DISTRIBUTION OF HEAVY MINERAL SANDS ADJACENT TO THE ALTAMAHA SOUND: AN EXPLORATION MODEL

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BULLETIN 110

Cover: Remote infrared image of the Altamaha Sound and surrounding area. White is exposed sand bodies, Light gray is marsh, Dark gray is vegetative cover. Scale is 1:80,000. North is to top of photo.

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by

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ABSTRACT

The Altamaha Sound and the surrounding tidal inlet-barrier island complex contain environments in which heavy mineral-bearing sediments are presently accumulating. The interaction of the various transport and deposition processes results in variations in the composition and concentration of the heavy mineral suite in each of the environments. A total of 209 samples were collected in order to evaluate the processes affecting distribution and concentration of these minerals. Petrographic analyses of these samples reveal the following average percentages of specific minerals within the heavy mineral fraction: ilmenite/leucoxene 36.1%, rutile 2.7%, zircon, 3.7%, staurolite, 4.7%, kyanite/sillimanite 11.7%, epidote, 24.4%, amphibole, 9.9%, monazite, tourmaline, garnet and magnetite, each less than 2.0%. Of the 209 samples, 67 contained greater than or equal to two percent heavy minerals by weight.

The general trend for heavy mineral concentration is an increasing maturity of the sediments away from the source river, with accompanying moderate increases in heavy mineral concentrations in the backshore and dune environments. Generally higher percentages of the titanium minerals (ilmenite, leucoxene, rutile) are present in the backshore and dune environments as compared to higher percentages of epidote, kyanite/sillimanite and amphibole in the channel and nearshore environments. Variations in mineralogy and texture are apparently the result of reworking in the higher energy environments, where wave action and aeolian processes concentrate the heavy minerals with higher specific gravities.

INTRODUCTION

General Statment

Sediments of fluvial-marine environments have long been recognized to contain heavy mineral sand constituents, often of economically exploitable quality and quantity. Heavy minerals are commonly defined as accessory detrital minerals, of a high specific gravity (equal to or greater than 2.85), which are components of sedimentary deposits. Heavy minerals commonly associated with the Georgia coastal environments are: ilmenite, leucoxene, rutile, zircon, staurolite, monazite, epidote, kyanite/sillimanite, amphibole, garnet and magnetite. Most abundant, and of most interest economically, are the titanium minerals: ilmenite, leucoxene and rutile. These minerals are used principally in the production of pigments and in the manufacture of alloys in the aerospace industry. Also of importance is zircon, useful for its high temperature, refractory properties. Staurolite and garnet are used as abrasives. Monazite, being a source of thorium, greatly enhances the value of the heavy mineral suite.

Throughout a large portion of the southeastern United States Atlantic Coastal Plain, the Pleistocene and Holocene coastal marine environments are morphologically barrier island complexes. In Georgia a series of barrier island shorelines of early Pleistocene to Holocene age stretches from the present coast to approximately 80 miles inland. The Pleistocene barrier islands have been mined for heavy minerals sands in both Georgia and Florida. Pleistocene deposits in the Folkston area of Charlton County, Georgia were mined until 1974, when the principal ore body is reported to have been depleted (Cooper and Pickering, 1977). Exploration activity, to date, for heavy mineral sands in Georgia has consisted of large-scale sampling surveys, relatively few samples taken over a large area, with little or no paleoenvironmental analysis. By studying the present barrier islands and the processes by which they are formed and modified, it may be possible to determine sites of concentration of the economic heavy mineral sands. From this it might then be possible to extrapolate to the paleo-barrier islands, focusing on geographically and morphologically equivalent portions of the older barrier islands to locate economic heavy mineral deposits.

Objective and Scope

The objective of this study is to develop a depositional model for economic deposits of heavy mineral sands in barrier island environments. The derived model will involve a delineation of the variations in the overall concentration of heavy mineral sands, and the variation in the heavy mineral suite in each of the depositional environments occurring throughout the study area. The area under investigation is the modern Altamaha delta and associated depositional environments, shown in Figure 1. The deposits to which this model may be applicable are the inland and offshore, Pleistocene barrier island deposits of the southeastern U.S. Atlantic Coastal Plain and continental shelf, which were formed under similar conditions and by similar process during previous sea level "stillstands."

This study is not intended as an economic feasibility study for heavy mineral sand exploitation on the present barrier island coastline of Georgia. It is intended solely to develop an exploration model applicable to the older Pleistocene paleo-barrier islands located in less environmentally sensitive areas.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the staff of the Coastal Resources Division, Georgia Department of Natural Resources, without whose able assistance, the field portion of this study could not have been completed. We would also like to thank the staff of Little St. Simons Island for their assistance during sample collection on that island. Dr. Vernon Henry, Geology Department, Georgia State University, Dr. Pamela Gore, Geology Department, Emory University and Dr. Norm Herz, Geology Department, University of Georgia provided indispensable advice through their reviews of this manuscript.

GEOLOGIC SETTING

General Statement

The series of terraces that reach across the Coastal Plain of Georgia, as well as the other southeastern Atlantic states, are generally acknowledged to be marine paleo-shorelines and associated environments. Originally, these terraces were considered to be remnants of wave-cut benches (Veatch and Stephenson, 1911; LaForge and others, 1925). Subsequent study has shown them to be the result of various and changing processes (Cooke, 1930, 1931, 1943; MacNeal, 1950; Doering, 1960; Hails and Hoyt, 1972, Hoyt, 1967, 1969; Georgia Geologic Survey, 1976; Huddlestun, 1988). These shorelines trend parallel or sub-parallel to the present coast in a series, with the oldest shoreline located approximately 80 miles inland. A total of 13 shorelines have been described in Georgia. They range in age from early Pleistocene to Recent (present-day), decreasing in age in a seaward direction. They are, from oldest to youngest, Hazelhurst, Pearson, Claxton, Argyle, Waycross, Okefenokee, Wicomico, Penholoway, Talbot, Pamlico, Princess Anne, Silver Bluff and the present shoreline (Huddlestun, 1988). Elevations range from 260 feet to sea level.

Figure 2 depicts the seven youngest shorelines from the Wicomico to the present. These are composed of discrete relatively well-defined bodies of unconsolidated sand. They are generally interpreted to represent barrier island complexes of varying degrees of morphologic complexity, and are potential sites for heavy mineral sand concentration. The Waycross and Okefenokee terraces are composed of less clearly defined sand bodies with origins similar to the younger terraces. The older terraces are principally wave-cut terraces without associated barrier island sand bodies (according to Huddlestun, 1988).

As mentioned in Hoyt and Hails (1967), the origin and nature of the terraces are best understood by comparison to the present complex of coastal environments (see Figure 3). The present-day barrier islands are composed of very fine- to medium-grained terrigenous sand. Each is relatively low-lying, although well developed dune fields occasionally reach elevations of 25 feet or more. These barrier islands are backed by lagoonal and marsh environments within which the principal sediments are terrigenous clay mixed with sand and silt. Intricate dissection of the islands is caused by migrating tidal rivers and creeks. The paths of these water courses, in many cases, appear to be influenced by underlying ancestral topography and by the drainage systems of older adjacent terraces.

The present Georgia sea islands are stratigraphically thin composites of Silver Bluff and recent features, which are only rarely more than 20 to 25 feet in thickness. On some islands, recent sediments are welded directly onto the Silver Bluff. On other islands, the two are separated by backbarrier marsh environment, as can be seen in Figure 2. The geomorphology of the Georgia sea islands is a result of the interaction of several processes, including fluvial-, tidal-, and longshore-currents; wind and wave action; as well as sediment source and quantity. During historical time, human activity has played an increasing role in affecting the configuration of the barrier islands and, potentially, the nature of the sedimentary

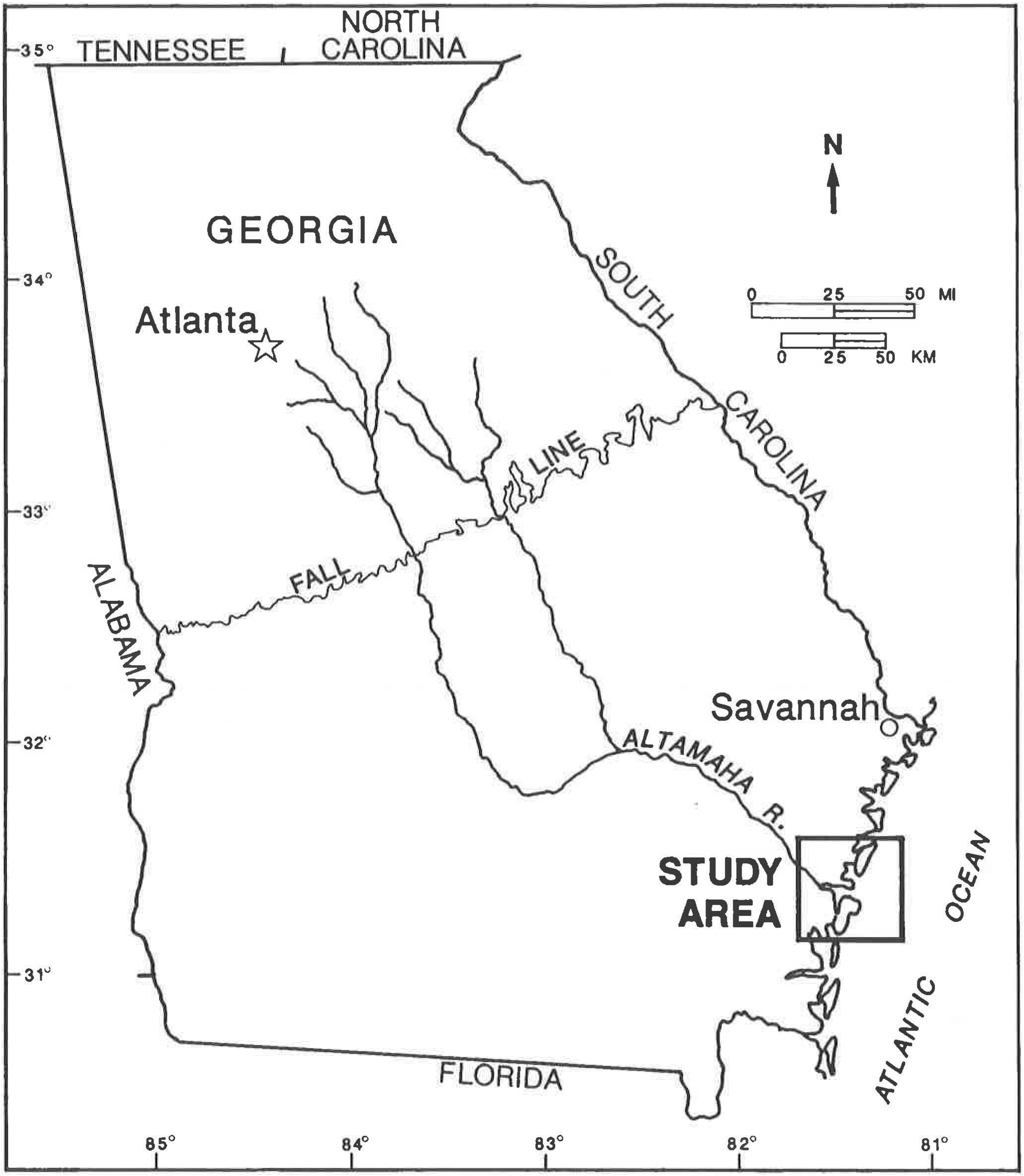

Figure 1. Location map of study area.

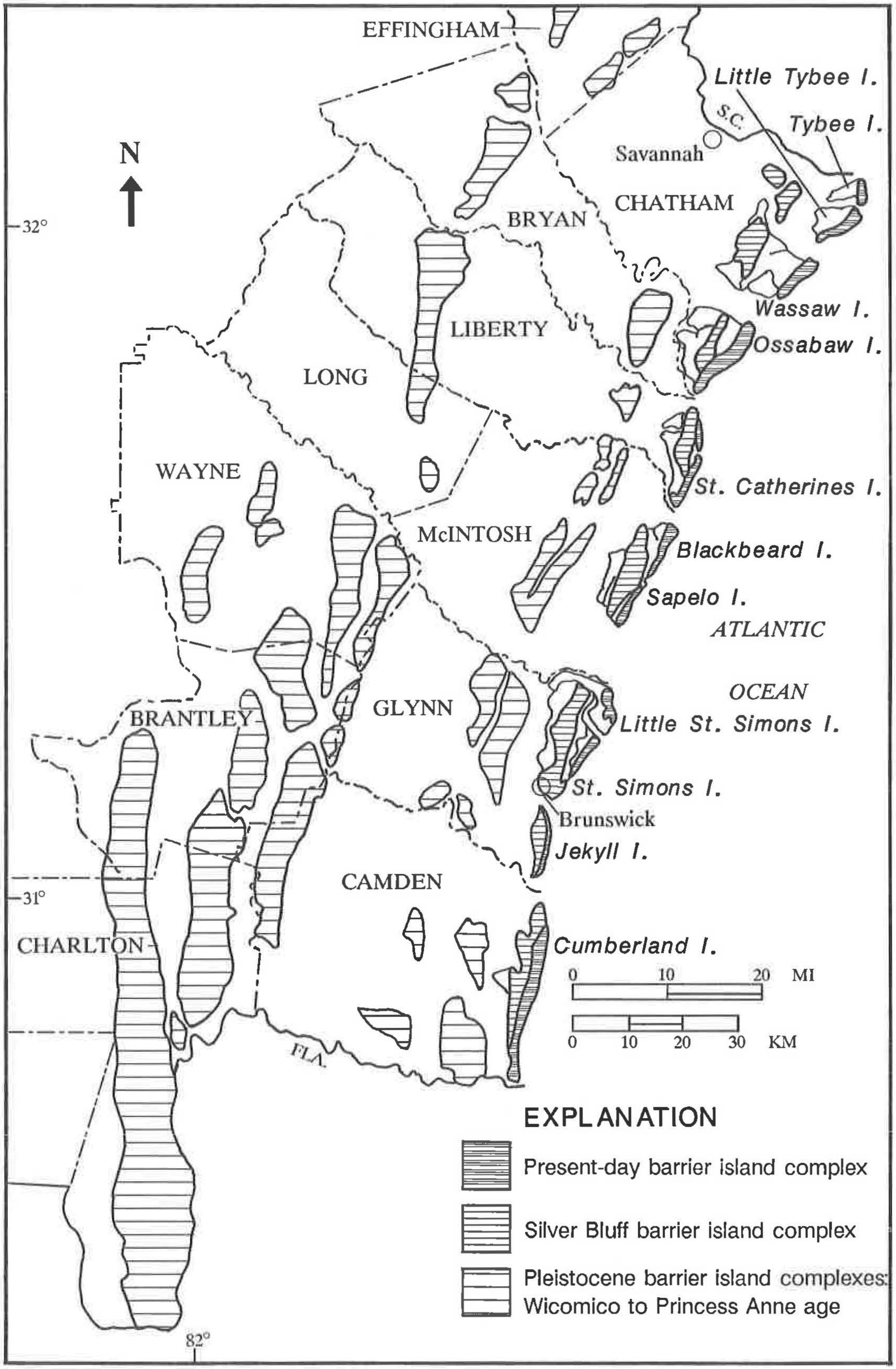

Figure 2. Map of coastal counties of Georgia.

