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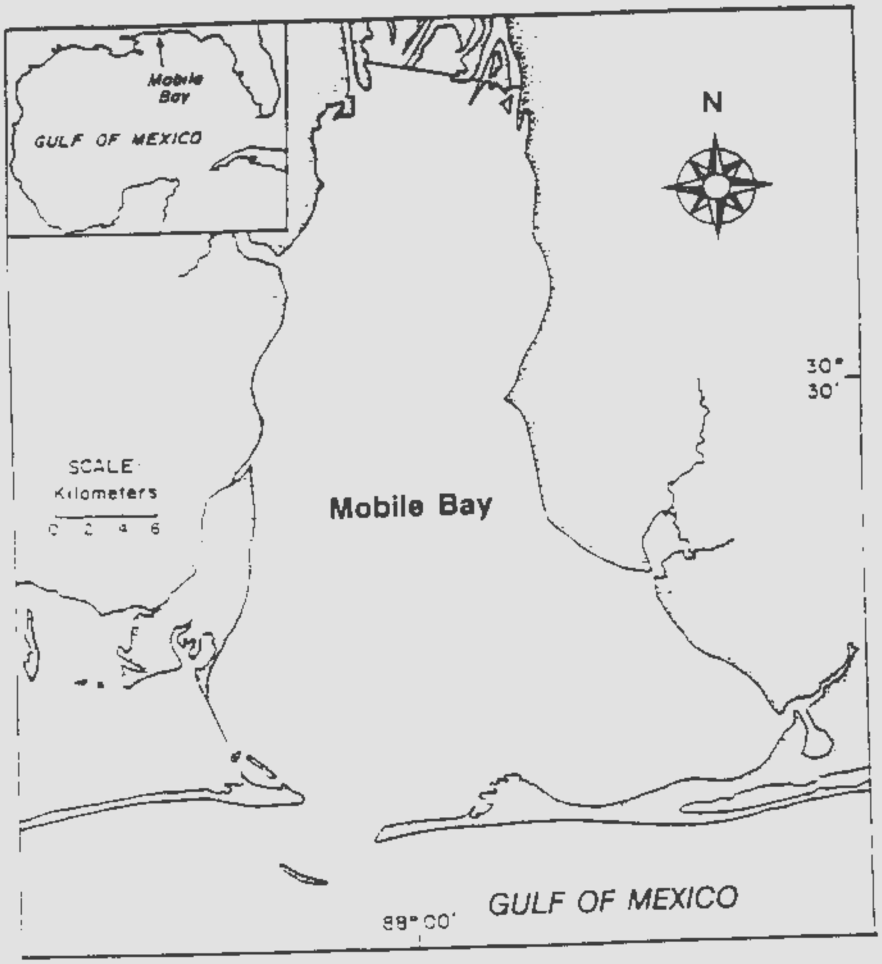

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
NOAA ESTUARINE PROGRAMS OFFICE

Phillip Hinesley

GEOLOGICAL AND GEOCHEMICAL CHARACTERIZATION

by

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INTRODUCTION

Mobile Bay is the primary depositional basin for the sixth largest river system in the United States. The rivers discharging into the bay drain a watershed of more than 110,000 km^2 (43,000 mi^2), which includes more than two-thirds of the State of Alabama and portions of neighboring Mississippi, Tennessee, and Georgia as well. The mean discharge of some 1,750 m^3/sec (62,000 ft^3/sec) ranks the contributory river system as the fourth largest in the United States, in terms of discharge, exceeded only by the Mississippi, Columbia, and Yukon (Ryan 1969). The rivers that ultimately discharge into the bay include the Warrior, Tombigbee, Tallapoosa, Coosa, Alabama, and Mobile (Fig. 1). Even with the major restrictions that have recently been imposed by various State an Federal regulatory agencies, the bay must still accept large quantities of effluent. As an example, an estimated 162 million gallons of municipal and industrial waste enters the bay each day solely from sources in the Mobile, Alabama area (Loyacano and Busch 1979). Hence, there is little surprise that analyses of bottom sediments and fauna collected in the bay yield levels of inorganic contaminants well above those from other bays in the northern Gulf of Mexico.

