic response and generally correlate with dynamic factors affecting sedimentation. Certain diagnostic minerals reflect the source area and are used as "natural tracers" to delineate direction of sediment movement. Analysis of sedimentary parameters also enables interpretation of direction of sediment transport.

The results of this investigation indicate that shoaling presently occurring in Brunswick Harbor is related to materials from a source in the Altamaha River. Sediment contribution to shoaling is introduced into the harbor through the tidal inlet between the barrier islands and from the MacKay River during greater than average discharge rates of the Altamaha River. Shoaling rates in the harbor also correlate with discharge rates of the Altamaha River.

This investigation demonstrates the value of sediment interpretation, based on knowledge of regional geology, to provide a basis for analysis of sediment movement in a coastal area. In such a complex coastal area as Brunswick, Georgia, the sediment characteristics augment hydraulic measurements and enable a more complete interpretation of the hydrodynamics involved. Such information has application to engineering design of coastal structures.

INTRODUCTION

With the deepening and widening of the channels to 30 feet by 400 feet in 1959, shoaling became a problem in Brunswick Harbor. Since then, prototype studies have been conducted by the U. S. Army Corps of Engineers to provide information for engineering remedial measures that might curtail shoaling.

An evaluation of the source and manner of sedimentation presently causing shoaling problems in Brunswick Harbor is more complex than for most harbors of the southeastern Atlantic coast. Brunswick Harbor, while largely a well-mixed salt water estuary, also receives a supply of sediment-laden fresh water discharged from a distributary stream of the Altamaha River. The amount of sediment transport in such a harbor fluctuates with the change of tides and fresh water discharge from the Altamaha River watershed. As a result, a large number of variables must be considered in order to fully evaluate the source of materials which cause local shoaling.

The purpose of this paper is to present an integrated approach utilizing the diagnostic minerals and sedimentary parameters to augment hydrodynamic and density pattern techniques in order to establish the source and manner of sediment distribution. Such a correlation will be shown to be of significant value in the evaluation of "long-term" hydrodynamic response and may engender a number of other ideas applicable to improved planning for estuary engineering.

DELINEATION OF THE PHYSIOGRAPHIC UNIT

An understanding of the source of materials presently causing shoaling problems in Brunswick Harbor logically begins with delineation of the "physiographic unit". The physiographic unit, as defined by J. W. Johnson (1959), is "a shore area so limited that the shore phenomena within the area are not affected by the physical conditions in adjacent areas".

The "physiographic unit", comprising the extended geographic dimensions of the Brunswick Harbor area, includes the watershed of the Altamaha River and Turtle River; the Atlantic Ocean constitutes the eastern boundary (Figure 1). The physiographic provinces in this watershed include the barrier islands, Pleistocene terraces, Coastal Plain Formation, and the Piedmont Province. The offshore area beyond the barrier islands connects with Brunswick Harbor through the tidal inlet between Jekyll and St. Simons Islands (Figure 2).

Sediment moves in the streams from the watershed as suspended sediment in the flowing water and as bedload along the channel bottom. The Altamaha River, draining the Piedmont Province, contains an abundant suspended load of colloidal clay as well as appreciable granular minerals from eroded crystalline rocks. According to records of the U. S. Geological Survey (1960), the Altamaha River has a mean annual discharge of 12,620 cfs; this is the largest recorded for rivers discharging along the Southeastern Atlantic States. Some of the Altamaha River discharge, during maximum peaks, will be shown to enter Brunswick Harbor through the MacKay River while the greater portion discharges directly into the Atlantic Ocean. The drainage area of the Turtle River extends inland less than 30 miles and the watershed is contained within the Pleistocene Terraces. The discharge of this river is negligible and its watershed is comprised of marine sediments which are a meager source of clay or materials normally constituting suspended sediments.

The route followed by suspended and bedload sediment into Brunswick Harbor is devious. It is convenient to visualize two main routes of travel; overland flow from the watershed and flow through the tidal inlet between barrier islands. Outflow components from Brunswick Harbor may be considered

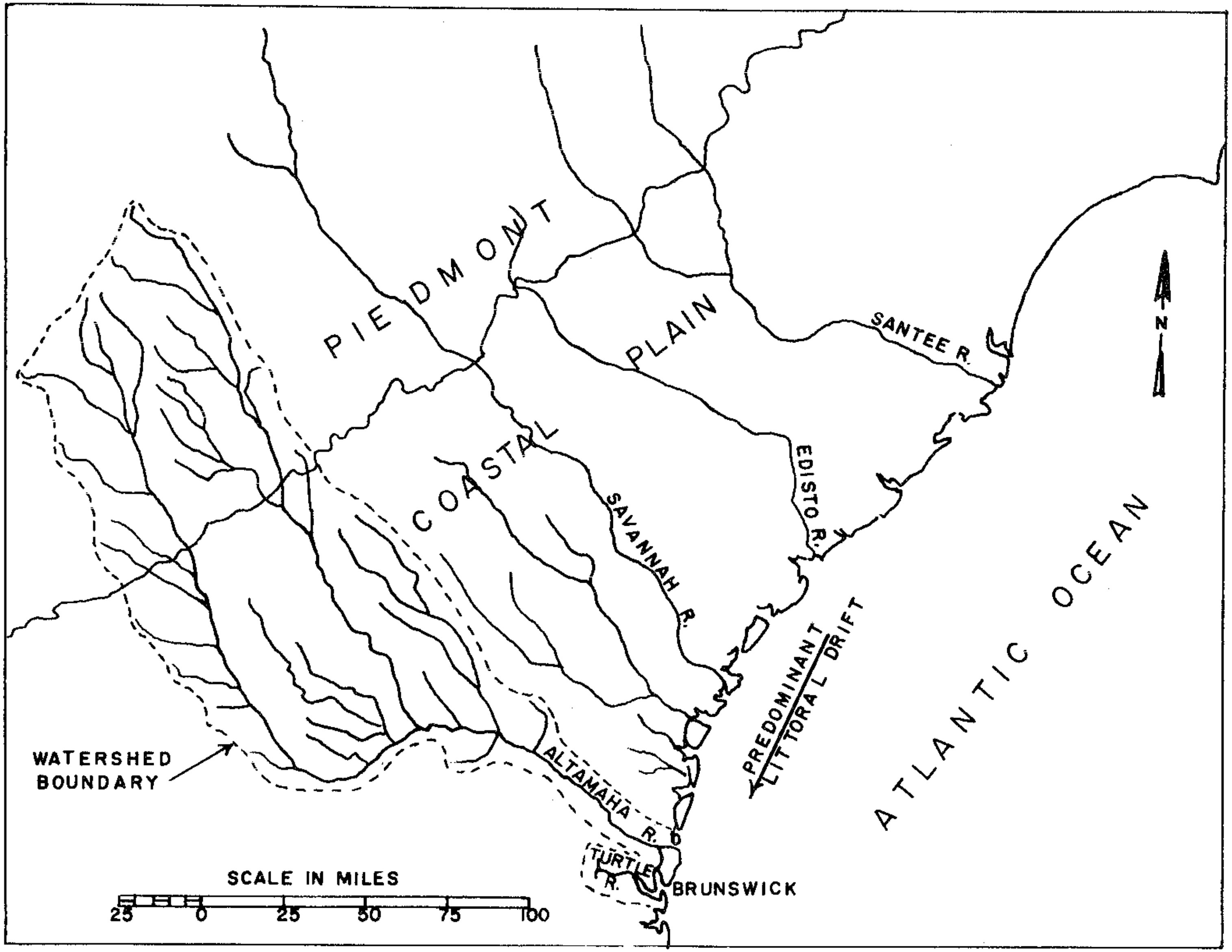


FIGURE I. DRAINAGE AREA COMPRISING WATERSHED OF BRUNSWICK HARBOR, GEORGIA.

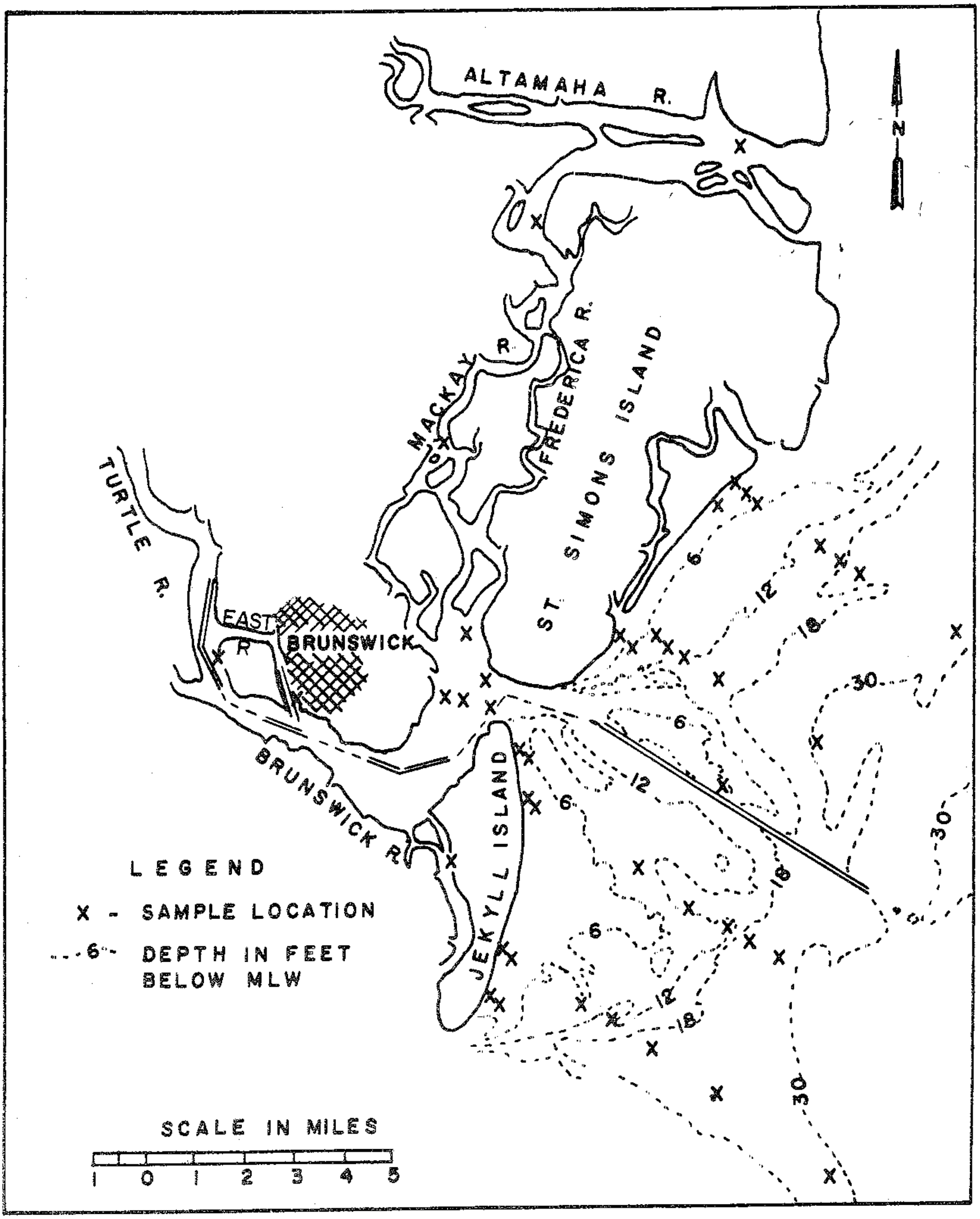


FIGURE 2. SEDIMENT SAMPLE LOCATIONS IN BRUNSWICK HARBOR AND VICINITY.

as the ebb discharge through the tidal inlet and deflection of the flow in a southerly direction by the littoral currents along the coast.

DESCRIPTION OF BOTTOM SEDIMENTS

Procedure

The sample locations of bottom sediments used in this investigation are shown in Figure 2. Samples were obtained by means of a flange scoop sampler during the period of 12 to 20 June 1963. Representative samples of approximately 2-pint volume were obtained for laboratory investigation.

Laboratory analysis consisted of standard methods as described by Krumbein and Pettijohn (1938). Clay sizes were determined by hydrometer settling velocity technique and computed as material finer than 0.005 mm. Compositional analysis consisted of petrographic and chemical techniques. Percent of sample-weight comprising shell was determined by leaching of the sediment with dilute HCL, and organic matter, significant in some harbor samples, was determined by chemical analysis. Petrographic analysis was performed on all sediment greater than 0.074-mm. grain size; diagnostic minerals in samples containing appreciable clay and silt had their composition percentage adjusted to reflect their relation only to those sediment particles in the sand-size range All heavy minerals were computed by point count and reported as percent composition of the heavy-mineral suite.

Analysis of Sedimentary Parameters

The median diameter, sorting coefficient, and skewness were computed from the weight-accumulation curve and the largest diameters of quartz were obtained by direct measurement from the largest sieve size by means of the binocular microscope. The median diameter and maximum quartz size values were found to be most significant for correlation purposes; spatial distribution is shown in Figure 4.

The largest average median diameter value occurs in the Altamaha River sample and values of similar magnitude occur in the MacKay River; values decrease toward the harbor. Median diameter values in the offshore area show anomalous highs where shell content is appreciable. Maximum quartz size correlates with median diameters except where shell is abundant.

Most sediment samples were found to be well sorted with sorting coefficients ranging between 1.2 and 1.45. Notable exceptions were (a) sample locations in Altamaha, MacKay and Turtle Rivers, (b) three offshore sample locations in which shell content is at a maximum and (c) two samples at the harbor entrance.

Skewness computations reveal that most sediment samples are in adjustment with their environment. Samples containing many grade sizes and

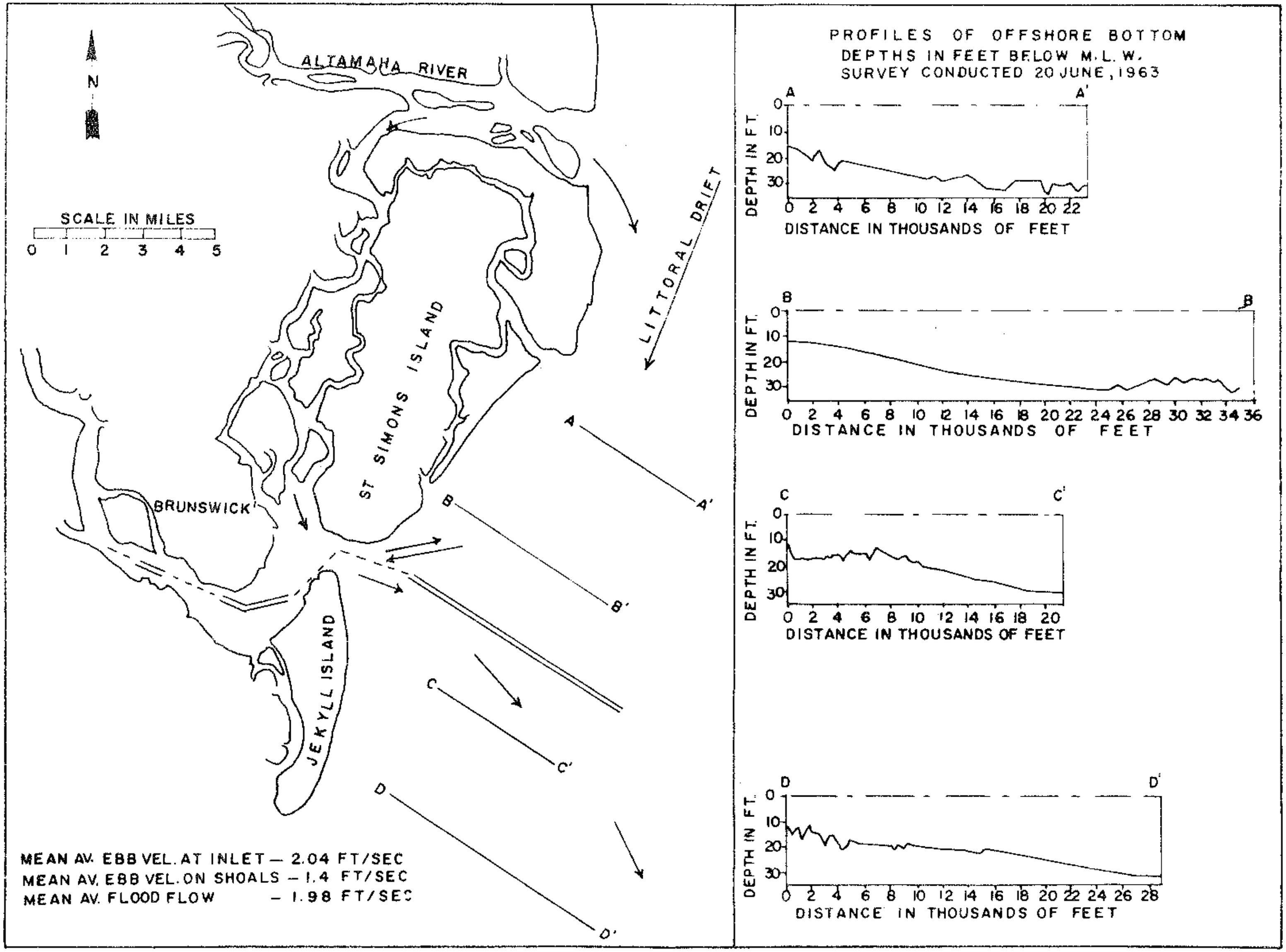


FIGURE 3. BOTTOM PROFILES AND CURRENT VELOCITY DIRECTION IN OFFSHORE AREA OF BRUNSWICK, GEORGIA. DATA FROM U.S. ARMY CORPS OF ENGINEERS SURVEYS.