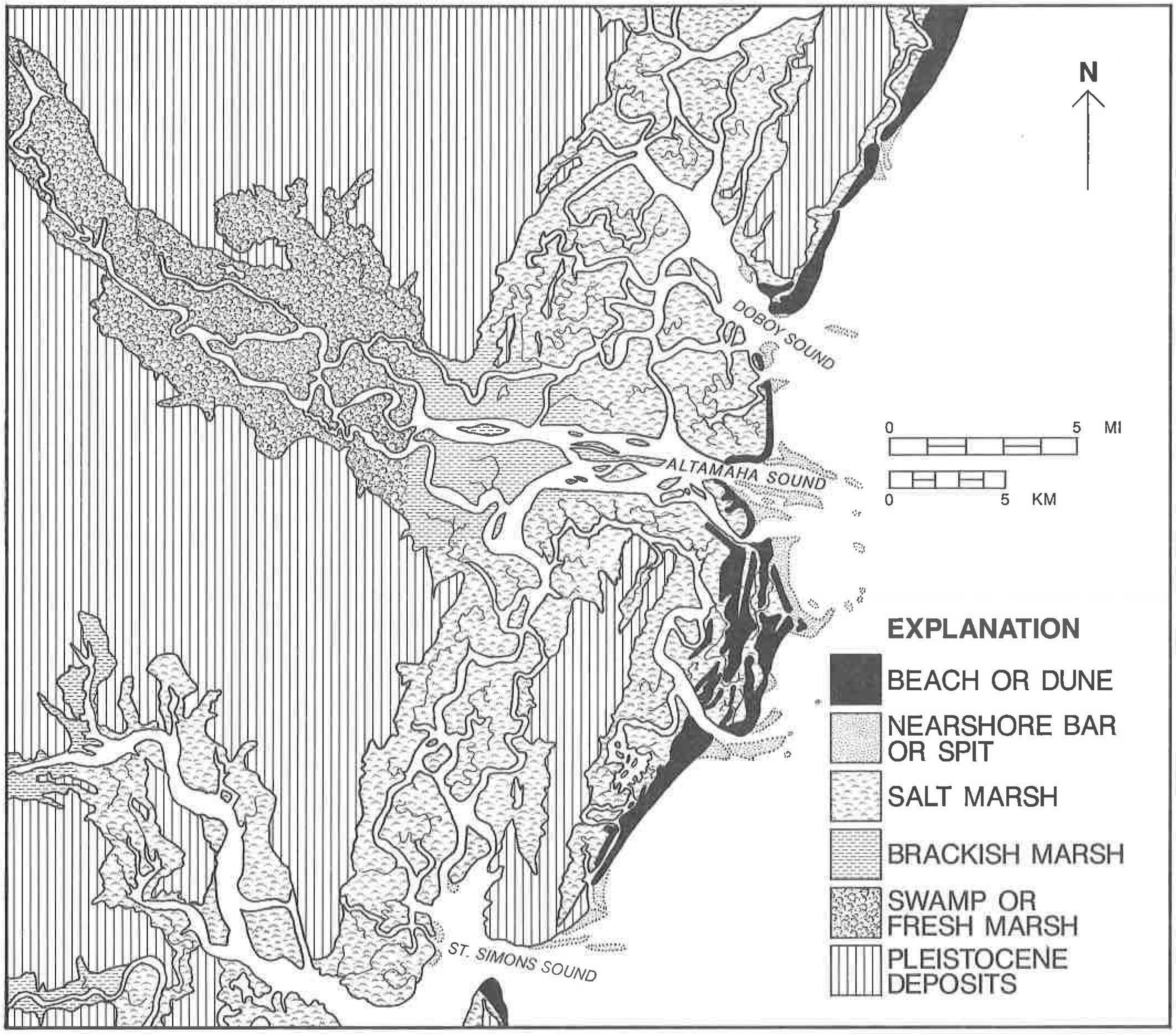

Figure 3. Holocene depositional environments of the Altamaha Sound and surrounding areas.

deposits. These activities include dredging and damming of rivers, and construction on the islands. The study area was chosen, in part, because of the relatively small role human activity has played in the area. The Altamaha River is not subject to major dredging activity and the adjacent islands (Sapelo, to the north, and Little St. Simons, to the south), are not currently the sites of major development.

Origin and Development of Barrier Islands

There are three general theories for the formation of an "idealized" barrier island. DeBeaumont (1845) suggested that locally derived sediments are eroded at the breaker zone of the nearshore and deposited as seaward bars by wave action, eventually building up to become emergent, as depicted in Figure 4(A). Gilbert (1885) postulated that the sand bodies are developed as spits accreting off headlands or deltas as a result of sediment transport by longshore currents. These spits eventually are breached and detached from the headland or delta, forming discrete islands (Figure 4(B)). Hoyt (1967) suggested that some barrier islands actually result from transgressions during which rising sea levels inundate the shoreline, detaching dune beach ridges from the new shoreline as shown in Figure 4(C). These new islands then migrate and are altered in morphology depending on local dynamics.

Numerous authors, including Leontyev and Nikiforov (1965), Hoyt (1967), Cooke (1968), Fisher (1968), Hoyt (1968 a&b), Schwartz (1971), Kelley (1981), Rampino and Sanders (1981), Leatherman (1983), and Stubblefield and others (1983), have discussed the various theories of barrier island formation. The current consensus suggests that in most situations, barrier island formation is the result of a complex combination of each of these processes, modified by hydrodynamic and aeolian activities.

PREVIOUS HEAVY MINERAL SAND STUDIES

Heavy Mineral Sand Studies in Georgia

Previous published works on heavy mineral sands in Georgia have generally focused on relatively isolated environments on the present sea islands, or have been regionally extensive reconnaissance sampling surveys with relatively few samples. Little consideration has been given in the literature to depositional modeling. Although the heavy mineral mining industry has been actively exploring in Georgia for many years, the results of their studies, in most cases, have not been released.

Published studies which examine sand composition in restricted areas of Georgia's modern sea islands include Neheisel (1962 and 1965), and Woolsey and others (1975). Neiheisel (1962) collected 50 samples from the Pamlico, Silver Bluff and Recent barrier island terraces. A number of these samples were located on the present day beaches. Neiheisel (1966) concluded that concentration of heavy mineral sands tends to occur within the backshore zone on the island front. An additional finding was that an enrichment of the economically valuable heavy minerals occurred in the older terraces as a result of chemical decay of the less stable, and coincidentally less valuable, heavy minerals. Woolsey and others (1975) examined heavy mineral concentrations occurring in the backshore/dune zones of Sapelo Island and noted that the interactions of wind and wave activity were concentrating heavy minerals in these zones.

Published studies concerning paleobarrier islands of Georgia fall into two categories. The first is that of relatively localized studies, directed at economic evaluations of specific sand bodies, with little or no interpretation of depositional environments. Mateer (1961), Abercrombie (1965) and Furlow (1967) conducted surveys to evaluate a Pamlico terrace sand body near Brunswick, Georgia on the then proposed route of Interstate Highway 95. Friddell (1980) examined this sand body and another Pamlico sand body in McIntosh County. Friddell's study involved an attempt to verify aeroradiometric anomalies through the analysis of augured samples. Again, the scope of these studies did not include development of a depositional model.

The second category of published investigations is that of large scale regional reconnaissance studies. These studies encompassed large areas but, with relatively few samples taken. Such studies include those of Neiheisel (1962), Giles and Pilkey (1965), Smith and others (1967), and Hails and Hoyt (1972). The Giles and Pilkey (1965) study encompassed Coastal Plain sediment samples from North Carolina to Florida. Although they did not develop a depositional model, Giles and Pilkey (1965) found that beach sands contain relatively larger amounts of elongate heavy mineral grains, while dune sands were relatively enriched in equidimensional heavy mineral grains. They also concluded that rivers deriving sediments from local Coastal Plain sources contain a more stable suite than those which have their sediment source in the Piedmont. Both of these findings have significance in the determination of depositional environments in which economic heavy mineral sands might occur. The commercially more valuable minerals, specifically the titanium-bearing minerals and zircon, are among the

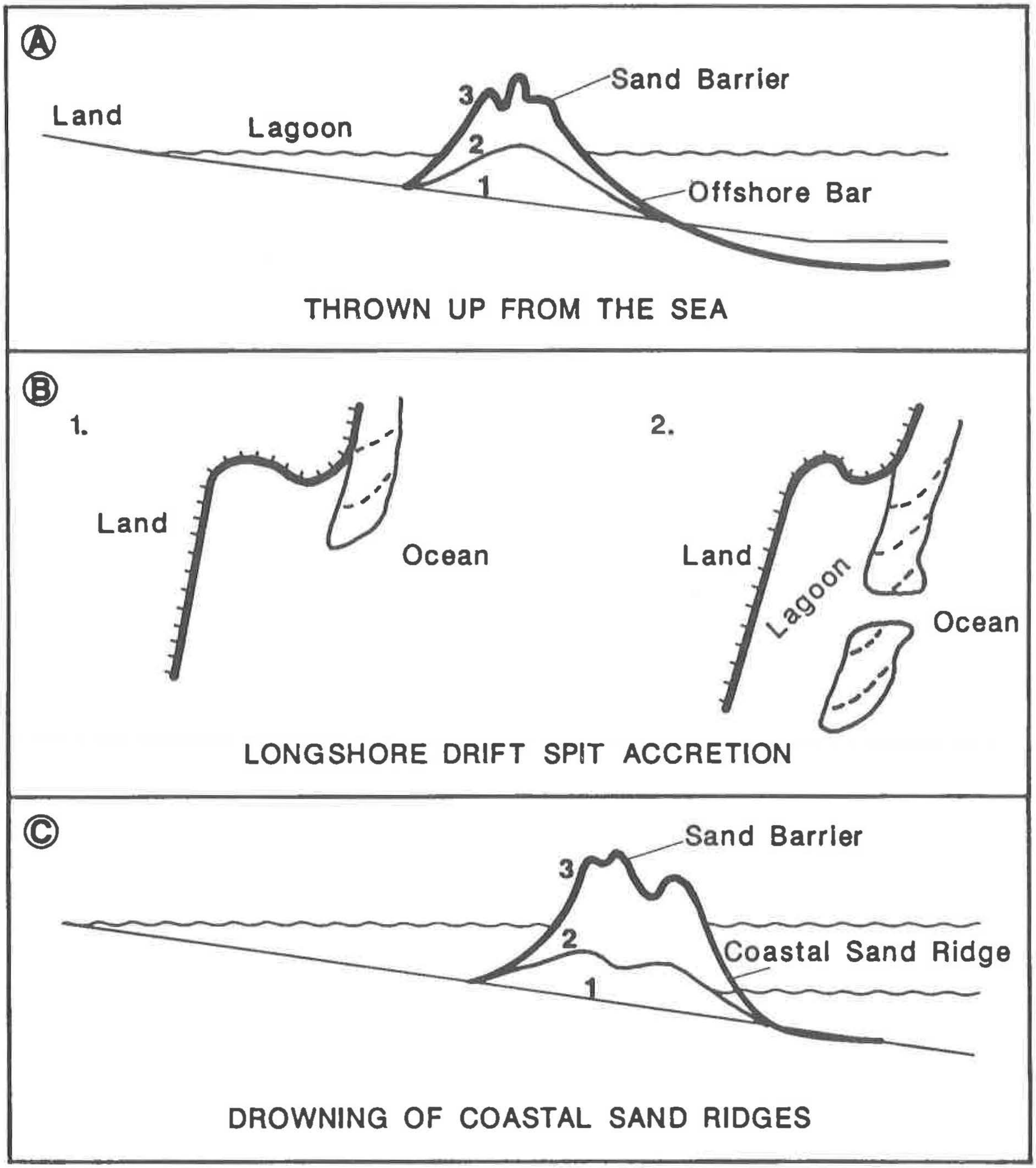

Figure 4. Basic theories of barrier island formation: (A). Evolving from an offshore bar (De Beaumont, 1845). (B). Evolving from longshore drift-spit accretion (Gilbert, 1885). (C). Evolving from the drowning of coastal sand ridges (Hoyt, 1967). For A and C, the numbers 1,2, and 3 generally refer to initial, intermediate, and final stages of development. For B, 1 represents the initial stage of development and 2 represents the final stage of development.

most stable constituents and are, therefore, relatively more abundant in the more mature sediments. These minerals also tend to be equidimensional.

Giles and Pilkey (1965) and Hails and Hoyt (1972) showed that the provenance of the Georgia barrier island sediments is the Georgia Piedmont via the Savannah and Altamaha Rivers. This Piedmont material was transported to the coast and deposited during the Pleistocene and Holocene. Much of the sediment was reworked during subsequent regressive-transgressive cycles.

Heavy Mineral Sand Studies in Northern Florida

A number of investigations of barrier island terraces have been made in Florida (Pirkle and others 1974, Pirkle and others, 1984, Force and Garner, 1985). These studies can be used to gain insight into the depositional processes influencing heavy mineral occurrences. Northeastern Florida heavy mineral sand deposits have been mined intensively for more than thirty years. As a result, more study has been made of environments of deposition in Florida than in Georgia. Both the Georgia and Florida paleo-barrier systems have similar provenance and were formed by similar processes during the same sequence of Pleistocene shoreline fluctuations.

Four distinct ore bodies have been studied in northeastern Florida (Figure 5). They are, in order of increasing age: the Yulee deposits north of Jacksonville; the Boulougne and Green Cove Springs deposits, northwest and southwest of Jacksonville, respectively; and Trail Ridge, to the west of Green Cove Springs.

Trail Ridge deposit is the oldest of the ore bodies in this area. Force and Garner (1985) describe high angle dune crossbedding in the face of the mine dredge pond. This suggests the importance of aeolian processes in regard to possible mechanisms of concentrations in heavy mineral sand deposits. Force and Garner (1985) pointed to the fact that a predominance of the exploration efforts have been directed at paleo-shoreline placers; thereby, possibly, overlooking interior dune fields as possible prospects.

Green Cove Springs and Boulougne are considered to be beach ridges formed on a regressional beach plain during either a stillstand or minor transgression (Pirkle and others 1974; Pirkle, and others 1984). The Yulee deposits are interpreted as occurring on the Pamlico shoreline south and down-longshore drift of the ancestral St. Marys River. The economic concentration is believed to be the result of sorting caused by the interaction of ocean currents and the sediment-bearing river currents (Pirkle and others 1984). These deposits were further concentrated by wind and wave action.

DESCRIPTION OF THE PRESENT-DAY ALTAMAHA RIVER DELTA AND SURROUNDING AREA

The present day Altamaha River delta and surrounding environments occupy approximately 21 miles along the southern portion of the central Georgia coast (Figure 6). The Altamaha River is among the largest fluvial systems in Georgia and the southernmost system along the Atlantic coast to drain the crystalline terrain of the Southern Appalachian Piedmont. The confluence of the Altamaha River with the Atlantic Ocean yields a wide variety of coastal landforms. Approximately 20 miles upstream from its mouth, the Altamaha River undergoes a transition from a narrow terrace-flanked alluvial valley to a gently widening, upper delta plain. The upper delta plain environment is characterized by several closely spaced, meandering distributaries, with well developed natural levees. Between the tributaries, freshwater swamps are present.

Five to six miles upstream of the Altamaha River mouth, the upper delta grades gradually into the much broader lower delta plain. Here, the distance between distributaries increases and natural levees are smaller. The most noticeable features of the lower delta plain are the widening of the main channel, due to the convergence of the North and South Altamaha Rivers, and the abundance of lens-shaped islands and tidal bars within those river channels. Surrounding these islands and bars, the bifurcating river channels average 6 to 10 feet below mean sea level (BMSL) in depth. Scours, some of which exceed 20 feet BMSL, occur within these channels.

The dominance of coastal hydraulic processes (waves, tides, and longshore currents) on sediment discharge is responsible for the morphology at the Altamaha River mouth. Tidal conditions are semi-diurnal, range up to 10 feet during spring tides, and average approximately 6.6 feet throughout the tidal cycle (Hubbard and others, 1979). Wave height in the river mouth (and throughout the oceanfront in the study area) averages one foot (Tanner, 1960). Longshore currents transporting sediments to the south contribute to the river mouth morphology, as seen in the extensive shoal development along the southern margin of the delta. Linear sand shoals extending seaward from the river mouth represent ebb tidal delta components as described by Hayes (1975, 1980) and Oertel (1975). As a result of the hydrographic regime, the morphology of the Altamaha River mouth resembles that a meso-tidal mixed energy estuary (wave-modified, tide dominated) as proposed by Hayes (1975, 1980) in his model.

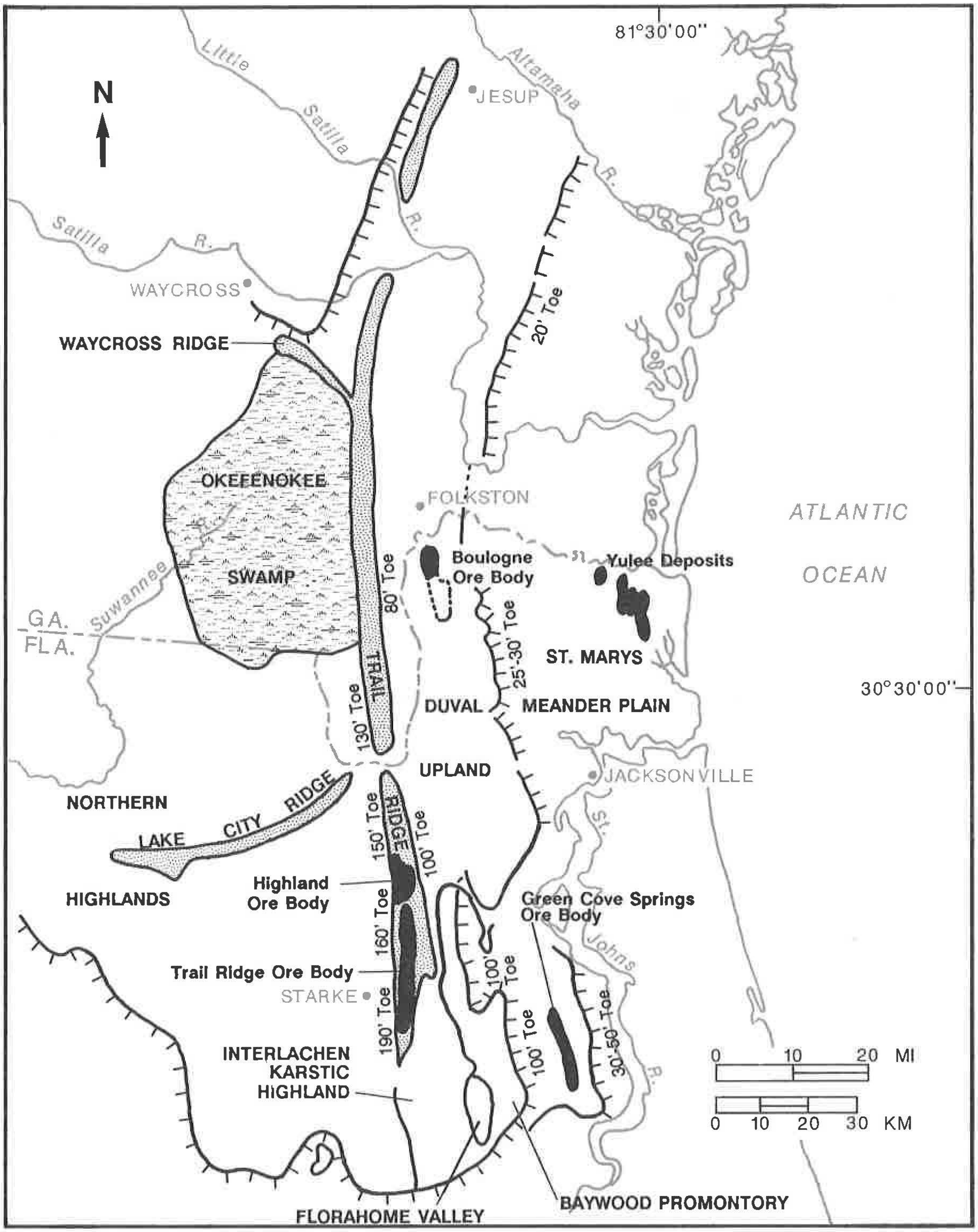

Figure 5. Location of Florida heavy mineral deposits.

