HEIGHTS

Heights in feet above Mean High Water

AUTHORITIES

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POLLUTANT TRANSPORT IN MISSISSIPPI SOUND

Thomas F. Lytle and Julia S. Lytle

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INTRODUCTION

Mississippi Sound is an elongated, shallow embayment bordered on the north by a series of small bays, marshes, bayous and rivers and on the south by a chain of offshore islands. Varying from 4.5 to 14 miles in width, it extends from Louisiana to Alabama and forms the southern boundary of Mississippi. Fresh water is introduced by the East and West Pascagoula rivers in the eastern region, by the Tchoutacabouffa and Biloxi rivers emptying into Biloxi Bay in the central region, and by the Wolf and Jourdan rivers that drain into St. Louis Bay and the Pearl River in the western region. Fresh water also enters the Sound at the eastern extreme from Mobile Bay and from Lake Borgne at the western boundary of the Sound. Some Mississippi River water may also pass through the Chandeleur Sound into the Mississippi Sound. Tidal exchange with Gulf of Mexico waters occurs through island passes, with salt water intruding into all coastal rivers.

The Sound is part of the "fertile fisheries crescent" of the northern Gulf and is one of the most valuable fisheries nursery grounds of the world. Abundant seafood resources in this area have in the past been only modestly tapped. Only recently has the full potential of this resource been realized and developed. But grave concern now exists for the continued success of this fishery resource because of industrial development in the region. The economic necessity of industrial expansion within the state has prompted state, county and municipal incentives that have resulted in the ranking of Mississippi among the top states in industrial climate. To those who have witnessed careless industrial development in other states, generous tax incentives for increased industrialization are regarded with apprehension. This region also has great potential for residential growth in the next decade as the populace is drawn to the "sun-belt" states. Some demographic studies have predicted that Mississippi will experience the greatest relative population growth of the southeastern states during the last years of this century with most growth predicted for the six coastal counties. The distinction of state and federal territorial mineral rights in coastal waters has been a topic of much debate in Mississippi. A pending court decision to designate tracts within Mississippi Sound under federal jurisdiction will be significant for a more substantial reason than the loss of economic entitlements in the Sound. It underscores the urgency with which development is taking place along the coastline and the rapid growth of interests other than the traditional fishing industry. Because of the economic bonus associated with industrial, residential and petroleum resource expansion, it is highly unlikely that any real deterrents will be placed in the way of this development. One problem that accompanies all types of development is pollution. Previously viewed as a necessary by-product of progressive growth, this unconcerned attitude towards pollution has been fostered by a real lack of scientific information to properly assess the impact of an increasing pollution level on Mississippi Sound.

Various studies conducted in the Mississippi Sound have been designed to establish "typical" values of certain pollutants[1-4] but have been severely limited in the scope of analysis and geographic coverage. The Mississippi Bureau of Pollution Control has until recently collected only water samples in the Sound. Only a few sediment collection sites are routinely sampled by the U.S. Environmental Protection Agency (EPA) and the U.S. Geological Survey (USGS). A continuing survey by the National Marine Fisheries Service (NMFS) has been geared to look at trace metal levels in shellfish. All data programs prior to 1979 have insufficiently addressed the many valid concerns and questions that exist regarding pollution in the Sound. This is unfortunate in that Mississippi has one of the most farsighted coastal zone management plans of all coastal states but one that has been implemented with no comprehensive information about pollution. Because pollution can have a widespread and longlasting effect on the aquatic environment, areas of concern that must emerge in a scientific investigation of pollution are: (1) the types of pollutants present in the system; (2) where pollutants are found: in water, sediments or biota; (3) current state of pollution in the Sound; (4) migration or transport of pollutants throughout the Sound; (5) environmental

significance of pollution; and (6) use of scientific data to constructively ameliorate the problem of pollution. The principal investigators (PIs) began this study in 1979, cognizant of these concerns, and with overall objectives to characterize pollutants in Mississippi Sound, clarify those processes responsible for pollutant movement and develop criteria essential for coastal management based upon sound scientific information.

TYPES OF SAMPLES AND ANALYSIS SELECTION

A pollutant study, even for a relatively small geographic region such as the Mississippi Sound, involves an extensive sampling and analysis program. Because possible choices of analysis and sample sites are infinite, the study plan was initiated by addressing the questions, "What kinds of pollutants are most likely to be found in the Sound?" and "What type of sample will yield the most meaningful pollutant information?" Substantial information exists designating organics as the major pollutant class in the coastal zone of Mississippi. National Pollutant Discharge Elimination Systems (NPDES) permits for municipal and industrial effluents in the Pascagoula River system (Table 1) graphically demonstrate this point and remind us of the statement by Cairns[5] that, "All industries discharging wastes are using the environment as an extension of their waste disposal systems." There is a noticeable absence of much heavy metal input to Mississippi waters as indicated by these permits, in contrast with Mobile Bay, further east, where abundant quantities of heavy metals have been found by Drs. Wayne Isphording and George Lamb of the University of South Alabama. The heavy metals cannot be ignored; however, the primary target pollutants of this study, based on permit information[4, 6], are the organic materials.

Analytical Variables

Figure 1 displays some of the sediment chemical data gathered in the Escatawpa-Pascagoula River in a preliminary phase of this study. Note the very high levels of organic matter (expressed as organic C) even above industry, with values approximately an order of magnitude higher than those found in other regions of the eastern Mississippi Sound. These results (the preponderance of organic chemical manufacturing and production plants in Bayou Casotte, the Escatawpa River and the Bernard Bayou industrial complexes along with NPDES permits for these plants) suggested several types of organic pollutants as prime candidates for thorough investigation. Phenolic compounds are components of numerous effluents and are among the "priority pollutants" compiled by the EPA[7]. The presence of detectable levels of phenols in sediments is alarming in view of the ease with which they are converted to quinones[8] under these conditions. Although synthesized naturally by bacteria, the parts per million (ppm) or $\mu g/g$ levels of phenols that we have found in sediments from the eastern Sound possibly indicate an anthropogenic rate of contamination that exceeds sediment degradation rates.

TABLE 1.

Compiled NPDES discharge limits including industrial and municipal discharge in Pascagoula River area.

Parameter	Average (lb/day)
Biological Oxygen Demand (BOD)	11,622.00
Chemical Oxygen Demand (COD)	1,392.00
Oil and Grease	793.00
Total Suspended Solids (TSS)	40,894.00
Sulfide	18.00
Total Kjeldahl Nitrogen (TKN)	7,268.00
Phenol	27.26
Pentachlorophenol	0.18
Total Iron	98.04
Chromium	28.70
Zinc	16.40
Total Phosphorus	2,282.00
Ammonia (NH_3)	5,510.00
Nitrate-Nitrite Nitrogen	38.00
Cadmium	8.20
Fluorine	482.00
Heavy metals (Cd, Cu, Cr, Pb, Ni, Zn)	55.80
Hexavalent Chromium	1.70

From several lines of evidence and results of previous work, petroleum-like hydrocarbons took highest priority in this pollution study[8]. The aromatic hydrocarbons are particularly troublesome, for many of these compounds are highly carcinogenic[9-15]. Aromatics may be responsible for the relatively high incidence (compared with other Gulf of Mexico sites) of presumed neoplastic cells found in the American oyster *(Crassostrea virginica)* and other mollusks in the Pascagoula River region of the Sound[16]. The possibility of petrogenic hydrocarbon intrusion into the Sound can only increase in the future. The operation of a superport off the Louisiana coast, a one-billion-dollar expansion of an oil refinery in Pascagoula, pipelines now criss crossing the Sound and oil drilling off Louisiana and Alabama only add to the probability of an oil spill incident. Sewage treatment plants add considerably to the hydrocarbon burden and also to heavy metal loads[17] of receiving waters[18,19]. Local creosote plants and coal-fired power plants are sources of aromatics[20,21]. Urban storm runoff is another source of petroleum hydrocarbons[22] which most likely results from careless disposal of used motor oils[23]. Oil sheens in navigation waters, a manifestation of dirty disposal practices of commercial boat operators, also add to hydrocarbon contamination. To avoid overlooking certain other important pollutant compounds, a broad spectrum approach was taken in regard to analysis of selected samples. Organic carbon was measured to serve as a gross indicator of pollution and to provide information about organic matter deposition and fate[24]. Kjeldahl nitrogen analysis of sediments has proven useful as an indicator of sewage pollution[25] and in tracing the sources of organic matter[26,27]. Furthermore nitrogenous organic wastes are among the more effective sediment components in accumulating trace metals[28].

Sample Type

Because of low water solubility many toxic compounds accumulate in sediments. This tends to add to their stability and may account for enchanced concentrations[22,29-41]. Hydrocarbons and other organic materials[22,29-41] are readily adsorbed by fine-grained sediments and particulates. The association of organic pollutants with fine-grained material may, in fact, enhance the ability of the sediments to adsorb other toxic materials[17,25,42] and may account for dispersal of pollutants over broad regions[35,43,44]. The net effect of estuarine circulation is to recirculate and trap sediments in the estuary. Preference in analysis has been given to sediments because of their tenacity for pollutants, their capacity to retain pollutants in a locale for long periods of time, their preservation of the pollution history of an area and for their potential toxicity over extended intervals of time. Biota and water column studies, though valuable in assessing an acute pollution incident are, with usual sampling constraints, of negligible value in describing the long-term state of pollution in an area. Therefore, to gain the maximum scientific information, most effort was devoted to sampling and analyzing sediments.

Although grab samples from surface sediments were essential for some study elements of this program, core samples were viewed as yielding a greater wealth of pertinent information. By sectioning a core, one gains an historical perspective on pollution in any region; the industrial evolution of a region may be traced by profiling anthropogenic wastes in the sediment column. By examining the vertical distribution of pollutants a more accurate estimate may be made of actual overall pollutant levels in the sediments than would be allowed by a surface grab sample. Furthermore, realistic dredging impact assessments depend upon precise knowledge of pollutant content in all sediment strata. This can only be gained by careful examination of sediment cores analyzed at discrete stratigraphic intervals.

SAMPLE COLLECTION AND ANALYSIS SCHEME

In the design of the sampling analysis program two questions were asked: "Where would be the most desirable sample locations?" and "What would be the best sampling and analysis techniques?" With emphasis on sediment analysis, careful selection was made of sample sites to properly map the distribution of pollutants and assess the movement and deposition of polluted sediments. Freshwater discharge and surface currents are primarily responsible for the sediment migration and deposition patterns seen in the Sound; however, tidal currents[26] and macrobenthos also play a role[41,45]. Other less obvious modes of sediment movement are storm scouring, dredging[46] and fish trawling[47]. Dredging associated with construction and maintenance of new projects can increase turbidity and release pollutants into the water column[48,49]. This is of particular concern in the Gulf of Mexico where one half of all U.S. maintenance dredging is done[50]. Duxbury[51] has stressed that all of these mechanisms for sediment movement and deposition, primarily of fine-grained materials, must be considered in a sampling scheme.

Site Selection

Considerable attention was given to sample site selection to ascertain where fine-grained sediments are being deposited in the Sound. Help from previous geological surveys and actual reconnaissance trips pinpointed these areas fairly well. Because there were more fine-grained deposits than could realistically be analyzed in a sediment-coring program, preference was given to those in the vicinity of known or suspected pollutant sources, in areas that have been sampled by previous investigators, in regions far removed from pollutant sources to serve as control sites and at locations that were in the path of rivers and tidal flow into and across the Sound. Surface grab samples proved invaluable in filling the gaps left in the coring program, as well as in providing access to areas inaccessible to the sediment core drilling rig.

During the course of this study sediment cores were collected from 43 sites and, among surface samples collected, 49 have been selected for description in this report.

The location of sampling sites in the Sound are shown in Figure 2. Descriptions of each site and the specific criteria used in selection are contained in Tables 2 and 3.

Collection

Considerable effort was expended in 1979 in developing a core collection scheme that would be amenable to necessary contamination controls[52] and give necessary volumes of material and minimize sediment disturbance. Sediment core samples were obtained with vibracore sampling equipment. Precleaned 10-foot aluminum coring tubes were fitted with a pneumatic impacting piston vibrator on top of a 4-inch inside diameter (i.d.) core pipe. No liner was used. A steel H-beam, supported by four legs, was placed upon the seabed where it served as a support tower to guide the vibrator and core pipe into the sediment. An air compressor onboard the support vessel provided the driving air by means of a single wire-reinforced hose.

This method of collection provided undisturbed, noncompacted core samples. Cores were placed immediately into an insulated 12-foot chest onboard ship and packed with dry ice. They were placed subsequently in a walkin freezer at the end of each sampling day and stored at −20°C until analyzed. Throughout the program, special precautions were taken to avoid any contamination from sampling and storage containers.

Surface samples were collected using an Ekman Grab sampling device. Sediments were placed in precleaned gallon cans (nonlacquered), using care not to contaminate the sample. Sediment samples for chemical analysis were cooled until brought into the lab. Before freezing, the samples were homogenized by stirring, aliquots removed for the various chemical analyses, and then all were frozen at −20°C until time of analysis.

Treatment of Sediment Samples

Sediment samples were handled according to the scheme in Figure 3. Upon removal of a core from the freezer, the aluminum tube was cleaned thoroughly with warm, soapy water.

TABLE 2.

Sediment core sample sites in Mississippi Sound.

Station No.	Name	Date Sampled	Coordinates	Description
1	Davis Bayou	October 1981	30°23.1′N 88°48.9′W	Near mouth of Davis Bayou; nursery area; historical data station; nonpoint source site.
2	South Deer Island	October 1981	30°20.3′N 88°50.0′W	Mouth of Biloxi Bay; historical data station; nonpoint source site.
3	Old Fort Bayou	October 1981	30°25.2′N 88°51.0′W	Ocean Springs residential area; nonpoint source site.
4	Deer Island	October 1981	30°22.9′N 88°53.0′W	Fine-grained depository from Biloxi Bay.
5	Goat Island	October 1981	30°24.6′N 88°54.5′W	Near I-110 bridge into Biloxi; nonpoint source site.
6	Keesler AFB	October 1981	30°25.1′N 88°55.8′W	Historical data station; nonpoint source site at mid-point in Biloxi Bay.
7	Popps Ferry	October 1981	30°24.7′N 88°58.4′W	W. Biloxi Bay, spoil and bridge construction area; nonpoint source site.
8	Gulfport Lake	October 1981	30°25.2′N 89°04.1′W	Junction at Bernard Bayou and Industrial Seaway; heavy industrial area, major sewage outfall; fisheries trawl station.
9	Gulfport Channel	October 1981	30°18.8′N 89°01.8′W	East of spoil bank on eastern side of ship channel; trans-Sound site.
10	Cedar Lake	October 1981	30°26.5′N 88°56.9′W	Above most industrial development; historical data station; nonpoint source site.
11	Power Plant	October 1981	30°26.1′N 89°01.1′W	In oxbow lake near power plant in Biloxi River.
12	Big Lake	October 1981	30°24.5 N 89°00.2′W	Discharge canal from power plant; confluence of several waterways.
13	Edgewater	October 1981	30°20.4′N 88°58.2′W	South of Beauvoir or Edgewater Plaza; trans-Sound site.
14	Point aux Chenes	November 1979	30°18.7′N 88°29.2′W	Oil refinery discharge canal into Mississippi Sound; historical data station.
15	Bayou Casotte	November 1979	30°21.3′N 88°30.9′W	Heavy boat traffic, industrial park east of East Pascagoula River mouth.
16	Mouth East Pascagoula River	November 1979	30°20.2′N 88°33.5′W	Large shipbuilding industry nearby; mouth of river with serious pollution problems.
17	McInnis River	November 1979	30°24.9′N 88°31.4′W	Escatawpa River; bridge construction; sewage outfall.
18	Griffin Point	November 1979	30°25.2′N 88°34.1′W	Sewage outfall; historical data station; below confluence of Escatawpa and East Pascagoula rivers.
19	Paper Mill	November 1979	30°25.1′N 88°29.5′W	Escatawpa River; canal adjacent to large paper mill.
20	Escatawpa River Control	November 1979	30°26.4′N 88°28.3′W	Above most industry on Escatawpa River.
21	East Pascagoula I-10	November 1979	30°26.3′N 88°33.6′W	Above confluence with Escatawpa River; near I-10 bridge construction; nonpoint source site.
22	Bayou Chemise	November 1979	30°24.1′N 88°35.7′W	Natural channel between East and West Pascagoula rivers; nonpoint source site.
23	Dead River	November 1979	30°25.6′N 88°37.2′W	West Pascagoula River; oxbow lake with adjacent marina and residential area.
24	Mary Walker Bayou	November 1979	30°23.4′N 88°36.8′W	Heavy boat traffic; West Pascagoula River.
25	Mouth West Pascagoula River	November 1979	30°21.0′N 88°38.4′W	Below all riverine pollutant sources.
26	East Mississippi Sound	November 1979	30°15.9′N 88°25.8′W	Trans-Sound site.

TABLE 2. Sediment core sample sites in Mississippi Sound (continued).

Station No.	Name	Date Sampled	Coordinates	Description
27	Horn Island	October 1980	30°14.7′N 88°35.4′W	North central portion of island; trans-Sound sample.
28	Bellefontaine Point	November 1979	30°18.5′N 88°43.8′W	Beach front between Ocean Springs and Pascagoula; westernmost extent of shoreward flow of West Pascagoula River.
29	Round Island	November 1979	30°19.1′N 88°36.2′W	South of East Pascagoula River and in path of discharge.
30	West Horn Island	June 1982	30°14.9′N 88°45.9′W	Western end of Horn Island; trans-Sound site.
31	Heron Bay	June 1982	30°10.4′N 89°28.4′W	Between St. Louis Bay and Pearl River; deposit site for latter.
32	Petit Bois Island	October 1980	30°12.4′N 88°27.0′W	North side of island; trans-Sound site.
33	West Ship Island	June 1982	30°13.6′N 88°57.5′W	Western end of West Ship Island; trans-Sound site.
34	Pass Marianne	June 1982	30°14.3′N 89°11.5′W	North of Cat Island; deposit site for sediments from Lake Borgne.
35	Ship Island Pass	June 1982	30°12.9′N 89°02.8′W	North of Camille cut in Ship Island; trans-Sound site.
36	Cat Island Channel	June 1982	30°11.6′N 89°07.0′W	Southwest of "Spit Cove" on southern tip of Cat Island; monitoring input from west.
38	Mouth Jourdan River	June 1982	30°20.9′N 89°21.2′W	Input from Jourdan River into St. Louis Bay.
39	St. Louis Bay bridges	June 1982	30°18.5′N 89°18.7′W	Between railroad and highway bridges; sediments from St. Louis Bay.
40	Mouth Wolf River	June 1982	30°21.0′N 89°18.3′W	East of Grassy Point; input from Wolf River.
41	Bayou La Batre	October 1980	30°20.1′N 88°17.1′W	Heavy industrial park east of Mississippi-Alabama line.
42	Dauphin Island	October 1980	30°16.1′N 88°16.0′W	North side of island; trans-Sound site.
43	D'Iberville	October 1981	30°22.4′N 88°57.3′W	South of Royal d'Iberville Hotel; deposit site for Biloxi Bay sediments.
44	Bernard Bayou	October 1981	30°24.3′N 89°00.9′W	In southern "elbow" of bayou; nonpoint source site.

TABLE 3.

Surface sample station location and description.