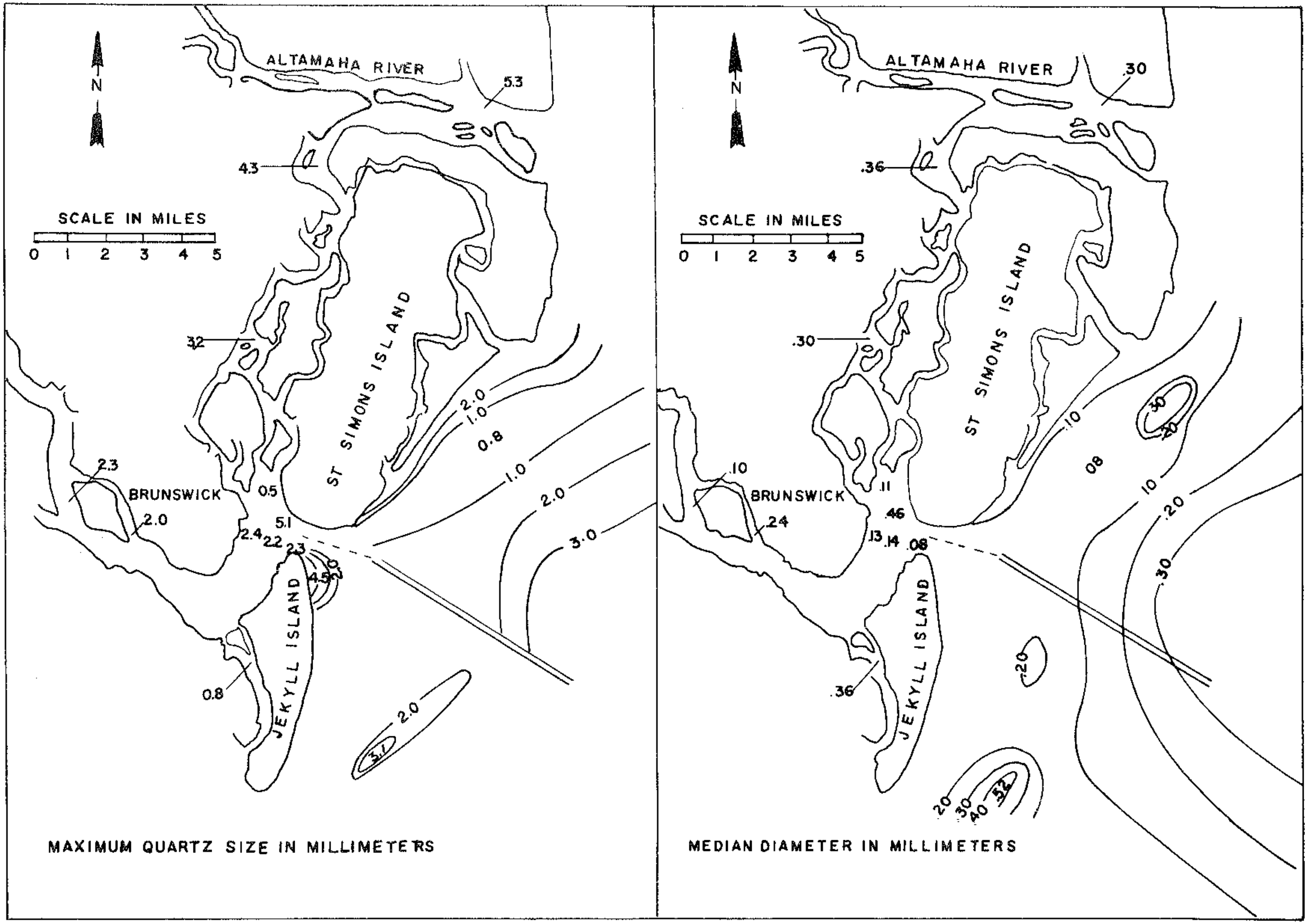


FIGURE 4. MAXIMUM QUARTZ SIZE AND MEDIAN DIAMETER OF BOTTOM SEDIMENT IN BRUNSWICK HARBOR AND VICINITY.

therefore having a large value of S_o but a small value of S_k are those (a) containing appreciable shell or (b) river sediment from Altamaha River and northern reach of MacKay River.

Conclusions regarding sedimentary parameter values are as follows:

1. Sediment samples from Altamaha River and northern portion of MacKay River reflect the typically poorer sorting of rivers containing detritus from an upland source and where discharge variation causes wide disparity of competence in transport. The net movement appears to be from the Altamaha River through MacKay River toward Brunswick Harbor.

2. Harbor entrance sediment sorting and size distribution is less well defined but apparently related to mixing by tidal currents, contributions from MacKay River, and nearby erosion along the tidal inlets.

3. Local anomalous sedimentary parameter values offshore are attributed to influence of high shell content from the marine environment. Such influence is apparent when comparison is made with shell distribution shown in Figure 5.

4. Of real significance offshore is the lower mediam diameter and lower maximum quartz size values occurring between 6 and 18-foot depths north of the channel. As shown in Figure 2, this area represents a channel through the northern fan-shaped tidal delta and also correlates with direction of maximum tidal currents depicted in Figure 3.

Shell and Organic Matter

Only minor amounts of shell material (calcium carbonate) are found in the rivers and estuaries of the Brunswick area (Figure 5). High carbonate values, greater than 20 percent, occur along the southern fan-shaped portion of the delta area. Other offshore bottom locations show a more regular distribution ranging between 5 and 10 percent.

The shell material is indigenous to the marine environment and in mixing with the inorganic mineral detritus from the northern beaches and upland sources, it tends to have a modifying effect on sediment parameter values. The generally flat to curved nature of the shell shape in contrast to more rounded quartz particles results in greater hydraulic response for the shell material. As a result, the shell predominates in larger sieve sizes.

Appreciable organic matter occurs only in the samples of the inner harbor area in a strong reducing environment which is characterized by the pronounced blue-gray color. The amount of organic matter (worm and other biologic assemblages) appears directly related to the amount of clay in the bottom sediment. The maximum clay content and organic matter occur in the sample from East River which is also the site of maximum shoaling in the harbor area.

According to Kofoed and Grosline (1963), organic matter concentrations in Apalachicola Bay, Florida, are attributable to low permeability of fine sediments which inhibits the exchange of biochemical products. Small pore spaces of silts and clays inhibit water circulation, as well as oxidation and bacterial action, causing removal of biochemical products to be restricted.

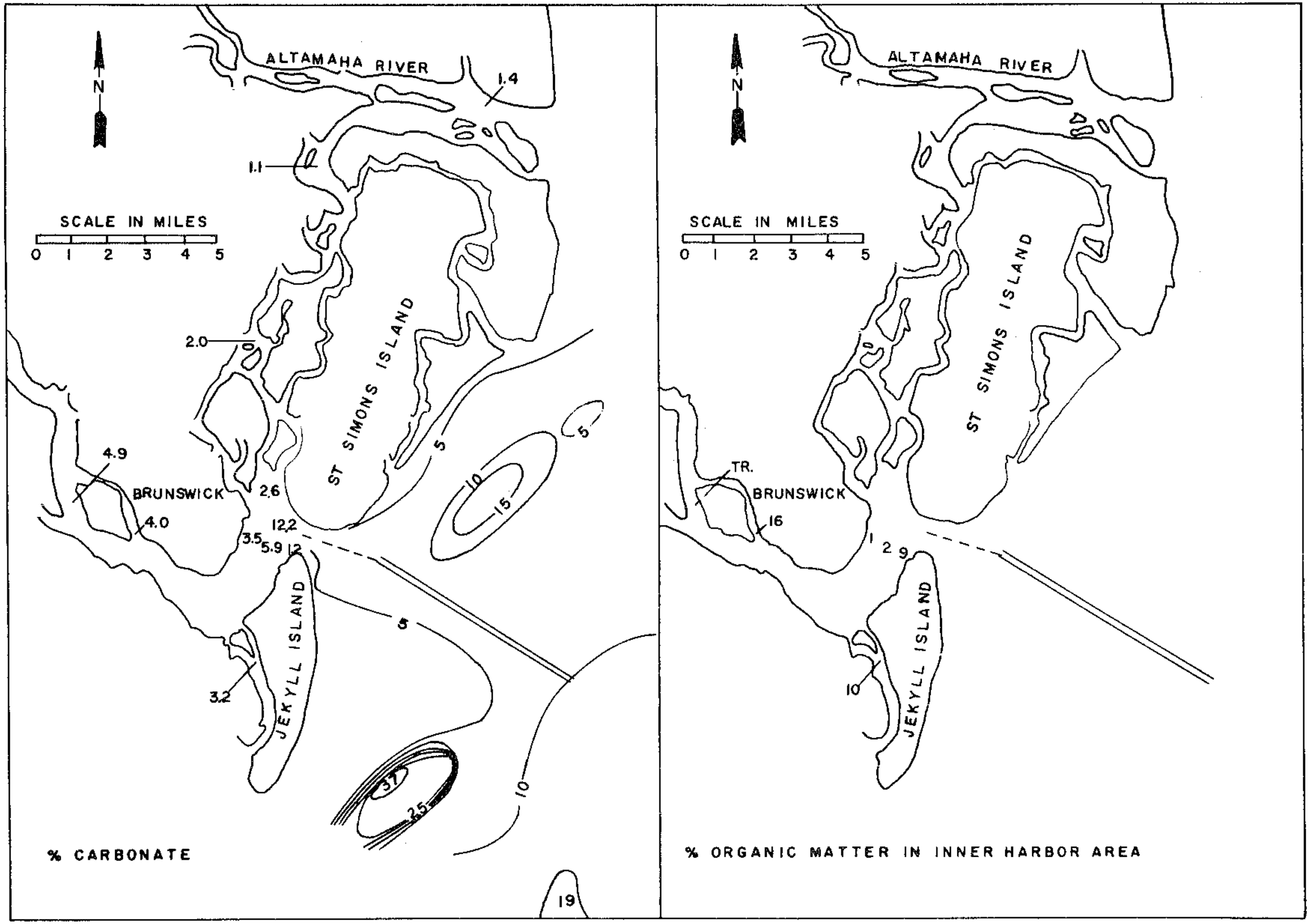
Krone (1962), in reporting on sediment from San Francisco Bay area, noted that suspended or recently deposited sediment had a light brown color while sediment more than a few centimeters below the bottom surface had a grayish color ranging from light gray to black. Such color changes, according to Krone, are associated with the change of ferric hydroxide to ferrous ions by bacterial reduction and finally to ferrous sulfide after reduction of sulphate ions. Such a reducing environment exists in Brunswick Harbor for sample locations shown in Figure 5.

Hornblende Distribution in Bottom Sediment

Hornblende, in the sand-size fraction of sediment, is especially diagnostic as related to distribution of sediment from the source areas. Appendix A is a regional study which clearly shows that hornblende occurs in amounts ranging between 9 and 40 percent of the heavy-mineral suite in rivers draining the Piedmont but seldom exceeds trace amounts in rivers draining the Coastal Plain formations. This fact is related to the geologic history and stability of hornblende; hornblende in older Coastal Plain formations has been leached by acid solutions since deposition. Hornblende transported by rivers from the Piedmont source area to the marine environment is stable because of the basic conditions in this environment which are conducive to its preservation.

Hornblende distribution in rivers is shown in Figure 4 of Appendix A. In the "physiographic unit" constituting Brunswick Harbor, hornblende is absent in the Turtle River drainage area but is abundant in the Altamaha River sediment originating in the Piedmont. Along the barrier islands and offshore area, hornblende is abundant due to the stabilizing influence of the basic marine environment.

Hornblende distribution in Brunswick Harbor and vicinity is shown in Figure 6. Since an impoverishment of this mineral from the source drainage area for Turtle River, the hornblende occurring at Brunswick in East River was contributed from a rich hornblende source in the Altamaha River through MacKay River and/or through the tidal inlet. In the offshore area, hornblende increases in the seaward direction but anomalous highs exist north of the channel between the 6 and 18-foot depth contours. This is the locus of the deepening across the north tidal delta and, as will be shown later, appears to define the zone of sediment movement into Brunswick Harbor from the offshore area. The anomalous high south of the channel is in the line of projection of ebb flow conditions across the shoal area (see Figure 3).



% CARBONATE

% ORGANIC MATTER IN INNER HARBOR AREA

FIGURE 5. DISTRIBUTION OF SHELL CARBONATE AND ORGANIC MATTER FOR LOCATIONS IN BRUNSWICK HARBOR AND VICINITY.

Feldspar Distribution in Bottom Sediment

Feldspar, like hornblende, is diagnostic to rivers draining the Piedmont. It occurs in trace amounts in sediment above the tidal area in the Turtle River drainage area but comprises between 5 and 10 percent of the Altamaha River and offshore marine sediments. A reduction of feldspar ratio from 9 to 6 percent through MacKay River toward the harbor is shown in Figure 6. In the offshore area, higher ratios occur in these areas reflecting tidal current movement as shown in Figure 3. Sediment from the more northerly beaches contain less feldspar than is introduced by the Altamaha River to the littoral currents operating along the coast. The reduced ratio south of the channel is probably related to the diffusion of feldspar in the southerly littoral drift direction from the rich Altamaha River source (Figure 6).

Clay and Mica Distribution

Clay and mica are diagnostic to rivers draining the Piedmont and are restricted to zones of relatively low energy level in the coastal regions. Clay and mica occur in the bottom sediment for sample locations as depicted in Figure 7. Both these materials are absent from beach sands because of the high energy levels associated with surf action.

The clay particles (less than 0.005-mm. grain size) represent more nearly the short-term response of hydrodynamic agencies in contrast to the sand-size sediment. Although clay is more abundant in East River, adjacent to Brunswick, the source of this material is believed to be in the direction of the tidal inlet rather than Turtle River. The clay will be shown in a later section to correlate with Altamaha River discharge and other dynamic factors.

In the offshore area, both clay and mica occur most abundantly in the bottom sediment defined by the 6 to 18-foot bottom contours (Figure 7). The clay and mica in bottom sediment south of the channel also appear to reflect the ebb tidal flow as shown in Figure 3.

Differential thermal and X-ray diffraction analyses would be of value in determining possible diagnostic compositional features of the clay such as exist in the heavy-mineral suite of sand-size particles. Such procedure is recommended in future studies designed to reflect source materials.*

Mica in the sand-size fraction of bottom sediments has great hydraulic response because of its flat, thin shape and its transport characteristics are similar to those of clay. This relationship is reflected in the similarity of distribution patterns for these materials shown in Figure 7.

NET MOVEMENT REFLECTED IN SEDIMENT ANALYSIS

The sand-size sediment and sedimentary parameter values reflect "long-term" hydrodynamic response while clay reflects the "short-term" effect.