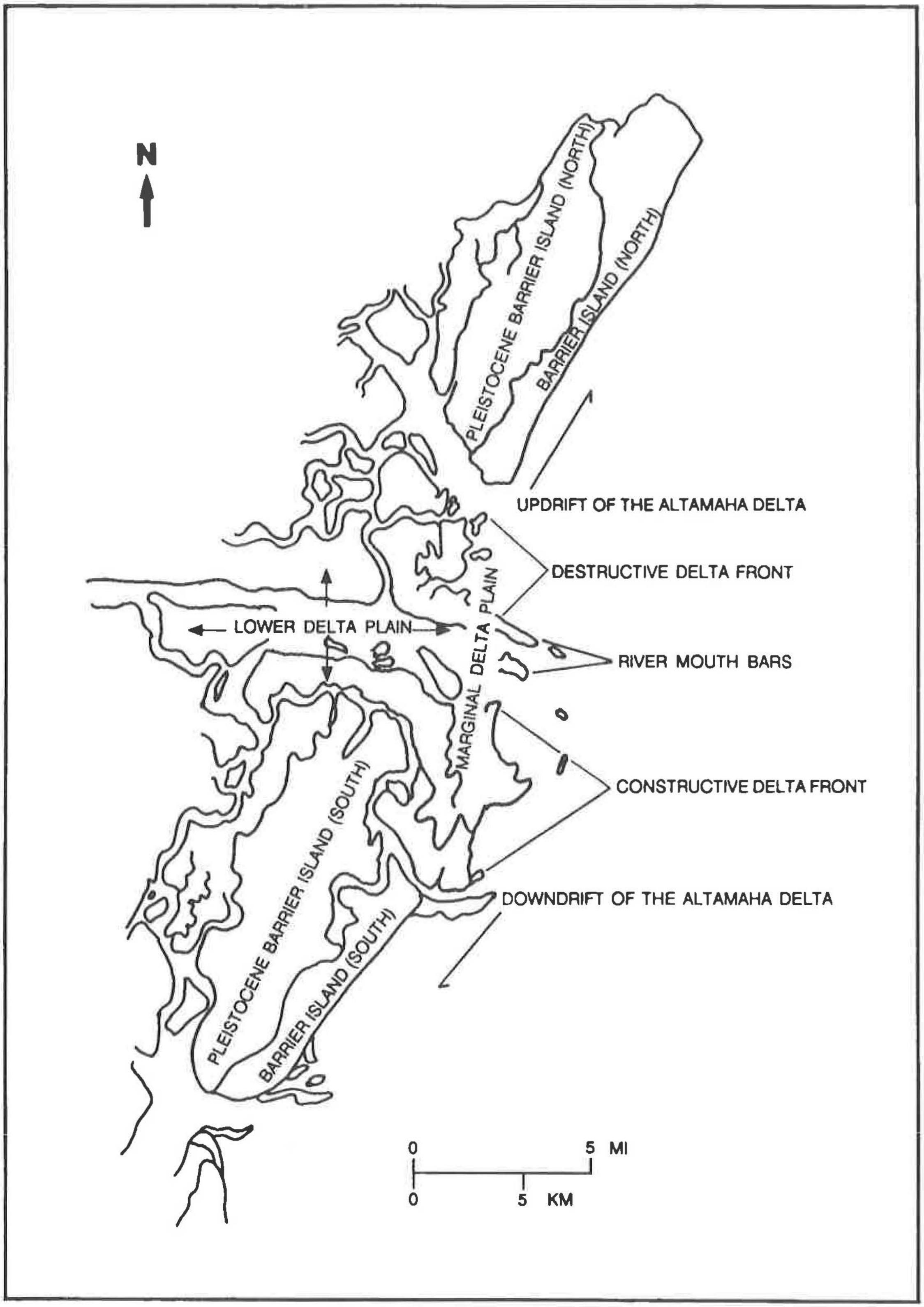

Figure 6. Depositional environments of the Altamaha River sediment transport system.

Flanking the mouth of the main distributary, the shoreline of the Altamaha River delta extends approximately five miles along the seaward fringe of Wolf, Egg, and Little St. Simons Islands. Dynamic marine processes (waves, tides, longshore currents) dominate this environment. The delta front shoreline of Wolf Island, north of the main distributary, is described as a destructive shoreline and is characterized by an eroding marsh foreshore (Figure 7), sand picket beaches, and extensive washover sandflats transgressing into the marsh behind it. South of the main distributary, the net southerly transport of delta front sand renourishes the shoreline along the northern end of Little St. Simons Island, indicating a constructive phase. Shoreline growth is evidenced by a well-developed nearshore bar platform adjacent to the shoreface (Figure 8). Dune-field and beach-ridge growth, particularly evident on the northern portion of the island, reflect the prograding nature of the southern shoreline of the delta. This contrast between the eroding Wolf Island shoreline and the prograding Little St. Simons Island shoreline is the direct result of the pronounced southerly longshore drift.

Little St. Simons Island, shown in high-altitude, aerial, infrared imagery in Figure 9, represents the marginal deltaic environment. A series of beach- and dune-ridge complexes, separated by marshes or pans, make up the interior of the island. These ridge complexes are sub-parallel to each other and indicate the position of previous Holocene cusp-shaped shorelines. The ridge complexes illustrate the progradational nature of the island to the present shoreline. Figure 10 depicts the extensive spit system extending northeast from the southern end of the island, moving sand northward at the expense of barrier islands to the south. Wave refraction is believed to be the mechanism responsible for this movement of sand to the northeast on Little St. Simons Island, counter to the longshore drift direction. Similar observations of wave refraction-induced transport reversals have been well documented by Hayes (1975), Hayes and others (1976), and Fitzgerald (1976).

Barrier islands flank the marginal deltaic setting and are separated from it by inlets and their associated ebb-tidal deltas. These islands represent the coastal-marine member of the study area environments. The morphology and dynamic processes related to barrier islands and tidal inlets in Georgia have been extensively investigated by, among others, Hoyt and Weimer (1963), Hoyt and others, (1966) and Hoyt and Henry (1965). Barrier islands along the Georgia coast are similar to those along the South Carolina coast where their morphology has also been extensively studied (Hayes and others, 1976; Barwis, 1976; and Brown, 1977). Sapelo Island and Sea Island (Figures 11 & 12 for Sapelo and 13 for Sea Island) are the northern and southern limits of the study area. The general shape of these islands resembles an arcuate "drumstick." This type of morphology results from the modifications of the wave and tidal current regime in response to migrating tidal inlets and their associated ebb-tidal deltas (Hayes and others, 1976). Figure 14 is a diagrammatic representation of an idealized, southeastern U.S., Atlantic-coast, barrier-island complex. The "drumstick" model accurately describes the St. Simons barrier island complex (Figure 13). A variation from the model is a large spit which can be seen prograding up drift, subparallel to the coastline from the mouth of the Hampton River. This prograding spit exists in response to the previously described sediment transport reversal along this segment of Little St. Simons Island.

Sapelo Island, at the northern end of the study area, is fronted by two small recent beaches, Nanny Goat Beach and Blackbeard Island. The depositional components of the "drumstick" morphology can be seen in the bifurcating beach-ridges of Blackbeard Island, and in the recurved spit of Nanny Goat Beach (see Figure 11 and 12, respectively).

In summary, the study area contains a wide variety of geomorphologically distinct environments including the upper delta plain, lower delta plain, delta front, estuarine river mouth, marginal delta plain, inlet and associated ebb-tidal delta, and barrier island environments. Within each environment there exists a unique assemblage of subenvironments, resulting from the interactions within the hydrographic regime at the confluence of a major river and the mesotidal mixed energy coast.

METHODOLOGY

Field Techniques

<u>Sample Site Selection</u>

Initial review of the study area was accomplished using U.S. G.S., 7.5 minute, topographic quadrangle maps, N.O.A.A. 1:40,000 scale navigational maps, and color infrared aerial imagery. The 7.5 minute topographic maps covering the field area are: Altamaha Sound, Darien, Doboy Sound and Sea Island. The maps and imagery provided information on possible sample site locations and general accessibility.

Sample site locations were selected with the intent to cover a representative sampling of the various environments and subenvironments in the study

Figure 7. Photograph of Wolf Island transgressive beach.

Figure 8. Photograph of the north end of Little St. Simons Island, showing accretion of sand on the inlet mouth and nearshore bar environment. View is to the west towards Little St. Simons Island, across intertidal sand bodies.

Figure 9. Remote infrared image of Little St. Simons Island depicting linear dunes. White is exposed sand,Gray is marshes, Dark is vegetation covered sand bodies. Scale is approximately 1:80,000. North is to top of photo.

Figure 10. High-altitude aerial photograph of the south end of Little St. Simons Island depicting extensive spit and bar system (Pelican Spit, indicated by arrow). Scale is 1:80,000. North is to top of photo.

Figure 11. Remote infrared image of Blackbeard Island and north half of Sapelo Island. Scale is approximately 1:80,000. North is to top of photo.

Figure 12. Remote infrared image of Nanny Goat Beach and south half of Sapelo Island. Scale is approximately 1:80,000. North is to top of photo.

Figure 13. Remote infrared image of St. Simons Island "complex" of, from northeast to southwest, Little St. Simons, Sea, and St. Simons Islands. Scale is approximately 1:80,000. North is to top of photo.

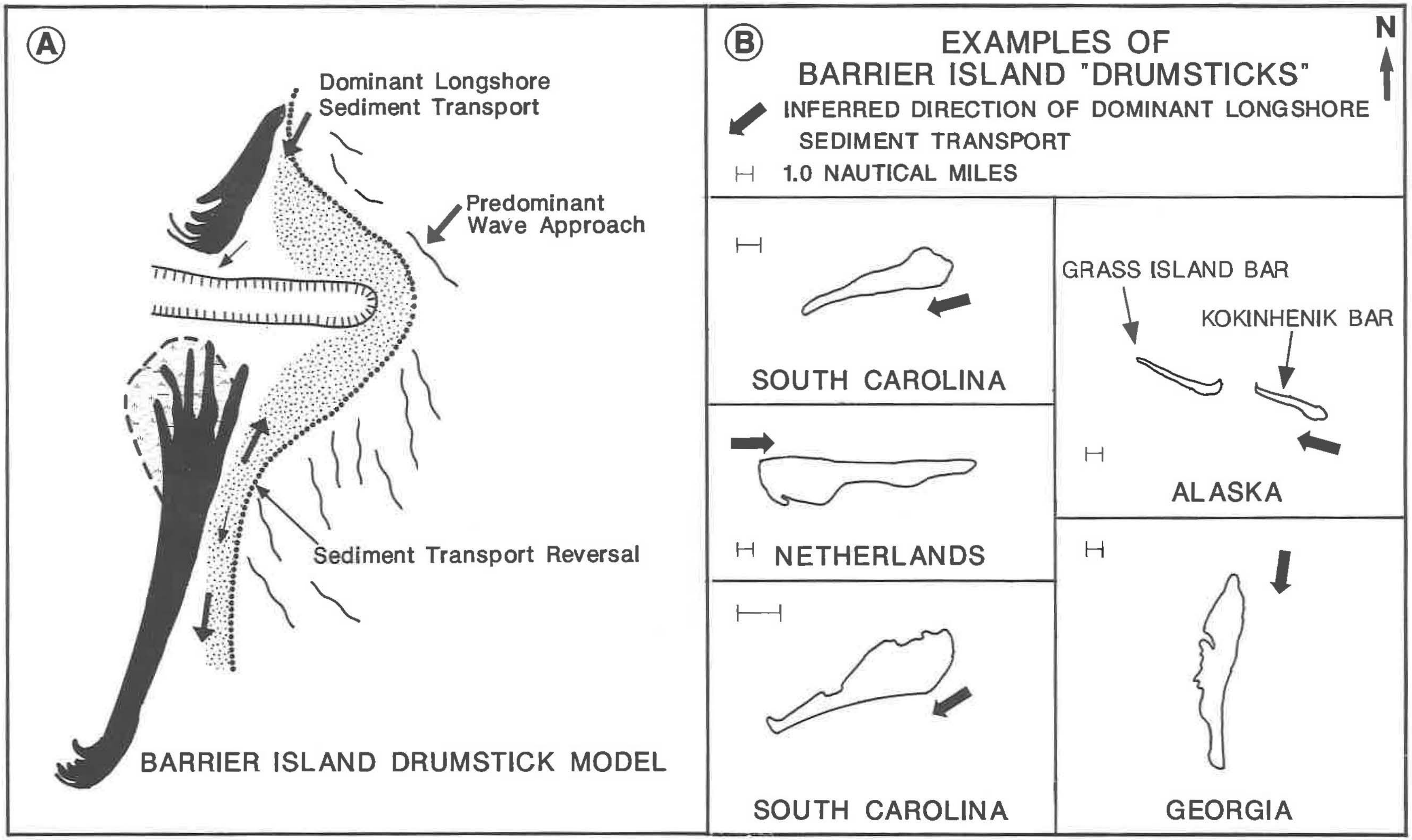

Figure 14. Barrier Island "drumstick" model.

area. Sample locations are shown in Plate 1. Environments sampled were: lower delta plain distributary channel, marginal delta plain, river mouth bars, and adjacent barrier islands. Additionally, adjacent Silver Bluff environments were sampled. The subenvironments sampled within the depositional environments were: channel margin beach, river mouth bars north and south of the Altamaha Sound, nearshore bar, foreshore, backshore, active frontal dune, washover fan, storm ridge and interior dune (Figure 15). In the field, the locations of the sample sites were determined by triangulation with navigational markers and various man-made structures, using a Brunton pocket compass and Rangematic(R) MK-5 distance finder. Constraints on the geographic distribution of sample sites included proximity to man-made structures such as rock groins and seawalls (which may alter hydrodynamics of mineralogy) and accessibility by land or boat. Sample sites were plotted on navigational maps and topographic maps.

Sample Collection

Two methods were used to collect heavy mineral-bearing sediment samples. A Ponar-design, one gallon capacity grab sampler was used to collect samples from channel bottoms and subtidal bars in the Altamaha River and adjacent channels and sounds. The second method was to collect samples in supratidal and intertidal (exposed at low tide) areas. Such subaerial exposures were sampled either from trenches or by hand auger. Samples were stored in 5.5" x 8" cloth bags and transported to the laboratory for analysis. A total of 209 samples were collected.

Laboratory Analysis

Separation Techniques

Samples were prepared for 202 of the 209 collected samples, using standard heavy liquid separation methods. The procedure involved wet sieving 200 grams of sediment from each sample with a 4 phi mesh, oven drying the greater than 4 phi fraction, and splitting each sample to obtain a 50 gram sample. The 4 phi lower size limit was chosen in accordance with the work of Poole (1958), Bates and Bates (1960), Hails and Hoyt (1972) and Friddell (1980). Folk (1980) discussed the relative grain sizes of heavy minerals and pointed out that they tend to occur at grain sizes averaging 0.5 to 1.0 phi less than the accompanying quartz grains. Current industry separation methods favor very fine sand as a minimum grain size limit for economic production. The 50 gram sample was placed in a 500 milliliter separatory funnel containing about 350 milliliters of acetylene tetrabromide (specific gravity 2.964), stirred, and allowed to settle for one hour. The heavy mineral grains which had settled out were drained into an open-end funnel lined with filter paper. The stirring and settling procedure was repeated four additional times with the modification that the three intermediate separations were allowed to settle for one-half hour each prior to draining. The final stirring and settling step was allowed a one hour settling time. The mineral grains collected on the filter paper were washed several times with acetone to remove residual heavy liquid and were air dried in a fume hood. After drying, the heavy mineral separates were weighed on a Mettler model PE-360 electric balance and stored in five milliliter glass vials. The weight percent was then calculated for each sample. The basic techniques utilized in the separation follow those in Krumbein and Pettijohn (1968), Carver (1971), Garner (1978), and Friddell (1980).

Petrographic Slide Preparation and Analysis

Heavy mineral grain mounts were prepared for 149 (74%) of the 202 samples separated. Seven of the 209 grab samples contained only clay and were not analyzed. Two of the 149 samples prepared were collected from surface concentrations of heavy minerals and were not included in the statictical averages.The 149 grain mounts included all samples containing 2% or more by weight, heavy mineral fraction (a total of 67 samples) and 55% of those samples containing less than 2% heavy mineral fraction (a total of 82). Slide preparation involved sieving out grains larger than 2 phi. Removal of grains larger than 2 phi achieved grain size infirmity and eliminated problems during slide mounting. Each sample was divided using a riffle-type microsplitter until approximately 2000 grains were obtained. These grains were mounted on a petrographic slide with petrographic epoxy (index of refraction = 1.54), capped with microscope coverglass, and allowed to dry. Individual grains were identified and counted using a petrographic microscope at 10X magnification. A minimum of 300 grains were identified and counted for each slide, following Dryden (1931).