Map Key[1]	Station Name	Location	Selection Rationale
BB	St. Louis Bay bridges	Between L&N railroad and Hwy 90 bridges	Same as location of core #39[2]
BP	Bayou Pierre	West Pascagoula River	Railroad trestle, marina; chemical industry
CD	Chevron North Dock	Bayou Casotte docks for Chevron U.S.A.	Site of 2,000-barrel oil spill
CI	Coley Island	Confluence of Biloxi River and Bernard Bayou	Mixing zone for effluents from power plant and chemical industries with river discharges
CT	Cooling Tower Canal	Above dredged area in Bayou Casotte	Some effluent in canal; deposit site of recent sediments in bayou
DB	Davis Bayou	Site of Gulf Islands National Seashore Headquarters	Same as location of core #1[2]
DI	Deer Island	West of mouth of Biloxi Bay	Same as location of core #4[2]
DR	Dead River	West Pascagoula River	Same as location of core #23[2]
EB	Elevator Bayou	East bank, near mouth of East Pascagoula River	Down river from most pollutant sources
ER	Escatawpa River Bridge	Old bridge on river	Several industries in vicinity
FB	Old Fort Bayou	East of mouth of Biloxi Bay	Same as location of core #3[2]
GB	Graveline Bayou	Mouth of bayou	Municipal sewage in bayou, prohibited oyster beds
GC	East Gulfport channel	Mid-distance between Coliseum and Ft. Massachusetts in Sound	Collection site of river, harbor discharges into western Sound
GL	Gulfport Lake	Back Bay Biloxi	Same as location of core #8[2]
GP	Griffin Point	Escatawpa River	Same as location of core #18[2]
HB	Heron Bay	East of Pearl River mouth	Same as location of core #31[2]
HC	Hewchem Industrial Canal	Western end of Industrial Canal in Back Bay Biloxi	Numerous industrial waste inputs
HI	Horn Island	North of eastern end of island	Same as location of core #27[2]
HM	Halter Marine	Escatawpa River	Shipbuilding; other industry in vicinity
IS	Industrial Seaway	Western end of Back Bay Biloxi	Transportation route for industry in Gulfport Lake
LY	Lake Yazoo	Mouth of East Pascagoula River	Near shipbuilding; depository for acetylene production waste; residential area
MC	Mississippi Chemical East Bank	Bayou Casotte, dredged area	Region of several large chemical industries
ML	McInnis Lake	Escatawpa River	Same as location of core #17[2]
MW	Mary Walker Bayou	West Pascagoula River	Same as location of core #24[2]
OG	Open Gulf	South of Horn Island in Gulf of Mexico	Mixture of land-derived and marine pollutants
PM	Paper Mill	Escatawpa River	Same as location of core #19[2]
PP	Pogey Plant	Escatawpa River	Fishmeal processing; chemical plant
PW	Power Plant	Biloxi River near barge entrance to Jack Watson Power Plant	Same as location of core #11[2]
RC	Reichhold Industrial Canal	Eastern end of Industrial Canal in Back Bay Biloxi	Site of industrial waste leaking into canal
RP	R' les Point	Back Bay Biloxi	Multi-use industrial zone
SI	West Ship Island	Western end of island, north of Ft. Massachusetts	Same as location of core #33[2]
TC	Turkey Creek	Bernard Bayou at western end of Gulfport Lake	Variety of industries; residential area
TI	Twin Islands	Mouth of West Pascagoula River	Down river from all pollutant sources in river

TABLE 3. Surface sample station location and description (continued).

Map Key[1]	Station Name	Location	Selection Rationale
VA	V.A. Hospital	Southern bank of mid Back Bay Biloxi	Sewage treatment plant
WP	West Prong	Bayou Casotte	Upstream from industrial complex
CEX	Corning East Bank	Mouth of Bayou Casotte	Industrial site
CHX	Chevron West Bank	Bayou Casotte, west of Chevron U.S.A.	Industrial site
CNX	Control	Upper reaches of Bayou Casotte	Control site above all industry in Bayou Casotte
GLX	Graveline Lake	Upstream of Graveline Bayou	Sewage outfall
GSX	Gypsum Stack	Above dredged region of Bayou Casotte	Deposit site of industrial effluents
IDX	Inner Discharge Canal	Point aux Chenes, up drainage canal for oil refinery	Refinery effluent
MDX	Mouth Discharge Canal	Point aux Chenes, mouth refinery discharge canal	Refinery effluent
TAX	Pascagoula Transect #1	Transect point closest to Bellefountaine Point extending to Dog Keys Pass	High river flow from Pascagoula River across Mississippi Sound
TBX, TCX, TDX, TEX, TFX	Pascagoula Transect #2–6	Increasing distances from Bellefountaine Point on transect	High river flow from Pascagoula River across Mississippi Sound
PCX	Power Plant Canal	Canal leading to Jack Watson Power Plant	Cooling water discharge from power plant

[1] See Figure 2.
[2] See core site descriptions in Table 2.

The core then was placed into a box with specially constructed circular saw guides which permitted lengthwise cuts to be made in the core tube without cutting into the enclosed sediment material. After two lengthwise opposing cuts were made, half of the tube was lifted away to permit examination of the core sample. Cores were examined and geological sediment units were noted by Dr. Ervin Otvos of the Gulf Coast Research Laboratory (GCRL). All geological descriptions were recorded on videotape and in written document to facilitate interpretive correlation of chemical and geological characteristics. Boundaries of geologic sequences were used to determine where a core would be sectioned. Where no obvious geological variations existed throughout a core, divisions were made at 20 cm intervals. The outer 2 to 3 mm were removed to exclude any contamination from the core tube. Each section of the cores and all surface grab samples then were subdivided into aliquots for hydrocarbon, grain-size, percent moisture, phenol, total (TOC) analysis, and tracer compounds. For

those analyses which were not made immediately, subsamples were frozen.

Sediment treatments in leachability, suspension property and toxicity studies will be discussed in the section, **Environmental Stress Index.**

Hydrocarbon Analysis

Following the methods outlined in Figure 4, sediment was thawed, slurried with methanol (MeOH) to remove water and then extracted three times with dichloromethane using ultrasonics to facilitate extraction. Filtrates and the hexane extract of the MeOH wash were combined and reduced in volume; elemental sulfur was removed by refluxing extracts with activated copper wool for 12 hours. An aliquot of these extracts was taken for lipid weight and the remaining lipid saponified with 0.5N KOH-MeOH:water [1:1, volume/volume (V/V)] for 12 hours.

After saponification, hexane was used to extract the nonsaponifiable fraction. The hexane extracts were taken to near dryness on a rotary flash evaporator at $\leq$ 30°C. The extract was chromatographically separated on a column of 1:2 (V/V) alumina-silica gel (both fully activated). The adsorbent/sample load [weight/weight or (W/W)] was always > 100/1.

Aliphatics were eluted with two-column volumes of hexane followed by two-column volumes of the mixture dichloromethane-hexane (20/80, V/V) to elute aromatic hydrocarbons. The efficiency of separation of the column parameters was checked with a mixture of authentic aliphatic and aromatic hydrocarbons and found to result in no cross contamination. Aliquots of the aliphatic and aromatic fractions were taken to determine gravimetric weights. Before gas chromatography (GC), the aromatic fraction was analyzed by fluorescence spectrophotometry.

Gas chromatography separations were obtained using a Perkin-Elmer (PE) 3920 with all-glass split injection onto a 15-m × 0.25-mm i.d. fused silica capillary column coated with 0.25 micron (μ) film thickness of Dura Bond 1 (J & W Scientific). Each fraction also was chromatographed on a PE 990 with 2-m × 3.2-mm i.d. columns of 4% FFAP and 3% SE-30 on Anakrom AS, 90/100 mesh. Helium was used as the carrier gas. The data were quantified using a PE Sigma 10 data system. Tentative identification of peaks was by comparison of retention times on all GC phases with those of standards.

The use of other tools was required for polynuclear aromatic hydrocarbon (PNA) analysis and for the other compounds comprising the majority of organic wastes found in many samples. It was for this reason that in 1979 the PIs were able to arrange a cooperative working arrangement with the EPA Priority Pollutant Laboratory at the Mississippi Test Facility in Bay St. Louis, MS. This arrangement was to have provided our program with accessibility to quite nonselective mass spectral analysis necessary for the PNAs[11,53-59] and other toxic agents and also was to have broadly expanded the EPA program and fill a definite deficiency of their sample coverage in the Mississippi Sound. However, because the EPA lab used 0.25-inch i.d. columns in their gas chromatography-mass spectrometry (GC/MS) instrumentation system, the sensitivity, column efficiency and resolution were not acceptable for our analysis. For this reason, an agreement was made with Dr. Robert Settine, Department of Chemistry, University of Alabama in Birmingham, to have samples analyzed using a Hewlett Packard 5985A GC/MS computerized system. Samples were injected splitless onto a 25-m × 0.2-mm i.d. glass capillary column coated with SE-54. Helium was used as a carrier gas and the temperature was programmed from 90°C to 250°C at a rate of 4°C per minute. The total effluent from the column entered the mass spectrometer through a heated inlet with no molecular separator. The mass spectrometer was operated at an ionization energy of 70 eV, with a scan time of 65 scans/minute over a mass range of mass/charge (m/e) 45—450.

All aromatic fractions were concentrated to 10.0 mℓ in 20/80 (V/V) dichloromethane/hexane and analyzed by fluorescence spectrophotometry[59] using a PE MPF-44 fluorescence spectrophotometer before GC analysis. Excitation and emission spectra were recorded to determine general fluorescence characteristics. Synchronous scanning of the excitation and emission wavelengths was performed by offsetting the monochromators by 20 nanometers (nm); the emission between 220 and 500 nm was recorded. This spectral recording is reputed

to give better resolution, especially for the PNAs, than the emission spectra obtained with fixed excitation[38].

The Geology Section of GCRL provided grain-size data and sediment biotype record through foraminiferal analyses on all core segments. Phenol levels were determined by colorimetric procedures[60,61]. Total organic carbon levels in sediments were measured combustimetrically using a Leco induction furnace. Total Kjeldahl nitrogen values were determined by a micro-Kjeldahl procedure[62].

POLLUTANT DISTRIBUTION

The question of most profound interest to the private sector of Mississippi is: "How serious is the state of pollution in the Mississippi Sound?" As an initial attempt to answer that question, the results of analysis of all surface sediment samples have been gathered in Table 4. In addition to all grab samples, the top segment of each sediment core is included to give a surface sample grid that covers all regions of the Sound. The Sound has been broken into very broad divisions for purposes of comparison. The Pascagoula River System, including the East and West Pascagoula rivers, Escatawpa River and Bayou Casotte, is the region of most diverse and concentrated industrialization. Some regions have experienced the effects of reckless pollution practices in the past, particularly in the Escatawpa River and Bayou Casotte. The industrialization of the western portions of Biloxi Bay along Bernard Bayou occurred later than the Pascagoula River and, consequently, was implemented in a period of more earnest environmental consciousness. Nevertheless, incidents occurring at a number of industrial and sewage treatment plants in that area have exhibited almost the same level of disregard for safe discharge practices as frequently happened in the Pascagoula River area. With the exception of some light industrial parks, St. Louis Bay remained relatively undisturbed until the construction of a large titanium dioxide plant on the north shore in the late 1970's.

In dividing the Sound into broad divisions for discussion purposes, the region seaward of the river estuaries and bays, including the offshore islands, is referred to simply as the Mississippi Sound System (or Open Sound). In a more general sense, this geographical unit would include the rivers and bays along the mainland shore. Only little waste discharge enters the Sound directly; notable examples

TABLE 4.

Chemical composition of Mississippi Sound surface sediments.

General Location	Location Name[1]	Location Code[2]	TKN[3] (mg/g)	TOC[4] (%)	Total HC[5] (μg/g)	Aromatic HC[6] (μg/g)	Phenols[7] (μg/g)
Pascagoula River System	McInnis Lake	17/ML	4.24 /—[8]	14.0 /—	1,510 /—	246 /—	1.56 /—
	Griffin Point	18/GP	2.79 /—	3.30 /—	338 /—	57.1 /—	1.30 /—
	Paper Mill	19/PM	3.81 /—	12.2 /—	306 /—	0.00 /—	2.43 /—
	Dead River	23/DR	0.86 /2.09	0.145 /—	137 /—	0.032/—	0.861/—
	Mary Walker Bayou	24/MW	— /3.26	— /3.64	855 /—	139 /—	1.09 /—
	Point aux Chenes	14	0.000	0.277	0.2	0.00	0.120
	Bayou Casotte	15	1.19	2.66	4,660	325	0.836
	Mouth E. Pascagoula River	16	0.000	0.863	14.8	3.93	0.462
	Escatawpa River Control	20	3.18	7.14	794	113	0.687
	E. Pascagoula I-10	21	0.73	1.94	51.2	14.5	0.806
	Bayou Chemise	22	0.45	0.828	6.96	1.20	0.000
	Mouth W. Pascagoula River	25	0.73	0.850	12.9	3.30	0.246
	Round Island	29	0.51	1.82	90.6	10.0	0.534
	Lake Yazoo	LY	0.573	2.49	9,850	1,930	0.907
	Elevator Bayou	EB	1.84	3.86	56.8	11.1	1.36
	Twin Islands	TI	0.571	0.206	3.59	0.717	0.480
	Halter Marine	HM	2.20	6.51	————	————	1.84
	Pogey Plant	PP	1.15	4.85	31.1	1.79	0.865
	Mississippi Chem., E. Bank	MC	————	4.17	149	22.2	—
	Bayou Pierre	BP	2.15	3.96	577	374	0.415
	Mississippi Hwy. Dept.[9]		0.54	11.4	1,730	197	1.10
	Escatawpa River Bridge[9]	ER	————	10.9	1,870	110	1.84
	West Prong	WP	1.06	2.82	13,300	1,000	2.75
	Graveline Bayou	GB	0.395	0.454	98.0	28.2	2.07
	Chevron N. Dock	CD	0.71	1.37	95.1	15.6	0.437
	Cooling Tower Canal	CT	0.809	2.61	8,460	684	
Biloxi Bay System	Davis Bayou	1/DB	0.76 /—	1.58 /—	18.4 /—	8.13 /—	1.17 /—
	Old Fort Bayou	3/FB	0.71 /—	1.35 /—	3.69 /—	0.963/—	0.299/—
	Deer Island	4/DI	0.55 /—	0.692 /—	170 /—	77.1 /—	0.763/—
	Gulfport Lake	8/GL	1.08 /—	3.67 /—	24.3 /—	10.6 /—	0.354/—
	Power Plant	11/PW	0.23 /—	0.315 /—	1.15 /—	0.410/—	0.505/—
	South Deer Island	2	0.220	0.866	5.44	1.62	0.254
	Goat Island	5	0.99	1.62	101	8.45	2.39
	Keesler AFB	6	1.59	2.04	99.4	10.1	0.335
	Popps Ferry	7	0.69	1.58	25.2	7.91	0.490
	Cedar Lake	10	0.76	1.44	7.56	3.15	0.260
	Big Lake	12	1.41	2.30	243	50.9	1.15
	Bernard Bayou	44	0.07	0.868	38.0	6.34	0.285
	Rhodes Point	RP	0.719	2.00	217	41.9	0.324
	V.A. Hospital	VA	1.60	2.65	109	21.2	0.297
	Industrial Seaway	IS	0.307	2.93	8,600	2,610	0.548
	Turkey Creek	TC	1.28	1.99	704	156	0.632
	Reichhold Industrial Canal	RC	2.59	2.62	1,900	419	0.580
	Hewchem Industrial Canal	HC	0.88	1.53	550	89.5	0.347
	Coley Island	CI	0.31	1.31	227	2.91	0.492
St. Louis Bay System	Heron Bay	31/HB	1.32 /—	0.328 /—	37.0 /—	9.15 /—	0.378/—
	St. Louis Bay Bridges	39/BB	1.07 /—	2.08 /—	63.9 /—	9.77 /—	0.773/—
	Mouth Jourdan River	38	1.39	1.83	32.5	7.04	0.537
	Mouth Wolf River	40	0.97	1.56	12.8	3.52	0.485
Mississippi Sound System	Horn Island	27/HI	0.112/—	0.0959/—	0.985/—	0.070/—	0.224/—
	West Ship Island	33/SI	0.97 /1.07	1.19 /1.29	29.9 /—	3.52 /—	0.470/—
	Gulfport Channel	9	0.26	1.17	11.7	1.91	0.602
	Edgewater	13	0.44	1.10	20.7	3.63	0.302
	E. Mississippi Sound	26	0.07	0.370	2.13	0.071	0.319
	Bellefontaine Point	28	0.44	0.526	16.1	2.90	0.390

TABLE 4. Chemical composition of Mississippi Sound surface sediments (continued).

General Location	Location Name[1]	Location Code[2]	TKN[3] (mg/g)	TOC[4] (%)	Total HC[5] (µg/g)	Aromatic HC[6] (µg/g)	Phenols[7] (µg/g)
Mississippi Sound System (continued)	West Horn Island	30	0.26	0.597	6.37	0.826	0.282
	Petit Bois Island	32	1.08	0.303	69.9	3.99	1.77
	Pass Marianne	34	0.69	1.11	27.5	2.42	0.655
	Ship Island Pass	35	0.39	0.883	8.77	1.05	0.341
	Cat Island Channel	36	0.26	0.678	4.80	0.547	0.456
	Bayou La Batre	41	0.0045	0.563	12.3	1.54	0.842
	Dauphin Island	42	0.048	1.31	27.4	11.0	1.62
	D'Iberville	43	1.45	1.36	38.8	6.60	1.15
	Open Gulf	OG	0.73	1.09	18.9	3.77	0.285
	East Gulfport Channel	GC	1.55	1.36	34.5	5.91	0.529
Secondary Locations	Mouth Discharge Canal	MDX	----	----	822	214	---
	Inner Discharge Canal	IDX	----	----	134	48.0	---
	Corning East Bank	CEX	----	2.98	27.5	3.88	---
	Chevron West Bank	CHX	----	0.891	181	4.87	---
	Gypsum Stack	GSX	----	3.24	67.0	5.56	---
	Control	CNX	0.31	4.24	1,580	163	0.488
	Graveline Lake	GLX	1.38	1.57	238	37.8	---
	Pascagoula Transect #1	TAX	0.12	0.133	7.74	3.87	0.038
	Pascagoula Transect #2	TBX	0.41	0.389	7.82	2.11	0.860
	Pascagoula Transect #3	TCX	0.30	0.304	11.1	----	0.860
	Pascagoula Transect #4	TDX	1.36	1.65	18.3	11.6	2.05
	Pascagoula Transect #5	TEX	0.75	1.31	63.5	14.1	3.37
	Pascagoula Transect #6	TFX	1.11	0.997	25.6	4.67	2.41
	Power Plant Canal	PCX	8.48	24.7	98.5	41.5	1.15

[1]A detailed description of core and surface sample locations may be found in Tables 2 and 3.
[2]Master stations are either surface grabs (2-letter code) where complete bio-geo-chemical analyses were performed or core samples (2-digit code) or both. In columns of tabulated data where both core and samples were collected at the same site, data from the top segment of these cores precedes data from surface grab samples. Secondary stations (3-letter code) were sites for only select chemical data collection. Refer to Figure 2 for geographic locations.
[3]Total Kjeldahl nitrogen, dry sediment wt. basis.
[4]Total organic carbon, dry sediment wt. basis.
[5]Total gravimetric wt., of aliphatic and aromatic hydrocarbons, dry sediment wt. basis.
[6]Gravimetric wt., dry sediment basis.
[7]Total phenols, measured colorimetrically, reported dry sediment basis.
[8]Data not available.
[9]Stations from essentially same location.

are the industrial sites in Bayou Casotte. Results in Table 4 give convincing evidence that, with regard to concentration levels of pollutants within the sediments, the Open Sound is less polluted than any of the associated rivers and bays where the primary pollutant sources are located.

St. Louis Bay and Open Sound Systems

Uniformity of distribution of chemical constituents is evident in surface samples from both St. Louis Bay and the Open Sound systems. Overall levels of TOC and phenols are about the same for both of these systems. Total Kjeldahl nitrogen values seem somewhat elevated in St. Louis Bay though at D'Iberville and East Gulfport Channel, near population centers and shipping channels in the Sound, TKN exceeds those of St. Louis Bay. The same could be said for hydrocarbons which, at isolated spots in the Open Sound, are high but in St. Louis Bay are consistently at levels approximately twice those of the Open Sound. Aromatic hydrocarbons show an even greater accentuation in St. Louis Bay sediments than total hydrocarbons when compared to the Open Sound.

Biloxi Bay System

Total Kjeldahl nitrogen and TOC values of

Biloxi Bay are slightly elevated above those of the Open Sound with outstanding TKN values noted for sediments at Reichhold Industrial Canal and unusually high TOC at Gulfport Lake. Examples of hydrocarbon values vastly higher than in Open Sound sediments are numerous in Biloxi Bay. The two highest values occur in the Industrial Seaway and the Reichhold Industrial Canal. Aromatic hydrocarbons also occur in much higher amounts in Biloxi Bay than in the Open Sound. Hydrocarbon levels occur with almost exaggerated variability in Biloxi Bay, while TKN, TOC and phenol values are fairly uniform. This uniformity probably results from a broad array of sources in the Sound releasing these organics. Hydrocarbons are released in large quantities from only a select group of discharge sites near those regions with dramatically high sedimentary hydrocarbons. Only one Biloxi Bay site, Goat Island, had a phenol content significantly higher than values found in the Open Sound samples.

Pascagoula River System

The Pascagoula River System region is noteworthy for having widely divergent values for all variables reported in Table 4 and for values that consistently exceed not only the Open Sound but Biloxi Bay and St. Louis Bay systems as well. It is suggested, again, that the the cause for these divergent values is extreme fluctuation in the quantity of discharge material released near each sampling site. Unlike the other regions, TKN values show strong interstation variations with amounts at McInnis Lake, Paper Mill and Escatawpa River Control being the highest values found in the whole study effort. Total organic carbon values show equally strong variations, exceeding 10% at three sites along the Escatawpa River (McInnis Lake, Paper Mill and Escatawpa River Bridge). Hydrocarbons display the same aberrant behavior observed at Biloxi Bay with extremely high hydrocarbon levels found at Bayou Casotte, Lake Yazoo and West Prong. The aromatic hydrocarbons follow the same pattern as the total hydrocarbons. Fluctuations in phenol values are not as extreme as in the other variables. In summary, the facts that emerge in looking at the total picture of surface sediment pollutants in the Sound are as follows:

1. The Pascagoula River System is the most seriously polluted region of the Sound.
2. The Biloxi Bay System is less polluted than the Pascagoula River System but significantly higher than the Open Sound System.
3. The St. Louis Bay System is only slightly more polluted than the Open Sound System.
4. The highest pollution levels were found in only very localized regions, not broad areas.
5. The greatest fluctuations in pollutant values and gravest pollution problem were noted in hydrocarbons.
6. Fairly uniform distributions of organics occur in the Open Sound System in sharp contrast with the river and bay systems.