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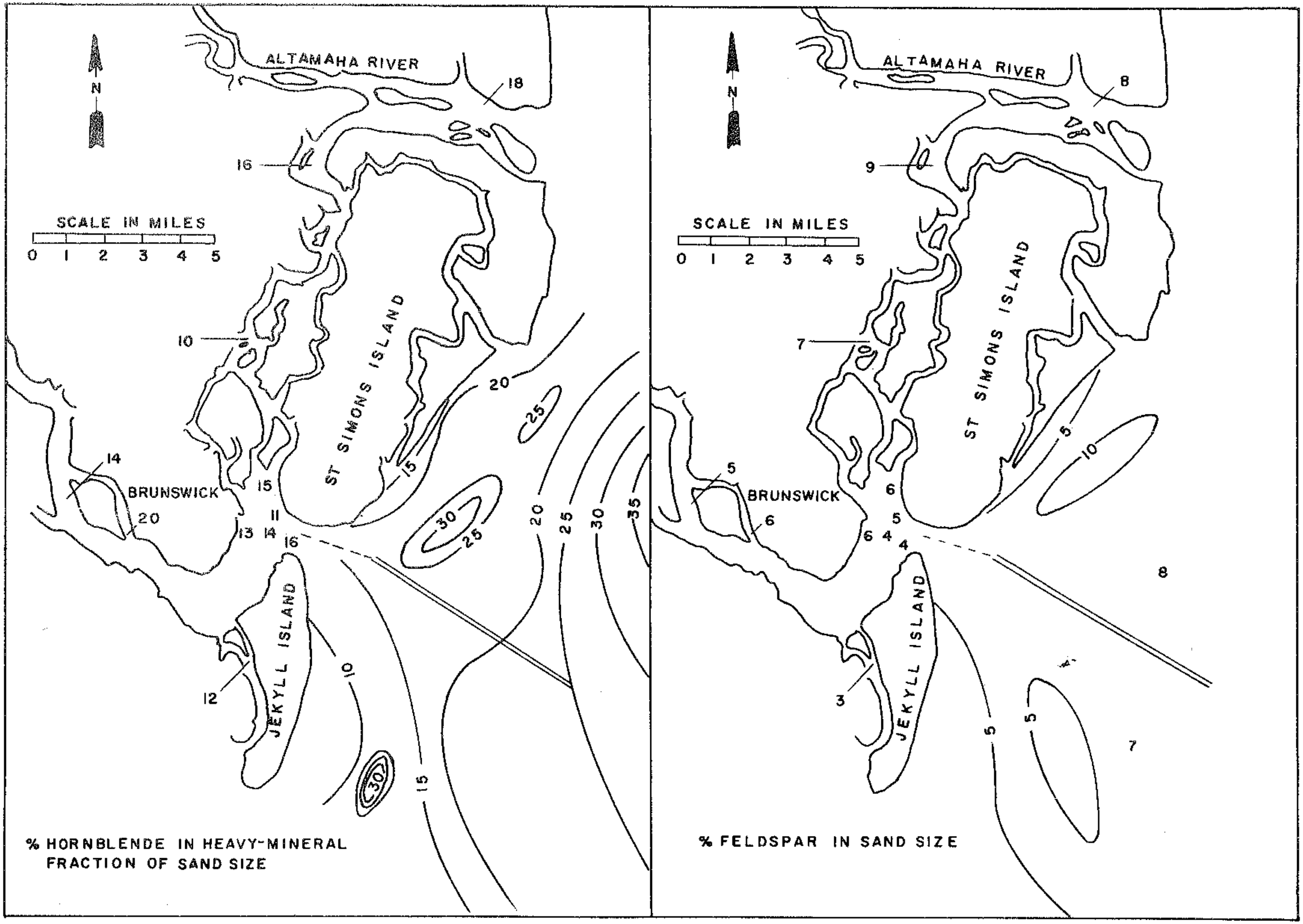
*Since going to press, X-ray diffraction analysis of several samples reveals that kaolinite ratios of the clay fraction appear to reflect the source area and short-term hydrodynamic response; such data tend to confirm conclusions of this report.



% HORNBLENDE IN HEAVY-MINERAL FRACTION OF SAND SIZE

% FELDSPAR IN SAND SIZE

FIGURE 6. DISTRIBUTION OF HORNBLENDE AND FELDSPAR FOR LOCATIONS IN BRUNSWICK HARBOR AND VICINITY.

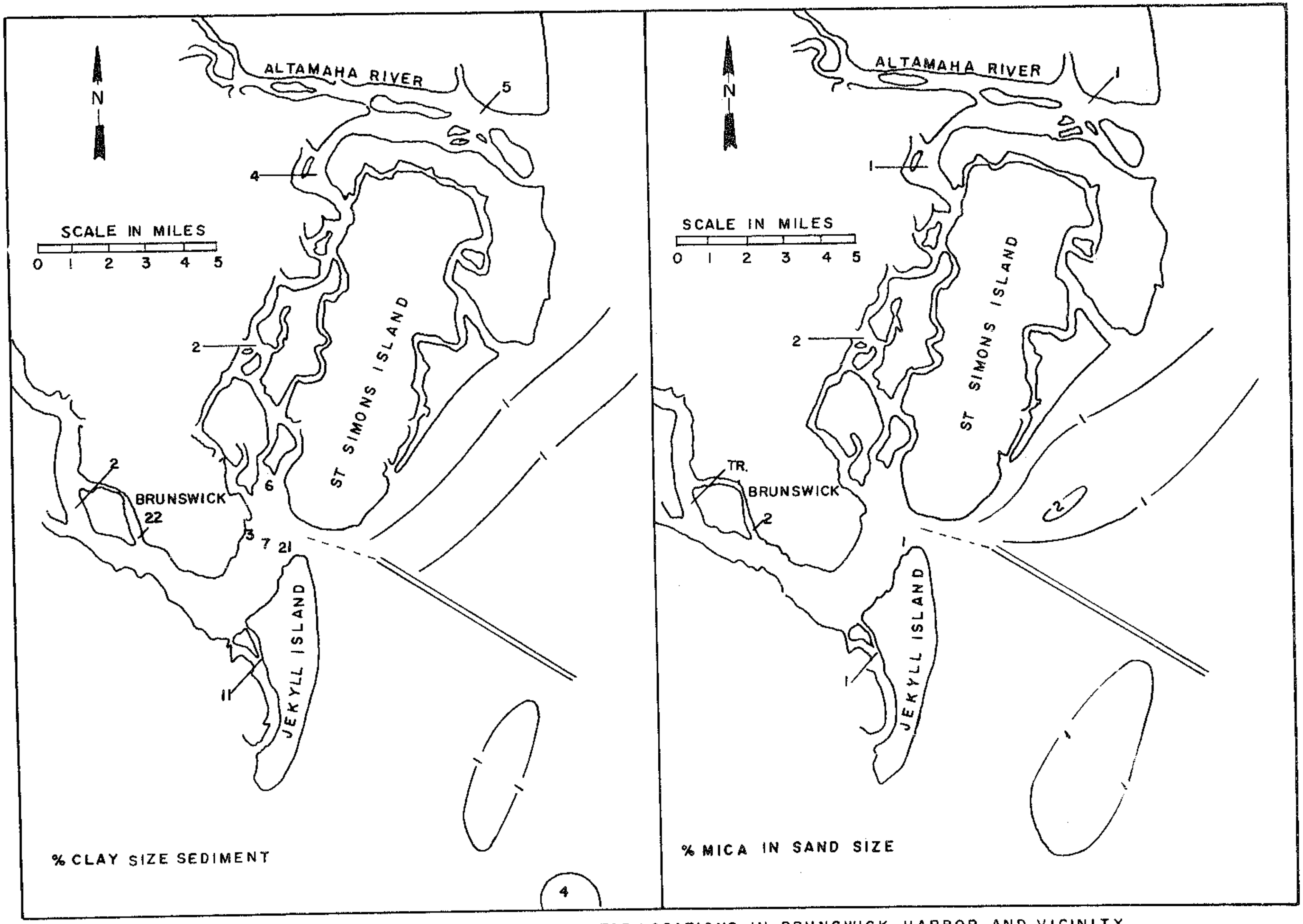


FIGURE 7. DISTRIBUTION OF CLAY-SIZE SEDIMENT AND MICA FOR LOCATIONS IN BRUNSWICK HARBOR AND VICINITY.

Analysis of bottom sediments in Brunswick Harbor and vicinity suggests the following:

1. Median diameter values, maximum quartz diameters, hornblende, and feldspar distribution suggest net movement of bedload sediment from Altamaha River through MacKay River to Brunswick Harbor when the Altamaha River attains greatest competence and capacity for sediment transport.

2. The bottom sediment in the channel across the north shoal in the offshore area, between 6 and 18-foot depths, reflects the contributions of sediment projected from the mouth of the Altamaha River by littoral currents and the effects of tidal currents operating through the tidal inlet between the barrier islands.

3. Sediment contribution from Turtle River drainage area is negligible and shoaling experienced at Brunswick is not appreciably affected from this source.

4. Sediments to the site of heavy shoaling in East River, at Brunswick, are supplied from the harbor entrance to the east with one component probably from the Altamaha River and another component through the tidal inlet.

The shoaling material in East River is predominantly silt and clay which reflects short-term hydrodynamic response. It will be demonstrated that the source materials are regulated by Altamaha River discharge and hydrodynamic factors effecting the transfer to the shoaling area.

CAUSE OF SHOALING IN BRUNSWICK HARBOR

General Concepts

An evaluation of the cause of shoaling in Brunswick Harbor is more complex than that for most harbors of the southeastern Atlantic coast because the harbor area, while largely a well-mixed salt-water estuary, also receives a quantity of sediment-laden fresh-water discharge from a distributary stream of the Altamaha River during times of large discharge from the upland sources.

Trainor (1963) lists the general causes of shoaling as (1) the purely mechanical process of settling; (2) flocculation due to interaction of salt water and silt-bearing fresh water; (3) bedload movement; and (4) density currents resulting from mixing of salt and fresh water.

In Brunswick Harbor, a purely mechanical process of settling will be shown to occur at shoaling areas as a result of reduced energy level and predominance of bottom flood over bottom ebb flow. Bedload movement has been presented in earlier sections. Density currents resulting from mixing of fresh and salt water will be considered for a salinity investigation conducted in the MacKay and Frederica Rivers. Flocculation of colloidal clays, when fresh water enters salt water, has been explained in a most

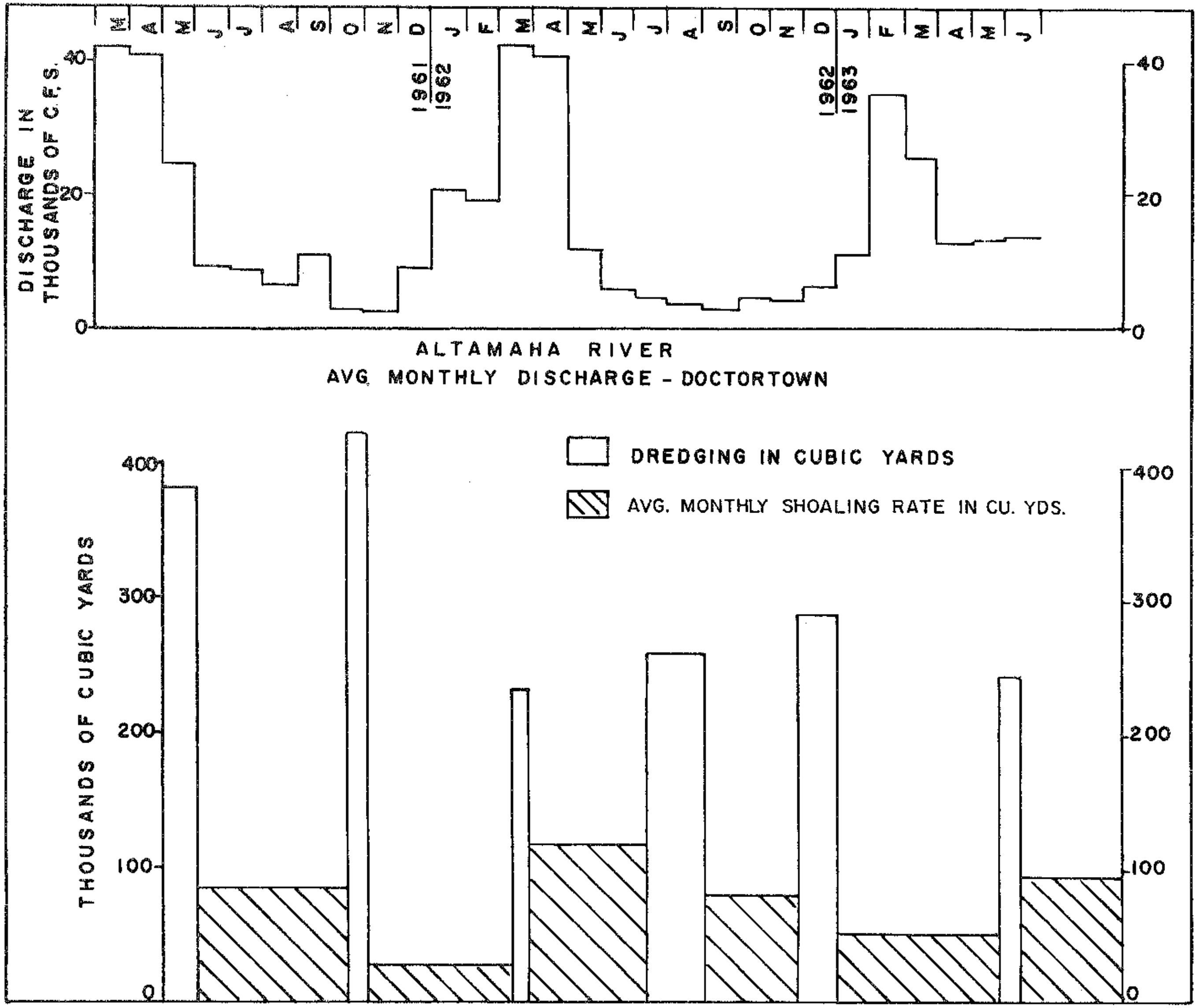


FIGURE 8 BRUNSWICK HARBOR SHOALING RATE VS. ALTAMAHA RIVER DISCHARGE. DATA AFTER HARRIS (1963).

interesting manner by Krone (1962) and is currently the topic of research by the Tidal Hydraulics Committee to gain further knowledge of the mechanisms involved with this material which causes shoaling problems in harbors.

The influence of regional geology in relation to supply and distribution of sediment from the marine environment has been considered in earlier sections. To this concept must be added the influence of the hydrologic cycle in providing greater quantities of shoaling materials during seasonal events.

Shoaling Rate Versus Altamaha River Discharge

Harris (1963) shows a correlation between shoaling rate in Brunswick Harbor and discharge of the Altamaha River (Figure 8). Greatest discharge of the Altamaha River occurs in the spring months; shoaling rates are greater in the harbor area at this time as revealed by dredging records. This evidence strongly suggests the influence of the more abundant sediment load from the river as being the source of much of the shoaling experienced in the harbor. Contributions of sediment from the Turtle River are regarded as negligible because of the small watershed with a lean supply of shoaling materials.

Sediment Movement Through MacKay and Frederica Rivers

The movement of suspended sediment through the MacKay River to Brunswick Harbor is regulated by the discharge rate of the Altamaha River and probably occurs only during greater than average discharge. This is apparent from salinity studies reported by Harris (1961).

Salinity measurement made with a Solou-bridge in-place salinity meter at several points in the vertical at stations in the MacKay and Frederica Rivers during a tidal cycle are shown in Figure 9. The discharge of the Altamaha River during this period of investigation (3,300 cfs) was well below average. Analysis of the salinity measurements reveals a partly mixed estuary in which density stratification is evident. The interface, between low salinity values (5 p.p.t.) from Altamaha discharge and salt-water intrusion from the harbor, appears to exist between stations 16 and 17 (Figure 9) in MacKay River. Current-velocity measurements were not obtained during this investigation.