Grain Size Analysis

Grain size analyses of eight samples, representative of the various subenvironments, were performed according to procedures outlined by Folk (1980), using one phi intervals. The purpose of this analysis was to examine the homogeneity of the grain size distributions.

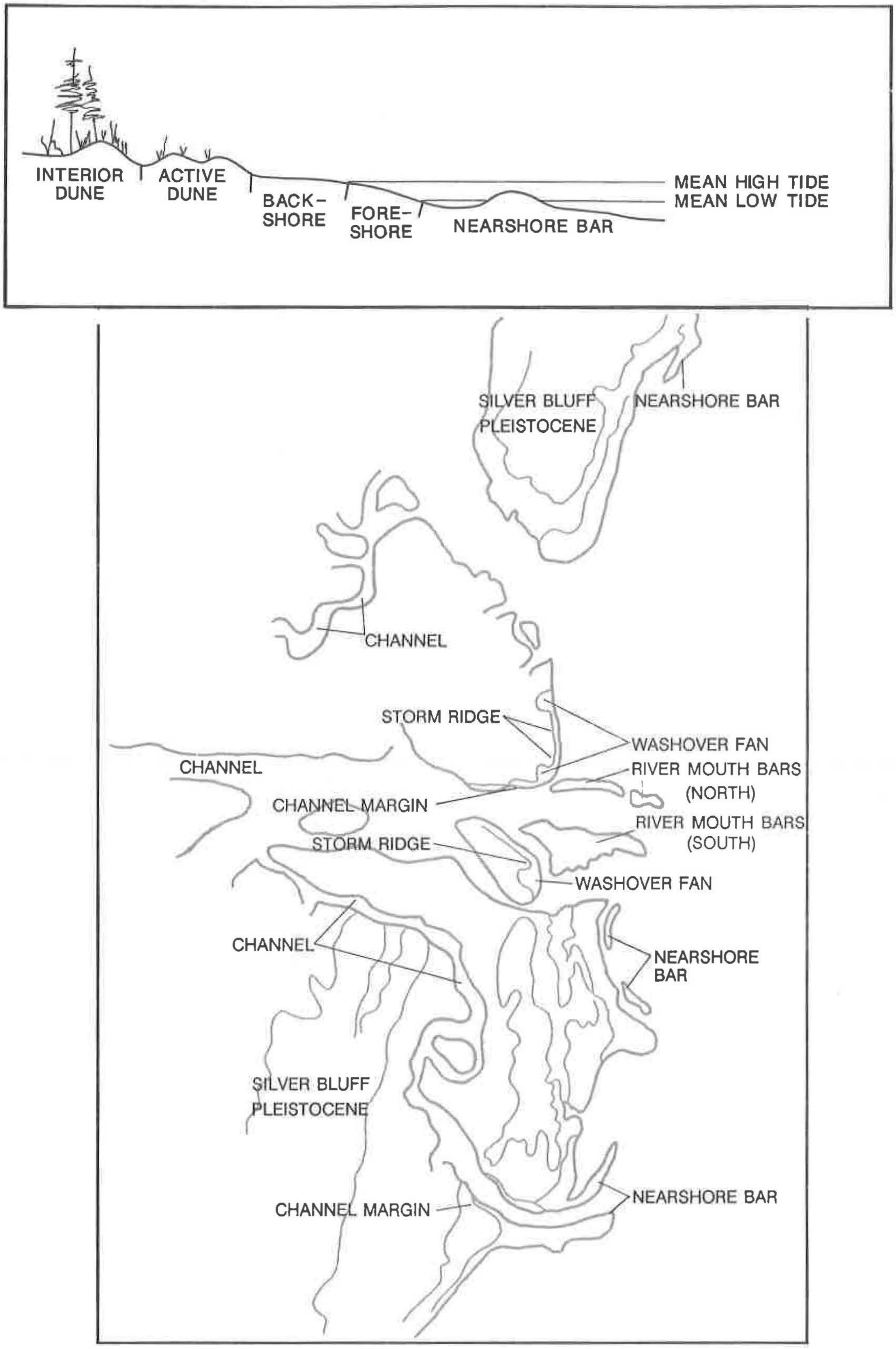

Figure 15. Schematic diagram depicting depositional subenvironments.

Interpretation of Data

Mineralogy

Discussions with regional representatives of the heavy mineral industry in the southeastern United States indicated that heavy mineral concentrations of 2.5 to 3.0% by weight are the minimum acceptable value for economically feasible development of the resource, taking into account the mineralogy generally found in the Georgia-Florida Coastal Plain placer deposits. For the purpose of the present study, 2.0% or more by weight, is defined as the baseline for "potential economic concentration." This more liberal cut-off point is used to assure that minor fluctuations in the depositional processes will not eliminate a particular environment or geographic location from consideration in developing the model. However, as previously mentioned, the purpose of this study is not to determine specific sites of concentration, but rather to examine the dynamic regimes which serve to concentrate heavy mineral sands within the study area.

Since heavy mineral sands in the Georgia-Florida area are mined principally for titanium-bearing minerals, minerals in the samples were divided for comparison into "economic", "non-economic," and "economic accessory" minerals. The "economic" category is defined for this study as containing the minerals ilmenite, leucoxene and rutile. Emphasis in the present study is on variations in the percentage of these economic minerals in the environments and subenvironments of the study area. Common "economic accessory" minerals which can influence the economic feasibility for production include: zircon, staurolite, monazite and garnet. The "non-economic" category includes epidote, kyanite-sillimanite and amphibole. Depending on the overall abundance of the heavy mineral fraction and the nature of the "economic accessories" present, the minimum percentage of "economic" minerals in the total fraction needs to be around 40% in order for an area to be considered for development.

Environments and Subenvironments of Deposition

The overall depositional regime of the study area is the result of the interaction of two complex hydrodynamic systems: 1) the Altamaha River, draining the Piedmont and Coastal Plain of Georgia, and 2) the barrier island-tidal inlet systems of the Georgia coast. The depositional regimes of these environments are divided into, those within the influence of the Altamaha River; and, those outside its influence (updrift of the longshore currents). Additionally, samples were taken from the Silver Bluff sand bodies. These are grouped separately for comparison with the recent sediments. The several depositional environments examined in the present study are listed in Table 1 and are depicted in Figure 6.

Within each of the environments of deposition, there is a series of subenvironments, each influenced by varying interactions of the current, wind and wave processes. These subenvironments are examined within each of the depositional environments and then compared across the entire study area. These subenvironments are defined in Table 2 and depicted schematically in Figure 15.

RESULTS

General Statement

Samples were analyzed for heavy mineral concentration, by weight, and for mineralogy of the heavy mineral fraction, by point count. For reference, the results for each sample, listed by depositional environment and sample number, are shown in the Appendix. The location of each sample is shown on Plate 1. In comparing percentage variations, for both heavy mineral concentrations and economic heavy mineral percentages, the arithmetic mean was computed for the categories being compared (environment, subenvironment within each environment, and subenvironments across the study area). Due to the relatively small sample populations in most of the categories analyzed, a more sophisticated statistical analysis was deemed inappropriate. Medians and standard deviations were computed to provide a qualitative analysis for the mean.

Grain Size Analysis

Samples generally representative of the depositional regimes within the study area were collected and subjected to a rudimentary analysis in order to determine whether or not significant variation occurs in the grain size distribution found in these regimes. It should be emphasized that this analysis is not intended to be an exhaustive study, but rather to provide a general sense of the grain size found in the study area.

The subenvironments represented include: channel sediments, active dune, foreshore, and Pleistocene relict dune. Table 3 depicts the results of the analysis. With the exception of the channel bottom samples, the very fine sand fraction predominates. The non-fluvial samples are moderately well-sorted, fine-skewed leptokurtic. In contrast, the channel samples are poorly-sorted, skewed to nearly sym-

TABLE 1.

Depositional Environment Terminology.

Constructive Delta Front -	Southern portion of the Altamaha marginal delta plain front. Nourished by longshore drift and river transported sediment. Characterized by large accreting sand bodies.
Destructive Delta Front -	Northern portion of the Altamaha marginal delta plain front. Dominated by erosion and transgression.
Barrier Island North -	Barrier island subenvironments in the study area which are up-drift and outside the Altamaha River sediment transport and deposition influence.
Pleistocene (North&South) -	Silver Bluff-age and earlier barrier islands.
River (Channel) -	Lower delta plain river bottoms of the Altamaha River and its distributaries.
River Mouth Bar -	Intertidal sand bodies located at the seaward margins of the Altamaha Sound inlet.
Barrier Island South -	Barrier island subenvironments located south of the Altamaha delta front; down-drift of the longshore current.

TABLE 2.

Depositional Subenvironment Terminology.

Active Dune -	Portion of the barrier island front immediately landward of the backshore. Consisting of dunes not yet stabilized by vegetation, and, therefore, still actively influenced by aeolian activity.
Backshore -	The portion of the beach which is supratidal.
Channel Margin -	Small scale, narrow sandy beaches or"levee-like" features deposited on the margins of the Altamaha River and its distributaries, primarily at inlet mouths.
Foreshore -	Portion of the barrier island landward of the active dunes. Comprises most of the island by area. Stabilized and modified by relatively permanent vegetation.
Nearshore Bar -	Generally longshore, intertidal bars isolated from the foreshore and submerged during rising and high tides.
River mouth Bar (North) -	Intertidal sand bodies located at the seaward, northern portion of the Altamaha Sound inlet; updrift of the longshore current.
River mouth Bar (South) -	Intertidal sand bodies located at the seaward, southern portion of the Altamaha Sound inlet; downdrift of the longshore current.
Storm Ridges -	Low sand ridge at the landward limit of the beach, marking the limit of waves during storms.
Washover Fans -	Deposits of sand washed over beach-front dunes or storm ridges during storms.

TABLE 3.

Grain Size Analyses.

Environment	Grain Size Fraction Percentages: medium silt	coarse silt	very fine sand	fine sand	medium sand	coarse sand or greater
Channel bottom						
Scour Hole	11	0	0	41	33	15
Mid Channel	24	0	0	64	10	2
Foreshore						
Downdrift of River	0	21	62	10	7	0
Further Downdrift	21	75	4	0	0	0
Active Dune						
Downdrift of River	0	12	67	21	0	0
Further Downdrift	0	14	72	14	0	0
Pleistocene						
Interior Remnant Dune	0	8	80	12	0	0
Remnant Dune Adjacent to Distributary Channel	0	20	74	6	0	0

metrical mesokurtic. The Pleistocene samples are somewhat better sorted than Recent-age samples.

Depositional Environments

The heavy mineral concentration and suite of a particular sample site is a function of that site's location relative to the sediment transport system. In the study area the sequence within the sediment transport system can be generally described as follows:

> The source river transports the sediment to the coastal area, the lower delta plain. Longshore currents become the primary agent of transport at the confluence of the river with the ocean. As the sediments are moved downcurrent into a variety of depositional environments, the interaction of currents, waves and wind affect the heavy mineral fraction of the sediment load.

Thus, the nature of the heavy mineral fraction in a depositional environment should be influenced by a particular sample site's position relative to source river and longshore current. For example, variation can be expected to occur between barrier island environments upcurrent and downcurrent from the Altamaha River.

The overall heavy mineral fraction in the main distributary channel is 0.44% (median = 0.34%, standard deviation = 0.37). The percentage increases to 1.74% (median = 1.55%, standard deviation = 0.88) in the river mouth bars, where tidal and longshore currents begin to interact with the river current to rework the sediment. South of the river on the constructive delta front of the marginal delta plain the heavy mineral concentration is 1.52% (median = 1.31%, standard deviation = 1.11)(Table 4). The constructive delta front is the site of a large amount of sediment deposition. An example of the massive shoal and spit development can be seen in Figure 8.

Heavy mineral sands are not concentrated in these aggradational sites. Further down the longshore current, where the principal effect of the hydrodynamic processes is erosional, lighter grains are moved down the transport system and heavy mineral concentration increases. In the barrier island environments south of the river, heavy mineral concentration averages 3.09% (median = 1.78%, standard deviation = 3.72). The relatively large standard deviation shows the variable nature of the depositional subenvironments within this environment. Immediately north of the Altamaha River the destructive delta front of the marginal delta plain, located at Wolf Island, has heavy mineral concentrations averaging 3.31% (median = 2.37%, standard deviation = 2.63). The destructive delta front is an area undergoing extensive erosion, as evidenced in Figure 7. This erosion has winnowed the sediment and continuously removes the lighter grains concentrating the heavy minerals.

In the barrier island environments north of the Altamaha River, sediments are not being derived from the Altamaha River system. They are, in effect, the southernmost products of the Savannah River sediment transport system, strongly influenced by inner shelf and nearshore processes. These sediments may serve as examples of an end product of a heavy mineral sand transport system, and provide a comparison for sediments derived from the Altamaha River. The overall heavy mineral sand concentration for these northern samples, collected on Sapelo Island, is 1.87% (median = 1.12%, standard deviation = 1.89). This overall percentage for the heavy mineral fraction is much lower than the average obtained for the barrier island heavy mineral fraction south of the Altamaha River (3.09%), immediately downdrift of the source river. It is also much lower than the average concentration (3.3%) of the sediments deposited and reworked on the destructive delta front on Wolf Island, directly across Sapelo Sound. Assuming that the Savannah River and the Altamaha River, both draining the Georgia Piedmont are carrying a similar suite of heavy minerals, the conclusion from this comparison is that heavy mineral sands are deposited in higher concentration closer to the river mouth.

None of the Altamaha River channel samples contained $\geq$2.0% heavy mineral sands. From the river mouth bars, 35.7% of the samples contained $\geq$2.0% heavy minerals (Table 5). Samples from the constructive delta front contained a smaller percentage of sample sites with potentially economic quantities of heavy minerals (28.4%). The barrier island environments south of the river averaged 45% of the sample sites with potentially economic quantities ($\geq$2.0%) of heavy minerals. This trend is similar to that seen in overall heavy mineral concentration.

In the samples from the adjacent destructive delta front 62.5% of the samples contained $\geq$2.0% heavy mineral sands. The barrier island environment north of the river (Sapelo Island) 28.5% of the samples contained $\geq$2.0% heavy minerals.

The percentage of economic heavy minerals, as defined in this study, shows a decrease in these constituents from 44.55% (median = 46.98%, standard deviation = 8.06) in the main distributary channel of the Altamaha River; 32.82% (median = 31.50%, standard deviation = 8.16) in the river mouth bars; 34.55% (median = 34.53%, standard deviation = 9.79) in the constructive delta front; and 36.35% (median = 35.92%,

TABLE 4.

Mean Percentage, by Weight, of Total Heavy Mineral Fraction by Depositional Environment.

Depositional Environment	Number of Samples	Total Heavy Mineral fraction (WT%) Mean%	Median%	Standard Deviation
Constructive Delta	74	1.52	1.31	1.11
Destructive Delta	16	3.31	2.37	2.63
Barrier Island North	21	1.87	1.12	1.89
Barrier Island South	40	3.09	1.78	3.72
Pleistocene North	7	1.34	1.17	0.68
Pleistocene South	8	3.14	2.59	1.85
River mouth Bars	14	1.74	1.55	0.88
Channel	20	0.44	0.34	0.37
TOTAL	200			

TABLE 5.

Relative Distribution of Heavy Mineral Percentage by Depositional Environment.

Depositional Environment	Total number of samples	Number of samples < 2% HM	Number of samples ≥ 2% HM
Constructive Delta	74	53	21
Destructive Delta	16	6	10
Barrier Island North	21	15	6
Barrier Island South	40	22	18
Pleistocene North	7	6	1
Pleistocene South	8	2	6
River mouth Bar	14	9	5
Channel	20	20	0
TOTAL	200	133	67

TABLE 6.

Mean Percentage of Economic Heavy Mineral Content of Heavy Mineral Fraction by Depositional Environment for Petrographically Analyzed Samples.

Depositional Environment	Number of Samples	Economic Heavy Mineral fraction(%grains) Mean%	Median%	Standard Deviation
Constructive Delta	49	34.55	34.53	9.79
Destructive Delta	15	43.61	39.81	10.55
Barrier Island North	10	44.64	45.55	3.72
Barrier Island South	35	36.35	35.92	9.83
Pleistocene North	5	54.60	55.68	4.59
Pleistocene South	8	42.65	46.34	9.54
River mouth Bars	8	32.82	31.50	8.16
Channel	19	44.55	46.98	8.06
TOTAL	149			

standard deviation = 9.83) in samples from the barrier island environment south of the Altamaha River (Table 6). It is apparent that while the trend is toward an increase in total heavy mineral concentration immediately down-drift from the river mouth, the relative proportion of the titanium-bearing minerals remains fairly low and fairly consistent.

Under the reworking conditions present in the destructive delta front, this percentage increases to an average of 43.61% (median = 39.81, standard deviation = 10.55). In this environment the relatively high concentration of the titanium-bearing minerals is perhaps a result of the maturity of the sediments deposited. The lighter fraction may have been removed from the environment by post-depositional, aeolian-influenced winnowing, or chemical weathering.