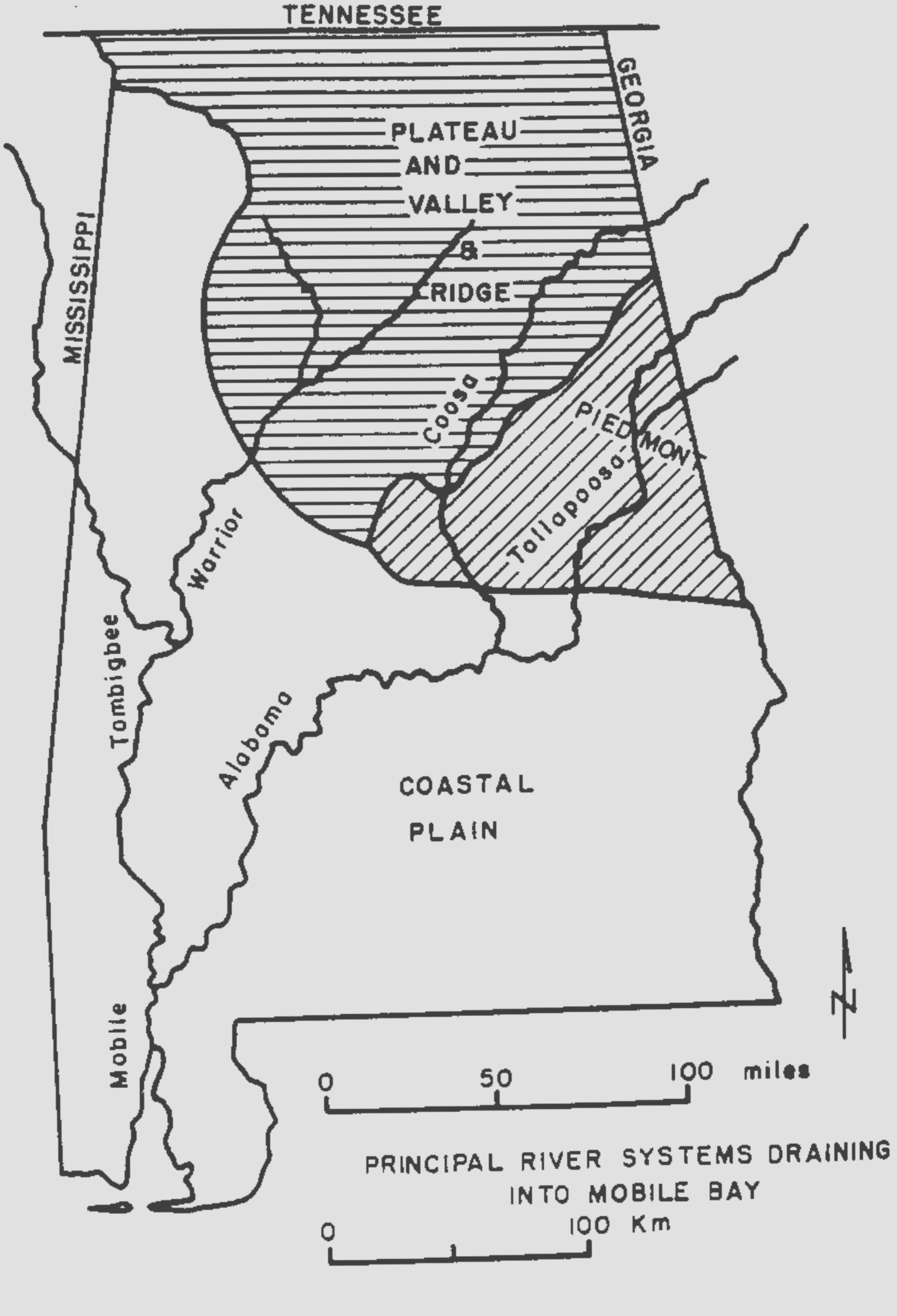
DESCRIPTION

Size

Mobile Bay is separated from the Gulf of Mexico by the Dauphin Island barrier island complex and by the westward prograding spit that forms the Fort Morgan Peninsula. In terms of size, the bay is approximately 50 km (31 miles) long and varies in width from 16 km (10 mi) just east of the city of Mobile to over 38 km (24 mi) near its southern limit where Bon Secour Bay adds substantially to its size. The total surface area of the estuary is approximately 1,070 km^2 (413 mi^2) and depths in the bay generally range from less than 1 m (3 ft) to over 9 m (30 ft).

Average depths are more on the order of 3 m (10 ft) (Crance 1971). A 12.2 m (40 ft) deep ship channel has been dredged nearer to the western side of the bay in order to allow commercial vessels access to the Port of Mobile and to permit

Figure 1. Physiographic map of Alabama (modified after Lamb, 1979).



passage of ships utilizing the Tennessee-Tombigbee Waterway System. This channel is 122 m (400 ft) wide and is currently being deepened to a depth of 14.5 m (48 ft) to accommodate deeper draft vessels.

Development

The estuary that now includes Mobile Bay lies adjacent to the Gulf of Mexico near the southern terminus of the Gulf Coastal Plain physiographic province (Fig. 1). Mobile Bay was formed by the flooding of a Pleistocene-age river valley as a result of the melting of the last (i.e., Wisconsin) ice sheet. The original river that occupied the site discharged well offshore of the present coastline and, in fact, can still be identified by the presence of a large, submerged, arcuate delta complex whose base is about 16 km (10 mi) wide and extends nearly 6.5 km (4 mi) offshore into the Gulf of Mexico. Because the top of this submerged delta is presently some 3 m (10 ft) below sea level, it is apparent that the most recent event in the Pleistocene history of coastal Alabama involved a rise in sea level of about 3 m (10 ft). This was sufficient not only to cause drowning of the ancestral Mobile River channel itself but also a large area of the adjacent flood plain. Collectively, these both are now incorporated as Mobile Bay (see Carlston 1950; Lamb 1979). The in-filling of the northern part of the bay that formed the present-day delta at the head of the bay accompanied this rise in sea level and represents deposition that took place in a bay that was much larger that the present bay system, possibly extending as far north as Mt. Vernon, Alabama (Lamb 1979). The present bay, therefore, is a geologically young estuary and dates from the last major eustatic rise in sea level. Its present shape also largely dates from this event, making the age of the bay only a few thousand years at best.