Since the Altamaha River discharge at the time of salinity measurements was considerably lower than average, it is logical to assume that at higher discharge the interface between salt and fresh water would be displaced toward the harbor. That such a condition does exist at higher than average discharge, enabling suspended sediment to reach the harbor area via MacKay and Frederica Rivers, is supported by the following observations:

1. U. S. House Document No. 34, 52d Congress (1898) reported "During the freshet of February and March 1891, some of the Altamaha River discharge took place through Frederica and MacKay Rivers into St. Simons Sound and the

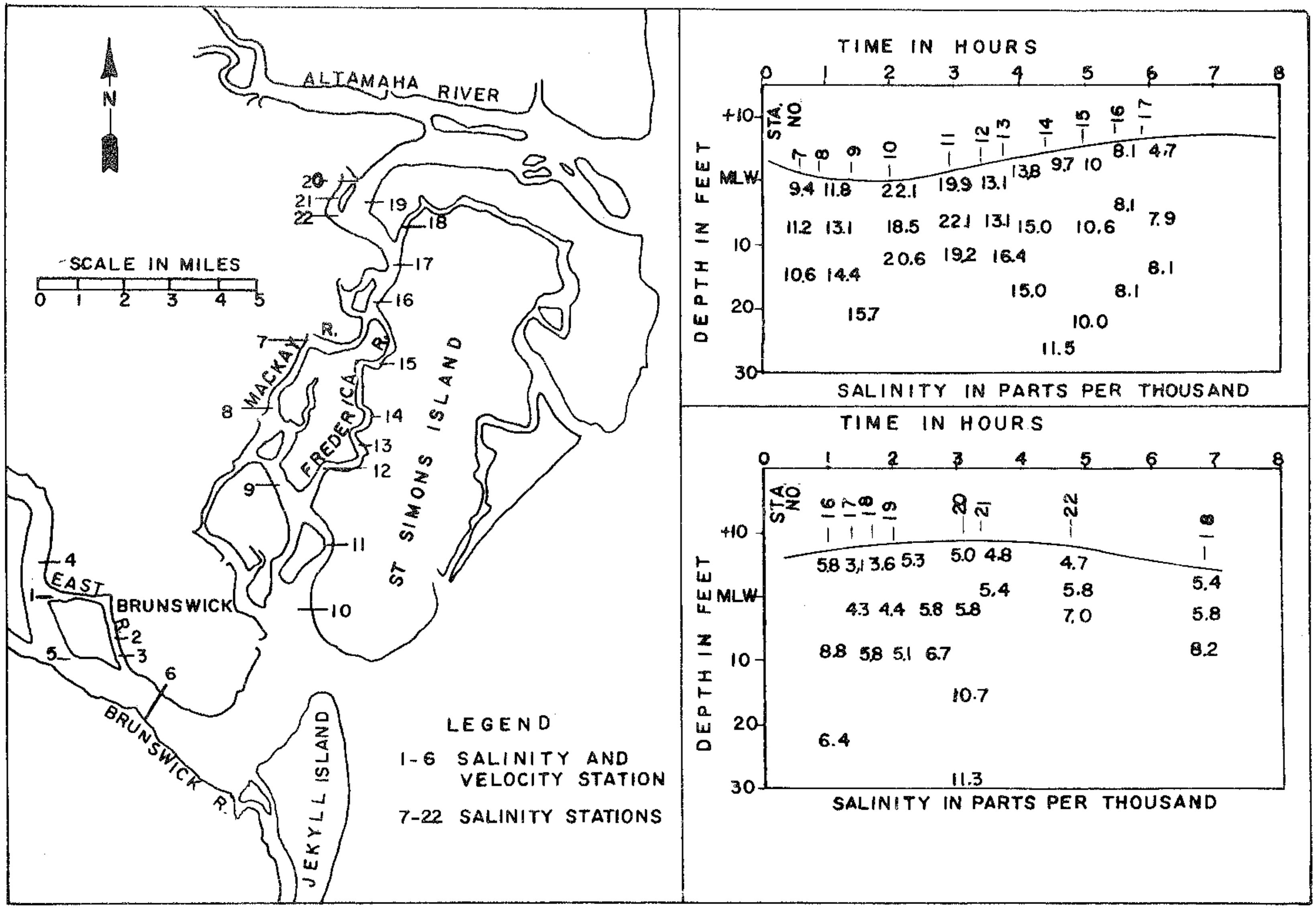


FIGURE 9. SALINITY MEASUREMENTS AT STATIONS IN MACKAY AND FREDERICA RIVERS AT VARIOUS DEPTHS DURING THE TIDAL CYCLE. DATA FROM U.S. ARMY CORPS OF ENGINEERS, W.E.S. INVESTIGATION OF 13 AND 19 OCTOBER 1959.

sea, as was shown by the reddish color of the water that often extended several miles into the sea at low water".

2. Maximum shoaling rates occur at times of high discharges of the Altamaha River (Figure 8).

3. Sedimentary parameter values and diagnostic minerals in the bedload sediment suggest net sediment movement toward the harbor through the distributary streams from the Altamaha River.

Further salinity, suspended sample, and velocity determinations during periods of greater discharge of the Altamaha River could produce more quantitative data as regards suspended sediment contributions to the Harbor area from the foregoing avenue of approach.

Sediment Movement Through the Tidal Inlet

In previous sections it has been shown that fine-grained materials, capable of causing shoaling in Brunswick Harbor, occur in the offshore area between 6 and 18-foot depths in the natural channel across the northern shoal. Additional source materials may exist in the troughs of sand waves in the offshore area.

As shown in Figure 3, suspended sediment discharged into the Atlantic Ocean from the Altamaha River will be directed southward by the littoral currents. Tidal currents operating through the inlet between the barrier islands at the harbor entrance are propagated through this natural channel and are believed responsible for shaping this channel through the shoal area. Sediment found in this channel is fine-textured and comprised of material more similar to that believed to be contributed by the Altamaha River. This is clearly shown in Figures 4, 5, 6, and 7. The tidal velocities also appear adequate to cause an exchange of the clay, silt, and mica through the inlet. In view of the nature of the dynamic agents operating in this offshore area, it is believed that this avenue of approach for transfer of sediment through the inlet is the more plausible for the majority of time periods. It is not certain if ebb flow contributes some of this material to the offshore area; actual suspended samples during the tidal cycle would be necessary to determine this.

Although quantitative data are not available as regards amounts of suspended clay contributed from MacKay River or through the tidal inlet, it seems rather certain that shoaling materials are introduced to the harbor entrance from these two avenues of approach. Mixing of sediment at the harbor entrance probably results in the admixture of sediment carried toward the city of Brunswick by flood tides.

Sediment Transport in Brunswick Harbor

The principal shoaling area in Brunswick Harbor is in East River at location 3 shown in Figure 9. This area has been extensively studied by the

Corps of Engineers because of the hazard to shipping in this area. Therefore, consideration will be given to the mechanism of transport of sediment to this shoaling area.

In previous sections, it has been stated that upland contribution from Turtle River is considered negligible. The main source of shoaling materials is believed to be from the Altamaha River discharge with a component through the MacKay River and another component through the tidal inlet between the barrier islands. These components are projected toward the shoaling area by flood tides.

According to Harris (1963) salinity measurements at stations 1 through 6 (Figure 9) showed a maximum salinity difference of 2 parts per thousand from surface to bottom, indicating that the harbor area is salt water. Volume measurements at station 6 also indicate that total flood flow equals total ebb flow with no marked difference in velocity flow at different depths.

Perhaps the most significant data regarding shoaling rates in East River appear in velocity profiles obtained at station 3 (Figure 9) at the site of maximum shoaling. The total flood and ebb discharges at various elevations are shown in Table 1.

TABLE 1

VELOCITY PROFILES AT LOCATION IN EAST RIVER

Depth	Flood	Ebb
	Cubic Feet	
Surface to 0.0 ft MLW	81,579,600	167,704,200
0 to -10 ft MLW	205,027,200	269,791,200
-10 to -20 ft MLW	165,402,000	139,575,600
-20 to -30 ft MLW	75,078,000	47,349,000

It is evident from this tabulation that flow below -10 feet MLW was predominantly flood in the upstream direction. The velocity in this lower stratum was extremely low and also the flood flow contains the highest sediment concentration. It was concluded from this investigation that major shoaling results because of the low energy level and predominance of flood flow which contains greatest sediment concentration. Greatest deposition occurs when sediment loads are largest in this low-energy zone; this occurs when upland contributions are largest in the spring.

Engineering control measures to reduce shoaling in East River involve reduction of the tidal prism and deflection of the bottom water strata into Turtle River.

SUMMARY AND CONCLUSIONS

Analysis of sedimentary parameters, mineral composition, and existing hydrodynamic data from Brunswick Harbor and vicinity in Georgia, appears to reflect the following:

1. The avenues of sediment transport for shoaling materials to Brunswick Harbor are revealed in the distributive patterns of the sediment as being (a) through the MacKay River from a source in the Altamaha River and (b) through the tidal inlet between Jekyll and St. Simons Islands. Sediment source contribution from the Turtle River drainage area is negligible as reflected by "control minerals".

2. Determination of direction of sediment movement is facilitated by associating diagnostic minerals with the source areas. In this investigation hornblende is effectively used as a natural tracer".

3. A correlation exists in the offshore area between (a) direction of littoral drift (b) sediment texture and composition related to bottom topography, and (c) tidal current movements.

4. Correlation of the Altamaha River discharge and the shoaling rate in Brunswick Harbor reveals maximum shoaling during maximum discharge of this river. Salinity studies and sediment characteristics support the view that during maximum discharge, considerable shoaling material is introduced into Brunswick Harbor from Altamaha River via MacKay and Frederica Rivers as well as through the tidal inlet between the barrier islands.

5. Maximum shoaling rate occurs in a reduced energy zone where bottom flood currents predominate over bottom ebb currents during periods when abundant source material is introduced from the watershed via the approach directions indicated in 4 above.

ACKNOWLEDGMENTS

The writer wishes to thank the Secretary of the Army and staff for sponsoring his participation in graduate courses at the Georgia Institute of Technology, a summer course at Massachusetts Institute of Technology, and field trips to the study area. The assistance of Mr. C. P. Lindner, Chief, Engineering Division, U. S. Army Engineer Division, South Atlantic, was invaluable in directing the activity of this investigation to objective goals and contributing to the success of this project. Consultations and assistance from Mr. Frank M. Bell, Director of the Laboratory, U. S. Army Engineer Division, South Atlantic and Mr. John W. Harris, Chief, Rivers and Harbors Section, U. S. Army Engineer District, Savannah, is gratefully acknowledged. Appreciation is also extended to Professors H. W. Straley III, Charles E. Weaver and M. R. Carstens of the Georgia Institute of Technology for critical review of selected portions of this paper.

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APPENDIX A

HEAVY-MINERAL STABILITY ZONES, SOUTH CAROLINA-GEORGIA

ABSTRACT

The heavy-mineral suites of the barrier island, beach, and continental shelf area of South Carolina and Georgia are generally similar but Pleistocene terraces and Coastal Plain formations contain a heavy-mineral suite that is impoverished in less-stable mineral species. These stability zones are probably related to environmental factors after deposition. A less-sharply defined stability zone occurs in the younger Pleistocene terraces between the barrier islands and older Pleistocene terraces.

Analysis of the heavy-mineral suite, from sediments in rivers with heads in the Piedmont and in shorter rivers originating in the Coastal Plain formations, reveals a contrast as sharply defined as the stability zones in these formations. Rivers draining the Piedmont contain an abundance of less-stable hornblende and epidote. The abundance of these less-stable mineral species in the coastal areas appears related to the ability of streams, originating in the Piedmont, to transport these materials from the rich source area to the coastal environment. Hornblende, because of its relative abundance and diagnostic properties, reflects the mechanism of transport.

Knowledge of the source, transport mechanism, and influence of environmental factors on heavy minerals could have application in harbor and coastal studies.

INTRODUCTION

In recent years, heavy-mineral investigations of the coastal area sediments, physiographic provinces, and rivers of South Carolina and Georgia have enabled the accumulation of data of significant value in establishing knowledge of source areas and manner of distribution of these minerals Much data materialized from mineral surveys to evaluate potential economic minerals in the sediments. Additional knowledge resulted from river and harbor studies, beach studies, and investigations of the continental shelf areas.

The pattern revealed by the heavy-mineral assemblages appears related to the concept of stability zones In older Coastal Plain formations a disparity is noted of certain less-stable mineral species which occur in relatively fair abundance in rivers draining the Piedmont and in coastal features.

The purpose of this paper is to delineate the heavy-mineral zones in the area depicted (Figure A-1) and to relate the distribution from the

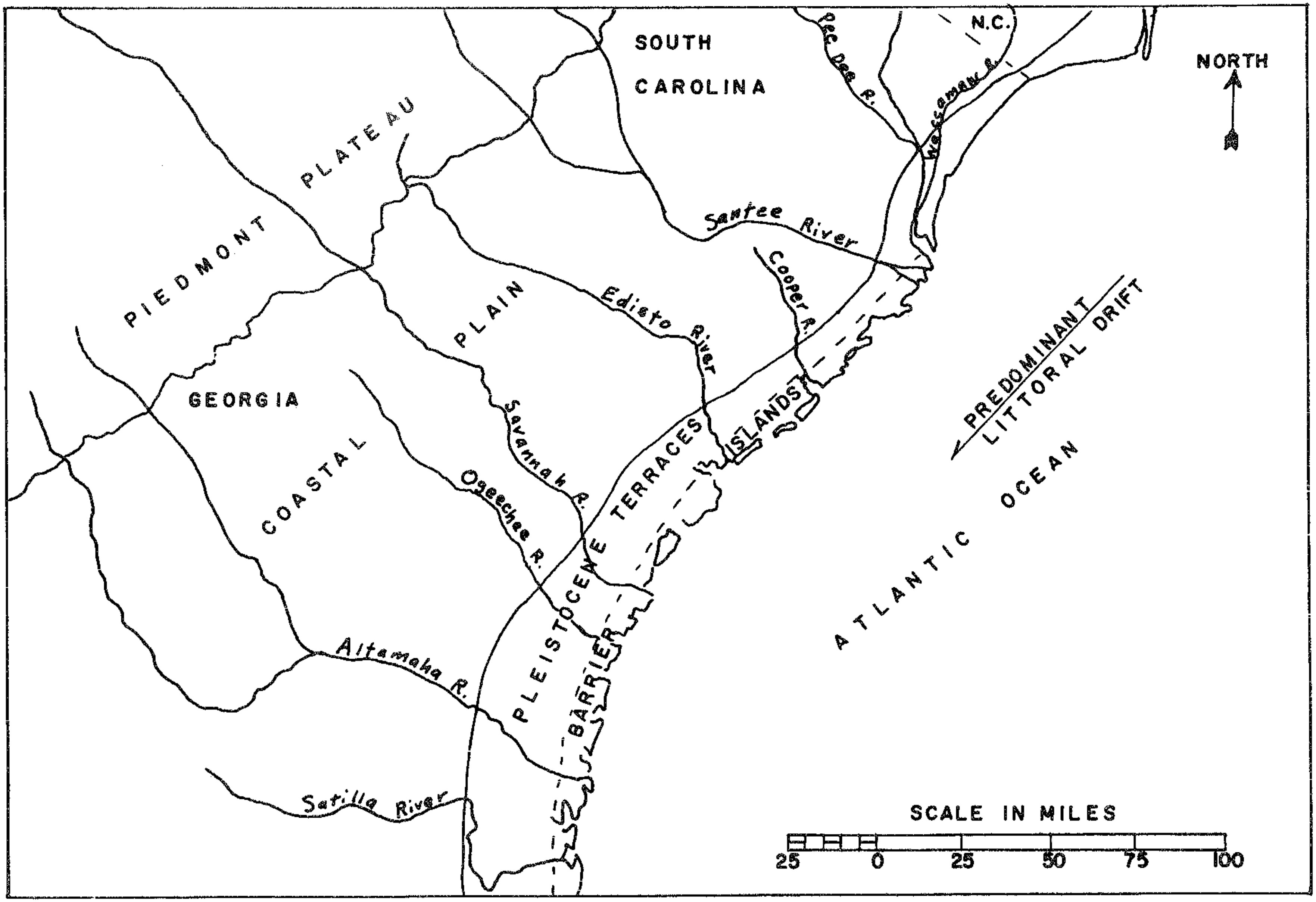


FIGURE A-1. MAP OF PHYSIOGRAPHIC FEATURES AND STREAMS OF SOUTH CAROLINA AND GEORGIA.

source areas with the various factors involved. A clear understanding of the regional distribution of the heavy-mineral species and mechanisms effecting transport from the source area could have real value to applied coastal engineering, harbor, and oceanographic endeavors.