Economic Accessory Minerals

Zircon concentrations appear to follow the general trend established for the total heavy mineral fraction. The zircon fraction comprises 3.7% of the total heavy mineral fraction in the Altamaha River channel and the downdrift river mouth bars, decreasing to a mean of 3.01% in the constructive delta front. In the barrier island environment south of the Altamaha River the zircon mean increases to 3.86%. For zircon, as well as for the total heavy mineral fraction, a marked increase is seen in the mean concentration in the destructive delta front (mean = 4.92%). On Sapelo Island, zircon is about as abundant as in the downdrift component of the Altamaha sediment transport system, averaging 3.64%. Monazite concentrations follow a similar pattern to that of zircon, with percentage means ranging from 1.89% in the Altamaha channel, to about 2.04% in the southern, down-drift barrier island environment. The deviation from the pattern appears in the destructive delta where the concentration is slightly lower, 1.73% (mean), and in the updrift barrier island environment, where the monazite fraction averages 1.35% (mean)(Table 7). Again, it must be noted that the overall concentration of monazite in the samples was low enough that identification errors could strongly influence derived totals.

Staurolite concentrations appear to follow a pattern similar to the major non-economic minerals, epidote, amphibole and kyanite/sillimanite. This may be due to staurolite's relatively light specific gravity, and its generally bladed, tabular habit, relative to the titanium-bearing minerals. From an average abundance of 3.42% (mean) in the Altamaha River channel bottom samples, staurolite abundance increases to 4.8% in the constructive delta front samples, and to 4.9% in samples from the downdrift barrier island environment. The destructive delta front contains an average mean staurolite concentration of 4.93%. Economic accessory mineral concentrations are shown in Table 7.

Pleistocene (Silver Bluff) Environments

Samples were collected from Silver Bluff barrier islands in the study area, adjacent to the Recent environments. The nature of the heavy mineral fraction is of interest for comparison to the Recent sediments. Most of the Pleistocene samples were collected from environments correlative to the interior dune environment of the recent portion of the study area.

The heavy mineral fraction in the Pleistocene samples collected south of the Altamaha River averages 3.14% (median = 2.59%, standard deviation = 1.85). The samples north of the Altamaha River, and presumably from a transport system other than that of the paleo-Altamaha River, averaged only 1.34% (median = 1.17%, standard deviation = 0.68). The lower standard deviation suggests that the sediments from north of the Altamaha River are more uniform, possibly as a result of a greater degree of sorting, which occurs as the sediment moves further down the transport system. The economic mineral fraction for Pleistocene samples north of the Altamaha River averages 54.60% (median = 55.68, standard deviation = 4.59), while the average south of the river for Pleistocene samples is 42.65% (median = 46.34, standard deviation = 9.54). This variation, again, suggests a more mature sediment in the samples from the transport system north of the Altamaha River Delta. Of the Pleistocene barrier island samples collected to the north of the river, only 14.3% contained $\geq$2.0% heavy mineral fraction (Table 5). Of those from the Pleistocene south of the Altamaha River, 75.0% contained $\geq$2.0% heavy mineral fraction. This result is similar to that seen in the Recent environments; in that depositional environments, at the far downdrift end of the transport system, have significantly fewer heavy minerals overall than reworked sites closer to the source river.

Depositional Subenvironments within the Depositional Environments

General Statement

As noted, the Altamaha River Delta and surrounding area present a complex depositional scenario for heavy mineral sands, with the barrier island-tidal inlet system processes interacting with those of the Piedmont-draining river system. The heavy mineral concentration and composition can be expected to

TABLE 7

Summary of Petrographically Analyzed Samples by Depositional Environment.

Depositional Environment	Number of Samples	Economic Heavy Mineral%	Ilmenite	Leucoxene	(% of grains) Rutile	Zircon	Monazite	Staurolite
Constructive Delta	49	34.55	27.31	4.68	2.57	3.01	2.01	4.83
Destructive Delta	15	43.61	36.49	3.89	3.23	4.92	1.73	4.93
Barrier Island North	10	44.64	36.24	5.31	3.09	3.64	1.35	5.07
Barrier Island South	35	36.35	29.24	4.34	2.77	3.86	2.04	4.92
Pleistocene North	5	54.60	42.23	7.74	4.63	4.16	1.73	6.13
Pleistocene South	8	42.65	33.56	4.99	4.10	4.60	2.29	4.65
River mouth Bar	8	32.82	26.81	4.10	1.90	3.28	1.54	5.27
Channel	19	44.55	37.77	5.04	1.74	3.70	1.89	3.42
TOTAL	149							

vary across each environment in response to the relationship of the sediment transport system to the tidal currents, wave activity and wind activity.

Generally, for all subenvironments, heavy mineral concentration is markedly higher in channel margin samples, with a steady percentage decline in river mouth bars, nearshore bars, and in the foreshore. An increase is seen in the backshore, with the highest concentrations being in the active dune subenvironment. High percentages are seen in environments with higher energy transport processes and erosional activity, than in those environments where massive amounts of sediment deposition is occurring. Figure 16 depicts the average heavy mineral concentrations for each subenvironment within the depositional environments.

In any economic analysis of heavy mineral deposits, the overall heavy mineral concentration is less important than the percentage of the economic minerals. By examining each of the subenvironments within each of the environments for economic concentrations (≥2.0% total heavy mineral fraction) as well as concentration of the economic minerals, a clearer picture of the areas of interest emerge. These relationships are discussed in the following sections and shown in Figure 17 and Table 8.

Channel Margins

Channel margin samples were taken in the destructive delta front, constructive delta front, and in the southern down-current portions of the study area. The sediments in these locations were the result of deposition and reworking of river bottom sediments in the relatively high energy environments of the Altamaha River margins and in the margins of subsidiary distributaries. In the constructive delta front, 50% of the channel margin samples contained ≥2.0% heavy minerals (Appendix). Concentrations of economic heavy minerals were relatively low (mean = 35.45%). This relative "dilution" of heavy mineral content was probably an effect of the accretionary nature of the constructive delta front, where large amounts of sediment are deposited with little winnowing. In channel margin samples from the erosional regime of the destructive delta front, 60.0% of the samples contained a 2% or greater heavy mineral fraction, of which 48.55% represent economic heavy minerals. In channel margin samples from Sea Island, in the southern portion of the study area, 75.0% of the samples contained a 2% or greater heavy mineral fraction, of which 39.70% were economic heavy minerals.

River Mouth Bars, Nearshore Bars, Foreshore

Rivermouth bar deposits generally contained non-economic heavy mineral concentrations. Heavy mineral concentrations exceeded 2.0% in 66% of samples collected from bars on the southern fringe of the Altamaha Sound (12.5% on bars on the northern fringe), but economic heavy minerals averaged from 29.96 (north) to 35.68% (south) of the total fraction (Appendix). Nearshore bar samples were taken from the constructive delta, Barrier Island North and Barrier Island South depositional environments. On the constructive delta 27.0% of the samples had ≥ 2.0% heavy mineral fraction with a mean economic mineral pecentage of 26.77. No nearshore bar samples taken from the Barrier Island North or South environments had ≥ 2.0% heavy mineral fraction. Foreshore samples were taken from the constructive delta, Barrier Island North and Barrier Island South environments. On the Constructive Delta only 1 sample had ≥ 2.0% heavy mineral fraction with a economic mineral content of 46.06%. The Barrier Island North environment had no Foreshore samples with ≥ 2.0% heavy mineral fraction while the Barrier Island South environment had 12.5% of the samples containing ≥ 2.0% heavy minerals (Appendix).

Backshore

The backshore subenvironment showed either low total heavy mineral percentages or low economic mineral percentages. Only 16.7% of the samples from the Barrier Island North environment contained ≥2.0% of heavy mineral fraction, with the titanium-bearing fraction being 38.37%. 66.7% of the backshore subenvironment samples on the destructive delta front had ≥2.0% heavy mineral fraction but the economic heavy mineral content averaged only 35.7%. Constructive delta front samples averaged ≥2.0% in only 20% of the samples collected. The economic mineral content comprised only 30.63% of the total heavy mineral fraction. In the Barrier Island South environment, 50% of the samples collected in the backshore subenvironment contained 2.0% heavy mineral concentration, but the economic mineral content was low, at 32.53% on the average (Appendix).

Apparently the high percentage of heavy minerals observed in the backshore, in the form of veneers and interlayers, is somewhat deceptive. In sampling a vertical column of backshore sands of up to two feet in depth, and homogenizing the sample prior to analysis, heavy mineral fractions were lower than expected.

TABLE 8.

Mean Percentage, by Weight, of Heavy Mineral Fraction by Depositional Subenvironment.

Subenvironment	Number of Samples	Mean Heavy Mineral%	Median Heavy Mineral%	Standard Deviation
Active Dune	42	2.95	2.04	3.03
Interior Dune	30	2.19	1.88	1.40
Backshore	21	1.92	0.72	2.86
Foreshore	22	1.16	1.13	0.75
Nearshore Bar	20	1.36	1.42	0.74
Storm Ridge	6	2.68	1.17	3.62
Washover Fan	6	2.31	1.73	1.69
River mouth Bar North	8	1.36	1.23	0.44
River mouth Bar South	6	2.27	2.15	0.98
Channel Margin	17	2.80	2.20	2.97

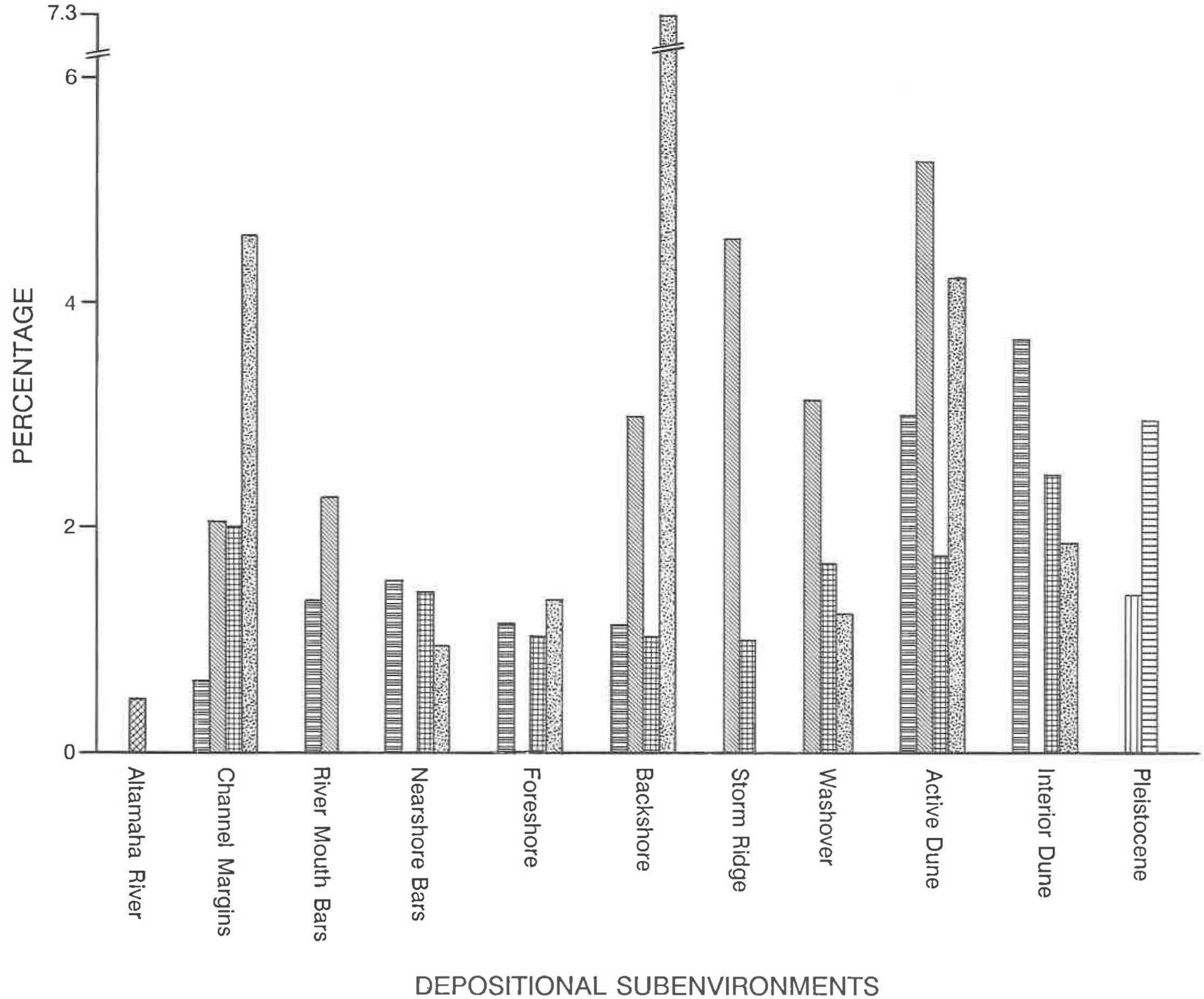

Figure 16. Mean percentage,by weight, of heavy mineral fraction by depositional subenvironment.

Sample from north of Altamaha River influence

Sample from the destructive delta front

Sample from the constructive delta front

Sample from south of the delta (downcurrent)

Sample from Altamaha River channel

Sample from Pleistocene barrier island north of the Altamaha River

Sample from Pleistocene barrier island south of the Altamaha River

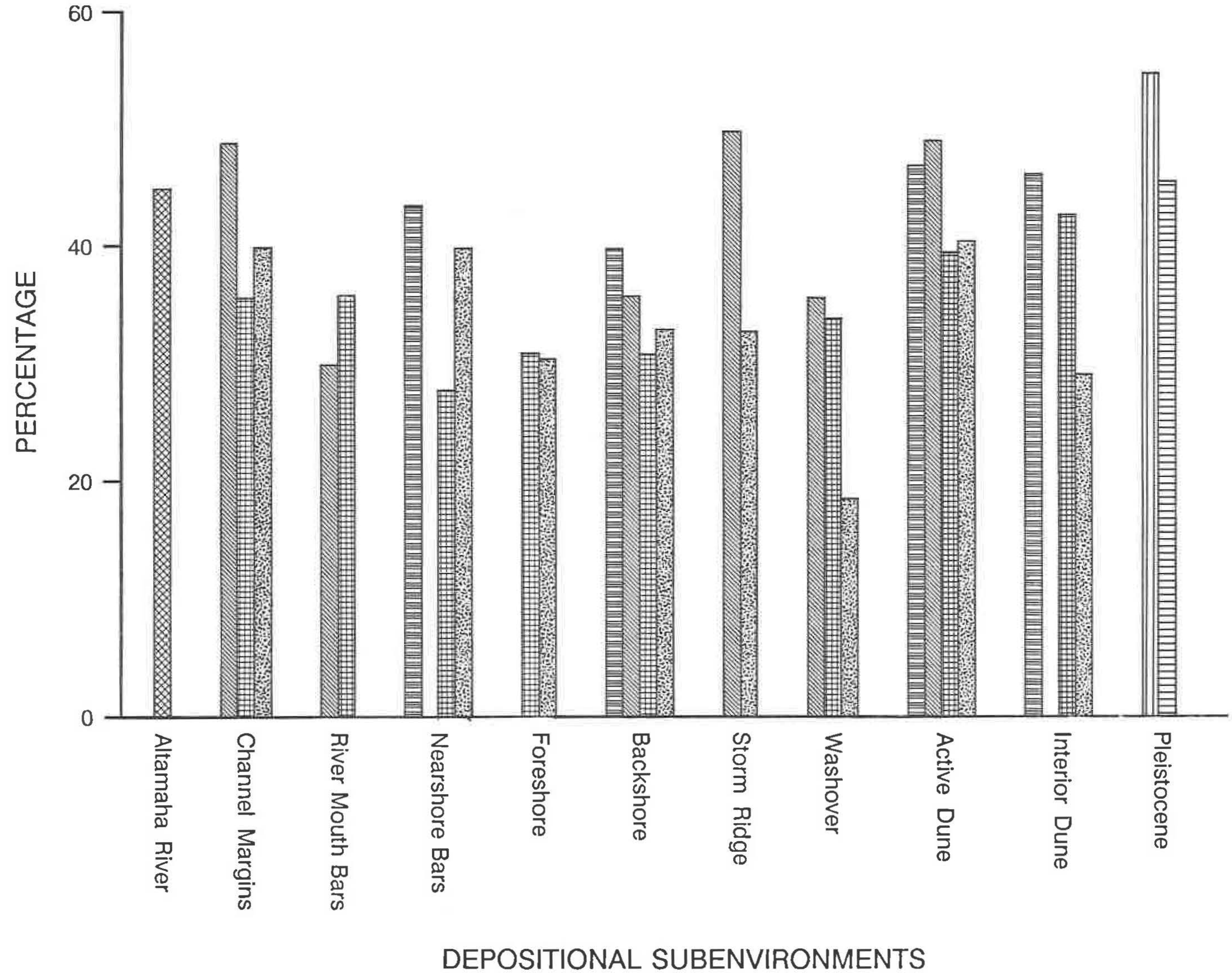

Figure 17. Mean percentage, by grains, of economic heavy mineral content by depositional subenvironment.

