A SEDIMENTOLOGIC STUDY OF MOBILE BAY, ALABAMA

by

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ABSTRACT

Mobile Bay is the terminus of the fourth largest river system in terms of discharge in the United States. Currently an average 4.7 million tons of suspended sediment and an unknown quantity of bed load are being transported into the estuary. The dominant terrigenous clastics are quartz, kaolinite, and montmorillonite.

Circulation patterns within the estuary are controlled primarily by the river discharge, tides and geometry of the bay. The most important short term variations are due to meteorological tides. Depending upon the season and/or year the estuary may be classified as highly stratified, moderately stratified, or, with the exclusion of the ship channel, vertically homogenous on the basis of its circulation pattern.

Comparisons of the bathymetry of 1847-51 and 1960-62 indicate an average shoaling of 1.7 feet per century. Considerable variation in sediment rates exist in various areas within the estuary ranging from zero to more than ten feet per century. The majority of anomalously high rates are a result of changes in

circulation and bathymetry due to dredging operations. On the basis of computed sediment accumulation over the 110 year period approximately 1.4 million tons of suspended sediment is currently by-passing the estuary and being deposited to the south and west of the tidal inlet.

Clean quartz sands are around the periphery of the bay generally in water depths less than six feet. The majority of the bay bottom sediments consist of silty clays and clays. Multiple linear regression surfaces illustrate decreasing grain size and increased sorting downbay and to the southeast. Higher montmorillonite content near the bay-head delta and increasing kaolinite content toward the southeast in Bon Secour Bay are attributed to sediment dispersal patterns, differences in sedimentation rates and to an increased kaolinite content in the suspended river sediments over the historic period as a result of the development of agriculture within the drainage basin.

The distribution and ages of the buried oyster reefs indicate a progressive downbay migration in response to progradation of the bay-head delta and changing circulation patterns within the estuary over the past five to six thousand years.

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INTRODUCTION

Location

Mobile Bay encompassing approximately 392 square miles is on the northeast Gulf of Mexico east of the Mississippi delta.

The estuary is slightly more than 31 miles long ranging in width from 8 to 10 miles in the northern two-thirds but broadening to about 24 miles in its lower reaches where an eastward embayment, Bon Secour Bay, is situated (Figure 1). Its southern end is nearly completely blocked from the open Gulf by the westward migrating bay mouth barrier known as Mobile Point and by Dauphin Island, the eastermost of the barrier island chain that marks the outer margin of Mississippi Sound.

The investigation of the marine geology of Mobile Bay and its adjacent continental shelf was undertaken in order to extrapolate from the Pleistocene and Holocene sedimentary history of the estuary its probable future pattern of development. This report is concerned with the contemporary sediments, their characteristics and rates of deposition, as a function of (1) present estuarine circulation and bathymetry, (2) river discharge and drainage basin characteristics, and (3) natural and man-induced changes in these parameters through the historic period of the estuary. A paper in progress summarizes the Pleistocene and Holocene geologic evolution of the Bay based on borings and continuous seismic profiling.

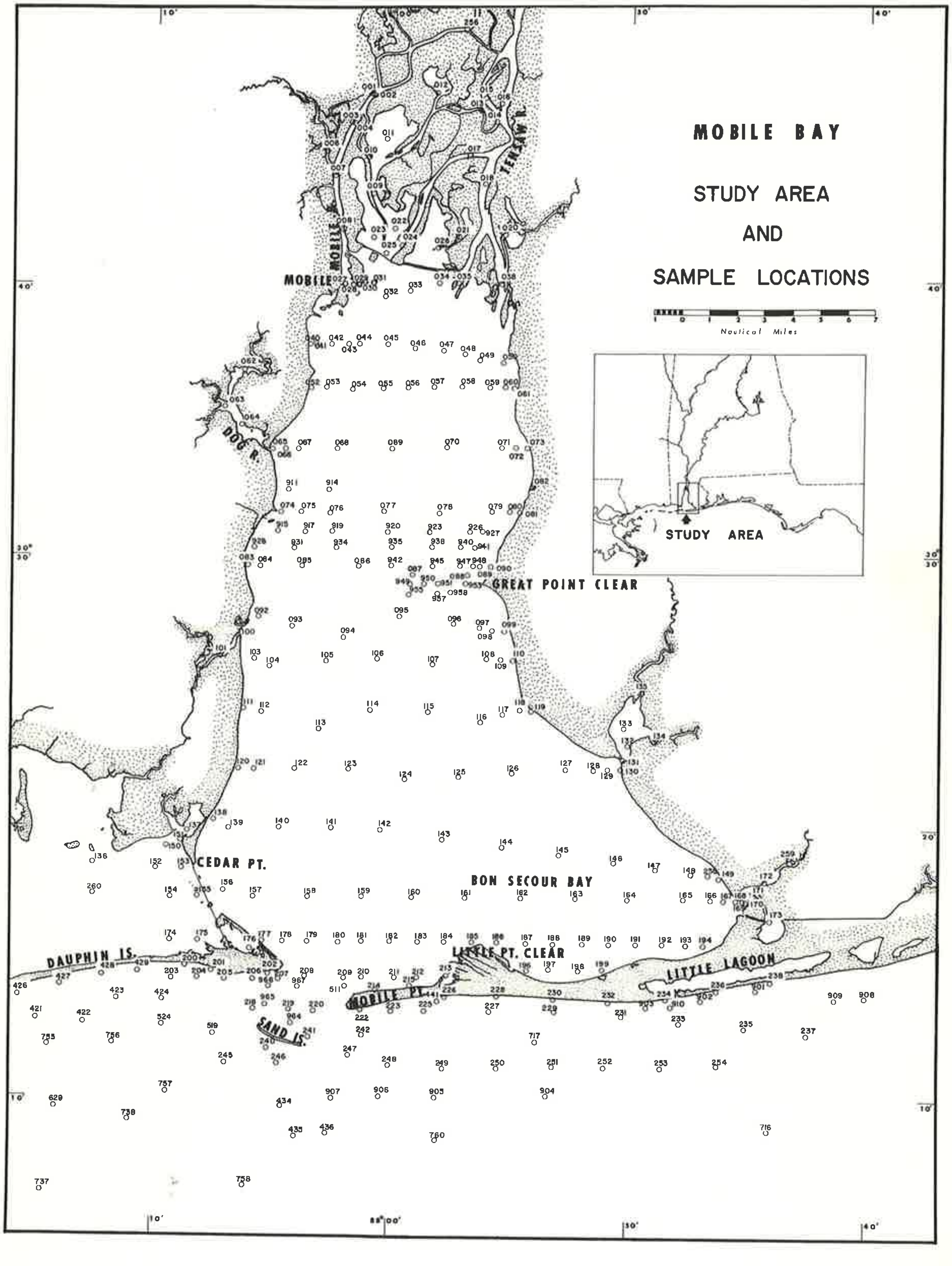
Climate

The areas of Baldwin and Mobile counties which border Mobile Bay have a humid, nearly subtropical climate. There are no dry seasons. Rainfall averages 64 to 66 inches a year. Annual temperatures range from 50°F to 84°F in Mobile County on the western side of the estuary and 54°F to 80°F on the eastern side in Baldwin County. Hurricanes occasionally occur in late summer and early fall. Snowfall is rare. The prevailing winds at Mobile are from the north during the fall and winter (September through February) shifting to the south in the spring (March through June) and southwest in summer (July and August).

The large amount of rainfall and high temperatures reduce the organic content of the soils and cause a great deal of leaching (McBride and Burgess, 1964).

Physiography

Mobile Bay is situated in the East Gulf Coastal Plain. Due to variations in resistance to erosion and


MOBILE BAY
STUDY AREA
AND
SAMPLE LOCATIONS
Nautical Miles
STUDY AREA
MOBILE
TENSAW R.
DOG R.
GREAT POINT CLEAR
CEDAR PT.
BON SECOUR BAY
DAUPHIN IS.
LITTLE PT. CLEAR
LITTLE LAGOON
MOBILE PT.
SAND IS.

the gentle seaward dip of the underlying strata, a cuesta-like elevated dissected plain inclined southward forms the fundamental topography of the region. There is a gentle decrease in elevation from three hundred feet north of Mobile to one hundred feet near the coast where the slopes abruptly increase.

Steep bluffs are situated on both sides of Mobile Bay, immediately adjacent to the shoreline along the north and eastern side of the bay and approximately five miles inland on the western side where a series of flat-topped hills rise from a low-lying undulating plain located between the bluffs and the estuary.

The dominant geomorphic feature of the region is the floodplain and delta of the Mobile-Tensaw river system averaging approximately ten miles in width north of Mobile. From the floodplain a series of discontinuous stream terraces rise on one or both sides of the river valley. Carlston (1950) recognized a total of five marine, estuarine, and stream terraces adjacent to the floodplain.

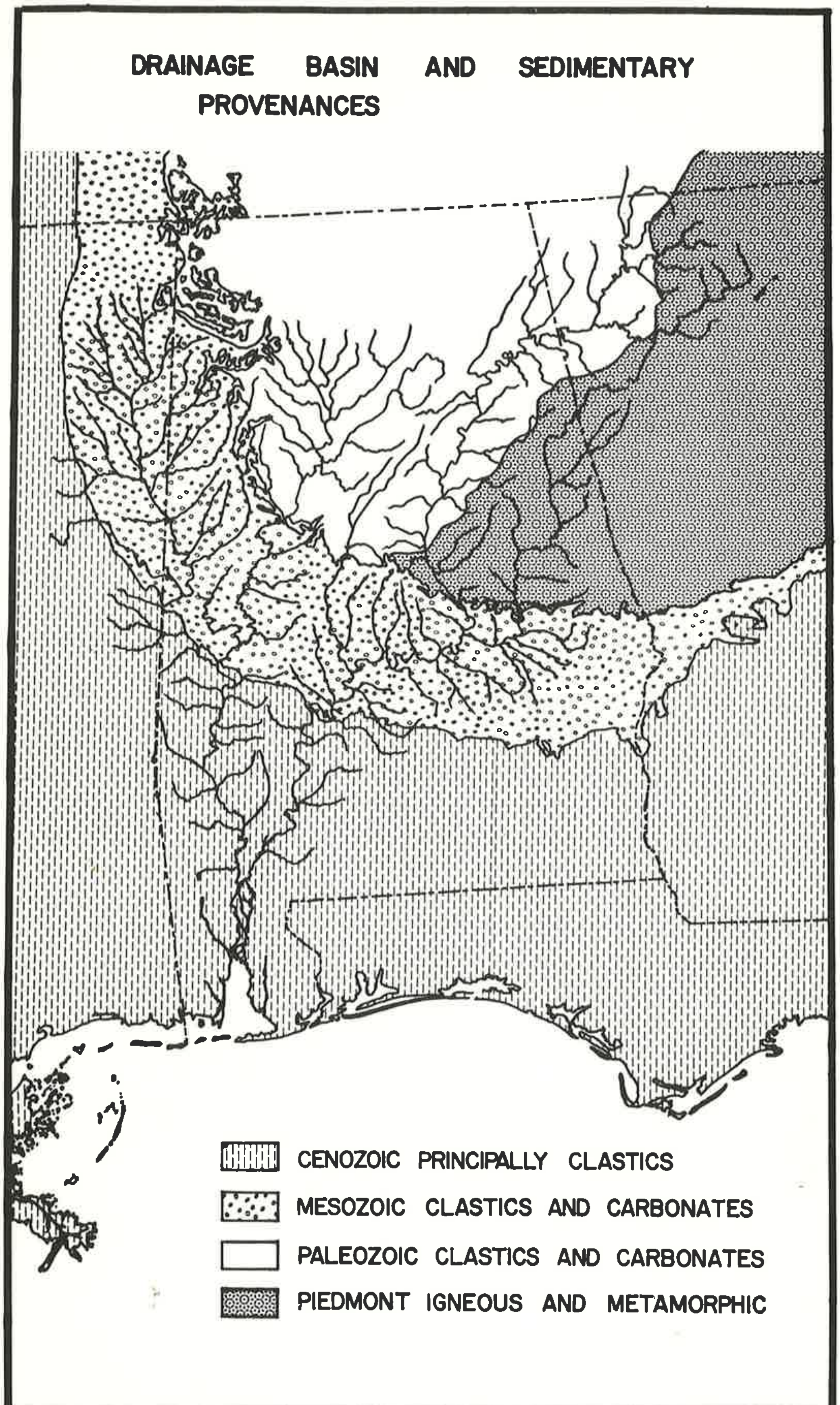
Along the western shore of the bay there is a belt of coastal salt marshes that border Mississippi Sound. Seaward of these marshes is Dauphin Island. Dunes ranging from 25 to 40 are the dominant topographic feature upon the island and are confined to the Gulf side and eastern end.

The coastal region on the eastern side of the bay is dominated by the Mobile Point peninsula, a barrier with rows of dunes paralleling the coast and a string of fresh and salt water lakes situated between an older and more recent seaward extension of the barrier.

Regional Geology

The extensive drainage basin of the Mobile River system flows over strata ranging in age from Precambrian to Recent and in genesis from igneous and metamorphic to sedimentary (Figure 2). The headwaters of the Alabama River, originating in the Blue Ridge and Piedmont Provinces flow through metamorphic and igneous complexes. The north-central portion of the drainage basin contributes sediments derived from the Paleozoic clastics and carbonates of the folded Appalachians. South and westward are located Cretaceous sedimentary strata dipping toward the Gulf and Mississippi Embayment. These in turn are overlain by the Tertiary and Quaternary clastics possessing similar attitudes.

It has been suggested or implied by various authors including Murray (1960, 1961), Tanner (1964, 1966) and Copeland (1968) that Mobile Bay and the Mobile River are the site of a graben. The geometry of the estuary and relationships to known structural trends (Pickens-Gilbertown system) in the Gulf Coast suggest


DRAINAGE BASIN AND SEDIMENTARY PROVENANCES
CENOZOIC PRINCIPALLY CLASTICS
MESOZOIC CLASTICS AND CARBONATES
PALEOZOIC CLASTICS AND CARBONATES
PIEDMONT IGNEOUS AND METAMORPHIC

this is plausible. Copeland (1968) points out that there are still many unknowns associated with the "graben". The major fault representing the west flank of the graben has never been penetrated. Copeland further states he finds it difficult to fit Mobile Bay into the subsurface trace of the graben. He postulates the graben turns westward north of Mobile rather than down the axis of the bay and explains the high escarpments on the eastern shore of the bay as possibly representing minor en echelon faults associated with the graben.

Mobile Bay, the bay-head delta, and floodplain are underlain by Pleistocene to Recent stream and estuarine deposits of sand and clay. The basal bed of alluvium, generally coarse sand and gravel, disconformably overlies estuarine deposits of endurated clays of purported Miocene age. Peterson (1947) states that wells in the Mobile area generally encounter these Miocene beds beneath 80 to 150 feet of alluvium. The Miocene deposits consist of gray dense clay, sandy clay, fine argillaceous sand and medium to coarse sand with a gravelly sand about 300 feet thick at the base. The beds thicken and dip to the southwest in Mobile County.

The elevated high plains on both sides of the estuary are capped by sand, gravel, and lenticular white to variegated clays of the Citronelle formation of Pliocene or Pleistocene Age. the Citronelle ranges from 40 to 130 feet thick in coastal Alabama, dipping south at 6 to 8 feet per mile (Carlston, 1950).

Marine, estuarine, and stream deposits of Pleistocene to Recent Age border the estuary forming a zone approximately one mile wide along the eastern shore and six miles wide on the western side. Along Mississippi Sound and the Gulf Coast these sediments form a border 2 to 4 miles in width. On the western shore, approximately 3 miles inland from the present coast a barrier with elevations in excess of 25 feet extends 4 miles eastward from the former shoreline. Carlston (1950) calls this a Pamlico spit although he states the name implies no particular Pleistocene sea level stand.

MOBILE RIVER SYSTEM

Drainage Basin

Mobile Bay is the terminus of the Mobile River system which consists of more than 43,000 square miles of drainage basin, draining nearly two-thirds of Alabama, the northwestern section of Georgia and the northeastern portion of Mississippi (Figure 2). This system has two major branches; the Alabama River the eastern, the Tombigbee River the western branch.

The Alabama River originates at Montgomery at the confluence of the Coosa and Tallapoosa Rivers, both of which originate in the Blue Ridge Mountains of northwestern Georgia. Large dams and hydroelectric plants are located on both streams in the steep reaches near the fall line.

The Tombigbee River rises in northeastern Mississippi and flows southward to its confluence with the Alabama River about 30 miles north of Mobile Bay. Its principal tributary is the Black Warrior River which joins the Tombigbee River at Demopolis. Four major lock and dam systems were constructed between 1939 and 1960 on these two rivers with a fifth system under construction in 1964 (Peirce, 1966). Prior to their construction a series of smaller locks and dams had been built for navigational purposes between 1895 and 1915; most of which are now obsolete.

The Mobile River, formed by the confluence of the Tombigbee and Alabama Rivers, consists of an intricate network of anastomosing channels for its entire length over the prograding Mobile River delta. The two principal distributaries are the Mobile River which enters Mobile Bay on the western side of the delta and the Tensaw River which flows into the bay near its eastern border.

Discharge

Due to its proximity to the Mississippi drainage system the magnitude of the volume of water discharged by the Mobile River system is usually overlooked. A mean annual discharge of 59,000 cfs ranks the Mobile system as the fourth largest river system of the United States, exceeded only by the Mississippi, Columbia, and Yukon systems (data from Morisawa, 1968). The total flow into the Mobile River is about equally contributed by the Alabama and Tombigbee Rivers and any additional runoff from the drainage basin between these rivers and the delta front is negligible.

TABLE 1

DISCHARGE IN CFS THAT WAS EQUALLED OR EXCEEDED FOR THE WATER YEARS 1940 - 1956

(Compiled from data published by Peirce, 1959)

Percent of time	Mobile River at Mt. Vernon	Tombigbee River near Leroy	Alabama River at Claiborne
1	300,000	140,000	150,000
2	260,000	120,000	130,000
5	180,000	97,000	99,000
10	130,000	76,000	72,000
20	85,000	48,000	45,000
30	58,000	27,000	32,000
40	41,000	16,000	24,000
50	32,000	9,500	18,000
60	25,000	6,400	15,000
70	19,000	4,600	13,000
80	15,000	3,300	11,000
90	12,000	2,200	9,100
95	9,900	1,600	7,800
97	8,800	1,400	7,100
98	8,100	1,200	6,700
99	7,500	970	6,300

The median daily discharge of the Mobile River into the Bay is 32,000 cfs and varies from 10,000 cfs during an average dry period to over 120,000 cfs during flood stages (Table 1). In periods of low flow the discharge of the hydroelectric reservoirs on the Coosa and Tallapoosa Rivers cause the Alabama River to contribute the major part of the flow of the Mobile River. During periods of unusually high water, discharge approaches a half million cfs with a maximum recorded discharge of 533,000 cfs during the flood of February - March, 1961 (Gamble, 1965). Peirce (1966) states that this flood magnitude has a recurrence interval of 200 years. Robinson, et al (1956) state that flows greater than 100,000 cfs overflow the Mobile River distributary channels and are in part discharged over the delta swamps. The minimum discharge, or low water period, usually occurs during September through November while flood stages usually prevail from January through May.