GENERAL PHYSIOGRAPHIC SETTING

The South Carolina and Georgia coastline forms a part of the arc of a circle which extends from Cape Fear, North Carolina to Palm Beach, Florida. Situated in the more central portion of the arc, the South Carolina and Georgia coasts are farthest from the main axis of the Gulf Stream and according to Helle (1958) and Tanner (1960) are in the zone of least energy level in relation to adjacent coasts. The pattern of barrier island development is also more pronounced in this reduced-energy zone than for adjacent coastal areas. Taken as a whole, these barrier islands follow a pattern of sandy beaches on the east or ocean side and extensive salt-water marshes between the sandy islands and the mainland. (Figure A-1)

Extending inland from the marshes are several Pleistocene terraces which range in width from less than 10 miles near the South Carolina-North Carolina boundary line to more than 30 miles in southern Georgia (Figure A-1). According to MacNeil (1950) the shore lines of these terraces, regarded as peaks of marine transgression ascribed to glacial oscillations, are: Silver Bluff (8 to 10-foot altitude), Pamlico (24 to 35-foot altitude), Wicomico (100-foot altitude), and Okefenokee (150-foot altitude). In contrast to the light-colored sands of the barrier islands, these marine terraces are (a) yellowish-brown to reddish-brown in color, (b) generally more indurated, and (c) commonly contain well-developed soil profiles with variations depending on the nature of the vegetation. The mineralogical contrast between barrier islands and surficial terrace sands of the mainland will be shown to be significant.

Extending inland from the Pleistocene terraces to the Piedmont plateau are the older Coastal Plain formations comprised of Tertiary and Cretaceous sediments. The Coastal Plain width ranges from 100 miles in North Carolina to 200 miles in Alabama with altitudes generally less than 300 feet. It will be shown that the rivers originating in the Coastal Plain stand in sharp contrast to the rivers originating in the Piedmont as regards mineral assemblages.

SEDIMENT-TRANSPORT AGENTS

Any evaluation of sediment distribution must take into consideration the dynamic agents of transport. The principal transport agents are the rivers draining the Coastal Plain and the littoral currents operating along the coast.

The principal rivers of South Carolina and Georgia are shown in Figure A-1. Some of them have heads in the Piedmont; others originate in the

Coastal Plain. Stream characteristics as compiled by the U. S. Geological Survey (1960) are listed in Table A-1.

TABLE A-1

STREAM CHARACTERISTICS

River	Years of Record	Average Annual Discharge (cfs)	Maximum Recorded Flow (cfs)
Waccamaw	8	839	10,300
Pee Dee	20	8,693	220,000
Santee	16	2,024	155,000
Cooper	--	Negligible	Negligible
Edisto	19	2,383	24,300
Savannah	25	11,170	270,000
Ogeechee	21	2,100	26,300
Altamaha	27	12,620	178,000
Satilla	27	1,955	68,100

From the above tabulation, it is noted that the rivers with heads in the Piedmont Plateau have the largest discharge. These rivers drain a source area of eroded crystalline rocks rich in hornblende and granite gneiss. It will be shown in a later section that the rivers not only contribute appreciable sediment relative to discharge but also contain an assemblage of minerals reflecting the source area.

Littoral or alongshore currents are instrumental in distributing sediment along the South Carolina and Georgia coast. The direction of littoral drift is a function of the meteorological conditions; bearing of the coast line, and amount of refraction of the wave as it approaches the beach. By analysis with wave refraction diagrams, the writer (1959) demonstrated that predominant littoral drift along the central South Carolina coast is to the southwest; other investigators have also reported predominant littoral drift as being in a southerly direction along the southeastern coast of the United States. Mineral differences in the beach sands north and south of the Santee River (Figure A-1) also reflects the direction of littoral transport, as will be shown in a later section.

Tidal currents, wind waves and swell, and aeolian agencies are important locally in distribution of sediment transported by littoral currents. Foxworth, Priddy, Johnson, and Moore (1962) present an interesting detailed discussion of this topic which is of value in understanding heavy-mineral separations effected by each of these agents.

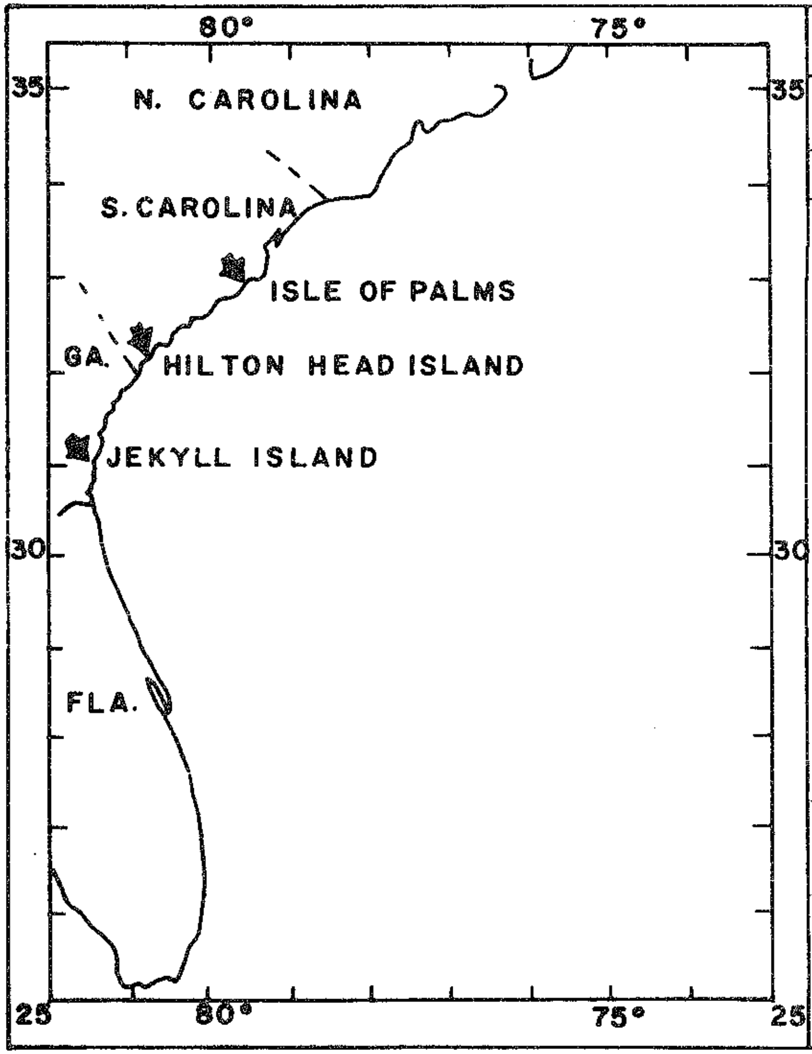
HEAVY-MINERAL SUITE OF BEACHES AND BARRIER ISLANDS

Martens (1934) reported on the heavy minerals in a beach sample from Folly Island, South Carolina and several from Georgia beaches. This cursory analysis revealed a heavy-mineral suite composed of mineral species approximating the following order of distribution: ilmenite, epidote, hornblende, staurolite, zircon, kyanite, sillimanite, rutile, tourmaline, garnet, monazite, magnetite, and other miscellaneous species. Subsequent investigations of the beach sands at mean high water mark at regular intervals by the writer (1958, 1959 and 1962) revealed a similar heavy-mineral suite. The more systematic samples at 2-mile intervals along the South Carolina coast show a marked increase of epidote and hornblende south of the Santee River (Figure A-1). According to Grosline (1963), Dr. B. F. Buie also noted a marked increase of epidote in the area of the Santee River which matches a similar mineralogical pattern in the shelf sediments near that section of coast. Local variation in the ratio of mineral species along the South Carolina and Georgia beaches appears related to degree of concentration and is attributed to selective removal by water agencies of minerals with prismatic shape and, therefore, greater hydraulic response. Several of the upper beach areas along the barrier islands contain anomalous surface occurrences of "black sands" which consist mostly of heavy minerals and minor amounts of quartz; the black coloration is due to black ilmenite which is the most abundant constituent of the heavy-mineral suite.

The barrier islands contain a heavy-mineral suite markedly similar to that of the beaches. Highland portions of these barrier islands consist of frontal dunes, parallel dunes, and beach ridges extending to the marsh area on the west. The degree of heavy-mineral concentration varies considerably in these sand deposits with greatest concentration occurring in the frontal and parallel dunes in proximity to "black sand" occurrences along the upper beach. Local heavy-mineral ratio variation of the barrier islands appears related to degree of concentration and hence appears to reflect the beach source area and the mechanical separation by water agencies taking place on the beach prior to transport inland by aeolian agencies.

The location of extensive heavy-mineral investigations across barrier islands of the South Carolina and Georgia coasts is shown in Figure A-2. Grid-system sampling techniques were employed on the highland sandy portions of these islands to obtain quantitative knowledge of the degree of heavy-mineral concentration and heavy-mineral species. Analysis of tabulated values shows a generally higher average of hornblende and epidote on the Isle of Palms than on Hilton Head Island or Jekyll Island. Sillimanite appears in greater ratio on Jekyll Island and zircon appears slightly more in abundance in the beaches and barrier islands south of the Edisto River (Figure A-1).

Henry and Hoyt (1963) report a heavy-mineral suite similar to that of the other barrier islands from cursory samples taken on Sapelo Island located along the central Georgia coast. It is noteworthy that on these barrier islands the less-stable minerals such as hornblende and epidote



RANGE AND AVERAGE WEIGHT PER CENT OF HEAVY-MINERAL SUITE OF BARRIER ISLANDS OF S. CAROLINA AND GA.

	ISLE OF PALMS		HILTON HEAD		JEKYLL ISLAND	
	NEIHEISEL, 1958		MC CAULEY, 1960		NEIHEISEL, 1962	
MINERAL	RANGE	AVG.	RANGE	AVG.	RANGE	AVG.
RUTILE	1-5	2.3	4-8	5.5	3-8	5.6
ZIRCON	4-14	6.4	8-20	11.7	9-17	13.2
TOURMALINE	†	†	PR-0.8	0.4	1-4	1.6
MONAZITE	PR-2	0.8	0.6-2.3	1.2	PR-2	1.2
GARNET	1-2	1.5	1-2	1.3	1-2	1.0
ILMENITE	17-35	27.4	28-43	35.0	24-48	39.2
STAUROLITE	3-12	7.5	†	†	3-5	3.7
KYANITE	3-8	5.8	†	†	1-2	1.3
EPIDOTE	21-39	33.3	16-17	16.7	10-21	14.8
HORNBLENDE - PYROXENE	2-30	11.9	5-7	6.0	3-17	7.1
SILLIMANITE	‡	‡	†	†	5-15	7.3
MISCELLANEOUS		2.1		11.8		3.9
NUMBER OF SAMPLES	56		256		16	

† INCLUDED IN MISCELLANEOUS GROUP

‡ INCLUDED WITH KYANITE

IGURE A-2. LOCATION AND HEAVY-MINERAL SUITE OF BARRIER ISLANDS ALONG THE SOUTH CAROLINA AND GEORGIA COASTS are in fair abundance; this relationship, however, will be shown to differ in the Pleistocene terraces of the mainland.

HEAVY-MINERAL SUITE OF THE CONTINENTAL SHELF

The first published analysis of the heavy-mineral suite in the offshore area of Southeastern Atlantic coast was that by Tyler (1934) for the areas off the North Carolina and Florida coasts. More recent heavy-mineral investigations, reported by Pilkey (1963) and Grosline (1963), covered the continental shelf area beyond the 100-fathom curve. The sample locations and heavy-mineral analyses of these investigations are shown in Figure A-3.

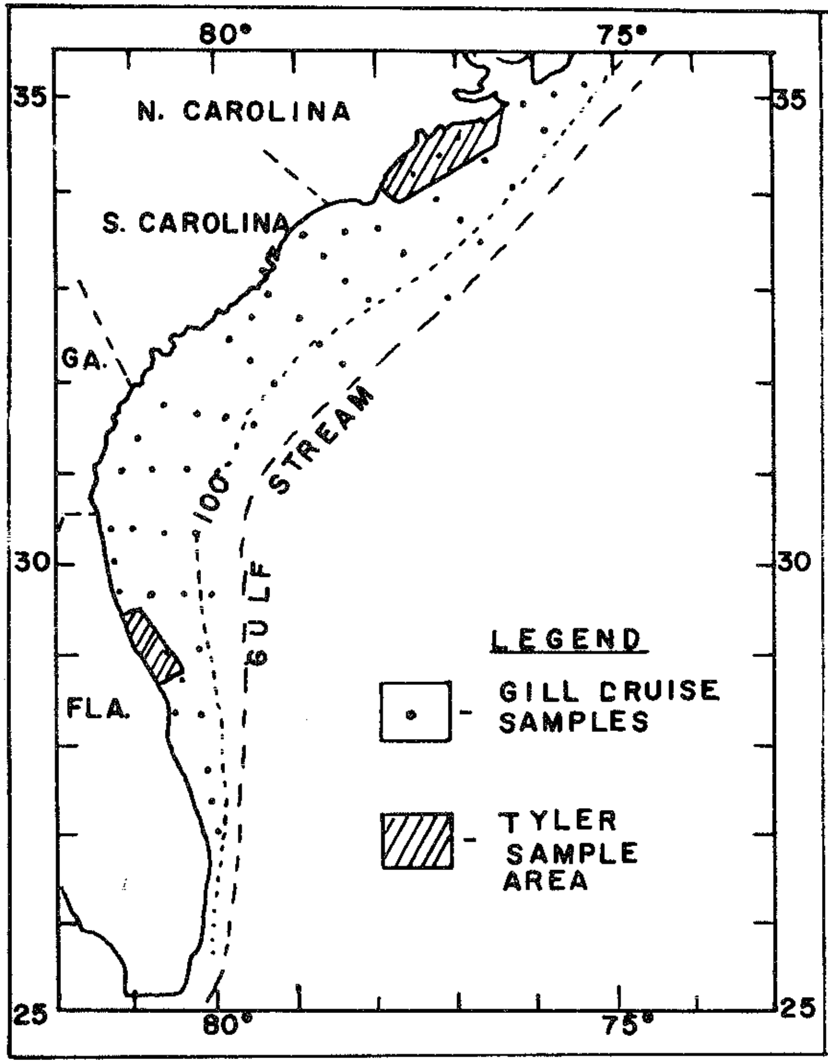
The heavy-mineral suite of the continental shelf is markedly similar to that found along the present beaches and across the barrier islands. Both hornblende and epidote occur in relatively high proportions. Garnet, averaging about 1 percent of the heavy-mineral fraction in beach sands, shows a marked increase to 4 percent in the continental shelf areas. Zircon is of slightly lower proportion in the shelf sediments than along the beaches or barrier islands.

Both Pilkey and Grosline distinguish two heavy-mineral provinces based on epidote content in the sediment. The epidote province appears to reflect the mineralogical differences previously defined in the beach sands in the vicinity of the Santee River. The role of rivers and environment will be more apparent in later sections after review of the Coastal Plain sediments.

HEAVY-MINERAL SUITE OF PLEISTOCENE TERRACES

Detailed knowledge, such as exists for heavy minerals in the barrier islands, is generally lacking for Pleistocene terraces of South Carolina and Georgia. Reconnaissance investigations by Dryden (1958) and Neiheisel (1962) indicate a general impoverishment of the less-stable mineral species in these terrace features. The lower Silver Bluff terrace appears to contain local epidote and hornblende; a maximum of 2 percent hornblende and 7 percent epidote was found in a sample near Shellmans Bluff, Georgia. Henry and Hoyt (1963) report similar or higher ratios in this same general vicinity but do not indicate if samples were confined to barrier island sands or the terraces of the mainland. Dryden (1956) indicates that the limited heavy-mineral suite is found in Pleistocene deposits lying at or above 60 to 75 feet in altitude. Until these lower terraces are studied in more detail, it is suggested that, in light of more recent investigations, the younger terraces between the older Pleistocene terraces and barrier islands be considered a "middle ground" as regards the heavy-mineral suite.

In the Trail Ridge, Florida heavy-mineral deposits situated in one of the older Pleistocene terraces, Spencer (1948) indicates an impoverishment of hornblende and epidote. The general order of heavy-minerals occurring



AVERAGE WEIGHT PER CENT OF HEAVY-MINERAL SUITES	TYLER, 1934		PILKEY, 1963	GILL CRUISE, *
	FLA.	N.C.	ATLANTIC SHELF	
OPAQUES †	44	50	40	42
STAUROLITE	6	18	7	15
EPIDOTE	24	5	12	13
HORNBLENDE	5	4	16	12
KYANITE	1	2	3	1
TOURMALINE	1	1	2	6
GARNETS	3	7	4	4
APATITE	PR.	PR.	PR.	2
SILLIMANITE	5	4	2	2
ZIRCON	9	8	3	2
TREMOLITE	-	—	-	0.3
RUTILE	2	1	2	PR.
NUMBER OF SAMPLES	36	75	56	20

† OPAQUES ARE PROBABLY MAINLY ILMENITE AND MINOR LEUCOXENE AND MAGNETITE.

