Heavy Minerals of Sand from Recent Beaches of the Gulf Coast of Mississippi and Associated Islands

RICHARD D. FOXWORTH, RICHARD R. PRIDDY, WENDELL B. JOHNSON,
and WILLARD S. MOORE

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DIRECTOR AND STATE GEOLOGIST

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Table 1*

Analyses of Heavy Minerals in Mississippi Sound Beach Sands

(Adapted from Foxworth, 1958)

MAINLAND													
SAMPLE BY CODE	ML-1	ML-2	ML-2a	ML-3	ML-3a	ML-4	ML-4a	ML-5	ML-6	ML-7	ML-8	ML-8a	ML-9
GRADE SIZE	0.175	0.175	0.175	0.175	0.124	0.175	0.175	0.246	0.175	0.175	0.246	0.246	0.175
WT. % SEPARATE	1.18	0.87	4.56	2.18	55.80	0.92	1.18	0.16	0.11	0.39	0.21	1.11	0.79
Magnetite**			1.32	1.26	1.18	4.92	18.60			7.70	7.30		6.30
MINERAL FREQUENCY IN PERCENT													
Andalusite				0.1	0.1	0.2			0.2				
Apatite		0.4											
Augite & diopside				0.3									
Dolomite & siderite									0.2			0.1	
Epidote													
Garnet—colorless			0.2	0.3					0.2			0.1	
Hornblende—common	0.5	0.2	0.6			0.7			0.2	0.1			0.1
Hypersthene													
Ilmenite	10.1	6.2	7.9	9.8	29.4	15.5	12.1	8.0	7.2	10.5	0.9	8.3	9.6
Kyanite	32.1	27.1	30.4	29.1	24.9	25.8	35.5	29.5	30.6	25.0	17.2	20.4	33.6
Leucoxene	5.0	4.7	1.2	4.1	2.3	2.0	5.0	1.1	8.4	5.8		0.1	5.6
Limonite & hematite	5.0	7.4	8.7	8.9	11.4	9.5	4.8	2.2	6.9	3.8	0.9	1.2	7.7
Mineral X						0.2		0.5	0.2				
Pigeonite													
Pyrite & marcasite							0.3	0.5	0.2	0.3			
Rutile	0.5	0.9	0.4	0.5	3.8	0.7	1.5	0.2	0.7	1.4	0.6	1.2	0.3
Sillimanite	0.3	0.2	0.2	0.1	0.1	0.2	0.7	2.5	2.4	1.2	8.6	4.3	
Spinel	0.1				0.1	0.2	0.3						
Staurolite	27.6	28.8	34.2	24.7	22.0	34.0	29.1	27.7	26.5	27.4	12.1	19.3	24.5
Titanite (sphene)			0.2				0.1						
Tourmaline—brown	15.2	20.3	13.9	9.6	3.8	10.2	8.4	24.0	11.5	21.4	53.9	42.2	16.1
Do blue	0.1	0.7	0.2	0.1	0.1	1.7		0.2			0.9	0.3	0.3
Do green	1.4	1.4	1.2	1.0	0.3	0.7	0.3	2.5	1.6	1.4	3.8	2.2	1.0
Do colorless		0.9		0.1		0.2		0.2	1.2	0.7	0.3	0.1	0.3
Zircon	0.7		0.4	0.3	0.7	1.5	0.7	0.5	0.9	0.3	0.3	0.1	0.3
Total % "heavies"	98.6	99.2	99.5	99.0	99.1	100.1	98.8	99.6	99.1	99.3	99.5	99.9	99.4

	DEER ISLAND				ROUND ISLAND	
SAMPLE BY CODE	D-1	D-2	D-3	D-3a	R-1	R-1a
GRADE SIZE	0.124	0.175	0.175	0.175	0.175	0.175
WT. % SEPARATE	1.63	1.76	0.27	1.10	0.68	4.41
Magnetite**					2.26	2.20
MINERAL FREQUENCY IN PERCENT						
Andalusite						
Apatite						
Augite & diopside						
Dolomite & siderite						
Epidote						
Garnet—colorless						
Hornblende—common	0.2	0.1			0.1	
Hypersthene						
Ilmenite	19.7	14.2	9.5	9.1	6.9	5.3
Kyanite	19.3	33.9	22.1	26.8	34.7	31.1
Leucoxene	2.0	3.5	4.0	4.4	2.3	2.0
Limonite & hematite	7.6	3.3	2.1	1.6	3.5	3.0
Mineral X		0.1		0.1	0.1	
Pigeonite						
Pyrite & marcasite	0.4	0.1		0.5	0.4	
Rutile	4.1	2.3	1.3	0.9	0.4	0.4
Sillimanite	0.4	0.1		1.3	0.5	0.8
Spinel						
Staurolite	19.3	28.6	16.1	17.9	27.6	17.5
Titanite (sphene)				0.1		
Tourmaline—brown	21.8	12.4	40.7	34.8	20.5	35.8
Do blue						0.2
Do green	1.4	0.3	2.1	0.9	1.0	2.4
Do colorless			1.3	0.7	1.2	1.2
Zircon	3.0	0.3	0.2	0.1	0.4	
Total % "heavies"	99.2	99.2	99.4	99.2	99.6	99.7

CAT ISLAND										
SAMPLE BY CODE	C-1	C-2	C-2	C-2a	C-3	C-3a	C-4	C-4a	C-5	C-5a
GRADE SIZE	0.175	0.175	0.246	0.175	0.246	0.175	0.175	0.175	0.175	0.175
WT. % SEPARATE	0.22	2.44	1.81	18.80	1.16	31.20	0.51	2.40	1.39	4.10
Magnetite**	3.20	6.20	3.40	0.40	0.90	4.20	9.90	0.17	5.80	2.00
MINERAL FREQUENCY IN PERCENT										
Andalusite						0.1		0.1		
Apatite										
Augite & diopside										
Dolomite & siderite										
Epidote										0.1
Garnet—colorless								0.1	0.3	
Hornblende—common		0.6								
Hypersthene										
Ilmenite	17.9	7.2	4.0	1.5	4.5	7.4	8.3	10.2	15.2	13.5
Kyanite	43.9	30.4	21.6	39.4	25.3	34.3	21.5	26.6	34.8	27.6
Leucoxene	4.3	0.8	0.6	2.5	0.3	3.1	7.5	6.7	4.2	3.9
Limonite & hematite	2.1	1.4	0.8		0.1	2.1	3.5	2.7	3.9	3.1
Mineral X		0.2	0.2		0.3	0.5	0.7	1.4	0.6	0.9
Pigeonite	0.3									
Pyrite & marcasite		0.4				0.5	0.3	0.7		0.5
Rutile	2.5		0.2	0.7		0.7	1.1	0.3	3.3	2.9
Sillimanite	2.1	1.4	1.0	1.1	0.9	0.7	2.7	1.1		1.3
Spinel			0.2						0.3	
Staurolite	14.2	24.6	34.4	30.3	42.2	36.4	19.6	26.1	24.1	35.0
Titanite (sphene)					0.1					
Tourmaline—brown	9.1	29.8	33.4	16.7	22.9	13.0	32.6	22.5	9.7	8.7
Do blue		0.2		0.1			0.3			0.1
Do green	0.3	1.0	1.4	0.1	2.0	0.1	0.3	0.5		0.3
Do colorless	1.0	1.8	2.0	6.9	0.7	0.1	0.3	0.1		0.1
Zircon	1.0					0.1	0.3		2.7	0.9
Total % "heavies"	95.7	99.8	99.8	99.3	99.3	99.1	99.0	99.1	99.1	98.9

SHIP ISLAND							
SAMPLE BY CODE	S-1	S-1a	S-2	S-2a	S-3a	S-4	S-4a
GRADE SIZE	0.175	0.124	0.246	0.124	0.124	0.246	0.124
WT. % SEPARATE	11.10	93.50	4.31	95.70	78.30	5.01	94.70
Magnetite**	0.85	1.17	3.50	0.50	8.70	3.70	0.76
MINERAL FREQUENCY IN PERCENT							
Andalusite			0.1				
Apatite							
Augite & diopside						0.2	
Dolomite & siderite			0.5				
Epidote							
Garnet—colorless		0.1				0.2	
Hornblende—common	0.3		0.7	0.3			0.1
Hypersthene			0.1				
Ilmenite	7.4	33.8	9.5	41.6	31.5	9.9	40.0
Kyanite	32.1	21.1	26.9	17.5	7.8	27.3	21.8
Leucoxene	1.4	2.8	0.7	1.8	1.6	1.4	2.5
Limonite & hematite	1.4	3.6	1.0	2.0	2.3	1.9	3.4
Mineral X			0.1				
Pigeonite	0.3						
Pyrite & marcasite	0.3	0.7	0.1	0.3	0.9		0.3
Rutile	1.0	8.3	0.5	8.2	16.1	0.2	7.9
Sillimanite	0.7		0.5			1.1	
Spinel				0.5			
Staurolite	30.7	20.5	47.1	17.9	11.5	31.8	17.2
Titanite (sphene)				0.1			
Tourmaline—brown	22.6	2.4	9.8	0.9	1.3	21.1	1.8
Do blue						1.1	
Do green	1.0		0.8			2.8	
Do colorless	0.3		0.1		0.3	0.2	
Zircon		5.7		7.8	26.3	0.2	4.4
Total % "heavies"	99.5	99.0	98.5	98.9	99.6	99.4	99.4

	HORN ISLAND						PETIT BOIS ISLAND				
SAMPLE BY CODE	H-1	H-1a	H-2	H-2a	H-3	H-4a	PB-1	PB-1a	PB-2	PB-3	PB-3a
GRADE SIZE	0.246	0.175	0.246	0.175	0.351	0.175	0.246	0.246	0.246	0.246	0.246
WT. % SEPARATE	0.18	36.50	1.23	21.10	0.15	9.30	0.05	0.94	0.33	15.00	1.80
Magnetite**	5.60	1.20	0.80	2.20		3.40		1.00		0.20	0.30
MINERAL FREQUENCY IN PERCENT											
Andalusite											0.1
Apatite											
Augite & diopside											
Dolomite & siderite			0.3	0.4							
Epidote											
Garnet—colorless	0.4										
Hornblende—common			0.3		0.8	0.2					0.1
Hypersthene											
Ilmenite	11.0	12.0	8.8	6.7	16.3	10.0	10.0	9.4	20.7	7.7	9.1
Kyanite	28.5	31.7	26.4	39.0	27.0	35.4	24.0	32.9	18.9	35.3	22.5
Leucoxene	1.3	2.0	0.3	1.5		3.7		0.2		0.3	0.1
Limonite & hematite	2.3	2.3	1.1	2.8	1.6	4.2	2.0	1.0		1.3	0.7
Mineral X			0.3	0.2				0.2	3.1		
Pigeonite	0.4			0.2							0.1
Pyrite & marcasite										0.7	
Rutile	0.4	0.6	0.1					0.6	0.9	0.1	0.1
Sillimanite	4.1	1.0	1.3	0.2	2.4	0.5	4.0		1.8		1.6
Spinel											
Staurolite	23.9	43.4	36.8	32.7	14.7	34.5	28.0	35.3	15.3	40.4	35.1
Titanite (sphene)								0.4			
Tourmaline—brown	23.9	4.6	22.4	13.3	33.6	9.4	28.0	18.5	37.8	9.5	27.1
Do blue	0.4			0.4			2.0				0.3
Do green	0.9	0.6	0.7	1.0	0.8	0.8		0.8	2.7	0.5	1.4
Do colorless	0.4	1.3	0.3	1.0	0.8			0.2	0.9	0.1	0.7
Zircon						0.8	2.0			0.1	0.1
Total % "heavies"	97.9	99.5	99.1	99.4	98.0	99.5	100.0	99.5	102.1	96.0	99.1

* The augite, diopside, and pigeonite of Foxworth are classed as clino-pyroxene by Johnson; the hypersthene of Foxworth is Johnson's ortho-pyroxene. In the average sample, Johnson recognized 0.2 percent monazite which Foxworth did not recognize.

**Magnetite in percent by weight.

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LETTER OF TRANSMITTAL

Office of the Mississippi Geological Survey

University, Mississippi

January 15, 1962

Hon. Henry N. Toler, Chairman, and
Members of the Geological Survey Board

Gentlemen:

Herewith is Mississippi Geological Survey Bulletin 93, Heavy Minerals of Sand from Recent Beaches of the Gulf Coast of Mississippi and Associated Islands, by R. D. Foxworth, R. R. Priddy, W. B. Johnson, and W. S. Moore.

The basis for this report, furnished by R. D. Foxworth, was his master's thesis submitted to the University of Missouri Graduate School. The decision of the Survey Board to broaden the scope of the thesis and to publish as a Bulletin was indeed wise. This decision was made months before the work actually began due to the fact that the expense of the additional research had to be borne by the Survey.

I feel that this report will have a far reaching effect on the future attention given to the sands of Mississippi. The economic potentiality of these coastal sands point out the urgent need to study the sand of several geologic formations throughout the State.

It should be noted that a heavy mineral operation could also provide a supply of good quality glass sand — a product that has been searched for by the Survey for many years. Once the heavy minerals are extracted, virtually all the remaining material will be quartz sand.

Respectfully submitted,

Tracy W. Lusk
Director and State Geologist

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HEAVY MINERALS OF SAND FROM RECENT BEACHES OF THE GULF COAST OF MISSISSIPPI AND ASSOCIATED ISLANDS

RICHARD D. FOXWORTH, RICHARD R. PRIDDY, WENDELL B. JOHNSON, and WILLARD S. MOORE

ABSTRACT

Heavy minerals in beach and dune sands of the mainland and associated islands of the Mississippi Gulf Coast may have commercial value. For many years they have been the subject of study by geology students at the Gulf Coast Research Laboratory, Ocean Springs, Mississippi.

These minerals are commonly called "heavies" because the specific gravity is at least 2.72, in contrast to quartz sand which is only 2.65. In the average coastal beach or dune sands the "heavies" range from 2 to 6 percent. Quartz grains and organic debris constitute the remainder. The grains of heavy minerals range in size from silt to fine sand, smaller than the grains of quartz. Most are conspicuous because of color—amber, brown, black, or green, in contrast to the clear to white quartz grains. Consequently the "heavies" are easily seen where concentrated by waves, currents, winds, and tides in thin laminae to as much as 30 to 95 percent. On a few mainland beaches and on the Gulf side of the barrier islands, interlaminated quartz sands and "heavies" may average 60 percent heavy minerals. Concentrations of 1 to 3 percent are of the order mined profitably in Florida.

Twenty-six different species of heavy minerals are recognized, most of which are metamorphic. The original source is postulated as the metamorphosed-intruded rocks of the southern Appalachians. Intermediate sources are probably the overlapping Paleozoic rocks of Alabama and Tennessee and the Cretaceous and Eocene sediments of the Coastal Plain of Mississippi, Alabama, and western Georgia. A still active transporting agent is the rivers which drain the Plain. However, the immediate source of most of the heavy minerals is Pleistocene and Recent muds which are being reworked continuously by wave action.

The investigation is chiefly the work of Richard D. Foxworth, now geologist with Texaco, Inc., in Midland, Texas. The problem was the subject of his thesis which was submitted to the University of Missouri in March 1958. Later studies of heavy min-

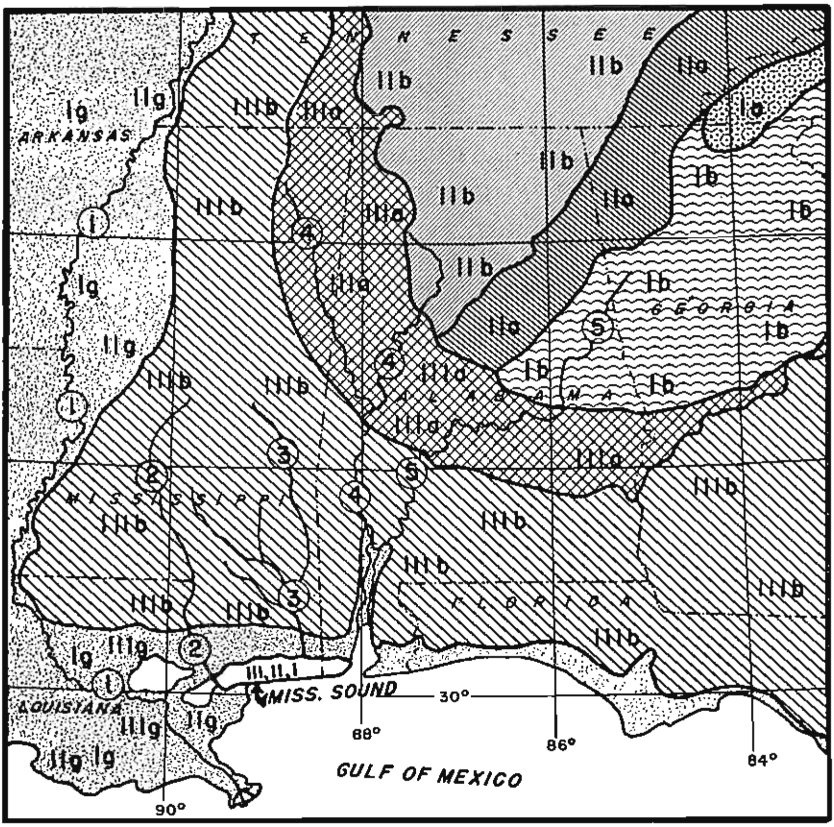

Figure 1.—Index map showing regional relations of Mississippi Sound

Notable Rivers Draining Upland	Cycles of Heavy Mineral Erosion
	Ia. First cycle in Blue Ridge Province
	Ib. First cycle in Piedmont Province
① Mississippi	IIa. Second cycle in Ridge and Valley Province
	IIb. Second cycle in Cumberland Plateau Province
② Pearl	IIIa. Third cycle in Cretaceous Coastal Plain
	IIIb. Third cycle in Tertiary Coastal Plain
③ Pascagoula	Ig, IIg, IIIg. First, Second, and Third Cycle minerals carried by Mississippi River
④ Mobile-Tombigbee	III, II, I. Cycle minerals, in that order in Mississippi Sound
⑤ Alabama	

erals of the Mississippi Sound have been made by Wendell B. Johnson and Richard R. Priddy of the geology faculty of Millsaps College, Jackson, Mississippi, and by Willard S. Moore, geology-chemistry major at Millsaps.

Although the heavy minerals vary in species and in concentration from place to place, Foxworth has shown that for the Sound, as a whole, the order of abundance in percent is: staurolite 25.7, kyanite 24.1, tourmaline 20.4, ilmenite 11.8, magnetite 3.6, limonite-hematite 3.4, leucoxene 2.5, zircon 2.0, rutile 1.7, sillimanite 1.3, and andalusite 1.1. The staurolite, kyanite, sillimanite, and andalusite might be extracted for valuable refractory material. The ilmenite, leucoxene, rutile, and the less than 0.2 percent titanite may be a source of titanium metal and titanium oxide. Zircon is the chief source of zirconium metal. Both titanium and zirconium are important minerals in missile construction. Twelve other minerals are present in quantities of 0.1 to 0.5 percent.

INTRODUCTION

This bulletin presents a review of studies of heavy mineral grains, often termed "heavies," in beaches and dunes of quartz sand along the mainland of the Mississippi Coast and the associated islands. The investigation was designed to determine the mineral species, their sources, and their concentrations, with a view toward exploitation of the richer deposits. Publication of the data was suggested in 1959 by Mellen[1] who authored "Mississippi Mineral Resources," Bulletin 86, Mississippi Geological Survey.

The Mississippi mainland, the Mississippi Sound, and the islands are shown on the infolded map (Plate 1). The regional relations of the Sound to the Gulf of Mexico on the south and to the states on the north which contribute "heavies" are shown on the index map (Figure 1).

The Mississippi Sound is a body of shallow brackish water some 85 miles in length west-east and 7 to 15 miles in width. It extends from the mouth of Pearl River (the Louisiana-Mississippi line) at about longitude 89° 45′ west to Mobile Bay in southwest Alabama at about longitude 88° west. The mainland on the north is about one-half artificial beach and one-half grassy

Figure 2.—High tide berm consisting of heavy minerals, Sound side of tidal flats, west end, East Ship Island. Photo by W. S. Moore, July 1959.