Sample from north of Altamaha River influence

Sample from the destructive delta front

Sample from the constructive delta front

Sample from south of the delta (downcurrent)

Sample from Altamaha River channel

Sample from Pleistocene barrier island north of the Altamaha River

Sample from Pleistocene barrier island south of the Altamaha River

Additionally, the economic fraction was lower than that which would permit a viable development, because of the high relative percentage of non-economic heavy minerals such as epidote and amphibole.

Storm Ridges and Washover Fans

At the interface of the backshore and active dune subenvironments, two small scale, ephemeral subenvironments were found. These are storm ridges and washover fans. In the study area, storm ridges were found on the smaller, low relief, erosional islands surrounding the Altamaha Sound inlet. These ridges were composed of sand and debris deposited over finer-grained sediments during storm activity. The mineralogy of the sediments in these storm ridges varied greatly across the study area. Ridges on Wolf Island, on the destructive delta front, contained a heavy mineral suite with an average of 49.31% economic heavy minerals. About 33% of these samples had a total heavy mineral fraction of ≥2.0%. On Egg Island, a part of the constructive delta front, economic heavy minerals averaged 32.45%, but none of the samples collected contained ≥2.0% heavy mineral fraction.

The washover fan samples, with 50.0% containing ≥2.0% heavy mineral concentrations, averaged economic heavy mineral percentage of 32.33%. Two-thirds of the washover samples in the destructive delta front contained ≥2.0% heavy mineral concentration. One-third of the samples from the constructive delta front averaged ≥2.0% heavy mineral fraction. The small number of samples collected from storm ridges and washovers made these statistics uncertain. A larger sample population would be necessary before higher statistical confidence could achieved.

Active Dunes

In the active dune subenvironment, the percentage of samples containing heavy mineral concentrations ≥2.0% was high for all depositional environments, with the exception of the constructive delta front, where 32% of the samples averaged ≥2.0% heavy mineral fraction. In the constructive delta front, the economic mineral content averaged 39.19% of the total heavy mineral fraction. In other dune subenvironments samples with ≥2.0% heavy mineral concentration ranged from 87 to 100% of the total collected. The economic mineral content ranged from 40.50 to 48.56% of the total heavy mineral fraction.

Interior Dunes of the Barrier Islands

Samples from the interior of the barrier islands were collected primarily from vegetation-stabilized or relict dunes. The subenvironments in many cases contained heavy mineral suites of ≥2.0% of the total sample. In the constructive delta front interior dune samples, 56% of the total contained ≥2.0%, the economic fraction comprised 42.69% of the total. In the Barrier Island South environment 29% of the samples contained ≥2.0 heavy mineral fraction, with an average economic mineral content of 36.01%.

Pleistocene (Silver Bluff) Barrier Islands

Interior dune samples from the Silver Bluff portion of Sapelo Island, north of the Altamaha River transport system, were generally non-economic, only 15% of the samples had ≥2.0% heavy mineral fraction. However the relative amounts of economic heavy minerals were high in these samples (54.60%). South of the Altamaha River, 80.0% of the interior dune samples from the Silver Bluff had ≥2.0% heavy mineral concentrations. Economic heavy mineral content accounted for 44.98% of the total heavy mineral fraction. The lower overall heavy mineral concentration in the northern Pleistocene samples probably reflects the relatively greater distance from the source of the heavy minerals. Relative to the southern Silver Bluff, the higher percentage of the titanium-bearing minerals in the northern Pleistocene samples was probably the result of the winnowing out of the lighter constituents. The overall high percentage of economic heavy minerals in the Silver Bluff reflected the greater extent of chemical weathering and removal of the less stable non-economic heavy minerals such as epidote and amphibole.

Overall Depositional Subenvironments

The comparison of heavy mineral concentration and mineralogy examined in the depositional subenvironments across the entire study area forms a generalized model for such sites, in effect averaging out any "source river" influence across the study area. The mean heavy mineral fraction in the sand of the Altamaha River (channel) was about 0.44% (median = 0.34, standard deviation = 0.37)(Table 4). The mean increased markedly on the channel margins, to 2.80% (median = 2.20, standard deviation = 2.15). Farther down the sediment transport system the percentage drops, river mouth bars south averaged 2.27% (median = 2.15, standard deviation = 0.98), nearshore bars averaged 1.36% (median = 1.42, standard deviation = 0.74), and the foreshore averaged 1.16% (median = 1.13, standard deviation = 0.75)(Table 8). As the sediment was moved back onshore through wave and tide activity, concentration of heavy mineral increased noticeably. The backshore averages 1.92% heavy minerals, although a large amount of variation was seen across the study area (median percentage = 0.72, standard deviation = 2.86). Storm ridges and washover fans, both of which were small scale and infrequently occurring features, had relatively high, heavy mineral concentrations of 2.68% and 2.31%, respectively (median = 1.17, standard deviation = 3.62 for storm ridges, median = 1.73, standard deviation = 1.69 for washover fans).

The higher average concentration occurred in the active dune subenvironment, 2.95%, with a fairly large variation across the study area (median = 2.04, standard deviation = 3.03). Concentration of heavy minerals declined somewhat in the interior dune subenvironment, to 2.19%, but showed less variation across the study area (median = 1.88%, standard deviation = 1.40). Table 8 summarizes these results.

In comparing the number of samples, from each subenvironment, in which the heavy mineral fraction was greater than or equal to the cut-off percentage (2.0%), a trend occurred similar to that shown by the means. No samples with potentially economic heavy mineral percentages occurred in the Altamaha River channel. In the channel margin subenvironment, 58.8% of the samples had heavy mineral concentrations of greater than or equal to 2.0%. The number of samples with at least 2.0% heavy minerals was lower in the river mouth bar north subenvironment (12.5%), in the nearshore bars (20.0%), and in the foreshore (13.6%). The number of samples with heavy mineral fractions of greater than or equal to 2.0% increased to 28.6% in the backshore; 47.6% in the active dune subenvironment; and decreased slightly to 46.7% of the samples collected in the interior dune subenvironment. The small number of total samples (six) in each of the washover fan and storm ridge subenvironments showed a great deal of variation; the percent of samples with at least 2.0% heavy minerals was 16.7% and 50% respectively. Table 9 summarizes these results.

The economic mineral content of the heavy mineral suite showed a trend similar to that of overall heavy mineral abundance, with some variation. The average percentage of economic heavy minerals is high in the channel margin subenvironment, 40.07% (median = 40.69% and standard deviation = 11.52) but the subenvironment, generally, was not laterally extensive in the study area. River mouth bars North and South of the Altamaha Sound contained 29.96% and 35.68% respectively, nearshore bars averaged 30.93% (median = 28.74% standard deviation = 8.35), foreshore samples averaged 30.48% (median = 29.85%, standard deviation = 8.35). An increase was seen in the backshore zone, with the economic fraction making up 33.69% (median = 35.07, standard deviation = 7.31) of the total heavy mineral suite. The economic mineral fraction averaged 41.00% (median = 39.81%, standard deviation = 11.2) in active dune subenvironments, which was at the low end of the acceptable range for economic development.

The samples from the interior dunefields contained economic heavy minerals comprising 43.90% (median = 45.82, standard deviation = 9.33) of the total fraction. Presumably, this relatively high percentage was due to differential transport out of this environment of the lighter, more tabular heavy minerals. The kyanite/sillimanite group and the amphiboles are examples of these lighter minerals which may be more easily transported by aeolian processes. Additionally, this enrichment may be enhanced to a degree by the early stages of differential chemical weathering of the less stable "light" heavy minerals, such as amphiboles and epidote. The summary of these results is shown in Table 10.

Economic Accessory and Non-economic Heavy Minerals in the Subenvironments

Several "non-economic" heavy minerals, in addition to the "economic" minerals, may be present in varying amounts in the suite commonly occurring in coastal Georgia sediments. Epidote, kyanite/sillimanite, and amphibole, of no real value to the heavy mineral industry, were present in significant amounts, averaging 24.04%, 11.72%, and 9.96%, respectively, across the study area. "Economic accessory" minerals occur in varying amounts and can enhance the value of the suite if present in quantities that make their separation economical. These economic accessory minerals include: zircon, staurolite, monazite and garnet. In general, these "economic accessories" follow the trend of the "economic" category of heavy minerals, in variation of concentration across the subenvironments of the study area, moving down the sediment transport system (Table 11). An increase in concentration was seen in the "economic accessory" minerals from the channel margin samples to the river mouth bar north and south samples. However, a decrease occurred in the river mouth bars south, the nearshore, and foreshore. An increase over foreshore percentages oc-

TABLE 9.

Relative Distribution of Heavy Mineral Percentage by Depositional Subenvironment.

Subenvironment	Total number of samples	Number of samples < 2%HM	Number of samples > 2%HM
Active Dune	42	22	20
Interior Dune	30	16	14
Backshore	21	15	6
Foreshore	22	19	3
Nearshore Bar	20	16	4
Storm Ridge	6	5	1
Washover Fan	6	3	3
River mouth Bar North	8	7	1
River mouth Bar South	6	2	4
Channel Margin	17	7	10

TABLE 10.

Mean Percentage of Economic Heavy Mineral Content in Heavy Mineral Fraction by Depositional Subenvironment for Petrographically Analyzed Samples.

Subenvironment	Number of samples	Mean Economic Mineral%	Median Economic Mineral%	Standard Deviation
Active Dune	33	41.00	39.81	9.57
Interior Dune	25	43.90	45.82	9.33
Backshore	12	33.69	35.07	7.31
Foreshore	13	30.48	29.85	8.35
Nearshore Bar	13	30.93	28.74	8.35
Storm Ridge	5	42.57	37.76	11.35
Washover Fan	6	32.33	31.92	8.72
River mouth Bar North	4	29.96	27.03	7.82
River mouth Bar South	4	35.68	36.16	6.24
Channel Margin	13	40.07	40.69	11.52

TABLE 11.

Summary of Petrographically Analyzed Samples by Depositional Subenvironment.

Sub-Environment	Number of Samples	Economic Heavy Mineral%	Ilmenite	Leucoxene	% grains Rutile	Zircon	Monazite	Staurolite
Active Dune	33	41.00	33.02	4.989	2.99	3.51	2.29	5.03
Interior Dune	26	43.90	34.68	5.30	3.81	4.05	1.92	4.85
Backshore	13	33.69	27.17	4.23	2.29	3.71	1.81	4.83
Foreshore	13	30.48	24.43	4.32	1.73	2.69	1.29	4.62
Nearshore Bar	13	30.93	23.04	5.35	2.54	2.88	1.51	4.75
Storm Ridge	5	42.57	36.21	3.40	2.96	5.81	2.07	5.55
Washover Fan	6	32.33	25.05	3.90	3.38	2.64	1.21	5.70
River mouth Bar North	4	29.96	24.67	3.44	1.85	2.86	1.49	6.60
River mouth Bar South	4	35.68	28.96	4.77	1.95	3.70	1.59	3.94
Channel Margin	13	40.07	33.59	3.42	3.06	4.73	2.38	4.89

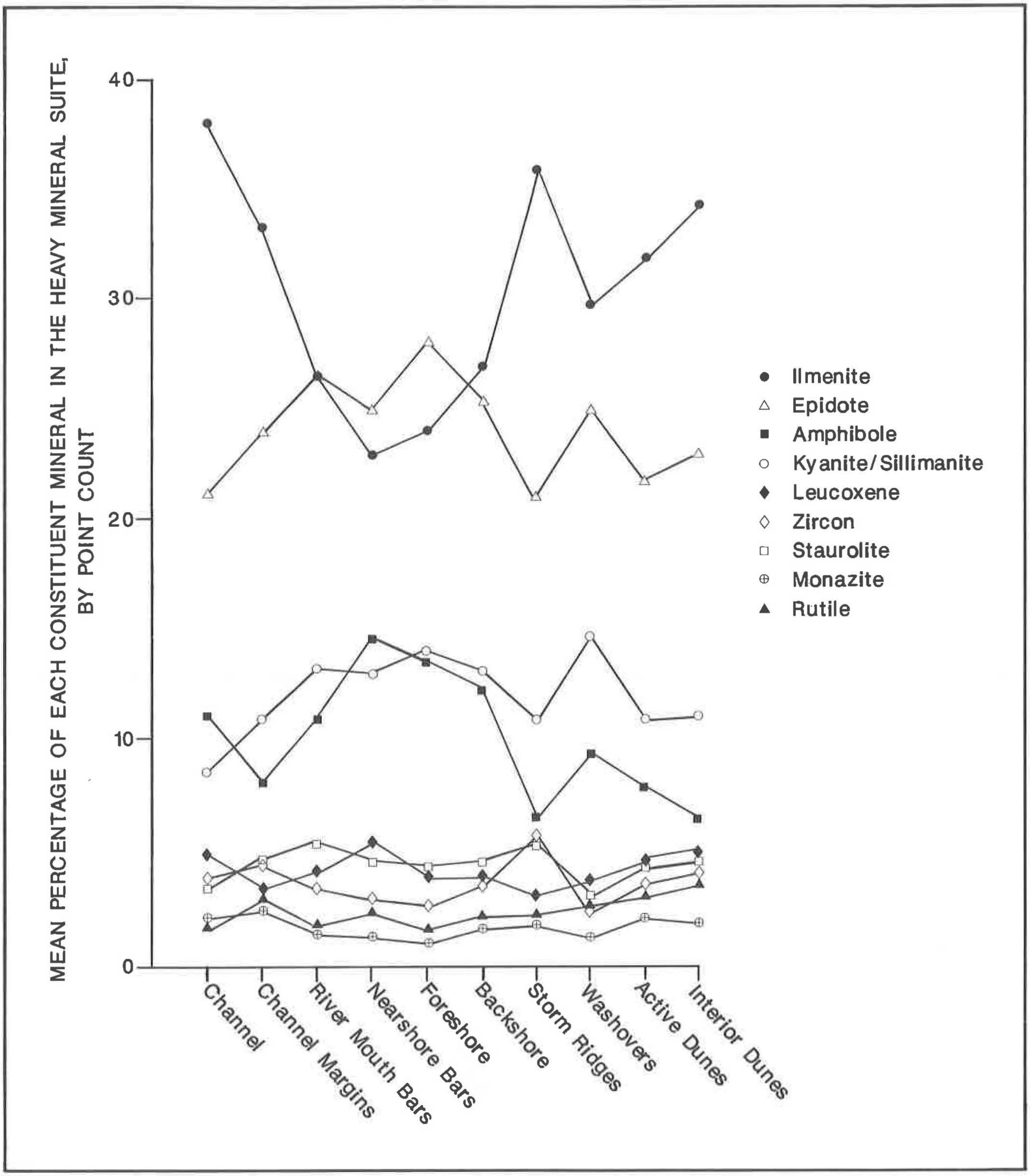

Figure 18. Mean percentage of heavy mineral constituents by depositional subenvironment.

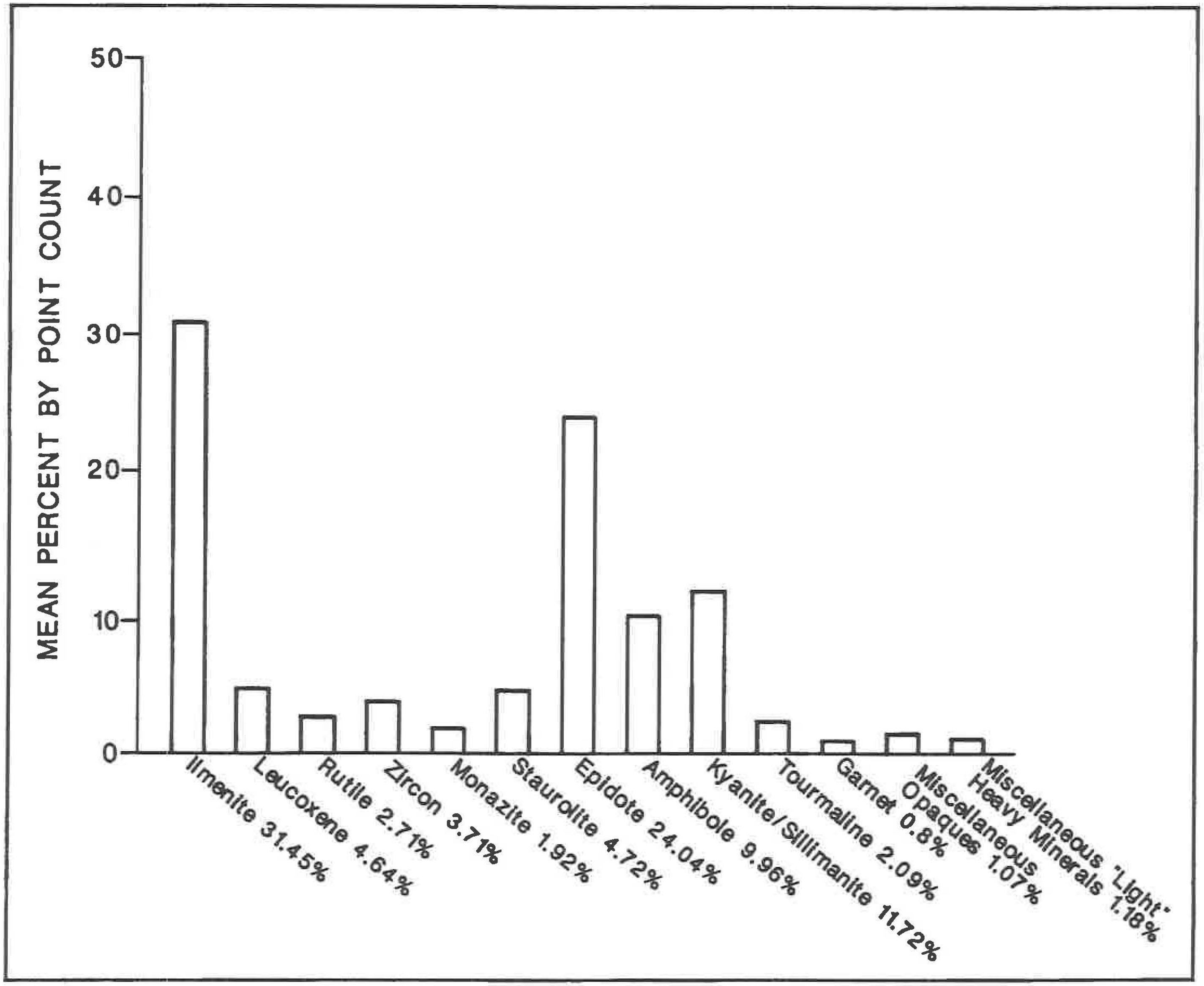

Figure 19. Overall heavy mineral suite constituents for the study area.

curred in the backshore, continuing in the active dunes and in the samples from the interior dunes. Percentages were relatively high in the storm ridges and washover fans. Throughout the subenvironments, the "economic accessory" mineral averages were as follows: zircon, ranged from about 2.6% in the foreshore and washovers, to about 5.8% in the storm ridges, to about 4.1% in the interior dune samples. Staurolite ranged from about 5.7% in the washover fans and 4.6% in the foreshore, to about 6.6% in the river mouth bars north and 4.9% in the interior dunes. Monazite, ranged from about 1.5% to slightly more than 2.3% across the sediment transport system. It should be noted that monazite is on occasion somewhat difficult to distinguish in petrographic microscope analyses from thicker epidote grains. As a result, monazite percentages may be somewhat lower than cited. Garnet was not abundant in the study area, averaging about 0.8%. Figure 17 details accessory mineral percentages in depositional environments.