* ANALYSIS BY U.S WILDLIFE SERVICE AS REPORTED BY GROSLINE (1963)

AVERAGE WEIGHT PER CENT OF HEAVY MINERALS IN ALL SAMPLES IS LESS THAN 0.5 %.

FIGURE A-3. SAMPLE LOCATIONS AND AVERAGE HEAVY—MINERAL SUITES FROM NEAR-SHORE BOTTOM AND ATLANTIC SHELF OF THE SOUTHEASTERN STATES in these sands is: ilmenite, staurolite, zircon, rutile, leucoxene, sillimanite, tourmaline, kyanite, and rarer miscellaneous species. Less than 40 miles east, along the Florida coast, Martens (1934) reports as much as 25 percent epidote and 6 percent hornblende in the heavy-mineral suite; this is generally similar to the Georgia beach sediment.

It seems apparent from all investigations conducted to date that the older Pleistocene terraces contain a stable heavy-mineral suite. The younger Pleistocene terraces contain low ratios of epidote and hornblende locally which are probably related to environmental factors that will be considered in a later section.

HEAVY-MINERAL SUITE OF THE COASTAL PLAIN FORMATIONS

The heavy-mineral suite of the Coastal Plain of South Carolina and Georgia has been investigated to a limited extent by Dryden (1958), Cazeau (1962) and others. All the heavy-mineral suites of these reconnaissance studies appear to reveal a general absence of hornblende and a disparity of epidote and garnet.

Cazeau (1962), in a cursory study of the formations of the Coastal Plain within a radius of 35 miles of Columbia, South Carolina, observed that the most common opaque minerals were magnetite-ilmenite, hematite, leucoxene, and opaque rutile in varying amounts. The transparent heavy-mineral fraction as analyzed by Cazeau is listed in Table A-2.

TABLE A-2

TRANSPARENT HEAVY-MINERAL FRACTION SOUTH OF COLUMBIA, S. C.

Mineral	Tuscaloosa Formation	Congaree Formation	Black Mingo Formation	Warley Hill Formation	Post Eoc. Sand Unit
Tourmaline	85	15	41	14	67
Sillimanite	Tr	9	17	4	ABS
Zircon	6	20	22	35	12
Rutile	6	7	3	23	21
Garnet	ABS	Tr	9	ABS	ABS
Monazite	ABS	ABS	2	ABS	ABS
Kyanite	ABS	48	2	21	ABS
Others	2	1	4	3	-

Mertie 1953) and Dryden (1958) were essentially concerned with determining the abundance of monazite in the Coastal Plain sands but their investigations also revealed a heavy-mineral suite in which hornblende, epidote, and garnet were generally absent. Dryden's study is based on 456 samples; 293 from the Tuscaloosa formation, 16 from the McBean formation, 36 from the Barnwell formation, and 40 from Pleistocene deposits. While only monazite is tabulated for most sample locations, the following range and average heavy-mineral content are indicated for 12 samples from the Tuscaloosa formation:

> "The titanium-bearing minerals ilmenite, leucoxene, and rutile are the most important industrial minerals in the sediments. The percent of opaques (dominantly ilmenite and leucoxene) varied from 41 to 78 and averaged 55.5. Rutile made up 2.3 to 11.7 percent of the heavy minerals and averaged 5.1 percent. Zircon averaged 20.5 percent and ranged in amount from 9.0 to 32.6 percent. The high-alumina minerals include kyanite, sillimanite, and staurolite, and all range widely in their percent distribution. Staurolite made up 0.3 to 13.7 percent of the heavy minerals and averaged 2.8 percent. Kyanite and sillimanite together form less than 2 percent of the heavy minerals in 8 samples, but are 5.5, 10.1, 9.5 and 7.5 percent of the heavy fraction in other samples."

Dryden and Dryden (1956) state that "only the limited suite is found from the non-marine Tuscaloosa through the marine Cretaceous and Tertiary Formations." They indicate that garnet, epidote, and hornblende are present in a very few samples and "there, only as the rarest of constituents".

Thus it appears that numerous observations in the Coastal Plain formations reveal a general disparity of hornblende, epidote, and garnet.

HEAVY-MINERAL SUITE OF RIVERS DRAINING THE PIEDMONT AND COASTAL PLAIN

The vital clue relating differences in the heavy-mineral suite of the Coastal Plain formations and the barrier islands and continental-shelf deposits appears in the contrast of mineral species occurring in the sediment and flood plains of rivers draining the Piedmont and Coastal Plain. The correlation to source area of sediment and environmental effects on stability of minerals is also dramatically revealed in this contrast analysis.

Very little was known about the heavy-mineral suite of rivers draining the South Carolina and Georgia physiographic provinces prior to investigations by the Corps of Engineers (1951), Dryden (1958), Cazeau and Lund (1959), and Neiheisel (1962). Even these investigations were oriented toward economic mineral evaluations, harbor projects, or investigative reconnaissance studies with no attempt toward correlation with regional conditions. Dryden (1958), however, made an important observation in recognizing that "the heavy-mineral suite of rivers draining the Piedmont differ from Coastal Plain sediment in containing epidote, garnet and hornblende." Heavy-mineral analysis of the continental shelf sediment along the South Carolina and Georgia coasts by Pilkey (1962) and Grosline (1963) showed a similarity of the heavy-mineral suite with that of the Altamaha River and beach sands in the littoral deposits south of Santee River as compiled by the writer (1959 and 1962) in earlier investigations. Heck (1951), in analysis of bottom sediment from the Cooper River with short drainage area from Coastal Plain formations, found a disparity of hornblende above the tidal range.

The recognition by all investigators of abundant hornblende in the rivers draining the Piedmont Province and the disparity occurring in the Cooper River draining the Coastal Plain formations were the factors responsible for further river-sediment investigation. As part of a Secretary of the Army Research Fellowship, the writer sampled rivers draining the Georgia Coastal Plan. Samples were obtained during December 1963 from the Ogeechee, Canoochee, Satilla, and Turtle Rivers from geographic locations shown in Figure A-4. Results of analysis of the heavy-mineral suite revealed a range of total hornblende and pyroxene from trace amounts to 2 percent of the heavy-mineral fraction. A contrast of hornblende content in the heavy-mineral fraction of the rivers draining the Piedmont and Coastal Plain provinces of South Carolina and Georgia is shown in Figure A-4 and listed in Table A-3.

TABLE A-3

HORNBLENDE FRACTION OF HEAVY-MINERAL SUITE IN RIVERS DRAINING THE PIEDMONT AND COASTAL PLAIN PROVINCES

	Percent Hornblende	
	Range	Average
Piedmont Source		
Savannah River	16 to 41	23
Altamaha River	9 to 27	20
Chattahoochee River	23 to 34	28
Coastal Plain Source		
Ogeechee River	Trace to 2	1
Canoochee River	1	1
Satilla River	Trace to 2	Trace
Turtle River	Trace	Trace

Note: 1. Hornblende includes any trace amount of green pyroxene.
2. Chattahoochee River drains the Georgia Piedmont but drains into the Gulf of Mexico. Analysis by Cazeau & Lund (1959).
3. Savannah River analysis by Heck (1951).
4. Altamaha River analysis by Neiheisel (1962).

From the foregoing, it is apparent that rivers draining the Coastal Plain contain a restricted heavy-mineral suite in which hornblende rarely exceeds trace amounts. The maximum hornblende (2 percent) occurs near the mouth of the Ogeechee River and this high representation may be partly a result of tidal current contribution from the beaches.

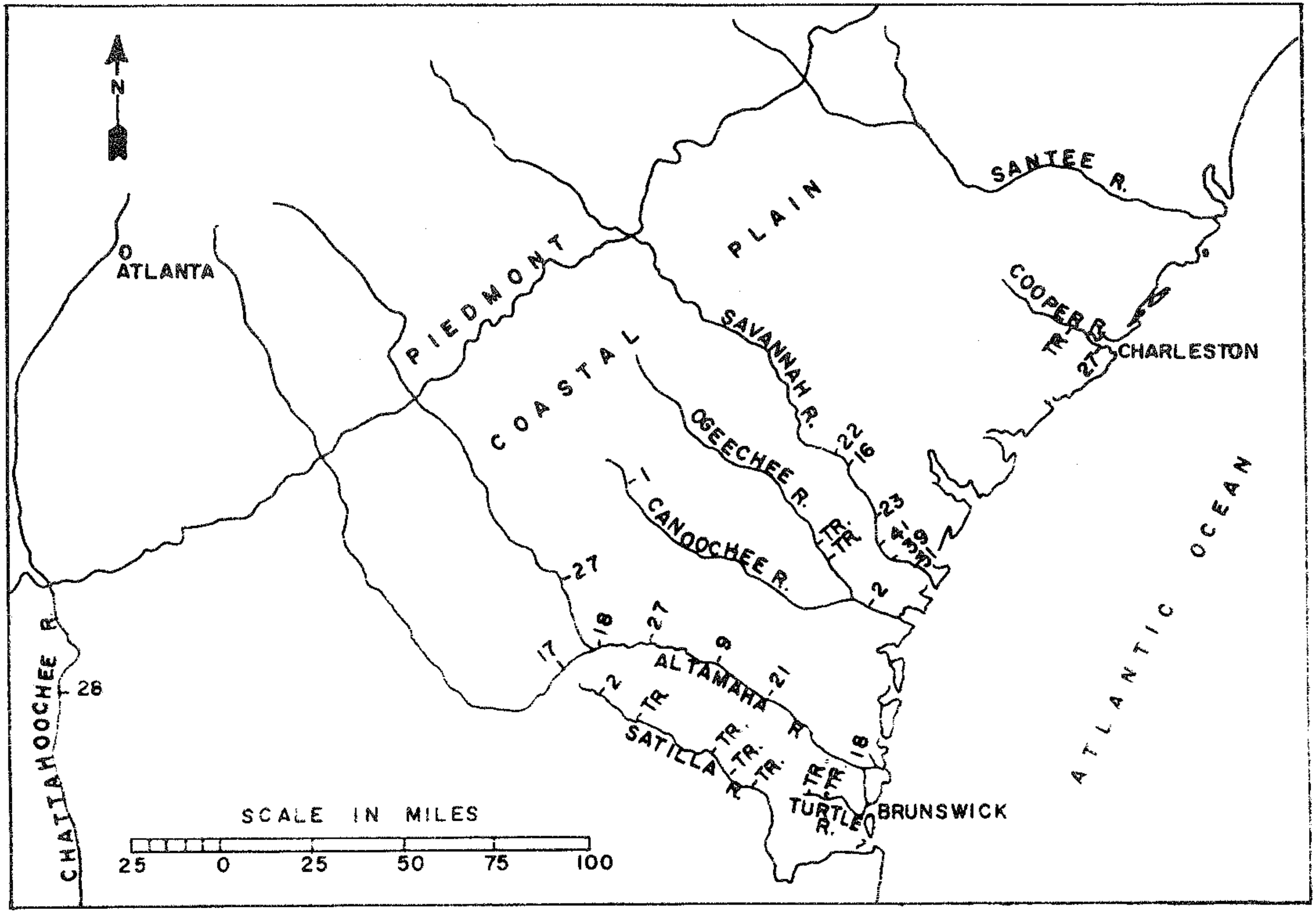


FIGURE A-4. HORNBLENDE FRACTION OF HEAVY-MINERAL SUITE FROM STREAMS DRAINING THE PIEDMONT AND COASTAL PLAIN AREAS.

Rivers draining the Georgia Piedmont Province contain hornblende ranging from 9 to 41 percent of the heavy-mineral fraction and a general average of 25 percent (Table A-3 and Figure A-4). That hornblende is abundant in the Piedmont Province and virtually absent in Coastal Plain formations has been previously cited in early sections of this report. Dryden (1958) did not report specifically which of the rivers draining the Piedmont represented his observation that hornblende, garnet, and epidote were characteristic of such streams. An earlier paper by Dryden and Dryden (1956) implied that all streams draining the crystalline area (Piedmont) cut the uniformity of the Coastal Plain with a full mineral suite and divided the area as a whole into a kind of mosaic.

Although the Santee River has not been sampled, the increase of hornblende and epidote south of this river, along the beaches and shelf area, has been reported by several investigators Since littoral drift is in a predominantly southerly direction along the South Carolina and Georgia coasts, it appears likely that contributions of these minerals from the Piedmont source area is responsible for the notable increase reflected in the marine environment. It will be shown in a later section that the marine environment is instrumental in preserving the stability of hornblende in contrast to solution and decay with time effected by the terrestrial environment.

Epidote tends to be less represented in river sediment with a source area in the Coastal Plain formations containing the restricted heavy-mineral suite but to a less marked degree than hornblende. Feldspar enjoys a similar relationship. Garnet is less diagnostic to this relationship which may in part be related to the less-abundant nature of this mineral in the source area by contrast to hornblende, epidote, and feldspar.

Analysis of the heavy-mineral suites of the bed loads of rivers draining the Piedmont Province reflects an abundance of hornblende from this rich source area which correlates with the abundance of this mineral occurring in the marine environment. Coastal Plain formations, ranging from Cretaceous to Pleistocene in age, contain disparate amounts of this mineral as a result of its instability under leaching, acidic conditions with time. Rivers with heads in these Coastal Plain formations are characterized by impoverishment of hornblende but complement other source areas. This relationship makes hornblende diagnostic in sedimentation studies in some of the estuaries along the coast as well as delineating source and direction characteristics affected by dynamic agents.

STABILITY ZONES

According to Crickmay (1952), hornblende gneiss is one of the more abundant crystalline rock types in the Georgia Piedmont. Mertie (1963) in a study of the more acidic saprolites found the principal heavy minerals to be monazite, ilmenite, epidote, sillimanite, kyanite, sphene, hematite, and opaque black minerals. Thus the heavy-mineral species of the Piedmont available for transport by rivers are rich in hornblende, epidote, and garnet as well as the more stable mineral species. The restricted heavy-mineral suite occurs in the Coastal Plain formations and older Pleistocene terraces. Along the coastal region, continental shelf, and sediments of rivers draining the Piedmont, the heavy-mineral suite is again full.

The foregoing relationship suggests the concept of "Stability Zones" as proposed by Pettijohn (1957). This concept proposes that "all sediments deposited had about the same suite at the time of deposition, but that because of intrastratal solution, the older beds have lost all unstable species". The sediments of the older Cretaceous and Tertiary formations in the South Carolina and Georgia Coastal Plain probably had a similar source material of sediments but impoverishment of hornblende, epidote, and garnet has taken place since deposition as a result of intrastratal solutions. Hornblende and epidote are listed by Pettijohn (1957) and others as being least stable in the general order of stability of heavy-mineral suites and garnet varies from middle to low-order stability according to various authorities.

TRANSPORT FROM SOURCE AREA

The abundance of hornblende in the Piedmont source area as well as the unique prismatic shape of this mineral is diagnostic to an understanding of the transport medium. The shape characteristic of this mineral enables a hydraulic response that is probably only exceeded by mica. Although one of the less-stable heavy minerals, its transport rate by rivers is relatively rapid since high ratios of this mineral exist along the entire course of the river from source area to discharge into the ocean.

The selective removal of hornblende along beaches relative to other co-existing heavy minerals has been observed by several investigators for anomalous "black sand" deposits. In the vicinity of Santee River, the abundant contribution of hornblende and epidote by a river source is apparent and the spread southward along the coast by littoral currents is observed in these minerals.

The abundance of hornblende in the continental shelf area is probably in part attributed to the relatively rapid transport from the source area, ability to be transported farther by offshore currents, and greater stability due to the "alkaline" marine environment.

ENVIRONMENTAL FACTORS

The stability zones of the Coastal Plain formations are a resulting factor of environment affecting chemical decay of less-stable mineral species since deposition. It is the opinion of Keller (1962) that a particular mineral assemblage is an indicator product of an environment which can be described in terms of pH, Eh, temperature and other factors. Keller listed the decomposition sequence of mineral species in which hornblende ranked third; hornblende in this sequence is only exceeded in weathering potential by gypsum and calcite.