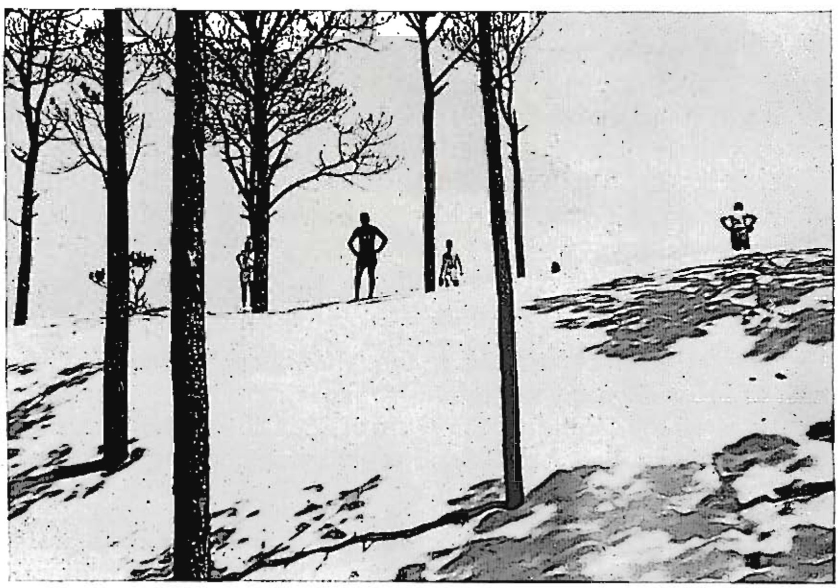

Figure 3.—Migrating sand dune, Dauphin Island, Gulf side, near east end. The white quartz sand contains 1 to 2 percent heavy minerals. Photo by W. S. Moore, June 1959.

tidelands. A chain of sandy barrier islands, Cat, Ship, Horn, Petit Bois, and Dauphin, comprises the Sound's south limit. All but Dauphin Island are in the bounds of Mississippi. Although the shallow bottoms are mostly mud, some sandy silt, and only a little sand, they are being constantly reworked by waves and currents which have built the barrier islands and presently help maintain the natural sand beaches (Figure 2). Winds may further rework the sands as dunes (Figure 3).

The study is primarily the work of Richard D. Foxworth, the senior author. He became interested in the heavy minerals of the Mississippi mainland and associated islands as a Millsaps College undergraduate while enrolled in a course in marine sedimentation at the Gulf Coast Research Laboratory, Ocean Springs, Mississippi, in July-August 1956. His instructor, Richard R. Priddy, suggested a more thorough investigation of the minerals as a thesis. The problem was pursued in graduate school at the University of Missouri. Foxworth[2] completed his thesis, "Heavy Minerals of Sand from Recent Beaches of the Gulf Coast of Mississippi and Associated Islands," in March 1958.

The junior authors, Priddy, Johnson, and Moore, restudied phases of Foxworth's investigations and made additions and refinements of their own. Priddy of the Millsaps College geology department edited the work of the others in view of his 14 summers of geochemical studies of Mississippi Sound. Wendell B. Johnson of the same department reviewed Foxworth's mineral identifications and studied other heavy mineral suites, from inland Mississippi, from the Chandeleur Islands to the south, and from both coasts of Florida. Willard S. Moore, geology-chemistry major at Millsaps, contributed a study of West Ship Island where the minerals are presently in great concentration (Figure 4).

OTHER INVESTIGATIONS

Only two investigations have dealt specifically with the heavy minerals of Mississippi Sound, the 1958 thesis of Foxworth[2] and the incomplete work of James L. Harding which is recorded in an unpublished Gulf Coast Research Laboratory geology course report, August 1958. Later, while instructor in geology at Mississippi Southern College, Harding[3] made additional heavy mineral studies which were presented at the March

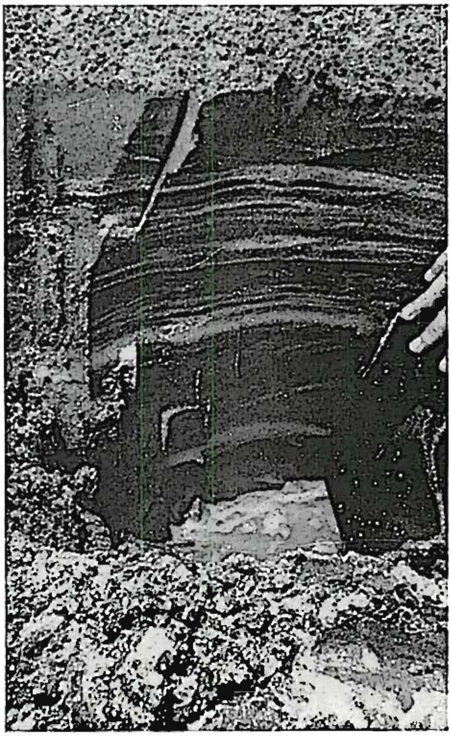

Figure 4.—An unusual concentration of heavy minerals in a berm, Sound side, west tip of West Ship Island. Photo by W. S. Moore, July 1959.

24-26, 1960 meeting of the Southeastern Section of the Geological Society of America in Lexington, Kentucky.

Reports dealing indirectly with the heavy minerals or with the petrology of Mississippi Sound before Foxworth's investigations are those of Dohm[4] 1936, Goldstein[5] 1942, Marion[6] 1951, Barton[7] 1952, Priddy *et al.*[8] 1955, and Butts[9] 1957. In the interval 1950-1958 references to heavy mineral distribution and species are scattered through the reports of geology courses at the Laboratory.

However, since Foxworth's field work, two investigations dealing with sediments of the north coast of the Gulf of Mexico have been published by van Andel and Poole[10] in March 1960 and by Hsu[11] in September 1960. In addition, Snowden[12] completed a thesis in May 1961, which included analyses of Biloxi Bay sediments and identification of heavy mineral content.

The investigations are summarized in chronological order.

The work by Dohm[4], although primarily an investigation of the Mississippi River Delta region, includes data on heavy mineral analyses of 4 samples from Cat Island, 1 sample from Pascagoula, Mississippi, and 3 samples from Pearl River (Plate 1). Dohm includes in his paper a list of 35 heavy minerals—3 varieties of hornblende, 3 varieties of tourmaline, and 2 varieties of garnet. Of the 8 samples mentioned above only 2 are beach sand samples, 1 from Cat Island and 1 from Pascagoula. The others are dune samples, bottom samples, and samples taken from borings. Despite the diverse methods of sampling, the mineral varieties are similar although the frequency percentages of the heavy minerals differ laterally.

Dohm points out that it is unlikely that the "heavies" were carried by the Mississippi River and that those on Cat Island were derived from the east rather than from the Mississippi or Pearl Rivers. The chief differences between the sands in the Mississippi River samples and those from Cat Island are a higher zircon content and a higher percentage of metamorphic minerals in the Cat Island samples.

Goldstein[5] studied samples from the northern Gulf of Mexico in an area which he termed the "East Gulf Petrologic Province." This Province extends from Pearl River to Pensacola, Florida, and includes the area of this investigation. Goldstein lists 29 species of heavy minerals—3 varieties of hornblende, 3 varieties of tourmaline, and 2 varieties of garnet. Goldstein, like Dohm, did not confine his studies to beach sands but sampled many offshore bottoms.

Goldstein makes the following statement with regard to the minerals:

> "The Eastern Gulf Province contains a metamorphic assemblage which is derived largely from the Southern Appalachian region, either directly from the metamorphic rocks or the bedrock complex or from surficial deposits of Pleistocene (?); reworked Tertiary sands, shales and limestones probably furnished only minor amounts of material.
>
> "A relatively high content of ilmenite, staurolite, kyanite, zircon, tourmaline, and sillimanite characterizes the sediments of this province. The percentages of magnetite, amphiboles, and

pyroxenes are all low, probably owing to the character of the source rocks rather than to the instability of these minerals under processes of weathering."

Much information concerning the adjacent Mississippi Delta is available but will not be included because it represents a different sedimentational province, its minerals having been derived largely from glacial outwash contributed by Pleistocene ice sheets in eastern Canada and the states of the upper Mississippi valley.

Marion[6] studied beach and bottom sediments from Biloxi Bay and adjacent parts of the Mississippi Sound. He reported primarily on the physical properties of the sand size material in the beaches and shallows of the Biloxi-Ocean Springs area (Plate 1). In his study of the apron of sand which protects the toe of the Biloxi-Gulfport seawall, Marion observed that currents carried a few heavy minerals which were left as laminae in the quartz sands of storm berms or concentrated along concrete groins which have been built to control beach erosion.

A year later Barton[7] made a petrographic study of bottom sediments from the Back Bay of Biloxi and Biloxi Bay. He separated silt-sized material from sand and clay by elutriation and found the silts to be chiefly quartzose. In the sand fraction Barton reported authigenic potash feldspar and a heavy mineral suite composed chiefly of tourmaline, kyanite, garnet, topaz, zircon, hornblende, and some authigenic spherulitic pyrite. These findings, again, showed that the sediments of the shallows were the immediate sources of the heavy mineral laminae occasionally found on beaches and bars.

Priddy, *et al.*[8] reported on the mineral composition of many bottom samples and a few beach samples in the west part of the Mississippi Sound. The research was based at the Gulf Coast Research Laboratory in the summers of 1952, 1953, and 1954. The bottom sediments of the Mississippi Sound were recognized as two textural types. Soft, muddy bottoms are referred to as "shrimp bottoms," which are the habitat of bottom feeding shrimp. Firm, sandy or silty bottoms, of much lesser extent, are referred to as "oyster bottoms" because they may support oyster reefs. The mineral composition of both types of sediments was determined to be essentially the same, the chief textural differences being attributed to finer grain size and higher gelatinous, flocculant, and organic content in the "shrimp bottoms." The mineral distribution of the approximately one percent "heavies" in the "oyster bottoms" in the west end of the Sound adjacent to Lake Borgne is: muscovite, garnet, biotite, epidote, feldspar, apatite, magnetite, and zircon, in that order of abundance. Off Cat Island the bottoms yielded a different suite of heavy minerals, in this order of abundance: kyanite, staurolite, ilmenite, and garnet, the latter showing surprisingly little abrasion. It is thus apparent that the Mississippi River contributed "heavies" in the extreme west which are different from those nearer the center of the Sound.

An investigation of 2 offshore samples from the Bay of St. Louis and 8 offshore samples from Horn Island was reported by Butts[9], a Mississippi State University geology student. After removing and weighing the silt-clay fractions, he studied the sand residues. Heavy minerals were extracted from the ½ to ¼ mm. grain sizes and identified. Butts states that "the heavy minerals present and in their general order of abundance as found in most of the samples are from greater to lesser: Tourmaline, Magnetite, Rutile, Zircon, Hematite, Ilmenite, Leucoxene." No mention is made of staurolite and kyanite which Foxworth and Johnson discovered in such abundance. Butts concludes his report with this interesting paragraph.

> "The heavy minerals present originated in gneisses, pegmatites, and acid igneous rocks apparently from the Appalachian region. The iron minerals are indigenous of basic rocks. Marcasite and pyrite found in the bay sample are characteristic of the reducing environment present there. Leucoxene found in small quanities in many of the samples is an alteration product of ilmenite resulting from long or repeated transportation and deposition. From their source in the Appalachians, the materials have undoubtedly gone through several cycles of erosion and deposition on the southern coastal plain. Their resting place is now at the edge of the Gulf of Mexico; their ultimate place of deposition can only be speculated."

Harding reported on a "Preliminary Study of Heavy Minerals of Mississippi Sound and Adjacent Eastern Areas" as part of his contribution to course work at the Gulf Coast Laboratory. His report of a broader investigation "Heavy Mineral Occurences on the Islands of Mississippi Sound and Adjacent Areas of the Mainland" was presented at the March 1960 meeting of the Southeastern Section of the Geological Society of America. The abstract Harding[3] wrote is quoted below:

> "Samples of heavy minerals have been collected for 3 years at localities from the Alabama-Florida state line on the east to Cat Island, Mississippi, on the west.
>
> "The marked similarity of mineral suites from each of the sampling stations indicates a common source. However, changes in the degree of concentration at each of the locales manifest reworking of the near-shore and bottom sediments. The primary control of this present depositional cycle is being exercised by littoral drift. This is further evidenced by the southwestward migration of the island masses.
>
> "Petrographic examination shows that the most frequent minerals of the heavy fraction, following bromoform separation, include ilmenite, kyanite, rutile, staurolite, tourmaline, and zircon with minor amounts of hornblende and monazite."

It is unfortunate that Mr. Harding's complete work is unpublished.

In investigating the sources of Recent sediments in the northern Gulf of Mexico, van Andel and Poole[10] reported that sand-sized sediments are contributed by a large number of streams, and to a lesser extent, by marine erosion of coastal deposits, mainly of Pleistocene age. Further, they recognized five heavy mineral provinces: Eastern Gulf, Mississippi, Western Gulf, Texas Coast, and Rio Grande. The Eastern Gulf Province includes the Mississippi Sound. It is characterized by a kyanite-staurolite association which they believe is derived from the Cretaceous and younger sedimentary mantle of the Appalachians, like that now being contributed by the Tombigbee River rather than the old core which should only supply a zircon assemblage. Later in this report reference is made to several of the mineral analyses of van Andel and Poole. Also, later, the idea of different heavy mineral assemblages contributed by the several physiographic provinces is pursued (Figure 1).

An excellent but complicated report on the texture and mineralogy of the Recent sands of the Gulf Coast is that of Hsu[11]. Although primarily an attempt to determine the major transportation paths for the beach sands for the entire Coast, he recognized those beach sands east of the Mississippi River as mature quartz sands which contain practically no feldspar and have a mature heavy mineral suite rich in staurolite and kyanite. Unfortunately his sampling of the East Gulf Coast was confined to Alabama and west Florida beaches and rivers. But it is gratifying to note that these sands have nearly the identical mineral assemblage as Mississippi's beaches. Several of Hsu's mineral analyses are cited.

The most recent work mentioning the "heavies" is a thesis by Snowden[12] entitled "Geologic and Chemical Environment of Biloxi Bay, Mississippi" (Plate 1). In studying the physical, chemical, and sedimentological environment, 29 bottom water samples and corresponding sediment samples along 6 evenly spaced traverses were taken. Snowden discovered that, mineralogically, the bottoms are chiefly quartz of sand and silt size particles, and finer particles of kaolinitic and montmorillonitic clay. Accessory minerals are heavy minerals from 0.14 and 0.40 percent by weight. The order of abundance of "heavies" in this small fraction is 26 percent zircon, 20 percent ilmenite-magnetite, 15 percent kyanite, 14 percent staurolite, 10 percent leucoxene, 6 percent tourmaline, 4 percent pyrite, 3 percent rutile, and 1 percent sillimanite.

LOCATION AND DISCUSSION OF THE AREA

LOCATION

The area described in this report is shown by a full scale reproduction of a part of the regional topographic map printed by Army Map Service, Corps of Engineers (Plate 1):

Mobile, Ala.; Miss.; La. (New Orleans to Mobile) NH 164,

scale 1 inch to 250,000 inches
(approximately 4 miles to the inch)
for sale by U. S. Geological Survey,
Denver 2, Colorado, or Washington 25, D. C.
Price 50 cents

Fortunately, this topographic map includes the whole of Mississippi Sound. It is preferred to nautical charts because the details of the mainland and islands are sharper and because the water area shows enough depth figures to convey the idea of the Sound's bottom configuration and has many notations as to the nature of the bottom, whether mud, soft, hard, sticky, or shells. The regional location of topographic map NH 164 is shown as an inset in Plate 1.

However, the map, Plate 1, may be supplemented by two nautical charts and by numerous topographic quadrangles. The charts are:

Chart 1268 Lake Borgne and Approaches
(Cat Island to Point Aux Herbes)
scale 1 inch to 80,000 inches
(approximately 1.15 nautical miles per inch or
1.126 land miles per inch)

Chart 1267 Mississippi Sound and Approaches
(Dauphin Island to Cat Island)
same scale as Chart 1268

Both compiled by Coast and Geodetic Survey
For sale at most harbors including
Pass Christian, Gulfport, Biloxi, and Pascagoula, Miss.
Price $1.00 each

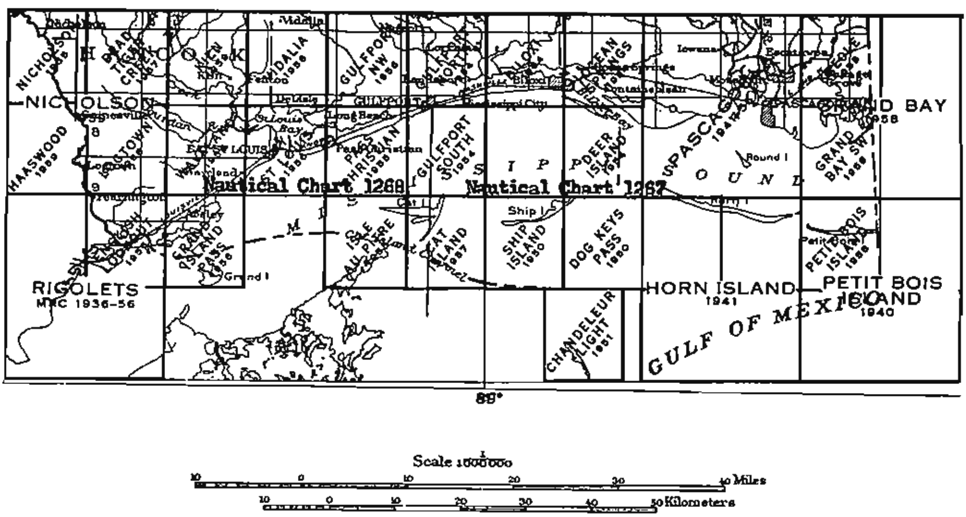

Figure 5.—Map coverage of the area by topographic quadrangles and by nautical charts 1268 and 1267.

The positions of the nautical charts 1268 and 1267 are shown in Figure 5, overtyped on the index map of the topographic quadrangles. For simplicity, it can be remembered that Chart 1268 covers the Sound area west of Gulfport whereas Chart 1267 covers the Sound area east of Gulfport to Dauphin Island.

The topographic quadrangles which, collectively, cover most of the area are shown in the guide map, Figure 5. Another quadrangle, West Horn Island, is now being surveyed. All, whether 15 minute quadrangles or 7½ minute quadrangles, are published by the United States Geological Survey, Washington 25, D. C., and are priced at 30 cents each.

PHYSIOGRAPHY

In so far as is known, the physiography of the Mississippi Coast has not been studied except incidental to other investigations. Therefore, it is necessary to derive the information from the literature concerning regional aspects of the eastern Gulf of Mexico.

Price[13] described the Mississippi Coast in regional terms as being a part of the alluvial coast of the northern Gulf of Mexico, Texas to west Florida:

> "Where the closest mountains, usually old mountains, are located far or moderately far inland the runoff and sediment load from the lands has been large and long continued, interior plains are succeeded by broad coastal plains and continental shelves, and the coast is of deltaic or alluvial type."

After a sufficiently long oceanic standstill, an alluvial coast will have a smooth bottom except toward its outer margin. Organic reefs are few or absent, and the shore line is smooth to irregularly deltaic. The sediments have even to spotty distribution, usually sand extending from the shore to depths of from 5 to 10 fathoms followed by silt or sand and mud. Exceptions are found at the mouths of deltaic rivers.

A subsector of the northern Gulf of Mexico is designated the "Terraced Deltaic Plain" by Price[14]. This area is characterized by a fairly steep coastal plain (eight feet of slope per mile near the coast in some places) with Pleistocene-Recent deltas (Apalachicola, Pascagoula, and Pearl) and by a minor amount of embayment due to drowned stream valleys. The large, cuspate Apalachicola delta of Florida and the long, broad, and shallow Mobile Bay of Alabama are the striking features of the subsector.

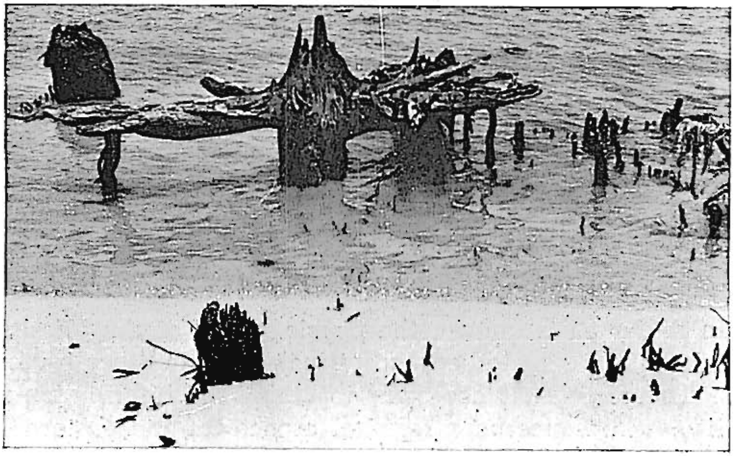

Figure 6.—Cypress stumps, Bellefontaine Beach between Ocean Springs and Pascagoula. The roots are exposed at low tide. Root span is 10 feet. These and other "ghost forests" exposed by wave erosion are often falsely believed to be evidence of submergence. Photo by W. S. Moore, July 1959.