The variations in pollutant levels among the various sites become more pronounced by examining Figures 5 through 8 in which the organic variables listed in Table 4 are plotted individually as discrete ranges of concentrations. Names of sites may be ascertained by comparing Figures 5 through 8 to the map in Figure 2 and accompanying keys in Tables 2 and 3.

Total Organic Carbon

Total organic carbon values are the result of all organic components in the sediment, both natural and man-made. Because natural levels of organic residues from plant and animal life are typically 1 to 2%,[44] pollution must be rather extreme to permit one to exclude natural variation as the cause of high TOC values. In Figure 5 there appears a preponderance of extremely high TOC values in the Pascagoula River System, values that point irrefutably to extraordinary pollution by man-made organics. Fairly high values in Bayou Casotte in view of reduced TOC values in the eastern Open Sound also strongly indicate extensive pollution in this segment of the Pascagoula River System. Though not as conclusive, the Biloxi Bay region contains sediments seemingly of abnormally high TOC especially at the western end. The Open Sound stations south of Gulfport and Biloxi are in the path of outflow from Biloxi Bay and also in the region of boat traffic to Gulfport Harbor. It is not surprising then to find TOC values in this region of the same magnitude as Biloxi Bay. However, only a weak case can be made for transport from remote regions in Biloxi or other regions to these

Open Sound areas, because the transect of stations north of Horn Island, which is in the path of trans-Sound flow of the Pascagoula River, apparently has experienced very little input from the Pascagoula River System. Total organic carbon appears to be a good assessment of pollution only where exceedingly high levels of organic pollutants are released and near the sources of these releases.

Total Kjeldahl Nitrogen

Total Kjeldahl nitrogen values are more specific than TOC because TKN is responsive only to those organic compounds containing nitrogen such as would be released by fishmeal-processing plants and sewage treatment plants. Again the concentrations must be substantial to discount natural variation in background levels. In Figure 6, the most distinguishing characteristic is the occurrence of high TKN values in the bays and rivers along the coastline as compared to the Open Sound System. In St. Louis Bay, Biloxi Bay and the Pascagoula River one effect of residential development seems to have been an elevated load of nitrogenous wastes being introduced to the sediments. The impact is not very startling, neither is there any region where industrially derived nitrogenous wastes are of such magnitude as to exhibit extreme TKN values.

Phenols

The distribution of total phenols shown in Figure 7 is more problematic than that for TOC and TKN. Though phenols are almost ubiquitous components of industrial discharges, they are fairly unstable in a sedimentary environment and quickly degrade to quinones.[29] Values of phenols elevated significantly above background, therefore, indicate a rate of introduction that exceeds the rate of degradation. The majority of "high-phenol" sediments are located near industrial dump sites, in the Escatawpa River, Bayou Casotte and Biloxi Bay. "Low-phenol" or background values are found throughout most of the Sound. The explanation of anomalously high phenols near Petit Bois and Dauphin islands is not readily apparent but may indicate transport and deposition of phenol-rich sediment materials from industrial dump sites in Mobile Bay.

Hydrocarbons

In Figure 8 ranges of total hydrocarbons in surface sediments are displayed. Aromatic and aliphatic hydrocarbons are depicted as a fraction of the total. The contrast of bay and river sediments to Open Sound sediments is truly astonishing particularly in the Pascagoula region where total hydrocarbons reach levels 100 to 1,000 times those of the Open Sound, where the typical background range is 1 to 10 ppm. What is not surprising is the enrichment of sediment hydrocarbons near suspected sources: refineries, marinas, shipping canals, and certain chemical manufacturing plants. The low level transport of organic pollutants into the Mississippi Sound is demonstrated in the hydrocarbon distribution shown in Figure 8. Very little enrichment in hydrocarbon values was noted beyond the mouth of the Pascagoula River, Bayou Casotte or Biloxi Bay although stations in the Open Sound were deliberately positioned to coincide with sites of deposition of river- and bay-derived sediments. It is suggested that, like other organic pollutants, hydrocarbons tend to become associated with particulate matter, aggregate and precipitate in the immediate vicinity of their source. This is made even more apparent by observing the large variations in hydrocarbon levels between stations of close proximity in the Pascagoula River and Biloxi Bay. The deterrents to migration of large quantities of hydrocarbons from their contaminant source has resulted in a total ecological system that may be described as heavily polluted but only in very well-defined localized areas.

The ratio of aromatic hydrocarbons to aliphatic hydrocarbons is a feature easily discerned from Figure 8 and is one that reflects the anthropogenic source of these hydrocarbons. Obviously, the classification of hydrocarbon source, i.e., whether due to crude oil, fuel oil, sewage, etc., varies throughout the Sound as indicated by variations in this ratio. Of further significance, increased ratios of aromatic/aliphatic hydrocarbons warrant additional concern because aromatic hydrocarbons possess greater toxicity than aliphatics.[63–67] Samples collected in Bayou Casotte contain the highest total concentration of hydrocarbons. Fortunately, the level is due to a much greater

abundance of contamination by aliphatic than by aromatic hydrocarbons. This result was rather unexpected considering the oil tanker traffic serving a refinery in Bayou Casotte. Crude oil typically contains higher ratios of aromatics to aliphatics than disclosed in sediment analysis of this region. However, refinery products and wastes of other chemical companies along the Bayou could be responsible for a skewed dominance of aliphatics. Little comfort may be taken in noting the lesser quantities of hydrocarbons in many sections of Biloxi Bay sediments compared to the Pascagoula region because vast quantities of hydrocarbon contaminants have been released in the Gulfport Lake-Bernard Bayou industrial area with decidedly higher proportions of aromatics than found in the Pascagoula River System.

Pollutant versus Natural Hydrocarbons

Because hydrocarbons have emerged as the single-most problematic contaminant in Mississippi Sound, additional discussion is required to give proper insight to the full measure of the dangers of hydrocarbons in the environment. There is a great deal of background data on the toxic effects of petroleum hydrocarbons on marine life. However, because there are hydrocarbons of nonpetroleum origin in the environment, the potential hazards and the environmental chemistry of hydrocarbons are complicated. Although there have been numerous studies on oil pollution, most have dealt with spills and acute pollution. Only recently have there been studies dealing with chronic oil pollution, the fate of oil in the environment and the potential hazards associated with polluted sediments.

Most attempts to assess the inputs of hydrocarbons to the marine environment have concentrated on those from petroleum sources, and then primarily on those directly relating to the production and shipment of petroleum and its products. Although marine transportation contributes the major input of petroleum pollution, a very significant input comes from municipal waste and urban/river runoff. Few studies focus attention on nonpetroleum-derived hydrocarbon inputs. There are two primary sources of hydrocarbon input to the marine environment: recent biogenic matter and petroleum. Recent biogenic matter can include biosynthesized hydrocarbons and can also give rise to polynuclear aromatic hydrocarbons (PNA) by combustion either naturally (forest fires) or by man's activity (wood burning).

There is considerable difficulty in distinguishing between the petrogenic and biogenic origin of hydrocarbons in sediments, because sediments are sinks for both. Features of petroleum hydrocarbons include: a homologous series of normal alkanes showing no odd-to-even carbon number predominance; a homologous series of isoprenoid alkanes (n-C_{15} – n-C_{21}); multiple homologous series of saturated cycloalkanes (i.e., steranes and triterpanes); multiple series of aromatic hydrocarbons, particularly alkyl-substituted benzenes, naphthalenes, PNAs and an extensive unresolved mixture dominated by cycloalkanes (naphthenes), the characteristic "unresolved complex mixture" or UCM.

Features of recent biogenic hydrocarbons include: a restricted range of n-alkanes frequently showing a strong odd carbon number/even carbon number ratio when derived from terrestrial vegetation (usually with n-C_{25}, n-C_{27}, n-C_{29} and n-C_{31} as the main components) although, if of the marine origin, the odd/even ratio may be low perhaps with the predominance of n-C_{17} or n-C_{15} alkanes; the predominance of a single isoprenoid, usually pristane, with phytane generally believed to be absent from unpolluted recent sediments; and the presence of acyclic or cyclic alkenes in significantly greater abundance than the saturated analogues, frequently eluting from the gas chromatograph very near n-C_{17} or between n-C_{20} and n-C_{22}. Although some of these unsaturated hydrocarbons are of terrestrial origin, some are clearly believed to be marine. Although there are claims that some organisms are capable of biosynthesizing aromatic hydrocarbons (simple unsubstituted forms), it can be assumed that the majority of aromatic hydrocarbons are derived from petroleum (particularly substituted forms) and pyrolytic activity.

Table 5 lists the principal sources of petrolium hydrocarbons entering the ocean.[68] There is a vast literature relating to oil releases from tanker operations, particularly spillage;

however, other sources are not so well documented or even acknowledged.

Oily water discharges can be expected from both oil production and refinery processes. The major source of oil-contaminated effluent from coastal refinery operations is from cooling water and associated discharges from cracking plant, scrubbers, etc. Recirculating water cooling and air cooling are being used to an increasing extent and plants are tending to install more sophisticated oil-water separation facilities, usually gravity separation/dissolved air flotation, frequently followed by sand or biofiltration. These changes are leading to an improved quality of effluent, normally below 25 ppm *total oil*. One major concern, however, is that refinery effluents are important sources of aromatic hydrocarbons, notably the PNAs.

Depending on the data source, as well as the extrapolation and assumptions employed, various figures have been derived for the significance of these discharges in global estimates of hydrocarbon input into the sea. One point is certain, however, they represent a major input route. Because such discharges are inshore, usually in environmentally important regions such as estuaries, their likely impact could be greater. Major sources of hydrocarbons in municipal wastes are: sewage derived alkanes (including cycloalkanes) which contribute the large UCM characteristic of sewage polluted sediment; sewage derived aromatic hydrocarbons, notably PNAs, derived from food, drainage of domestically employed oils (lubricating, fuel, crank case, etc.); road runoff, which is particularly rich in PNAs presumably from bituminous road surfaces, sump oils, vehicle exhaust, tire wear and rain (atmospheric PNAs); industrial discharges into municipal sewers contaminated by used lubricating oils, gas scrubber discharges, high-temperature furnace wastes, etc. The major sources of hydrocarbons from industry are: lubricating and fuel oils particularly in engineering operations with used lubricating oils being particularly rich in PNAs; PNA discharge from industry involving high temperature/pyrolytic activity, e.g., smelting works, shale processing, iron and coke works.

TABLE 5.

Budget of petroleum hydrocarbons introduced into the ocean.[1]

Source	Input Rate (mta)[2] Best Estimate	Probable Range
Natural seeps	0.6	0.2 – 1.0
Offshore production	0.08	0.08 – 0.15
Transportation		
LOT tankers	0.31	0.15 – 0.4
Non-LOT tankers	0.77	0.65 – 1.0
Dry docking	0.25	0.2 – 0.3
Terminal operations	0.003	0.0015 – 0.005
Bilges bunkering	0.5	0.4 – 0.7
Tanker accidents	0.2	0.12 – 0.25
Nontanker accidents	0.1	0.02 – 0.15
Coastal refineries	0.2	0.2 – 0.3
Atmosphere	0.6	0.4 – 0.8
Coastal municipal wastes	0.3	––
Coastal nonrefining, Industrial waste	0.3	––
Urban runoff	0.3	0.1 – 0.5
River runoff	1.6	––
Total	6.113	

[1] Data taken from Johnston[68]

[2] mta = million metric tons/year

Gas Chromatographic Data

Gas chromatograms of hydrocarbons extracted from surface sediments at three sites in the Sound will demonstrate some of the diverse pollutant hydrocarbon features previously mentioned. The hydrocarbon chromatograms shown in Figure 9 were obtained from a sediment sample in the discharge canal of a major oil refinery in Bayou Casotte. Three distinct suites of hydrocarbons are in evidence: one from refinery wastes and two of natural occurrence. The presence of crude oil and refinery products is signaled by the constellation of PNAs in the aromatic chromatogram including phenanthrene, pyrene, benzofluorene and chrysene and also in the aliphatic fraction where there are pronounced peaks corresponding to the low molecular weight *n*-alkanes < n-C_{20}. Both pristane and phytane are prominent aliphatic components as a further indication of the refinery wastes. Terrestrial plant remnants are seen in the assemblage of high molecular weight hydrocarbons ($\geq n$-C_{20}) where a decided preference for the odd numbered homologues is in evidence, and a dominance of n-C_{29} reflects the parentage of these

hydrocarbons in typical marsh plants. A third hydrocarbon source seen in these chromatograms is shown to be algae by the elevated quantities of the n-C_{15} and n-C_{17} alkanes, presumed of algal origin, residing in the aliphatic chromatogram of Figure 9.

In chromatograms of aliphatic and aromatic hydrocarbons from sediments near a boat marina at Mary Walker Bayou, only anthropogenic hydrocarbons are discernible. Abundant PNAs, which have been identified and labeled in Figure 10, reflect a petroleum source as was noted at Point aux Chenes. However, in contrast to residues of refinery wastes, the aliphatic hydrocarbons at this site are not dominated by the n-alkanes. The very complex suite of aliphatic hydrocarbons consisting primarily of branched and cyclic components completely masks the n-alkanes and points to fresh and combusted motor fuels.

At Griffin Point, a site near a sewage outfall, clear indications of the impact of sewage hydrocarbons can be seen in sediment hydrocarbon chromatograms (Figure 11). Oily residues are indicated by the presence of PNAs (those labeled compounds shown in the aromatic chromatogram), an aliphatic assemblage that includes both pristane and phytane and the "hump" underlying the peaks on this chart, i.e., the UCM mentioned earlier.

Oil-Indicating Variables

In an effort to use hydrocarbon data to detect the presence of pollutant hydrocarbons, observations of general shapes and characteristics of gas chromatograms are often supplemented with mathematical variables derived from chromatograms. These variables are purported to be good indicators of the presence of petroleum hydrocarbons[69,70] and give a more objective means of appraising chromatographic data than actual visual examinations of the chromatograms. Eight of the more useful variables are compiled in Table 6 for all of the surface samples collected in this study. The first two of these variables are somewhat repetitive of the data shown in Table 4 and Figure 8. However, the aliphatic and aromatic weights reported in Table 6 are compilations only of those constituents in each hydrocarbon fraction that are sufficiently resolved in the gas chromatographic separation to be quantitated. Those quantities reported in Table 4 and Figure 8 include those hydrocarbons concealed in the UCM and those that fail to elute from the chromatograph during the programmed cycle. Therefore, values for these two fractions in Table 6 are less than those documented earlier in this report. Because the gas chromatographic measurements of these two variables in Table 6 are more 'hydrocarbon-specific,' conclusions concerning likely hydrocarbon sources tend to be somewhat more reliable than the gravimetric measurements reported in Table 4. However, these variables do not in any case refute conclusions drawn from gravimetric data but strengthen them.

In the Pascagoula River System those stations that stand out because of hydrocarbon levels are McInnis Lake, Bayou Casotte, Escatawpa River Control, Lake Yazoo, Mississippi Highway Department, West Prong, and Cooling Tower Canal. The order by concentration of discrete hydrocarbons is not the same as for the gravimetric data in Table 4. The most noticeable difference is that the samples taken from Bayou Casotte have considerably less gas chromatographic hydrocarbon material than would have been suggested by the gravimetric data. Rather than discount the gravimetric data as being reflective of excessive amounts of extraneous nonhydrocarbon material, this disparity indicated that further study would be necessary to disclose the nature and source of this material. The results of this research will be discussed later in this text. Among other locations in the Sound, the aliphatic and aromatic gas chromatographic weights are at levels causing grave concern primarily in those regions where results of gravimetric estimations in Table 4 have also suggested alarming levels. Specifically in the Biloxi Bay System, the Industrial Seaway and Reichhold Industrial Canal have pronounced hydrocarbon concentrations indicating high levels of pollution. Of the remaining sites, attention is again drawn to the paucity of hydrocarbon material in the sediments of the Open Sound and those stations in the bays and rivers of St. Louis Bay.

Because the aliphatic fraction in fresh petroleum is generally enriched with n-alkanes versus branched and cyclic aliphatic constituents, the ratio of n-alkanes to total aliphatics is regarded

TABLE 6.

Hydrocarbon parameters of Mississippi Sound surface sediments.[1]

Location Name	Location Code[2]	Aliphatics Dry Sediment Weight (ppm)	Aromatics Dry Sediment Weight (ppm)	*n*-Alkanes Aliphatics (%)	Pristane / *n*-C_{17}	Phytane / *n*-C_{18}	Pristane / Phytane	Odd/Even C ⩽ 20	Odd/Even C ⩾ 21
Pascagoula River System									
McInnis Lake	17/ML	86.2	15.9	32.6	*	1.05	*	0.637	1.26
Griffin Point	18/GP	16.7	5.05	48.8	1.54	1.06	1.07	0.874	1.34
Paper Mill	19/PM	26.8	2.95	58.8	0.512	0.256	1.23	1.13	3.32
Dead River	23/DR	6.45	0.168	55.5	1.43	1.71	1.32	0.423	1.43
Mary Walker Bayou	24/MW	6.89	28.9	*	2.13	7.00	2.33	*	*
Point aux Chenes	14	0.424	0.142	36.9	0.456	0.717	0.716	0.636	2.15
Bayou Casotte	15	31.8	21.7	38.7	74.3	2.66	1.17	1.44	0.618
Mouth East Pascagoula River	16	0.396	0.988	66.2	0.882	0.625	2.42	1.07	3.47
Escatawpa River Control	20	62.5	50.5	69.8	2.19	1.72	2.35	0.862	4.95
East Pascagoula I-10	21	1.27	2.25	59.1	0.958	3.88	1.15	1.93	0.745
Bayou Chemise	22	0.869	0.411	74.3	0.482	0.826	0.768	1.01	3.23
Mouth West Pascagoula River	25	0.692	0.482	57.0	0.855	0.830	1.18	0.294	2.40
Round Island	29	4.52	0.438	57.5	0.616	0.979	0.787	0.502	3.76
Lake Yazoo	LY	825	17.2	11.5	0.793	1.18	1.32	*	*
Elevator Bayou	EB	2.49	2.49	58.1	0.946	1.10	0.606	0.526	1.44
Twin Islands	TI	0.310	0.200	30.8	0.0757	1.38	0.0928	1.94	2.63
Halter Marine[3]	HM	—	—	—	—	—	—	—	—
Pogey Plant[4]	PP	—	—	—	—	—	—	—	—
Mississippi Chem. E. Bank		2.95	0.519	61.0	0.637	0.994	0.573	0.755	0.639
Bayou Pierre	BP	16.0	99.4	49.3	1.03	2.68	0.429	0.922	2.77
Mississippi Hwy Dept.[5]		525	20.3	43.9	2.29	1.76	1.87	1.01	1.62
Escatawpa River Bridge[5]	ER	59.7	10.0	49.5	1.23	1.08	1.60	0.972	1.74
West Prong	WP	92.4	31.8	63.5	1.60	1.99	1.01	0.526	1.77
Graveline Bayou	GB	7.37	3.41	67.4	0.705	0.535	2.00	0.422	1.93
Chevron N. Dock	CD	2.51	2.00	40.5	1.60	0.735	1.53	0.509	3.12
Cooling Tower Canal	CT	37.3	19.8	*	4.24	2.86	0.831	*	*
Biloxi Bay System									
Davis Bayou	1/DB	4.80	0.336	51.7	0.972	0.899	0.797	0.897	4.70
Old Fort Bayou	3/FB	2.09	0.318	45.9	0.929	0.966	1.31	0.682	3.74
Deer Island	4/DI	3.78	2.41	59.3	1.48	0.981	0.807	0.968	0.183
Gulfport Lake	8/GL	8.87	1.07	52.4	18.5	0.606	16.3	0.753	6.13
Power Plant	11/PW	0.433	0.0338	41.0	0.536	0.484	1.36	0.818	2.33
South Deer Island	2	1.28	0.310	60.8	0.440	0.370	1.85	0.369	4.01
Goat Island	5	4.70	0.816	64.4	0.649	0.688	1.72	0.674	3.83
Keesler AFB	6	19.5	1.34	34.5	1.12	0.845	1.63	0.674	3.51
Popps Ferry	7	6.43	2.91	46.0	2.40	0.691	4.39	1.41	4.58

TABLE 6. Hydrocarbon parameters of Mississippi Sound surface sediments (continued).[1]