Suspended Sediment

The U.S. Army Corps of Engineers has monitored the suspended sediment load daily since 1952 at stations on the Tombigbee and Alabama Rivers near their confluence (Table 2). As might be expected most of the sediment reaches the estuary during periods of high discharge. The Tombigbee and Alabama Rivers appear to transport approximately equal quantities of suspended sediment in proportion to their discharge; with a slightly higher suspended sediment content in the former. During periods of relatively low river discharge (June - October) a higher percentage of the total load is delivered by the Alabama River. This does not necessarily reflect entrapment of sediment behind the dams on the Tombigbee and Black Warrior as these rivers have a disproportionately lower discharge at low flow (Table 1). In fact, the lower annual sediment concentration in the Alabama River may be a result of the regulation of the discharge

TABLE 2

SUSPENDED SEDIMENT LOAD (12-YEAR MONTHLY AVERAGE)
TOMBIGBEE AND ALABAMA RIVER SYSTEMS,
1952 - 1963

(Compiled from unpublished data, U. S. Army, Corps Engineers, Mobile District)[1]

Month	Tombigbee River[2] (tons)	Alabama River[3] (tons)	Combined (tons)
January	335,661	240,899	576,560
February	519,171	385,863	905,034
March	558,482	472,974	1,031,456
April	378,742	437,710	816,452
May	181,524	207,015	388,539
June	48,253	112,583	160,836
July	71,963	88,089	160,052
August	12,308	42,620	54,928
September	13,794	49,216	63,010
October	18,670	44,550	63,220
November	65,529	51,969	117,498
December	191,090	186,670	377,760
Annual Totals	2,395,187	2,320,158	4,715,345

[1]Based on daily suspended sediment data.

[2]Station near Leroy, Alabama.

[3]Station at Claiborne, Alabama.

by the hydroelectric dams in the upper reaches of the Coosa and Tallapoosa Rivers.

Assuming the gaging stations on the Alabama and Tombigbee Rivers reflect the bulk of suspended sediment transported by the system it is estimated that the suspended sediment load reaching the delta front and estuary averages 4.7 million tons/year; ranging from a low of 2.1 million tons in 1952 to 8.3 million tons in 1961 (Table 3). Most of this sediment reaches the estuary during periods of high discharge. For example, of the total 8.3 million tons transported during 1961, 5.2 million tons entered the estuary between January and March. This alone exceeds the average estimated annual rate.

The clay size fraction of the suspended load is composed dominantly of montmorillonite and kaolinite. Griffin (1962) analyzed samples from the Tombigbee River at Jackson (near Leroy) and the Alabama River at Claiborne. His analysis indicates higher kaolinite contents in the Alabama River reflecting more kaolinitic soils in the eastern portion of the Mobile River drainage basin.

No quantitative data is available on the quantity of bed load transported by this system, but it might be estimated as 10% or less of the suspended sediment load.

TABLE 3

COMBINED SUSPENDED SEDIMENT LOAD (MONTHLY TOTALS)
TOMBIGBEE AND ALABAMA RIVERS[1]
FOR YEARS OF MINIMUM (1952)
AND MAXIMUM (1961) DISCHARGE
1952 - 1963

(Compiled from unpublished data, U. S. Army, Corps Engineers, Mobile District)

Month	1952	1961
January	337,275	194,703
February	226,764	1,417,677
March	806,818	2,459,166
April	299,555	1,316,858
May	156,665	171,588
June	78,849	360,901
July	29,094	299,476
August	55,417	75,382
September	20,155	129,697
October	19,607	39,223
November	15,183	69,002
December	86,444	1,783,230
Totals:	2,131,826	8,316,903

[1]Based on daily suspended sediment data from stations near Leroy on Tombigbee River and Claiborne on Alabama River.

BATHYMETRY

Methods

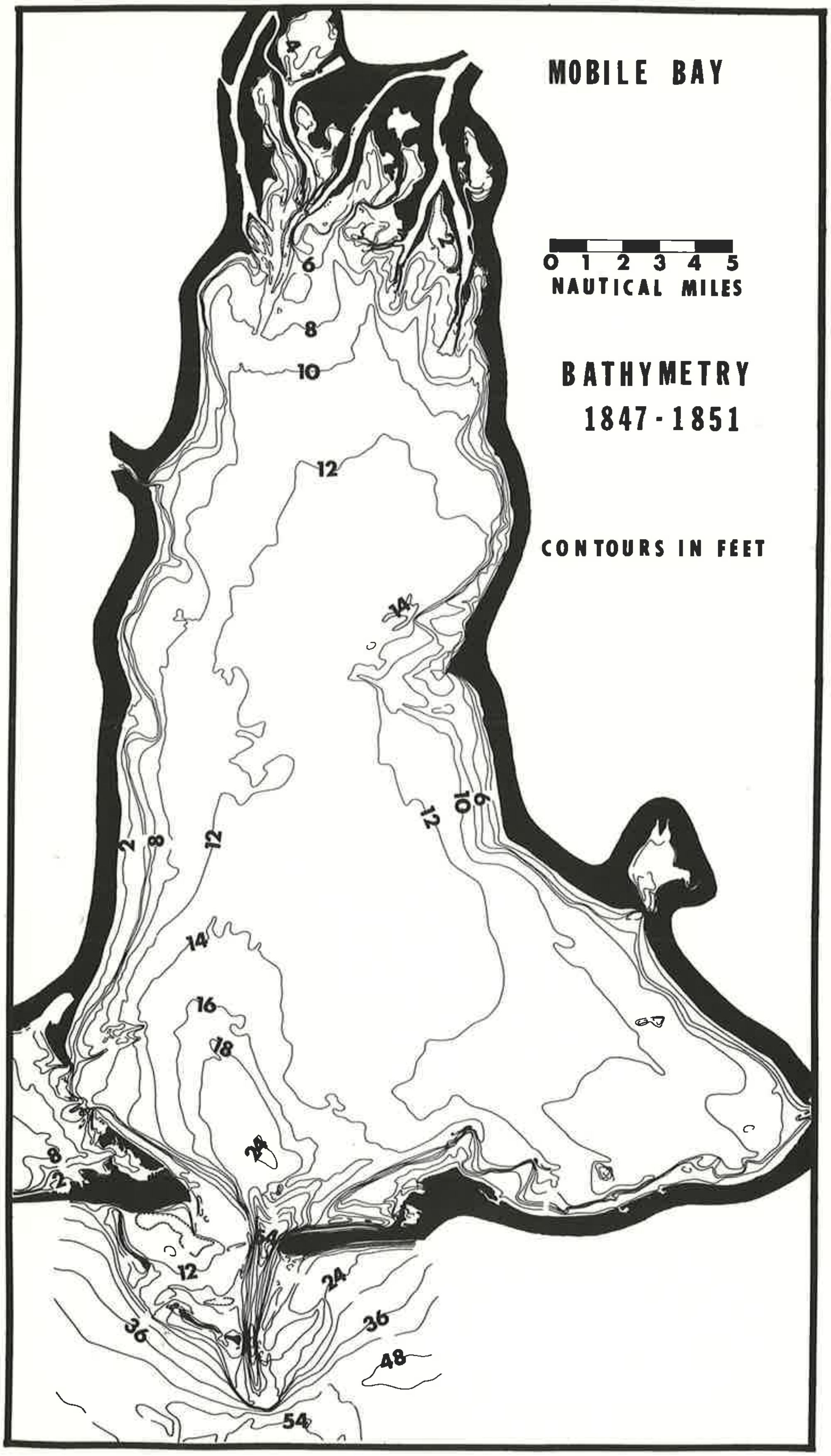
Unpublished hydrographic survey sheets of the U.S. Coast and Geodetic Survey were contoured on a one foot interval for the surveys of 1847 - 1851 and 1960 - 1962. Both the older and recent surveys have enormous detail with tens of thousands of soundings within the estuary. The soundings of the older survey were given to the nearest tenth of a foot within the estuary and to the nearest foot in offshore areas. A high degree in accuracy is assumed by the shallow depths within most of the bay and the proximity of the shoreline which aided in navigational fixes. Soundings of the 1960 - 1962 survey are to the nearest foot.

Although depths were corrected for various tidal stages against tide gauges, errors would be introduced by sea level being somewhat different on one side of the bay than the other, particularly during periods of strong winds. It is assumed these errors are negligible due to the number of soundings and agreement of intersecting tract lines made at various times within the estuary during both surveys. A second potential error is the selected mean low water level for the 1847-1851 survey. As it was established for purposes of that particular survey it may or may not have been the actual mean low water level of the 1960-62 survey. As discussed by Marmer (1952) sea level may differ seasonally in the Gulf of Mexico but again this potential error would be on the order of less than a foot and constant for the 1847-51 survey.

As the survey sheets of the 1847-1851 survey are either on scales of 1:10,000 or 1:20,000 and the 1960-1962 survey sheets range from 1:5,000 to 1:20,000 it was necessary to reduce the resultant contoured sheets by photogrammetric techniques to a common scale to compile a single chart of the entire estuary for each of the two surveys. The final maps (Figures 3 and 4) were contoured on a two foot interval within the estuary excepting river, tidal, and dredged channels which were contoured on a six foot interval where practicable and outlined in areas where slopes were so steep as to result in a merger of contour lines. The offshore area was contoured on a six foot interval.

Bathymetry 1847 - 1851

The bathymetry of 1847-1851 gives the natural configuration of the estuary bottom prior to the modifications of man; specifically before the advent of the ship channels and associated spoil banks (Figure 3).


MOBILE BAY
0 1 2 3 4 5
NAUTICAL MILES
BATHYMETRY
1847 - 1851
CONTOURS IN FEET
6
8
10
12
14
2
8
12
12
10
6
14
16
18
24
8
2
54
12
24
36
36
48
54

In the 1850's the floor of the bay was essentially flat, ranging in depth from 10 to 14 feet and gently sloping (approximately 1 foot per mile) toward a central axis and the Gulf. Around the periphery of the bay there existed a narrow shelf extending from the shoreline to depths of 4 to 6 feet. The width of this shelf was variable, averaging 0.5 to 1.0 miles but extending in places more than two miles into the estuary. Between the narrow shelf and flat bay floor there existed a slope from 4 to 6 feet to 8 or 10 feet with gradients ranging from 8 feet per mile to 30 feet per mile. In the northern portion of the bay the bathymetry is complicated by the progradation of levees associated with the distributaries of the Mobile delta into the estuary. Towards the south the tidal inlet between Mobile Point and Dauphin Island was scoured to depths between 54 and 58 feet; shallowing both landward and seaward. Within the estuary the tidal inlet bifurcated into a Y-shaped configuration with a wide, gently sloping, western limb and a narrower, smaller, more steeply sloping eastern limb. These two limbs possibly reflected tidal scour; the eastward limb maintained by the incoming flood tides and the western limb developed by both ebb and flood tidal currents. Seaward of the tidal inlet a large tidal delta existed with depths of less than

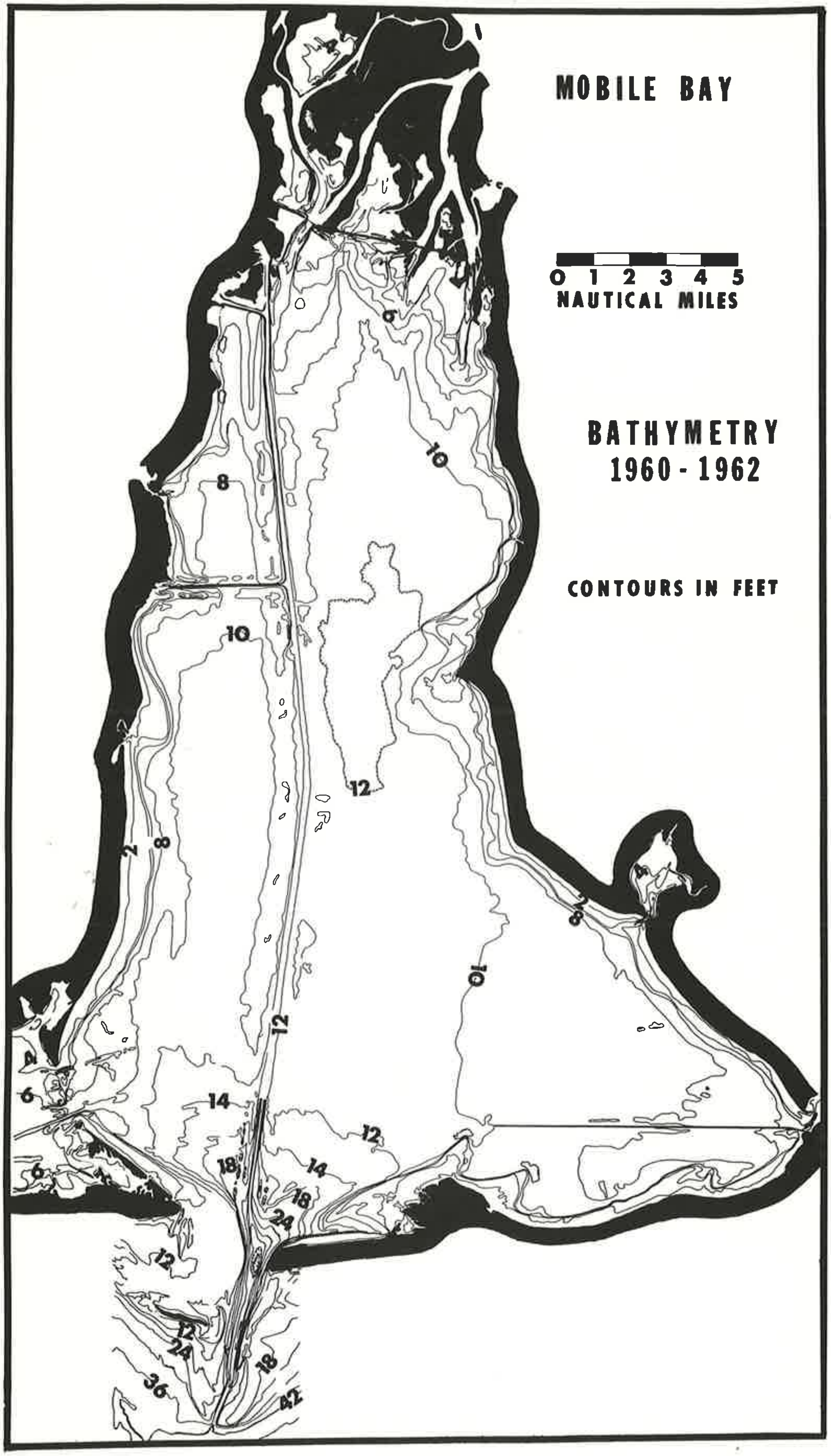
18 feet. Superimposed on the seaward margin of the tidal delta were three islands.

Around the periphery of the estuary several large submerged sand bars or spits normal to the shoreline occurred. The two largest were to the north and off Great Point Clear ranging in depth from 6 to 8 feet and extending two or more miles out into the estuary. On the western shore opposite Great Point Clear another large bar extended eastward into the bay. Along the shoreline of the Mobile Point barrier two sets of bars extended northward into the estuary. The largest of the two was off Little Point Clear; the smaller set was eastward of this location. At this time their origin is unknown but their locations suggest an association with the former westward terminus of the Mobile Point barrier as it was migrating westward.

A few oyster reefs have sufficient extent and relief to be reflected on the map; particularly several in Bon Secour Bay and off Cedar Point. These reefs had relief on the order of 4 to 6 feet above the bay bottom.

Bathymetry 1960 - 1962

Radical changes in bathymetry occurred during the intervening century (Figure 4). Among the more significant modifications is a general shoaling of the broad flat bay bottom to depths ranging from 10 to 12


MOBILE BAY
0 1 2 3 4 5
NAUTICAL MILES
BATHYMETRY
1960 - 1962
CONTOURS IN FEET
6
10
8
10
12
2
8
2
8
10
12
14
12
18
14
18
24
12
12
24
36
18
42
6
6

feet rather than 10 to 14 feet as in the 1850's.

The bathymetry has been complicated by the construction of the main ship channel from the city of Mobile to the deeper waters of the tidal inlet and the channel dredged through the outer bar of the tidal delta. The ship channel is presently 400 feet wide by 40 feet deep. The spoil banks extend along both sides of the main ship channel to a point just north of Great Point Clear. South of this position most of the spoil material is confined to the western side of the ship channel to the vicinity of the tidal inlet. The relief on these spoil banks is greater than six feet in the northern part of the estuary to two and three feet from Great Point Clear southward. A series of "hummocks" of spoil material in water depths greater than 14 feet extend along the western side of the ship channel in the tidal scoured lower reaches of the bay.

The spoil banks associated with a secondary channel south of Dog River extending west from the main ship channel known as the Hollingers Island Channel, has virtually isolated the northwestern part from the main body of the estuary.

The construction of the Intracoastal Waterway across Bon Secour Bay has had little effect upon the bathymetry outside the confines of the dredged channel.

Excluding the construction of the main ship channel the major modification of the estuarine bathymetry has been the shoaling and recession downbay of the aforementioned western limb of the tidal inlet. Offshore there has been a realignment of the outer reaches of the tidal inlet to a more westward position; this may be a result of the dredging operations across the bar seaward of the tidal inlet. Of the three islands bordering the outer margin of the tidal delta only one remains in 1960 and it has migrated landward.

The shallower, less than six foot depths, portions of the bay indicate little change since the 1850's. The similar configurations and depths of the major previously mentioned bars and spits attest to their relative permanency; particularly the two sets along the Mobile Point barrier.

The oyster reefs off Cedar Point and in Bon Secour Bay indicate less relief in 1960 - 1962 than was present in 1847 - 1851.

ESTUARINE CIRCULATION

Circulation patterns within Mobile Bay are controlled primarily by the river discharge, tide, and the physical dimensions of the bay; the most important short term variations are due to meteorological tidal conditions.

TABLE 4

TIDAL RANGES

(From U. S. Army Corps Engineers Alabama Coast Hurricane Report, House Document No. 103, 90th Congress, 1st Session, 1967)

Tide Gage location	Stages in feet referred to mean sea level (Datum of 1929)				
	Mean high	Mean low	Mean tide level	Mean diurnal	Years of record
Fort Gaines, Dauphin Is.	+1.00	+0.02	+0.52	0.98	8 years
Cedar Point	+1.05	-0.35	+0.35	1.40	9 years
Mobile State Docks	+1.13	-0.28	+0.45	1.46	24 years

The mean range of astronomical tides is about 1.0 feet at the lower end of the bay and 1.5 feet at the upper end (Table 4). The extreme range, except during storms, is 3 to 5 feet (Bisbort, 1957). North winds frequently lower the water surface to below mean low water for extended periods and stages 1.9 feet below mean low water are not uncommon (U. S. Army Corps Engineers, 1953).