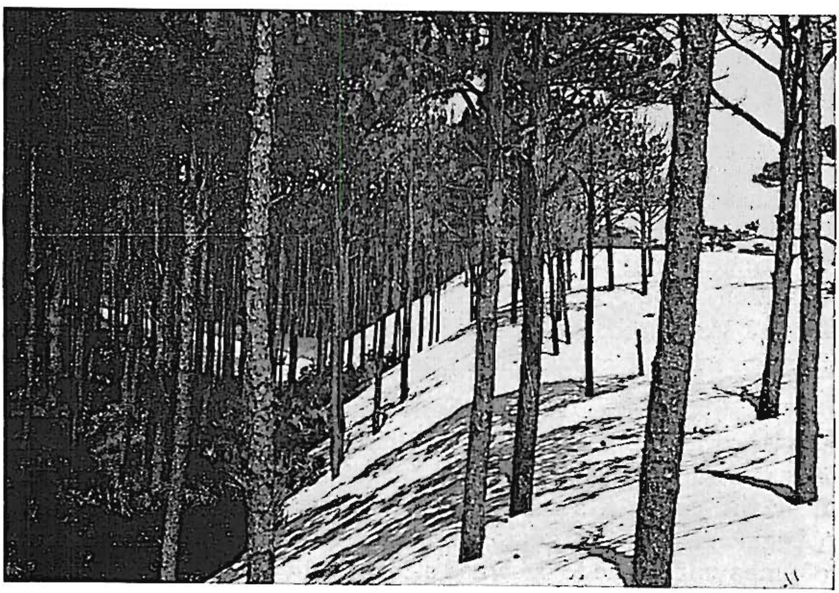

Figure 7.—Dune sands encroaching on a pine forest, Dauphin Island, Gulf side. Here the white quartz sand is flecked by dark heavy minerals. Photo by W. S. Moore, June 1959.

Brown, *et al.*[15] stated that the present shore is being submerged and that the headlands are being eroded. The evidence cited is wave-cut scarps and tree stumps standing in sea water (Figure 6). Foxworth visited the areas and agreed with Brown that this part of the coast appears to be undergoing slow submergence. However, Priddy does not subscribe to the idea of submergence inasmuch as he has seen living forests choked by migrating dunes and has seen them exhumed and covered again in successive weeks (Figure 7). Further figures obtained by radiocarbon 14 dating indicate that some of the stumps partly exposed on the mainland shore at Bellefontaine Point are late Pleistocene, not Recent, and that they belong to another sea level cycle.

In direct support of Price's belief in an oceanic standstill, Priddy cites the stability of the wooded cores of the barrier islands which form the south limit of the Mississippi Sound and which have been catching and holding quartz sand and a few heavy minerals for many centuries. It is this stability which, in Priddy's opinion, also accounts for the trapping of other "heavies" on the higher mainland shores and on the beaches of Deer Island and Round Island, both near the mainland.

MAINLAND

The Mississippi mainland shores are about 80 percent sand beaches and 20 percent broad, tidal, grassy marshes. The sands are mostly quartz but they contain 1 to 2 percent heavy minerals. As the marshes are very high in organic content, they are not considered of consequence except in places where waves have eroded grassy headlands and left narrow, low beaches. Foxworth's beach sampling stations are shown on Plate 1.

The wider beaches of quartz sand and disseminated heavy minerals are about half natural and half artificial. In the west, a discontinuous beach has been formed from Clermont Harbor to Bay St. Louis where waves are truncating parallel beach ridges and vales obliquely. Across the Bay of St. Louis starts what is reported to be the longest artificial beach in the world. 26 miles from Pass Christian east to the east tip of the peninsula on which Biloxi is built. Actually, this beach has been created by the pumping of sandy mud ashore to form an apron of sand protecting the toe of a continuous concrete seawall, which protects, in turn, U. S. Highway 90 and the residences and commercial properties inland which are built on ancient beach ridges paralleling the seawall and the Highway. Except for short artificial beaches at Ocean Springs and Pascagoula and for a broad and high natural beach at Bellefontaine Point, the mainland east of Biloxi is chiefly marshland.

BARRIER ISLANDS

The barrier island chain off the coast of Mississippi consists of four islands. From east to west, they are Petit Bois, Horn, Ship, and Cat. The first three are elongate east-west. The latter has two east-west axes and a northeast-southwest axis on the east side.

Petit Bois Island. In 1944 Petit Bois Island was 7.5 miles long and had a maximum width of 0.75 mile in the east half. Dunes on the Island rose to 20 feet above mean sea level at only one point, on the west end. Other dunes of heights above 10 feet extended along the south and north shores far to the east. In 1958, geology students at the Gulf Coast Research Laboratory noted that wave action had removed nearly one mile from the east end.

Horn Island. Horn Island, which was 14 miles long in 1944, attains a maximum width of nearly 0.75 mile across the western half. Several dune peaks reach above 20 feet in elevation but are of very limited extent. Much of the inter-dune area just west of the center of the Island is occupied by brackish water ponds up to several acres. Storm action these last several years has progressively lopped off the eastern two miles.

Ship Island. On some maps Ship Island is shown as a single landmass eight miles in length. However, currently it is in two parts connected by a narrow low tide bar nearly two miles in length, indicating where the Island was cut by the 1946 hurricane. The bar has since been built up, scoured away, and rebuilt several times. In a few places West Ship Island is nearly one-half mile in width. It is now 3.25 miles in length. East Ship Island is a mile in width at its east end and tapers southwest to a blunt point, a distance of two miles. Dune elevations are 10 to 18 feet on both Islands. West Ship Island is important in this report because, as will be shown, the position of long abandoned

Fort Massachusetts indicates how the west tip has grown, and because West Ship Island has a surprising concentration of heavy minerals as determined by Moore.

Cat Island. Cat Island is the most western of the barrier chain and is unique in that it has a huge spit which is perpendicular to the Coast at the east end (Plate 1). Penfound and O'Neill[16] gave a description which is just as applicable today:

> "Cat Island comprises an area of about 7 square miles. It consists of two east-west axes attached at their eastern extremities to a long, narrow, north-south axis which is convex on the Gulf side. The more northerly east-west spit is composed of two to sixteen sand ridges from four to ten feet in height and from a few feet to an eighth of a mile in width. They alternate with parallel depressions in which the floor is usually wet and often continuously covered with water, in some places to a depth of six feet. The other spit includes fewer and lower sand ridges and is mainly marshy in character.
>
> "The north-south spit is very different from either of the foregoing. It is composed of an eroding shoreline on the Gulf side, various hillocks and dunes in the interior and a zone of deposition on the western shoreline. On the Gulf shoreline ghost forests of pine and oak extend more than a hundred feet into the Gulf, and black, peaty soil, which could have been formed only in the marshes, is a conspicuous feature of the lower beach. . . . Throughout the dune area many blow-outs occur, and the Island is constantly changing in topography. At the junction of the east-west spits with the north-south axis the sand is advancing steadily over the marsh. This fact, together with the presence of peaty soil and ghost forests on the Gulf shoreline, indicates that the island is gradually moving westward."

Evidences of erosion on the east (Gulf) side of Cat Island are abundant. Here, old swamps and old beaches are being removed, exposing tree stumps and roots and black peaty soil.

FORMATION OF THE BARRIER ISLANDS

Several theories have been advanced for the formation of the barrier islands. Johnson[17] stated that the barrier islands, which he called offshore islands, were characteristic of an emergent coastline. He believed that the island was originally a submerged feature which was brought above the water by a lowering of sea level or by an upwarping of the crust.

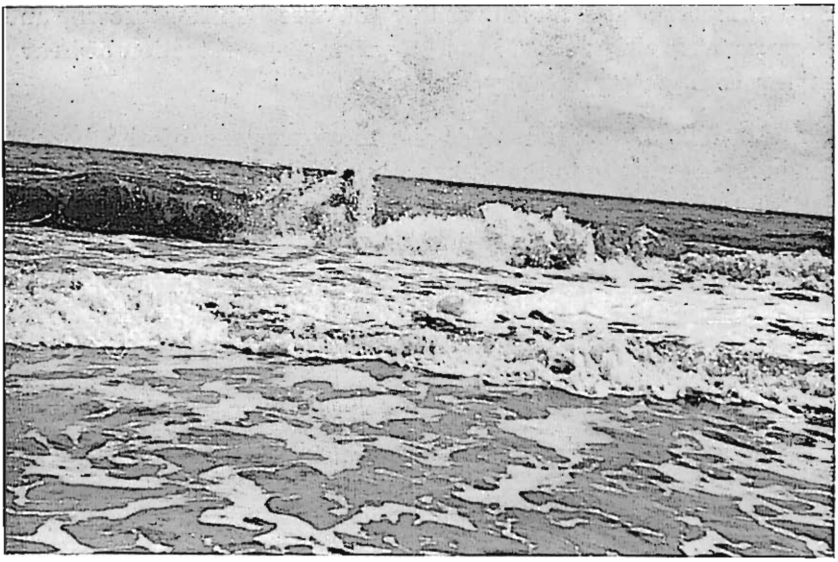

Figure 8.—Swell waves, an agent of heavy mineral transport, Gulf side, Dauphin Island. Spray from the breaking waves nearly covers a six foot man standing in the shallows. Photo by W. S. Moore, June 1959.

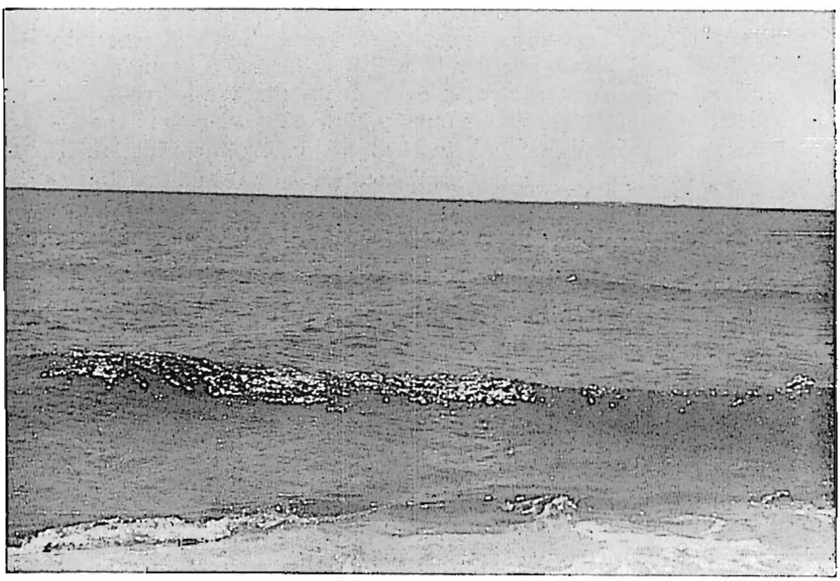

Figure 9.—Cross wave action of the type which moves heavy mineral grains toward beaches, west tip of West Ship Island. Wind waves from the south, in the foreground, are superimposed on ground swell waves from east. Photo by W. S. Moore, August 1961.

But Fenneman[18] concluded that a barrier island was formed as an equilibrium structure on a shallow shelving coast, regardless of its sea level history.

Price[19] concurred with Fenneman. From a study of bottom profiles of the Gulf region, Price believed that the barrier islands should have the following characteristics: (1) they are associated with well developed equilibrium profiles, (2) they are found on shallow coasts, (3) they are associated with areas where sand, gravel, or cobble are abundant along the shore, and (4) they are found where onshore wave attack is strong. Of these, items 1 and 2 apply to the Mississippi Coast. Item 3 also applies in the sense that the muddy bottom contains abundant sand. However, item 4 can not be considered strong.

However, Price[20] again emphasized that bars are the product of exceptionally high sea level caused by storms. He quotes Evans[21] as stating that waves operating at a steady sea level modify underwater bars, but do not tend to build them above sea level. From this information it is concluded that the bars of the Gulf region are begun and built underwater by waves and currents, but that high water of storm intensity is required to bring the bar above sea level. Once above sea level, normal waves and currents can continue to build the island. If this reasoning is correct, the quartz sand and the 2 to 6 percent of heavy minerals on the barrier islands have been derived from the nearby bottoms and transported by abnormal water movements, to be concentrated in bars and beaches by normal waves and currents, especially at high tide. The work of normal swell waves breaking on a calm day are shown in Figure 8. Cross-wave action on another calm day is shown in Figure 9.

SHIFTING OF THE BARRIER ISLANDS

Longshore drift is considered by Price[22] to be the agent bringing sediments to the barrier islands. Priddy believes that this drift combined with wave deposition is responsible for historic shifting of the islands. Foxworth agrees that at present the "heavies" are probably being augmented by currents which sweep from east to west. From Foxworth's study of heavy minerals, from a study of publications, and from old maps of Ship Island, it is evident that the sands necessary for the continued growth of the barrier islands are initially supplied by such currents.

The best evidence of shifting is provided by a map of West Ship Island, a portion of Nautical Chart 1267 (Figure 10). On it is drawn a semicircle west of Old Fort Massachusetts which marks the 1866 terminus of the Island as determined by military maps in The Library of Congress, photostatic copies of which were purchased from the caretaker of the Fort. The comparative position of the west end with respect to the Fort in 1866 and

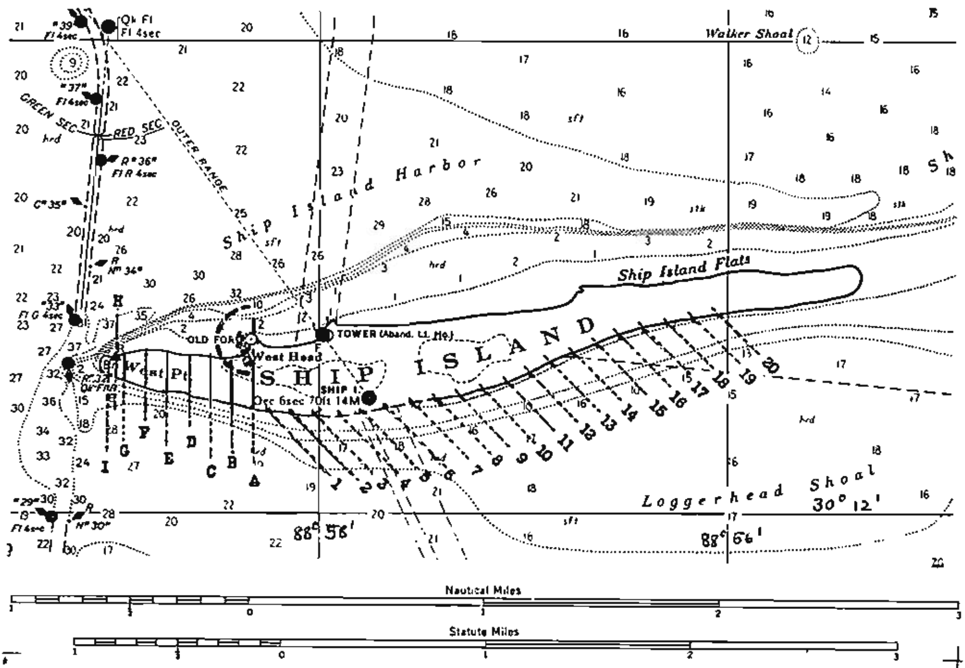

Figure 10.—Map of West Ship Island showing migration of the Island and Moore's sampling stations. The heavy dashed arc indicates the west end of the Island in 1866. Old Fort Massachusetts is now nearly surrounded by Mississippi Sound waters. Nine north-south traverses providing 62 hand auger sites are shown by the lines A through I, west of the Fort. On the Gulf side, east of the Fort, 20 hand auger samples were taken, as indicated. This map is a portion of Nautical Chart 876, revised February 8, 1960.

1957 shows a shift to the south of about 1,100 feet and movement to the west of about 3,200 feet, indicating deposition on the west and south and erosion on the north (Sound) side. The aerial view, Figure 11, shows the erosion of the north shore and the near isolation of the Fort. Evidence that erosion had progressed to near its present stage in 1926 is shown by the group photo-

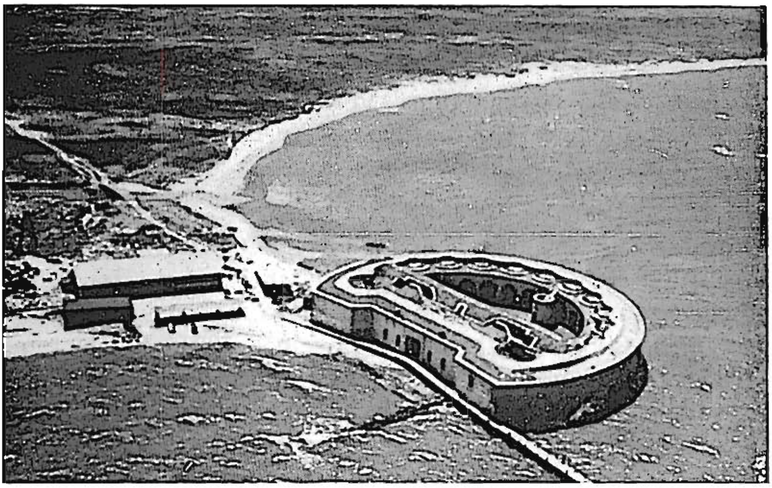

Figure 11.—Aerial view of Old Fort Massachusetts looking southwest across the western part of West Ship Island to the Gulf of Mexico in the distance. The Fort would have long since been cut off by Sound waters were it not for a riprap of igneous and metamorphic rocks at the Fort's left, east side.

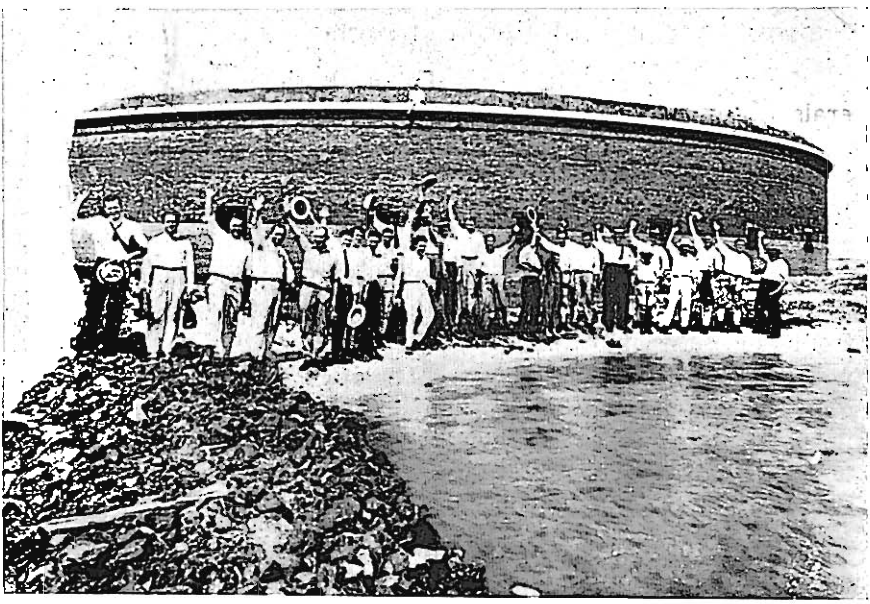

Figure 12.—An illustration of historic beach erosion. Photo was taken in 1926 when a narrow beach still existed on the Sound side of Old Fort Massachusetts, Ship Island. Today the Fort is nearly surrounded by water as the Sound shore has receded and the Gulf side advanced seaward. Photo compliments of Mr. J. R. Anderson, Gulfport, Mississippi.

graphed on the narrow beach on the Sound side of the Fort (Figure 12).

Brown, *et al.*[23] have emphasized the migration south by pointing out that, about three miles east of Fort Massachusetts on the Island's north side, a flowing well is about 100 yards from the shore, a well which was originally located on the Island.

Similarly, maps in possession of the Gulf Island National Wildlife Refuges, Biloxi, Mississippi, show that Horn Island has been extended westward nearly two miles since 1848, but that there has been little extension since 1929. In September 1960, a storm swept away nearly two miles of the east end although there has as yet been no noticeable westward compensating growth.

Instead, a pronounced southward shift of the treeless, west one-fourth of Horn Island, is indicated by aerial photos. The photos show that beach ridges and lakes which trend west-northwest—east-southeast are being truncated obliquely on the north (Sound) side and that the west three miles has been extended due west by Gulfward growth of storm berms.

It is therefore evident that the quartz sands and heavy minerals which make up the bulk of the barrier islands are now moving westward—some by currents within the Sound and some by Gulf currents aided by wave action. In theory, those sands presently included in the Gulf muddy bottoms are Pleistocene materials deposited subaerially through runoff of the Mississippi-Alabama coastal plain when glacial seas were much lower than now. By the same reasoning some of the sands derived from the Mississippi Sound were deposited with finer materials when Pleistocene seas were a little higher. But these Sound muds are doubtless being augmented today by quartz sand, heavy minerals, silt, and clay brought in by existing streams which were periodically more active than now, during the glacial stages of the Pleistocene.

DEER ISLAND AND ROUND ISLAND

In addition to collecting "heavies" from the mainland and from the barrier islands, Foxworth sampled sands of Deer Island bordering Biloxi Bay and sands of Round Island at the mouth of the Pascagoula River. The high beaches of both islands are attributed to combined wave and current action which winnowed clastics brought in by rivers. Aerial photos suggest that Deer Island started as a bar at an earlier sea level stage, before the lower reaches of the Biloxi River system were drowned to make the Bay. As Round Island changes size and shape yearly, it is evident that even now waves and currents are winnowing river borne sediments at the mouth of the Pascagoula.