CONCLUSIONS

Based on the findings of this study, some general statements can be made concerning heavy mineral distributions in the modern depositional systems typical of the Georgia coast. First, the overall heavy mineral concentration throughout the study area was 1.98% (median = 1.41%, standard deviation = 2.27). The titanium-bearing fraction (economic fraction, as defined in this study) throughout the study area was 38.78% (median = 39.20, standard deviation = 10.56). As the standard deviations show, variation was great in many environments and subenvironments. Concentrations of specific minerals, across the study area, as determined from point counts of grain-mounted slides, is shown in Figure 18.

In terms of total heavy mineral concentration, this study has shown that the initial concentrations in the source river were low, and required a higher energy environment to begin concentration of the heavy minerals by winnowing out lighter materials. But comparison with suites from the downdrift termination of the Savannah River sediment transport system supports the hypothesis that concentrations of the heavy minerals decrease as distance from the source river increases.

The degree of sediment reworking and winnowing has an effect on heavy mineral concentrations. The active dune subenvironments, being a product of the progressive reworking by wave action, longshore currents, tidal currents, and aeolian processes showed the highest overall degree of enrichment in heavy minerals of economic interest. Concentrations of heavy minerals also increased in the erosional/transgressive subenvironments, such as on the destructive delta front and erosional portions of the barrier islands.

Smaller scale features which contained significant concentrations of heavy minerals of economic interest include channel margin deposits, and, in some cases, storm ridges and washover fans. In situations where these features are of a larger scale, economic quantities of heavy minerals may be a possibility. Interior, stabilized or relict dunes are potential sites of concentration, but become less so with increasing distance from the source river. Of all the subenvironments sampled, the nearshore and foreshore subenvironments were generally the least prospective for heavy mineral concentration. This was especially true in the constructive delta front and in areas with similarly high rates of sedimentation where relatively little winnowing occurs.

The samples collected in the Pleistocene Silver Bluff barrier islands tend to support the overall findings of this study. Heavy mineral concentrations were higher in the environments adjacent to the source river than in the areas presumed to be the terminus of the sediment transport system. In addition, chemical weathering processes appear to have concentrated the more stable, titanium-bearing minerals at the expense of the less stable minerals such as epidote, amphibole, and kyanite/sillimanite.

Of the "economic accessory" minerals of economic interest, zircon appeared to follow the general trend of the titanium-bearing minerals, increasing to some extent in the higher energy regimes. Monazite followed this trend, but to a lesser degree and with some variations, possibly as a result of a higher susceptibility to weathering. Staurolite generally followed the trend of the lighter, less stable major constituents, decreasing in concentration in the higher energy environments.

In summary, dune paleo-environments within the paleo-barrier islands, immediately downdrift from the Altamaha, Ogeechee, and Savannah River systems, represent the most favorable exploration targets for heavy mineral sand deposits.

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APPENDIX

APPENDIX

Heavy Mineral Percentages by Depositional Subenvironments

Depositional Environment	Sub Environment	Sample No.	Heavy Mineral Wt %	Total Economic Mineral %	Economic Minerals (% grains)			Economic Accessory Minerals (% grains)		
					Ilmenite	Leucoxene	Rutile	Zircon	Monazite	Staurolite
Constructive Delta	Active Dune	5-3	3.79	48.54	43.57	3.22	1.75	4.97	4.39	4.68
Constructive Delta	Active Dune	6-3	0.33	32.48	25.65	6.17	0.66	1.29	2.59	6.49
Constructive Delta	Active Dune	6-4	0.43	32.16	21.02	9.55	1.59	2.55	4.78	5.41
Constructive Delta	Active Dune	6-7	1.35	39.32	31.89	5.26	2.17	2.17	1.24	4.95
Constructive Delta	Active Dune	6-8	0.39	27.63	19.38	5.08	3.17	3.49	5.71	5.39
Constructive Delta	Active Dune	6-9	4.02	56.59	48.55	3.22	4.82	5.79	2.25	3.54
Constructive Delta	Active Dune	6-18	0.33	38.12	32.93	3.67	1.52	1.83	1.22	3.96
Constructive Delta	Active Dune	6-19	2.50	34.53	26.79	3.87	3.87	2.38	2.38	5.06
Constructive Delta	Active Dune	6-20	1.96	36.83	29.30	4.84	2.69	3.23	1.34	5.37
Constructive Delta	Active Dune	6-22	3.41	36.94	28.98	3.98	3.98	1.99	0.28	5.11
Constructive Delta	Active Dune	6-38	1.55	26.02	15.05	8.78	2.19	1.25	0.63	5.34
Constructive Delta	Active Dune	31-2	3.20	40.12	31.92	4.86	3.34	3.95	2.13	5.47
Constructive Delta	Active Dune	31-9	1.58	42.90	30.35	10.21	2.34	1.28	2.87	2.56
Constructive Delta	Active Dune	32-14	3.19	56.50	48.16	4.64	3.70	5.57	2.17	1.54
Constructive Delta	Active Dune	6-21*	0.94							
Constructive Delta	Active Dune	6-30*	1.63							
Constructive Delta	Active Dune	6-32*	0.73							
Constructive Delta	Active Dune	6-35*	0.58							
Constructive Delta	Active Dune	31-1*	0.90							
Average			1.73	39.19	30.97	5.53	2.70	2.98	2.43	4.63
Constructive Delta	Interior Dune	32-1A	2.74	39.82	31.61	4.56	3.65	3.35	1.21	5.47
Constructive Delta	Interior Dune	32-1B	4.22	57.54	48.50	3.31	5.73	5.42	3.32	3.61
Constructive Delta	Interior Dune	32-2	5.24	50.92	41.16	5.49	4.27	6.40	2.74	4.27
Constructive Delta	Interior Dune	32-4	2.76	43.07	36.31	4.00	2.76	4.61	2.15	3.08
Constructive Delta	Interior Dune	32-6	1.87	33.74	25.46	5.83	2.45	0.61	0.31	4.91
Constructive Delta	Interior Dune	32-7	2.18	31.02	22.03	6.67	2.32	1.45	1.16	4.35
Constructive Delta	Interior Dune	31-8*	0.58							
Constructive Delta	Interior Dune	32-3*	1.23							
Constructive Delta	Interior Dune	32-5*	0.99							
Average			2.42	42.69	34.18	4.98	3.53	3.64	1.82	4.28

APPENDIX (cont.)

Heavy Mineral Percentages by Depositional Subenvironments

Depositional Environment	Sub Environment	Sample No.	Heavy Mineral % Wt%	Total Economic Mineral %	Economic Minerals Ilmenite	Leucoxene (% grains)	Rutile	Economic Accessory Minerals Zircon	Monazite (% grains)	Staurolite
Constructive Delta	Backshore	6-2	0.96	35.31	28.71	3.96	2.64	2.97	2.31	4.95
Constructive Delta	Backshore	6-10	1.67	31.68	25.16	4.35	2.17	2.48	2.48	5.59
Constructive Delta	Backshore	6-31	2.46	34.83	26.79	5.66	2.38	3.27	2.38	4.46
Constructive Delta	Backshore	31-3	0.29	21.93	17.25	3.51	1.17	0.87	0.29	2.92
Constructive Delta	Backshore	32-8	2.21	29.41	24.41	2.94	2.06	3.23	2.06	7.35
Constructive Delta	Backshore	6-24*	0.68							
Constructive Delta	Backshore	6-34*	0.30							
Constructive Delta	Backshore	6-37*	0.39							
Constructive Delta	Backshore	31-7*	0.60							
Constructive Delta	Backshore	32-13*	0.66							
Average			1.02	30.63	24.46	4.08	2.08	2.56	1.90	5.05
Constructive Delta	Foreshore	6-1	1.41	37.65	30.86	4.94	1.85	4.32	3.40	5.86
Constructive Delta	Foreshore	6-5	0.77	18.97	15.96	2.41	0.60	2.41	3.01	5.12
Constructive Delta	Foreshore	31-5	0.20	19.45	15.81	3.34	0.30	1.22	0.00	3.65
Constructive Delta	Foreshore	31-6	0.78	39.69	33.33	3.94	2.42	2.73	0.91	1.52
Constructive Delta	Foreshore	32-9	2.98	46.06	36.67	5.45	3.94	3.94	0.61	4.24
Constructive Delta	Foreshore	32-11	1.61	23.26	18.02	3.49	1.75	1.45	1.16	6.11
Constructive Delta	Foreshore	6-25A*	0.38							
Constructive Delta	Foreshore	6-25B*	1.42							
Constructive Delta	Foreshore	6-26*	1.33							
Constructive Delta	Foreshore	6-36*	0.20							
Constructive Delta	Foreshore	31-4*	0.30							
Constructive Delta	Foreshore	32-12*	0.93							
Average			1.03	30.85	25.11	3.93	1.81	2.68	1.52	4.42

APPENDIX (cont.)

Heavy Mineral Percentages by Depositional Subenvironments

Depositional Environment	Sub Environment	Sample No.	Heavy Mineral % Wt%	Total Economic Mineral %	Economic Minerals			Economic Accessory Minerals		
					Ilmenite	Leucoxene (% grains)	Rutile	Zircon	Monazite (% grains)	Staurolite
Constructive Delta	Nearshore Bar	6-11	1.29	27.87	24.15	2.17	1.55	1.55	0.62	6.19
Constructive Delta	Nearshore Bar	6-13	0.13	25.73	19.94	4.83	0.96	2.25	2.57	2.89
Constructive Delta	Nearshore Bar	6-14	0.83	32.23	21.69	6.02	4.52	3.92	1.81	3.92
Constructive Delta	Nearshore Bar	6-15	2.63	36.69	30.58	3.36	2.75	2.75	2.14	4.59
Constructive Delta	Nearshore Bar	6-16	1.86	25.72	17.88	7.21	0.63	1.57	1.25	6.58
Constructive Delta	Nearshore Bar	6-17	2.09	31.12	22.36	6.04	2.72	3.93	3.02	9.06
Constructive Delta	Nearshore Bar	6-28	1.92	28.16	18.68	6.89	2.59	2.29	0.86	4.59
Constructive Delta	Nearshore Bar	6-33	2.66	28.04	20.73	5.18	2.13	2.74	1.52	5.19
Constructive Delta	Nearshore Bar	28-1	2.33	11.22	3.16	3.40	4.66	5.28	2.48	3.12
Constructive Delta	Nearshore Bar	28-2	1.54	28.74	22.58	4.11	2.05	1.17	0.59	3.52
Constructive Delta	Nearshore Bar	6-23*	1.41							
Constructive Delta	Nearshore Bar	6-27*	0.83							
Constructive Delta	Nearshore Bar	28-3*	0.18							
Constructive Delta	Nearshore Bar	28-4*	0.52							
Constructive Delta	Nearshore Bar	32-10*	1.26							
Average			1.43	27.55	20.18	4.92	2.46	2.75	1.69	4.97
Constructive Delta	Storm Ridge	26-1	1.15	36.42	29.19	4.62	2.61	4.33	0.58	8.67
Constructive Delta	Storm Ridge	26-2	0.75	28.48	22.42	3.03	3.03	2.42	2.73	5.76
Constructive Delta	Storm Ridge	26-4*	0.42							
Average			0.77	32.45	25.81	3.83	2.82	3.38	1.66	7.22
Constructive Delta	Washover Fan	6-29	2.25	31.78	22.25	4.91	4.62	2.31	1.16	8.67
Constructive Delta	Washover Fan	26-3	1.05	35.94	29.28	3.19	3.47	1.74	1.16	5.51
Average			1.65	33.86	25.77	4.05	4.05	2.03	1.16	7.09

APPENDIX (cont.)

Heavy Mineral Percentages by Depositional Subenvironments

Depositional Environment	Sub Environment	Sample No.	Heavy Mineral % Wt%	Total Economic Mineral %	Economic Minerals			Economic Accessory Minerals		
					Ilmenite	Leucoxene (% grains)	Rutile	Zircon	Monazite (% grains)	Staurolite
Constructive Delta	Channel Margin	5-1	2.20	36.90	30.28	4.10	2.52	3.15	1.58	3.79
Constructive Delta	Channel Margin	5-4A	3.56	46.98	41.27	3.69	2.02	8.72	7.72	2.01
Constructive Delta	Channel Margin	5-4B	1.38	39.66	33.71	4.25	1.70	2.55	2.83	4.82
Constructive Delta	Channel Margin	6-6	1.00	18.27	16.41	0.93	0.93	2.48	0.31	5.26
Constructive Delta	Channel Margin	5-2**	13.63	55.06	49.05	3.48	2.53	6.33	3.80	2.53
Average			2.04	35.45	30.42	3.24	1.79	4.23	3.11	3.97
Destructive Delta	Active Dune	21-3A	2.98	39.81	31.85	3.50	4.46	5.40	0.00	6.05
Destructive Delta	Active Dune	21-3B	7.54	57.30	50.14	3.72	3.44	4.30	1.72	4.58
Destructive Delta	Active Dune	25-2**	20.60	54.63	48.46	2.47	3.70	9.26	4.01	5.86
Average			5.26	48.56	41.00	3.61	3.95	4.85	0.86	5.32
Destructive Delta	Backshore	21-1	5.21	31.94	23.96	5.32	2.66	1.48	0.89	5.62
Destructive Delta	Backshore	25-1	1.71	36.15	28.81	3.39	3.95	3.95	1.98	4.81
Destructive Delta	Backshore	25-4A	2.06	38.98	32.77	4.52	1.69	7.91	2.54	4.52
Average			2.99	35.69	28.51	4.41	2.77	4.45	1.80	4.98
Destructive Delta	Storm Ridge	21-6	1.19	49.11	43.75	4.17	1.19	7.44	2.08	4.46
Destructive Delta	Storm Ridge	21-7	1.87	37.76	29.91	3.02	4.83	2.72	0.61	5.43
Destructive Delta	Storm Ridge	25-5A	10.72	61.06	55.76	2.18	3.12	12.15	4.35	3.43
Average			4.59	49.31	43.14	3.12	3.05	7.44	2.35	4.44
Destructive Delta	Washover Fan	21-5	5.88	47.52	39.13	4.04	4.35	5.60	1.55	3.42
Destructive Delta	Washover Fan	21-8	2.37	32.06	23.53	4.71	3.82	1.77	0.88	4.11
Destructive Delta	Washover Fan	25-4B	1.09	28.31	21.54	4.31	2.46	0.92	0.92	6.46
Average			3.11	35.96	28.07	4.35	3.54	2.76	1.12	4.66

APPENDIX (cont.)