TABLE 5

STORM TIDES IN ALABAMA (1772 - 1964)

(From U. S. Army Corps Engineers Alabama Coast Hurricane Report, House Document No. 108, 90th Congress, 1st Session, 1967)

Date storm crossed coast	Landfall	Stage at Mobile (feet above mean sea level)
4 Sept. 1772	Not available	8.2
23 Aug. 1852	Not available	8.0
11 Aug. 1860	Not available	6.4
15 Sep. 1860	Not available	7.0
30 July 1870	Not available	7.0
19 Aug. 1888	Lake Charles, La.	7.2
2 Oct. 1893	Pascagoula, Miss.	8.4
15 Aug. 1901	Grand Isle, La.	7.4
27 Sep. 1906	Mobile, Ala.	9.1
20 Sep. 1909	Grand Isle, La	7.0
14 Sep. 1912	Mobile, Ala.	4.4
29 Sep. 1915	Grand Isle, La.	6.4
5 July 1916	Gulfport, Miss.	10.8
18 Oct. 1916	Pensacola, Fla.	3.2
28 Sep. 1917	Pensacola, Fla.	1.2
20 Sep. 1926	Pensacola, Fla.	4.5
1 Sep. 1932	Bayou La Batre, Ala.	4.5
10 Sep. 1944	Mobile, Ala.	3.8
19 Sep. 1947	New Orleans, La.	4.7
4 Sep. 1948	Grand Isle, La.	4.4
30 Aug. 1950	Mobile, Ala.	3.9
24 Sep. 1956	Ft. Walton Beach, Fla.	2.2
15 Sep. 1960	Pascagoula, Miss.	3.9
3 Oct. 1964	Franklin, La.	4.2

Hurricane winds have raised the water levels in the bay as much as 10.8 feet above and as much as

10.5 feet below mean sea level. The highest recorded tide of 10.8 feet at Mobile occurred during the July, 1916 hurricane. This stage was about 3 feet higher than that reached at Dauphin Island about 30 miles south at the entrance to the bay and is believed to have been the result of additional wind setup inside the shallow bay and the funneling effect of its converging shorelines. Hurricanes strike this portion of the coast with a frequency of one per six years (Table 5).

Average current velocities associated with the flood and ebb tides are presented in Table 6. The maximum currents predicted at Mobile Bay entrance are 3.3 knots for a duration of three days in January, June, and December (U. S. Coast and Geodetic Survey, Tidal Current Tables, 1969).

TABLE 6

AVERAGE TIDAL CURRENT VELOCITIES (DIURNAL) IN KNOTS

(From U. S. Coast and Geodetic Survey, Tidal Current Tables, 1969)

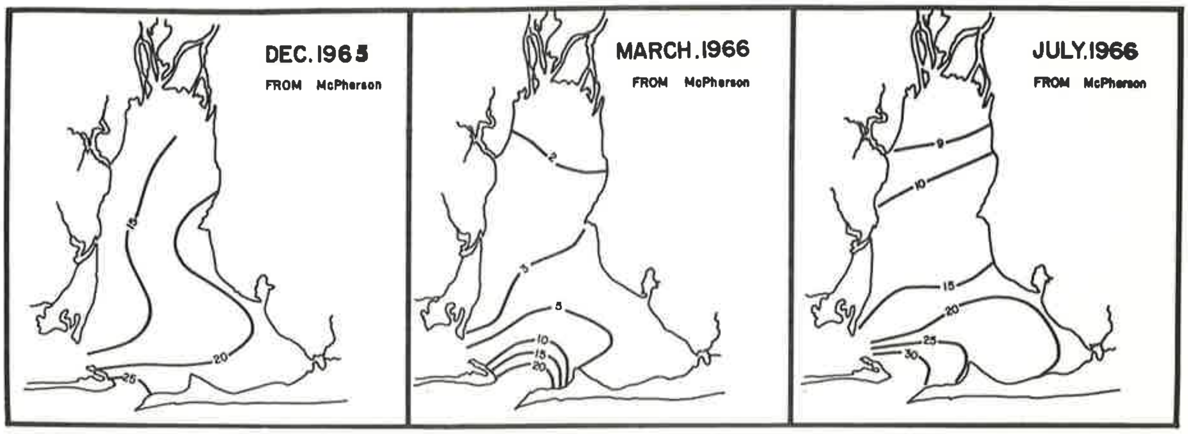
Location	Flood Tide	Ebb Tide
Main ship channel entrance	0.7	1.0
Mobile Bay (off Mobile Point)	1.4	1.5
Channel, 6 miles N. of Mobile Point	0.6	0.5
Mobile River entrance	0.3	0.7
Tensaw River entrance	0.4	1.0
Pass aux Herons	1.3	1.3

Although no quantitative data is recorded, higher current velocities undoubtedly exist during hurricanes, particularly when the wind is blowing from the north on the ebb tide. The U. S. Army Corps Engineers (1949) state that with strong winds the maximum current velocity may be 4 mph on the outer bar, 3 mph in the bay channel and 2 mph in the river channel.

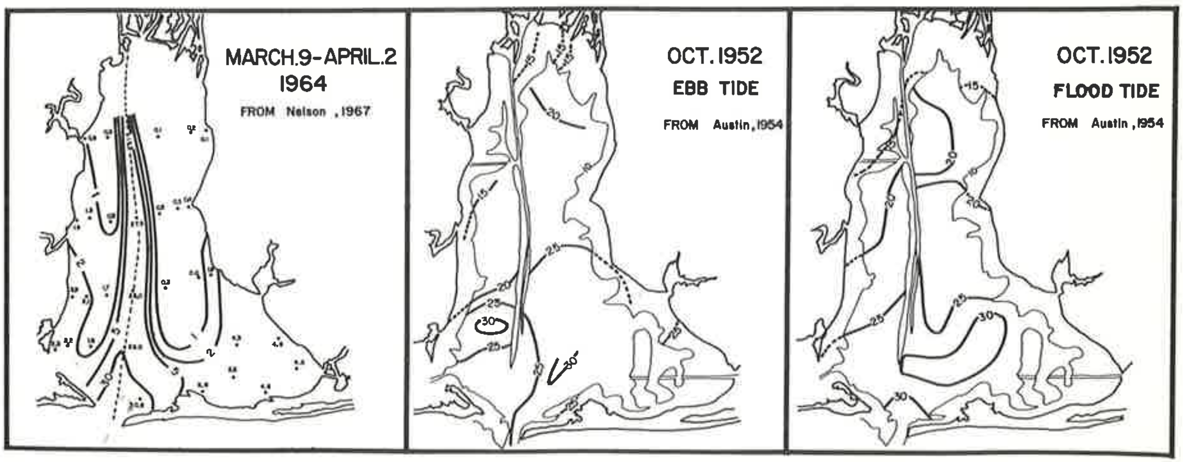
Little data exists on the circulation and distribution of salinity within the bay. The only synoptic study, conducted by Austin (1954), was during a six day period in October, 1952. His maps indicate that the river discharge into the bay is primarily through the Mobile-Tensaw river system and then downbay on the western side of the main ship channel (Figure 5). Austin's study indicates that on the ebb tide the surface waters discharge along essentially linear paths southward and eastward with 85% of the discharge through the Mobile Point tidal inlet directly into the Gulf of Mexico; the remaining 15% through various passes into Mississippi Sound (Figure 5). Austin states water is still ebbing through Pass aux Herons into Mississippi Sound 15 minutes to an hour after flood tide waters commence entering through the Mobile Point inlet.

The bulk of the surface water entering through the Mobile Point inlet on flood tide is deflected first to the east and then northward in a counterclockwise

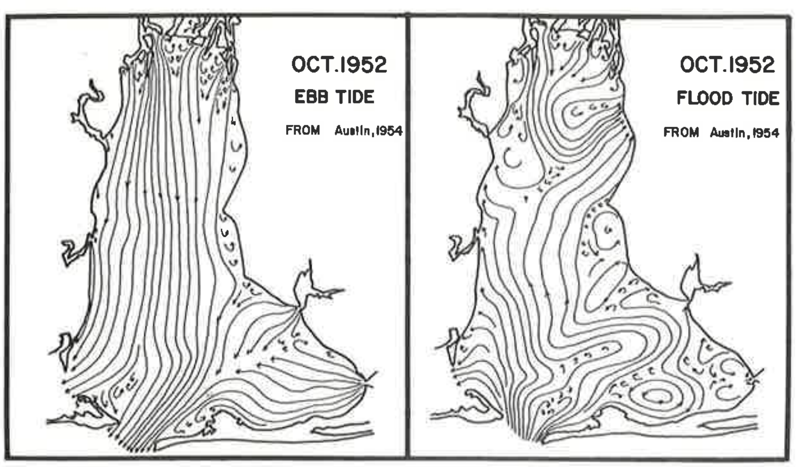
SURFACE SALINITIES



BOTTOM SALINITIES



SURFACE CURRENTS



gyre (Figure 5). During flood tide the river flow moves a few miles down the bay on its western side then is deflected eastward and northward by the rising tide. Austin states that during the flood stage the river water continues to flow downstream toward the Gulf although its movement is slowed, piled upward, and near the bottom possibly pushed back.

Superimposed on the counterclockwise gyre associated with the flood tide in Bon Secour Bay are regions of convergence and divergence indicating a complicated local vertical circulation.

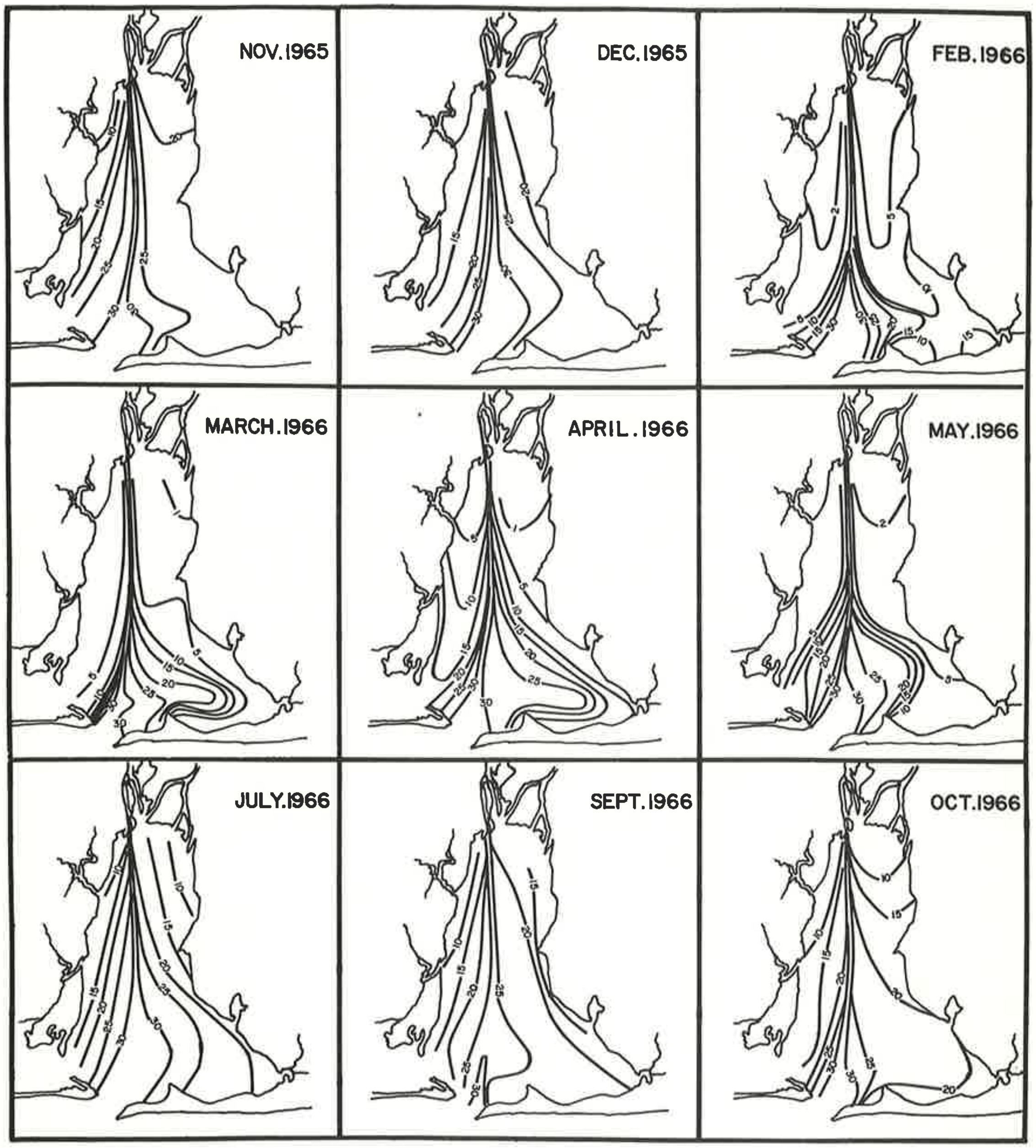
Seasonal fluctuations in river discharge often result in an almost total change in the characteristics of the water mass within Mobile Bay. This allows the bay to be seasonally and/or yearly classified on the basis of its circulation as: 1) highly stratified, 2) moderately stratified, or, with the exclusion of the ship channel, 3) vertically homogenous. In any given year the extremes in water mass characteristics coincide with the seasons of low and high river discharge. Further modifications of the water mass characteristics undoubtedly occur due to the size and shallow depths within the estuary during periods of abnormal meteorological conditions such as hurricanes.

Austin's (1954) data on vertical salinity and temperature distributions was gathered over a six day period in October, 1952, during the season of low river discharge in a year of below average river discharge. Additional information on salinity is provided by Nelson (1967) for 1963-64 and McPhearson (unpublished) for 1965-66. Although both sets of data represent only readings at ebb and flood tide gathered over a one to two week period at various stations within the estuary, some idea of seasonal variations between high to low discharge stages can be gained.

For example surface isohalines for December, 1965, reflect the discharge of fresh water down the western side of the estuary during the season of low discharge (Figure 5). As river discharge increased during March, 1966, the surface waters throughout the bay were fresher as indicated by the migration downbay of the isohalines.

During March, 1966, the estuary was either moderately stratified or vertically homogenous as reflected in a comparison of the bottom salinities (Figure 6) and surface salinities (Figure 5) at that time. In March of the preceeding year, 1964, Nelson's data (Figure 5) indicates that with the exception of the ship channel and a small area to the east of the tidal inlet bottom salinities of less than 5 ppt existed throughout the estuary. At that time, although the data is not synoptic, it would appear the estuary was vertically homogenous with the exception of the main ship channel where a

BOTTOM SALINITIES



highly stratified to moderately stratified condition prevailed. Comparisons of bottom salinities from November, 1965, through October, 1966, based on McPhearson's data illustrate the flushing of the entire bay in periods of high river discharge (February and March) and the gradual migration upbay of the isohalines during periods of low river discharge (Figure 6). The counterclockwise circulation of the surface water indicated by Austin (1954) is reflected in the higher salinities within Bon Secour Bay. The counterclockwise circulation of the bottom water may in part be due to the Coriolis effect but spoil banks along the western side of the ship channel undoubtedly partially deflect the incoming bottom waters and contribute to their eastward deflection.

The existence of the ship channel complicates the circulation pattern within the estuary by introducing a salt water wedge up the entire length of the bay.

This wedge within the ship channel has undoubtedly modified the original circulation pattern within the estuary. Prior to its dredging the controlling depth over the outer bar at the entrance to the Mobile Point inlet was 23 feet; the average depth within the bay, approximately 10 to 12 feet; and the bar at the mouth of the Mobile River was 5 feet deep. The initial appropriation for the improvement of the ship channel was made in 1826; between that date and 1857 a channel 10 feet deep was dredged through the shoals in Mobile Bay up to the city of Mobile. Between 1870 and 1934 the channel was deepened and widened periodically and reached its present dimensions between 1955 - 1957 (Table 7).

TABLE 7

DREDGED CHANNEL DIMENSIONS 1870 - 1967

(From Bisbort, 1957 and C. & G. S. Chart 1266)

Approximate Date Completed	Ship Channel Dimensions	Approximate Date Completed	Entrance Bar Channel Dimensions
1870-76	10' to 13' (depth)		
1880-89	17' (depth)		
1889-96	27' x 50' to 100'	1902	30' x 300'
1910-14	27' x 200'		
1918-26	30' x 300'	1917	33' x 450'
1930-34	32' x 300'	1930	36' x 450'
1955-57	40' x 400'	1957	42' x 600'
1967	40' x 400'	1967	42' x 600'

Studies by the U. S. Army Corps of Engineers (1949) from November, 1944 to January, 1946, indicated that the wedge extends as much as 23 miles up the Mobile River during periods of low river discharge (10,000 cfs) and is forced downriver to the head of the bay during periods when the discharge exceeds 50,000 cfs. They concluded that the maximum salt water intrusion occurred between January 15 and June 1 and that between June 1 and January 15 the salt wedge migrated downriver to the head of the estuary. At the time of the study (1944-46) the controlling depth of the ship channel within the bay was 32 feet with a channel width of 300 feet. The increase in channel size between 1955 and 1957 may have increased the average maximum penetration and salinity within the salt water wedge.

PROCEDURES

Field Methods

A total of three hundred and ten bottom grab samples of the upper two to three inches of sediment were utilized in various aspects of this study (Figure 1). These were collected using various cabin cruisers and patrol craft and a variety of grab sampling devices. Navigation was by dead reckoning from the smaller boats and by radar from the patrol craft. Twenty-five samples used in a study by Upshaw, et al (1966) were obtained from Pan American Petroleum Corp.; their original sample numbers were retained.

The sampling design was primarily a series of east-west traverses with samples taken on two, one, and half mile intervals as shorelines were approached. Additional samples were taken where maximum sediment variability was anticipated.

Laboratory Methods

Textural, limited mineralogical, and geochemical analysis as follows: 310 samples were used for carbonate analysis, 245 of these were used in the textural analysis, and 225 samples containing more than a trace of clay were analyzed for relationships of the dominant clay minerals (Tables 9 through 12, appendix).

Samples subjected to textural and clay mineral analysis were washed three times to remove soluble salts prior to wet sieving through a 62 μ screen to separate the gravel and sand grades from the silt and clay fractions. A calgon solution was used to prevent flocculation of the clays. Zero and six hour 50ml pipetted samples were used to determine the percentage of silt and clay. Size distributions of the fine fraction into whole phi units was accomplished by coulter counter analysis of an aliquot portion of the fine fraction. The coarse fraction (greater than 62 μ) was dried and sieved through a nest of screens having openings one phi unit apart.

Clay mineral identification is based on the x-ray diffraction of slides of the less than 2 μ oriented clay aggregates and by their response to glycolation. Ratios of the dominant clay minerals, montmorillonite and kaolinite, were computed on the basis of unweighted peak area measurements from the diffractogram of the glycolated sample. The peak area was determined as the product of the basal peak height and the width at half peak height.