HEAVY MINERAL TRANSPORT, DEPOSITION, AND CONCENTRATION

Only a few of the mechanics of heavy mineral transport and deposition are understood because currents shift frequently and because winds and tides are constantly changing. Rarely is a set of conditions maintained long enough to complete a study. Within hours, even minutes, one of the three may change. To date it appears that longshore currents and swell waves are the most sufficient in moving "heavies" shoreward; that wind waves assisted by high tides are most effective in depositing them on beaches; and that storm waves, rain runoff, and dry winds are best at concentrating the heavy minerals once they are on the beaches.

TRANSPORT BY LONGSHORE CURRENTS

Unfortunately it is impossible to see currents moving "heavies" in the Sound. One must guess the current's efficiency by its behavior and the work it has done. The following observations (and deductions) as to transport by longshore currents must suffice:

(1) Longshore currents move east to west at rates of 1 to 3 miles per hour on the Gulf side of Dauphin, Petit Bois, Horn, and Ship Islands. Aided by incoming tides the movement is at 3 to 6 miles per hour, probably scouring the shallow sandy muds and sands which comprise the nearshore bottoms.

(2) These currents are also the chief agent in moving the Islands westward, as already explained in the "Formation of the Barrier Islands."

(3) Longshore currents at rising tide move north through the passes between the Island and into the Sound at rates of 1 to 3 miles per hour.

(4) On early ebbing tide the surface currents are reversed. They move west along the Sound side of the Islands, at rates of 2 to 4 miles per hour, and enter the Gulf through the passes. Deeper currents are, at the same time, still moving east through the deep and narrow channels, Plate 1, behind the Islands, presumably scouring the bottom sands and marls.

Figure 13.—Laminae of "heavies" draped over a tide berm. On the crest the laminae thicken. East side of Cat Island at middle of its east arm. Photo by W. S. Moore, August 1960.

(5) On late ebbing tide both the shallow and deep longshore currents race out through the passes at rates of 4 to 8 miles per hour, which if sustained, emphasize the southward convexity of the bars at the pass mouths (Plate 1). Within the last 100 years, both the shallow and the deep outward moving currents have removed a portion of the Sound side of West Ship Island (Figures 11 and 12).

(6) Except for Cat Island which is now being reworked extensively on its east end, Figure 13, the east end of each barrier island contains fewer "heavies" than the

west end, Figures 2 and 4, hence heavy minerals must be in transit westward.

(7) Heavy mineral grain sizes are progressively smaller from island to island, westward, according to H. B. Scott, a 1959 student in Marine Geology at the Gulf Coast Research Laboratory, as recorded in a course report.

(8) The same decrease in grain size is shown by Foxworth's sampling as recorded in terms of median diameters, Table 2, discussed later in this report.

(9) Longshore currents are rarely noted along the mainland beaches except where the slow westward movement combines with wave action in winnowing the sands forming the apron which protects the nearly straight Pass Christian-Gulfport-Biloxi artificial beach. That the "heavies" are actually moving is evidenced by trapping them in cans buried to the lip. A small concentration of "heavies" is thus ready to be put ashore by wind waves.

TRANSPORT BY TIDAL CURRENTS

Tidal currents, rather than longshore currents, are more effective in transporting "heavies" along the mainland beaches:

(1) Combined with wave action, tidal currents make bay mouth bars of sand, Plate 1, at the mouth of the Bay of St. Louis, the east tip of Biloxi Peninsula, the mouth of Old Fort Bayou, and the mouth of Davis Bayou. In these bars the "heavies" to quartz sand ratio is as great as 1 to 20 rather than 1 to 100 as in adjacent muddy bottoms.

(2) Also, combined with wave action, tidal currents maintain a small spit on the northwest end of Deer Island opposite Biloxi, on the west tip of Marsh Point southeast of Ocean Springs, and near Pascagoula at the entrance to Graveline Bayou, and on the northwest side of Round Island.

(3) Combined with wave action tidal currents make three broad aprons of sand containing more than the usual

amount of "heavies," south and southeast of Deer Island, south of Round Island, and northeast of Round Island.

TRANSPORT BY SWELL WAVES

In heavy mineral transport it is easy to recognize the role of swell waves. The term "swell waves" is used here because Priddy has observed that these are the agents which move most of the "heavies" shoreward (northward) but deposit few of them, whereas wind waves throw them on the beach and then help concentrate the heavy minerals by winnowing away the lighter weight quartz sand.

Swell waves are defined as high amplitude waves generated at sea by a storm. They may pound toward a shore in the calmest weather and with surprising force (Figure 8). These waves are efficient in moving "heavies" shoreward because they have wave heights of 1 to 4 feet and wave lengths of 20 to 50 feet. Thus swell waves ground in waters 1 to 4 feet in depth and scour the bottom, holding the sands suspended in the surf long enough for the next swell wave to carry the materials forward, both the lighter quartz fraction and the "heavies."

The transporting ability of swell waves may be amazing because they may pound a beach for days, usually aided by prolonged high tides which were piled high by the same storm which produced the waves. Further, movement shoreward by swell waves may be increased by oblique wind waves, Figure 9, which help suspend particles torn from the bottoms. Thus successive swell waves can carry more "heavies" shoreward.

The angle at which the swell waves attack the shore is believed to be of great importance in moving "heavies." Priddy and Smith[24] have demonstrated that bars are driven ashore more rapidly if the waves strike obliquely. In this way broad aprons of sand are readied for wind waves to deposit on the beaches. In making the study in the clearer Gulf waters of Horn Island, sand grains of quartz and "heavies" alike, were actually seen to move, by traction, as en echelon bar crests moved at rates of 10 feet per hour at angles of 20 to 70 degrees toward the shore. In contrast, bars approaching shores at 90 degrees moved much slower. Arcuate berms noted in aerial photos show that swell waves striking obliquely from the southeast have gradually built the west tip of West Ship Island seaward, compensating for the erosion of its Sound side by longshore currents, as explained in "Shifting of the Barrier Islands" (Figures 10 and 11). Of special interest in this report are the surprisingly heavy mineral concentrates here, as described by Moore.

Figure 14.—Tidal flat paved with heavy minerals overlying white quartz sand, east side of Cat Island at the middle of its east arm. Photo by W. S. Moore, August 1960.

WIND WAVES DEPOSIT HEAVY MINERALS

Photographs prove conclusively that wind waves are the most important depositors of heavy minerals on the beaches, either without aid or when accompanied by high tides.

The work of wind waves depends on winnowing. This process can be observed in a few minutes at the swash line where wind waves, generated by even gentle breezes, slap quartz sand and some "heavies" onto the shore. Then, as each wave is spent, the back rush of water returns most of the light weight quartz sand to the sea but maroons the heavy minerals on the forebeach.

During squalls the wave height increases so the sands are moved higher onto the beach. Then the "heavies" are deposited as a berm, a ridge several inches in height and a foot or two in breadth (Figures 2, 4, and 13). If the squall occurs at or near high tide the ridge is termed a high tide berm. Successive berms may be built one atop another as indicated by several convex laminae of "heavies" (Figure 13). As the wind waves are making the high tide berm, an occasional larger wave sloshes over the ridge and distributes the quartz sand and the included "heavies" in a tidal flat (Figure 14).

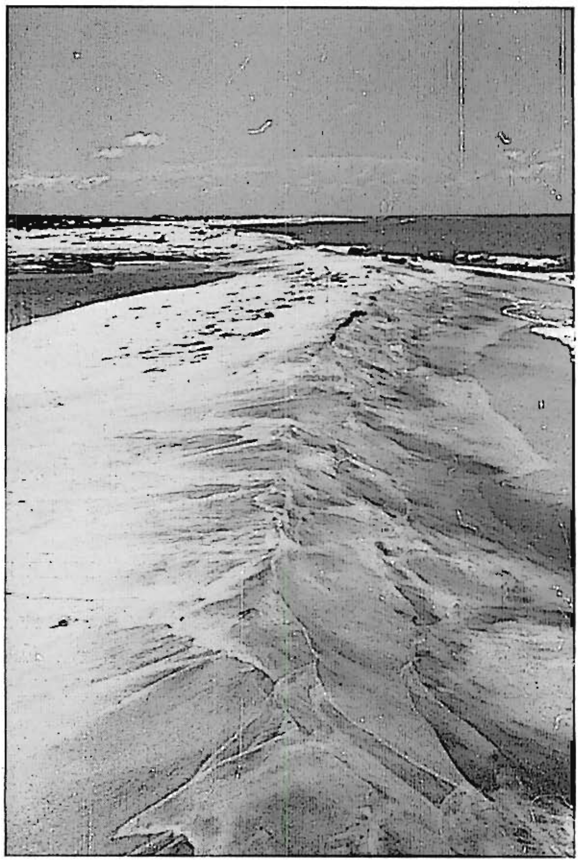

Figure 15.—Wind waves redistribute "heavies" where the waves roll over narrows. Darker sands are heavy minerals. Low tide. This east tip of Horn Island was swept away by a storm, September 1960. Photo by W. S. Moore, August 1960.

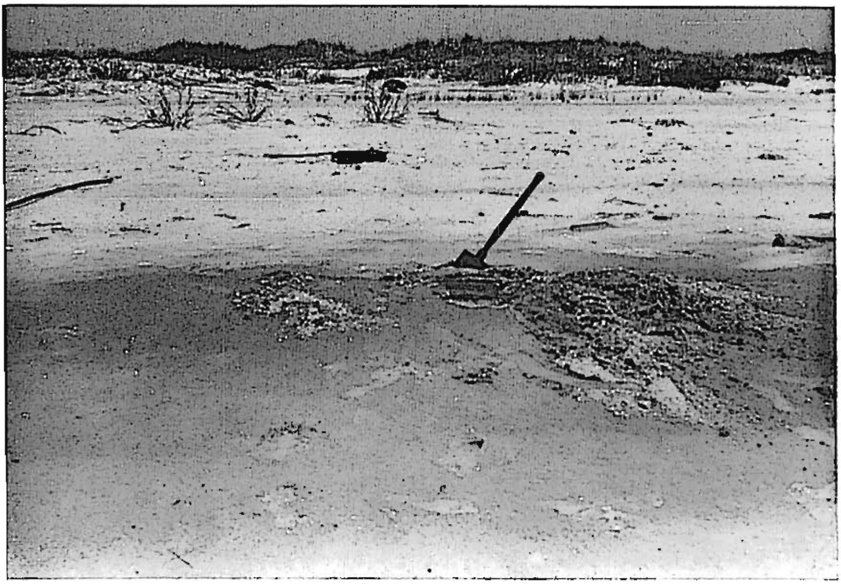

Figure 16.—Pavement of "heavies" created by storm waves reworking the sands. Behind first line of sand dunes, Gulf side of West Ship Island at hand auger station 10. Photo by W. S. Moore, August 1961.

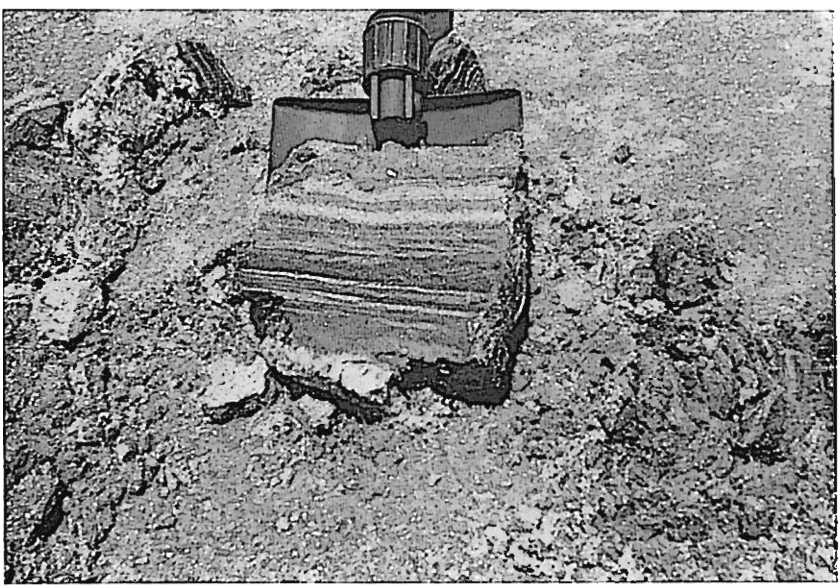

Figure 17.—Spade full of back beach "heavies" where successive wind waves had over-topped a storm berm. Heavy mineral laminae are dark, quartz laminae are light. Gulf side of West Ship Island at station 17. Photo by W. S. Moore, August 1961.

Figure 18.—Dark "heavies" on a back beach, Gulf side of West Ship Island at hand auger hole 5. The bed was 4 inches in thickness and analyzed 54 percent heavy minerals. Photo by W. S. Moore, August 1961.

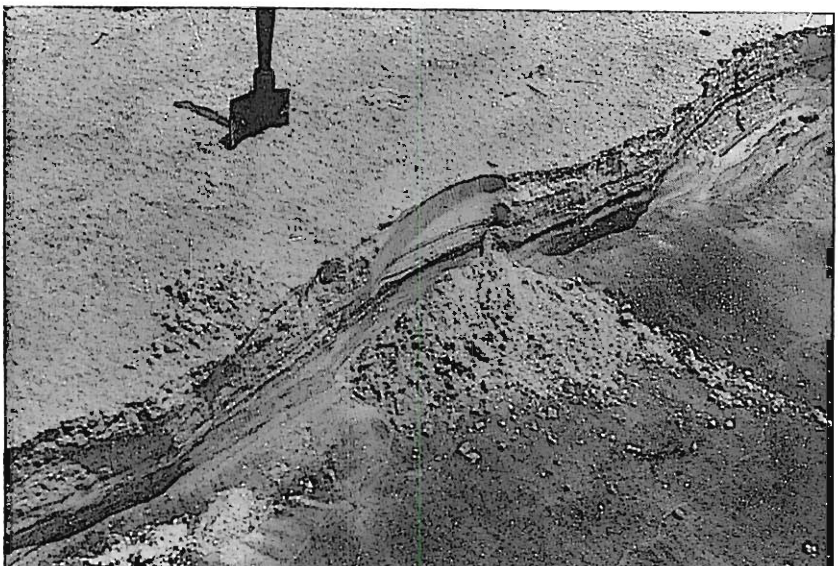

Figure 19.—Eroding beach redistributing "heavies" at ebbing tide with moderate wind wave action. The heavy minerals in the foreground form a laminae on a high angle forebeach. Hand auger station 7, Gulf side, West Ship Island. Photo by W. S. Moore, August 1961.

WIND WAVES CONCENTRATE HEAVY MINERALS

Although the authors have not observed the work of wind waves during actual storms, visits shortly thereafter indicate that, in places, the waves have concentrated thick beds of heavy minerals on the beaches. As autumn and winter storm waters roll across the narrower parts of the barrier islands they may redistribute the "heavies" and quartz sand alike (Figure 15); or they may rework the sands far inland where the islands are broad but low, to form pavements of "heavies" among sand dunes (Figure 16); or they may maroon the heavy minerals on a back beach where the larger waves overtop storm berms (Figure 17 and 18).

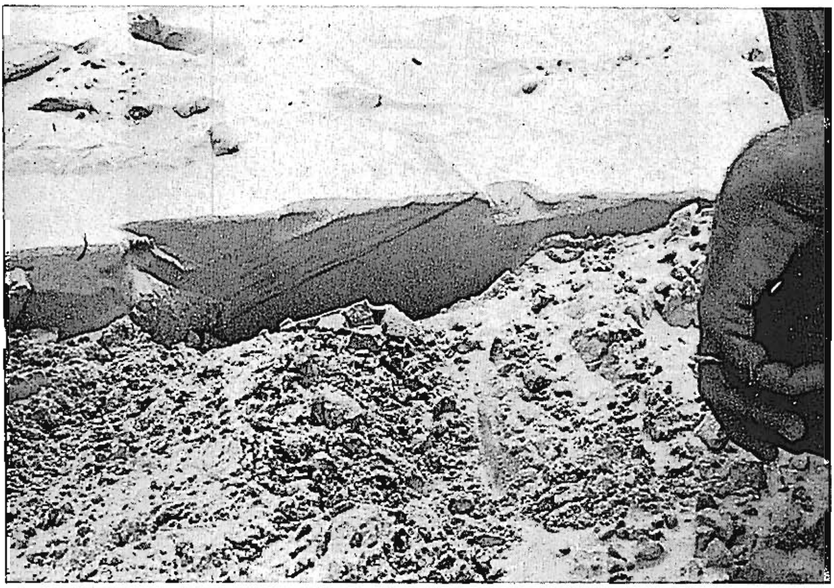

Figure 20.—Inclined laminae of heavy minerals being exposed, Cat Island, east end, north spit. These "heavies" show the depositional slope of old forebeaches. Photo by W. S. Moore, August 1961.

However, even moderate wind waves may erode beaches and return some of the "heavies" to the sea, to be cast on shore by subsequent moderate waves (Figure 19). Under these conditions laminae of "heavies" among beds of quartz sand are being spread on the high angle forebeach. Interesting records of successive forebeach heavy mineral deposits are frequently exhumed (Figure 20). In places, excavations to determine the extent and concentration of heavy minerals have revealed the records of complicated wind wave deposition and erosion, probably over several seasons (Figure 21).

Figure 21.—Intertongued beds of "heavies," Gulf side of West Ship Island, due south of "6 sec. flashing beacon," at hand auger hole 6. The concentrate tested 52 percent "heavies." Photo by W. S. Moore, July 1959.

RAINWASH CONCENTRATES HEAVY MINERALS

On the low beaches, especially on those of the barrier islands and those surrounding Biloxi Bay, excessive rains rework the interbedded "heavies" and quartz sand. This is another form of winnowing for here the light weight quartz grains are washed down the gentle slopes and the heavy minerals are left behind as pavements. Excavations by Moore to determine the concentration of "heavies" on the west tip of West Ship Island and on the Gulf side have revealed many such pavements. One ripple-marked heavy mineral pavement covering several acres is renewed each Spring on the Gulf side of West Ship Island, opposite Old Fort Massachusetts (Figure 22).

DRY WINDS CONCENTRATE HEAVY MINERALS

On the Mississippi Coast the term "dry winds" is used to denote wind action unaccompanied by rain. Dry winds concentrate heavy minerals by winnowing only after rains have washed the salt water from the sands of a berm, backbeach, or tidal flat. At any season winds up to 15 miles per hour are maintained on the Coast for as much as a week at a time, and for some minutes winds on the edge of a squall may reach velocities of 30 to 40 miles per hour.

Both are responsible for dune building, Figures 3 and 7, where light weight quartz sand and smaller grains of "heavies" are moved alike. At first observation there appears to be little sorting but blowouts and storm cuts in the dunes indicate stronger winds where laminae of heavy minerals are inclined. Further, the dunes on the Gulf side of a barrier island contain more "heavies" than those on the Sound side, testifying to transport on the Islands of the quartz sand farther by prevailing winds from the Gulf.

However, the greatest winnowing by dry winds is accomplished on the berms, Figure 23, and on the tidal flats, Figure 24. In a stiff breeze one can watch quartz sand blowing, leaving the "heavies" behind as a pavement. In a lighter breeze quartz sand may cover a pavement of heavy minerals.

SAMPLING OF HEAVY MINERALS

Most of the samples of heavy minerals collected were obtained by Foxworth in July-August 1956 or in August 1957. His sampling locations are shown on the map (Plate 1). His findings comprise Table 1, "Analyses of Heavy Minerals in Mississippi Sound Beach Sands." The analyses of few other samples taken by Priddy and Moore in July-August 1958, July-August 1959, March-April 1960, and August 1960, are not recorded here because they merely confirm the findings of Foxworth. Moore collected for eight days in July-August 1961, from the west end

Figure 22.—Fresh water ripple marks in heavy mineral pavement, Gulf side of West Ship Island, opposite the Fort. Later, winds filled the trough with white quartz sand. Photo by R. R. Priddy, April 1960.

Figure 23.—A storm berm concentrate of heavy minerals being covered with quartz sand by dry winds, station I 7, Gulf side of West Ship Island. Note the white quartz sand forming wind ripples and piling in the lee of the shovel. Photo by W. S. Moore, August 1961.

of West Ship Island, west of Old Fort Massachusetts, and one day from the Gulf side of the remainder of West Ship Island, Figure 10, to determine thicknesses of the deposits and percent "heavies," not mineral analyses.

Most of Foxworth's samples were taken from the forebeaches, the area which lies between high and low tide. One exception is a lamination sample from the center of Ship Island which is above normal high tides but which is underwater during storms.

COLLECTION OF SAMPLES

Two techniques in sampling were used in collecting heavy minerals, coring the thicker beds and scraping the thinner beds, laminations. Four-inch cores were obtained where trenching indicated a concentrate of dark sands at least that thickness. A can, open at both ends, was thrust into the deposit and then the can and core were lifted out after the surrounding sand had

Figure 24.—Wind ripple marks on a tidal flat paved with "heavies," Sound side, west end of East Ship Island. Photo by W. S. Moore, July 1959.

been dug away. Laminated "heavies" were shaved from concentrates of less than one inch in thickness by the blade of a trenching tool. Approximately 300 grams of heavy minerals were collected by each method.