Location Name	Location Code[2]	Aliphatics Dry Sediment Weight (ppm)	Aromatics Dry Sediment Weight (ppm)	*n*-Alkanes Aliphatics (%)	Pristane / *n*-C_{17}	Phytane / *n*-C_{18}	Pristane / Phytane	Odd/Even C ≤ 20	Odd/Even C ≥ 21
Biloxi Bay System (con't)									
Cedar Lake	10	0.919	0.314	23.9	2.44	0.286	6.02	0.817	4.38
Big Lake	12	16.3	5.45	24.2	4.21	3.32	1.17	1.36	2.15
Bernard Bayou	44	3.60	0.631	43.0	1.98	1.54	1.12	0.340	1.72
Rhodes Point	RP	5.42	2.68	56.8	0.637	2.25	0.279	1.03	1.67
V.A. Hospital	VA	9.44	1.60	72.5	0.840	1.27	0.421	0.245	1.24
Industrial Seaway	IS	130	205	*	*	*	*	*	*
Turkey Creek	TC	77.4	27.0	39.7	*	1.27	*	1.44	0.311
Reichhold Indus. Canal	RC	93.7	81.4	13.9	1.77	1.12	1.00	0.580	1.51
Hewchem Indus. Canal	HC	56.2	9.94	27.7	1.05	1.60	1.45	1.12	2.12
Coley Island	CI	25.0	29.0	39.0	3.03	2.32	0.685	0.915	1.19
St. Louis Bay System									
Heron Bay	31/HB	7.48	0.694	47.6	0.613	0.733	1.14	0.794	3.48
St. Louis Bay Bridges	39/BB	7.06	1.87	57.1	0.828	0.889	1.04	0.930	3.57
Mouth Jourdan River	38	12.9	2.52	58.7	0.989	0.836	1.67	0.480	3.93
Mouth Wolf River	40	1.95	0.743	45.0	0.515	1.01	0.836	0.632	3.22
Mississippi Sound System									
Horn Island	27/HI	0.164	0.0242	57.3	0.820	0.686	1.51	0.843	1.44
West Ship Island	33/SI	7.57	0.493	27.1	1.09	0.815	1.72	0.872	3.87
Gulfport Channel	9	1.87	0.438	64.9	0.686	0.728	1.19	0.614	4.50
Edgewater	13	2.28	0.708	69.6	0.416	0.437	1.51	0.526	3.68
East Mississippi Sound	26	0.160	0.0601	51.7	0.732	0.761	0.750	0.633	2.49
Bellefontaine Point	28	1.46	0.276	50.0	1.10	0.770	2.74	0.833	3.30
West Horn Island	30	1.42	0.0869	30.4	0.851	1.08	1.55	1.40	3.53
Petit Bois Island	32	6.51	1.58	61.1	0.360	1.06	1.57	1.33	2.06
Pass Marianne	34	3.65	0.213	48.7	0.759	0.941	1.49	1.04	5.01
Ship Island Pass	35	2.60	0.173	46.6	1.04	0.892	1.60	1.22	5.09
Cat Island Channel	36	1.56	0.188	35.9	1.23	1.11	2.41	0.919	3.56
Bayou La Batre	41	0.691	0.0730	68.4	0.891	0.894	1.57	0.674	1.94
Dauphin Island	42	1.50	0.135	80.7	*	0.185	*	0.586	2.87
D'Iberville	43	2.11	0.497	64.8	0.477	0.547	0.799	0.887	3.01
Open Gulf	OG	1.35	0.544	49.8	0.607	0.605	1.47	1.12	2.08
East Gulfport Channel	GC	3.78	0.885	48.5	0.567	0.705	1.21	0.722	4.15
Secondary Locations									
Mouth Discharge Canal	MDX	33.7	6.61	*	*	*	*	*	*
Inner Discharge Canal	IDX	11.0	1.92	42.6	0.169	3.11	0.761	5.53	3.23
Corning East Bank	CEX	1.66	0.443	71.2	0.716	0.702	0.642	0.635	0.988

TABLE 6. Hydrocarbon parameters of Mississippi Sound surface sediments (concluded).[1]

Location Name	Location Code[2]	Aliphatics Dry Sediment Weight (ppm)	Aromatics Dry Sediment Weight (ppm)	*n*-Alkanes Aliphatics (%)	Pristane / *n*-C_{17}	Phytane / *n*-C_{18}	Pristane / Phytane	Odd/Even C ≤ 20	Odd/Even C ≥ 21
Secondary Locations (con't)									
Chevron West Bank	CHX	1.50	0.188	44.6	1.08	0.966	1.04	0.778	0.785
Gypsum Stack	GSX	1.74	0.204	51.7	0.510	1.04	0.718	1.09	0.765
Control	CNX	338	4.05	*	*	*	*	*	*
Graveline Lake	GLX	1.96	4.37	76.2	0.252	0.813	0.594	0.820	0.730
Pascagoula Transect #1	TAX	0.308	0.0759	59.2	0.176	0.931	0.221	1.07	1.22
Pascagoula Transect #2	TBX	0.417	0.204	62.7	0.256	0.707	0.406	0.973	1.03
Pascagoula Transect #3	TCX	0.434	0.138	51.8	0.363	0.717	0.773	1.22	2.53
Pascagoula Transect #4	TDX	2.27	1.90	56.3	0.362	1.42	0.320	1.05	1.36
Pascagoula Transect #5	TEX	1.75	2.12	55.4	0.225	0.686	0.760	1.29	1.41
Pascagoula Transect #6	TFX	0.603	0.422	52.4	0.308	0.542	0.928	0.956	1.25
Power Plant Canal	PCX	22.0	7.10	86.8	0.165	0.543	0.386	0.875	5.58

*Resolution of key components in gas chromatogram insufficient for this computation.

[1] Parameters are derived from gas chromatographic data obtained on each surface grab sample or surface section of sediment core. The parameters are calculated as follows: quotient of sums of all individual components in aliphatic (and aromatic) fractions and dry sediment weight in μg/g (ppm); percentage of aliphatic hydrocarbons that are *n*-alkanes; ratios of the isoprenoids, pristane to *n*-heptadecane (*n*-C_{17}), phytane to *n*-octadecane (*n*-C_{18}) and pristane to phytane; ratio of odd numbered *n*-alkanes to even numbered *n*-alkanes with carbon chains of 20 or fewer carbons and the same ratio for carbon chains exceeding 20 carbons.

[2] Refer to Figure 2 for location.

[3] No hydrocarbon analysis done at this station.

[4] Gas chromatograms not of suitable quality for quantitation.

[5] Stations from essentially same location.

as another supporting factor for assigning a petroleum source to hydrocarbons in sediments. The tabulation of this variable in Table 6 adds very little to the interpretive understanding of hydrocarbon sources of Sound sediments. The values are almost uniformly high for all surface samples, the exceptions being two highly polluted sites, Lake Yazoo and Reichhold Industrial Canal. Apparently, either a nonpetroleum source or highly degraded oil is the dominant hydrocarbon source at both sites. Little can be said for all other sites except that some petroleum-derived hydrocarbon material may be present in all the samples, but no conclusive evidence is suggested by this variable. The three ratios that are functions of pristane and phytane also do not give clear indications of hydrocarbon source. The two ratios utilizing the *n*-alkane 'neighbors' (n-C_{17} and n-C_{18}) from gas chromatograms (see Figures 9 through 11) tend to have maximum values at inland sites near industrial sources with lesser values in the Open Sound and the western bays and rivers of the Sound. Of the two, the phytane/n-C_{18} is a more emphatic indication of oil pollution because, as previously stated, phytane is rarely found as a component of biologically derived hydrocarbons. The most demonstrably petroleum/hydrocarbon-polluted sediments from this criterion are Mary Walker Bayou, E. Pascagoula I-10, Cooling Tower Canal, and Big Lake, all areas of high boat traffic and/or industrial activity. In alliance with a high phytane/n-C_{18} ratio, one also looks for a reasonably small ratio of pristane/phytane to indicate sufficient quantities of phytane to preclude a false positive statement of pollution based upon the phytane/n-C_{18} ratio alone. All pristane/phytane ratios at sites where the individual isoprenoid/*n*-alkane ratios indicated pollution were sufficiently low to give additional support to conclusions of pollution.

The ratios of odd *n*-alkanes to even *n*-alkanes reported in Table 6 were measured for both low and high molecular weight ranges. In an examination of these ratios, a search is made for reflections of the low molecular weight *n*-alkanes in petroleum that have no preference for odd or even carbon chains or natural terrestrial hydrocarbons which typically are of higher carbon number and have a pronouncement of odd numbered homologues. There are a great number of samples with low molecular weight *n*-alkanes having odd/even ratios approaching unity including those presumed to be oil polluted but also including those with little other evidence of such pollution. Again, this ratio is a necessary but insufficient indication of oil pollution. The odd/even ratios in the high molecular weight range are quite high at most stations reflecting the large quantities of terrestrial organic material introduced to the Mississippi Sound. Low values of this variable are difficult to interpret because both polluted and nonpolluted samples produced these values.

It cannot be overemphasized that the oil-indicating variables are limited in their ability to identify pollutant sources. All of the variables must be used in conjunction to arrive at relatively clear assignments of pollutant source. It must be added that, in the case of Mississippi Sound sediments, the hydrocarbon sources are so many and so diverse that a simplistic approach with mathematical variables serves only to reinforce the need for diligent and thorough examinations of the actual gas chromatograms. Only by such examinations can the researcher pinpoint those subtle features that escape notice in mathematical formulations but are crucial to understanding the composition of the hydrocarbon fractions and to unraveling the myriad sources of these hydrocarbons. Even careful examination of gas chromatograms cannot, in every case, give clear-cut identification of all suspect compounds or elicit explanations of the source of these compounds. Aromatic hydrocarbons pose especially difficult identification problems.

Fluorescence and Gas Chromatography/Mass Spectrometry (GC/MS)

Most identification problems of PNAs can be resolved by using fluorescence spectrophotometry and combined GC/MS. Excitation, emission, and synchronous-emission fluorescence spectra have been recorded and are on file in analog and digital formats for each sediment core section and all surface grab samples. These spectra are especially useful in verifying the authenticity of aromaticity of the so-called aromatic fraction. Because polyolefinic material is chromatographically similar to aromatic hydrocarbons, a considerable quantity of an

aromatic fraction may be composed of non-aromatic constituents. Fortunately most of these olefinics do not fluoresce, therefore, fluorescence techniques are another avenue to the characterization of the hydrocarbons. The most explicit fluorescence spectra were the synchronous scans which Wakeham[71] describes as yielding definite information about ring size of the polynuclear aromatics. The information gathered from fluorescence spectra was the basis of several conclusive remarks made on hydrocarbon compositions that contradict those which would have been reached by gas chromatographic data alone, and has documented the need for fluorescence spectra in hydrocarbon analyses.

A wealth of information can be gathered from GC/MS data. Depending on the unique fragmentation patterns of all organic compounds, the technique can quite clearly discern most of the PNAs in the presence of non-aromatic hydrocarbon materials. Furthermore, because GC/MS can give total information on discrete areas of a gas chromatogram not just those compounds that emerge as distinct peaks, data become available on compounds that either co-elute with other substances identified by gas chromatographic retention times or are camouflaged in the UCM. In all samples where either extraordinary quantities of aromatics were found or unusual distributions or preponderance of those PNAs with known carcinogenic properties occurred, GC/MS analyses were performed. These data have been archived in both graphical and tabular formats. With few exceptions, these GC/MS data have greatly added to the identification credibility provided by other techniques.

One startling example where both fluorescence spectra and GC/MS data served to refute conclusions based upon gas chromatographic data is shown in Figure 12. All the peaks labeled POI (polyolefinic isoprenoid) in the aromatic chromatogram of this sample from Bayou Casotte initially were identified as PNAs since retention times matched those of authentic PNAs. However, analysis of the Bayou Casotte core (No. 15), located very near but collected three years earlier, proved these tentative identifications to be wrong. Gravimetric and gas chromatographic data indicated abundant aromatic hydrocarbons in the surface segment of this core; fluorescence spectra indicated neither this abundance nor the ring-size distribution suggested by the chromatograms. Mass spectra proved that, indeed, most of what appeared to be the aromatic fraction from this sample were not aromatic at all but consisted of material producing a spectrum with a prominent peak of 69 m/e ratio, suggestive of isoprenoid-type hydrocarbons, not fused-ring aromatic structures. Parent peaks, i.e., peaks corresponding to the full molecular weight of subject compounds, suggested polyunsaturated compounds. Therefore, these compounds, which should be geochemically unstable, were called POIs. Because of their instability, samples collected in this vicinity in 1982 showed fewer of these POI structures as seen in Figure 9 and 12, but these compounds would have entirely escaped notice without the use of both fluorescence spectra and GC/MS data.[59] Thus, to provide the proper level of accuracy to the interpretation of hydrocarbons in sediment samples from Mississippi Sound, all pertinent analytical procedures must be used, and researchers must be thoroughly trained in the interpretation of the various results.

QUANTITATIVE POLLUTANT ASSESSMENT

Analysis of surface sediments from Mississippi Sound has provided a two-dimensional picture of pollution; one defines the relative significance of various classes of pollutant compounds, and the other labels regions of the Sound where pollution levels reflect careless waste-disposal practices. However, a three-dimensional scan of pollutants including vertical profiles in the sediment column is required before two very pressing questions may be adequately answered. If asked, "Is there a way to accurately assess the total magnitude of the pollution problem?" or "How does pollution in any one area affect adjacent areas and the whole Sound?", an examination of the geochemical data obtained on the sediment cores provides information with which to address these questions. All chemical and geological data accumulated for each core have been converted to a form for computer-bank storage and retrieval, but the very volume of data is quite awkward to present in tabular form. Therefore, a graphic format has been devised to depict all of the more salient geological and chemical features of the sediment strata at each of the 43 core sites. The overriding criterion for the graphical technique was to summarize in as dramatic but effective a manner as possible those data considered to be most useful to groups or individuals who could profit from knowledge of these data. A number of potential user groups were identified in the design phase for this data format, but the group whose needs seemed to be most substantial was the U.S. Army Corps of Engineers (COE). Therefore, a certain amount of bias was built into the format for the anticipated needs of the COE.

At present, the COE is responsible for dredging 290 million cubic yards of sediment each year[72] with one half of all maintenance dredging being done in the Gulf of Mexico.[50] Under certain circumstances, the COE's permitting process requires sediment cores to be collected, homogenized, and analyzed for heavy metals, "oil and grease" (a catch-all phrase for extractable organic matter), and other pollutant materials. Although this technique recognizes the fallacy of using surface samples to estimate subsurface pollutant levels, the requirement for homogenization obliterates much of the most interesting and useful information to be gathered from core sediment analysis. Dredging operations predicated upon an "averaged" sediment analysis tend to diminish or ignore altogether the significance of variations with depth of chemical and geological constituents of the sediment column and the historical and anthropogenic implications of these variations. As mentioned before, analysis of discrete strata within the sediment column sets boundaries on the vertical extent of pollution and establishes pollution levels accurately as a function of depth, two factors of high utility to the COE but ones not available through homogenized core analysis.

The graphical profiles for 43 sediment cores collected in Mississippi Sound are contained in Appendix I. The information displayed represents a considerable condensation of the data, particularly for hydrocarbons and to a lesser extent for the geology. Fully comprehensive hydrocarbon analysis on sediment core segments allows much more in-depth interpretation than for phenols, TOC or TKN values. The comments on the right margins of these profiles summarize some interpretive ideas not implicit in the concentration levels but important in understanding the source, history and nature of the pollutant hydrocarbons found in the various sediment strata. Strong emphasis is given to the granulometric (fraction grain size) data for each core because there is normally a strong affinity of hydrocarbons and other organics for the fine-grained materials (silt and clay) in the sediments.[22,29-41] Conformity to this association can be gathered by observing similarities in the contours of silt-clay percentages with the organic constituents. Substantial deviation from similar profiles is a strong indication of anthropogenic input. Foraminiferal data were used to establish the boundaries between sediments of the two geological units, those of Pleistocene and the Recent (Holocene). This constitutes another data base on file for future reference.

Visual examinations and observations by Dr. Ervin Otvos of the Gulf Coast Research Laboratory, Ocean Springs, MS, have been

recorded both in log books and on videotape as a document of the geological history of each region of the Sound. At least one particular application of the core data would require use of these supplemental geological records. Because the physiographic structure of sediments can change rather abruptly over relatively small geographical distances, it would be desirable to be able to extrapolate the data collected from a single core to much of the surrounding territory without additional core collection and analyses. This would be especially desirable where dredging or other disruptive activities would cover extensive tracts of river or bay bottoms. Even though the various geological strata would vary in their exact vertical positions and thickness values, in the sediment columns near the drill sites, the geological sequences would be virtually identical. The various geological units may be identified by cursory examination of other cores collected from adjacent sites and by comparison with the geological features of the appropriate core that has been examined in detail. By assigning pollutant-concentration levels to each geological unit in each core and to the same units in cores from adjacent areas, other profiles could be constructed. These additional profiles would give a sufficiently detailed description of the area to make possible a truly creditable impact study of dredging.

Core Stratigraphy

The 43 profiles shown in Appendix I present a very diverse array of sediment types and pollutant distributions with depth. However, after careful scrutiny there appears to be basically six types of profiles that describe the various sediment stratigraphies of the Sound, examples of which will be discussed in detail with references to possible user applications.

Uniform sediment and organic content. At Mouth W. Pascagoula River, Davis Bayou, South Deer Island, Bellefontaine Point, Cat Island Channel, Ship Island Pass, and Edgewater locations (Figures I-4, I-14, I-17, I-34, I-35, I-40, and I-41), there is little variation in the sediment and chemical components, with depth or age of deposit. Organic content has fairly low values and, with the possible exception of the top 20 to 40 cm of the sediment column, is not of sufficient concentration to be alarming. Disruption of sediments during dredging and similar operations in these sites would not merit any particular attention because of low-pollutant concentrations and uniformity of composition at all stratigraphic levels.

Great variations in sedimentary and chemical composition. Another group of profiles also includes low concentrations of anthropogenic waste materials but displays extraordinary variations in the organic and geologic components with depth. Examples of this type profile can be found at E. Pascagoula I-10, Dead River, Escatawpa River Control, Mouth Wolf River, D'Iberville, Horn Island, Petit Bois Island, and West Ship Island locations (Figures I-6, I-7, I-9, I-29, I-30, I-31, I-37, and I-42). In every case, the concentration curve of total organic matter almost perfectly coincides with the clay concentration curve. Correlation of the organic matter with the silt content is not evident in these profiles. This is strong evidence for the association of organic matter with the finest (clay) grain size fraction. Such pronounced variations with depth substantiate that different sedimentary processes have occurred over the course of Holocene deposition in these areas. When samples from different core depths are homogenized and analyzed as done in some pollutant-assessment programs, depending on what depths these subsamples have been taken, the analysis data obtained from various sets of subsamples would produce sets of radically different geochemical composition. Only a very crude estimate of sediment composition could be gathered by this sampling and analysis technique.

Pleistocene sediment units in cores. Another group of core sites contains sediment strata in which the size-fraction concentration values (e.g., clay content) do not coincide with the concentration of organic matter. Examples of stations with this behavior are: Point aux Chenes, Mouth E. Pascagoula River, Bayou Casotte, Big Lake, Mouth Jourdan River, Mouth Wolf River, East Mississippi Sound, and Bayou La Batre (Figures I-3, I-12, I-13, I-22, I-28, I-29, I-36, and I-39). All of these samples come from Pleistocene sediments that underlie the Holocene deposits and predate them by at least 80 thousand years.[73] The depositional

environment of the uppermost Pleistocene deposits was fluvial (depositions in river channels and flood plains). The Pleistocene part of the drillhole profiles must be treated separately. Although the Pleistocene deposits tend to be rich in clay compared to the overlying Holocene deposits, organic constituents in them are less evident. Due to degradation processes they have dwindled in the intervening period. The correlation of organic content with clay content is maintained in each division. Again, depending on the depth of penetration of test cores, a homogenized sample could give a distorted record of the original sediment composition and deposition environments. The surface samples would tell amost nothing of the underlying sediments.

High pollution level in surface sediments. At several locations throughout the Sound, the most outstanding feature of the sediment column is high hydrocarbon pollution in the surficial deposits. Mixing with underlying sediments was inhibited. The best examples are found at Mary Walker Bayou, Popps Ferry, Deer Island, Goat Island, Bernard Bayou, St. Louis Bay Bridges, and Heron Bay locations (Figures I-8, I-18, I-19, I-21, I-24, I-26, and I-27). At each of these sites the level of hydrocarbons in the surface sediments vastly exceeds hydrocarbon levels in strata below the surface that have similar percentages of clay and TOC, thereby suggesting an anthropogenic source of surface hydrocarbons. Analyses further document the actual source of these hydrocarbons as coming from sewage, refinery products, combusted fuel oil, or crude oil spills. Surface samples would have led to an estimate of overall sediment pollution levels far greater than actually exists. These profiles might even suggest the feasibility of using a very cautious dredging and disposal technique for surface deposits followed by a less cautious methodology for deeper deposits if dredging were considered in these areas.