Carbonate was determined by titration for calcium and magnesium of an acid digested ground fraction of the raw sample using E.D.T.A. and a modification of the method outlined by Turekian (1956).

Mathematical Analysis

Grain size data determined by pipetting, coulter counter, and sieving was handled conventionally and the textural parameters mean grain size, standard deviation (sorting), skewness, and kurtosis were determined by the method of moments using digital computer from the percent of sediment in each whole phi unit.

Three dimensional surfaces were developed by computer for various sediment parameters as a function of their longitude and latitude using multiple regression (Goodell, 1967). The highest order surface of best fit, that was statistically significant at the 95% confidence level as determined by analysis of variance, was selected. This mathematical surface and its accompanying residuals or deviations from the surface was plotted for each of the sediment characteristics.

The foregoing mathematical treatment of sediment parameters smooths the data and illustrates any statistically significant regional trends. The residuals from the trend surface either reflect local (secondary) trends or randomness. Interpretation of the significance of the resultant trend surfaces is still subjective, the foregoing mathematical and statistical treatment simply is a device to avoid some of the bias induced by contouring raw data.

Mobile Bay and the adjacent shelf region are two distinct environments. As a consequence the sediments from these two areas were treated as two separate populations for regression analysis of the data.

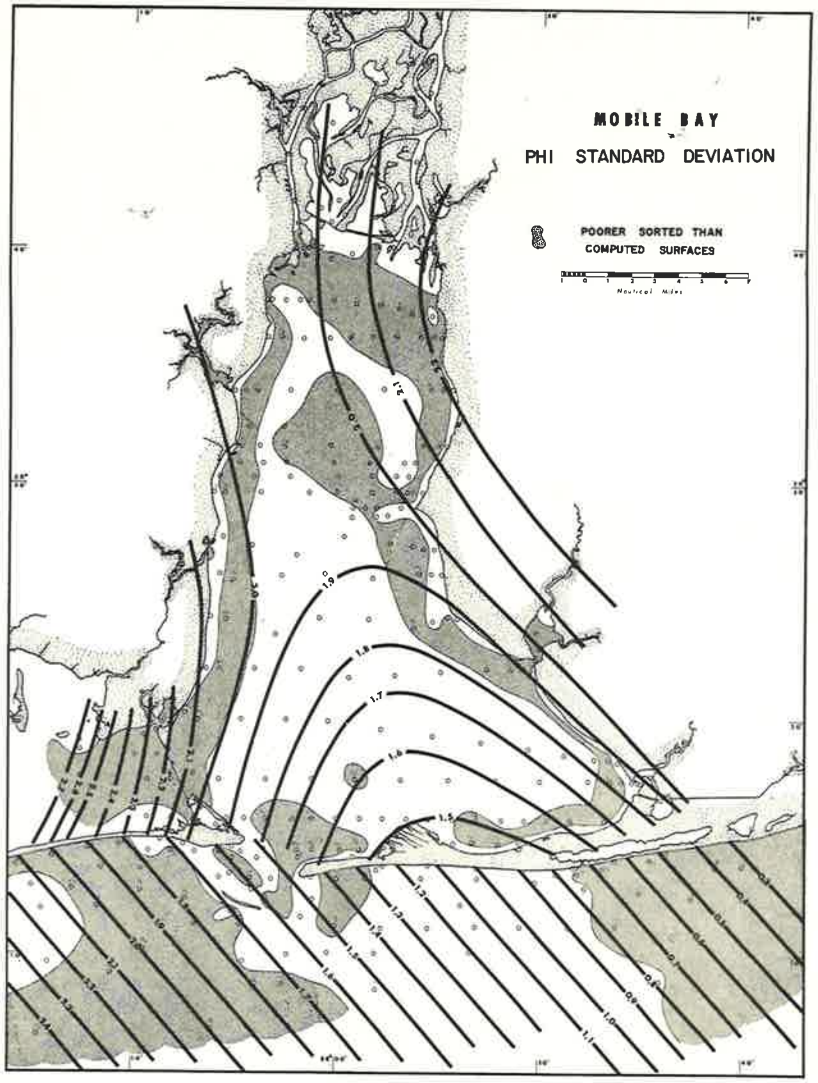
SEDIMENT CHARACTERISTICS

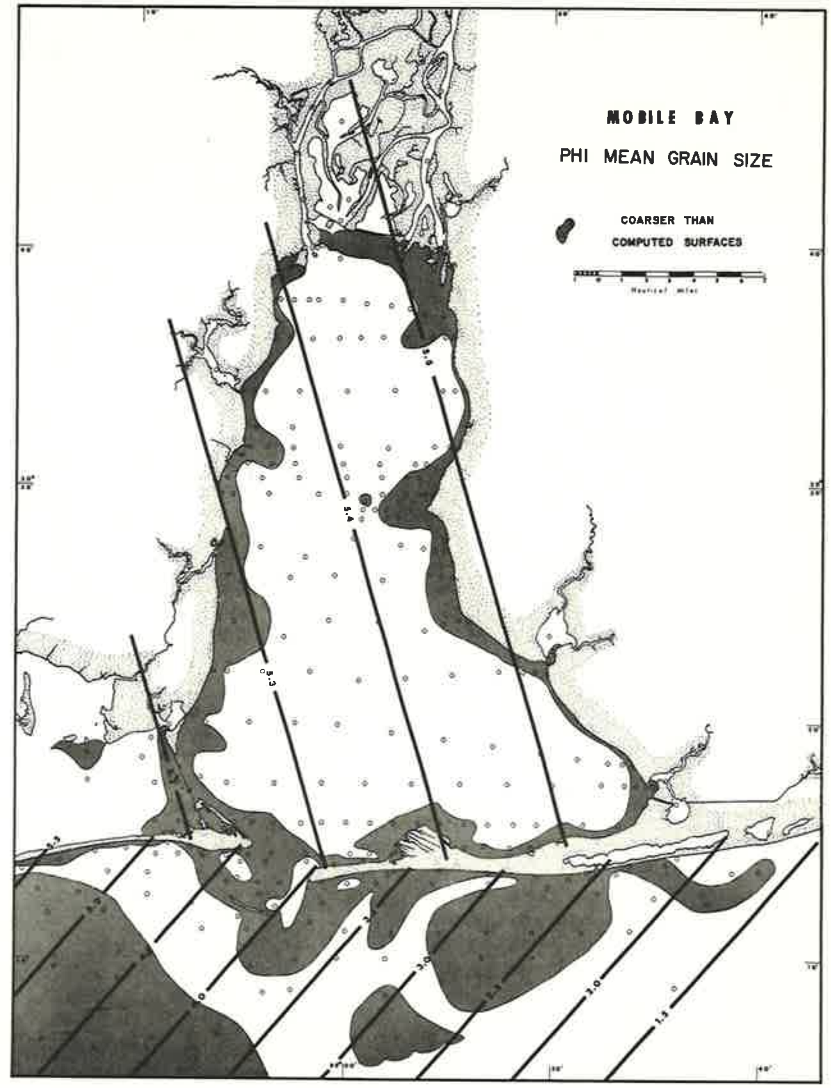
Textural Parameters

In Mobile Bay the mean grain size which ranges from -3.97 to 1.23 phi is best represented by a linear surface (Figure 8). This essentially uniform distribution lacks any pronounced trend although there is a slight decrease in mean grain size from southwest to northeast with the mean grain size in the silt grade (5 phi). The residuals, or data not accounted for by the surface, indicate finer sediments toward the center and coarser sediments around the periphery of the bay in water depths usually less than six feet.

The surface of best fit for the offshore data is again linear and indicates a progressive coarsening of the sediments toward the east and south. The fine residuals east of the tidal inlet are mostly sand and are essentially a consequence of the low (coarse) phi values of the best fit surface.

Sorting within the bay improves towards the center and towards the southeast (Figure 7). Residuals representing poorer sorting (larger phi standard deviation values) form a zone around the shoreline of the bay


MOBILE BAY
PHI STANDARD DEVIATION
POORER SORTED THAN
COMPUTED SURFACES

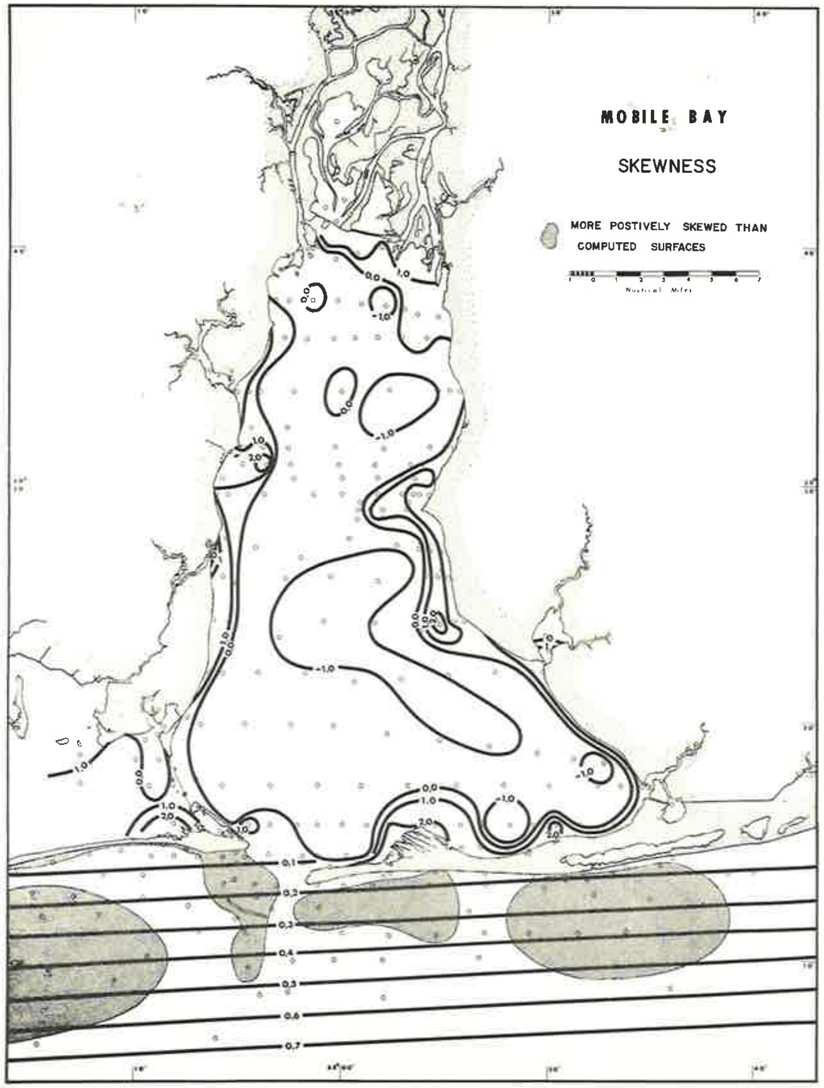

MOBILE BAY
PHI MEAN GRAIN SIZE
COARSER THAN
COMPUTED SURFACES

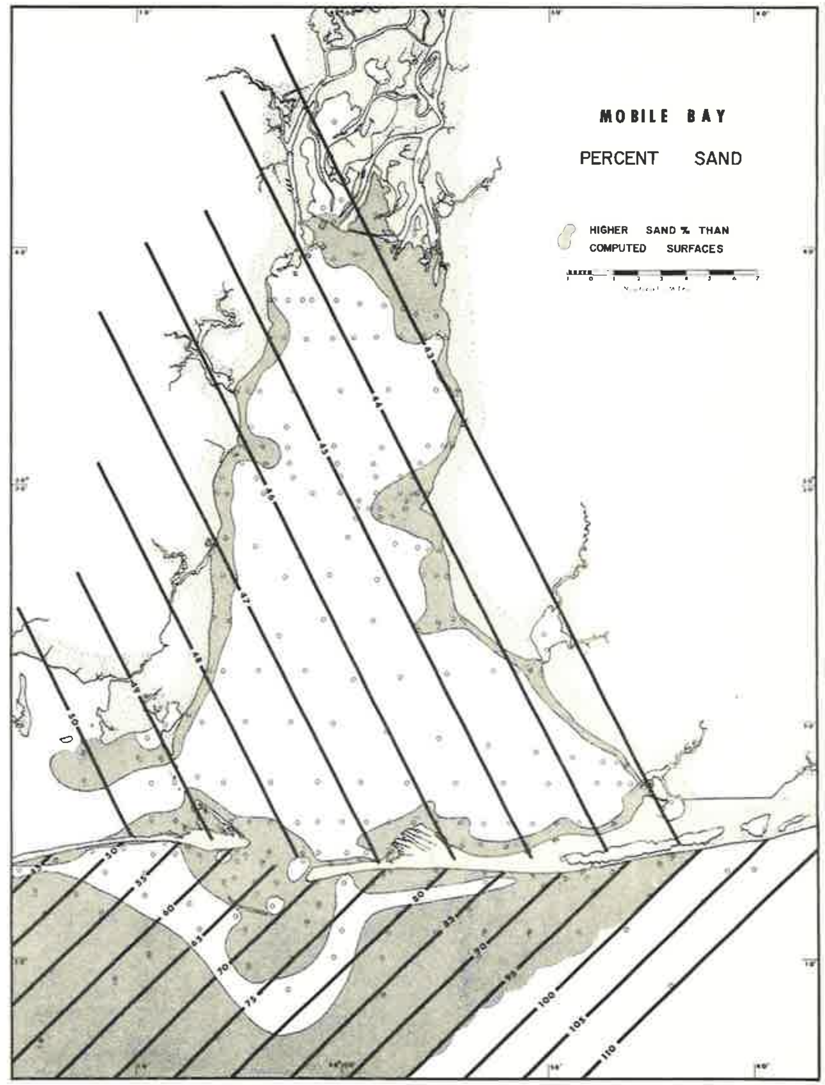
coinciding approximately to the break in slope from the shallower (less than six feet) to deeper areas of the bay.

Offshore a linear surface indicates better sorting towards the east. Residuals of poorer sorting in the extreme eastern offshore area are a consequence of the low values (well sorted) of the trend surface in this region. All of the samples east of longitude 87°50' W. have standard deviations of 1.00 or less. Standard deviation values for all samples in the bay and offshore areas ranged from 0.45 to 3.92 phi.

Skewness values within the study area range from +2.53 to -1.37. In the estuary none of the computed surfaces were significant at the 95% confidence level. The raw data indicates that there is a tendency for the coarser sediments around the periphery of the bay to be skewed toward the positive (finer sizes) whereas negatively skewed values predominate toward the center of the bay in areas of finer grained sediment (Figure 9).

The linear surface of the shelf reflects increased symmetry of the size distribution toward the shoreline with increasing skewness toward the finer sizes offshore. Residuals of the computed surface east of longitude 87°50' W. are primarily a result of the good sorting of the sediments in this region. For


MOBILE BAY
SKEWNESS
MORE POSTIVELY SKEWED THAN COMPUTED SURFACES
Nautical Miles


MOBILE BAY
PERCENT SAND
HIGHER SAND % THAN COMPUTED SURFACES
Nautical Miles

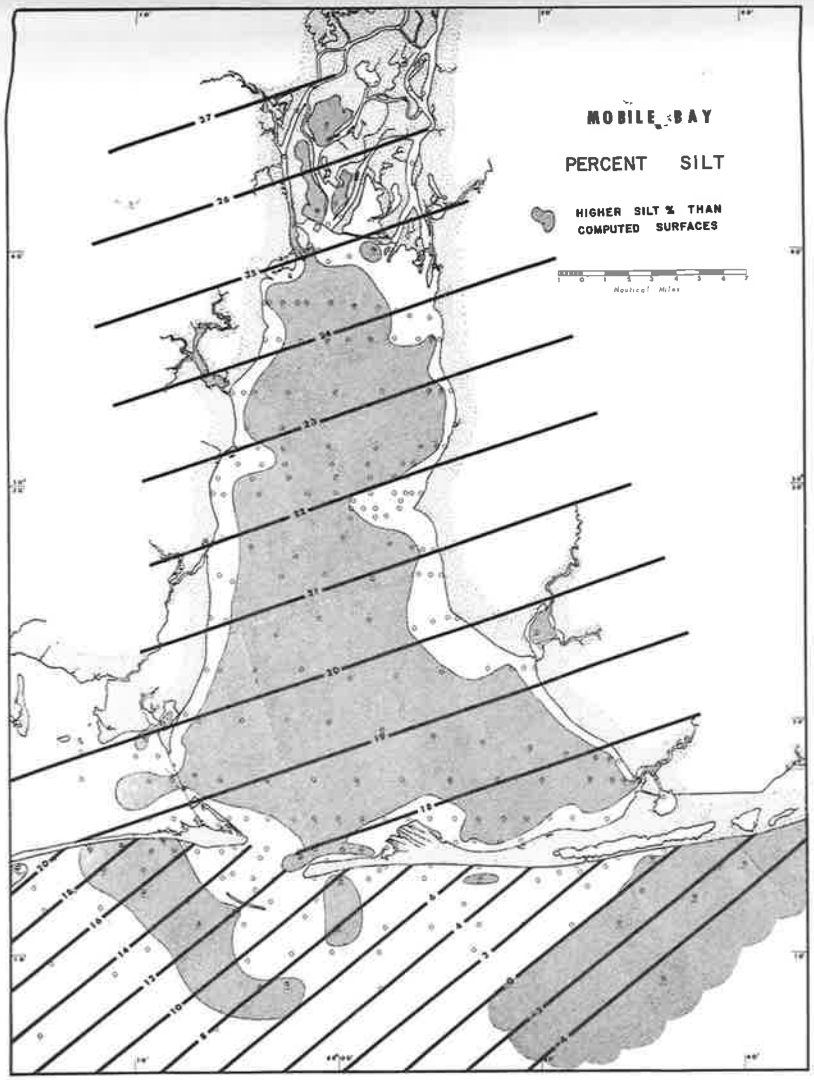
example, the ten samples in the easternmost shelf area indicated as having residuals more positively skewed than the computed surface range from 0.47 to 0.98 phi standard deviation with an average value of 0.75 phi. The skewness of these samples ranges from 0.22 to 1.57 and averages 0.76.