Not all deposits, even the richer appearing ones, were sampled. Only those sands were used which were easily accessible at high normal tide and which could be relocated on charts or maps. Concentrates which had collected in the lee of driftwood and other temporary obstructions were passed by.

Foxworth, Priddy, and Moore, experienced difficulties in sampling because of squalls at any time of the year, usually rough water on the Gulf side of the barrier islands, shoal water approaches to many beaches, and lack of geographical control. The later drawback will be rectified as soon as the class in Civil Engineering, which is now based at the Gulf Coast Research Laboratory late each summer, establishes permanent survey stations.

CODE NUMBERS OF SAMPLES

A simple method of coding the samples was used. A letter represents the general locality of sampling and a number shows a specific locality, Plate 1 and Tables 1, 2, 3, 4, and 6 (to be discussed later). General locality designates are:

ML	Mainland	PB	Petit Bois Island
C	Cat Island	D	Deer Island
S	Ship Island	R	Round Island
H	Horn Island		

Further, the method of taking the samples is explained by the code. For example, ML-2 indicates that the "heavies" were obtained by coring whereas ML-2a indicates that dark sand was scraped from laminations at the same locality as ML-2. The purpose of collecting surface laminated heavy minerals was to make comparisons with the core samples as to grain size and mineral content.

The same code is used in recording mineral analyses of the "heavies" (Table 1). Table 1 is entitled "Analyses of Heavy Minerals in Mississippi Sound Beach Sands."

SAMPLE LOCATIONS

(Plate 1, Table 1)

Mainland		
ML 1	Core	narrow beach, just east of mouth of Bayou Caddy
ML 2	Core	broad beach, Bay St. Louis city pier
ML 2a	Lamination	broad beach, Bay St. Louis city pier
ML 3	Core	broad beach at Pass Christian, old Marine school

ML	3a	Lamination	broad beach at Pass Christian, old Marine school
ML	4	Core	broad beach, east Gulfport along U. S. Highway 90
ML	4a	Lamination	broad beach, east Gulfport along U. S. Highway 90
ML	5	Core	broad beach, Edgewater Gulf Hotel, U. S. Highway 90
ML	6	Core	broad beach, in Biloxi, opposite tip of Deer Island
ML	7	Core	broad beach, Ocean Springs, municipal pier
ML	8	Core	narrow beach, apex of Bellefontaine Point
ML	8a	Lamination	narrow beach, apex of Bellefontaine Point
ML	9	Core	narrow beach, Pascagoula municipal beach at River mouth
Round Island			
R	1	Core	narrow beach, south side, at abandoned lighthouse
R	1a	Lamination	narrow beach, south side, at abandoned lighthouse
Deer Island			
D	1	Core	narrow, steep beach, middle of Island, northeast side
D	2	Core	sandy spit, northwest end, opposite Biloxi
D	3	Core	wide, low beach, middle of Island, southwest side
Cat Island			
C	1	Core	broad beach, north tip of north arm of Island
C	2	Core	broad beach, middle of Island, east end
C	2a	Lamination	broad beach, middle of Island, east end
C	3	Core	broad spit, west end of south arm
C	3a	Lamination	broad spit, west end of south arm
C	4	Core	narrow spit, west end of Island
C	4a	Lamination	narrow spit, west end of Island
C	5	Core	narrow beach, middle of Island, north side, old harbor
C	5a	Lamination	narrow beach, middle of Island, north side, old harbor
Ship Island			
S	1	Core	blunt bar, west end of Island
S	1a	Lamination	blunt bar, west end of Island
S	2	Core	broad but low beach, middle of Island, Gulf side
S	2a	Lamination	broad but low beach, middle of Island, Gulf side
S	3	Core	(omitted because of contaminating peat)

S	3a	Lamination	narrow storm berm, middle, north side, at old dock
S	4	Core	bar at stream mouth, middle, north side
S	4a	Lamination	bar at stream mouth, middle, north side
Horn Island			
H	1	Core	broad beach, 2 miles from east tip, south side (this beach swept away, Sept. 1960)
H	1a	Lamination	same as H-1
H	2	Core	narrow, low bar, east tip of Island (this bar swept away, Sept. 1960)
H	2a	Lamination	same as H-2
H	3	Core	wave cut cliff of sand, middle, north side
H	4	Core	(omitted because most of dark material proved peat)
H	4a	Lamination	broad beach, 2500 feet east of west tip, south side
Petit Bois Island			
PB	1	Core	steep, narrow bar, west end of Island
PB	1a	Lamination	steep, narrow bar, west end of Island
PB	2	Core	broad beach, middle of Island, north side
PB	3	Core	blunt low bar, east end of Island
PB	3a	Lamination	blunt low bar, east end of Island

LABORATORY METHODS AND PROCEDURE

In the laboratory Foxworth prepared each sample of sand containing heavy minerals for mechanical analysis. The sands were first sized, then the "heavies" were separated, the minerals were identified, and the frequencies were counted. The methods used are described in considerable detail in order that further studies may be made easier. The laboratory procedure used is outlined on the flow sheet (Figure 25).

MECHANICAL ANALYSIS

The samples Foxworth collected at the 27 locations, Plate 1, weighed about 300 grams each. These sands were reduced by the quartering method to about 150 grams. The portions were then washed, weighed, and allowed to dry at room temperature for several days. The dried materials were split, using a Jones-type sample splitter, to 100 grams and weighed to the nearest gram on a torsion balance.

Each sample was screened through a set of Tyler sieves which was shaken by a Tyler Rotap machine equipped with an automatic timer. Shaking was for 15 minutes, the time recom-

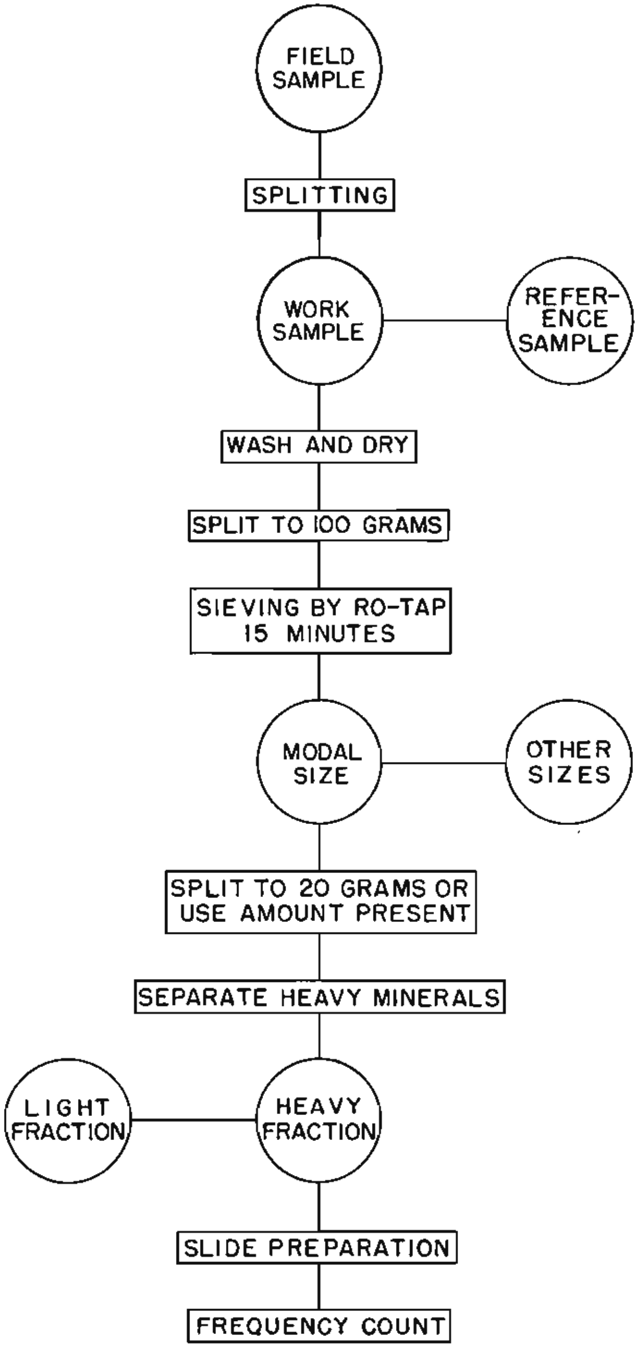

Figure 25.—Flow sheet for laboratory procedure.

mended by Keller[25], who found that under similar conditions of analysis at least 12 minutes shaking was necessary to give percentages reproducible to within one percent.

The combination of seven sieves used were based on the $\sqrt{2}$ and $\sqrt[4]{2}$ scale, and the sieves were chosen so that the openings corresponded as nearly as possible. The sieve sizes used and the corresponding phi numbers are recorded in Table 2.

TABLE 2

SIEVE SIZES AND CORRESPONDING PHI NUMBERS

Tyler Sieves	*Phi Numbers*
0.991 mm	0
0.495 mm	1.0
0.351 mm	1.5
0.246 mm	2.0
0.175 mm	2.5
0.124 mm	3.0
0.061 mm	4.0
Pan	

After sieving, the weight of sand remaining on each screen was recorded and the fractions were filed for the heavy mineral separation and analysis. The size distribution of the samples is shown by weight in grams (Table 3). The code numbers designate collecting points (Plate 1).

The data obtained are represented by the logarithmic phi scale, following after Krumbein[26]. The logarithmic equation $\phi = \log_2 E$ (where E is the diameter in mm of the grains) when applied to the Wentworth scale gives integers for those Wentworth grades used. These integers greatly simplify the computation of the quartile functions. The phi numbers that correspond to the grade sizes used are shown in Table 2.

TABLE 3

SIZE DISTRIBUTION OF THE SAMPLES BY WEIGHT, IN GRAMS
(SAMPLES ARE BY CODE, PLATE 1)

Sample	.991 mm	.495 mm	.351 mm	.246 mm	.175 mm	.124 mm	.061 mm	Through .061 mm (pan)
ML-1	T	1	7	40	47	6	T	T
ML-2	T	2	5	27	51	14	1	
ML-2a		T	1	16	54	23	5	1
ML-3	T	22	41	23	11	3	T	T

TABLE 3—(CONTINUED)

ML-3a		T	1	9	35	35	20	1
ML-4	2	19	18	22	23	15	2	T
ML-4a	T	2	11	26	37	22	3	T
ML-5		7	15	36	34	8	1	T
ML-6		2	10	35	40	13	T	T
ML-7	1	3	7	20	43	22	4	T
ML-8	T	6	26	51	15	2	T	T
ML-8a		1	11	43	31	12	2	T
ML-9		T	4	37	45	12	1	1
D-1		2	16	47	31	3	T	
D-2	T	21	39	33	7	1	T	
D-3		1	5	30	53	11	1	
D-3a		T	6	28	42	18	6	1
R-1	T	4	15	38	34	7	1	1
R-1a		T	2	13	51	26	8	1
C-1		T	22	63	14	1	T	
C-2		1	5	45	45	5	T	
C-2a		T	1	26	53	17	4	T
C-3		1	5	50	39	4	1	T
C-3a	T	1	2	13	56	25	4	T
C-4		1	3	45	47	4	1	T
C-4a		T	1	21	57	15	7	T
C-5	T	T	4	32	54	10	1	T
C-5a		T	1	14	59	19	7	T
S-1		T	2	42	44	8	3	T
S-1a		T	T	6	31	36	25	1
S-2	T	3	10	41	31	13	3	T
S-2a		T	1	10	32	44	12	2
S-3a		T	1	8	31	34	25	1
S-4		4	9	48	32	6	2	
S-4a		1	1	10	28	38	19	2
H-1	T	6	29	52	11	1	T	T
H-1a		1	8	34	35	18	3	T
H-2	T	6	21	55	17	1	T	
H-2a	T	10	7	12	57	13	T	T
H-3	T	15	45	37	3	T	T	
H-4a		T	T	4	45	43	7	1
PB-1	T	27	43	24	6	T	T	
PB-1a		3	6	42	35	13	1	T
PB-2	T	33	60	6	T	T	T	T
PB-3		4	10	39	31	15	1	T
PB-3a		1	11	61	22	4	T	T

*T indicates that a trace of material was present.

The quartile and median values were obtained by plotting cumulative curves for all samples. The median and quartile values are reported in phi numbers by reading directly from the cumulative curves. The median is found by reading the values where the 50 percent line intersects the curve. The first and third quartiles are found by taking readings where the 25 and 75 percent lines, respectively, intersect the curve.

The phi median diameter is the diameter which is larger than 50 percent of the diameters in the distribution, and smaller than 50 percent, according to Krumbein and Pettijohn[27]. The first quartile ($Q_1\phi$) is the diameter which has 75 percent smaller than itself and 25 percent larger than itself. The third quartile ($Q_3\phi$) is the diameter which has 25 percent of the distribution smaller than itself and 75 percent larger than itself.

The quartile deviation ($QD\phi$) was computed by substituting the quartile values directly in the equation

$$QD\phi = (Q_3\phi - Q_1\phi)/2$$

The quartile deviation is a measure of average spread of the curve.

Quartile and median values ($Md\phi$) and the quartile deviations are shown as parts of Table 4.

TABLE 4

DATA FROM CUMULATIVE CURVES

$Q_1\phi$ FIRST QUARTILE, $Md\phi$ MEDIAN, $Q_3\phi$ THIRD QUARTILE, $QD\phi$ QUARTILE DEVIATION, $Skq\phi$ SKEWNESS, AND So COEFFICIENT OF SORTING

Sample	$Q_1\phi$	$Md\phi$	$Q_3\phi$	$QD\phi$	$Skq\phi$	So
ML-1	1.9	2.0	2.2	.15	.05	1.11
ML-2	1.9	2.2	2.4	.25	—.05	1.19
ML-2a	2.0	2.3	2.6	.30	0	1.23
ML-3	1.0	1.4	1.7	.35	0	1.27
ML-3a	2.2	2.6	3.0	.40	—.05	1.33
ML-4	1.1	1.8	2.3	.60	—.1	1.48
ML-4a	1.7	2.3	2.5	.40	—.2	1.31
ML-5	1.5	1.9	2.2	.35	—.05	1.27
ML-6	1.8	2.0	2.3	.25	.05	1.19
ML-7	1.9	2.2	2.5	.30	0	1.23
ML-8	1.4	1.7	1.9	.25	—.05	1.18
ML-8a	1.7	2.0	2.2	.25	—.05	1.18
ML-9	1.8	2.1	2.3	.25	—.05	1.19
D-1	1.6	1.9	2.1	.25	—.05	1.17
D-2	1.0	1.4	1.7	.35	—.05	1.26
D-3	1.9	2.1	2.3	.20	0	1.14
D-3a	1.9	2.1	2.5	.30	.1	1.23
R-1	1.6	1.9	2.2	.30	0	1.23
R-1a	2.1	2.3	2.6	.25	.05	1.20

TABLE 4—(CONTINUED)

C-1	1.5	1.8	2.0	.25	—.05	1.20
C-2	1.7	2.0	2.3	.30	0	1.23
C-2a	1.9	2.2	2.5	.30	0	1.23
C-3	1.7	2.0	2.2	.25	—.05	1.18
C-3a	2.1	2.3	2.5	.20	0	1.15
C-4	1.8	2.0	2.3	.25	.05	1.19
C-4a	2.0	2.2	2.5	.25	.05	1.17
C-5	1.9	2.1	2.3	.20	0	1.14
C-5a	2.1	2.3	2.5	.20	0	1.15
S-1	1.8	2.1	2.2	.20	—.2	1.14
S-1a	2.3	2.7	3.0	.35	—.05	1.28
S-2	1.7	2.0	2.3	.30	0	1.23
S-2a	2.3	2.6	2.8	.25	—.05	1.19
S-3a	2.3	2.7	3.0	.35	—.05	1.28
S-4	1.7	1.9	2.1	.20	0	1.14
S-4a	2.2	2.6	3.0	.4	0	1.33
H-1	1.3	1.6	1.8	.25	—.05	1.19
H-1a	1.7	2.1	2.5	.40	0	1.31
H-2	1.5	1.8	1.9	.20	—.1	1.15
H-2a	1.9	2.1	2.4	.25	.05	1.18
H-3	1.1	1.4	1.7	.30	0	1.26
H-4a	2.1	2.5	2.8	.35	—.05	1.28
PB-1	1.0	1.1	1.6	.30	.2	1.23
PB-1a	1.8	2.0	2.3	.25	—.05	1.19
PB-2	0.9	1.1	1.3	.20	0	1.15
PB-3	1.7	2.0	2.3	.30	0	1.23
PB-3a	1.6	1.8	2.0	.20	0	1.15

If the frequency curve is symmetrical, the median exactly coincides with the point halfway between the first and third quartiles, but if the curve is asymmetrical it is said to be skewed. If the curve is skewed, this means the quartiles move away from the median; if the median moves to the left, it indicates that the sample contains a larger amount of coarse material than fine material, and if the median moves to the right, there is more fine material. This phi skewness (Skqϕ) was computed by substituting the quartile values in the formula propounded by Krumbein and Pettijohn[28].

$$Skq\phi = 1/2\,(Q_1\phi + Q_2\phi - 2Md\phi)$$

To determine the sorting coefficient (So) of the samples, a method proposed by Trask[29] was used. This sorting coefficient can be determined by two methods: as advocated by Krumbein and Pettijohn[30] who used the formula

$$QD\phi = \log_2 So$$

to draw a conversion chart from which the value of So may be read directly if the QDϕ is known; or the formula

$$So = Q_1/Q_3$$

can be used, but the quartile measurements can not be logarithms.

Skewness (Skqϕ) and coefficient of sorting (So) are shown as parts of Table 4.

Average medians, quartile deviations, and sorting coefficients are shown in Table 5 for the entire Mississippi Sound area and for the islands and the mainland. Similar data has been prepared for all the lamination and core samples (Table 5).

TABLE 5

AVERAGE MEDIAN, QUARTILE DEVIATION, AND SORTING COEFFICIENT FOR ALL SAMPLES

Location	Mdϕ	QDϕ	So
Total area	2.02	0.28	1.21
Deer Island	1.87	0.27	1.20
Round Island	2.10	0.27	1.20
Cat Island	2.10	0.24	1.18
Ship Island	2.37	0.29	1.22
Horn Island	1.91	0.29	1.22
PB Island	1.60	0.25	1.19
Mainland	2.03	0.31	1.24

TABLE 6

AVERAGE MEDIAN, QUARTILE DEVIATION, AND SORTING COEFFICIENT FOR 19 LAMINATION SAMPLES AND 27 CORE SAMPLES

Type Sample	Mdϕ	QDϕ	So
Lamination	2.30	0.29	1.33
Core	1.83	0.27	1.20

SELECTION OF GRADE SIZE FOR HEAVY MINERAL STUDY

Foxworth's selection of grade size of heavy mineral sand grains for optical examination, line 2 of Table 1, was based chiefly on studies made by Rubey[31]. This investigator believed that the best choice is the modal size, the fraction which represents the same relative position within the size-distribution curve of each sample. However, the selection has several weak points: (1) the variations in size caused by abrasion of grains are not eliminated, (2) variations in size due to irregular size-distribution of the heavy minerals in the source rocks are not eliminated, (3) the ability of large waves to set on shore both small and large grains where as gentle waves can only deposit small grains, and (4) color pleochroism and birefringence of different grains are not easily compared when sizes are different.

Fortunately, in those heavy minerals of the Mississippi Coast studied, the variation in modal size is rather small. The range in 98 percent of the modal sizes was either 0.124, 0.175, or 0.246 mm. A single anomaly is size 0.351 in H-3 sample (Table 1). In 70 percent the sizes were 0.124 or 0.175 mm. By experiment Foxworth discovered that samples which showed the same modal size yielded comparable results.

A method for selecting sizes for study recommended by Rubey[32] was also tried but was abandoned. The idea is to choose grains of two sizes and mix them, first a relative size and second the actual size, or the same grain size for each sample. The difficulty in applying this method was that "heavies" in some Gulf Coast samples of beach sand were insufficient to mix them with other samples in equal proportions.

HEAVY MINERAL SEPARATION

A heavy liquid is used to separate heavy minerals from the sieved fractions of washed Gulf Coast beach sand samples. The medium is satisfactory for laboratory extraction but it is far too expensive for commercial use. To remove the "heavies" economically various electromagnetic, electrostatic, and flotation procedures must be used.

In the laboratory the heavy liquid chosen by Foxworth was tetrabromethane, as advocated by Twenhofel and Tyler[33], which has a specific gravity of 2.96 at 20 degrees Centigrade. However, because of its availability, Moore used bromoform (specific gravity 2.89) for extracting the "heavies" from the beach sands of West Ship Island which he collected in 1961. Bromoform is the medium used by Milner[34] in techniques he developed. In studying insoluble residues of Indiana and Ohio Niagaran rocks, Priddy[35] employed a "heavy" Thoullet's Solution, a saturated water solution of potassium iodide, potassium hydroxide, and mercuric iodide which was difficult to control because of varying humidity and temperature. The specific gravity of tetrabromethane and bromoform varies slightly with vapor pressure, not with humidity and temperature.