Heavy Mineral Percentages by Depositional Subenvironments

Depositional Environment	Sub Environment	Sample No.	Heavy Mineral % Wt%	Total Economic Mineral %	Economic Minerals			Economic Accessory Minerals		
					Ilmenite	Leucoxene (% grains)	Rutile	Zircon	Monazite (% grains)	Staurolite
Destructive Delta	Channel Margin	21-2	1.72	48.43	38.11	8.31	2.01	3.44	1.15	5.73
Destructive Delta	Channel Margin	21-4	2.99	38.94	31.78	2.80	4.36	3.74	0.93	5.30
Destructive Delta	Channel Margin	23-2	2.36	64.96	58.52	1.93	4.51	4.83	2.57	3.85
Destructive Delta	Channel Margin	25-5B	2.52	41.87	37.81	2.50	1.56	8.13	3.75	6.25
Destructive Delta	Channel Margin	25-3*	0.75							
Average			2.07	48.55	41.56	3.89	3.11	5.04	2.10	5.28
Barrier Island North	Active Dune	51-1	8.08	50.43	41.21	4.32	4.90	3.75	0.58	6.34
Barrier Island North	Active Dune	51-3B	3.52	41.77	35.00	5.23	1.54	3.70	0.63	4.92
Barrier Island North	Active Dune	51-7	4.04	48.00	39.69	5.23	3.08	4.31	2.78	5.53
Barrier Island North	Active Dune	51-12*	0.74							
Barrier Island North	Active Dune	51-18C*	0.82							
Barrier Island North	Active Dune	51-19C*	0.53							
Average			2.96	46.73	38.63	4.93	3.17	3.92	1.33	5.60
Barrier Island North	Interior Dune	51-13	2.16	45.82	39.32	4.02	2.48	3.72	2.17	6.19
Barrier Island North	Interior Dune	51-20	5.10	45.62	36.62	5.35	3.65	4.79	1.41	5.35
Average			3.63	45.72	37.97	4.69	3.07	4.26	1.79	5.77
Barrier Island North	Backshore	51-3A	1.84	40.62	33.44	5.31	1.87	2.19	0.62	4.69
Barrier Island North	Backshore	51-19B	2.80	38.37	29.07	5.81	3.49	2.62	1.75	5.23
Barrier Island North	Backshore	51-2*	0.72							
Barrier Island North	Backshore	51-6*	0.67							
Barrier Island North	Backshore	51-11*	0.24							
Barrier Island North	Backshore	51-18B*	0.57							
Average			1.14	39.50	31.26	5.56	2.68	2.41	1.19	4.96

APPENDIX (cont.)

Heavy Mineral Percentages by Depositional Subenvironments

Depositional Environment	Sub Environment	Sample No.	Heavy Mineral % Wt%	Total Economic Mineral %	Economic Minerals (% grains)			Economic Accessory Minerals (% grains)		
					Ilmenite	Leucoxene	Rutile	Zircon	Monazite	Staurolite
Barrier Island North	Foreshore	51-3*	1.46							
Barrier Island North	Foreshore	51-10*	0.82							
Average			1.14							
Barrier Island North	Nearshore Bar	51-4	1.42	41.50	33.43	4.61	3.46	4.61	1.15	4.90
Barrier Island North	Nearshore Bar	51-5	1.60	45.48	33.33	9.35	2.80	3.74	0.00	2.19
Average			1.51	43.49	33.38	6.98	3.13	4.18	0.58	3.55
Barrier Island North	Channel Margin	51-18A*	0.26							
Barrier Island North	Channel Margin	51-19A*	1.12							
Average			0.69							
Barrier Island North	Channel	24-1	0.73	48.80	41.32	3.89	3.59	3.00	2.40	5.39
Average			0.73	48.80	41.32	3.89	3.59	3.00	2.40	5.39
Barrier Island South	Active Dune	19-1	4.52	51.27	43.63	4.82	2.82	4.82	2.27	4.82
Barrier Island South	Active Dune	19-2	14.96	45.19	35.26	7.37	2.56	3.85	5.13	2.56
Barrier Island South	Active Dune	19-2B	7.86	45.77	34.80	6.27	4.70	3.76	1.57	6.27
Barrier Island South	Active Dune	19-4	1.69	39.55	31.01	4.43	4.11	6.96	4.11	7.28
Barrier Island South	Active Dune	19-5	6.01	56.96	49.54	4.33	3.09	5.27	2.48	5.27
Barrier Island South	Active Dune	19-7	1.87	38.95	29.92	4.67	4.36	2.18	2.18	6.23
Barrier Island South	Active Dune	19-9	11.13	45.73	37.50	4.88	3.35	3.05	6.40	4.88
Barrier Island South	Active Dune	19-12	2.42	29.95	23.26	6.11	0.58	1.16	2.62	5.80
Barrier Island South	Actvie Dune	20-3A	2.31	21.39	14.76	5.12	1.51	1.21	0.60	5.12
Barrier Island South	Active Dune	20-4	2.11	51.32	42.52	4.11	4.69	8.21	2.35	5.57
Barrier Island South	Active Dune	20-5	3.06	33.84	27.06	4.42	2.36	1.77	0.88	5.29
Barrier Island South	Active Dune	20-8	1.20	25.86	21.07	1.97	2.82	3.09	1.40	3.93
Barrier Island South	Active Dune	20-9	1.19	33.52	28.11	2.55	2.86	4.14	2.33	5.42
Barrier Island South	Active Dune	28-8	2.47	47.63	39.69	4.13	3.81	3.17	1.59	5.39

APPENDIX (cont.)

Heavy Mineral Percentages by Depositional Subenvironments

Depositional Environment	Sub Environment	Sample No.	Heavy Mineral % Wt%	Total Economic Mineral %	Economic Minerals			Economic Accessory Minerals		
					Ilmenite	Leucoxene (% grains)	Rutile	Zircon	Monazite (% grains)	Staurolite
Barrier Island South	Active Dune	28-11*	0.22							
Average			4.20	40.50	32.72	4.66	3.12	3.76	2.57	5.27
Barrier Island South	Interior Dune	8-1B	1.57	41.34	31.84	5.87	3.63	5.31	1.68	4.47
Barrier Island South	Interior Dune	8-2	0.85	34.68	27.61	5.72	1.35	2.36	3.70	4.71
Barrier Island South	Interior Dune	8-4	0.91	35.92	27.51	3.88	4.53	5.18	2.59	7.12
Barrier Island South	Interior Dune	20-12	0.70	24.18	17.11	3.24	3.83	1.78	1.78	5.61
Barrier Island South	Interior Dune	20-13	1.19	29.12	22.22	5.10	1.80	3.00	0.60	1.51
Barrier Island South	Interior Dune	20-15	2.90	49.27	40.06	4.46	4.75	5.64	2.67	2.97
Barrier Island South	Interior Dune	20-16	4.72	37.53	30.77	3.69	3.07	4.63	1.85	4.60
Average			1.83	36.01	28.16	4.57	3.28	3.99	2.12	4.43
Barrier Island South	Foreshore	19-3	0.53	25.69	19.50	4.33	1.86	2.48	1.55	4.33
Barrier Island South	Foreshore	19-6	2.00	29.85	23.69	4.62	1.54	2.46	0.92	4.00
Barrier Island South	Foreshore	19-8	2.44	31.29	23.93	4.29	3.07	1.84	1.84	5.84
Barrier Island South	Foreshore	19-10	1.97	24.77	18.58	4.33	1.86	0.93	1.24	4.95
Barrier Island South	Foreshore	20-6	0.53	25.52	20.18	4.75	0.59	3.56	0.00	6.53
Barrier Island South	Foreshore	20-7	1.57	31.88	29.06	2.19	0.63	4.38	1.56	4.06
Barrier Island South	Foreshore	28-10	1.58	42.22	32.05	8.08	2.09	3.29	0.60	3.89
Barrier Island South	Foreshore	28-9*	0.27							
Average			1.36	30.17	23.86	4.66	1.66	2.71	1.10	4.80
Barrier Island South	Backshore	19-11	0.66	19.00	14.33	3.74	0.93	2.49	2.49	3.11
Barrier Island South	Backshore	20-10	13.61	46.06	41.33	2.21	2.52	11.04	1.89	4.73
Average			7.14	32.53	27.83	2.98	1.73	6.77	2.19	3.92

APPENDIX (cont.)

Heavy Mineral Percentages by Depositional Subenvironments

Depositional Environment	Sub Environment	Sample No.	Heavy Mineral % Wt%	Total Economic Mineral %	Economic Minerals (% grains)			Economic Accessory Minerals (% grains)		
					Ilmenite	Leucoxene	Rutile	Zircon	Monazite	Staurolite
Barrier Island South	Nearshore Bar	28-5	1.58	39.61	31.02	6.37	2.22	1.66	1.66	4.99
Barrier Island South	Nearshore Bar	28-6*	0.51							
Barrier Island South	Nearshore Bar	28-7*	0.63							
Average			0.91	39.61	31.02	6.37	2.22	1.66	1.66	4.99
Barrier Island South	Washover Fan	20-3B	1.21	18.35	14.56	2.21	1.58	3.48	1.58	6.01
Average			1.21	18.35	14.56	2.21	1.58	3.48	1.58	6.01
Barrier Island South	Channel Margin	20-1	2.38	33.06	27.69	2.26	3.11	2.54	1.41	4.24
Barrier Island South	Channel Margin	20-11	13.00	40.69	33.23	3.11	4.35	8.07	2.17	4.66
Barrier Island South	Channel Margin	20-14	2.55	45.34	39.13	2.17	4.04	6.30	1.86	5.90
Barrier Island South	Channel Margin	20-2*	0.53							
Average			4.62	39.70	33.35	2.51	3.83	5.64	1.81	4.93
Pleistocene North	Interior Dune	23-1	0.91	49.85	40.87	6.50	2.48	2.79	1.86	4.64
Pleistocene North	Interior Dune	51-8	1.16	56.97	45.40	6.53	5.04	5.34	0.59	8.61
Pleistocene North	Interior Dune	51-9	1.89	49.12	37.65	7.06	4.41	5.00	1.47	6.47
Pleistocene North	Interior Dune	51-14	2.61	55.68	40.23	9.62	5.83	4.37	2.33	4.66
Pleistocene North	Interior Dune	51-16	1.31	61.38	47.01	8.98	5.39	3.29	2.39	6.29
Pleistocene North	Interior Dune	51-15*	0.36							
Pleistocene North	Interior Dune	51-17*	1.17							
Average			1.34	54.60	42.23	7.74	4.63	4.16	1.73	6.13

APPENDIX (cont.)

Heavy Mineral Percentages by Depositional Subenvironments

Depositional Environment	Sub Environment	Sample No.	Heavy Mineral % Wt%	Total Economic Mineral %	Economic Minerals (% grains): Ilmenite	Leucoxene	Rutile	Economic Accessory Minerals (% grains): Zircon	Monazite	Staurolite
Pleistocene South	Interior Dune	4-2A	3.90	48.37	38.58	5.34	4.45	4.15	2.97	5.93
Pleistocene South	Interior Dune	4-3B	2.62	48.94	36.09	8.26	4.59	3.36	0.92	3.98
Pleistocene South	Interior Dune	4-4	4.29	46.69	36.91	6.31	3.47	3.78	1.89	2.84
Pleistocene South	Interior Dune	7-1	2.56	45.98	39.23	3.54	3.21	4.50	1.29	4.18
Pleistocene South	Interior Dune	7-2	1.09	34.94	26.81	2.11	6.02	6.32	3.01	5.42
Average			2.89	44.98	35.52	5.11	4.35	4.42	2.02	4.47
Pleistocene South	Channel Margin	4-2B	7.19	45.51	34.49	4.93	6.09	3.77	3.48	6.38
Pleistocene South	Channel Margin	4-3A	2.06	20.29	14.29	3.43	2.57	3.71	1.14	5.43
Average			4.63	32.90	24.39	4.18	4.33	3.74	2.31	5.91
Pleistocene South	Channel	7-3	1.41	50.45	42.04	6.01	2.40	7.21	3.60	3.00
Average			1.41	50.45	42.04	6.01	2.40	7.21	3.60	3.00
Rivermouth Bar	North	21-10A	1.16	29.86	25.51	2.90	1.45	2.03	1.74	8.12
Rivermouth Bar	North	21-10C	1.71	24.20	17.78	3.21	3.21	0.58	1.17	6.71
Rivermouth Bar	North	21-11A	1.87	42.74	37.90	3.02	1.82	5.45	1.21	6.67
Rivermouth Bar	North	21-11B	2.04	23.02	17.49	4.61	0.92	3.37	1.84	4.91
Rivermouth Bar	North	21-9A*	0.91							
Rivermouth Bar	North	21-9B*	1.30							
Rivermouth Bar	North	21-10B*	0.74							
Rivermouth Bar	North	21-11C*	1.14							
Average			1.36	29.96	24.67	3.44	1.85	2.86	1.49	6.60

APPENDIX (cont.)

Heavy Mineral Percentages by Depositional Subenvironments

Depositional Environment	Sub Environment	Sample No.	Heavy Mineral % Wt%	Total Economic Mineral %	Economic Minerals: Ilmenite	Economic Minerals: Leucoxene (% grains)	Economic Minerals: Rutile	Economic Accessory Minerals: Zircon	Economic Accessory Minerals: Monazite (% grains)	Economic Accessory Minerals: Staurolite
Rivermouth Bar	South	22-1B	3.74	43.46	37.50	4.17	1.79	5.06	2.37	3.27
Rivermouth Bar	South	22-1C	3.25	33.13	26.37	5.47	1.29	3.86	1.61	3.54
Rivermouth Bar	South	22-2A	2.12	39.18	30.70	5.56	2.92	5.26	0.88	2.05
Rivermouth Bar	South	22-2C	2.18	26.94	21.26	3.89	1.79	0.60	1.50	6.89
Rivermouth Bar	South	22-1A*	0.93							
Rivermouth Bar	South	22-2B*	1.39							
Average			2.27	35.68	28.96	4.77	1.95	3.70	1.59	3.94
Channel	-	1-1	0.34	58.52	46.44	9.29	2.79	5.26	3.10	3.10
Channel	-	2-1	0.33	53.99	45.14	5.71	3.14	6.86	2.57	2.00
Channel	-	3-2	0.48	40.68	32.61	7.76	0.31	4.04	2.48	3.11
Channel	-	3-3	0.10	42.11	33.08	6.77	2.26	1.13	1.51	2.63
Channel	-	3-4	0.22	42.42	37.88	2.65	1.89	3.03	1.89	3.79
Channel	-	3-5	0.20	54.68	50.52	2.08	2.08	3.81	3.81	3.81
Channel	-	3-6	0.90	50.80	45.05	3.19	2.56	8.31	7.03	3.83
Channel	-	3-7	0.03	32.47	21.40	8.49	2.58	1.48	1.11	2.95
Channel	-	3-8	0.13	47.69	42.76	3.29	1.64	2.96	1.64	0.99
Channel	-	3-9B	0.71	46.98	42.77	3.61	0.60	3.31	1.81	2.72
Channel	-	3-10	0.40	47.18	40.95	4.75	1.48	2.08	0.59	5.93
Channel	-	3-11	0.07	49.22	42.37	5.29	1.56	3.43	1.25	4.36
Channel	-	3-12	0.44	50.00	44.19	3.55	2.26	3.23	2.26	3.87
Channel	-	3-14	0.58	45.73	40.33	4.55	0.85	4.55	1.14	4.55
Channel	-	3-16	0.22	48.31	41.71	5.12	1.48	5.03	1.18	2.96
Channel	-	3-18	0.34	38.66	33.93	4.13	0.60	1.78	0.89	2.07
Channel	-	3-19	1.10	38.10	33.33	3.58	1.19	5.65	0.59	2.68
Channel	-	3-20	1.54	26.89	22.69	3.08	1.12	2.80	0.56	3.92
Channel	-	4-1A	0.15	31.94	20.42	8.90	2.62	1.57	0.52	5.76

APPENDIX (cont.)

Heavy Mineral Percentages by Depositional Subenvironments

Depositional Environment	Sub Environment	Sample No.	Heavy Mineral % Wt%	Total Economic Mineral %	Economic Minerals Ilmenite	Leucoxene (% grains)	Rutile	Economic Accessory Minerals Zircon	Monazite (% grains)	Staurolite
Channel	-	3-1*	0.50							
Channel	-	3-15***								
Channel	-	3-17***								
Channel	-	4-1***								
Channel	-	5-4***								
Channel	-	5-6***								
Channel	-	5-7***								
Channel	-	5-8***								
Average			0.44	44.55	37.77	5.04	1.74	3.70	1.89	3.42

NOTES:

* No Petrographic analysis performed, sample was included in averages of total heavy minerals.
** Sampled from surface concentration of heavy minerals, sample not used in averaging.
*** Sample contained only clay-size material.


HEAVY MINERAL SAMPLE LOCATIONS
ALTAMAHA SOUND STUDY AREA
N
RICHARD J REYNOLDS STATE WILDLIFE REFUGE
SAPELO
Cabretta Inlet
Area subject to frequent change
Sapelo Island
University of Georgia Marine Institute
DOBOY SOUND
Doboy Island
Rock Island
Queens Island
WOLF ISLAND NATIONAL WILDLIFE REFUGE AND WILDERNESS AREA
Wolf Island
Rockdedundy Island
ALTAMAHA RIVER
ALTAMAHA SOUND
MC INTOSH CO
GLYNN CO
LITTLE SAINT SIMONS ISLAND
Egg Island
Butler Point
HAMPTON RIVER
FORT FREDERICA NATIONAL MONUMENT
SAINT SIMONS ISLAND
Sea Island
Pelican Spit
Saint Simons Island
ST SIMONS SOUND
Ridgeville
Darien
Meridian
Carnigan
Landing Strip
Malcolm McKinnon Airport
81°22'30"
81°15'00"
31°22'30"
31°15'00"
31°07'30"
EXPLANATION
28-3 Sample location
GEORGIA
STUDY AREA
CONTOUR INTERVAL: 2 METERS
0 1 2 3 4 5 KILOMETERS
0 1 2 3 MILES
Base map from U.S. Geological Survey 1:100,000 map of Brunswick, GA., 1981.

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