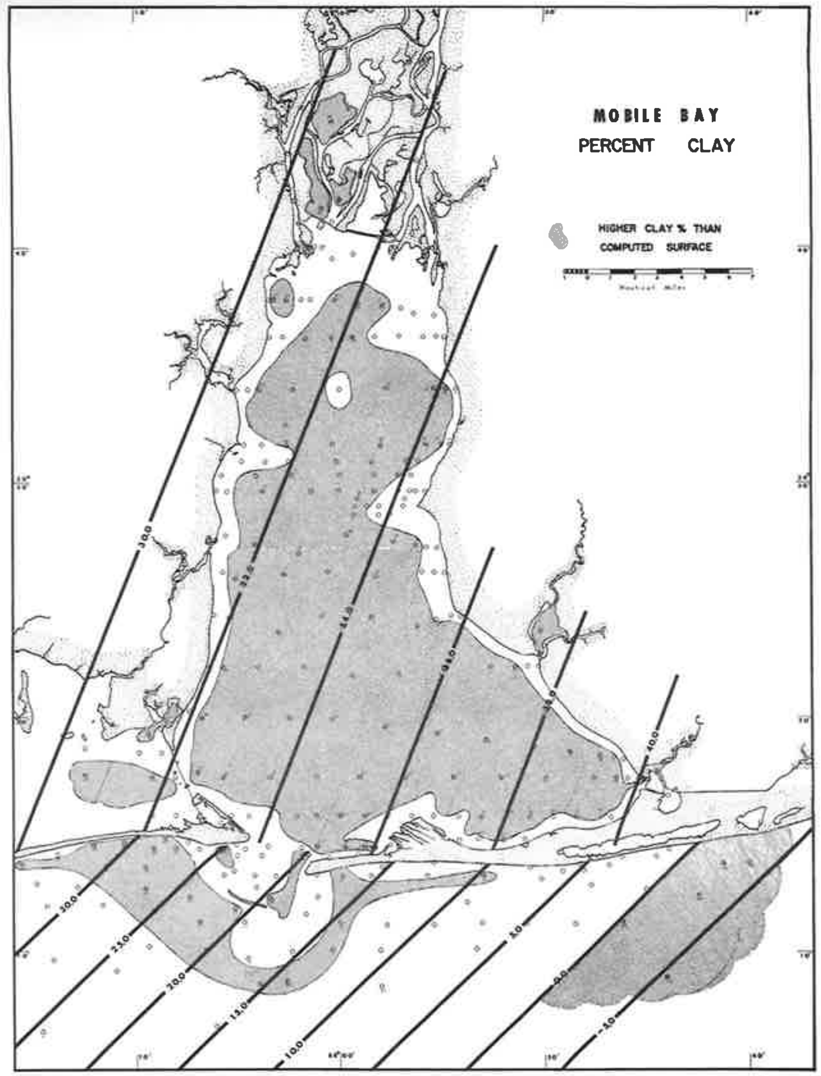
Kurtosis for the bay and shelf areas ranges from -1.79 to 64.53. The mathematical surfaces were not plotted although the surfaces for both the bay and offshore areas are linear. The majority of the samples indicate a leptokurtic distribution for kurtosis values in the area.

Size Percentages

Sand percentages within the area range from 0.02% to 99.99%. In the bay a linear surface dips toward the southwest with residuals from the computed surface reflecting higher percentages of sand in the shallow, generally less than six feet, nearshore areas around the estuary (Figure 10). Offshore a linear surface indicates increasing sand content seaward and eastward.

Silt percentages vary from 0.00% to 60.43% in the area with a linear surface indicating increased silt content from the barriers towards the bay head delta (Figure 11). The residuals illustrate higher silt


MOBILE BAY
PERCENT SILT
HIGHER SILT % THAN COMPUTED SURFACES
Nautical Miles


MOBILE BAY
PERCENT CLAY
HIGHER CLAY % THAN COMPUTED SURFACE
Nautical Miles

content toward the center of the bay, mostly in water depths greater than six feet. Offshore the silt percentage increases to the north and west as reflected by a linear surface and silt percentages are lower than within the estuary. Residuals of higher silt content are situated primarily to the southwest of the tidal inlet.

The clay content of the sediments ranges from 0.00% to 80.10%. A linear surface dips to the southeast within the estuary, reflecting increasing clay percentages toward Bon Secour Bay (Figure 12). Residuals from the computed surface illustrate lower clay content in the shallower (less than six feet) areas and directly south of the bay-head delta.

Offshore a linear surface is oriented approximately the same as the surface fitted to the silt data; that is, clay increases towards the northwest with above average percentages off of and adjacent to the tidal delta in water depths greater than six feet.

Percent Carbonate

Total detrital carbonate within the area ranges from 0.00% to 100.00% (Table 11). Excepting the oyster reefs more than 90% of the samples contain less than 4% carbonate. Those samples with more than 4% carbonate contain several valves of pelecypods and occasional gastropods.

TABLE 8

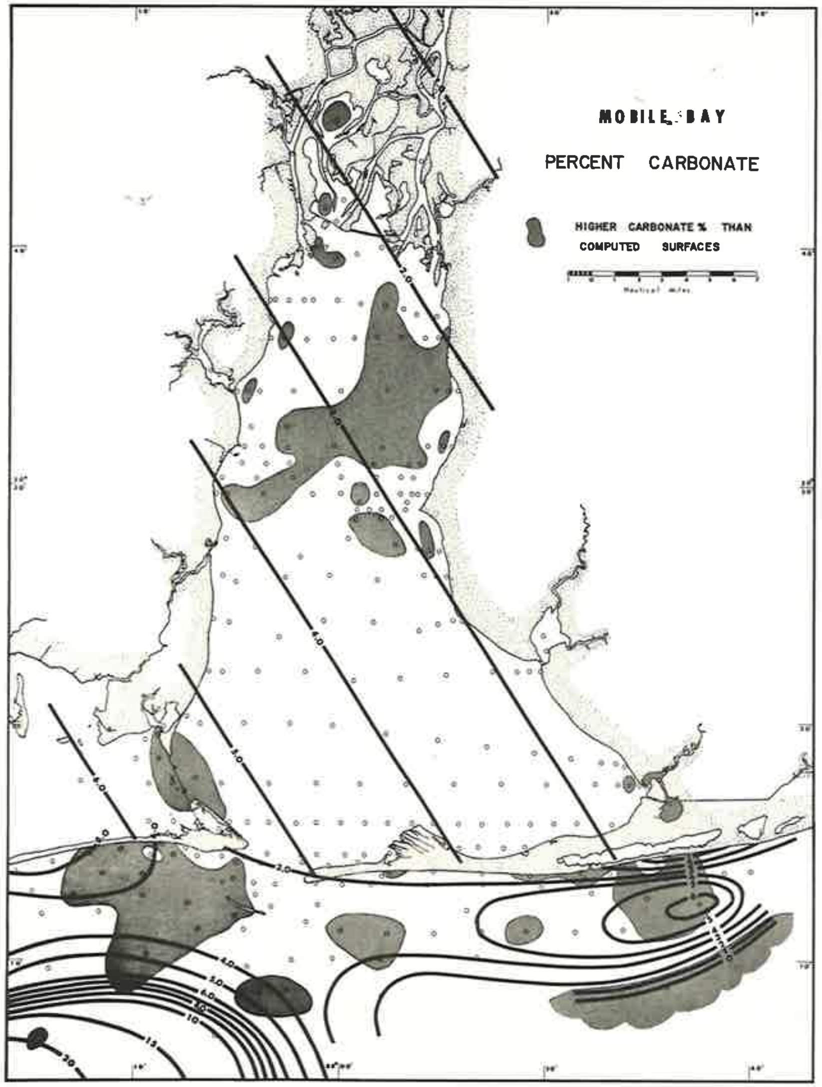
RELATIONSHIP BETWEEN CARBONATE CONTENT AND GRAVEL SIZE MATERIAL

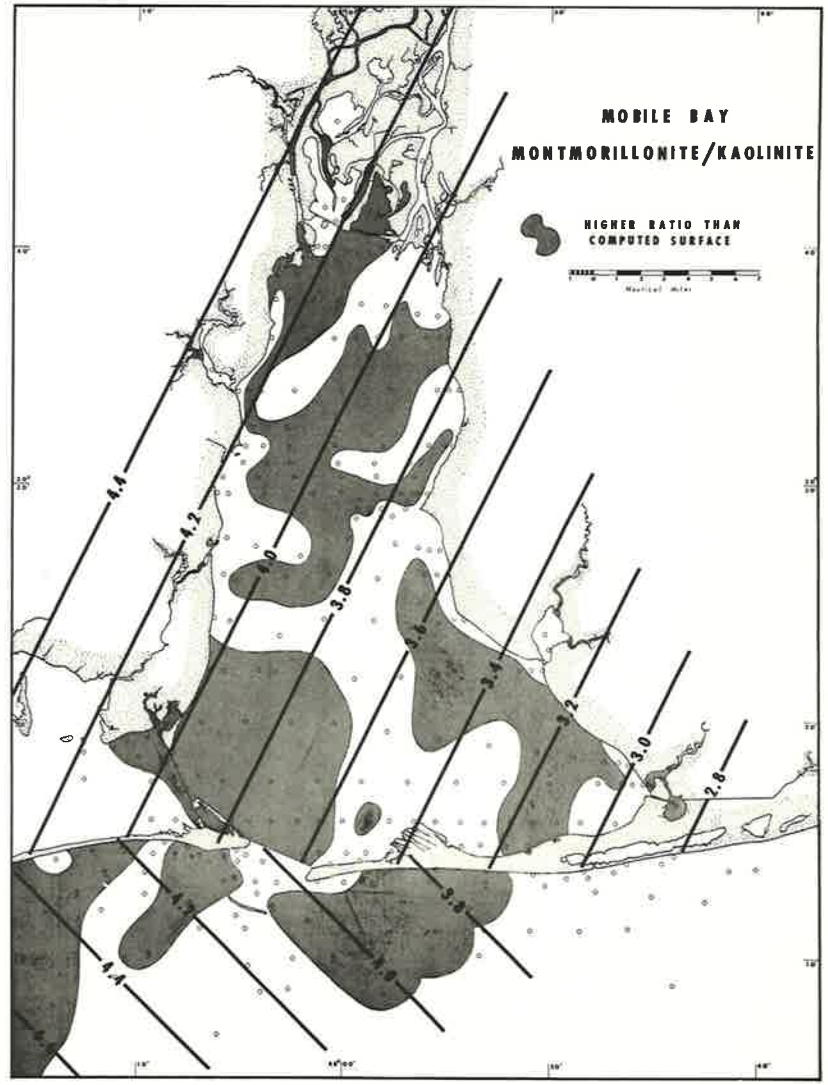
Percent Gravel	>4%	2-4%	< 2%
1%	14 samples 5.71%	9 samples 3.67%	5 samples 2.04%
0.5-1%	11 samples 4.49%	5 samples 2.04%	6 samples 2.45%
0.5%	16 samples 6.53%	79 samples 32.24%	100 samples 40.83%

Percent Carbonate

A positive relationship exists between gravel size particles and total carbonate content (Table 8). The majority (60.98%) of the forty-one samples containing more than 4% carbonate have greater than 0.5% gravel size material. Conversely, of the fifty samples having greater than 0.5% gravel 39, or 78%, have 2% or greater carbonate content. These relationships illustrate (1) most of the coarser than sand grade material is shell detritus and (2) higher than 4% carbonate percentages usually reflect the presence of whole and disarticulated pelecypod valves.

In the estuary proper a linear surface is gently inclined toward the southwest (Figure 13) indicating a slight increase in carbonate content toward the Gulf.


MOBILE BAY
PERCENT CARBONATE
HIGHER CARBONATE % THAN COMPUTED SURFACES
Nautical Miles


MOBILE BAY
MONTMORILLONITE/KAOLINITE
HIGHER RATIO THAN COMPUTED SURFACE
Nautical Miles
4.4
4.2
4.0
3.8
3.6
3.4
3.2
3.0
2.8

This trend is probably influenced by the greater number of high carbonate samples from the Cedar Point oyster reef. Residuals of high carbonate percentages in the northern part of the bay correspond to samples containing either fragments of Crassostrea virginica in the vicinity of the oyster reefs around Great Point Clear or whole and disarticulated valves of other pelecypods. Therefore the anomalous carbonate highs are accounted for by presence of "in situ" shells and not transported detrital carbonate.

Offshore the greater variability in regional distribution of carbonate content is reflected in a cubic surface. Both the surface and residuals indicate an increasing carbonate content to the southwest of the tidal inlet.

Clay Mineralogy

The dominant clay minerals within the area are kaolinite and montmorillonite. Minor and variable quantities of illite-mica and chlorite are present but were not analyzed in detail due to their low concentration and to problems inherent in quantitatively treating the measurements of unweighted peak area ratios where the 10Å and 17Å peaks tend to overlap and obscure areas of intermediate peaks.

Montmorillonite/kaolinite unweighted peak area ratios based on the 7Å/17Å peaks range in value from

0.2 to 7.4. A linear surface shows a decrease in the peak area ratios toward the southeast within the estuary indicating a trend of increasing kaolin content toward Bon Secour Bay (Figure 14). The distribution of residuals from the trend surface appear to be random.

On the shelf a linear surface reflects increasing montmorillonite content offshore and westward toward the Mississippi delta with no apparent secondary trend reflected in the residuals.

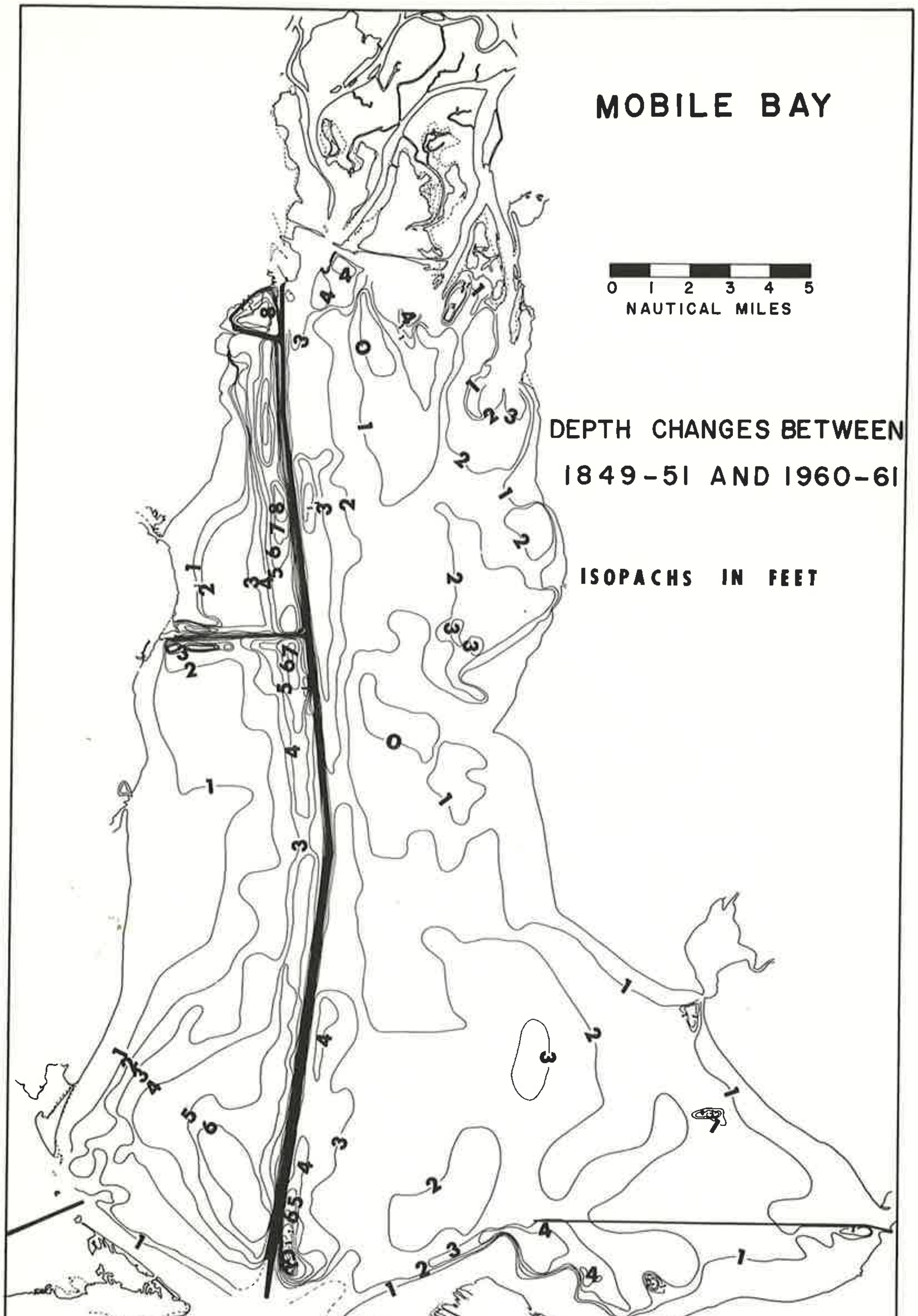
RATES OF SEDIMENT ACCUMULATION

Methods and Assumptions

In order to determine rates of sediment accumulation within the bay the two bathymetry maps contoured on a one foot interval for the surveys of 1847 - 1851 and 1960 - 1962 were superimposed and the differences in depths were compared. The resultant map gives depth changes over the 110 year period 1850 - 1960 (Figure 15).

Assumptions made in calculations of rate of sediment accumulation include: (1) negligible eustatic changes in sea level in the Gulf over the past 110 year period, (2) negligible subsidence of the estuary over this period, and (3) negligible compaction of the sediments.

These assumptions, if invalid, would tend to increase the rate of sediment accumulation as a higher sea level (either eustatic, tectonic, or both) and compaction of sediments would tend to increase the volume within the estuary beyond that used in the calculations. Marmer (1952) has estimated on the basis of changes in positions of tide gauges, rises of sea level along the Gulf Coast ranging from 2.44 feet per century for


MOBILE BAY
0 1 2 3 4 5
NAUTICAL MILES
DEPTH CHANGES BETWEEN
1849-51 AND 1960-61
ISOPACHS IN FEET

Galveston Bay to 0.85 feet per century at Key West with an average rise of 1.63 for the Gulf Coast. This relative change in sea level if real, is due to both eustatic and tectonic influences. Marmer points out that the rate of rise is highly variable; for instance at Galveston between 1909 and 1937 he estimates sea level rise at 0.015 feet per year while between 1937 and 1950 the rate increased to 0.05 feet per year. The short period of record and the possibility of error in positioning the tide gauges makes these estimates questionable. Coleman and Smith (1964) computed the rate of subsidence of salt marshes 50 to 75 miles west of the Mississippi delta as 0.24 feet per century over the past 2,000 years assuming no eustatic sea level rise or compaction; this conflicts with the estimate of Gutenberg (1941) of a 0.4 foot per century eustatic rise of sea level. A review of figures in Fisk and McFarlan (1955) indicates no downwarping in the vicinity of Mobile Bay, in fact it might be possible to infer uplift of the shelf off Mobile Bay in response to overloading in the Mississippi delta region. At the other extreme Russell (1967) mentions regional subsidence in the Mobile delta above the present estuary on the order of 10 feet over the past 3,000 years. His basis is subsidence of indian mounds in the floodplain; this might be attributed to compaction under the load of the mounds rather than regional subsidence.

Fisk and McClelland (1959) state that recent sediments on the Louisiana shelf off the Mississippi delta to depths of 360 feet show negligible compaction and loss of water. Therefore the assumption that there is negligible compaction of recent sediments within Mobile Bay appears not unreasonable.