Whichever heavy liquid is used, the point to remember is that "heavies," those minerals having a density of at least 2.72, are separated from quartz sands whose specific gravity is 2.65.

The equipment used by Foxworth and Moore for extracting the heavy minerals by heavy liquids is simple: (1) a funnel battery in which glass funnels can be mounted on a top row and other glass funnels can be placed beneath them on a bottom row, (2) funnels equipped with rubber tubing and pinchcocks, (3) filter paper inserted in the funnels of the lower row for trapping the "heavies," (4) small beakers to catch the used heavy liquid drained through the filter paper, (5) acetone or carbon tetrachloride which is used to wash the "heavies" free of heavy liquid, tetrabromethane and bromoform, respectively, and (6) stirring rods and watch glasses.

The following are the steps in the separating procedure which must be followed either in a chemistry hood or out of doors:

(1) Close pinchcocks at bases of the upper funnels;

(2) Introduce enough heavy liquid to make these upper funnels 3/4 full;

(3) Add 20 grams of whatever grade size of sand is selected for extraction of its "heavies";

(4) Alternately stir and let settle for one hour;

(5) Open pinchcocks and permit the "heavies" to drain into the lower funnels where they are caught on filter paper;

(6) As soon as the heavy liquid drains through the filter paper and is being caught in beakers below, the "heavies" are washed repeatedly, with acetone if tetrabromethane is used, or with carbon tetrachloride if bromoform is used, to remove excess heavy liquid;

(7) Remove filter paper containing "heavies" as soon as they are air-dried;

(8) Reload lower funnels with filter paper, open pinchcock, collect light weight sand grains on the paper, save the heavy liquid for further use, and discard the light weight grains; and

(9) Air-dry the "heavies" for several days at room temperature, weigh this heavy fraction, record weight, and store heavy mineral separates in glass vials whose labels record sample number, grain size, and weight, preparatory to identifying the minerals and making frequency counts of the several minerals.

After the separated fraction had dried for several days at room temperature, the heavy fractions were weighed and the weights recorded. The "heavies" were then stored in glass vials for later study, for making frequency counts, for identification of mineral species, and for determining phi medians, sorting coefficients, and skewness.

FREQUENCY COUNT OF HEAVY MINERAL GRAINS

Before mounting the grains of "heavies" for a frequency count, Foxworth considered three problems: (1) could similar minerals be distinguished in the grain mounts; (2) in what mounting medium should the grains be studied; and (3) what should be the length of the frequency count?

Because it is difficult to distinguish between magnetite and ilmenite it was desirable to remove one. Due to its magnetic intensity (I), magnetite was easily withdrawn by an electromagnet, leaving the ilmenite which has a magnetic rating of II. On weighing the residue of heavy minerals, the difference was recorded as percent magnetite (Table 1).

Then the samples were studied under the petrographic microscope to determine the frequency of the remaining mineral grains. Three mounting media were considered: Lakeside 70 cement, Canada balsam, and piperine. The first two could not be used because the indices of refraction are too low to permit rapid identification of the non-opaque "heavies." In contrast, piperine was satisfactory because its high index of refraction of 1.680 is fairly close to those of most of the heavy minerals. Further, the piperine mounts are easily made by mixing the grains with piperine powder on a glass slide, heating until melted, and then adding cover glasses. After standing several days the piperine tends to crystallize but this can be prevented by baking the slides at 180° Centigrade for one hour, as suggested by Martens[36].

In many samples heavy mineral grains in the modal size were so numerous that the volume had to be reduced with a Jones-Type micro-splitter before mounting. Such large quantities are, of course, desirable. Most separates studied are in grade size 0.175 (Table 1). However, in other separates the modal sizes did not yield sufficient grains for an adequate count so another grade size in which the "heavies" were most abundant was used, as indicated by the sizes 0.246, 0.124, and 0.351 (Table 1). Although it may be necessary, it is misleading to switch grade sizes when making mineral counts because some mineral species may have larger grains than those of other mineral species in the same sample. An illustration is the two underlined analyses C-2, Table 1, which show pronounced differences in magnetite, ilmenite, kyanite, and staurolite content.

In considering the length of count to be employed, Foxworth tried the method advocated by Chayes[37] who discovered that the critical range for number of frequency analysis is between 500 and 2000 grains, as Chayes[38] shows in a graph. The increased accuracy of a 1000 grain count as to one of 500 grains is graphed as a 2.5 percent error as against an error of only 0.8 percent. Of course, a 500 count is less time consuming.

If the sample volume permitted, Foxworth counted 1000 heavy mineral grains, as indicated on Table 1, where certain analyses have odd decimals. In ML-1, for example, percent and number of grains are related thus:

hornblende	0.50	percent	recognized	5	grains	in	1000
ilmenite	10.10	"	"	101	"	"	"
kyanite	32.10	"	"	321	"	"	"
leucoxine	5.00	"	"	50	"	"	"
rutile	0.50	"	"	5	"	"	"
spinel	0.10	"	"	1	"	"	"
staurolite	27.60	"	"	276	"	"	"
etc.							

In contrast, the first C-2 sample listed in Table 1, was analyzed on a 500 grain count, where the decimals are even numbers:

magnetite	6.20	percent	recognized	31	grains	in 500
hornblende	0.60	"	"	3	"	" "
ilmenite	7.20	"	"	36	"	" "
kyanite	30.40	"	"	152	"	" "
staurolite	24.60	"	"	123	"	" "
etc.						

All counts were made by using a click type mechanical stage. Only those grains were counted which passed under the cross-hairs of the petrographic microscope.

Figure 26.—Photomicrograph (left) of West Ship Island "heavies." Total magnification 43.2; uncrossed prisms; Ansco Veraspan fine grain film, speed 40. Photographed by Johnson and Smith, July 24, 1961. Tracing from film on the right. Mineral grains designated thus: E epidote, I ilmenite, K kyanite, Le leucoxene, M monazite, Mg magnetite, R rutile, c-P clino-pyroxene, o-P ortho-pyroxene, and Z zircon.

IDENTIFICATION OF HEAVY MINERALS

The minerals in the heavy mineral suites were studied by conventional petrographic methods. Foxworth's extracts were restudied by Johnson. Johnson agreed with Foxworth's mineral identifications with but three minor exceptions, all are depicted in the photomicrograph, Figure 26, of a Ship Island sample collected in 1960. It is Johnson's preference to place augite, diopside, and pigeonite in the difficult to differentiate clino-pyroxene group. By the same reasoning, he would prefer to call Foxworth's hypersthene (enstatite) ortho-pyroxene, another difficult group. In his inspection of beach heavy mineral separates, Johnson discovered 0.3 percent monazite grains, unreported by Foxworth, a mineral of no consequence in the Sound but very important in Florida.

Actual identification of the minerals comprising the "heavies" was first made by the single grain method—immersing them grain by grain, in the conventional index oils. Once the individual grains were recognized their optical properties were measured in piperine mounts. After several slides had been carefully studied, mineral grains could be identified and counted by observing relief, color, pleochroism, and cleavage. In this procedure Winchell's *Elements of Optical Mineralogy, Part II—Descriptions of Minerals,* 1951, was the chief reference. Where mineral grains were unidentifiable by the petrographic scope, Foxworth resorted to X-ray analyses. Any further study of the heavy minerals should be patterned after the same method.

RESULTS OF MECHANICAL ANALYSES

Data obtained from Foxworth's mechanical analyses are interesting but the samplings were too far spaced to furnish much information on the heavy mineral grain size in the beaches and dunes of the whole area. In this respect, Moore's close hand-augering of West Ship Island, Figure 10, represents the near ideal method in obtaining sands for size and mineral studies.

Further, the sizes of Foxworth's 27 cored sands, Table 1, must not be compared with the sizes in his 19 lamination samples because the latter are by definition thin deposits of "heavies" marooned on the beaches by gentle wind waves. Laminae were scraped up for the express purpose of determining if their "heavies" were different from storm deposited "heavies." In general, most grains in laminae are the smallest in beach sands and the most prevalent in dunes (Table 1).

PHI MEDIAN

The average phi median of all the lamination samples is 2.30 (0.20 mm), and the average phi median of all the core samples is 1.83 (0.28 mm) (Table 6). Hence the lamination sand is smaller than the typical beach sand as represented by the core samples. The difference is to be expected because the lamination samples were laminae of concentrated heavy minerals and because these heavy minerals are predominantly fine-grained. As stated above, no valid comparison can be made between the areas, but the general trend indicates that the sand becomes finer to the west. This seems to have some relation to the direction of the prevailing currents (from east to west). Probably with additional work a direct correlation of the two can be made for this area.

SORTING COEFFICIENT

The sorting was measured by the coefficient of sorting (So) suggested by Trask[39]. Mechanical analyses of the heavy mineral grains showed that both the core and lamination samples are well sorted, in the range 1.11 to 1.48 with an average of 1.21 (the average So for good sorting is 2.5 or less). The difference between core and lamination samples is actually very small (Table 6).

SKEWNESS

The quartile skewness in all samples is also very small (Table 4). Only three samples skewed appreciably (ML-4a, S-1, and PB-1). There were 20 samples with minus skewness, 8 with plus skewness, and 18 with zero skewness.

RESULTS OF HEAVY MINERAL ANALYSES

The heavy minerals of the mainland and island beaches of the Mississippi Sound are 27 in number, as recognized by Foxworth. They are listed in Table 1, which also indicates (1) the sample code number corresponding to the 46 samplings (and one repetition, C-2) shown on Plate 1, (2) the grade size of "heavies" examined, and (3) the weight percent of heavy sand separate used. The magnetite content is shown in percent by weight, the material removed by an electromagnet. Because of their similar optical properties, several minerals are recorded in pairs—augite and diopside, dolomite and siderite, limonite and hematite, and pyrite and marcasite. Four varieties of tourmaline are differentiated, abundant brown and much less abundant blue, green, and colorless.

DESCRIPTION OF MINERALS

The mineral identifications and the abundance determinations are by Foxworth (Plate 1). Johnson used Foxworth's piperine slides and unmounted grains and some "heavies" collected in 1961 to review Foxworth's identifications. Chemical formulae are included in the discussion of 19 minerals below; the conventional formula on the left and the type formula, if different, on the right. There are also observations on the source or sources of each mineral, based on Milner[40], unless otherwise indicated.

Andalusite Al_2SiO_5 Al_2OSiO_4

Colorless; occurs in irregular, sub-angular grains. The grains are clouded by inclusions which are possibly carbonaceous.

Possible Source. Granites and contact metamorphic rocks.

Epidote $Ca_2(Al, Fe, Mn)_3(OH)Si_3O_{12}$ $Ca_2Al_2OHSi_3O_{12}$

Only a minor amount of epidote was found. The grains observed were lemon-yellow in color and irregular to subangular in shape.

Possible Source. Metamorphic rocks, especially altered impure limestones, also from altered igneous rocks.

Garnet $Ca_3Al_2Si_3O_{12}$ $A_3B_2(SiO_4)_3$ where A=Ca, Fe″, Mn″

and where B=Al, Fe‴, Cr

Under petrographic microscope only the colorless variety of garnet was found. However, study under the stereoscope revealed a few grains of pink garnet. Both varieties were well rounded.

Possible Source. Metamorphosed limestone, schist, nepheline-syenites.

Hornblende $Ca_4Na_2(MgFe)_8(AlFe)_2(Al_4Si_{12}O_{44})(OH,F)_4$

Brown to greenish-brown in color, somewhat platy and elliptical to elongate in outline. Most grains are pleochroic.

Possible Source. Igneous and metamorphic rocks, especially granite, syenite, diorite, diabase, gneiss, and mica schist.

Ilmenite $FeTiO_3$

Opaque, brown to black with submetallic luster and tinge of purple in reflected light. The grains are plentiful. They are irregular to rounded. The white alteration product, leucoxene, can be observed on some of the grains.

Possible Source. Common in many igneous and metamorphic rocks, such as granite, syenite, diorite, diabase, gneiss, and mica schist (Kraus, Hunt, and Ramsdell, 1951, p. 292).

Kyanite Al_2OSiO_4

Colorless, tabular, elongate in direction of the "c" axis and partings 90 degrees to the elongation. Usually the elongate grains are rounded along the edges. Other grains are somewhat elliptical in outline and do not show partings. Inclusions are common and some grains are highly altered.

Possible Source. Metamorphic rocks, especially mica schists and certain gneisses.

Leucoxene TiO_2

Opaque, white to yellow-white in reflected light. Grains are irregular to subrounded in shape with very highly pitted surfaces. An X-ray defraction analysis was run to verify the identification. The "d" spacings were identical to those of rutile. This confirms the conclusions of Tyler and Marsden[41], that leucoxene does not exist as a distinct mineral species. They restrained the name to designate micro-crystalline TiO_2.

Possible Source. Generally believed to be an alteration product of ilmenite.

Limonite $Fe_2O_3 \cdot nH_2O$ *and Hematite* Fe_2O_3

The total amount of these minerals is so small and they are so difficult to separate that they are grouped. Both are brown to yellow and opaque. Limonite is yellow-brown in reflected light whereas hematite is red.

Possible Source. Priddy believes that both minerals may be deposited in the shallower bottoms surrounding the islands during the influx of saltier waters. They may, also, be oxidation products of iron or steel cast on beaches in driftwood, later to be eroded, and still later to be thrown on the beaches by wind waves. Again, limonite and hematite may be oxidation products of pyrite and marcasite formed in nearshore reducing bottoms, carried into saltier water, and cast on the beaches by waves.

Mineral X

Very small grains, too small to identify by petrographic scope and too small to pick out for X-ray analysis—hence *Mineral X*. The grains are colorless, elongate prismatic, have parallel extinction, and an index of refraction greater than 1.680.

Pyrite FeS_2 FeSS *Marcasite* FeS_2 FeSS

Mineral grains and slightly abraded crystals or crystal clusters of pyrite or marcasite are found in about half the beach sands, although in very small amounts. Both minerals are opaque and have a brassy yellow color in reflected light.

Possible Source. Because both minerals oxidize rapidly, they are believed to be indigenous to the Sound. Both Barton[42] and Snowden[43] described them in their theses dealing with inshore bottoms where reducing conditions were prevalent. Similar reducing conditions exist in places along the barrier islands where the shores are marshy.

Rutile TiO_2

Brownish-red to deep-red grains varying in shape from well-rounded to irregular. The thicker, dark-red grains are nearly opaque. Some grains are striated.

Possible Source. Acid igneous rocks and some metamorphic rocks. Frequently derived from the decomposition of ilmenite.

Siderite $FeCO_3$

Gray, rounded to sub-rounded grains. Has prominent rhombohedral cleavage lines. Often stained brown along the cleavages.

Possible Source. Clay ironstone and allied stratified deposits. Also from metalliferous veins.

Sillimanite Al_2OSiO_4

Highly altered grains not identifiable by petrographic microscope but recognized by X-ray diffraction.

Possible Sourse. Metamorphosed limestone and dolomitic limestone. In some schists.

Spinel (Fe, Mg)Al_2O_4 (Mg, Fe, Zn, Mn) (Al, Cr) $_2O_4$

Subrounded to rounded, green to blue grains; isotropic. Difficult to distinguish from garnet under petrographic microscope so checked by X-ray diffraction analysis. (Spinel is also called pleonaste.)

Possible Source. Metamorphosed limestones and dolomitic limestones. In some schists.

Staurolite $HF_2Al_9O_8Si_4O_{16}$

Plentiful red-brown, brown, and yellow-brown very irregularly shaped grains marked by hackly to subconchoidal fracture. All grains are pleochroic. Inclusions are common.

Possible Source. Some schists. In contact metamorphic rocks.

Tourmaline $(Na,Ca)_5(Al,Fe,Mg,Mn,Ti)_{27}(Si,B)_{27}O_{86}(OH)_4$

$XY_3Al_6(OH)_4(BO_3)_3Si_6O_{18}$

X=Na,Ca, rarely K Y=Mg,Al,Li,Fe, etc.

Plentiful grains varying from brown to blue to green to colorless with brown the most common. Some grains are perfect hexagonal crystals; others are somewhat rounded elongate grains; and some are transparent to translucent.

Possible Source. Pneumatolytic acid igneous rocks, pegmatites, some schists, some gneisses, and some phyllites.

Zircon $ZrSiO_4$

Colorless grains of two types; prismatic grains which are slightly rounded, and elliptical to well-rounded grains. Inclusions are common and are mostly alligned with the elongation.

Possible Source. Acid and intermediate igneous rocks; less commonly in some schists and metamorphosed limestones.

HEAVY MINERAL TRANSPORT INTO MISSISSIPPI SOUND

It is obvious that most of the minerals in the "heavies" described above and listed in Table 1 have been brought into the Mississippi Sound from a metamorphic-igneous source. Foxworth repeatedly noted that they were transported by rivers heading in the southern Appalachians, a view that other writers before him held and a belief that later students have enlarged. Several expressions of an Appalachian origin for the heavy minerals are mentioned briefly in "Other Investigations."

In the next few pages Priddy ventures to interpret these writings and explain (1) how these heavy minerals were brought into the Sound, (2) why the Mississippi Coast "heavies" differ from the residual "heavies" in the southern Appalachians, (3) how some were incorporated in sedimentary rocks and later released by erosion, and (4) why there is such a great variation in the size and shape of a heavy mineral grain. The study may seem academic but it may lead to the finding of "heavies" inland in Mississippi, in the higher beaches of the Gulf Coast, in upland river deposits, and in upland marine sands or marls which mark ancient strandlines.

PRESENT DRAINAGE CONTRIBUTES HEAVY MINERALS

The present drainage, which contributes "heavies" to the Mississippi Coast and which has probably carried heavy minerals for several millions of years, consists of five notable rivers and many small streams. The rivers are numbered on the map, Figure 1, from west to east (1) Mississippi, (2) Pearl, (3) Pascagoula, (4) Mobile-Tombigbee, and (5) Alabama. The map also shows the physiographic provinces drained. Roman numerals I, II, and III designate the cycles of erosion of the heavy minerals in each province: Ia first cycle in the Blue Ridge and Ib in the Piedmont where the minerals available for transport are little altered; second cycle IIa in the Ridge and Valley Province and IIb in the Cumberland Plateau where the minerals least resistant to erosion have been lost; and third cycle IIIa in the Cretaceous Coastal Plain and IIIb in the Tertiary Coastal Plain in which only the most resistant minerals of cycle I have survived. Third cycle "heavies" are shown in the first of the photomicrographs by Johnson, Figure 26, of a Ship Island separate. Here, the minerals are kyanite, staurolite, tourmaline, ilmenite, leucoxene, zircon, and rutile, in that order of abundance.

The drainage and heavy minerals data are summarized (Table 7). The percent column is Priddy's estimates of "heavies" now being carried by the rivers into the Sound. The next column shows the areas of the Sound receiving the heavy minerals. Column 4 indicates the area drained, by physiographic provinces. After each province, the cycle of erosion of the heavy minerals contributed is shown by Roman Numerals I, II, III, the designation used in Figure 1.

TABLE 7

NOTABLE RIVERS NOW CONTRIBUTING HEAVY MINERALS TO MISSISSIPPI SOUND
(THE MISSISSIPPI SOUND IS DESIGNATED ON FIGURES 1 AS III, II, I)

Rivers	*Percent "Heavies"*	*Area Receiving*	*Area Drained*	*Erosion Cycles (Figure 1)*
Mississippi	2	extreme west	[a]glaciated Miss. Valley	Ig, IIg, IIIg
			Coastal Plain	IIIb
Pearl	10	west one-fourth	Coastal Plain	IIIb
Pascagoula	8	central part	Coastal Plain	IIIb
Mobile-Tombigbee	30	extreme east	Coastal Plain	IIIa & IIIb
			[b]Cumberland Plateau	IIb
Alabama	30	extreme east	Coastal Plain	IIIa & IIIb
			[b]Ridge & Valley	IIa
			[c]Piedmont	lb
shorter streams	20	central part	Coastal Plain	IIIb

[a]First cycle heavy minerals are contributed by the Mississippi River as surprisingly fresh fragments of assorted igneous and metamorphic rocks derived from the Canadian Shield through glacial erosion, hence the designation Ig. To this material has been added second cycle "heavies" as the Paleozoic rocks of the upper Mississippi Valley were abraided by glaciers and as some second cycle minerals were made available through the fluvatile erosion of the Paleozoics below the glacial border, designation IIg. The River also carries a few third cycle minerals brought in by tributaries draining the Coastal Plain, designated IIIg.

[b]Second cycle heavy minerals eroded from the Paleozoic beds of the Cumberland Plateau, IIb, and from the Ridge and Valley Province, IIa, are brought directly to the Gulf by the Mobile-Tombigbee and Alabama Rivers, respectively. Enroute across the Coastal Plain they pick up third cycle minerals IIIa and IIIb which had been incorporated in those strata.

[c]First cycle "heavies" are derived directly from the igneous and metamorphic rocks of the Piedmont and are carried Gulfward by the Alabama River. Enroute they are augmented by second cycle "heavies" IIa from the Ridge and Valley Paleozoic strata and from the Coastal Plain sediments, cycles IIIa and IIIb.