Man's recorded impact on the bay is, therefore, even more recent and, excepting its use by prehistoric tribes, dates less than 1,000 years. While the first known historical visit to the bay is still the subject of some controversy, a bronze plaque located in front of the Old Inn, on Fort Morgan peninsula, bears the inscription: "In memory of Prince Madoc, a Welsh explorer who landed on the shores of Mobile Bay in 1170 and left behind with the Indians the Welsh language." Whether fact or fiction, the alleged visit by this unchronicled Welshman has received serious attention by a number of scholars because of identical Welsh and Indian words used by tribes as far north as Tennessee and as far south as Mexico.

Historical knowledge of visits to Mobile Bay can be traced to 1519 when Alonzo Pineda, while on an exploration expedition, first entered the "Bay of Ochus" (various spellings), as it was then known by the local Indian tribes. Pineda renamed the bay Espirtu Santo and, during his 40 day stay, explored the surrounding area and mapped the bay. Panfilo de Narvaez, in 1528, is also thought to have visited the bay, largely as a consequence of a need for fresh water. Somewhat later, in 1540, Francisco Maldonado is reported to have anchored in the bay with four ships in order to resupply DeSoto's ill-fated expedition. Since that time, Mobile Bay was visited at least six different times before the Spanish began several ill-fated attempts to colonize the area, commencing in 1558. Actual settlement of the Mobile Bay area, however, was forced to await its "rediscovery" by the LeMoyne brothers, Iberville and Bienville, who entered the bay in 1699 and found it an ideal site for a settlement. Iberville, in 1702, moved the Capital of French Louisiana, then at Maurepas (near present Ocean Springs, Mississippi), to the Mobile Bay area. The region has been continuously occupied since that time.

Sedimentological History

As with all estuaries, Mobile Bay has been characterized by gradual infilling. The general pattern has been to fill most rapidly near the head (i.e., the present delta region) and then to fill in progressively the more distant areas. Natural events, such as major storms, may slow or temporarily reverse this trend (see Isphording and Imsand 1987), as may also the activities of man, but the ultimate fate of all estuaries is to gradually become filled in. Consequently, it is likely that within the next thousand years or so Mobile Bay will probably become an alluvial-deltaic plain similar to the present delta at the head of the bay (Hardin et al. 1976). This trend is well illustrated by examination of historical maps of the bay and comparing them with present bathymetric charts. A British Admiralty Chart dated 1771, for example, showed that the water depth at the head of the bay, directly east of the City of Mobile, averaged approximately 7 feet; similar measurements taken by the "U.S. Engineering Corps," in 1864, for the same area showed average depths of about 6 feet indicating a shoaling rate near the head of the bay of approximately 1 foot per 100 years. While this rate might at first seem excessive [in view of the fact that measurements on the Gulf of Mexico continental shelf are more on the order of 0.4 mm/yr (0.13 ft/100 years)], measurements made in other Gulf Coast estuaries are well in excess of this value [see Isphording, Imsand, and Flowers (1987)]. In Apalachicola Bay, Florida, for example, the average sedimentation rate has been calculated at 6.74 mm/year (2.21 ft/100 years). Further, sedimentation values calculated by Hardin, et al. (1976) also fall within this same magnitude range indicating that Mobile Bay is similar in terms of its overall sedimentation rate (see Table 1) to other bays in the northern Gulf that are the termination sites of large rivers.

The effects of man's activities on sedimentation rates within the bay are striking and have caused infilling at rates orders of magnitude greater than those attributable to natural processes. Ryan (1969), for example, has estimated that rates in excess of 3 ft/100 years may well exist in the area immediately south of the delta. Isphording, et al. (1984) have shown that the bulk of the acceleration of sedimentation rates in Mobile Bay can be traced to the early 1800's when extensive development of cotton and tobacco farming was initiated within the State, utilizing slave labor. The clearing of land for agriculture invariably was accompanied by markedly increased erosion rates into nearby streams (Fig. 2) and this sediment load ultimately found its way into Mobile Bay. Hence, examination of maps of the bay drafted prior to 1830 show striking differences when compared with those drawn in the interval from 1840 to 1870. Numerous additional distributary channels are apparent in the delta complex at the head of the bay and the increased amount of sediment being carried into the bay caused the near isolation of a number of other areas that were previously open to the bay. An excellent example of this can be seen in the development of D'Olive Bay, located in the extreme northeastern portion of Mobile Bay (Fig. 3). Maps constructed of the bay prior to 1862 make no mention of D'Olive Bay, nor is it even shown as existing. The formation of the spit that separates it from Mobile Bay probably

Figure 2. Sediment discharge for various watersheds (from Isphording et al. 1984).