In addition to the consequences of higher sediment accumulation rates within the estuary due to the invalidity of one or more of the foregoing assumptions; errors in the following assumptions would tend to cause a variation in the estimated amount of sediment by-passing the estuary and being contributed to the Gulf: (1) the average density of sediments currently accumulating in the estuary is 35.5 lbs/ft^3, (2) the suspended sediment load delivered by the river system has averaged 4.7 million tons per year over the past century and (3) the contribution of sediment from sources other than suspended river sediment has been negligible.

The average dry weight density for Mobile sediments was determined empirically by drying and weighing 17 samples of known volume of typical silty clays, clayey silts and muds taken from the estuary. The second assumption appears reasonable as no trend of increasing or decreasing suspended sediment load over the twelve year period 1952 - 1963 was noted. The third assumption considers overwash from the barriers during hurricanes, erosion of shorelines, wind blown sediment, and organic debris from plant (marshes) and animal (principally oysters) activity to be negligible relative to the 4.7 million tons of suspended sediment delivered annually by the river system. A possibly significant source of sediment is the bed load of the river system which could conceivably contribute up to 0.5 million tons annually although no estimates are available. It has been assumed in this study that the bed load is principally trapped at the front of the bay-head delta and is the origin of the sands and silty sands in this region (see Figure 17). Only a small portion of this delta front area was considered in the calculations of volume changes over the past century.

Calculations of Sediment Accumulation

On Figure 15 the isopachs reflect the variability of sediment accumulation rates within the estuary. The delta distributaries have advanced approximately one mile further seaward and there has been in-filling of some of the interdistributary bays. Although most of the deposition in the interdistributary bays is natural, the westernmost one, adjacent to the Mobile River and known as Polecat Bay, has been the site of deposition of large quantities of sediment removed from the Mobile River during dredging operations (Baldwin, 1956).

Around the periphery of the bay in areas dominated by clean quartz sands, in the shallow, less than six foot region, there has been little or no net sediment accumulation. In the vicinity of the delta, rates in excess of 4 feet per 110 years are noted. The natural distribution of the sediment has been obscured by the dredging of the ship channels and the construction of spoil banks, particularly along the western side of the estuary. In the northwest portion this spoil material averages 8 to 10 feet over extensive areas. If the effects of dredging are ignored it appears the central half of the bay may be a region of sediment by-pass. In Bon Secour Bay two to three feet of sediment has been deposited over the 110 year period, probably by flood tidal currents returning river-borne sediments through the tidal inlet that were first carried seaward by mechanisms discussed by Meade (1969). The former channel northwest of the tidal inlet received more than 6 feet of sediment along its axis during this period, probably due to cessation of a tidal current by the damming effects of the spoil deposits.

Excepting the delta region, changes along the shoreline were, for the most part, not of sufficient magnitude to be noted by comparing the two bathymetric maps. Carlston (1950) notes wave erosion of the bay shorelines and Austin (1954) estimates the rate of shoreline erosion at 0.5 feet per year but states this is not quantitative; wave erosion was noted during this investigation particularly along the western side of the bay but no attempt has been made to quantify the rate of recession. Two exceptions to this lack of rapid shoreline modification are an island constructed from spoil material to the southwest of the city of Mobile and the reduction in size and displacement of the offshore islands on the tidal delta.

Two oyster reef tracts within Bon Secour Bay indicate a net loss of between one and two feet. This possibly reflects subsidence of the reef masses into the underlying soft clays. A contributing factor could be the removal of more shell material during harvesting than was returned.

Most of the dredged material is concentrated in the northern part of the estuary. This is probably due to extensive shoaling as a consequence of cutting through the bar at the entrance to the Mobile River and the dredging of the main ship channel. The development of a salt water wedge up this channel might initially result in shoaling upstream of the river entrance bar and a gradual downstream migration of the maximum shoaling area through time in a manner similar to that observed by Simmons (1969) for the Mississippi distributaries, and Charleston and Savannah Harbors.

Considering the estuary as a whole the average rate of sediment accumulation is presently 1.7 feet per century. Rates of greater than 3 feet per century correspond either to (1) the area immediately bayward of the bay-head delta, (2) spoil deposits from dredging, or (3) former channels once maintained by currents now deflected by dredged channels and associated spoil banks. Bon Secour Bay appears to have the highest natural sediment accumulation rates indicating that from a standpoint of volume more sediment is being deposited near the entrance to the estuary than off the Mobile delta.

The calculated average value of 1.7 feet per century is in reasonable agreement with estimated rates of sedimentation of other Gulf Coast bays and estuaries. Shepard (1953) calculated rates of 1.26 feet per century for various Texas bays over a 65 year period on the basis of shoaling by a method similar to that used in the present study. Rehkemper (1969) estimated 1.2 feet per century for Galveston Bay on the basis of carbon-14 dates. Rainwater (1964) estimates 0.4 feet per century sediment accumulation in Mississippi Sound over the past 5,000 years.

Carbon-14 dates of oyster shells within Mobile Bay (Figure 16) indicate rates of sedimentation of 0.1 to 0.5 feet per century over the past 5 to 6 thousand years emphasizing that present rates determined by shoaling over the past century are considerably higher than in the past and probably still accelerating due to increased progradation of the bay-head delta.

Using the base map from which Figure 15 was constructed the total volume of sediment deposited in the estuary between 1850 and 1960 was estimated. Multiplying this volume times an average dry weight density of 35.6 lbs/ft^3 a total sediment accumulation of 365 million tons is estimated for this 110 year period. Assuming an average annual rate of 4.7 million tons of suspended sediment delivered to the estuary annually 520 million tons was delivered to the bay between 1850 and 1960. The balance or 155 million tons, represents an average discharge of 1.4 million tons of suspended sediment to the Gulf of Mexico annually. Such an estimate clearly does not reflect the actual annual rate of suspended sediment dispersed through the tidal inlet. As previously discussed in some years four times as much suspended sediment reaches the estuary from the rivers as in other years. Also, most of the above quantity of suspended sediment may be delivered in one or two months accompanied by high river discharge which in turn would generate a higher flushing rate from the estuary. The effects of hurricanes upon the dispersal into the Gulf are unknown and may be significant, especially when the winds are blowing from the north. In addition, the gradual progradation of the bay-head delta results in more suspended sediment being carried further downbay and by-passing the estuary in succeeding years.

Due to the assumptions that had to be made on various unquantified variables it is obvious the rate of sediment accumulation and sediment by-pass determined for Mobile Bay are only crude estimates subject to future refinement. It is believed, however, that they are in the proper order of magnitude. The variations in sediment accumulation for various specific regions within the estuary should be correct relative to each other regardless of the future status of the various assumptions necessitated for purposes of calculation.

OYSTER REEFS

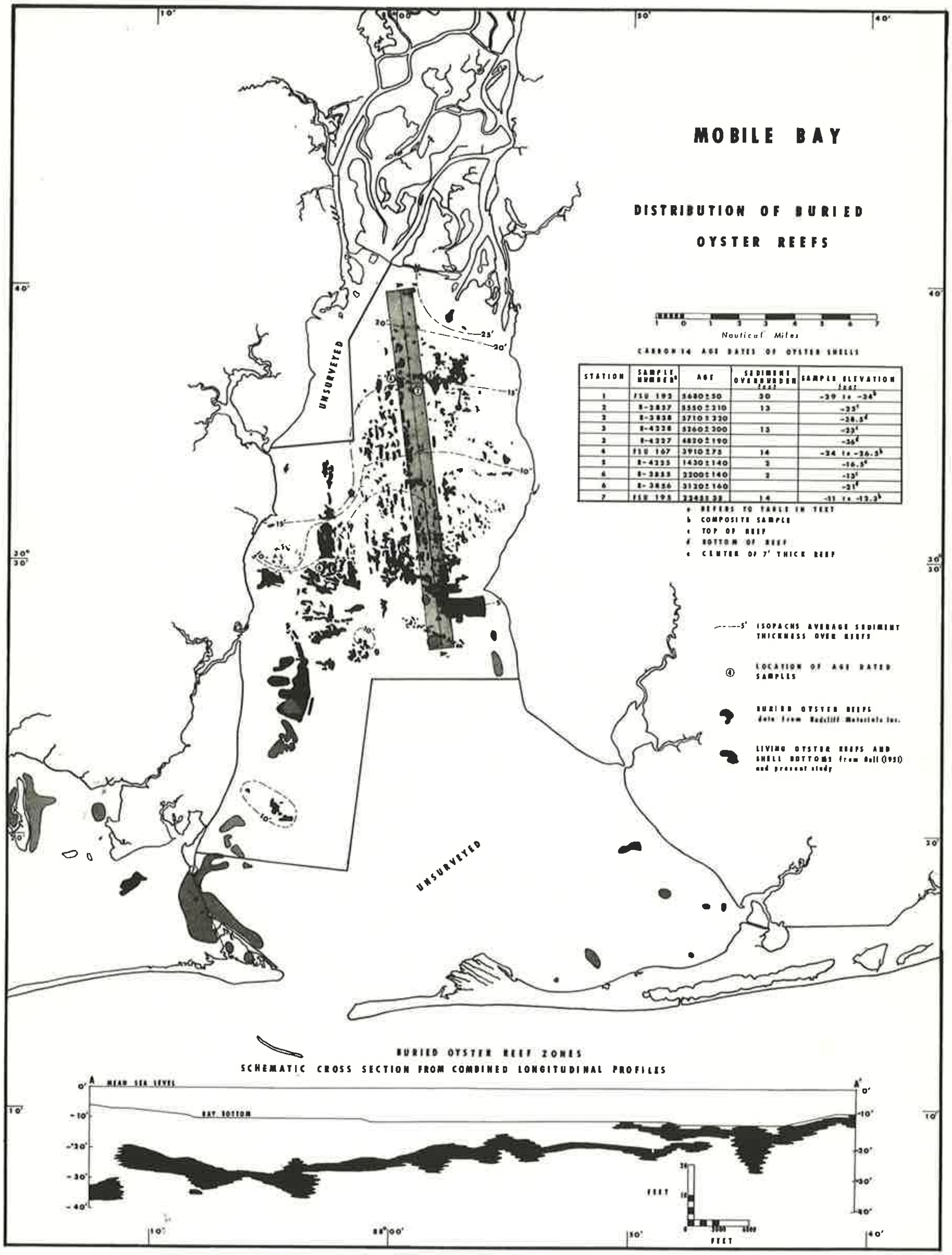
The distribution of the buried oyster reefs in Mobile Bay is derived from data provided by Southern Industries (Radcliff Materials Inc.) who has conducted extensive surveys of the extent of the buried reefs over the past twenty years (Figure 16). The distributions indicate the actual extent of the reefs at the time of the surveys. The north-south lineations of many of the reefs probably reflects strips of shell that have been removed by dredging. Many of the more extensive reefs indicated have subsequently been removed by dredging. The isopachs indicate approximate sediment cover over the reefs. A survey of the southern part of the bay, primarily Bon Secour Bay, indicated as unsurveyed on this figure was completed in late 1968 by Southern Industries in conjunction with the Alabama Bureau of Conservation. Results of this survey indicate this region is devoid of additional buried reefs (E. May, personal communication).

The location of living reefs in 1951 (Bell, 1952) is indicated on Figure 16. E. May (personal communication) states the results of a recent study conducted by himself shows the reported extent of many of these living reefs to be too large and somewhat in error as to position.

At present the living reefs of *Crassostrea virginica* (Gemlin) extend no further north than Great Point Clear. There has been a progressive decrease in size and a shift downbay of the oyster reefs during the time from the first published charts of 1894 to the present. This is evidenced by the works of Ritter (1895), Moore (1913), Bell (1952), and current studies by E. May of the Alabama Marine Resources Laboratory.

The reefs on the western side of the bay have suffered the greatest decline since 1894; in particular Whitehouse, Kings Bayou, and Buoy reefs. Furthermore the reefs reported by Ritter (1895) off Great Point Clear are no longer living.

A comparison of the bathymetric charts of 1847-51 and 1960-62 indicate a subsidence of one to two feet on two reef tracts in Bon Secour Bay over the 110 year period (Figure 15). Living reefs presently exist in positions indicated on the 1960-62 chart for these topographic highs (Figure 3). A possible explanation is that the rate of production on these reefs has not kept up with subsidence over this 110 year period, primarily due to compaction of the underlying sediments. Bell (1952) also notes that the reefs he studied seemed to be smaller and deeper than indicated by Ritter's



CARBON-14 AGE DATES OF OYSTER SHELLS

STATION	SAMPLE NUMBER[a]	AGE	SEDIMENT OVERBURDEN feet	SAMPLE ELEVATION feet
1	FSU 192	5680±50	30	-29 to -34[b]
2	I-2837	5550±210	13	-23[c]
2	I-2838	5710±220		-28.5[d]
3	I-4228	5260±200	13	-23[c]
3	I-4227	4820±190		-36[d]
4	FSU 167	3910±75	14	-24 to -26.5[b]
5	I-4225	1430±140	3	-16.5[e]
6	I-3855	2200±140	2	-13[c]
6	I-3856	3120±160		-21[d]
7	FSU 195	2245±33	14	-11 to -12.3[b]

a REFERS TO TABLE IN TEXT
b COMPOSITE SAMPLE
c TOP OF REEF
d BOTTOM OF REEF
e CENTER OF 7' THICK REEF

survey of 1894. Galtsoff (1964) outlines variables that could account for this decrease including changes in salinity, water temperature, stream discharge, quantity of nutrients, amount of suspended sediment, changes in current patterns and increases in number of predators and diseases; although the latter two would be dependent on increases in salinity.

Comparison of the location, extent, and age of the buried oyster reefs indicate the first reefs established themselves in the bay between 6,000 and 5,000 years B.P. This agrees closely with published data on other Gulf Coast bays and estuaries (Collier and Hedgepeth, 1950; Norris, 1953; Parker, 1960; Gunter, 1967; Lankford and Rogers, 1969).

Carbon 14 dates (Figure 16) from various reefs within Mobile Bay indicate they have progressively migrated downbay during the past 5,000 years. Initially the reefs were established in the northern part of the bay in the vicinity of the causeway and present delta. In this area reefs dating from 5,680 B.P. are found at an elevation of -29 to -34 feet beneath 30 feet of overburden. The cross section A-A' compiled from data in the shaded area of Figure 16 illustrates the reefs progressively decrease in age and are buried beneath less sediment downbay. Extinct buried reefs furthest downbay in the vicinity of Great Point Clear were living approximately 1,400 years ago. A clearly established pattern therefore exists of gradual migration downbay through the past 5,000 years probably due to the progradation of the Mobile delta with accompanying lowering of salinity in the upper bay below minimal levels for viable reefs. The oysters probably were migrating southward with the shofting isohalines. Factors that may have aided in this migration would be the gradual shoaling of the lower reaches of the bay resulting in the restriction and upbay migration of more saline bottom waters. Circulation patterns have been further modified by the westward migration of the Mobile Point barrier which would further restrict the inflow of open marine waters thereby further reducing the salinity within the bay.

The decline over the past seventy years of the living reefs on the westward side of the bay may be the result of radical changes in the circulation pattern. A comparison of the 1847-51 and 1960-62 bathymetry charts (Figures 3 and 4) indicates that in 1850 a broad shallow trough existed in the lower reaches of the bay extending from the tidal inlet northwestward toward Cedar Point. It is suggested this trough was maintained by a westward component of the flood tide through the tidal inlet with the bottom depth of this channel being the equilibrium profile during the period in which this bottom current was operative. This trough is considerably restricted on the 1960-62 bathymetric chart (Figure 3). During dredging operations the material removed from the ship channel is usually deposited in spoil banks on the westward side of the channel. This spoil material acts to deflect inflowing bottom waters to the east resulting in anomalously high rates of sedimentation in the position of this former channel (Figure 15). The diversion of this former westward flowing bottom current resulted in a lowering of salinity in the vicinity of the western oyster reefs with resultant diminishment in their productivity. A further contributing factor to their extinction is the ship channel spoil banks which probably have increased the flow of fresh water on ebb tide along the western margin.

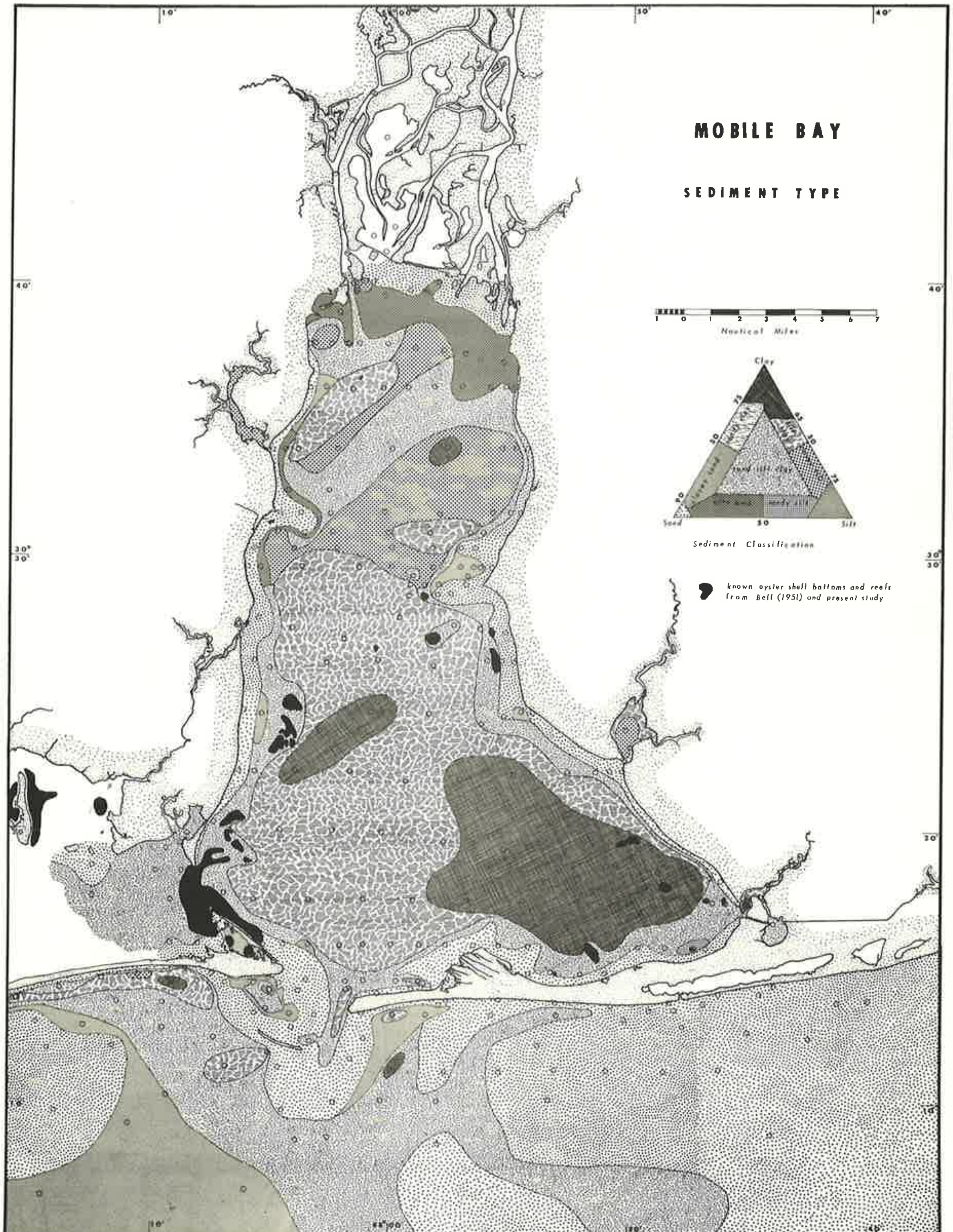
The most extensive living reefs are found in the area between Cedar Point and Little Dauphin Island. They probably reflect optimum salinity ranges and adequate currents to remove sediment deposited by self-siltation. Lund (1957) emphasizes the importance of adequate bottom currents to permit oysters from burying themselves in fine sediment removed during filtration for nutrients. This factor would be of paramount importance in an area such as Mobile Bay where the suspended sediment content is higher than many areas of oyster reef development. The periodic flushing (Galtsoff, 1930) of these reefs during flood stages of the river system destroys predators and undoubtedly is an additional contributing factor to their success.