Pollutants vertically diffused. At some regions of the Sound, mechanisms are in operation that tend to cause vertical migration of pollutants downward in the sediments at least 100 to 150 cm below the surface. Whether by diffusion or bioturbation, the net result is the occurrence of pollutant hydrocarbons and other pollutants in strata that were most likely deposited well before the pollutants were introduced. Cores from locations at Escatawpa River Control, Bayou Casotte, Davis Bayou, South Deer Island, Goat Island, Bellefontaine Point, and Bayou La Batre (Figures I-9, I-13, I-14, I-17, I-21, I-34, and I-39) are good examples of this type of pollutant behavior. Because of the downward percolation of pollutants in these sediments, care must be exercised in the handling of dredge materials taken from all sedimentary levels. This is especially true at Bayou Casotte (Figure I-13) where massive quantities of pollutant hydrocarbons are present in all of the Holocene deposits.

Buried units with high pollutant levels. Probably the most interesting sediment profiles were obtained from cores at stations where highly polluted sediment units are buried beneath more recent sediments that are not polluted. Examples of this sequence are found at Griffin Point, Escatawpa River Control, Deer Island, Big Lake, and Dauphin Island (Figures I-5, I-9, I-19, I-22, and I-43). The last two locations amply demonstrate the folly of using surface samples to establish sediment quality. A serious underestimation of pollutant hydrocarbon content at a given location would be gathered from surface samples. At Big Lake a rapid decline with depth in pollutant levels in the top 20 cm masks a large quantity of pollutant material between 40 and 80 cm in the sediment column. Profiles of cores from Deer Island and Escatawpa River Control reveal interesting features that surface samples or short cores with or without subsequent preanalysis homogenization would never suggest: extremely organic-rich sediments buried below the 200 cm depth at both locations.

Transport of Pollutants

Because sediment profiles describe the pollution status of each region of the Sound in such detail, a great deal more assurance may be gathered in examining transport processes using the depth profiles rather than with surface samples. The three major segments or compartments into which the Sound may be divided for a discussion of transport are the western (Pearl River and St. Louis Bay), central (Biloxi Bay), and eastern (Pascagoula River).

Western Mississippi Sound. The vicinity of the western Sound has only minimal industrial development that could lead to a serious enrichment of organic contaminants in the sediments. For this reason Lake Borgne, the Mississippi River and the Pearl River may be the sources of sediment pollutants. Pollutant input into the westernmost Sound areas has suggested the question, "Can pollutant migration into the Sound from Louisiana waters be detected?" The geochemical data profiles from sediment cores in the western Sound are displayed in Figures I-26 to I-29 and in Figures I-33 and I-35. These profiles accurately record the migration paths and extent of pollution in the western Sound. The core profiles from the western edge of the Sound at Heron Bay, Pass Marianne and Cat Island Channel (Figures I-27, I-33, and I-35) do not indicate a tremendous enrichment in the organic sediment constituents. Although the possibility of pollutant transport from Lake Borgne certainly is not excluded, it does not seem to have a profound effect on the pollutant levels on the western Sound. The region that would have experienced the greatest input from Lake Borgne would be near Pass Marianne (Figure I-33). The geochemical profile at this site shows many similarities with other sites in the western Sound. The total hydrocarbon concentration shows an approximately two-fold increase in the surface segments of the core compared with deeper segments. Beneath the recent deposit, the hydrocarbon concentration curve parallels the clay concentration curve. This is apparent in the Pass Marianne core where a large increase in clay contribution at the 200-cm depth is accompanied by a dramatic enrichment in total hydrocarbons. At similar depths, the same phenomenon is noted in all other western Sound cores except the location, Mouth Wolf River (Figure I-29).

Hydrocarbon levels in surface sediments at all western Sound sites exceed values that would be expected from the clay concentration data. Gas chromatography and GC/MS have indicated that the natural hydrocarbons are supplemented in surface sediments by hydrocarbons of petroleum origin accounting for the surface enrichment. However, this enrichment only brings the hydrocarbon levels to 20 to 60 ppm in surface sediments of the western Sound.

As noted by the remarkable similarity of core profiles from the western Sound, the uniformity of pollutant distribution at all sites in the western Sound indicates that there are no really significant point sources in the immediate vicinity of the Sound. This distribution pattern suggests remote pollutant sources that produce pollutant-laden sediments which are well mixed by the time they arrive at deposit sites throughout the western Sound. The more significant pollutant sources are probably Lake Borgne, the Mississippi River, and Biloxi Bay. Contributions from the Pearl River certainly do not significantly influence the pollutant content of Heron Bay, a probable site for Pearl River sediment deposition. The similarities between sediments at Heron Bay (Figure I-27) and other western Sound sites, far removed from the Pearl River, indicate a relatively small role for the Pearl River in adding pollutants to the Sound.

Profiles of cores from the two rivers that discharge into St. Louis Bay, the Wolf (Figure I-29) and Jourdan (Figure I-28), display organic component curves that very closely parallel the clay concentration curves. Evidence of slight oil pollution from residential and boating activities exists in surface sediments at both sites, but overall levels are low compared with those found at the mouth of the bay at the St. Louis Bay Bridges site (Figure I-26). The similarity of the profile at this site to other western Sound sites suggests tidal transport of pollutants from the Sound as the predominant pollutant source for St. Louis Bay.

The outstanding characteristic of organic composition of the western Sound sediments lies not in differences of concentrations, types or sources of pollutant hydrocarbons which are of insufficient magnitude to be distinctive, but in the distribution of the natural hydrocarbon component of the sediments. Sediments from Pass Marianne (Figure I-33) and those sites closer to shore indicate both terrestrial and marine hydrocarbons as the natural hydrocarbon source with a dominance of the former. However, Cat Island Channel sediments (Figure I-35) contain hydrocarbons derived from marine sources. This signature of terrestrial hydrocarbons within the Sound indicates that the primary area influenced by land-derived pollutants, which would behave as

the terrestrial hydrocarbons, does not extend beyond the offshore islands. Consequently, it may be presumed that organic pollutants found in sediments outside the islands of the western Sound can most likely be traced to an origin other than the origin of pollutants found along the Mississippi coast.

Central Mississippi Sound. Continuing further east, one encounters a group of three core sites: D'Iberville, Gulfport Channel, and Edgewater (Figures I-30, I-32, and I-41) that yield cores very similar in sediment composition. Very little TOC variation with depth is noted in these three cores indicating a fairly constant depositional record. The three cores are very distinct due to the presence of fresh, relatively undegraded fuel oil in the top segments of the cores. The decline in hydrocarbon concentration in a westerly direction and the low degree of geological degradation that have taken place in these hydrocarbons suggest a nearby source to the east, perhaps material transported from Biloxi Bay. A slight decrease in TKN (total Kjeldahl nitrogen) values westward between these sites also points to Biloxi Bay as the predominant source of sediment pollutants in the west-central Sound.

An even more convincing indication of pollutant transport westward from Biloxi Bay is found in the Deer Island core (Figure I-19) which is located closer to the mouth of the Bay than the aforementioned three cores. As expected a pronounced increase in pollutant hydrocarbons is noted in the surface sediment region of the core collected here compared to the three core sites further west. This region between Deer Island and the mainland is directly in the path of commercial and recreational boat traffic and could receive contaminants resulting from heavy boating traffic at the mouth of Biloxi Bay. It is suggested that the pollutants from Biloxi Bay move predominantly westward between the shore and Deer Island. Subsequently, they become diffused over a wide zone in the Sound, south of Gulfport-Biloxi. An examination of the pollutant profile at South Deer Island (Figure I-17) reveals considerably lower levels but similar types of pollutants as the Deer Island site does. This further suggests that the majority of pollutants that enter the Sound from Biloxi Bay are funneled north, rather than south, of Deer Island.

Traces of petroleum hydrocarbons in the surface veneer of sediments at Ship Island Pass and West Ship Island (Figures I-40 and I-42), are presumably the result of residual Biloxi Bay pollutants swept southward from the Sound into the Gulf of Mexico. As at Cat Island Channel the sediments near these island passes show an infusion of marine as well as terrestrial hydrocarbons suggesting an alternate source of petroleum hydrocarbons from the Gulf side of the islands.

The presence of only moderate quantities of pollutants throughout the core profile at Gulfport Lake (Figure I-20) is somewhat surprising considering the concentration of chemical industries east and west of this site and the abundance of pollutants in sediments near these facilities (see Reichhold Industrial Canal, Hewchem Industrial Canal, Turkey Creek, and Industrial Seaway in Table 4). However, the deposits at Gulfport Lake are composed mostly of sand and silt. These fractions do not have the capacity as clays do for binding organic pollutants. Big Lake (Figure I-22) is at the eastern end of the Industrial Seaway and also at the confluence of the Biloxi River. Bernard Bayou and the discharge canal from the Power Plant both empty into Big Lake where clay-rich deposits have accumulated much higher quantities of organic pollutants than Gulfport Lake. Considerably lower pollutant levels were found along Bernard Bayou (Figure I-24), another outlet of the Gulfport Lake industrial complex, indicating restricted movement of pollutants down this artery. Little historical evidence of pollution exists in the sediments of Biloxi River at the Power Plant and Cedar Lake sites (Figures I-16 and I-23). However, surface sample data from the power plant discharge canal (see Power Plant Canal and Coley Island in Table 4) and other sites along the Industrial Seaway do suggest these as likely sources of the material deposited at Big Lake. Another peak in pollutant-rich deposits occurs in the middle of Biloxi Bay in the Goat Island and Keesler Air Force Base region (Figures I-21 and I-25) probably because of ship traffic in the mid-bay area. The top 40 to 50 cm of sediments at these sites show strong evidence of organic contaminants with little indication of diffusion or intrusion of these pollutants deeper into the

sedimentary column. Lesser loads of pollutants have been transported further west of these sites at Popps Ferry (Figure I-18). Organic content contours that mirror clay content at Old Fort Bayou (Figure I-15) indicate that the majority of deposits at this eastern extremity of Biloxi Bay have occurred with little introduction of anthropogenic wastes to the sediments and additionally give further proof that most pollutants originating in Biloxi Bay are retained in sediments near the source. The core samples at Davis Bayou (Figure I-14) just east of the mouth of Biloxi Bay are somewhat problematic. Enrichment in pollutant hydrocarbons may have resulted from the recreational and fishing boat activities in the area, but the percolation of pollutants down through the entire 300-cm sediment sequence at this site is not easily explained. It appears that a large quantity of contaminated material has been dumped in this vicinity over a long period of time, possibly due to maintenance dredging in Biloxi Bay. The same explanation can be offered for the presence of pollutants at great depths near South Deer Island (Figure I-17), another known dumping site for dredge material.

Eastern Mississippi Sound. The greatest fluvial input to the Mississippi Sound occurs from the East and West Pascagoula rivers. Salinity gradient studies by C. K. Eleuterius[74] indicate that the river discharge after entering the Sound can be traced initially in a westerly direction near Bellefontaine Point with a subsequent southerly turn into the Gulf of Mexico, west of Horn Island. With this charted path of transport in mind, cores were chosen at strategic locations and examined for residues of the numerous pollutant sources in the Pascagoula and Escatawpa rivers. The sediment analysis at West Horn Island (Figure I-38) indicates exclusively terrestrial deposits as opposed to the terrestrial-marine or exclusively marine deposits found at other island sites. With the exception of a slight fingerprint of pollutant hydrocarbons in the surficial sediments, there is no real evidence of large-scale transport of pollutant-laden particulates across the Sound. Therefore, the terrestrial hydrocarbons must come primarily from plants growing in Horn Island marshes near this site. A case can be made, however, for pollutant transport at least to Bellefontaine Point as evidenced by pronounced levels of petroleum hydrocarbons in the top 50 cm of sediment deposits found there (Figure I-34). Virtually no influence of the Pascagoula River is observed in the sediment profile at Horn Island (Figure I-31) and no indication of riverine deposits seen in the analytical processing of these sediments. The very slight oil residue at the surface is probably attributable to pollutants originating in the Gulf, i.e., boat traffic.

Two sites in the East and West Pascagoula rivers were selected as control sites because they were upstream of most industrial development. The core profile for Dead River in the West River is shown in Figure I-7 and displays the very diverse history of geological deposits expected of an oxbow lake. The variations in TOC, TKN and hydrocarbons, though substantial, primarily duplicate variations in the clay content of the sediments and are responsive to geologic not anthropogenic influences. A major divergence from this tenet is seen in an examination of hydrocarbons at the top of the core. What seems to be a pollutant source appeared to be at odds with the location of this station so remote from known sources. However, it was discovered that a small boat marina along a secluded bayou in the West Pascagoula River had been connected by a narrow channel across Dead River some years ago. This accounts most probably for the polluted sediments occurring at this control station. The control station on the East Pascagoula River at E. Pascagoula I-10 was also located in an oxbow bend to assure sample collection of fine-grained materials in a low-energy, protected area of the river. The core profile here (Figure I-6), like that at Dead River, reflects mostly a complex geological record with TOC and TKN contours almost exactly replicating that of clay content. Dredging activities during highway construction of the I-10 interstate just up-river of this site has apparently added the surface hydrocarbon content. Below this, at 10 to 50 cm depth in the core, a higher concentration of contaminant material was probably introduced by tidal flushing from the lower East Pascagoula and Escatawpa rivers. Further downstream, off the West Pascagoula River (Figure I-8), the effect of boat traffic from the large marinas in Mary Walker Bayou on this bayou

can readily be seen in a surface veneer of sediments having high concentrations of degraded fuel oil with little evidence of any other large-scale pollution. The impedance to transport of pollutants down these rivers is documented in the core profile of a site at Mouth W. Pascagoula River shown in Figure I-4. Only small variations in geochemical composition are noted in the 250-cm sequence with little perceptible influence from pollutant sources upstream.

Most pollutants entering the eastern Sound are derived from sources in the East Pascagoula River and Bayou Casotte. Examination of core profiles from two sites, Paper Mill and McInnis Lake, in the Escatawpa River (Figures I-1 and I-2) reveals the gross quantities of pollutants discharged into the Escatawpa River, a tributary of the Pascagoula River. Stratigraphic profiles of TOC are almost an order of magnitude higher than would be expected with only natural organic material deposition. Phenol levels are imposing at the Paper Mill site, but hydrocarbon levels are the most disturbing. The high hydrocarbon levels at Paper Mill appear to be due to a combination of industrial sources whereas McInnis Lake and, to a lesser extent, Griffin Point (Figure I-5), further downstream on the Escatawpa River, show the clear imprint of sewage hydrocarbons[18,19,22,75-77], a reflection of sewage outfalls in both areas. A substantial reduction in pollution has taken place in the past 10 years as noted by the decline in hydrocarbon levels in the uppermost sediments of all three areas. Although this is an indication of improvement in attitudes of those responsible for pollution control in this area, nevertheless, the record of large-scale pollution remains inscribed in the sediment column and will be retained, effectively creating long-range environmental risks.

The Escatawpa River Control core profile shown in Figure I-9 indicates that the site was not removed from pollution sources as denoted by the very high levels of TOC and petroleum hydrocarbons at the surface. Upstream transport by tidal activity could not account for this enrichment. Boating around fishing camps in the area and possible illegal dumping practices in this upstream area must be involved. The peculiar nature of this core is not restricted to the surface because large quantities of hydrocarbons and TOC appear at the 300-cm depth where the sediment is almost entirely sand. Natural oil seeps might be suspected, but the distributions are unlike petroleum products. This portion of the Escatawpa River merits further geochemical study.

Below the confluence of the Escatawpa and East Pascagoula rivers, the site at Bayou Chemise connecting the East and West Pascagoula rivers was selected to monitor transport down both rivers and exchange through connecting bayous and channels. There is little evidence of massive transport between rivers to this site with very low hydrocarbon levels throughout the core sequence depicted in Figure I-10. There is some evidence of dredge material covering "natural" deposits at the surface of the core. Little impact is seen even from the nearest known source, Mary Walker Bayou, considering the difference in hydrocarbon distributions between the two sites. An indication of the inefficiency of pollutant transport downstream can be seen in the core profile (Figure I-11) from Round Island in the mixing zone of the East Pascagoula River and the Sound. All organic contents tend basically to follow the sediment composition trends with only traces of pollutant hydrocarbons at this site. A dichotomy exists in trying to explain higher values of hydrocarbons in sandy sediments at Bellefontaine Point than clay-rich sediments at Round Island if both are the result of transport from the East Pascagoula River because Bellefontaine Point is further removed from the mouth of the river. One plausible explanation is that the contaminant-laden particles derived from this river remain in suspension resulting in longer range transport and remote deposition of these particles. This, together with other possible pollutant sources near Bellefontaine Point, may account for this phenomenon.

Input of hydrocarbons from three core sites were selected to examine transport out of Bayou Casotte and the Chevron USA refinery discharge canal into Mississippi Sound. The core drilled in Bayou Casotte was taken north of the area subjected to maintenance dredging and accounts for an undisturbed record of pollutant deposition. The Point aux Chenes core was examined for evidence of pollutant migration from the discharge canal of the oil

refinery. Its location just west of this canal places it in the path of westward-directed currents that prevail throughout Mississippi Sound. In the path of transport west from Bayou Casotte into the Sound is the site of the Mouth E. Pascagoula River core.

At Point aux Chenes (Figure I-3), hydrocarbons are of very low concentrations (< 1 ppm at the surface and at most depths). Foraminiferal records give evidence of a brackish environment throughout the Holocene period. Aliphatic hydrocarbons from every segment in the Holocene section of the core represent a mixture of hydrocarbons from both terrestrial plants and marine organisms. Below the Holocene/Pleistocene boundary, hydrocarbons reflect only properties of terrestrial plants. Aromatic hydrocarbons occur only in ultra-trace amounts throughout this sedimentary sequence. No evidence is found for any petroleum pollution at this site. Even though this core site is in an area that could receive input from the refinery discharge canal, the water depth is less than three feet which prevents boat traffic, thereby reducing transport of polluted sediments westward from the discharge canal. Absence of pollution here indicates that most of the petroleum residues discharged with refinery waste-process water are trapped within the sediments of the discharge canal.

The core at the Mouth E. Pascagoula River (Figure I-12) contains a sediment assemblage with a different suite of hydrocarbons than those found at Point aux Chenes. With the exception of the top 50 cm, only residues of terrestrial plants are observed in these sediments. Hydrocarbons in the top segments of the core resemble petroleum and successfully mask terrestrial hydrocarbon characteristics. The aliphatic hydrocarbon distributions are very similar to those found at surface sample sites in Bayou Casotte. Boat traaffic and freshwater drainage substantially increase the turbulence and transport of waters issuing from Bayou Casotte and give rise to the deposition of polluted sediments 7,500 feet west of the mouth of the bayou.

The single most striking feature of the Bayou Casotte core profile (Figure I-13) is the abundance of hydrocarbons in all strata of Holocene deposits. Although behavior of other organic variables (TOC, TKN and total phenols) results in depth versus concentration patterns similar to that of percent clay, there is no apparent correlation of hydrocarbon concentrations with percent clay versus depth.

Below the Holocene/Pleistocene boundary in the Bayou Casotte core, a dramatically different sequence of sedimentary hydrocarbons exists, one that is quite similar to those analyzed in Pleistocene deposits at both the Point aux Chenes and Mouth E. Pascagoula River cores. Hydrocarbon concentration in surface sediments is at the 4,500 ppm level. The concentration drops very sharply below the 20-cm depth. It appears that industrial pollution began sometime during the deposition corresponding to the top 20 cm. Even below the 20-cm level, total hydrocarbons still exceed 1,000 ppm. In studies of simulated oil spills in diked ponds conducted at the Gulf Coast Research Laboratory, Ocean Springs, MS, it was similarly observed that downward vertical migration of oil did occur in the sediment column. It must be assumed that diffusion and efficient reworking mechanisms have been in operation at Bayou Casotte to account for pollutant hydrocarbons occurring at such concentrations in geologically "old" sediments.

Because of the considerable differences seen in the core profiles at sites in and around Bayou Casotte, decisions concerning dredging there require careful study. No particular alarm is warranted for dredging just east of Bayou Casotte. West of the bayou, discretion is required in handling the top 25 cm of the sediments. In the upper reaches of the bayou, extreme caution is required in dredging and spoil disposal of the entire 120 cm or more of Holocene deposits. There is an abundance of petroleum hydrocarbons in upper Bayou Casotte sediments compared with the lower bayou regions (see results in Table 4) near the oil refinery source. Extensive maintenance dredging occurs near the refinery which suggests dredging operations as the most plausible explanation for the difference in hydrocarbon levels between the two sites. Therefore, removal of surface contaminated sediment could actually be regarded as an improvement in the lower bayou region.