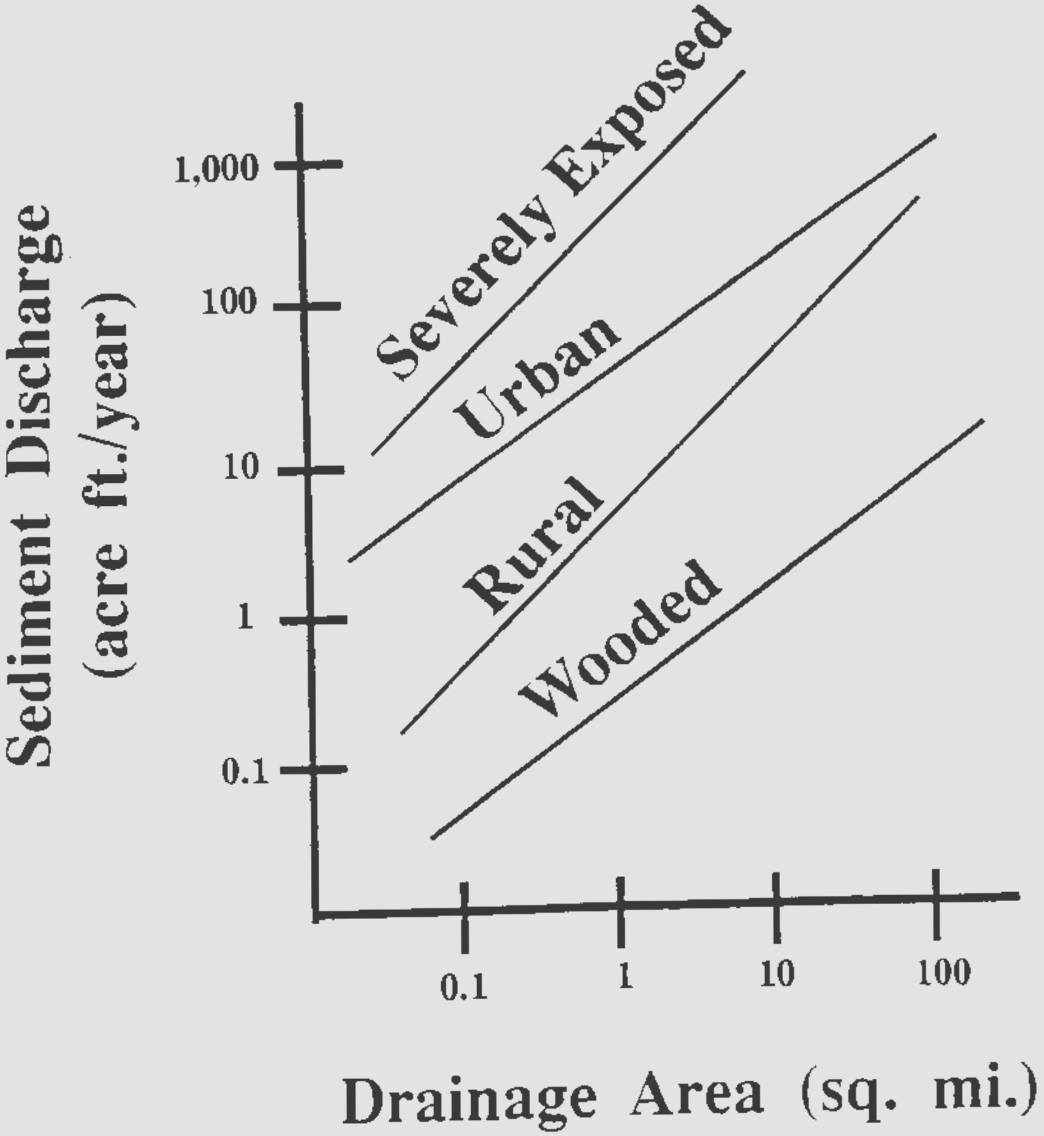


Figure 3. Map showing the location of D'Olive Bay (from Isphording et al. 1984).