DISCUSSION

The characteristics of the sediments within Mobile Bay are overwhelmingly controlled by the source area characteristics as modified by transportation in the Mobile River system. Non-fluvial sources such as windblown detritus, material derived from erosion of the shorelines, washover deposits and biogenous constituents (particularly oyster reefs), are of secondary importance. The ultimate distribution of the mineralogical and textural characteristics of the sediments reflect the control of the geometry of the depositional basin and responses to transportative processes within the estuary; primarily wave action and circulation patterns.

Ten sediment types are defined on texture (Figure 17). The classification is a modification of that proposed by Shepard (1954). Around the periphery of the estuary, confined primarily to depths less than 6 feet, are clean quartz sands; the silt and clay having been winnowed out by waves and currents. Although sand-size material is being contributed as bed load to the estuary most is deposited peripheral to the bay-head delta of the Mobile River and is found in decreasing quantity downbay. The sand fraction is greatly diminished within five miles on the eastern and eight miles on the western side of the estuary. This decrease is reflected in the changing sediment patterns: from clean sands to silty sands and finally a mixture of sand-silt-clay (Figure 17). The greater extent of coarser sediments on the western side coincides with the highest velocities of the ebb tidal current (Figure 5). The clean sands around the periphery of the bay are believed to be predominantly relict, based on the low rates of sedimentation in these regions (Figure 15). As previously mentioned, some erosion of the shoreline is taking place and may be contributing some sand to the shallows. The elongate, narrow sand ridges (observed on aerial photographs of the bay) extending outward into the estuary in depths of less than six feet suggest sand movement by tidal and longshore currents.

The vast bulk of the bay sediments are silty clays and clays with a general decrease in grain size toward the tidal inlet and eastward into Bon Secour Bay. These trends are reflected in increasing percentage of clay towards the southeast (Figure 12). The concentration of finer sizes in Bon Secour Bay are interpreted as reflecting transportation of the suspended sediment by the circulation system first downbay, out the tidal inlet, and then back into the estuary with the inflowing


MOBILE BAY
SEDIMENT TYPE
Nautical Miles
Clay
Sand
Silt
sand silt clay
sandy silt
Sediment Classification
known oyster shell bottoms and reefs from Bell (1951) and present study

flood tide bottom water in a manner such as discussed by Meade (1969). During transport the coarser silt sizes are gradually being deposited leaving progressively finer sizes in suspension. The trend of better sorting (Figure 7) downbay and toward the center is a further indication of such a circulation of the suspended sediment prior to deposition. The known counterclockwise flood tidal currents into Bon Secour Bay is further substantiation of such an interpretation.

A zone where nearshore sands mix with bay center silty clays exists around the periphery of the bay where steeper bathymetric gradients occur between the nearshore sand flats and the bay bottom. This zone, reflected by the residuals of poorer sorting (Figure 7), probably indicates the depth at which bay waves lose the competency to winnow. If such is the case this could be an index to the mean depths at which wave action is significant in scouring and transporting sediment.

The distribution of the montmorillonite/kaolinite ratios within the estuary presents some puzzling relationships if one assumes the clays are detrital in origin and that differential flocculation has caused an enrichment of montmorillonite in regions of increased salinity as suggested by the experimental work of Whitehouse, et al (1958). In this case higher kaolinite concentrations should be near the delta and progressively increasing montmorillonite seaward; the reverse is true in Mobile Bay (Figure 14).

Preliminary examination of the cores taken in the bay indicates that montmorillonite is more abundant with depth. This increase in kaolinite content relative to montmorillonite during the historic period of the estuary could be the result of the initiation of agriculture in the drainage basin resulting in increased kaolinitic soils being produced and eroded from the arable lands. Increased kaolinite percentages have been noted in progressively younger sediments from the Appalachicola drainage basin to the east (Schnable and Goodell, 1968) and from the Mississippi drainage basin to the west (Griffin and Parrott, 1964). Hyne and Goodell (1967) also noted increasing kaolinite content in progressively younger shelf sediments to the east off Choctawhatchee Bay although they attributed this to a change in the drift system rather than a change in kaolinite content of the river systems.

If there has been an increase in the kaolinite content of the suspended sediment the trend of the montmorillonite/kaolinite ratios is explainable as a further indication of the present higher depositional rates of the suspended sediments in Bon Secour Bay (Figures 14 and 15). As the sampling devices used picked up the upper 2 to 3 inches of sediment, areas of higher depositional rates would contain higher kaolinite content if there is increasing kaolinite in the suspended sediment delivered to the estuary through the historic period. The higher montmorillonite content in regions adjacent to the dredged channels and in the northern part of the estuary could be attributed to overturn of older (higher montmorillonite content) sediments by dredging in the channels and for buried oyster shell.

Immediately seaward of the tidal inlet there exists a lunate tidal delta of clean sand. Seaward of this tidal delta, in water depths usually greater than 12 to 18 feet, there is a region of sand-silt-clay reflecting the mixing of shelf sands with silts and clays derived from the estuary. The bulk of this fine grained sediment is deposited to the south and southwest of the tidal inlet in response to the predominant littoral drift. Some of the clays and silts are moved eastward in response to an eastward component of the littoral drift system that is operative during the summer months. Toward the east the shelf sands are progressively coarser and better sorted reflecting the relict nature of these sands (Figures 7 and 8). Increasing montmorillonite content toward the south and west probably reflect the increasing influence of the Mississippi sediments in this direction (Figure 14). Scruton and Moore (1953) and Shepard (1960) have observed sediment plumes extending from the Mississippi distributaries to areas east of Mobile Bay.

In conclusion, the Mobile River system is presently carrying an annual average of 4.7 million tons of suspended sediment and an unknown quantity of bed load to the estuary. At present most of this sediment which is dominantly clay and silt size, is flocculating in the ship channel and being deposited around the spoil banks on the western side of the estuary. The construction of the ship channel has resulted in the introduction of a salt wedge up the Mobile River and modified the natural circulation within the bay. In response to this changed circulation system, above average rates of sediment accumulation are occurring in the southwest portion of the bay. An estimated average of 1.4 million tons of suspended sediment is annually by-passing the bay and being deposited primarily south and west of the tidal inlet. Distribution and ages of buried oyster reefs indicate a progressive downbay migration through time in response to changes in the circulation system and progradation of the bay-head delta.

Ultimately, probably within the next millennium, if present rates of sedimentation persist, the estuary will cease to exist and the present delta will have prograded into the Gulf.

APPENDIX

TABLE 9

STATISTICAL PARAMETERS OF SEDIMENT
TEXTURAL DISTRIBUTION

Sample Number	Textural Properties: Phi Mean	Phi standard Deviation	Skewness	Kurtosis
011	8.200	1.449	-.814	3.859
021	8.179	1.446	-.845	4.583
022	7.782	1.665	-.607	2.346
023	8.416	1.241	-.919	5.272
024	3.116	1.722	1.168	4.500
025	2.878	1.683	1.454	7.793
026	3.911	2.059	.845	1.660
027	7.879	1.833	-.717	1.685
029	7.324	2.343	-.592	.510
030	7.770	1.951	-.866	3.311
031	2.942	1.536	1.240	5.800
032	2.256	3.664	-.224	.188
033	2.014	.755	1.865	28.871
034	4.816	2.243	.445	-.045
035	2.387	1.273	2.737	14.262
038	2.353	1.399	1.423	10.430
040	4.921	3.178	.123	-1.651
041	8.432	1.171	-.579	1.586
042	7.721	1.765	-.408	-.050
044	5.862	2.543	.058	-1.327
045	6.214	2.533	-.137	-.788
046	7.387	2.447	-.739	2.029
047	7.351	2.435	-.992	5.032
048	5.462	2.729	.173	-1.373
049	4.676	2.482	.280	.346
050	3.593	2.160	.273	4.240
052	3.023	1.549	1.028	4.694
053	3.567	2.474	.751	1.009
055	8.004	1.684	-.713	2.499
056	7.296	2.334	-.525	.271
057	5.507	2.914	-.409	1.733
058	5.238	3.048	.086	-1.414
059	5.168	2.540	.314	-.836
060	5.789	2.665	-.132	-.039
061	4.575	3.064	.195	-.966
062	7.413	2.008	-.714	1.980
063	6.889	2.073	-.373	.234
064	7.587	1.956	-.667	1.769
065	1.228	1.528	1.144	13.000

TABLE 9--Continued

Sample Number	Textural Properties: Phi Mean	Phi Standard Deviation	Skewness	Kurtosis
066	4.092	2.950	.385	-.823
067	7.824	2.004	-.704	1.439
068	7.739	1.682	-.450	.255
069	5.553	2.345	.137	-.748
070	8.270	1.829	-1.868	18.167
071	7.295	2.597	-1.016	5.396
072	7.335	2.194	-.485	.404
073	2.460	.595	-.143	1.072
074	4.201	2.084	.754	1.542
075	2.547	1.589	1.577	10.297
076	5.896	3.099	-.378	.245
078	6.883	2.740	-.759	3.272
079	7.360	2.073	-.451	-.752
080	6.473	2.714	-.218	-1.116
081	2.070	.893	.674	10.948
083	2.446	.904	.745	9.024
084	3.177	2.385	.833	1.893
085	7.959	1.401	-.363	.124
087	4.269	4.553	-.072	-1.640
088	3.236	2.740	.705	.477
089	3.898	2.806	.491	-.463
090	3.434	1.867	.862	4.372
092	3.066	1.032	1.544	15.242
093	8.135	1.407	-.589	1.910
094	8.190	1.444	-.581	1.126
095	7.885	1.461	-.268	-.832
096	7.339	2.560	-.647	.782
097	7.625	2.253	-.800	2.356
098	-3.969	2.207	1.067	4.016
099	1.895	.653	-.246	.989
100	6.039	2.626	-.064	-1.315
101	8.212	1.362	-.605	1.879
103	2.694	1.742	1.366	7.429
104	5.209	3.358	.087	-1.775
105	8.026	1.597	-.868	3.966
107	8.202	1.605	-1.440	12.663
108	4.395	3.187	.251	-1.264
109	2.545	1.421	1.396	9.642
110	1.941	.962	.766	13.142
111	2.778	1.255	1.508	11.829
112	2.310	2.099	1.296	5.492
113	8.318	1.571	-1.178	7.955
115	8.292	1.279	-.604	2.183

TABLE 9--Continued

Sample Number	Textural Properties: Phi Mean	Phi Standard Deviation	Skewness	Kurtosis
116	5.705	3.127	-.008	-1.785
117	2.568	1.072	2.184	24.121
118	5.122	2.732	.275	-1.312
119	2.639	1.175	.613	5.594
120	2.738	.979	1.300	10.929
121	7.380	2.384	-.552	-.128
122	8.441	1.130	-.501	.653
124	8.137	1.457	-.606	2.027
125	8.527	1.254	-1.042	8.467
126	8.530	1.157	-.925	6.782
127	6.015	3.237	-.141	-1.640
128	7.331	2.456	-.590	.168
129	2.442	2.130	1.157	4.538
130	1.985	1.053	1.162	18.190
131	2.512	2.963	.746	.682
132	2.346	1.374	1.602	13.880
133	7.672	2.002	-.586	.539
134	7.183	2.569	-.594	.167
135	7.923	1.897	-.995	4.489
136	2.765	1.057	1.828	19.170
137	7.450	2.202	-.536	.206
138	4.560	2.410	.481	-.578
139	7.575	2.281	-.719	1.073
140	8.303	1.196	-.462	.647
142	8.124	1.318	-.405	.175
143	8.076	1.435	-.575	1.556
144	8.400	1.315	-.846	4.862
145	8.455	1.300	-.962	5.201
146	8.740	.991	-.786	3.312
147	8.565	1.121	-.676	2.836
148	8.312	1.491	-1.103	6.533
149	2.117	.944	1.145	15.796
150	7.273	2.279	-.517	.157
151	4.505	3.848	-.297	-.039
152	5.290	2.730	.232	-1.252
153	4.299	3.921	-.307	.021
154	7.000	2.701	-.493	-.206
156	5.759	2.972	-.045	-1.593
157	7.983	1.525	-.579	1.314
158	7.659	1.660	-.297	-.692
160	7.954	1.797	-.836	3.145
161	8.250	1.286	-.628	2.470

TABLE 9--Continued

Sample Number	Textural Properties: Phi Mean	Phi Standard Deviation	Skewness	Kurtosis
162	7.800	1.255	-.203	.656
163	8.425	1.106	-.459	.534
164	8.478	1.081	-.501	.745
165	8.445	1.230	-.868	4.937
166	6.518	3.015	-.289	-1.219
167	5.345	3.410	-.160	-.878
168	2.992	1.247	1.592	12.608
169	8.366	1.258	-.682	2.810
170	1.546	1.243	1.300	12.031
171	8.293	1.600	-.963	4.341
172	7.578	1.969	-.528	.379
174	1.792	1.474	2.089	17.942
175	1.620	1.123	2.438	29.154
176	2.170	2.473	.840	3.375
177	1.327	.665	-.112	31.288
178	1.308	.583	2.175	64.534
179	3.785	3.357	.370	-1.115
181	7.579	2.006	-.633	1.207
182	8.066	1.466	-.724	3.097
183	8.292	1.262	-.677	3.295
184	1.870	.756	1.927	29.619
185	2.181	1.309	1.894	17.928
186	1.805	.750	2.316	41.787
187	1.939	.771	1.293	24.375
188	7.937	2.267	-1.020	3.288
189	8.341	1.403	-1.072	6.589
190	8.469	1.156	-.858	5.978
191	1.717	.965	1.993	28.766
192	6.487	3.373	-.328	-1.339
193	6.227	3.327	-.206	-1.536
194	1.865	1.111	.858	7.362
196	2.029	.690	1.318	26.825
197	2.440	1.456	1.696	13.420
198	7.519	2.545	-.704	.687
199	2.038	.696	1.042	21.800
200	7.986	1.606	-.736	2.588
201	1.557	.449	1.265	35.179
202	2.551	2.338	1.023	3.322
203	8.359	1.211	-.767	4.501
204	7.723	2.197	-.929	3.355
205	1.601	.629	-.325	21.726
206	4.993	3.159	.155	-1.645
207	1.741	.464	.514	7.812

TABLE 9--Continued

Sample Number	Textural Properties: Phi Mean	Phi Standard Deviation	Skewness	Kurtosis
208	1.480	.533	-.121	4.956
209	4.096	3.488	.223	-1.280
210	6.802	2.866	-.405	-.814
211	6.530	2.954	-.289	-1.321
212	7.959	1.974	-.937	3.317
213	1.349	1.144	1.992	23.483
214	1.648	.651	.627	11.860
215	1.491	.642	2.277	50.570
218	1.923	.766	.645	19.391
219	3.149	2.521	.848	1.413
220	1.640	.690	2.284	44.446
222	2.300	.548	-.158	21.534
223	8.073	1.931	-.996	3.718
225	3.102	2.299	.928	2.099
226	2.187	.659	-.446	1.732
228	2.413	.729	.798	17.416
229	6.609	3.099	-.399	-.586
230	2.211	.640	-.198	8.702
231	2.169	.577	.557	23.423
232	2.115	.677	-.295	5.737
233	2.196	.628	.584	25.332
234	2.049	.676	-.430	1.620
236	2.129	.690	.159	13.334
237	1.796	.739	.445	22.712
238	2.189	.669	.118	12.904
240	8.117	1.562	-.924	4.257
241	7.032	2.378	-.368	-.708
242	2.188	.666	1.213	24.388
245	8.282	1.439	-1.571	19.004
246	2.467	.660	2.534	49.818
247	2.338	.595	1.323	32.982
248	8.269	1.531	-1.008	4.908
250	2.668	.940	1.840	23.883
251	2.145	.611	.111	15.745
252	1.961	.932	.656	17.779
253	2.014	.719	.906	22.194
254	2.488	.975	1.571	24.167
258	7.770	2.282	-.958	2.055
260	5.611	2.987	.061	-1.710
421	1.599	.675	2.062	43.200
422	3.848	2.854	.447	-.399
423	5.077	3.432	-.086	-1.031
424	7.354	2.220	-.528	.292

TABLE 9--Continued

Sample Number	Textural Properties Phi Mean	Phi Standard Deviation	Skewness	Kurtosis
426	7.654	2.127	-.782	2.156
427	5.240	3.076	.135	-1.578
428	7.934	1.678	-.720	2.898
429	7.285	2.169	-.475	.155
434	2.379	.702	1.647	30.728
435	6.751	2.750	-.330	-1.000
436	7.408	2.240	-.521	.094
441	2.489	.734	-.067	15.318
511	7.652	2.264	-.868	2.593
519	7.121	2.497	-.463	-.271
524	5.982	2.927	-.215	-.677
629	2.318	1.136	1.071	16.629
716	2.105	.653	.404	20.163
717	2.228	.761	.000	19.201
737	3.494	3.499	.081	-.162
738	3.745	2.522	.568	.477
755	1.587	.714	2.054	48.847
756	2.642	1.611	1.198	8.187
757	4.172	2.789	.461	-.539
758	3.435	2.582	.622	.782
760	1.913	.596	.531	12.831
901	2.107	.724	.923	18.779
902	2.577	.816	1.085	15.738
903	2.330	.468	.221	20.420
904	2.239	1.007	-.357	22.121
907	2.327	.403	-.675	1.277
908	1.564	.625	-.839	10.309
909	1.939	.626	-.172	5.884
910	2.327	.912	.683	17.179
917	2.419	.524	2.214	60.613
941	1.895	1.030	1.809	22.637
953	1.634	1.119	1.404	17.884
957	1.783	1.070	.989	18.721
958	2.083	.615	.793	20.616
967	1.259	.719	-.519	12.222