At other regions on the periphery of the eastern Sound, core profiles are not as alarming as those found in the Escatawpa River or

Bayou Casotte. At East Mississippi Sound (Figure I-36), a core chosen to monitor input from Mobile Bay, surficial sediments do show the presence of pollutant hydrocarbons but only at insignificant levels. Most organic matter versus depth variations are simply attributable to differences in lithologic makeup of sediments, not to pollution from the east. It might appear that more pollutant hydrocarbons from Mobile Bay are carried outward and deposited on the northern side of Dauphin Island than at the East Mississippi Sound site. The profile for the core secured at Dauphin Island (Figure I-43) shows a preponderance of pollutant hydrocarbons in the top 50 cm. Dredge spoil disposal around this island would explain erratic decreases and increases in pollutant levels in the surficial sediments of a site this far removed from suspected sources. Substantial pollutant introduction from the Gulf of Mexico may be discounted by comparing the core profile from Dauphin Island to that of the next adjacent island, Petit Bois Island (Figure I-37), where no traces of any pollutant hydrocarbons could be detected in the core sediment sequence.

Bayou La Batre, the profile of which is shown in Figure I-39, was selected to indicate the movement of pollutants from another Alabama industrial complex to Mississippi Sound waters. It is interesting to note that only hydrocarbons (not TOC, TKN or phenols) occur at levels that can be recognized as having an anthropogenic source throughout the Holocene deposition. As suggested for sediments deposited near Bayou Casotte, dredging in this area should be done cautiously, and this caution must increase at sites closer to the pollutant sources in Bayou La Batre.

Tracer Studies

In the first stages of this research both fatty acids and hydrocarbons were examined as possible tracer compounds to follow the movement of pollutants from river sources, primarily the Pascagoula-Escatawpa, across the Sound and into the Gulf of Mexico. Hydrocarbons, though useful in estimating net effect of pollutant movement within the Sound, were of limited use in tracing transport in the rivers. The most useful tracer compounds are released from a single source, and the complexity and diversity of hydrocarbon sources along the Pascagoula River violated this criterion for suitability. Investigators have looked at fatty acids as tracers of pulp mill wastes[78] in fluvial systems. The presence of a large pulp mill on the Escatawpa River in the midst of an industrial complex prompted attention to an examination of fatty acids as tracers of paper mill wastes downriver and by inference other organic pollutants as well. Surface samples were collected above and below the paper mill (location indicated on Figure 2) and analyzed for fatty acid content and distribution. The success of other investigators using these compounds as tracers was based upon subtle changes in sedimentary fatty acids with introduction of pulp mill fatty acids. These subtleties are obliterated in the Pascagoula-Escatawpa River by dramatic differences attributable to variation in the fatty acid composition of the plant and animal communities that act as the natural sources of fatty acids in this river. Because results using fatty acids are nebulous at best, neither techniques nor the results will be discussed further.

Lignin degradation products. The most successful use of chemical tracers relied upon a group of compounds that are compositional building blocks of lignin, a component of all terrestrial, vascular plants. Nonvascular plants including most marine plants contain no lignin, therefore, lignin residues have been explored as indicators of a terrestrial origin of organic matter in sedimentary deposits.[79-82] In examining various plant materials thought to be suitable candidates for sedimentary lignin precursor material, Hedges and Parker[79] made several interesting observations. After oxidative digestion the lignins from plants yield a series of phenolic aldehydes, ketones and acids that are shown diagrammatically in Figure 13. The three stylized gas chromatograms in this figure display the lignin degradation products produced in the three major classes of plants. The three carbonyl derivatives of *p*-hydroxybenzene:*p*-hydroxybenzaldehyde, *p*-hydroxyacetophenone, and *p*-hydroxybenzoic acid are prevalent in oxidative treatments of algae and other nonvascular plants but are lesser constituents of vascular plants. These *p*-hydroxy compounds, arising from a nonlignin source but similar to lignin structural

units, are thought to be artifacts of amino acid degradation in the laboratory digestion procedure.[79] Angiosperms, the flowering plants including all vascular marsh plants, on the other hand, produce authentic lignin degradation products that consist primarily of two structural classes: the three vanillyl carbonyl phenolics, vanillin, acetovanillone and vanillic acid, and the syringyl compounds, syringaldehyde, acetosyringone and syringic acid. Gymnosperms, the conifers including pines, contain lignins, however, that yield only the vanillyl compounds when oxidatively degraded. Estuarine sediments of the central Gulf of Mexico derive most of their organic matter from flowering marsh plants and, therefore, are expected to contain roughly equal amounts of vanillyl and syringyl lignin compounds as shown in the angiosperm chromatogram of Figure 13.

The paper mill on the Escatawpa River uses pine as its primary source of raw materials and releases lignin waste products characteristic of gymnosperms, i.e., only vanillyl compounds, into the river. The waste release site in an industrial complex suggested the use of the paper mill as a point source of vanillyl lignin tracers, with enhanced vanillyl compounds in the sediments indicative of transport of paper mill wastes and, by extrapolation, other organic wastes down river and across the Sound. The hypothesis, then, is that under natural conditions, estuarine sediments of the Pascagoula River System contain approximately equal contributions of vanillyl and syringyl lignins. A significant alteration in this characteristic at any site is due to introduction of paper mill wastes. Sites where the ratio of vanillyl/syringyl is decidedly skewed to favor vanillyl are assumed to have received significant input of organic wastes including paper mill wastes from the region of the paper mill. Surface sediments were examined at sites within the East Pascagoula and Escatawpa rivers up and down river of the Paper Mill and across the Sound in the assumed route of Pascagoula River outflow to test this hypothesis. For comparison sediment samples from the West Pascagoula River and Biloxi Bay were examined as well as a dominant marsh plant, *Juncus roemerianus*, presumed to be the source of much of the naturally occurring lignin residues in Sound sediments.

Digestion and extraction of samples. The procedure for lignin residue analysis generally followed that of Hedges and Parker[79] and is outlined in Figure 14. Sediment samples were first acidified to remove carbonates, then all samples were dried at 35°C and ground. Digestion was carried out in a 200-mℓ Parr Bomb, the head fitted with a pressure release valve. The reaction mixture consisted of 10.0 g sediment, 10.0 g CuO, 100.0 mg $Fe(NH_4)_2(SO_4)_2 \cdot 6H_2O$ as an oxygen scavenger and 150.0 mℓ freshly boiled and nitrogen-purged 10N NaOH. All reagents were extracted with CH_2Cl_2 prior to use. Special precaution was taken at each step to prevent oxygen intrusion. The bomb was fitted into a brass sleeve wrapped in heating tape and controlled to give a temperature of 340°F in 20 minutes and maintain that temperature at ± 6° for three hours under pressure. A teflon® stirring bar was enclosed in the bomb which was positioned on a magnetic stirrer to achieve sample agitation during the entire digestion procedure. At the end of three hours the bomb was quick-cooled in ice water and the pressure released. The reaction mixture was removed and filtered through glass fiber pads, then acidified to a pH of 1.0. The extraction procedure was carried out in a specially fabricated liquid-liquid extractor using ethyl ether as solvent. As in the digestion step, oxygen contamination was to be avoided so the ether had to be extracted repeatedly with saturated stannous chloride solutions to remove peroxides. The extraction time was 16 hours after which the aqueous and ether phases were separated and the aqueous fraction extracted further with CH_2Cl_2. The aqueous portion was discarded, the extract was added to the ether fraction and the volume reduced to near dryness on a rotary evaporator. The sample was then resuspended in 50/50 $MeOH/CH_2Cl_2$ to 10.0 mℓ total volume. Two-mℓ aliquots were removed and dried completely under a stream of N_2 in a 100-μℓ reaction vial. An internal standard of *n*-eicosane (*n*-C_{20} alkane) was added along with 50 μg of Regisil®, a silylating reagent from Regis Chemical Company. The reaction vial was flushed with N_2, capped, magnetically stirred and heated for five minutes. After cooling, an injection of 0.5 μℓ was made on a Perkin-Elmer (PE) 3920 gas

chromatograph with all glass split injector. The fused silica column was coated with DB-1 (a silicone) and was temperature programmed from 90°C to 250°C at 4°/minute. Identification and quantitation of phenolic compounds were effected by using similar injections of standards of *p*-hydroxy, vanillyl, and syringyl compounds along with the cinnamyl phenols, *p*-hydroxycinnamic acid and 4-hydroxy-3-methoxy-cinnamic acid, and also *m*-hydroxybenzoic acid and 3,5-dihydroxybenzoic acid.

Results of phenolic analysis. A gas chromatogram of a suite of lignin degradation products is shown in Figure 15. Bellefontaine Point, just west of the mouth of the Pascagoula River, contains sedimentary lignin fragments that are typical for north-central Gulf estuarine sediments. Note that the two families of vanillyl and syringyl compounds are in about equal abundance with the aldehyde form predominant in each group, along with lesser amounts of the *p*-hydroxy and the cinnamyl compounds. The relative amounts of the various vanillyl and syringyl compounds, used to indicate the presence of paper mill wastes, can be observed by examining the data assimilated into Table 7. Data in columns A and B document that vanillin exceeds syringaldehyde and the total vanillyl compounds exceed the syringyl compounds by a considerable amount in sediments found immediately above and below the paper mill in East Pascagoula River. This enrichment is apparently due to pulp wood wastes being transported to these sites. These results are in stark contrast to those found with the predominant marsh plant *Juncus roemerianus,* which tends to favor the syringyl lignin compounds. Results at Griffin Point were at first rather perplexing because the vanillyl compounds were at higher levels and total phenols were at higher concentrations here than at Pogey Plant and Halter Marine which are closer to the Paper Mill. On closer scrutiny it was noted that sediment samples at Griffin Point contained wood fragments, remnants of a former lumber yard in this area. This result only confirms the hypothesis that increased loads of pine wood products into the river will increase the abundance of vanillyl lignin compounds in the underlying sediments.

At Dead River, approximately the same distance upstream in the West Pascagoula River as Griffin Point is in the East Pascagoula River, one can see vanillyl/syringyl abundance ratios that favor neither group as expected at sites with no pulp mill influence. Moving from the Escatawpa River down into the East Pascagoula River, ratios of vanillyl/syringyl compounds are encountered that definitely do not give evidence of paper mill wastes implying input almost exclusively of marsh plant lignin residues. The results at Elevator Bayou compare very favorably to those at Bayou Pierre which was equidistant up the West Pascagoula River. In the path of the Pascagoula rivers as they cross the Sound, the sites at Round Island, Bellefontaine Point and the two Pascagoula Transect sites also suggest minimal transport of paper mill wastes across the Sound and resemble results from V.A. Hospital, a site very far removed from the influence of the paper or lumber mills. The Open Gulf site, showing no preference for vanillyl or syringyl compounds, suggests little measurable waste input from the Pascagoula River System.

These data indicate fairly conclusively that not only do paper mill wastes generated in the Escatawpa River have limited mobility but more importantly that most organic pollutants are transported only very short distances from their source into the Mississippi Sound. The majority of pollutants, furthermore, are retained in the river sediments in the immediate vicinity of the pollutant sources. This conclusion was reached notably from the lignin residue study but was supported by all the other pollutant analyses of this program. The most profound ramification of this conclusion is that the Mississippi Sound and other similar coastal estuaries contain pockets of pollutants near the source of pollution. While it is fortunate that the pollutants are not widely dispersed, it is alarming that these "pockets" harbor vastly higher residues of pollutants than most land-use planners had previously assumed. This phenomenon must be fully recognized and awareness incorporated into the philosophy of coastal zone industrialization in order to prepare and implement realistic impact statements and guidelines.

TABLE 7.

Lignin degradation products in Mississippi Sound sediments.[1]

Sample Location[2]	General Area[3]	v[4]/s	V[4]/S	V + S[4] dry weight	V + S + P[4] dry weight	V + S + P[4] organic carbon
Escatawpa River Control	E. Pascagoula River	1.51	1.21	> 0.675[5]	> 0.675[5]	0.0945
Pogey Plant	E. Pascagoula River	2.28	1.79	1.00	1.18	1.243
Halter Marine	E. Pascagoula River	2.35	2.06	5.28	6.57	1.01
Griffin Point	E. Pascagoula River	2.56	2.66	8.95	10.5	3.17
Elevator Bayou	E. Pascagoula River	0.926	1.14	12.7	14.6	3.79
Round Island	E. Pascagoula River	1.53	1.27	0.229	0.229[5]	0.126
Bellefontaine Point	E. Pascagoula River	1.29	1.28	1.08	1.31	2.49
Pascagoula Transect #2	Mississippi Sound	0.997	1.15	0.714	1.11	2.86
Pascagoula Transect #4	Mississippi Sound	1.07	1.18	0.739	0.739[5]	0.447
Open Gulf	Mississippi Sound	1.06	1.00	0.0691	0.214	0.196
Dead River	W. Pascagoula River	1.08	1.15	3.24	3.80	4.47
Bayou Pierre	W. Pascagoula River	1.06	1.41	6.42	6.99	1.76
V.A. Hospital	Biloxi Bay	1.24	1.33	1.41	1.41[5]	0.533
Juncus roemerianus	plant precursor	0.403	0.418	113	137	—

[1] Escatawpa River Control, Round Island and Bellefontaine Point were surface samples taken from cores. *Juncus roemerianus* is the dominant marsh grass of the Sound and was analyzed by the same technique as used on the sediments. Other samples were surface sediment grab samples.

[2] See Figure 2 and Tables 2 and 3 for site location descriptions.

[3] The East Pascagoula River samples are in geographical order from the most upstream point to the river mouth. The Pascagoula Transects are in the area of river movement into the Sound. Dead River and Bayou Pierre are located in the West Pascagoula River at relatively the same distance upstream as Griffin Point and Elevator Bayou are in the East River. V.A. Hospital and Open Gulf are from far removed and unrelated areas and serve as controls.

[4] v/s = vanillin/syringaldehyde

V/S = Σ vanillyl compounds/Σ syringyl compounds

V + S/dry weight = Σ vanillyl + syringyl compounds/dry weight sediment (mg/10 g)

V + S + P/dry weight = Σ vanillyl + syringyl + *p*-hydroxy compounds/dry weight sediment (mg/10 g)

V + S + P/organic carbon = Σ vanillyl + syringyl + *p*-hydroxy compounds/total organic carbon X 100%

[5] Due to insufficient gas chromatographic resolution of at least one phenolic compound, these amounts are only minimal estimates of listed variable.

ENVIRONMENTAL STRESS INDEX

Throughout this study the prevailing sentiment has been that a survey of pollutant levels in Mississippi Sound in itself is very limited in its overall usefulness. The presence of pollutants in the sediments of a particular region is sufficient reason for concern because it indicates lack of necessary control of pollutant discharge. However, there are factors besides concentration of pollutants that decide the possible effects of sediment pollutants. Answers to the questions, "What pollutants are there and in what quantities?" only underline that which naturally follows, "Of what real importance is sediment pollution?" The bioavailability of these pollutants, i.e., the amount of pollutants to which organisms may be actively exposed, is of more fundamental concern than is the more esoteric question of the total amounts of pollutant present in the environment. Knowledge of the bioavailability of toxic agents in sediments is still insufficient to fully address the issue of harm posed by polluted sediments. To define this problem required a multifaceted examination of polluted sediments and development of a mechanism whereby all pertinent scientific information could be interpreted and used by all interested agencies and individuals. The system devised to provide this information is called the Environmental Stress Index. The index includes a numerical rating of the most important factors contributing to the potential dangers associated with polluted sediments in Mississippi Sound.

Constructing an environmental index is not unique to this research. Anderson et al.[83] assigned a "toxicity index" as a means of ranking toxicity potential of oil or oil components. Their index is not intended to aid in predicting the harm associated with a particular environmental incident of pollutant exposure but to evaluate laboratory exposure experiments. Other investigators have touted the utility of such indexing systems[84] applied to actual environmental conditions.

There is some controversy over the potential harm of disturbing sediments though it seems clear that resuspending "clean" sediments is of little environmental consequence.[85] The COE[86] and Chen et al.[87] found little degradation in water quality as a result of resuspending sediments contaminated with organic pollutants; however, Shaw et al.[48] and Boehm and Quinn[49] did find release of organic pollutants from similar contaminated sediments. Because it is generally presumed that the greatest impact of polluted sediments exists during periods when these sediments are resuspended in the water column, the majority of experimental procedures were aimed at assessing damage that would occur after sediment disturbances. The experimental parameters examined in the execution of the Environmental Stress Index for Mississippi Sound are: (1) **sediment toxicity** (How harmful will the sediments be if they are resuspended and what kinds of organisms will be ultimately affected?); (2) **suspension stability** (How much of the sediment will be suspended after a disturbance and for how long?); (3) **disturbance probability** (Just how likely are disturbances to occur in this or any other area?); (4) **biota susceptability** (Because the community of animals in all regions of the Sound is so diverse, how would a pollution incident affect these various regions?); (5) **pollutant level** (What is the concentration of various pollutants in the sediments?); and (6) **sediment leachability** (What is the likelihood that pollutants would be released from sediments into the water column following a disturbance?).

Sediment Toxicity

Samples collected at surface sediment sites were subjected to toxicological bioassays designed to give some predictive measure of the biological impact of disturbing these sediments. The bioassay procedures used were those developed by a joint effort of the EPA and the COE to examine possible results following a pronounced sediment disturbance.[20,22,36] These tests were run in three phases. A filtered liquid phase was used to evaluate the impact of dissolved chemical constituents released from the sediment during a sediment disturbance. A particulate phase measured the impact due to both the presence of suspended particles and any toxic components desorbed from the particles. A solid phase evaluated the biological effect of the sediment that settles after a disturbance.

Test organisms were exposed to preparations made as follows: liquid phase, using a 0.45 μ filtrate from sediment mixed with site water (1:4, V/V); particulate phase, using unfiltered sediment-water mixture (1:4, V/V); and solid phase, using the sediment settling from the particulate phase preparation with a fresh portion of site water.

The first two phases were designed to test free-swimming organisms. Organisms chosen were mysid shrimp (*Mysidopsis almyra*) and sheepshead minnows (*Cyprinodon variegatus*). In the solid phase, bottom feeders, mysid shrimp, and an amphipod (*Gammarus mucronatus*) were tested. Mortalities were determined at 24-hour intervals for 96 hours in the liquid and particulate phases, and only at the end of 96 hours in the solid phase test. Filtered collection site water and seawater were used as control media against which to assess significance of mortality data.[33] In those cases where significant mortality resulted from exposure to site water versus seawater, additional testing was done. Diluted seawater was substituted for site water, so that mortalities due to the sediment could be viewed separately from those due to the site water.

Bioassay results. Results of all tests are shown in Table 8. Perhaps the most striking feature of this display is that only 12 of the sedimentary regions tested produced significant mortalities, with most of these sites being in the eastern Mississippi Sound region. Of those in the eastern region, two are particularly noteworthy, Pogey Plant and Lake Yazoo, both of which produced very high mortalities to mysid shrimp in all exposure tests even when the exposure medium was diluted. Furthermore, all organisms were killed in every test condition used to test sediment from Lake Yazoo. The occurrence of highly toxic materials at the Pogey Plant location in the Escatawpa River is not really surprising since this environment had been devastated by industrial discharge practices of the 1960's. Although there has been considerable improvement in the water quality since that time and some resurgence of plant and animal life has occurred, the sediments bear the indelible imprint of past activities and reveal the insidiously long-range dangers of polluted sediments.

Very high levels of hydrocarbons in Lake Yazoo sediments (see Table 4) would have suggested a fairly high toxicity level but not as high as bioassay results indicate. This area was selected as a likely deposit site for sediments that had successfully migrated to the mouth of the East Pascagoula River. Known also as the Inner Harbor area, the lake is bordered on one side by a huge shipyard and on the other by an exclusive residential area. Surface sediments appeared to be a white-chalky material that, when agitated, produced an acetylene-like odor. In researching the history of the area, it was discovered that from 1965 to 1969, an acetylene manufacturing plant was located adjacent to Lake Yazoo and that large quantities of calcium carbide residues were dumped into the lake. During the course of this bioassay, pH was monitored and registered values consistently above 11. In a separate experiment, test organisms were exposed to seawater diluted to a salinity approximately that of the Lake Yazoo exposure with pH adjusted to 11 with NaOH. Mortality test results with NaOH exactly duplicated that with the Lake Yazoo sediments indicating that the overriding effect of these sediments after a disturbance would be one of pH perturbation caused by the carbide residues.

It should be noted that high levels of hydrocarbons in sediments, particularly aromatic hydrocarbons, are invariably accompanied by significant mortalities in the toxicity bioassays. Further examples of this circumstantial indictment of hydrocarbons as the causative agent of toxicity were found at Mary Walker Bayou, Paper Mill, Griffin Point, and Halter Marine in the Pascagoula River System, all having high sediment hydrocarbon values and high bioassay mortalities. Because hydrocarbons are so tightly bound to sediments, it was expected that toxicity brought about primarily by hydrocarbons would be more apparent in tests where organisms were exposed to actual particles of sediment as occurred in the particulate phase and solid phase studies. In all tests previously mentioned, except Halter Marine, particulate and solid phase exposures produced mortalities which equalled or even greatly exceeded those in liquid phase exposures attesting to a toxic agent(s) not easily desorbed from the sedimentary particles. The Halter Marine bioassays were the only tests in which the particulate

TABLE 8.