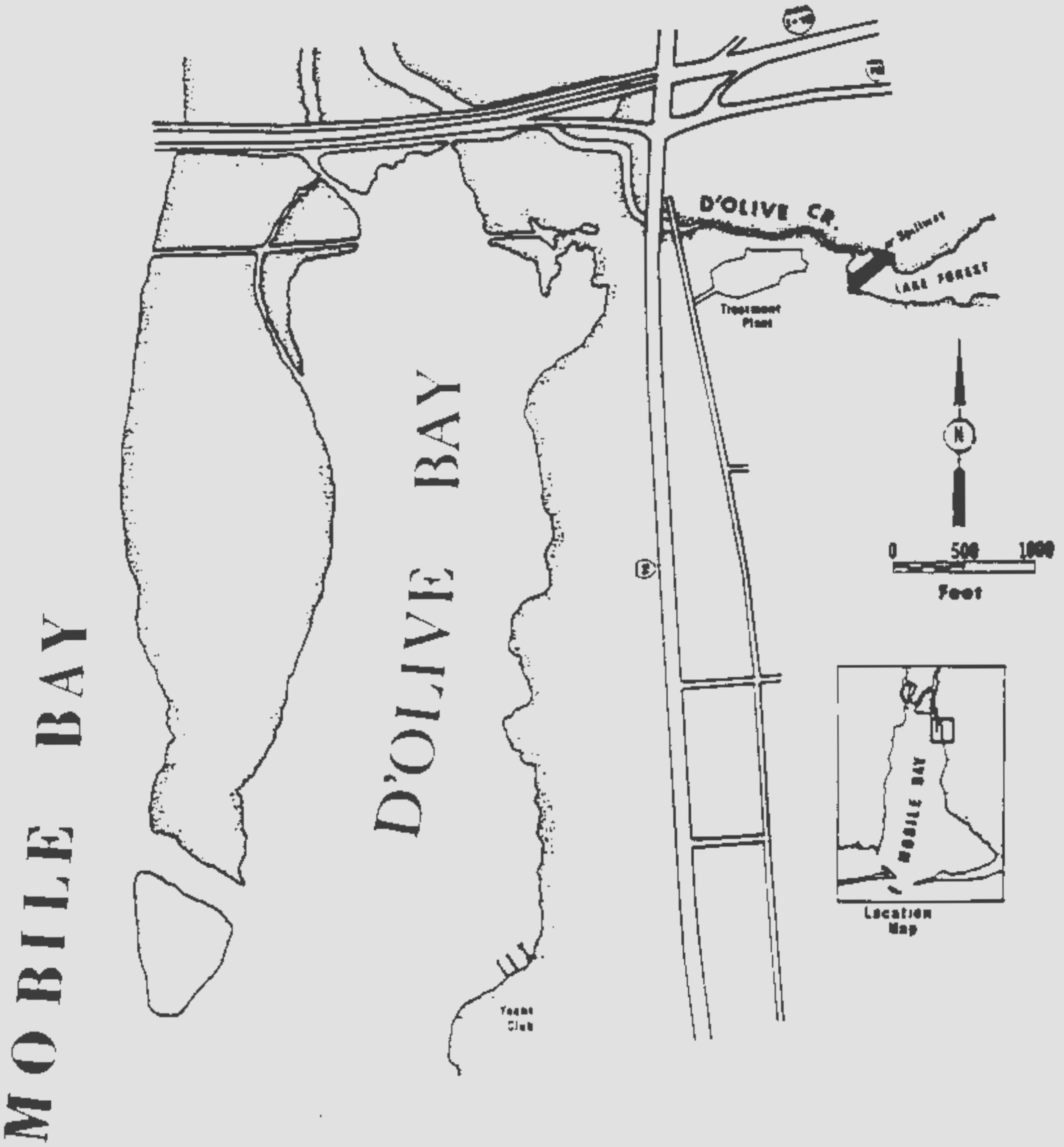


Table 1. Average annual depositional rates for upper Mobile Bay, lower Mobile Bay, and overall average rate (Modified from Hardin et al. 1976).

	Annual Average			120 Yr. Average
	1852	**1920**	**1973**	**1853-1973**
ENTIRE BAY				
Mean Depth (in feet)	10.71	9.60	8.71	
Infilling Rate		—1.63—	—1.68—	1.65
UPPER BAY				
Mean Depth (in feet)	8.90	7.60	7.07	
Infilling Rate		—1.91—	—1.00—	1.51
LOWER BAY				
Mean Depth (in feet)	12.52	11.59	10.35	
Infilling Rate (per 100 years)		—1.36—	—2.34—	1.79

began after 1820 as a result of increased sediment loading of the river system, coincident with agricultural development in the State (see Isphording, et al. 1984).

SEDIMENT CHARACTERISTICS

Sources

Five major river systems are responsible for collection and transport of sediments into Mobile Bay (see Fig. 1). These rivers originate far to the north of the bay in rocks of markedly different age and character and in rocks that have been subjected to significant differences in exposure and weathering. These differences have exerted controls not only on the amount of sediment contributed from a given area, but also on the mineralogy and chemistry of the detritus as well.

Areas drained by the Tallapoosa River, for example, include a large portion of east-central Alabama and extreme west-central Georgia, all of which are underlain by deeply weathered crystalline rocks of the southeastern Piedmont Province. The Coosa River, in contrast, originates within a folded sequence of limestones, shales, sandstones, etc. that belong to the Ridge and Valley Province. This region largely consists of more recently exposed Paleozoic-age rocks that include both the Blue Ridge Mountains and the Appalachian Range. To the west, the Warrior River drains rocks of similar age, however unlike those in the Ridge and Valley Province, those in the Cumberland Plateau region are essentially flat-lying. The remaining rivers, the Tombigbee, Alabama, and Mobile, all drain areas of geologically younger sediments that have been assigned to the Coastal Plain Province. Because these sediments are largely made up of uncemented sands, silts, and clays, they are more easily eroded and thereby contribute the greatest percentage of sediments of Mobile Bay.

Mineralogy

The mineral composition of Mobile Bay bottom sediments consists largely of the clay minerals montmorillonite (70 percent), kaolinite (20 percent), and illite (10 percent). Most of the montmorillonite can be traced to erosion of older Coastal Plain rocks, particularly those exposed in an arcuate zone lying nearer to the northern boundary of this province in an area known as the "Black Belt." This region gets its name from exposures of a dark brown to black, organic-rich, montmorillonite clay that belongs to the geological unit known as the Ripley Formation. Montmorillonite clays, unlike their kaolinite and illite counterparts, are extremely fertile and form excellent agricultural soils. On the negative side, however, their high cation exchange capacity coupled with their small particle size and extensive presence of lattice defects, result in these clays having an enhanced ability to absorb both organic and inorganic contaminants. Thus, as will be discussed below, the high percentage of these clays in Mobile Bay bottom sediments has worked to the bay's detriment.

The kaolinitic clays found in Mobile Bay, in contrast, are mainly derived from the ancient, deeply weathered rocks of the southeastern Piedmont (via the Tallapoosa River system). To a lesser extent, the mineral is also derived from younger sediments exposed in the southern part of the Coastal Plain province. Even though abundant in Mobile Bay bottom sediments, these clays create far less problems because of their minimal ability of absorbing, and retaining, organic and inorganic contaminants.