PHYSIOGRAPHIC PROVINCES CONTRIBUTING HEAVY MINERALS

The exposed rocks are reviewed by provinces, which presently contribute "heavies" to the Sound. Descriptions are generalized and brief because it is beyond the scope of this report to describe individual units except those which are known to contain heavy minerals of at least one percent concentration. The Piedmont Province is considered in some detail because (1) it is thought to be the first cycle source of many of the "heavies" entering the Sound today, (2) because it has been a first cycle direct source for millions of years, (3) because it has furnished most of the heavy detritus which has been incorporated in adjacent Paleozoic consolidated sediments as second cycle "heavies" and (4) because some of which were later reworked as third cycle mineral residues in Mesozoic and Cenozoic deposits which constitute the Coastal Plain. In contrast, the first, second, and third cycle "heavies," Ig, IIg, and IIIg, furnished by the Mississippi River are mentioned briefly because they contribute to sedimentation in the extreme west of the Sound, only.

PIEDMONT PROVINCE, Ib

The rocks of the Piedmont upland of Alabama and Georgia are igneous and metamorphic. They are believed by most geologists to be Archeozoic and Proterozoic in age. Therefore, erosion of these rocks would contribute "heavies" to the adjacent Paleozoic consolidated sediments, to the overlapping Coastal Plain sediments, and to the Sound.

According to Clements[44] the Archeozoic (Archean) rocks are chiefly gneissoid biotite granite, biotite gneiss, biotite augen gneiss, biotite-hornblende gneiss, diorite, olivine diabase, cortlandite, hypersthene gabbro, hypersthene-hornblende, biotite gabbro, pyroxene-hornblende rock, augite norite or hyperite, amphibolite, serpentine, hornblende-mica schist, and quartz schist.

In the younger Proterozoic (Algonkian) rocks of the Piedmont are abundant "heavies," especially in the garnetiferous and biotitic Ashland schist, a metamorphosed sediment. According to Adams[45], these strata were intruded by both acidic and basic dikes and sills making rock masses which are now recognized as irregular bodies of schists of hornblende, amphibole, and pyroxene-epidote. Acidic intrusive rocks include granites which are now mostly gneisses and which contain different quantities of hornblende. These, in turn, are intruded by aplites, pegmatites, and quartz veins. Thus, the Proterozoic beds, too, provide abundant "heavies," only a few of which withstand direct transportation to the Sound. Other weathered heavy detritus is incorporated in the adjacent Paleozoic consolidated strata or in the overlapping Coastal Plain sediments, which, by erosion, contribute cycles II and III heavy minerals to the Sound.

RIDGE AND VALLEY PROVINCE, IIa, CUMBERLAND PLATEAU PROVINCE, IIb

Successively west of the Piedmont plateau are the consolidated sedimentary strata comprising the Paleozoic terrance of the narrow Ridge and Valley Province and the broader Cumberland Plateau Province. These strata are reviewed in detail by Butts[46].

The rocks of the Ridge and Valley are chiefly Cambrian shales and silty sandstones, Cambro-Ordovician cherty dolomites, Ordovician shaly limestones, and Silurian variegated shales. The thick shales and the thinner sandstones received heavy minerals as the nearby Piedmont igneous and metamorphic rocks were folded, uplifted, and eroded, incorporating their detritus as second cycle "heavies."

In the Cumberland Plateau the rocks are chiefly Pennsylvanian coal measure silty shales, silty sandstones, and sandstones. In them are trapped other second cycle minerals which were eroded later from the re-folded and re-uplifted igneous and metamorphic rocks of the Piedmont area.

COASTAL PLAIN PROVINCE

The Coastal Plain sediments overlap the rocks of the other provinces. They are chiefly offlapping sands, gravels, clays, chalks, marls, and claystones, which were deposited in the broad Mississippi Embayment. These beds range in age from Upper Cretaceous to Recent. Most units thicken gulfward, and in so doing become less clastic downdip. Consequently their lapped edges, which are now extensively eroded, may have been early resting places for many of the heavy minerals which are being carried to the Gulf by the Pearl, Pascagoula, Mobile-Tombigbee, and Alabama Rivers (Table 7). This view is in accordance with the ideas of van Andel and Poole[10] who believed that the source of the mineral assemblage in the eastern Gulf was the Cretaceous and younger mantle of the southern Appalachians.

Upper Cretaceous Sediments, IIIa. On the surface in northeast Mississippi the Upper Cretaceous strata are exceedingly complex, as shown by Stephenson and Monroe[47]. However, their simplest sequence is, from base upward: Tuscaloosa gravels and sands; Eutaw sands, shales, and marls; Selma chalk and chalky clay; Ripley sands, chalks, and clays; and Prairie Bluff chalk. A related sequence is noted in Alabama and western Georgia, where the strata are more clastic. The sandier beds contain heavy mineral assemblages in varying degrees of maturity, especially the marls and sands which were deposited on ancient shorelines, well up the dip. As these littoral beds were successively eroded, they furnished the more resistant "heavies" to the younger, Cenozoic strata. Even now they contribute third cycle heavy minerals to the Sound as the outcrops are being eroded.

Cenozoic Sediments, IIIb. Cenozoic sediments by offlap, overlapped the Cretaceous strata in the shrinking Mississippi Embayment. They comprise the surface beds of the Coastal Plain throughout in most of Mississippi and in the southern parts of Alabama and Georgia.

In Mississippi the simplest sequence is Paleocene Midway black shales; Eocene Wilcox clays, sandy clays, and sands; Eocene Claiborne claystones, marls, sands, and clays; Eocene Jackson marine clays and marl; Oligocene limestones, marls, and clay shales; Miocene sands, silts, clays, and shales; and Pliocene gravels in the south one-third of the state. The best reference for detailed study of Paleocene and Wilcox strata is Grim[48]; for upper Wilcox to Miocene is Priddy[49]. Of the rocks mentioned above, the sands, sandy shales, and marls are the best repository for the third cycle heavy minerals. "Heavies" are concentrated at places in the thick Wilcox, Claiborne, and Miocene river-laid sands and are fairly well distributed through the Claiborne and Oligocene marls and marly sands which represent ancient shorelines.

Eastward in Alabama and Georgia the strandlines broaden. Further, many of the Paleocene, Wilcox, and Claiborne strata, which are non-marine in Mississippi, interfinger with marls or marly sands which increase in number and in thickness eastward. Thus many lower Cenozoic strata on the Alabama-Georgia line contain beach concentrated third cycle heavy minerals, providing many "heavies" for direct transport by short streams to the Gulf.

Some third cycle heavy minerals in terrace sands are also available for direct transport. These sands are believed to be the remnants of a Pleistocene alluvial blanket which was deposited atop older Coastal Plain offlapping beds during the several peaks of continental glaciation when streams had much greater carrying power than now. The terraces along U. S. Highway 80 in southeast-central Mississippi have been described recently by Priddy[49]. An analysis of the "heavies" in a terrace sand is on a later page, a sample collected by F. F. Mellen from Wilkinson County in the southwest corner of Mississippi.

ANALYSES OF COASTAL PLAIN HEAVY MINERALS

Several analyses of Coastal Plain heavy minerals are available. Six have been chosen as representative and are recorded here (Tables 8, 9, 10, and 11). Unfortunately, all analyses are not expressed in percent so direct comparisons can not be made.

Table 8 is an analysis by Needham[50] who in 1934 described the heavy minerals of the Upper Cretaceous Tombigbee sand of northeast Mississippi. He concluded that the crystalline complex of the southern Appalachians was the immediate source of the "heavies" and that sedimentary rocks contributed very minor amounts.

TABLE 8

"AVERAGE PERCENTAGE OF HEAVY MINERALS IN THE TOMBIGBEE SAND

Mineral	*Percent*
Epidote	25-50
Garnet	10-25
*Kyanite	10-25
*Ilmenite	10-25
*Tourmaline (Brn)	5-10
Zircon	1-5
Titanite	1-5
Sillimanite	1-5
*Staurolite	1-5
*Tourmaline (Blue)	1-5
Leucoxene	1-5
Biotite	1-5"

*chief "heavies" in Mississippi Sound

Although he did not show percent frequency of the individual minerals, Grim[51] has identified Eocene "heavies" for the whole of Mississippi, which he believes were derived from the southern Appalachian region. The relative amounts of minerals are recorded in Table 9, in a geologic sequence from base upward; Wilcox, Claiborne, and Jackson. In all three strata the four chief minerals are kyanite, staurolite, tourmaline, and ilmenite, as they are in the Mississippi Sound muds and beaches.

TABLE 9

HEAVY MINERALS OF THE EOCENE OF MISSISSIPPI
(ADAPTED FROM GRIM)

Jackson (Upper Eocene)
- Common Minerals
  - *Kyanite
  - *Tourmaline
  - *Staurolite
  - Sillimanite
  - *Ilmenite
  - Leucoxene
  - Rutile
- Common to Rare
  - Xenotime
- Common to Absent
  - Garnet
  - Epidote
- Rare to Absent
  - Andalusite

Claiborne (Middle Eocene)
- *Kyanite—Considerable abundance in every sample
- Zircon—Considerable abundance in every sample
- *Staurolite—Not so abundant as above but in every sample
- *Tourmaline—Small quantity in each sample
- Rutile—Small quantity in each sample
- *Ilmenite—Probably present in every sample
- Leucoxene—Varying amounts
- Sillimanite—Small quantity in 2/3 of samples
- Xenotime—Rare, present in 2/3 of samples
- Monazite—Rare, present in 2/3 of samples

Wilcox (Lower Eocene)
- *Kyanite—Dominant mineral in most samples
- *Staurolite—Not abundant but present in all samples
- *Tourmaline—Varying amounts, present in all but one sample
- Zircon—Considerable abundance, absent in one sample

*chief "heavies" in Mississippi Sound

TABLE 9—(CONTINUED)

Rutile—Small quantity in most samples
*Ilmenite—Small quantity in most samples
Sillimanite—Found in most sands
Leucoxene—Present in more than half of the samples
Others—Rare (epidote, garnet, topaz, anatase, titanite, hypersthene, corundum, xenotime, monazite, spinel, tremolite, biotite, and zoisite)
*chief "heavies" in Mississippi Sound

However, the suite of heavy minerals which Sun[52] presented as average for the whole Jackson Eocene of Mississippi differs from the Jackson "heavies" of Grim. Sun reports more zircon and rutile, as shown in Table 10. It is understandable how two geologists sampling these strata from different places and from different intervals can obtain different analyses, because the Jackson in west Mississippi is comprised of thick Yazoo silty, limy, marine clay overlying thin Moodys Branch marl whereas the thick Yazoo is comprised of marls, sands, and silts interfingering with limy clays near the Alabama line. By the same reasoning, the "heavies" in any composite Jackson section should differ from those in a strandline such as the very sandy Tombigbee, as reported by Needham.

TABLE 10

"AVERAGE PERCENTAGE OF HEAVY MINERALS IN THE JACKSON EOCENE

Mineral	*Percent*
Opaque	51
Non-opaque	49
Zircon	16
*Kyanite	29
*Tourmaline	10
Titanite	3
Rutile	8
*Staurolite	18
Sillimanite	10
Garnet (Spinel)	4
Andalusite	x
Epidote	2"

*chief "heavies" of Mississippi Sound

Unfortunately, systematic analyses of heavy minerals are not at hand for the Miocene, Pliocene, and Pleistocene beds. However, Brown, *et al.*[53] recorded "heavies" in cuttings from water wells drilled on the mainland and on the islands of the Sound. They reported the following minerals in Miocene to Recent strata, but have not attempted to determine their relative frequency: magnetite, siderite, pyrite, hornblende, tourmaline, muscovite, rutile, epidote, ilmenite, zircon, kyanite, staurolite, garnet, leucoxene, sphene (titanite), biotite, and limonite.

Of these, the siderite, pyrite, and limonite were probably formed in place in coastal sandy muds, just as they are today. The remaining "heavies" except biotite and muscovite are found in most Sound beaches and bottoms. It is the contention here that these micas survive in the Coastal Plain fluvatile strata but have been destroyed by abrasion as the "heavies" brought to the sea during Pleistocene glacial time have been reworked many, many times.

Very recently, Parnell[54] has provided some new, but not surprising information on the "heavies" of the old Tombigbee River terraces in northeast Mississippi. His listing shows that these Pliocene (?)-Pleistocene fluvatile deposits have a suite much like that of erosion cycle I in the Piedmont Province. These terrace "heavies" may very well be that "young" if they were transported rapidly by streams which had been rejuvenated by late Pliocene or early Pleistocene uplift. Unfortunately, Parnell indicates only relative amounts of "heavies" (Table 11).

TABLE 11

"RELATIVE AMOUNTS OF HEAVY MINERALS IN OLD TOMBIGBEE TERRACES

Opaque minerals	up to 60 percent
magnetite	equally dominant
leucoxene	equally dominant
limonite	lesser amounts
*ilmenite	lesser amounts
pyrite	lesser amounts
Non-opaque minerals	less than 40 percent
zircon	most abundant
rutile	in all samples, about 10 percent
hornblende	in all samples, less than 10 percent
*tourmaline	in all samples, less than 10 percent
biotite	in all samples, less than 10 percent
*kyanite	trace in all samples
sillimanite	trace in half the samples"

*chief "heavies" of Mississippi Sound

MISSISSIPPI SOUND HEAVY MINERALS COMPARED WITH OTHER COASTAL "HEAVIES"

Other investigations of the coastal heavy minerals from Texas to the Florida Keys and from the Keys to Virginia provide interesting comparisons with the Mississippi Sound "heavies." The segment from Texas to the Mississippi delta was studied to determine the sources of the sands. In contrast, the studies on both coasts of Florida and on the Atlantic Coast as far north as Virginia were undertaken to determine the economic value of the "heavies." Several large scale Florida extraction plants have rewarded these efforts.

Both the academic and economic studies have aided in writing this paper for they have (1) helped explain the sources of heavy mineral grains of sand, (2) confirmed the idea presented of cycles I, II, and III minerals reaching the Sound, (3) shown that some Mississippi beaches are richer in "heavies" than those processed in Florida, and (4) indicated that several of the chief heavy minerals in Mississippi may be of peculiar economic value if they do not lie too low to work.

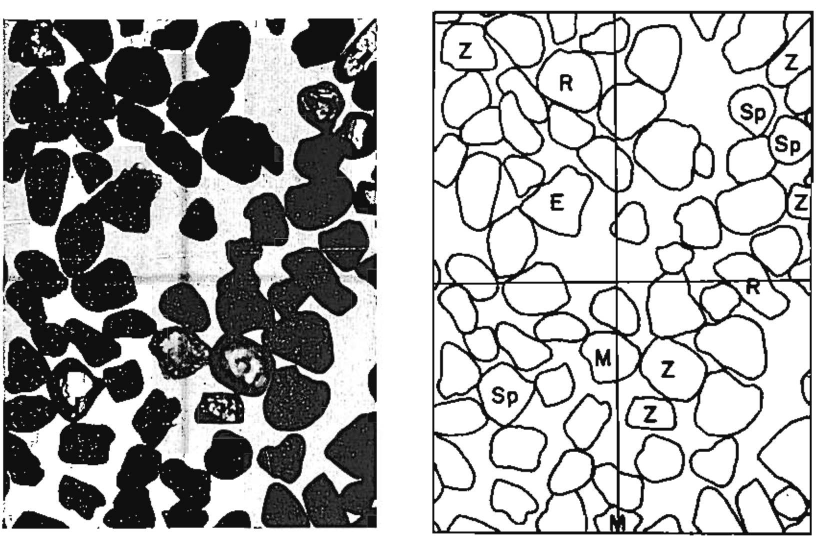

Figure 27.—Photomicrograph (left) of reworked Recent sands from the Mississippi upland, sandbar of Bayou Sara, irregular Section 23, T.1 N., R.2 W., Wilkinson County, collected by F. F. Mellen, June 6, 1960. Photographed by Johnson and Smith, August 1, 1961.

Tracing from film on the right. The unlabeled opaques are a balance of magnetite and ilmenite. Other mineral grains designated are: E epidote, M monazite, R rutile, Sp sphene (titanite), and Z zircon.

SOURCES OF HEAVY MINERAL GRAINS

It has been stated several times that the southern Appalachians is the source of the grains of heavy minerals on the bottoms and in the beaches of the Mississippi Sound. Proof has

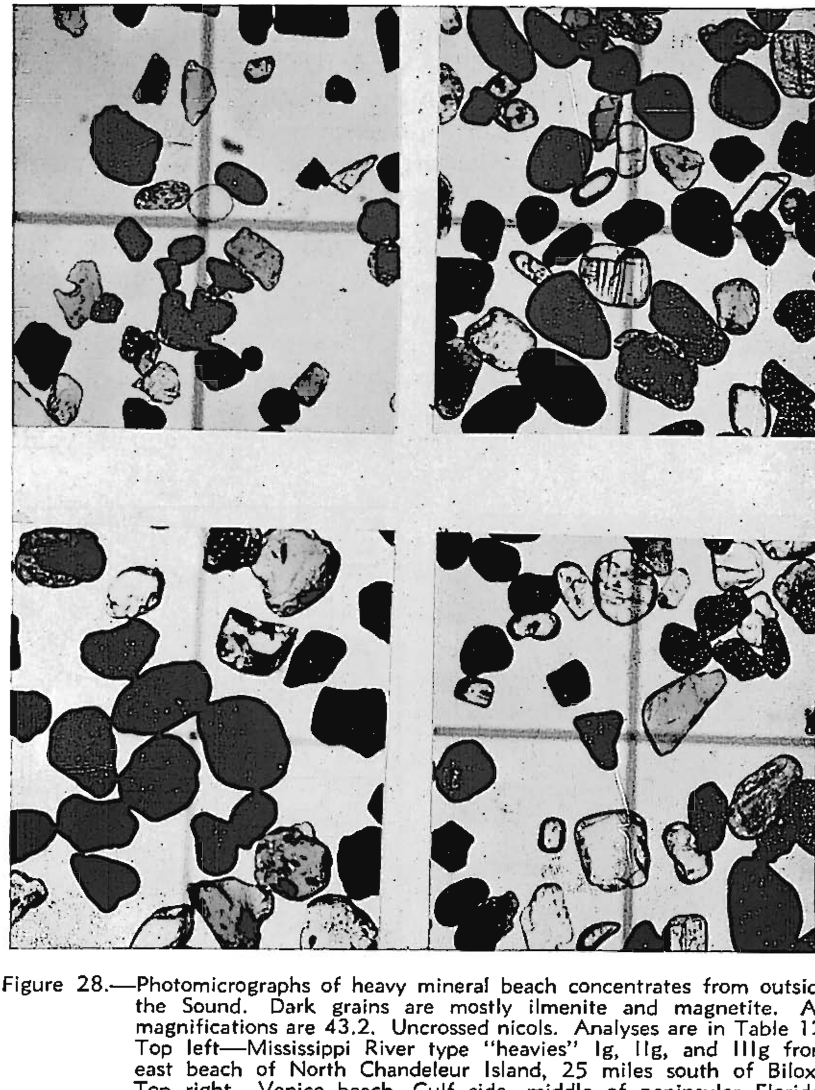

Figure 28.—Photomicrographs of heavy mineral beach concentrates from outside the Sound. Dark grains are mostly ilmenite and magnetite. All magnifications are 43.2. Uncrossed nicols. Analyses are in Table 12. Top left—Mississippi River type "heavies" Ig, IIg, and IIIg from east beach of North Chandeleur Island, 25 miles south of Biloxi. Top right—Venice beach, Gulf side, middle of peninsular Florida. Bottom left—Vero beach, Atlantic side, middle of peninsular Florida. Bottom right—Cape Canaveral beach, Atlantic side, middle of peninsular Florida.

been established by studying published analyses of other Gulf Coast beach sands and Atlantic Coast sands or by making analyses of critical beaches from Cat Island to near Jacksonville, Florida.

Twenty mineral suites are compared with Foxworth's "heavies." Although methods of sampling and reporting are inconsistent, different "heavies" were found and in different proportions than in Mississippi beaches because (1) the source rocks vary, (2) some "heavies" are in surprising amounts due to short transport, and (3) some of the mineral grains were not incorporated in Paleozoic, Cretaceous, or Tertiary sediments to be abraded later as these strata were eroded. Some of these variations are illustrated by the photomicrographs (Figures 27 and 28). A photomicrograph of a Ship Island separate has already been cited (Figure 26).

The numbered statements explain the differences in origin and transport which account for a few of the mineral suites. The chief constituents are compared to Mississippi Sound "heavies" which are a kyanite-tourmaline-staurolite-ilmenite assemblage.