Sediment bioassay mortalities.[1]

Site Name	Test Organism[2]	Percent Concentration[3]	Percent Mortalities								
			24 Hours		48 Hours		72 Hours		96 Hours		
			LP	PP	LP	PP	LP	PP	LP	PP	SP
Pascagoula River System											
Paper Mill	Mysid shrimp	100	0	0	0	20	15	?	45	80*	100*
		50	0	0	0	25	0	25	6.7	25	—
		10	0	5	5	10	10	30	20	30	—
	Sheepshead	100	0	0	25*	0	25*	5	25*	5	—
		50	0	0	0	0	0	0	0	0	—
		10	0	0	0	0	0	0	0	0	—
	Amphipods	100	—	—	—	—	—	—	—	—	100*
Pogey Plant	Mysid shrimp	100	60*	100*	80*	100*	100*	100*	100*	100*	100*
		50	20	100*	50*	100*	90*	100*	100*	100*	—
		10	35*	65*	55*	90*	60*	100*	80*	100*	—
	Sheepshead	100	0	0	0	0	0	0	0	0	—
		50	0	0	0	0	0	0	0	0	—
		10	0	5	0	5	0	5	0	5	—
	Amphipods	100	—	—	—	—	—	—	—	—	80*
Halter Marine	Mysid shrimp	100	0	5	20	10	35*	10	85*	15	20
		50	0	0	0	0	0	0	30	0	—
		10	0	0	5	5	10	5	10	5	—
	Sheepshead	100	0	0	0	0	0	0	0	0	—
		50	0	0	0	0	0	0	0	0	—
		10	0	0	0	0	0	0	0	0	—
	Amphipods	100	—	—	—	—	—	—	—	—	10
Escatawpa River Bridge	Mysid shrimp	100	0	0	0	25*	5	35*	5	45*	60*
		50	0	0	0	0	10	35*	20	40*	—
		10	0	0	0	0	5	10	10	10	—
	Sheepshead	100	0	0	0	0	0	0	0	0	—
		50	0	0	0	0	0	0	0	0	—
		10	0	0	5	0	5	0	5	0	—
	Amphipods	100	—	—	—	—	—	—	—	—	22.5
McInnis Lake	Mysid shrimp	100	0	0	0	0	0	0	10	0	5[4]
		50	5	0	10	0	10	0	15	5	—[5]
		10	5	0	5	0	5	0	5	10	—
	Sheepshead	100	0	0	0	0	0	0	0	0	—
		50	0	0	0	0	0	0	0	0	—
		10	0	0	0	0	0	0	0	0	—
	Amphipods	100	—	—	—	—	—	—	—	—	20[4]
Griffin Point	Mysid shrimp	100	10	10	10	10	10	25	10	25	60*
		50	0	5	0	5	5	5	15	10	—
		10	5	5	5	5	15	5	15	15	—
	Sheepshead	100	0	0	0	0	0	0	0	5	—
		50	0	0	0	0	0	0	0	0	—
		10	0	0	0	0	0	0	0	0	—
	Amphipods	100	—	—	—	—	—	—	—	—	87.5*
Elevator Bayou	Mysid shrimp	100	0	5	0	10	0	10	10	10	5
		50	5	10	10	10	10	10	15	20	—
		10	5	—	5	0	5	0	20	5	—
	Sheepshead	100	0	0	0	0	0	0	0	0	—
		50	0	0	0	0	0	0	0	0	—
		10	0	0	0	0	0	0	0	0	—
	Amphipods	100	—	—	—	—	—	—	—	—	5

TABLE 8. Sediment bioassay mortalities (continued).[1]

Site Name	Test Organism[2]	Percent Concentration[3]	Percent Mortalities								
			24 Hours		48 Hours		72 Hours		96 Hours		
			LP	PP	LP	PP	LP	PP	LP	PP	SP
Pascagoula River System (con't)											
Lake Yazoo	Mysid shrimp	100	100*	100*	100*	100*	100*	100*	100*	100*	100*[6]
		50	100*	100*	100*	100*	100*	100*	100*	100*	—
		10	15	0	35*	0	45	0	50	0	—
	Sheepshead	100	100*	100*	100*	100*	100*	100*	100*	100*	—
		50	0	0	0	5	0	5	0	5	—
		10	0	0	0	0	0	0	0	0	—
	Amphipods	100	—	—	—	—	—	—	—	—	100*[6]
Dead River	Mysid shrimp	100	0	0	0	0	0	0	5	0	10
		50	0	0	5	0	5	0	10	5	—
		10	0	0	0	0	0	0	0	0	—
	Sheepshead	100	0	0	5	0	5	0	5	0	—
		50	0	0	0	0	0	0	0	0	—
		10	0	0	0	0	0	0	0	0	—
	Amphipods	100	—	—	—	—	—	—	—	—	20
Mary Walker Bayou	Mysid shrimp	100	0	0	0	0	10	0	10	0	42.5*
		50	0	0	5	0	5	0	5	0	—
		10	0	0	0	0	5	6.3	5	14.3	—
	Sheepshead	100	0	0	0	0	0	0	0	0	—
		50	0	0	0	0	0	0	0	0	—
		10	0	0	0	0	0	0	0	0	—
	Amphipods	100	—	—	—	—	—	—	—	—	90*
Bayou Pierre	Mysid shrimp	100	0	5	0	5	0	5	0	5	15
		50	0	0	0	5	0	5	0	5	—
		10	0	0	0	0	0	0	0	0	—
	Sheepshead	100	0	0	0	0	0	0	0	0	—
		50	0	0	0	0	0	0	0	0	—
		10	0	0	0	0	0	0	0	0	—
	Amphipods	100	—	—	—	—	—	—	—	—	17.5
Twin Islands	Mysid shrimp	100	5	0	10	0	10	0	10	0	30
		50	0	0	0	0	0	0	0	0	—
		10	0	0	0	10	0	10	0	10	—
	Sheepshead	100	5	15	5	15	10	15	10	20	—
		50	0	0	0	10	5	10	5	10	—
		10	0	0	0	0	5	0	5	0	—
	Amphipods	100	—	—	—	—	—	—	—	—	10
Chevron N. Dock	Mysid shrimp	100	10	0	15	0	20	0	20	0	0
		50	5	0	5	0	5	0	5	0	—
		10	0	0	0	0	0	0	0	0	—
	Sheepshead	100	0	0	0	0	0	0	0	0	—
		50	0	0	0	0	0	0	0	0	—
		10	0	0	0	0	0	0	0	0	—
	Amphipods	100	—	—	—	—	—	—	—	—	15
Cooling Tower Canal 1	Mysid shrimp	100	85*	65*	100*	95*	100*	100*	100*	100*	100*
		50	40*	20	70*	75*	90*	95*	90*	95*	—
		10	0	5	5	25*	10	30*	14	40*	—
	Sheepshead	100	0	0	0	0	0	0	0	0	—
		50	0	0	0	0	0	0	0	0	—
		10	0	0	0	0	0	0	0	0	—
	Amphipods	100	—	—	—	—	—	—	—	—	47.5*

TABLE 8. Sediment bioassay mortalities (continued).[1]

Site Name	Test Organism[2]	Percent Concentration[3]	Percent Mortalities								
			24 Hours		48 Hours		72 Hours		96 Hours		
			LP	PP	LP	PP	LP	PP	LP	PP	SP
Pascagoula River System (con't)											
Cooling Tower Canal II[7,8]	Mysid shrimp	100	25*	30*	67*	67*	89*	94*	100*	100*	80*
		50	5	20*	20	45*	45*	60*	75*	65*	–
		10	0	0	0	0	0	0	15	15	–
	Sheepshead	100	0	0	0	0	0	0	0	0	–
		50	0	0	0	0	0	0	0	0	–
		10	0	0	0	0	0	0	0	0	–
	Gulf killifish	100	0	0	0	0	0	0	0	0	
		50	0	0	0	0	0	0	0	0	
		10	0	0	0	0	0	0	0	0	
	Amphipods	100	—	—	—	—	—	—	—	—	22.5*
West Prong	Mysid shrimp	100	45*	60*	80*	90*	85*	95*	85*	100*	75*
		50	15	20	30*	40*	45*	50*	50*	65*	–
		10	15	0	15	0	20	0	20	0	–
	Sheepshead	100	0	0	0	0	0	0	0	0	–
		50	0	0	0	0	0	0	0	0	–
		10	0	0	0	0	0	0	0	0	–
	Amphipods	100	—	—	—	—	—	—	—	—	25
Mississippi Chemical East Bank	Mysid shrimp	100	0	15	0	25	40	45	40	60*	25
		50	20	15	20	25	20	35	20	35	–
		10	20	20	30	20	35	25	35	35	–
	Sheepshead	100	0	0	0	0	0	0	0	0	–
		50	0	0	0	0	0	0	0	0	–
		10	0	0	0	0	0	0	0	0	–
	Amphipods	—	—	—	—	—	—	—	—	—	25
Graveline Bayou	Mysid shrimp	100	0	0	0	0	0	0	0	0	5
		50	0	5	0	5	0	5	5	10	–
		10	0	0	0	0	10	0	10	0	–
	Sheepshead	100	0	0	0	0	5	0	5	0	–
		50	0	0	0	0	0	0	0	0	–
		10	0	0	0	0	0	0	0	0	–
	Amphipods	100	—	—	—	—	—	—	—	—	2.5
Biloxi Bay Area											
Hewchem Industrial Canal	Mysid shrimp	100	15	0	25	30*	30*	35*	35*	60*	95*
		50	10	5	15	5	15	5	15	15	–
		10	0	0	0	5	0	5	0	15	–
	Sheepshead	100	0	0	0	0	0	0	0	0	–
		50	0	0	0	0	0	0	0	0	–
		10	0	0	0	0	0	0	0	0	–
	Amphipods	100	—	—	—	—	—	—	—	—	92.5*
Turkey Creek	Mysid shrimp	100	0	0	0	0	0	0	0	5	0
		50	0	0	0	0	0	0	0	0	–
		10	0	0	0	0	0	0	0	0	–
	Sheepshead	100	0	0	0	0	0	0	0	0	–
		50	0	0	0	0	0	0	0	0	–
		10	0	0	0	0	0	0	0	0	–
	Amphipods	100	—	—	—	—	—	—	—	—	10
Gulfport Lake	Mysid shrimp	100	5	0	5	35*	5	55*	5	65*	80*
		50	0	0	0	5	0	10	0	20*	–
		10	15	0	15	5	15	10	15	10	–

TABLE 8. Sediment bioassay mortalities (continued).[1]

Site Name	Test Organism[2]	Percent Concentration[3]	Percent Mortalities								
			24 Hours		48 Hours		72 Hours		96 Hours		
			LP	PP	LP	PP	LP	PP	LP	PP	SP
Biloxi Bay Area (con't)											
Gulfport Lake (con't)	Sheepshead	100	0	0	0	0	0	0	0	0	–
		50	0	0	0	0	0	0	0	0	–
		10	0	5	0	10	0	10	0	10	–
	Amphipods	100	—	—	—	—	—	—	—	—	85*
Industrial Seaway	Mysid shrimp	100	0	0	0	0	0	0	0	0	55*
		50	0	0	0	0	0	0	0	0	–
		10	0	0	0	0	0	0	0	0	5
	Sheepshead	100	0	0	0	0	0	0	0	0	–
		50	0	0	0	0	0	0	0	0	–
		10	0	0	0	0	0	0	0	0	–
	Amphipods	100	—	—	—	—	—	—	—	—	50
Reichhold Industrial Canal	Mysid shrimp	100	0	0	0	0	0	0	0	15	50*
		50	0	0	0	0	0	0	5	19	–
		10	0	0	0	0	0	0	5	0	–
	Sheepshead	100	0	0	0	0	0	0	0	0	–
		50	5	0	5	0	5	0	5	0	–
		10	0	0	0	0	0	0	0	0	–
	Amphipods	100	—	—	—	—	—	—	—	—	30*
Power Plant	Mysid shrimp	100	0	0	0	5	0	5	0	5	0
		50	5	0	5	0	5	0	5	0	–
		10	0	0	0	0	0	0	0	0	–
	Sheepshead	100	0	0	0	0	0	0	0	0	–
		50	0	0	0	0	0	0	0	0	–
		10	0	0	0	0	0	0	0	0	–
	Amphipods	100	—	—	—	—	—	—	—	—	12.5
V.A. Hospital	Mysid shrimp	100	0	0	0	0	5	0	5	0	0
		50	0	0	5	0	5	0	5	0	–
		10	5	0	5	0	5	0	5	5	–
	Sheepshead	100	0	0	0	5	0	5	0	5	–
		50	5	0	19	0	10	0	10	0	–
		10	0	5	0	10	0	10	0	10	–
	Amphipods	100	—	—	—	—	—	—	—	—	15
Rhodes Point	Mysid shrimp	100	0	0	0	0	0	0	5	0	5
		50	0	0	0	0	0	5	0	5	–
		10	0	0	0	0	5	0	5	5	–
	Sheepshead	100	0	0	0	0	0	0	0	0	–
		50	0	0	0	0	0	0	0	0	–
		10	0	0	0	0	0	0	0	0	–
	Amphipods	100	—	—	—	—	—	—	—	—	12.5
Deer Island	Mysid shrimp	100	10	0	10	0	10	0	10	0	5
		50	0	0	0	0	0	0	0	0	–
		10	0	5	0	5	0	10	0	15	–
	Sheepshead	100	0	0	0	0	0	0	0	0	–
		50	0	0	0	0	0	0	0	0	–
		10	0	0	0	0	0	0	0	0	–
	Amphipods	100	—	—	—	—	—	—	—	—	17.5

TABLE 8. Sediment bioassay mortalities (continued).[1]

Site Name	Test Organism[2]	Percent Concentration[3]	Percent Mortalities								
			24 Hours		48 Hours		72 Hours		96 Hours		
			LP	PP	LP	PP	LP	PP	LP	PP	SP
Biloxi Bay Area (con't)											
Old Fort Bayou	Mysid shrimp	100	0	0	0	0	0	0	0	5	15
		50	0	0	0	0	0	0	0	10	–
		10	0	0	0	0	0	0	0	0	–
	Sheepshead	100	0	0	0	0	0	0	0	0	–
		50	0	0	0	0	0	0	0	0	–
		10	0	0	0	0	0	0	0	0	–
	Amphipods	100	—	—	—	—	—	—	—	—	12.5
Davis Bayou	Mysid shrimp	100	0	0	0	0	0	0	0	0	0
		50	0	0	0	0	0	0	10	5	–
		10	0	0	0	5	0	5	0	5	–
	Sheepshead	100	0	0	0	5	0	5	0	5	–
		50	0	0	0	0	0	0	0	0	–
		10	0	0	0	0	0	0	—	0	–
	Amphipods	100	—	—	—	—	—	—	—	—	17.5
St. Louis Bay Area											
St. Louis Bay Bridges	Mysid shrimp	100	5	0	5	0	5	0	5	0	5
		50	0	0	0	0	0	0	0	0	–
		10	0	0	0	0	0	0	0	0	–
	Sheepshead	100	0	0	0	0	0	0	0	0	–
		50	0	0	0	0	0	0	0	0	–
		10	0	0	0	0	0	0	0	0	–
	Amphipods	100	—	—	—	—	—	—	—	—	12.5
Heron Bay	Mysid shrimp	100	5	5	5	10	5	10	10	10	10
		50	0	10	0	10	0	10	0	20	–
		10	5	0	5	0	5	0	5	5	–
	Sheepshead	100	0	0	0	5	0	5	0	5	–
		50	0	0	0	0	0	0	0	0	–
		10	0	0	0	0	0	0	0	0	–
	Amphipods	100	—	—	—	—	—	—	—	—	10
Mississippi Sound											
East Gulfport Channel	Mysid shrimp	100	0	0	0	0	0	0	0	0	0
		50	0	0	5	0	5	0	5	5	–
		10	0	0	0	0	0	0	5	0	–
	Sheepshead	100	0	0	0	0	0	0	0	0	–
		50	0	0	0	0	0	0	0	0	–
		10	0	0	0	0	0	0	0	0	–
	Amphipods	100	—	—	—	—	—	—	—	—	10
Ship Island	Mysid shrimp	100	0	0	0	0	0	0	0	0	0
		50	5	5	5	5	5	5	10	10	–
		10	0	0	0	0	0	0	0	0	–
	Sheepshead	100	0	0	0	0	0	0	0	0	–
		50	0	0	0	0	0	0	0	0	–
		10	0	0	0	0	0	0	0	0	–
	Amphipods	100	—	—	—	—	—	—	—	—	20
East Horn Island	Mysid shrimp	100	0	0	5	0	5	0	5	0	0
		50	0	0	0	0	0	0	5	0	–
		10	0	10	0	10	0	10	0	10	–
	Sheepshead	100	0	0	0	0	0	0	0	0	–
		50	0	0	0	0	0	0	0	0	–
		10	0	0	0	0	0	0	0	0	–
	Amphipods	100	—	—	—	—	—	—	—	—	5

TABLE 8. Sediment bioassay mortalities (concluded).[1]

Site Name	Test Organism[2]	Percent Concentration[3]	Percent Mortalities								
			24 Hours		48 Hours		72 Hours		96 Hours		
			LP	PP	LP	PP	LP	PP	LP	PP	SP
Mississippi Sound (con't)											
Open Gulf	Mysid shrimp	100	0	0	5	0	20	10	20	10	5
		50	0	0	5	5	10	10	15	15	—
		10	0	0	0	0	0	5	5	5	—
	Sheepshead	100	0	0	0	0	0	0	0	0	—
		50	0	0	0	0	0	0	0	0	—
		10	0	0	0	0	0	0	0	0	—
	Amphipods	100	—[4]	—[4]	—[4]	—[4]	—[4]	—[4]	—[4]	—[4]	15

*Significantly different from control test.

[1]Percent Mortalities at 24-hour intervals in 96-hour exposure tests are tabulated. Percentages are cumulative for the test period. The EPA 3-phase bioassays consisted of exposures to the soluble component of sediments (LP), to the soluble and suspended material after introducing sediment to test water (PP), and to material that settles after dispersion (SP).

[2]Test organisms were mysid shrimp (*Mysidopsis almyra*), sheepshead minnows (*Cyprinodon variegatus*) and an amphipod (*Gammarus mucronatus*).

[3]Concentrations of test solutions based upon 100% representing the usual conditions of testing, ie., preparation by mixing site water and sediment in 4:1 ratio (v:v). Fifty percent and 10% preparations are 100% preparations diluted 1:1 and 1:9, respectively, with ocean water that has been adjusted to proper salinity.

[4]Only the 96-hour cumulative total was measured for solid phase tests.

[5]No tests for these conditions.

[6]100% mortality noted at beginning of exposure test.

[7]Two sets of conditions in which ocean water was substituted for site water in the second set.

[8]Additional test organism used at this site, Gulf killifish (*Fundulus grandis*).

phase exposure produced fewer mortalities than did the liquid phase. One possible explanation is that the presence of suspended matter may have caused readsorption of the sediment components initially solubilized in both the liquid and particulate phase preparations. At this particular site, circumstances stabilizing sediment suspension would probably lower the long-range toxic effects whereas longer suspension times would increase toxic effects at other study sites. The toxicity dependence on suspension stabilities presaged the need for the suspension rate studies discussed later.

In-depth bioassays in Bayou Casotte. Because of strong indications that sediment-bound hydrocarbons were very likely the toxic agents in sediments of the eastern Sound areas, an expanded bioassay study was implemented in Bayou Casotte where the highest hydrocarbon levels were measured in Sound sediments (see Table 4) and where an oil spill had occurred in 1981. The five bioassays were run on sediments in the undredged upper reaches of Bayou Casotte (Cooling Tower Canal I and II, and West Prong) and near industrial sites in the dredged, lower bayou (Mississippi Chemical E. Bank and Chevron N. Dock).

At Mississippi Chemical E. Bank and Chevron N. Dock, only one test with mysid shrimp (particulate phase) yielded significant mortalities. Even exposure of bottom-feeding organisms to these sediments caused no significant mortalities nor were any behavioral problems noted during the course of the 96 hours. Bioassays revealed little difference in toxicity of sediments collected in the dredged bayou area before the 1981 oil spill (collection of Mississippi Chemical E. Bank sediment) compared with tests run one year after the spill (at Chevron N. Dock).

Bioassays conducted in the relatively undisturbed region of Bayou Casotte above Mississippi Chemical E. Bank were considerably different from those below that site. Results from the two locations sampled in March 1982, Cooling Tower Canal I and West Prong, revealed significant mortalities to mysid shrimp in all three tests on both sediments and to the amphipods only in the solid phase testing with the Cooling Tower Canal sediments. The water used in these

tests was also highly toxic. Water soluble fractions of crude and refined oils are toxic to estuarine organisms[30,88], and these samples were collected while a visible oil sheen was present. There was an acrid smell in the air and workmen in the area reported very erratic behavior of shrimp. To assure measurement only of the sediment impact, diluted seawater was used as the dispersal medium for the second collection at the Cooling Tower Canal II. Furthermore, an additional fish species, *Fundulus grandis,* was used in this test.