Illite, the remaining major clay mineral in the bay's sediments, is intermediate between montmorillonite and kaolinite in its ability to absorb pollutants. When considered on a world-wide basis, this mineral is the most common of all clays yet it makes up only 10 percent of Mobile Bay sediments. Its origin in these can be traced largely to the same montmorillonite-rich units that form the older Coastal Plain rocks and, to a lesser extent, the rock formations of the Ridge and Valley and Cumberland Plateau provinces.

Sediment Size

The bottom sediments of Mobile Bay are unique in the northern Gulf of Mexico in consisting, dominantly, of particles falling into Shepard's (1954) size range of "clay," "silty clay," and "sandy clay" (see Fig. 4). Put more simply, Mobile Bay has a larger proportion of very fine-grained sediments than any other northern Gulf estuary. This fact results chiefly from the extensive delta and distributary system that has built up at the head of the bay which has acted to trap coarser (larger) grained detrital material. As a consequence, only the finest particles are generally carried into the bay from the contributory river systems and any larger (sand) sized detritus is chiefly derived from erosion from immediately adjacent sedimentary units exposed around the bay's perimeter.

The dominance of the finer grain sizes in the bay is significant from an environmental standpoint because the finer the particle size, the larger the surface area and, consequently, its ability to absorb organic and inorganic contaminants. Thus, not only does the bay's mineralogy favor absorption of heavy metal and organic contaminants but the same phenomenon is also enhanced by the plethora of fine-grained particles that dominate its sediments.

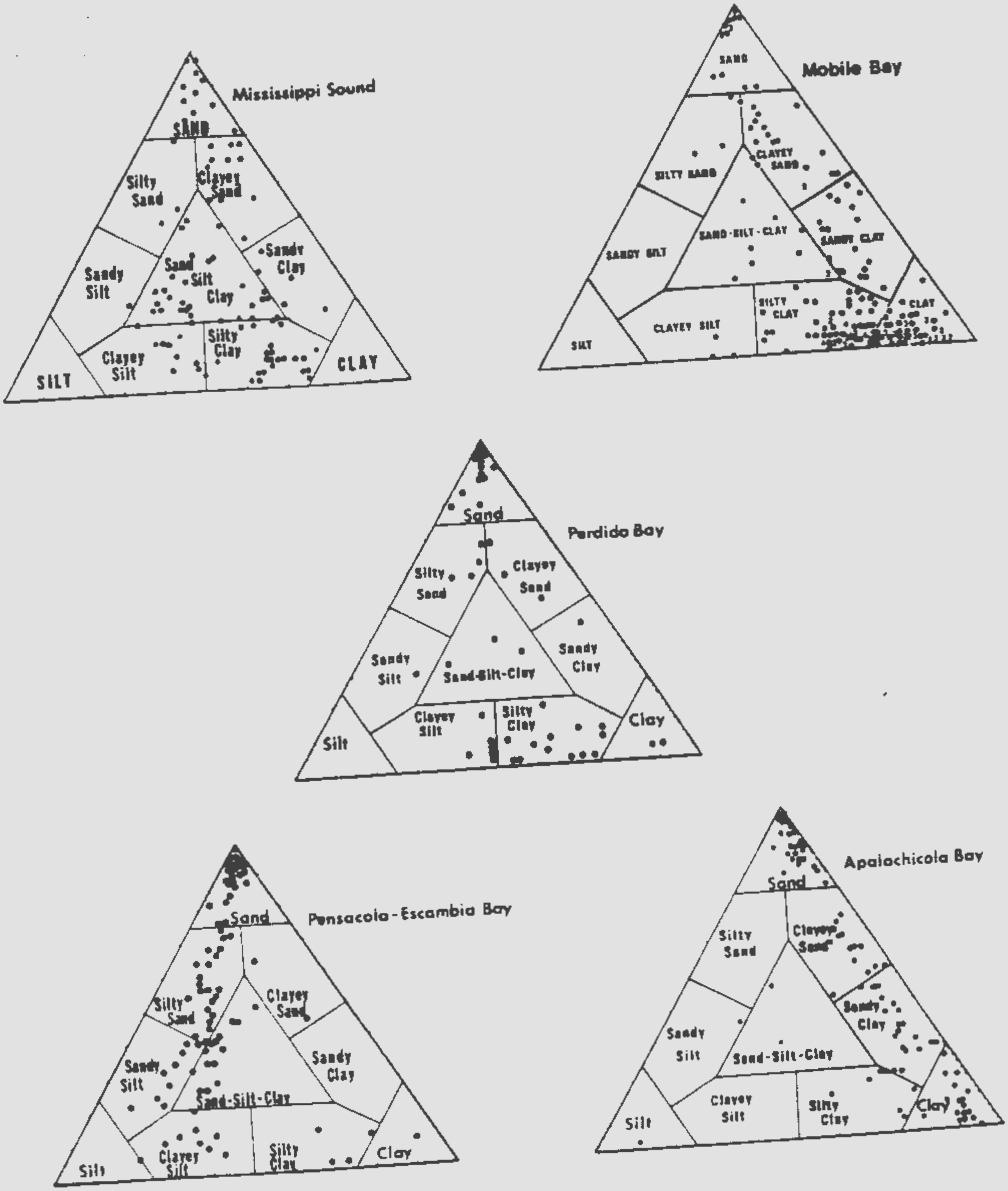
Organic Carbon Content

A third "strike" against Mobile Bay, from the standpoint of potential for environmental contamination, is found in the organic content of the bottom sediments. In an earlier publication (see Isphording, Stringfellow, and Flowers 1985) it was noted that Mobile Bay has the highest average content of organic carbon for any bay or estuary in the northern Gulf of Mexico (see Table 2.) The consequences of this lie in the fact that organic particles also have an enhanced ability of absorbing municipal and industrial pollutants and metal ions that are contributed to the bay by both natural and man-related processes. Hence, the combination of high montmorillonite content, high organic content, predominance of very fine-grained sediments, and a heavily industrialized contributory watershed has made it difficult for the bay to avoid the stigma of becoming "environmentally impacted."