TABLE 10

WEIGHT PERCENTAGE OF GRAVEL, SAND, SILT, AND CLAY

Sample Number	Size Properties			
	Gravel	Sand	Silt	Clay
011	.039	1.899	34.153	63.908
021	.097	2.427	34.284	63.192
022	.276	2.384	43.874	53.466
023	.003	1.651	27.620	70.726
024	.000	87.705	8.663	3.632
025	.152	91.503	3.396	4.950
026	.030	79.275	10.484	10.210
027	.032	6.095	33.011	60.862
029	.204	14.200	33.992	51.604
030	.236	6.577	36.888	56.299
031	.056	89.873	8.371	1.701
032	17.821	68.587	4.992	8.600
033	.000	99.229	.420	.351
034	.283	54.052	29.526	16.138
035	.016	95.736	2.714	1.535
038	.135	94.883	3.364	1.618
040	.006	51.623	21.032	27.338
041	.000	.151	31.260	68.589
042	.032	1.595	43.348	55.025
044	.076	32.827	36.789	30.309
045	.654	26.436	38.758	34.152
046	1.142	12.859	32.259	53.740
047	2.208	7.376	39.586	50.830
048	.128	54.888	15.064	29.919
049	1.161	60.851	19.803	18.184
050	1.962	83.346	6.709	7.983
052	.061	90.648	7.654	1.637
053	.393	81.270	4.730	13.608
055	.101	2.042	35.658	62.199
056	.259	16.392	32.265	51.083
057	3.467	16.142	53.846	26.545
058	.704	53.384	15.388	30.524
059	.310	55.047	20.083	24.561
060	1.766	20.283	47.626	30.325
061	1.562	54.529	19.531	24.377
062	.123	8.603	46.449	44.825
063	.391	14.162	50.846	34.601
064	.154	5.715	42.251	51.879
065	3.424	93.229	1.559	1.787
066	.330	67.958	11.873	19.838
067	.122	8.696	30.024	61.158

TABLE 10--Continued

Sample Number	Size Properties Gravel	Sand	Silt	Clay
068	.019	2.692	44.479	52.809
069	.364	28.745	48.405	22.486
070	1.845	.340	28.730	69.086
071	2.716	4.160	41.378	51.746
072	.269	8.397	40.549	50.784
073	.000	99.950	.050	.000
074	.311	79.250	8.454	11.985
075	.035	94.128	1.892	3.945
076	3.547	31.578	31.618	33.258
078	2.230	11.560	39.707	46.502
079	.385	2.698	47.021	49.896
080	.237	28.770	29.233	41.759
081	.160	98.500	1.192	.147
083	.000	99.265	.400	.335
084	.601	83.498	5.034	10.867
085	.010	.322	46.048	53.620
087	15.211	33.296	13.625	37.867
088	.048	79.412	6.256	14.284
089	.206	74.275	8.515	17.004
090	.664	89.697	2.770	6.868
092	.042	96.766	2.078	1.114
093	.000	.580	37.659	61.761
094	.000	.431	34.463	65.106
095	.000	.023	46.772	53.205
096	.632	15.285	27.583	56.499
097	.640	11.506	30.206	57.649
098	90.688	9.312	.000	.000
099	.094	99.902	.004	.000
100	.167	34.138	34.038	31.656
101	.021	.721	36.550	62.707
103	.000	91.311	3.501	5.188
104	.000	52.031	11.523	36.446
105	.000	3.561	36.578	59.861
107	.514	1.874	33.173	64.439
108	.769	62.465	12.485	24.281
109	.000	94.931	3.059	2.011
110	.271	99.013	.337	.379
111	.100	95.070	3.334	1.496
112	.000	89.884	3.290	6.826
113	.218	3.152	26.020	70.610
115	.029	.471	34.142	65.357
116	.007	46.568	15.212	38.214
117	.000	97.098	1.069	1.833
118	.000	59.301	13.994	26.705

TABLE 10--Continued

Sample Number	Size Properties Gravel	Sand	Silt	Clay
119	.000	97.875	1.351	.774
120	.000	94.947	4.819	.234
121	.000	18.159	28.145	53.696
122	.000	.151	30.866	68.983
124	.074	.699	37.702	61.525
125	.110	.479	25.037	74.374
126	.039	.765	26.250	72.946
127	.000	41.407	14.402	44.191
128	.005	16.454	29.110	54.431
129	.000	90.466	2.463	7.071
130	.421	98.522	.144	.913
131	.163	80.750	6.194	12.893
132	.131	95.438	1.986	2.445
133	.032	10.823	33.965	55.180
134	.019	17.605	31.349	51.026
135	.132	5.771	33.949	60.147
136	.068	96.407	2.053	1.472
137	.065	14.687	32.039	53.210
138	.000	68.241	17.334	14.425
139	.051	13.587	28.352	58.011
140	.000	.173	35.558	64.269
142	.000	.181	40.953	58.866
143	.017	1.482	39.333	59.168
144	.072	1.235	30.211	68.482
145	.000	1.982	25.101	72.916
146	.000	.166	19.734	80.100
147	.019	.116	26.011	73.854
148	.000	2.942	28.887	68.171
149	.000	98.881	.594	.525
150	.141	14.992	36.088	48.779
151	10.230	46.242	17.025	26.504
152	.604	60.305	9.942	29.149
153	11.546	51.723	11.331	25.400
154	.341	21.401	29.517	48.742
156	.114	42.425	23.217	34.243
157	.000	1.829	40.462	57.709
158	.000	.379	50.799	48.823
160	.069	5.161	35.295	59.475
161	.000	.358	36.464	62.678
162	.013	.412	60.483	39.092
163	.000	.177	32.269	67.554
164	.000	.135	29.486	70.379
165	.027	1.048	27.891	71.034
166	.042	28.928	23.426	47.604

TABLE 10--Continued

Sample Number	Size Properties			
	Gravel	Sand	Silt	Clay
167	4.179	40.733	20.368	34.720
168	.023	94.810	2.852	2.315
169	.022	.499	31.397	68.082
170	.118	96.952	2.290	.639
171	.000	3.046	26.968	69.986
172	.021	10.168	38.680	51.131
174	.007	95.780	1.105	3.108
175	.000	97.693	.773	1.534
176	2.748	86.050	3.086	8.117
177	.481	99.309	.126	.084
178	.072	99.649	.083	.195
179	.783	67.334	8.722	23.161
181	.158	8.755	39.989	51.098
182	.017	2.310	38.942	58.732
183	.038	.743	34.525	64.693
184	.000	98.838	.916	.245
185	.000	96.730	.826	2.444
186	.000	99.327	.212	.461
187	.000	99.464	.206	.330
188	.000	9.638	22.809	67.553
189	.000	2.453	29.816	67.731
190	.000	.636	29.862	69.503
191	.000	98.871	.253	.876
192	.036	31.446	13.904	54.615
193	.242	34.806	14.719	50.233
194	.023	98.769	.805	.403
196	.000	99.572	.190	.238
197	.000	95.569	.991	3.440
198	.091	16.384	22.397	61.127
199	.000	99.673	.121	.206
200	.046	3.947	38.181	57.826
201	.019	99.848	.108	.026
202	.485	88.118	2.268	9.128
203	.031	.739	32.410	66.820
204	.678	8.774	31.503	59.045
205	.758	99.157	.030	.055
206	.182	55.791	14.527	29.500
207	.057	99.891	.053	.000
208	.083	99.888	.029	.000
209	3.714	59.434	10.892	25.960
210	.233	26.474	24.383	48.911
211	.021	31.269	23.846	44.865
212	.057	7.655	28.779	63.509

TABLE 10--Continued

Sample Number	Size Properties Gravel	Sand	Silt	Clay
213	.000	98.147	.693	1.161
214	.000	99.769	.185	.046
215	.000	99.570	.192	.238
218	.527	99.021	.243	.209
219	.101	83.464	4.217	12.218
220	.022	99.433	.238	.306
222	.106	99.708	.140	.046
223	.000	7.098	24.045	68.857
225	.008	85.098	5.249	9.645
226	.064	99.933	.003	.000
228	.040	99.648	.057	.255
229	1.782	29.276	18.033	50.909
230	.053	99.883	.011	.053
231	.064	99.774	.056	.106
232	.088	99.837	.040	.035
233	.185	99.543	.124	.149
234	.070	99.892	.038	.000
236	.090	99.761	.030	.120
237	.619	99.065	.133	.183
238	.065	99.768	.069	.098
240	.009	3.873	34.527	61.591
241	.037	20.310	33.479	46.174
242	.005	98.853	.936	.207
245	.645	.185	33.679	65.492
246	.000	99.145	.379	.477
247	.000	98.872	.930	.199
248	.000	3.202	27.638	69.160
250	.000	98.279	.574	1.147
251	.134	99.717	.074	.074
252	1.176	98.171	.163	.490
253	.277	99.360	.146	.218
254	.370	97.839	.676	1.115
258	.000	11.116	26.146	62.737
260	.000	50.925	14.010	35.066
421	.022	99.558	.143	.277
422	.617	71.213	11.486	16.685
423	3.005	47.738	18.100	31.157
424	.161	14.438	35.550	49.851
426	.201	9.543	34.241	56.014
427	.044	54.780	13.818	31.359
428	.120	3.150	39.465	57.264
429	.155	13.153	39.845	46.847
434	.000	99.324	.319	.356

TABLE 10--Continued

Sample Number	Size Properties Gravel	Sand	Silt	Clay
435	.162	28.137	24.996	46.705
436	.059	15.720	33.127	51.094
441	.195	99.413	.287	.105
511	.183	9.337	34.853	55.626
519	.307	20.216	30.241	49.236
524	2.005	37.766	25.300	34.928
629	.819	96.998	.943	1.241
716	.204	99.530	.151	.115
717	.668	99.052	.054	.227
737	7.476	64.838	8.905	18.780
738	.872	77.971	7.915	13.242
755	.345	99.065	.230	.360
756	.395	93.959	2.168	3.478
757	.404	71.956	8.278	19.362
758	1.166	80.230	5.779	12.824
760	.038	99.823	.086	.053
901	.069	99.327	.420	.184
902	.048	98.522	1.100	.330
903	.000	99.847	.122	.031
904	1.134	97.860	.521	.486
907	.000	99.991	.009	.000
908	.856	99.140	.003	.000
909	.255	99.639	.107	.000
910	.612	97.970	1.000	.418
917	.000	99.666	.111	.223
941	.013	98.174	.871	.942
953	.232	98.214	.626	.928
957	1.286	97.434	.471	.808
958	.000	99.728	.163	.109
967	.932	98.934	.115	.019

TABLE 11

CARBONATE CONTENT

Sample Number	% $CaCO_3$	Sample Number	% $CaCO_3$	Sample Number	% $CaCO_3$
001	2.13	046	1.90	088	1.13
002	1.81	047	2.42	089	1.56
003	2.76	048	1.17	090	1.01
004	1.43	049	1.27	092	0.93
005	1.30	050	1.06	093	3.09
006	2.25	052	1.00	094	2.19
007	0.52	053	4.20	095	2.69
008	1.87	054	2.15	096	4.65
009	1.57	055	2.21	097	2.64
010	1.61	056	1.22	098	5.24
011	1.75	057	2.51	099	0.00
012	1.56	058	2.55	100	3.93
013	0.00	059	0.94	101	2.74
014	0.00	060	1.45	103	1.36
015	1.82	061	2.14	104	1.46
016	0.00	062	3.28	105	3.08
017	1.03	063	1.85	106	2.91
018	0.57	064	2.32	107	3.28
020	1.64	065	1.59	108	1.90
021	1.61	066	4.66	109	0.00
022	1.42	067	2.47	110	0.00
023	2.51	068	2.25	111	1.05
024	1.05	069	1.29	112	3.08
025	0.45	070	2.68	113	3.09
026	0.62	071	2.54	114	3.33
027	1.97	072	2.67	115	2.23
028	0.83	073	0.00	116	2.18
029	3.34	074	1.96	117	0.00
030	2.52	075	0.00	118	1.88
031	0.19	076	4.67	119	0.88
032	4.06	077	3.19	120	1.19
033	0.00	078	3.12	121	3.41
034	1.24	079	1.33	122	2.41
035	0.83	080	3.01	123	2.32
038	0.89	081	0.00	124	2.61
040	2.31	082	2.32	125	2.60
041	2.37	083	0.00	126	2.40
042	1.80	084	5.10	127	2.46
043	1.10	085	4.89	128	2.24
044	0.86	086	2.83	129	1.02
045	1.41	087	35.92	130	0.00

TABLE 11--Continued

Sample Number	% $CaCO_3$	Sample Number	% $CaCO_3$	Sample Number	% $CaCO_3$
131	1.31	174	1.90	220	0.88
132	0.00	175	0.95	222	2.23
133	2.29	176	3.80	223	4.42
134	2.34	177	0.00	225	2.64
135	1.85	178	0.00	226	2.54
136	0.81	179	1.77	227	1.73
137	1.62	180	3.60	228	1.55
138	1.14	181	2.69	229	15.81
139	2.86	182	3.16	230	1.43
140	2.34	183	1.07	231	0.99
141	3.18	184	0.84	232	3.59
142	2.13	185	0.80	233	2.87
143	2.66	186	0.00	234	2.81
144	2.96	187	0.00	235	11.94
145	2.87	188	2.84	236	1.91
146	2.84	189	2.82	237	6.58
147	2.63	190	2.94	238	2.63
148	2.30	191	0.00	240	4.27
149	0.00	192	2.22	241	2.43
150	2.51	193	1.33	242	1.13
151	15.54	194	0.00	245	3.65
152	2.38	196	0.73	246	1.35
153	6.51	197	0.96	247	1.32
154	5.28	198	2.33	248	3.69
155	100.00	199	0.82	249	4.79
156	5.50	200	5.36	250	1.11
157	2.88	201	1.05	251	1.43
158	2.69	202	1.60	252	6.31
159	2.36	203	3.60	253	2.27
160	2.85	204	4.92	254	1.53
161	2.82	205	2.79	256	1.52
162	3.08	206	2.74	257	0.74
163	3.04	207	0.00	258	1.78
164	2.80	208	0.74	259	1.63
165	2.76	209	2.77	260	1.75
166	2.07	210	4.12	421	0.70
167	19.94	211	3.99	422	4.35
168	0.69	212	3.42	423	6.37
169	2.93	213	0.00	424	8.15
170	0.00	214	0.00	426	4.61
171	2.62	215	0.00	427	1.74
172	2.42	218	4.24	428	7.16
173	13.30	219	2.09	429	7.47

TABLE 11--Continued

Sample Number	% $CaCO_3$	Sample Number	% $CaCO_3$	Sample Number	% $CaCO_3$
434	0.89	903	1.45	934	4.61
435	6.84	904	2.78	935	1.93
436	6.58	905	8.17	938	2.25
441	1.49	906	3.02	940	0.55
511	3.86	907	0.58	941	0.46
519	7.16	908	1.73	942	2.78
524	9.69	909	1.64	945	2.74
629	4.03	910	4.27	947	0.63
716	0.76	911	1.28	948	1.06
717	4.06	914	8.64	949	2.17
737	19.61	915	1.98	950	2.11
738	6.58	917	0.42	951	0.65
755	2.55	919	2.17	953	0.28
756	3.38	920	2.06	955	3.61
757	6.56	923	3.96	957	8.46
758	6.74	926	17.45	958	0.26
760	1.20	927	11.50	964	1.69
901	0.89	928	1.24	965	8.07
902	1.30	931	1.40	966	3.97
				967	0.95

TABLE 12

MONTMORILLONITE--KAOLINITE PEAK AREA RATIOS

Sample Number	Montmor. Kaolinite	Sample Number	Montmor. Kaolinite	Sample Number	Montmor. Kaolinite
001	5.2	050	3.3	097	2.1
002	5.7	052	1.3	100	3.5
003	6.4	053	5.1	101	4.1
004	7.4	054	4.4	103	2.4
005	4.7	055	2.7	104	5.7
006	1.9	056	4.1	105	4.8
007	5.1	057	3.5	106	7.2
008	4.1	058	3.9	107	3.2
009	4.5	059	3.9	108	4.4
010	4.8	060	3.9	109	2.5
011	2.5	061	4.2	112	3.1
012	4.2	062	1.6	113	2.9
017	3.2	063	4.9	114	2.1
018	1.4	064	3.4	115	3.1
020	2.8	065	3.0	116	3.9
021	4.9	066	4.4	118	2.6
022	2.2	067	2.6	121	4.4
023	3.8	068	3.8	122	4.3
024	5.2	069	4.1	123	5.4
025	3.6	070	4.5	124	3.2
026	5.4	071	2.3	125	2.4
027	5.1	072	2.7	126	3.5
028	4.7	074	3.5	127	3.7
029	3.7	075	2.7	128	3.7
030	4.1	076	5.3	129	3.2
031	4.0	077	6.0	131	2.6
032	5.0	078	4.0	133	3.1
034	6.0	079	3.6	134	3.5
035	2.4	080	5.2	135	3.8
038	3.2	084	3.2	137	4.5
040	5.8	085	4.8	138	4.6
041	3.6	086	4.1	139	4.2
042	4.3	088	4.4	140	5.5
043	4.3	089	4.3	141	6.6
044	4.5	090	2.2	142	4.3
045	4.6	092	2.0	143	3.4
046	3.6	093	3.0	144	3.7
047	2.8	094	3.1	145	2.7
048	6.0	095	3.9	146	4.5
049	3.4	096	2.8	147	3.3

TABLE 12--Continued

Sample Number	Montmor. Kaolinite	Sample Number	Montmor. Kaolinite	Sample Number	Montmor. Kaolinite
148	3.4	192	3.3	511	4.1
150	4.3	193	2.4	519	4.6
151	5.2	197	1.5	524	3.4
152	4.3	198	3.7	737	5.1
153	4.4	200	3.7	738	4.0
154	3.7	202	2.8	756	2.4
156	4.2	203	4.1	757	4.6
157	4.0	204	4.9	758	4.2
158	4.1	206	4.4	905	5.2
159	4.3	209	4.0	906	4.9
160	3.3	210	4.5	911	4.4
161	3.2	211	3.0	914	4.4
162	2.7	212	3.1	915	4.0
163	2.7	219	3.7	919	4.8
164	3.5	223	2.7	920	3.8
165	3.0	225	4.3	923	2.5
166	3.6	229	3.7	926	2.2
167	2.8	240	3.6	927	5.4
169	3.7	241	5.1	928	3.5
171	3.1	245	3.5	931	4.2
172	3.3	248	4.4	934	5.8
173	3.6	256	6.0	935	5.0
174	2.5	257	3.9	938	2.1
175	2.6	258	2.9	940	3.1
176	4.0	259	2.2	942	4.1
179	4.5	260	3.8	945	3.7
180	3.7	422	4.4	947	4.5
181	3.7	423	4.4	948	5.0
182	3.0	424	4.1	949	5.0
183	3.5	426	5.5	950	4.0
185	1.8	427	4.0	951	3.5
186	0.2	428	5.3	955	3.3
188	2.7	429	4.8	964	2.5
189	3.2	435	3.7	965	4.4
190	3.6	436	3.7	966	4.0

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