According to Gilluly, Waters, and Wooford (1958) the alteration of hornblende is like that of biotite, with similar products, but goes to completion faster. In an environment rich in carbonic acid and oxygenated waters, such as occur in the Coastal Plain formations, the products of chemical decay are insoluble clay and limonite while soluble products include magnesium bicarbonate, calcium bicarbonate, and silica which are carried off in solution.

Wieseneder and Maurer (1958) in an investigation of the heavy-mineral suite of the Vienna Basin found an impoverishment of hornblende and epidote in strata of age similar to other strata containing these minerals. The disparity of minerals was attributed to "aggressive brines" effecting chemical decay. Branlette (1941) showed that calcareous concretions of certain California sandstones contain about 40 percent hornblende in their heavy-mineral fraction whereas the matrix had but 5 percent. The hornblende in the sealed environment was unchanged with time. Thus, the circulation of solutions which effect leaching of less-stable mineral species appears to be one of the main factors involved in the disparity of certain mineral species in the Coastal Plain sediment; to this must be added time and other environmental conditioners.

In a speculative summary of heavy minerals in the Coastal Plain sediment of the eastern United States, Dryden and Dryden (1956) recognized the fact that non-marine sediments were leached of less-stable heavy minerals whereas marine sediments remain unaffected and retain the full suite. This fact correlates with the full suite of heavy minerals found by Pilkey (1962) and Grosline (1963) in the sediments of the continental shelf. It appears evident that the basic marine environment tends to maintain hornblende, epidote, and garnet which are unstable in the acidic non-marine environment. The rivers draining the Piedmont act as "arteries" in transporting the less-stable minerals to the marine environment where their stability increases as a result of the changed conditions.

The Pleistocene terraces are less-poorly defined into stability zones. Below an altitude of 60 to 70 feet the terraces locally contain significant hornblende and epidote. These local differences might be attributed to difference is soil-profile development. The contrast in color differences in this sediment seems significant and further field investigations may disclose non-homogeneous conditions related to environmental factors.

SUMMARY

The heavy-mineral suites in the sediments of South Carolina and Georgia differ in relation to amounts of less-stable mineral species and may be divided into stability zones on this basis The unrestricted heavy-mineral suite occurs in the Piedmont, sediments and flood plains of rivers draining the Piedmont, barrier islands, beaches, and the continental shelf. The impoverished heavy-mineral suite is found in Coastal Plain formations, sediments and flood plains of rivers draining the Coastal Plain and older Pleistocene terraces.

The unstable heavy-mineral suite of the coastal area and continental shelf appears related to the ability of rivers draining the Piedmont to carry these minerals from a source area rich in such materials to the coast. In the marine environment the stability of hornblende, epidote, and garnet is apparently increased because the pH factor and other environmental conditions are conducive to their preservation.

The relative proportion of the less-stable mineral species is diagnostic to the source area. Hornblende is especially diagnostic because of its hydrodynamic response and could be used as a natural tracer in reflecting source materials in harbor and coastal investigations.

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APPENDIX B

COMPARISON OF ENERGY LEVELS OF COASTAL AREAS - BRUNSWICK, GEORGIA AND NEW SMYRNA BEACH, FLORIDA

INTRODUCTION

The purpose of this appendix is to contrast the energy levels occurring along the coasts of Brunswick, Georgia and New Smyrna Beach, Florida. The swell and breaker heights have been observed over a period of years and reported by Helle (1958) for both sections of coast. By means of wave refraction diagrams and analyses thereof it is possible to establish differences of energy levels that exist between these two coastal areas and to correlate these data with observed surf characteristics. Once the physical differences related to energy levels are understood, it will be possible to contrast rates of erosion with those of the more rigorously studied coastal area of Florida.

GENERAL SETTING

The Georgia coastline forms part of an arc of a circle which extends from Cape Hatteras, North Carolina to Palm Beach, Florida. The location of Brunswick and New Smyrna Beach in relation to this arc and relative energy levels along the east coast of the Southeastern States is shown in Figure B-1. The energy levels reported by Tanner (1958), based on measured breaker heights, show the Georgia coast as the site of the lowest recorded energy level along this part of the southeastern coast. Energy levels rise sharply south of the Florida line.

The Continental Shelf to the 100-fathom curve extends about 80 miles off Brunswick, Georgia and about 45 miles off New Smyrna Beach, Florida (Figure B-1). Since the general direction of littoral transport is in a southerly direction and the streams of South Carolina and Georgia introduce considerable sediment to the littoral stream, the sediment of the shelf area is generally similar for these two coastal areas. The bearing of the shoreline at Brunswick is essentially N 23° E and at New Smyrna Beach about N 28° W. The bearing of the shoreline and difference in slope of the continental shelf between the two areas will be shown to be highly significant as regards energy relations derived from wave refraction analysis.

According to Martens (1935) the beach sands of South Carolina, Georgia and most of the northern part of the east coast of Florida would be described as fine (1/8 to 1/4 mm.). The beach sand is also well sorted for these coastal areas as indicated by measured coefficients of sorting. Sand dunes and beach ridges extend inland from the beach areas along these same coastal areas and materials eroded would be of similar composition. Physiographically, the Brunswick and New Smyrna Beach coastal areas are similar and sediments acted upon by dynamic water agents are of generally similar dimensions.

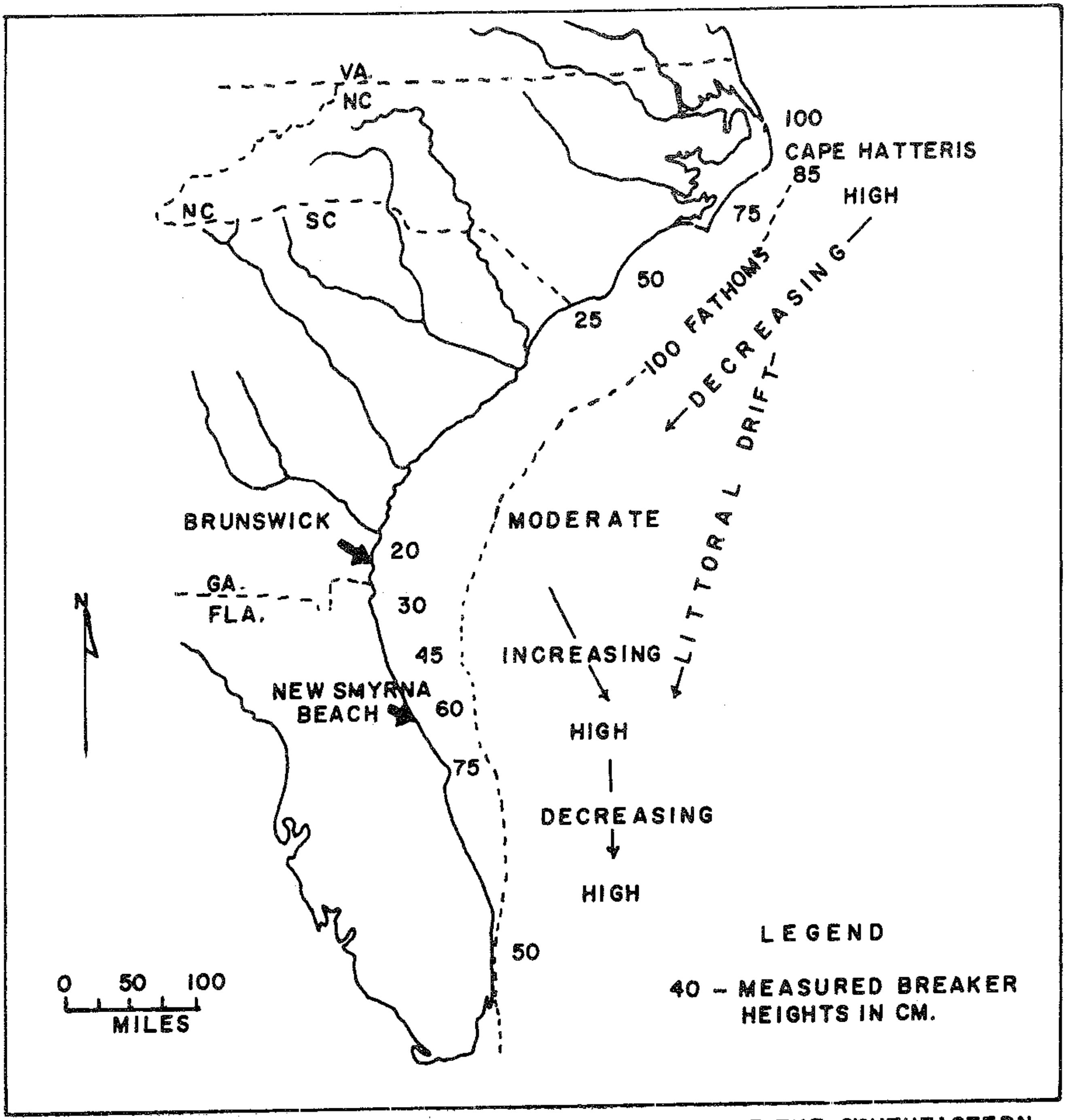


FIGURE B-1. ENERGY LEVELS ALONG THE EAST COAST OF THE SOUTHEASTERN STATES. AFTER TANNER (1958).

METEOROLOGICAL AND SURF CONDITIONS

The yearly average winds off the Georgia and Florida coasts, compiled from the records of the U. S. Hydrographic Office, are shown in Figure B-2. The wind rose is for each 5-degree square, with 30° N as the dividing line, and shows the average winds which prevail within that area as reported by ships at sea. The number of feathers show the average wind force on the Beaufort scale. The figure in the center gives the percentage of calms. The diagrams indicate that for both sections of coast, the predominant winds were from the northeast. In general, strong northeasterly winds prevail during the winter months and lighter southeasterly winds are dominant during the summer months.

Surf statistics, based on observations compiled by Helle (1958) for the Brunswick and New Smyrna Beach areas are shown in Figure B-2. The direction of swell and maximum and average breaker heights are based on visual observations taken at 4-hour intervals at U. S. Coast Guard stations between November 1954 and September 1956. The maximum and average breaker heights of 3.8 and 2.8 feet respectively at New Smyrna Beach, Florida are greater than the maximum of 2 feet and average of 0.95 foot observed at Brunswick, Georgia (Figure B-2).

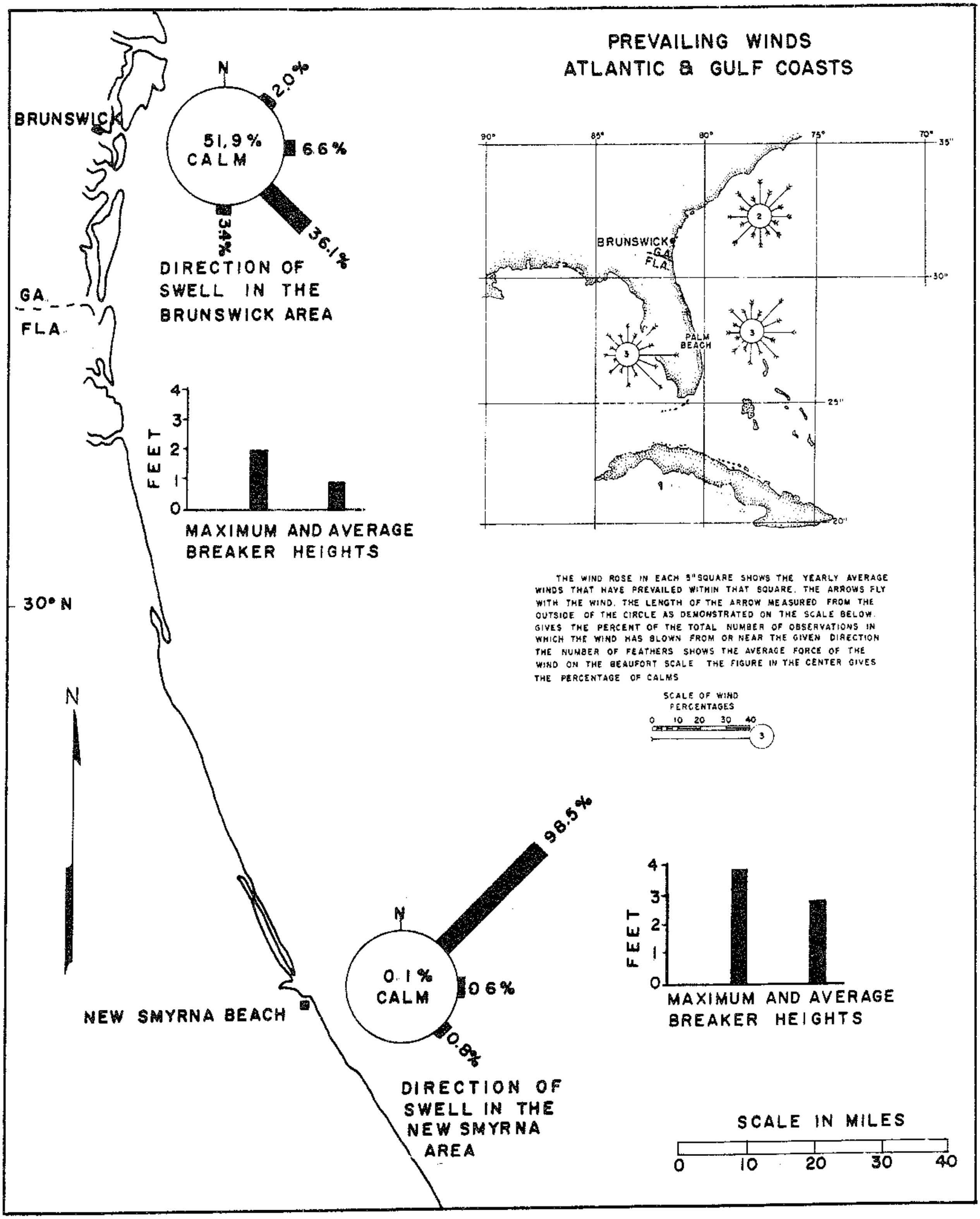
The predominant direction of surf is from the southeast at St. Simons Island, whereas, a predominantly northeasterly surf occurs at New Smyrna Beach. Since the direction of surf is the observed refracted wave direction, the angular differences between the net wind force direction and surf direction is the result of refraction of the waves due to shoaling conditions. Since greater differences exist between these directions off Brunswick, the degree of wave refraction must be more pronounced; this will be shown to correlate with wave refraction analysis.

WAVE REFRACTION DIAGRAM ANALYSIS

Having available statistical wind data and bottom topography charts, it is possible to construct wave refraction diagrams in accordance with techniques set forth in Beach Erosion Board Technical Report No. 4 (1961). This method assumes that for a wave advancing toward shore, no energy flows laterally along a wave crest, i.e., the transmitted energy remains constant between two lines, called orthogonals, perpendicular to wave crest as it passes over changing hydrography.

Wave refraction diagrams have been constructed for the two more significant wave approaches of the Brunswick and New Smyrna Beach coastal areas (Figure 3). A wave period of 7 seconds is used to approximate greater than average conditions and wave advance is from N 50° E and S 45° E to conform with major wind directions.

The concentration of energy related to the energy per unit crest length of deep-water wave is determined graphically by the spacing of wave orthogonals shown in Figure B-3. The energy coefficient or relative amount of



THE WIND ROSE IN EACH 5" SQUARE SHOWS THE YEARLY AVERAGE WINDS THAT HAVE PREVAILED WITHIN THAT SQUARE. THE ARROWS FLY WITH THE WIND. THE LENGTH OF THE ARROW MEASURED FROM THE OUTSIDE OF THE CIRCLE AS DEMONSTRATED ON THE SCALE BELOW. GIVES THE PERCENT OF THE TOTAL NUMBER OF OBSERVATIONS IN WHICH THE WIND HAS BLOWN FROM OR NEAR THE GIVEN DIRECTION THE NUMBER OF FEATHERS SHOWS THE AVERAGE FORCE OF THE WIND ON THE BEAUFORT SCALE THE FIGURE IN THE CENTER GIVES THE PERCENTAGE OF CALMS

FIGURE B-2. PREVAILING WIND DIAGRAM AND OBSERVED SURF CHARACTERISTICS OF THE BRUNSWICK GA. AND NEW SMYRNA BEACH, FLA COASTAL AREAS. SWELL AND BREAKER HEIGHT DATA AFTER HELLE (1958) AND WIND DIAGRAM FROM U.S. HOUSE DOCUMENT NO 772, 80TH CONGRESS.