Table 2. **Organic carbon content of northern Gulf of Mexico bays and estuaries (modified from Isphording, Stringfellow, and Flowers 1985).**

Location	Percent Organic Carbon
Mobile Bay	3.24
Mississippi Sound	0.82
Perdido Bay	1.33
Pensacola Bay	2.90
Apalachicola Bay	0.75

Figure 4. Ternary diagrams showing size analyses for samples from bay, estuaries, and coastal lagoons in the northern Gulf of Mexico (from Isphording, Stringfellow, and Flowers 1985).



SEDIMENT CHEMISTRY

General Discussion

Anthropogenic point sources of metals and organic compounds rank as the most important factor controlling pollutants entering Mobile Bay (Isphording and Flowers 1987). Brady (1979) reported that nearly 189 million gallons of industrial and municipal effluent is discharged into the bay each day just from sources located in the Mobile, Alabama area. When other contributions from cities and manufacturing firms located elsewhere in the water-shed are considered, it is obvious that literally thousands of point sources are contributing to the bay's contaminant load. Further, because of the restricted circulation patterns within the bay, it shallow depth, and the aforementioned high montmorillonite, organic carbon, and abundance of fine- grained sediments, it is no wonder that the bay contains higher metal values than any other bay in the northern Gulf. This can be seen in Table 3 which compares average values of metals in the bottom sediments of the bay with those from other bays in the region. Using the classification scheme developed by Prater and Hoke (1980) for assessing heavy metal contamination in harbors, it is evident from Table 4 that Mobile Bay is a moderately to heavily impacted harbor in terms of the concentrations of the metals considered.

Effect on Indigenous Fauna

To date, the etiological effects of heavy metals in marine organisms are only imperfectly known. Whereas some metals (e.g., iron and zinc) can apparently be tolerated at fairly high levels, others (cadmium, mercury, lead, etc.) can be hazardous to the organism even when ingested at extremely low levels. Knowledge of this fact is by no means new and can be traced to scholars living more than one thousand years ago. Hippocrates (370 B.C.), Pliny (A.D. 50), and Dioscorides (A.D. 100) noted the toxicity of high levels of lead whereas Aristotle (A.D. 300) described the properties of cadmium compounds and commented upon their health hazard. Similarly, Ramazzini described mercury poisoning that he traced to mercurial unctions being used by surgeons in the early 1700's and selenium poisoning was identified in Columbia, South America as early as 1560. More recently, investigators have become suspicious that a number of metals may be suspect in cardiovascular disease (vanadium, barium, copper, lithium, strontium) and others have been implicated in certain forms of cancer (arsenic, beryllium, cadmium, lead, nickel) (see Schroeder 1960; Voors 1971; Berg and Burbank 1972). High levels of mercury in fish contamination by industrial discharge were directly linked to mercury poisoning and related teratogenic effects in persons living adjacent to Minimata Bay, Japan, and the contamination of drinking waters by cadmium in mine wastes was identified as the causative factor in Itai Itai Byo disease, also in Japan (see Kurland et al. 1960).

Thus, even though many metals can be shown to be necessary for life functions, essentially all metals can be shown to produce harmful effects if certain threshold levels are exceeded. Hence, while the human body does attempt to regulate and prevent "spillover" by tying up the metals in the form of metalloenzymes (metallothioneins), excessive accumulation can take place with

Table 3. Bottom sediment heavy metal contents (in parts per million) for bays, estuaries, and coastal lagoons in the northern Gulf of Mexico.

Metal	Mobile Bay	Perdido Bay	Pensacola Bay	Escambia Bay	Blackwater Bay	Apalachicola Bay	Mississippi Sound
Cadmium	1.1	1.0	1.0	1.0	1.0	1.2	1.0
Lead	51.0	--	40.0	19.0	13.0	61.0	15.0
Iron	35,648.0	32,740.0	24,074.0	29,298.0	11,520.0	26,776.0	23,107.0
Nickel	57.0	36.0	16.0	9.0	3.0	28.0	24.0
Cobalt	15.0	27.0	10.0	12.0	5.0	18.0	13.0
Chromium	63.0	15.0	56.0	40.0	13.0	34.0	57.0
Copper	32.0	31.0	19.0	9.0	3.0	37.0	20.0
Zinc	120.0	72.0	140.0	43.0	20.0	57.0	74.0

Table 4. Classification of Mobile Bay sediments as being non- polluted (NP), moderately polluted (MP), or heavily polluted (HP) based on averages for harbors presented by Prater and Hoke (1980).