(1) Rio Grande River, Texas.
High epidote, ferromagnesian content from a nearby Tertiary volcanic source.
Analysis by van Andel and Poole.[55]

(2) Brazos River, Texas.
Cycle III pneumatotylic-metamorphic "heavies" eroded from central Texas Cretaceous and Tertiary strata.
Analyses by van Andel and Poole.[55]

(3) Sabine River, Texas.
Cycle III pneumatolytic-metamorphic "heavies" eroded from east Texas and west Louisiana Cretaceous and Tertiary strata.
Analysis by van Andel and Poole.[55]

(4) Mississippi River mouth (South Pass).
Chiefly igneous "heavies" of mixed cycles I and II, freshly derived from glacio-fluvatile material from Canadian and upper Mississippi Valley sources.
Analysis by van Andel and Poole.[56]

(5) Sandbar, Bayou Sara, Wilkinson County, upland Mississippi.
High magnetite, ilmenite, zircon content of "heavies" being eroded from a late Tertiary upland.
Collected by F. F. Mellen, studied by W. B. Johnson.

(6) Average of four bottom samples, Biloxi Bay, Mississippi Sound.
Cycles III, II, and I, chiefly pneumatolytic-metamorphic "heavies" which furnish the ilmenite, kyanite, staurolite, tourmaline suite in the Sound beaches and dunes.
Reported by Snowden.[57]

(7) Beach, North Chandeleur Island, south of Mississippi Sound.
High hornblende, garnet content of "heavies" being concentrated by waves as a Mississippi sub-delta is sinking.
Collected by J. R. Walther, studied by W. B. Johnson.

(8) Tombigbee River, northeast Mississippi uplands.
Cycle IIIa "heavies" eroding from Upper Cretaceous strata.
Analysis by van Andel and Poole.[55]

(9) Beach, Cape San Blas, Florida Panhandle.
A high kyanite, rutile, zircon assemblage transported from a nearby southern Appalachian igneous-metamorphic complex.
Reported by Martens.[58]

(10) Beach, Venice, Florida Gulf Coast.
High magnetite, epidote, hornblende, zircon assemblage contaminated by collophane derived from nearby pebble phosphate deposits.
Collected by W. S. Moore, studied by W. B. Johnson.

(11) Beach, Vero, Florida Atlantic Coast, site of Hobart mining operations for titanium minerals.
High ilmenite, epidote, monazite, rutile, zircon content probably concentrated by an eddy of the Gulf Stream.
Collected by W. S. Moore, studied by W. B. Johnson.

(12) Beach, Mineral City, Florida Atlantic Coast near Jacksonville, site of Humphreys mining operations for zirconium and titanium minerals.

High ilmenite, rutile, zircon content of "heavies" probably concentrated by an eddy of the Gulf Stream. Collected by W. S. Moore, studied by W. B. Johnson.

(13) Average of 265 beach samples from Hilton Head Island, South Carolina.
High ilmenite, epidote, rutile, zircon content of heavy minerals probably concentrated by an eddy of the Gulf Stream.
Reported by McCauley.[59]

CYCLE I, II, AND III MINERALS, ALIKE, MAY ENTER THE SOUND

Heavy minerals of erosion cycles I, II, and III may, alike, reach the Sound (Figure 1). Most have entered by stages which consumed millions of years. A few are transported by the present rivers.

In reviewing Tables 8 through 11, it is apparent that some of the "heavies" have dropped out or where conspicuously reduced in size and in quantity, some through chemical weathering and others by abrasion. A chart, Table 12, has been prepared to show the relative survival and relative mortality of the minerals which are, theoretically, available to the Sound. Lacking actual mineral counts, the relative amounts of heavy minerals surviving erosion are shown in tabular form.

TABLE 12
RELATIVE SURVIVAL OF HEAVY MINERALS, SOURCE TO THE SOUND

MINERALS making grains of "heavies"	probable chief CYCLE I "heavies" in southern Appalachian detritus				probable chief CYCLE II "heavies" from Paleozoic overlap (Priddy)				chief CYCLE III "heavies" eroded from Coastal Plain overlap				average "heavies" in Sound by Foxworth & Johnson, in order of abundance				
	ORDER OF SURVIVAL (A best, B good, C fair, D poor)																
	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	per-cent by count
Staurolite	x				x				x				x				25.7
Kyanite	x				x				x				x				24.1
Tourmaline	x				x				x				x				20.4
Ilmenite	x				x				x					x			11.8
Magnetite	x				x					x					x		3.6
[1]Limonite-hematite															[1]x		3.4
[2]Leucoxene						x					x				[2]x		2.5
Zircon	x					x				x						x	2.0
Rutile	x					x				x						x	1.7
Sillimanite	x					x				x						x	1.3
Andalusite	x						x					x				x	1.1
Mineral X															x		0.5
Clino-pyroxene		x					x					x				x	0.5
[1]Pyrite-marcasite																	0.4
Apatite		x					x					x				x	0.3
Dolomite-						x					x					x	0.3
siderite		x				x					x					x	
Hornblende		x					x					x				x	0.3
Monazite		x					x					x				x	0.3
Titanite	x					x					x					x	0.2
Spinel	x					x					x					x	0.2
Garnet	x					x					x					x	0.2
Epidote		x					x				x					x	0.1
Hypersthene		x						x				x				x	0.1
Topaz	x						x					x					
Xenotime		x						x				x					
Corundum	x						x					x					
Tremolite		x						x				x					
Muscovite		x					x					x					
Biotite		x					x										

[1]locally derived   [2]alteration product of ilmenite

CONCENTRATIONS OF HEAVY MINERALS ON WEST SHIP ISLAND

An idea of the extent of heavy minerals was obtained in July-August, 1961, when Willard S. Moore made nine trips to West Ship Island, Figure 10, to study mineral distribution in beach and dune sands. In eight visits, the west 4,000 feet of the Island were sampled west of Old Fort Massachusetts along nine north-south traverses. On the ninth study, August 31, a narrow belt of heavy concentrates was examined bordering the Gulf side of the Island for a distance of 12,000 feet east of the Fort.

HEAVY MINERALS, WEST TIP OF WEST SHIP ISLAND

The west tip of West Ship Island was selected for a pilot study due to the unusual concentrations of "heavies" which had been noted by Moore during 1958-1960 studies at the Gulf Coast Research Laboratory (Figures 4, 22, and 23). This area had been previously observed as a site of accretion, the Island's west 3,400 feet having been added in the last 100 years and the record of growth having been documented by parallel storm berms and high tide berms of sand, partly of heavy minerals, which are easily discerned on aerial photographs.

Nine north-south traverses were laid out in order to systematically obtain samples to measure the heavy mineral content of the part of the Island west of Fort Massachusetts. This area is some 4,000 feet in length east-west and averages some 750 feet in width, about 72 acres. The seven main sampling lines, A through G, were spaced 600 feet apart, successively west from the Fort. Each line was paced and divided into six equal parts, providing seven sampling locations (Figure 10 and Table 13). Two secondary traverses, H and I, were added nearer the west tip of the Island, 100 and 200 feet west, respectively, of traverse G, to enable detailed study of the low west promontory which is frequently covered during storms. At this tip storm berms are being laid, and there is a rapid change in the type of sediment. These last traverses, H and I, were divided in a manner similar to the main sampling lines but only 6 samples were obtained from traverse I, the most westerly, because of the narrowing of the Island (Figure 10). By this system 62 sampling sites were provided.

At most locations a hole was drilled with a two-inch hand auger. Due to caving, drilling was stopped at the water table which ranged from depths of 0.5 feet to 4.0 feet. At three places sampling was omitted because standing surface water made drilling impossible.

The samples were washed to remove sea salts and organic matter and then dried. A 10 gram portion of a homogeneous sample from each auger hole was then analyzed for percent heavy minerals by bromoform separation, in a manner similar to the use of tetrabromethane as explained by Foxworth.

Time did not permit petrographic differentiation of the heavy extracts from each hole. However, random examinations suggest a mineral suite similar to Foxworth's Ship Island samples S-1, S-1a, and S-2 which showed the chief mineral grains in the order of abundance in percent by count: staurolite 37, kyanite 21, ilmenite 14, tourmaline 9, zircon 6, rutile 5, magnetite 3, and sillimanite 1. Other minerals constituted the remaining 4 percent.

The concentration of "heavies" for each hole is shown in Table 13 which also lists the thicknesses of sand sampled (depth to water table), and a brief description of the adjacent area. The same tabulation also summarizes the percent by weight of "heavies" by traverses. A study of the thicknesses and concentrations reveals that the heavy minerals average 8.6 percent on the Sound side, 7.0 percent in the center of the Island, and 14.9 percent on the Gulf side. With only two exceptions they are also richer progressively eastward, traverse H through traverse A.

TABLE 13

CONCENTRATIONS OF HEAVY MINERALS IN 59 HAND AUGER HOLES, WEST END, WEST SHIP ISLAND

(PROGRESSIVELY WEST OF FORT MASSACHUSETTS, TRAVERSE A THROUGH TRAVERSE I)

Sample Number	Thickness Drilled in Feet	Percent "Heavies" by Weight	Description of Environment
A-1	3.0	7	ridge (Sound Side)
A-2	0.5	9	marsh
A-3	0.5	3	marsh
A-4	0.5	11	thin peat over sand flat
A-5	1.5	9	sand flat south of marsh
A-6	4.0	14	top of dune
A-7	1.5	34	storm berm (Gulf Side)
Average	1.6	12.4	
B-1	3.5	17	small dune or ridge (Sound Side)
B-2	2.0	4	ridge between marshes
B-3	0.5	8	marsh
B-4	1.0	8	flat between marshes
B-5	1.5	12	south edge of marsh
B-6	4.0	25	top of Gulf dune
B-7	1.0	12	storm berm (Gulf Side)
Average	1.9	12.3	
C-1	1.0	5	behind tidal berm (Sound Side)
C-2	0.5	7	marsh
C-3	0.5	10	marsh
C-4	0.5	4	marsh
C-5	1.5	14	sand flat, south edge of marsh
C-6	4.0	8	top of small Gulf dune
C-7	1.5	23	storm berm (Gulf Side)
Average	1.3	10.1	
D-1	1.5	19	behind berm—no dunes (Sound Side)
D-2	1.0	6	thin peat over sand flat
D-3	0.5	6	marsh
D-4	0.5	7	marsh
D-5	----	----	no sample (standing water)
D-6	1.0	15	south base of Gulf dunes
D-7	2.0	17	storm berm (Gulf Side)
Average	0.9	11.7	

TABLE 13—(CONTINUED)

Sample Number	Thickness Drilled in Feet	Percent "Heavies" by Weight	Description of Environment
E-1	1.0	12	behind tide berm (Sound Side)
E-2	1.0	3	south base of Sound dunes
E-3	1.0	4	north edge of marsh
E-4	—	—	no sample (standing water)
E-5	2.0	4	north base of Gulf dunes
E-6	0.5	14	tidal flat
E-7	2.0	17	storm berm (Gulf Side)
Average	1.0	9.0	
F-1	1.0	2	behind tidal berm (Sound Side)
F-2	2.5	5	sand flat
F-3	2.0	4	sand flat
F-4	1.0	8	sand flat
F-5	—	—	no sample (standing water)
F-6	1.0	8	south base of Gulf dunes
F-7	1.5	14	storm berm (Gulf Side)
Average	1.3	6.8	
G-1	1.0	19	tide berm (Sound Side)
G-2	2.5	5	sand flat
G-3	1.0	4	central dunes
G-4	1.0	8	central dunes
G-5	0.5	2	tidal flat
G-6	1.0	6	tidal flat
G-7	1.5	1	tide berm (Gulf Side)
Average	1.2	6.4	
H-1	2.1	1	tide berm (Sound Side)
H-2	1.5	4	north base of dunes, Sound side
H-3	2.0	4	central dunes
H-4	2.0	4	sand flat
H-5	1.0	5	tidal flat
H-6	—	—	tidal flat
H-7	2.5	6	tide berm (Gulf Side)
Average	1.7	3.4	
I-1	3.0	2	tide berm (Sound Side)
I-2	2.0	2	sand flat
I-3	2.0	6	sand flat
I-4	1.5	1	tidal flat
I-5	1.5	5	tidal flat
I-6	2.0	5	tide berm (Gulf Side)
Average	2.0	3.5	

CONCENTRATIONS OF HEAVY MINERALS, GULF SIDE, WEST SHIP ISLAND

The second pilot study of unusually good heavy mineral distribution was made by following the same belt of narrow but rich concentrations on the Gulf side of West Ship Island, as far east as possible.

Accordingly, on August 31, 1961, W. E. Brode of the Laboratory staff and Moore started at station seven of traverse A due south of Fort Massachusetts and sampled 12,000 feet eastward to longitude 88°, 56′ west, Figure 10, the east terminus of West Ship Island. They sampled each 600 feet, at stations numbered 1 through 20, from dunes, back beaches, and fore beaches. At some stations the sands were dark with "heavies" (Figures 16, 17, 18, 19, and 21). At other stations the heavy minerals were covered by white quartz sand. This information and data on the thicknesses of the sample, average thicknesses of the concentrates, and widths of the concentrates are listed with percent of "heavies" by weight (Table 14).

As in the study of sands west of Old Fort Massachusetts, the beach or dune sands were washed and dried, and the "heavies" extracted by bromoform. Again, only superficial petrographic examinations were made. The chief minerals were similar in number and percent to those west of the Fort: staurolite 36, kyanite 22, ilmenite 14, tourmaline 10, zircon 6, rutile 4, magnetite 3, and sillimanite 1. Other minerals constituted the remaining 4 percent.

TABLE 14

CONCENTRATION OF HEAVY MINERALS, GULF SIDE, WEST SHIP ISLAND (EAST OF FORT MASSACHUSETTS)

Sample Number	Greatest Thickness of Sample in Feet	Average Thickness of Sample in Feet	Width of Concentrate in Feet	Percent "Heavies" by Weight	Description of Environment
1	0.6	0.2	70	52	back beach, heavies at surface
2	0.6	0.3	110	37	back beach, heavies at surface
3	0.6	0.3	50	25	back beach, overlain by 0.5 foot quartz sand
4	1.0	0.6	30	45	concentration is wave cut
5	1.3	0.3	50	54	back beach, heavies at surface
6	0.6	0.2	70	52	back beach, south of 6 second flashing beacon
7	0.3	0.2	100	37	back beach, heavies at surface
8	0.9	0.4	50	55	back beach, heavies at surface
9	0.3	0.2	25	53	back beach, overlain by 0.1 foot quartz sand
10	0.6	0.5	25	28	behind first dune, heavies at surface
11	1.0	0.7	40	28	behind 2nd dune, 100 ft. from Gulf
12	0.3	0.3	40	37	dune area next to Gulf
13	0.3	0.3	15	25	behind dunes nearest Gulf
14	3.0	2.0	30	46	heavies disseminated through dunes
15	0.6	0.3	30	69	eroded dune area
16	1.5	1.0	60	47	overlain by quartz and 10% heavies
17	0.3	0.3	20	43	dune area
18	2.0	1.7	50	75	two layers separated by 6.2 feet of quartz sand
19	0.5	0.5	80	89	overlain by 0.6 foot quartz sand
20	0.8	0.5	15	29	heavies separated by 3, 0.2 foot layers of quartz sand
Average	0.8	0.5	47.5	46.3	

THE PROBABLE VALUE OF MISSISSIPPI SOUND "HEAVIES"

Heavy minerals appear to be in greater concentration in the Mississippi Sound beaches and dunes than in Florida, where they are being mined. However, the suite of Sound "heavies" differs markedly from those on the Florida coasts. Further, the Sound beaches and dunes are rather low, whereas most Florida beaches are steeper and the dunes higher and both present and ancient Florida deposits are workable.

Moore shows in Tables 13 and 14 that heavy minerals on West Ship Island vary from 1 to 89 percent and that the average is 46.3 percent in a narrow belt along the Gulf side, a distance of 12,000 feet. Of course, concentrations greater than 20 percent "heavies" are unusual. Thus, Priddy estimates from Foxworth's data that the quartz sands of the Sound average 2 to 6 percent "heavies," whereas analyses of Florida beach and dune sands by Martens[60] and by Calver[61] indicate an average of 1 to 3 percent. The heavy minerals are presently being extracted by dredges at two places on the Florida east coast, as noted in "Sources of Heavy Mineral Grains."

Some of the chief differences in the Mississippi Sound heavy minerals and those in Florida are shown in Table 15. On the left are listed those "heavies" which are in excess of 1 percent. The average "heavies" for the Sound is in column 1. Moore's superficial analysis of heavy minerals of West Ship Island is averaged in column 2. Johnson's analyses of Vero Beach and Mineral City are in columns 3 and 4. The known or probable uses of the heavy minerals are listed on the right.

TABLE 15

COMPARISON OF MISSISSIPPI SOUND AND MINED FLORIDA "HEAVIES" (IN PERCENT)

Heavy Minerals	Average for Miss. Sound	Average West Ship Island	Vero Hobart	Min. City Humphreys	Uses
Magnetite	3.0	3.6			possible ore of iron.
Ilmenite	14.0	11.8	54.2	52.3	source of titanium metal.
Epidote			4.2	7.8	
Pyroxene			1.3		
Garnet			2.6		abrasive.
Kyanite	22.0	24.1		3.2	ceramics, glass, enamels—withstands heat shock and electrical shock.
Leucoxene		2.5			source of some titanium metal for alloying steel.
Monazite			5.2	1.0	source of thorium and rare earths.
Rutile	4.0	1.7	5.2	5.8	pigments, welding rods, source of titanium for alloying steel.
Sillimanite	1.0	1.3	1.3	5.9	glass, enamel manufacture — withstands heat shock and electrical shock.
Staurolite	36.0	25.7	9.3	5.9	manufacturing cement.
Titanite			6.6		possible source of titanium for alloying steel and making white paint.
Tourmaline	10.0	20.4	1.3	1.8	radio apparatus.
Zircon	6.0	2.0	6.6	16.2	source of zirconium metal, abrasive, high temperature refractory.
Others	4.0	6.9	2.2	10.1	
Theoretical totals	100.0	100.0	100.0	100.0	

Moore visited the operations at Vero Beach and at Mineral City. Similar extractions of "heavies" are being accomplished at Lawtey, Florida, near Jacksonville, by the E. I. du Pont de Nemours & Company, Inc. Other heavy mineral extraction plants have operated at various times on the Florida coasts.

The mechanics of dredging, concentrating the "heavies" and separating the individual minerals are too complicated to be explained here. Martens[62] and Calver[60] review the history of heavy mineral extraction and include flow charts of the complicated processing. Sercombe[63] treats in a less technical but interesting manner the present space age demands for heavy minerals—rutile and ilmenite for sources of titanium to strengthen steel in plane and missile construction, zircon for high temperature electrical apparatus and for special enameling of missile nose-cones, and the radioactive monazite which the Atomic Energy Commission is currently reserving. Staurolite, tourmaline, and kyanite, the chief "heavies" of the Gulf Coast suite of heavy minerals, are also being stockpiled.

Thus the high staurolite, tourmaline, and kyanite content of the Mississippi Sound may have uses as yet undisclosed. Certainly, the ilmenite, leucoxene, rutile, and zircon fractions are important. In separating the above "heavies," the small amounts of monazite, garnet, and titanite may be recovered.

Priddy believes, and Foxworth implies, that some heavy minerals may locally predominate over others. If further petrographic work confirms a selectivity in concentration, it would be possible to process the sands of certain beaches and dunes in preference to others containing heavy minerals less in demand at a given time. In any event, the most desirable heavy minerals must be extracted from the least desirable. The latter can be stockpiled, awaiting demand or awaiting new technological developments which are now occurring at a highly accelerated rate.

Mellen[64] pointed out that the coastal terraces may furnish ancient but unweathered "heavies" which were incorporated in old dunes and beach ridges. A study of the inland beaches is worthy of a masters thesis, especially because a similar ancient beach ridge is worked by Hobart Co. at Vero Beach in conjunction with processing recent beach sands.

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MAP OF MISSISSIPPI GULF COASTAL AREA
(Designations indicate Foxworth's samplings)
ML-1
ML-2,2a
ML-3,3a
ML-4,4a
ML-5
ML-6
ML-7
ML-8,8a
ML-9
D-1
D-2
D-3,3a
C-1
C-2,2a
C-3,3a
C-4,4a
C-5,5a
S-1,1a
S-2,2a
S-3a
S-4,4a
H-1,1a
H-2,2a
H-3
H-4a
R-1,1a
PB-1,1a
PB-2
PB-3,3a
MISSISSIPPI SOUND
GULF OF MEXICO
LAKE PONTCHARTRAIN
LAKE BORGNE
CHANDELEUR SOUND
PASS MARIANNE
CAT ISLAND
SHIP ISLAND
HORN ISLAND
PETIT BOIS ISLAND
ST LOUIS BAY
BILOXI BAY
NEW ORLEANS
Gulfport
Pass Christian
Long Beach
Ocean Springs
Pascagoula
Bay St Louis
INTRACOASTAL WATERWAY
Scale 1:250,000
20 Statute Miles
30 Kilometers
10 Nautical Miles
LOCATION DIAGRAM FOR NH 16-4
MOBILE, ALA.; MISS.; LA.
200 000 FEET (MISS.)
2 500 000 FEET (LA.)
300 000 FEET (ALA.)
90°00'
89°00'
88°00'
30°00'