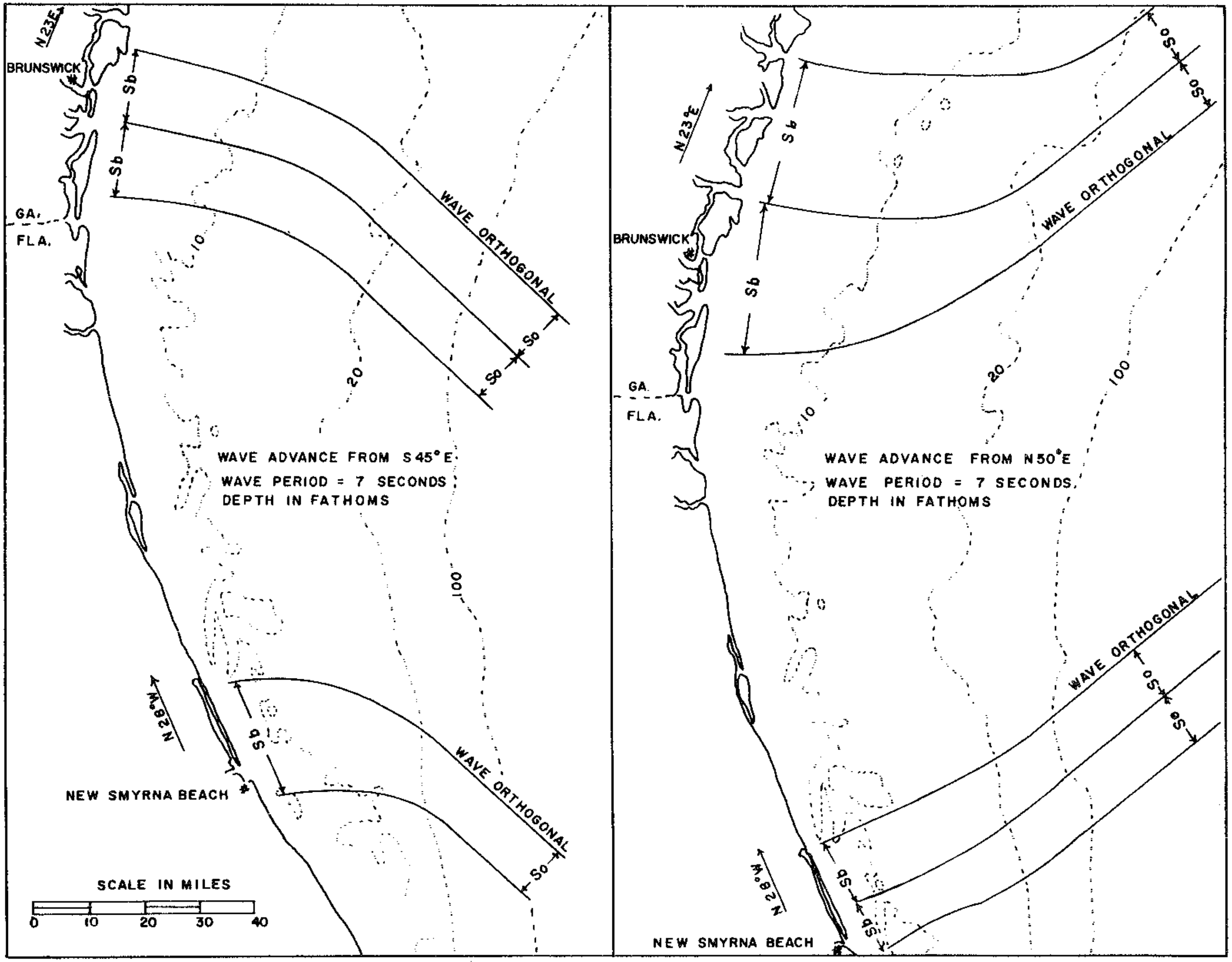


FIGURE B-3. WAVE REFRACTION DIAGRAMS OF BRUNSWICK, GA. AND NEW SMYRNA BEACH, FLA., COASTAL AREAS.

convergence or divergence due to wave refraction is determined by the ratio of the distance, S_o, between wave orthogonals in deep water to the distance, S_b, between the same orthogonals at the point where the wave breaks. The breaker height is proportional to the cube root of the wave energy; therefore, a refraction factor, K_b, for breaking waves, is defined as the cube root of the energy coefficient. These parameters are shown graphically in Figure B-3 and listed in Table B-1.

TABLE B-1

WAVE ENERGY AND BREAKER COEFFICIENTS FOR SELECTED WAVE APPROACH DIRECTIONS AT BRUNSWICK, GEORGIA AND NEW SMYRNA, FLORIDA

Location	N 50° E	S 45° E	N 50° E	S 45° E
	Energy Coefficient		Breaker Coefficient	
Brunswick	0.38	0.71	0.73	0.89
New Smyrna Beach	0.74	0.50	0.91	0.79

For the Brunswick area, the energy coefficient values show a high energy reduction for waves advancing from the northeast because of the amount of refraction resulting from this approach direction. The waves are refracted to such a degree that observers on the beach see the surf as approaching from the southeast. This would correlate with the data shown in Figure B-2 for observed wave approach. The breaker height coefficient is also smaller for this direction of wave approach.

The energy reduction and breaker height are less at the Brunswick area for wave approach from the southeast because less wave refraction occurs from this direction.

The wave refraction resulting at New Smyrna Beach differs from that of the Georgia coast in both magnitude and direction. The least wave refraction and strongest wave energy is from the northeast; this relationship appears in agreement with the observed surf statistics shown in Figure B-2.

The difference of wave refraction existing between the Brunswick and New Smyrna Beach coastal areas is a function of (a) bearing of the shoreline, (b) width and slope of the continental shelf, and (c) direction of wave approach governed by meteorological conditions. The steeper slope of the continental shelf enables closer approach to shore before the wave begins to be refracted and the shorter width also results in less wave refraction. The bearing of the shoreline in relation to wave approach determines the maximum amount of refraction that will occur since the tendency is for the waves to refract until crests are parallel to the shoreline. Less refraction is experienced if the angle of the deep-water wave approach is more nearly parallel to the shoreline such as occurs when the wave approach is from N 50° E off the New Smyrna Beach area and S 45° E off the Brunswick Coast.

Silvester (1963), concerned with model studies of littoral drift, recognizes the importance of the bearing of the shoreline and angle of wave approach. According to Silvester "the angle of approach of the swell is the most important characteristic to be reproduced in the model and should be investigated fully".

The reduced energy of the Georgia coast in contrast to that of other portions of coast along the southeastern Atlantic coast, as recognized by Tanner and Helle (previously cited), appears confirmed by wave refraction analysis. The main reason the Georgia coast lies in the lower energy level zone may be attributed to the width of the continental shelf, gentle offshore slope, and the fact that greatest refraction of waves occurs when the wind is from the predominant and strongest wind force direction.

HISTORIC COASTLINE CHANGES, BRUNSWICK, GEORGIA

The factors effecting shoreline changes along the coast are littoral current forces, wave and current action, and changes in sea level. By comparison of historic shoreline and offshore surveys since 1856, it is possible to establish the net effect of the interplay of these forces.

The earliest hydrographic survey along the Georgia coast was conducted by the U. S. Coast and Geodetic Survey in 1856. Since then several other surveys have been conducted. These data for the Brunswick coastal area were compiled by the Beach Erosion Board and presented in House Document No. 820, 76th Congress (1940). Figure B-4 shows the earliest and a more recent survey of mean high water shorelines along the Brunswick coastal area. Some of the conclusions presented in House Document No. 820 are:

> Since 1860, survey data indicate that there has been no appreciable change in the character of the offshore shelf between Altamaha and St. Simons Sounds except where the tidal channels have migrated. It is believed probable that there has been little change in the average volume of southerly littoral drift during this period.
>
> For distances of 3,000 feet east and west of St. Simons lighthouse (Figure B-4), erosion of the south shore of St. Simons Island has apparently been continuous at a slow rate over a long period of time. The erosion appears to have been caused by the combined effect of wave action and the high velocity of tidal currents near the shore. The broad expanse of shoal area offshore protects the south point from severe storm wave action, but local winds from the southeast produce wave action which erodes material from the upper shore, bringing it down to the tidal range where it may be carried away by currents. Increased exposure of the upland to wave erosion is brought about by lowering and narrowing the foreshore slope as a result of northward migration of the gorge.

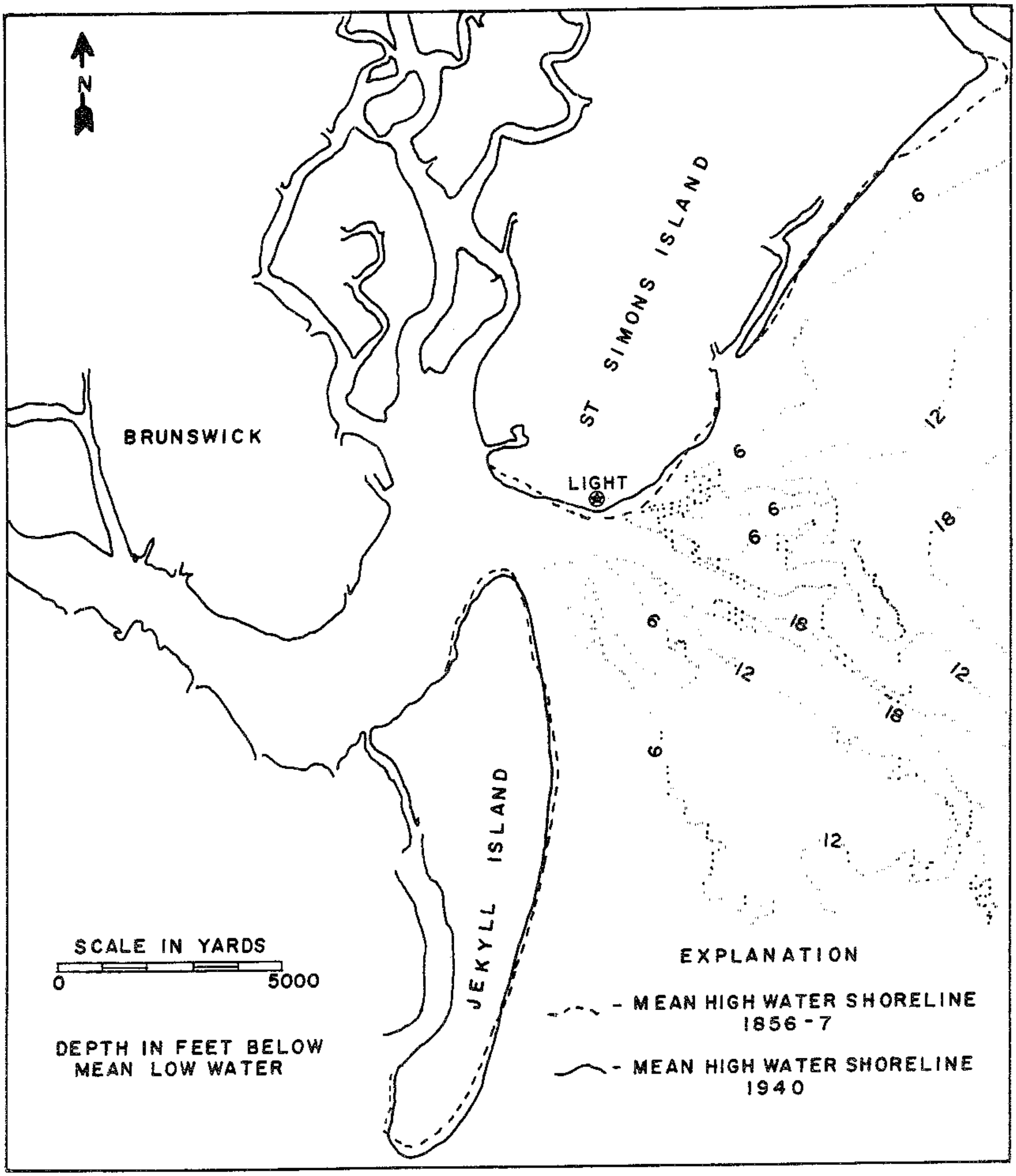


FIGURE B-4. MEAN HIGH WATER SHORELINE CHANGE IN BRUNSWICK, GEORGIA COASTAL AREA SINCE 1856 SHORELINE CHANGE FROM U.S. HOUSE DOC. NO. 820, 76 TH. CONG (1940)

The more severe erosion by wave action from the southeast appears to correlate with the wave refraction diagram analysis, previously cited, in that southeasterly wave advance is least affected by refraction and energy reduction is correspondingly less. Predominant littoral transport in a southerly direction would indicate that waves from the northeasterly direction, although refracted considerably from the predominant northeast approach direction, do not become parallel to the bearing of the coastline but break while still at an angle slightly north of this direction. Littoral current direction associated with wave action is the direction of the alongshore component upon resolving the direction vector of breaker advance on the shoreline into onshore and alongshore components relative to the bearing of the shoreline.

The reduced energy level along the Brunswick coastal area is reflected in relatively minor shoreline change in the last 100 years as indicated by historic survey data. Studies conducted along the Florida coastline reflect greater change, and both wave refraction analysis and observed surf characteristics support the view of higher energy levels.

COASTAL STABILITY, NEW SMYRNA BEACH, FLORIDA

Bruun (1962), in a study of the east Florida coastline, proposed a theory of erosion based on a rise of sea level. In this investigation it was determined that the gently sloping bottom of the New Smyrna Beach area, in contrast to more southerly locations in Florida, insures a slower response to erosion of the barrier beaches by rise in sea level. Bruun suggests that for a shoreline in alongshore quantitative equilibrium, the balance between eroded and deposited quantities in relation to sea level rise may be expressed by the two independent movements:

$$xe = a\ (b-x)\ d$$

$$x\ (e + d) = ab$$

In the equations, x denotes shoreline recession per year; a = the sea level rise per year; b = distance to 60-foot contour; e = elevation above sea level of shore at limit of erosion. The long-term sea level rise, based on historic tidal gage information from Florida, is 1.2 mm. per year.

For the areas north of Cape Canaveral to Daytona Beach (which include New Smyrna Beach), Bruun found the shoreline recession using a = 1.2 mm. per year; b = approximately 5 miles (8,000 m.); e = 4.5 m. (15 feet); and d = 18 m. (60 feet) yields:

$$x\ (4.5 + 18) = (8{,}000)\ (0.0012)$$

$$x = 0.43 \text{ m. or approximately } 1.4 \text{ feet.}$$

According to Bruun, erosion of the shoreline using the long-term response in rise of sea level is probably a realistic figure north of Cape Canaveral as these shores are rather stable.

The Georgia coast in the vicinity of Brunswick, although physiographically similar to that at New Smyrna Beach, differs mainly in the influx of sediment from the Altamaha River. The Altamaha River drains the Georgia Piedmont and transports appreciable sediment to the coast in this region. By contrast, the Florida coast has no large contribution of sediment from rivers draining such sediment-rich source areas as exist along the Georgia coast. Because of this sediment-influx variable, the equation used for the Florida coast is not applicable to the Brunswick coastal area. The sea level rise off the Florida coast may also differ from that off the Georgia coast since Bruun (1962) attributes an appreciable amount along the Florida coast to "secular deceleration of the Gulf Stream".

SUMMARY AND CONCLUSIONS

A comparison of the Brunswick and New Smyrna Beach coastal areas enables contrast of two areas of similar physiographic character but experiencing different degrees of coastal stability. Wave refraction analysis appears to correlate with observed surf-characteristics data. Significant factors are listed below:

1. The strongest wind forces with longest durations are from the northeasterly direction along both coastal areas. Waves approaching from the northeast are strongly refracted with resulting reduced energy levels along the Georgia coast but little refraction occurs at New Smyrna Beach, Florida for this wave approach direction.

2. The gentler bottom slope over greater distance and the bearing of the shoreline appear to be important factors affecting wave refraction from any given direction along the Brunswick coastal area.

3. Historic shoreline surveys since 1860 reveal minor changes along the Brunswick coast except for local conditions related to tidal and alongshore currents.

4. The greater shoreline recession experienced along the Florida coast appears to be related to: (a) higher energy levels, (b) less sediment supply, (c) closer proximity of the Gulf Stream effecting higher water levels, and (d) other factors such as sediment characteristics.

Observed surf data, wave refraction analysis, historic surveys, and other data indicate that the Georgia coastline is more stable than the Florida coastline, and more coastal engineering work has been necessary at the latter location because of this condition.

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