Metal	Classification
Cadmium	LLNE*
Lead	MP
Iron	HP
Nickel	HP
Chromium	MP
Copper	MP
Zinc	MP

*LLNE indicates that the lower limit for the classifications NP and MP have not been established for the metal in question.

deleterious effect upon the individual. Estuaries having high sediment metal pollution must therefore be viewed with concern, not only because of the effects on the indigenous fauna, but also because of the etiological consequences that may result by consumption of such fauna by other forms higher up in the trophic pyramid.

Metal Levels in Mobile Bay Fauna

Because of the high levels of heavy metals in the bottom sediments it might be suspected that fauna from Mobile Bay (especially filter feeders) would reflect this phenomenon by the presence of elevated quantities of certain metals in their tissue. To test this, specimens were collected from reefs throughout the bay of the common oyster *Crassostrea virginica* and metal levels were then determined. Oysters serve as an especially useful barometer for heavy metal contamination because a number of studies have documented the toxicity levels for different metals for this species and have also established the mechanism of metal uptake and tissue accumulation (see Zamuda and Sunda 1982: Zaroogian et al. 1979; Cunningham and Tripp 1973). Further, at least with respect to this species, once the metal has accumulated in the tissue, it apparently remains for a considerable time and is not easily eliminated. This was demonstrated by a study carried out by Mowdy (1981) who placed oysters from Mobile Bay in tanks for a period of six months and found that depuration levels amounted to only 25 percent for his time period. Similarly, Greig and Wenzlof (1978) showed that no significant elimination of cadmium had occurred in oysters after 40 weeks in a low cadmium environment.

That a definite relationship exists between heavy metals in bottom sediments and levels in the tissue of indigenous oyster species can be seen by examination of levels of zinc found in Gulf Coast oysters, shown in Table 5. Mobile Bay oysters contained significantly higher amounts of zinc than those from any other bay for which data were available. It should also be emphasized that the figures shown in Table 5 represent **average** values only; some specimens from Mobile Bay actually levels of zinc in excess of 4,000 parts per million! Table 6 shows a comparison of heavy metals in tissue for Mobile Bay oysters versus those from nearby St. Louis Bay (which was also characterized by high zinc levels). It is obvious that, with the exception of titanium, Mobile Bay specimens has considerably higher quantities of all other metal species.

SUMMARY

Few estuaries in the northern Gulf of Mexico have been the subject of more controversy than Mobile Bay during the past 10 years. Not only is the bay the location of the largest seaport in the northern Gulf, it also serves as the southern terminus of the Tennessee-Tombigbee Waterway and was recently designated as a homeport for a portion of the recently created Caribbean flotilla. Its development, however, has been a constant battle between those interested in further expanding the bay's resources versus those concerned that this will further impact the delicate environmental balance that now exists. Hence strong opposition was mounted against oil drilling in the bay, the basing of a hazardous waste incinerator ship near Mobile, deepening of the existing ship channel, and establishment of new sewage outfall lines, just to name a few examples. While some of the concerns of environmentalists have been shown to be unfounded (e.g. oil drilling, creation of dredge disposal islands in the bay, widespread organic contamination), other concerns must certainly be carefully considered. By virtue of the fact that the bay's bottom sediments are: (1) rich in smectite clays, (2) high in organic content, and (3) made up predominantly of very fine-grained sediments, any discharge of excessive levels of organic and/or inorganic contaminants into to bay will be assured of extended residence times. Because of this, there is also the likelihood some of these contaminants will become ingested by bottom feeders and filter feeding organisms. Ultimately, these contaminants may well be passed onto forms higher up the food chain and eventually reach man. Further, in view of the fact that the bay's bottom already are heavily loaded with some heavy metals, there is some doubt as to whether discharge levels presently approved by Federal and State agencies are, in fact, proper. While such quantities may well be safe for discharge into a bay containing bottom sediments made up of clean sands that have little ability to absorb contaminants, this same discharge into a bay containing sediments such as those in Mobile Bay that are already impacted may well create problems in the future. For this reason, all bays, estuaries, lagoons, etc. that are the sites of municipal and industrial effluent discharge should be carefully examined with respect to their sediment composition and properties in order that realistic restrictions may be imposed that will safeguard the site for the foreseeable future.

Table 5. Zinc levels (in ppm) in *Crassostrea virginica* for sites in southeastern United States (modified after Lytle and Lytle 1982; Isphording, Stringfellow, and Helton 1983).

Locations	Zinc (in ppm)
Mobile Bay, Alabama	1,887
San Antonio Bay, Texas	322
Flower Garden, Texas	268
Graveline Bayou, Mississippi	618
St. Louis Bay, Mississippi	821
Apalachicola Bay, Florida	158
U.S. Southeast Coast (average)	103

Table 6. Average heavy metal content (in ppm) in specimens of *Crassostrea virginica* from St. Louis Bay, Mississippi and Mobile Bay, Alabama. relative difference between samples from the two sites is shown as "concentration factor." St. Louis Bay is considered to be relatively free of heavy metal contamination. (Modified after Isphording and Flowers 1987).

Metal	St. Louis Bay Mississippi	Mobile Bay Alabama	Concentration Factor
Cobalt	0.04	11.0	275.0
Chromium	0.10	0.1	1.0
Copper	32.00	106.0	3.3
Iron	57.00	694.0	12.2
Nickel	0.20	18.0	90.0
Titanium	2.00	1.0	0.5
Vanadium	2.00	63.0	31.5
Zinc	821.00	1,887.0	2.3

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