Fundulus grandis proved as impervious to the affects of sediment toxicity as *Cyprinodon variegatus.* However, the mortality results for mysid shrimp (Figure 16) prove that the sediments do possess the potential to bring about significant alteration of the biological community. From Figure 16, it should be noted that significant mortalities occurred even when the liquid and particulate phases were further diluted with seawater before exposure tests were begun.

To determine cytopathic effects on fish after 96 hours of exposure, *F. grandis* and *C. variegatus* from Cooling Tower Canal II were narcotized by cooling and fixed whole in Lillie's fluid. The abdominal wall was opened to allow good fixative penetration. Specimens were fixed for two days, washed in running tap water overnight, and dehydrated in a graded series of alcohols. Specimens were cleared in chloroform and embedded in paraffin. Sections about 5 μ thick in both longitudinal and cross-sectional planes were cut on a rotary microtome, mounted on glass slides, and stained with hematoxylin and eosin. All major tissues and organs were examined. Although gill lamellae in some exposed fish showed separation of the outer epithelial layer from underlying layers, there appeared to be no major target organ effects.

It is easy to conclude that petroleum contaminants are the primary cause of toxicity in Bayou Casotte sediments. However, one cannot ignore the manufacture of ammonia by both the oil refinery and Mississippi Chemical Corporation which discharge in the region of the cooling Tower Canal site. Values of free ammonia were determined in site water before and after a dispersal of the subject sediment. High values of free ammonia occurred in all tests resulting in significant mortalities, with one notable exception. The highest value of free ammonia occurred in the dispersal of Chevron N. Dock sediment. However, this test medium had no perceptible affect on mysid shrimp. Because free ammonia in tests with high mysid shrimp mortalities was in the range toxic to certain marine organisms[89], it was decided to further explore ammonia toxicity to mysids. Mysid shrimp were exposed to levels of free ammonia at concentrations which were at and below those in sediment tests where significant mortalities occurred. Salinity, temperature, and pH were maintained at levels consistent with those observed in the sediment tests. No mortalities were observed for mysid shrimp at any of the ammonia-dose rates. These data and mysid survivals in the Chevron N. Dock test indicate that mysid shrimp should have been able to tolerate ammonia levels prevalent in every test. Ammonia released from these sediments then likely acts only in synergism, if at all, with other toxic components of these sediments.

Sediment bioassays gave little indication that sediments near the oil refinery docking facilities and at the site of the oil spill in 1981 pose any significant threat to the biological environment. Such optimism cannot be expressed for sedimentary environments in the upper bayou region. But even at these sites, one cannot completely discount the presence of Mississippi Chemical Corporation process water discharge and First Chemical storm runoff entering this part of the bayou. A combination of all may be essential to create the toxic sediment environment found in the upper reaches of Bayou Casotte.

No significant mortalities occurred in any bioassays conducted on sediments secured from the Open Sound or the western extremes in the St. Louis Bay region. However, some parts of Biloxi Bay exhibited high toxicities, specifically those sites along the Bernard Bayou-Industrial Seaway (Hewchem Industrial Canal, Industrial Seaway, and Reichhold Industrial Canal). Again these sites, like those in the eastern Sound, yielded sediment exposure toxicities (higher in the particulate and solid phase exposures) that indicated toxic compounds bound securely to the sedimentary particles. The presence of extraordinarily high

hydrocarbon concentrations in these sediments gives further support to the hypothesis that hydrocarbons are the prevalent and most profoundly toxic group of pollutant compounds found in Mississippi Sound.

This concept of sediment toxicity is obviously a function of pollutant level in the sediments and gives a more meaningful description to polluted sediments than do quantitative and qualitative chemical analyses alone. However, it must also be understood that toxicity tests can give an ill-defined picture of all conceivable circumstances which might arise in the exposure of organisms to contaminated sediments. The unique geochemical characteristics of specific pollutants cannot be predicted from toxicity tests but are relevant in assessments of polluted sediment impact. Therefore, chemical descriptions of the sediments must also be considered in the overall estimations of sediment toxicity.

To further simplify the results of these bioassays, a rating system was used for each test giving values of 1 to 5 for significant mortalities observed at the end of each 96-hour exposure. Using only results from undiluted exposure media, this produces six separate ratings. The individual values and average of these values, used in compiling the Environmental Stress Index, are listed in Table 9.

Suspension Stability

In a further attempt to investigate the overall impact of resuspension of contaminated sediments, settling rate characteristics were determined. The ratio of 1:4, V/V sediment and water were used as prescribed in the toxicological testing. Approximately 250 g of sediment were dispersed in the appropriate amount of site water in 1 gallon jars using a platform shaker for dispersal. At the end of a 5-minute shaking period, 1 minute elapsed before an initial 5-mℓ sample was withdrawn from 2 cm beneath the surface. After this initial collection, additional aliquots were withdrawn at 0.5, 1, 2-, 4-, 10-, 20-, 40-, 80-, 160-, 320-, 480-, 1440-, and 2880-minute intervals.

Suspended solids, measured gravimetrically[35], were plotted as percent of the initial value versus time elapsed from cessation of dispersal. Results of this study are contained in Appendix II. Temperature and salinities for most tests were room temperature and ambient salinity but, as indicated in the notes prefacing Appendix II, these conditions were sometimes adjusted to bracket the seasonal range in both or to explore other possible phenomena that might occur in a natural sediment disturbance. Because of their effect on biological exposure and chemical leaching, both rates of settling and total amount of suspended solids were evaluated to estimate the potential effect of man-induced and/or natural sediment disturbances. Each of the settling rate curves displayed in Appendix II may be described by one of eight settling descriptions and are so classified in the preface to Appendix II. These descriptions and examples of each are as follows:

Sediment settling properties. If sediments are of Class I, an initial disturbance will result in high to very high suspended solids loads (15,000 to 35,000 mg/ℓ). However, the overall effect would be rather short lived because these suspensions are very unstable and tend to settle abruptly after the agitation or disrupting forces cease. Sediments found at West Prong in Bayou Casotte and the Deer Island sites (Figures II-21 and II-34) are examples of these settling properties. There is a preponderance of this type of sediment in the Bernard Bayou industrial area of Biloxi Bay. The positive advantage of the quick settling rate is clear at West Prong where extremely high levels of total and aromatic hydrocarbons (see Table 4) would create a more serious toxicological problem if these sediments possessed the capacity to stay in a suspended state for significant lengths of time.

Sediments of Class II also yield high to very high suspended solids levels after agitation which stay suspended for brief periods of time (1 to 5 minutes) then settle very quickly. Exposure to high quantities of suspended matter with adsorbed pollutants would typically be for longer periods than Class I sediments. All of the samples from the Open Sound were of this type with a few also located in the Biloxi Bay system. Again, the rapid settling rate is an advantage. The Open Gulf (Figure II-42) is a good example of this settling characteristic.

Class III sediments are found almost exclusively in the Pascagoula River System, although

the Turkey Creek sediment is also of this type. Perhaps it is significant that all of these sediment sites are near sewage outfalls. Dispersion of this type of sediment results in a medium to high initial suspended solids load (3,000 to 45,000 mg/ℓ) which declines very steadily and gradually over extended periods of time and yields a sedimentation curve approximating a straight line. Paper Mill sediments (Figure II-1) perfectly exemplify Class III. Although they cannot be maintained in suspension at very high levels for as long as Class II sediments, Class III produce exposures to elevated suspension loads for much longer periods than would be the case with Class II.

Contaminated sediments whose suspension properties present the greatest potential for harm following a disturbance are the Class IV sediments found at Pogey Plant and Heron Bay (Figures II-2 and II-38). Following a disturbance of these sediments, medium high to high loads of suspended solids (10,000 to 20,000 mg/ℓ) would be retained in the water column for relatively long periods of time (10 to 100 minutes) without any noticeable settling followed by gradual decline after this period. Under test conditions agitation of the water column ceased after the initial suspension. However, in a real disturbance event at the Class IV sediment sites, agitating forces would not cease so abruptly. Therefore, organism exposure to very high suspended solid loads could be prolonged for very lengthy periods of time. High suspension stability cannot be explained at Heron Bay, but the use of detergents to clean boats in the Pogey Plant area of the Escatawpa River could easily account for the protracted suspension of sediments there if detergent residues were contained in these sediments.

Only two sediment sites fall into Class V, V.A. Hospital and Rhodes Point (Figures II-32 and II-33), both located in eastern Biloxi Bay. These sediments are like Class I in that very high suspension loads are produced after a disburbance (> 75,000 mg/ℓ) which drop abruptly at cessation of agitation. However, rather than plunging abruptly to background values, these sediments tend to drop to a secondary plateau for a short period of time before continuing another sharp decline to background values. Apparently at least one sedimentary component in this region of Biloxi Bay has settling characteristics different from the others, i.e., it is retained in suspension independent of the remaining sedimentary material.

Classes VI to VIII share one characteristic which elicits less concern than the Class I to V sediments, i.e., low to very low initial suspended solids arising from disturbances at these sites. There is only one Class VI sediment site, Halter Marine (Figure II-3), where very low suspension loads (< 400 mg/ℓ) follow agitation and then drop quickly to background. The three Class VII sediment sites, Escatawpa River (low salinity), Mary Walker Bayou and Bayou Pierre (Figures II-6, II-12 and II-13), are all in the Pascagoula River System and yield low suspended solids loads (< 1,000 mg/ℓ) followed by an almost linear decline (versus log time) as seen with Class III sediments. The two Class VIII sediment sites (also in the Pascagoula River System), Twin Islands and Graveline Bayou, have perhaps the most bizarre settling characteristics of any sediment tested. These sites, both near the mouth of West Pascagoula River, have sediments apparently composed of several distinct fractions, each of which has a unique suspension stability as depicted in the multi-stage settling curves for these sites in Figures II-14 and II-23.

Temperature and salinity effects. Because salinity and temperature regimes are so variable, some sites were studied at salinity and temperature extremes to investigate the effects of these parameters on settling characteristics. In Figures II-5 and II-6, one can see that higher salinity at Escatawpa River Bridge creates a heavier sediment load following a disturbance but more rapid settling. However, at Dead River (Figures II-9 and II-10), lower salinity favors higher suspended solids loads but maintains the slower settling rates of the high-salinity study. In contrast salinity seemed not to alter the settling properties at Industrial Seaway (Figures II-24 and II-26). At Cooling Tower Canal suspension stability studies were conducted at ambient temperature and also at four controlled temperature and salinity conditions. As indicated on Figures II-16 through II-20, the settling properties of this sediment were not affected by changes in either temperature or salinity. As evidenced

TABLE 9.

Environmental Stress Index.[1]

Site Name	Category I[2] Exposure Mortalities, 3-Phase							Category II[3] Suspension Stability				Category III[4]	Category IV[5]	
	Mysid Shrimp			Sheepshead		Amphipod								
	LP	PP	SP	LP	PP	SP	Average	Initial Suspended Solids	$t_{1/2}$	$t_{1/4}$	Average	Disturbance Probability	Biota Susceptibility	Index Product[6]
Pascagoula River System														
Paper Mill	1	5	5	2	1	5	3.2	3	2	2	2.50	3.4	2.67	72.6
Pogey Plant	5	5	5	1	1	5	3.7	4	5	5	4.50	4.0	2.00	133.2
Halter Marine	5	1	1	1	1	1	1.7	1	2	5	2.25	3.2	3.00	36.7
Escatawpa River Bridge	1	3	4	1	1	2	2.0	1	4	5	2.75	5.0	3.00	82.5
McInnis Lake	1	1	1	1	1	1	1.0	2	5	5	3.50	1.4	2.67	13.1
Griffin Point	1	1	4	1	1	5	2.2	4	5	5	4.50	2.8	3.00	83.2
Elevator Bayou	1	1	1	1	1	1	1.0	5	2	2	3.50	5.0	3.33	58.3
Lake Yazoo	5	5	5	5	5	5	5.0	4	3	2	3.25	2.0	4.33	141.0
Dead River	1	1	1	1	1	1	1.0	5	1	2	3.25	1.0	3.33	10.8
Mary Walker Bayou	1	1	3	1	1	5	2.0	2	4	5	3.25	2.4	3.33	51.9
Bayou Pierre	1	1	1	1	1	1	1.0	2	5	5	3.50	4.4	3.75	57.8
Twin Islands	1	1	1	1	1	1	1.0	1	4	5	2.75	2.2	3.33	20.1
Chevron N. Dock	1	1	1	1	1	1	1.0	4	2	2	3.00	5.0	3.33	50.0
Cooling Tower Canal	5	5	5	1	1	2	3.2	4	3	2	3.25	2.0	3.00	62.4
West Prong	5	5	4	1	1	2	3.0	5	3	2	3.75	2.0	3.33	74.9
Mississippi Chem. E. Bank	1	3	1	1	1	1	1.3	3	2	2	2.50	5.0	3.33	54.1
Graveline Bayou	1	1	1	1	1	1	1.0	2	3	5	3.00	2.6	3.67	28.6
Biloxi Bay System														
Hewchem Industrial Canal	2	4	5	1	1	5	3.0	4	1	1	2.50	3.8	3.33	94.9
Turkey Creek	1	1	1	1	1	1	1.0	5	3	3	4.00	3.0	3.00	36.0
Gulfport Lake	1	4	5	1	1	5	2.8	5	1	1	3.00	4.0	3.00	100.8
Industrial Seaway	1	1	3	1	1	1	1.3	4	3	2	3.25	4.0	3.00	50.7
Reichhold Industrial Canal	1	1	3	1	1	2	1.5	4	1	2	2.75	4.0	3.00	49.5
Coley Island[7]	--	--	--	--	--	--	--	5	1	1	3.00	3.0	4.33	--
Power Plant	1	1	1	1	1	1	1.0	3	1	1	2.00	2.4	3.67	17.6
V.A. Hospital	1	1	1	1	1	1	1.0	5	3	3	4.00	2.0	4.00	32.0
Rhodes Point	1	1	1	1	1	1	1.0	5	3	2	3.75	5.0	3.33	62.4
Deer Island	1	1	1	1	1	1	1.0	5	3	2	3.75	4.2	3.67	57.8
Old Fort Bayou	1	1	1	1	1	1	1.0	4	2	1	2.75	3.2	4.00	35.2
Davis Bayou	1	1	1	1	1	1	1.0	5	1	1	3.00	2.6	4.33	33.8
St. Louis Bay System														
St. Louis Bay Bridges	1	1	1	1	1	1	1.0	2	2	3	2.25	2.4	3.00	16.2
Heron Bay	1	1	1	1	1	1	1.0	3	5	4	3.75	1.6	3.67	22.0

TABLE 9. Environmental Stress Index (concluded).[1]

Site Name	Category I[2] Exposure Mortalities, 3-Phase							Category II[3] Suspension Stability				Category III[4]	Category IV[5]	
	Mysid Shrimp			Sheepshead		Amphipod								
	LP	PP	SP	LP	PP	SP	Average	Initial Suspended Solids	$t_{1/2}$	$t_{1/4}$	Average	Disturbance Probability	Biota Susceptibility	Index Product[6]
Mississippi Sound System														
E. Gulfport Channel	1	1	1	1	1	1	1.0	4	3	2	3.25	4.0	3.00	39.0
Ship Island	1	1	1	1	1	1	1.0	5	3	2	3.75	2.4	3.00	27.0
Horn Island	1	1	1	1	1	1	1.0	4	3	2	3.25	2.0	3.00	19.5
Open Gulf	2	1	1	1	1	1	1.2	5	3	2	3.75	2.0	2.83	25.5

[1]Higher number ratings indicate greater potential risk from polluted sediment in area.

[2]EPA Procedure. Exposure to soluble components of sediment (LP), suspended and solubles (PP) and settled sediment (SP). Test organisms are mysid shrimp (*Mysidopsis almyra*), sheepshead minnows (*Cyprinodon variegatus*), and an amphipod (*Gammarus mucronatus*). Ratings derive from mortalities at the end of 96-hour exposure to undiluted sediment/water preparations. The rating system is 5 for 80 to 100% significant mortality, 4 (60 to 79%), 3 (40 to 59%), 2 (20 to 39%), and 1 (<20%). The final column is an arithmetical average of the 6 tabulated ratings.

[3]Subcategory ratings derive from the highest rating value in the following scheme: 5 for initial suspended solids (after dispersion in water) (ISS) $\geq$ 30,000 mg/ℓ, time for initial solids to drop to one-half original value ($t_{1/2}$) $\geq$ 15 minutes, one-fourth original value time ($t_{1/4}$) $\geq$ 30 minutes; ratings of 4 for ISS $\geq$ 20,000 mg/ℓ, $t_{1/2} \geq$ 10 minutes, $t_{1/4} \geq$ 20 minutes; ratings of 3 for ISS $\geq$ 10,000 mg/ℓ, $t_{1/2} \geq$ 5 minutes, $t_{1/4} \geq$ 10 minutes; ratings of 2 for ISS $\geq$ 1,000 mg/ℓ, $t_{1/2} \geq$ 2 minutes, $t_{1/4} \geq$ 4 minutes; and ratings of 1 for ISS < 1,000 mg/ℓ, $t_{1/2} <$ 2 minutes and $t_{1/4} <$ 4 minutes. Average is computed by formula: $[2\,(ISS) + t_{1/2} + t_{1/4}]/4$.

[4]Rating determined by probability of sediment disturbance in this area: 5—high risk due to boat traffic, dredging, main stream flow, etc.; 4—restricted boat traffic, some natural protection; 3—infrequent disturbance except for tides; 2—isolated from main river flow and sporting activity; 1—disturbed only in rare circumstances.

[5]Vulnerability of organisms living in area. Considerations are: escape routes, ecological importance of indigenous species, life stages present, species diversity, mobility, and susceptibility to stress.

[6]Mathematical product of Category I average, II average, III and IV.

[7]Partial rating.

by these studies, the aspect of suspension stability is very complex and not easily characterized by one laboratory experiment under one set of conditions.

As a means of further simplifying the settling rate properties observed in each test, three very important characteristics of each curve in Appendix II were evaluated and given a separate numerical rating for inclusion in the Environmental Stress Index. These characteristics are: the initial suspended solids, the elapsed time for this amount to drop to one-half the original value and the time for the amount to drop to one-fourth. Increases in any one of these properties heightens the overall impact that sediments would have after a disturbance and are reflected in the rating system of Table 9.

Leachability

With sediment disturbances, certain constituents of the sediment may be released to the water column. The quantity released will be a function of pH, salinity, temperature, and other equilibrium considerations. A laboratory study was designed to simulate sediment disturbance to examine chemical changes in the water column affected by dispersal of contaminated sediments and to gain an insight into possible toxic substances that organisms were encountering in the bioassay studies.

A suite of chemical variables was chosen to depict changes in budgets of inorganic micronutrients, organic nitrogen and organic carbon. Sediment and site water (1:4, V/V, as in other tests) from all stations were agitated for two minutes on a platform shaker, immediately centrifuged and 0.45 μ filtered for analysis of soluble ammonia, nitrate, nitrite, total Kjeldahl nitrogen (TKN), orthophosphate, and silicate. Glass fiber filtration preceded the dissolved organic carbon (DOC) determination with no filtration prior to total organic carbon (TOC) analysis. Site water was used to establish background values and, with the exception of sediment exposure, was prepared identically. Analyses on all samples were as follows: ammonia, specific ion electrode; TKN, micro Kjeldahl procedure; nitrate, nitrite, orthophosphate and silicate, colorimetric; and DOC and TOC Oceanography International Carbon Analyzer.[35]

Because disturbance incidents may occur repeatedly at any given area and also under varying salinity and temperature conditions, additional tests were designed to determine the effect of both. At Halter Marine, Escatawpa River Bridge, Dead River, Cooling Tower Canal, Industrial Seaway and Power Plant sites, the sorption-desorption characteristics were measured under four sets of conditions representing combinations of extreme values of salinity and temperature typical for these regions. Salinity was adjusted by addition of ultrapure NaCl to all test water except at Cooling Tower Canal where site water, already at a maximum level, was diluted with distilled water to achieve the lower salinity. Another possible variable was pH, but early testing revealed that the sediment alone established the final pH after mixing with site water. Natural variations in pH were, therefore, considered to be of very minor significance in the chemical alteration of water exposed to resuspended sediment.

Because repeat suspensions of sediments might enhance or diminish release of constituents from sediments, another set of test conditions was run at the Dead River, Cooling Tower Canal, Industrial Seaway and Power Plant sites. Two suspensions using fresh volumes of site water were run successively on each sediment sample to suggest whether the sorption-desorption capacities of sediments would diminish during quickly repeated episodes of sediment disruption. An additional suspension was conducted on the same sediment sample one week later to measure the long-term effect one disturbance would produce on the chemical activity that these sediments would display in future, isolated disturbance incidents. At the Cooling Tower Canal site these long-term effect studies were further expanded to include temperature and salinity variations in each of the repeat suspensions. Results of all these tests are contained in Table 10.

Pascagoula River System. There seems to be no discernible pattern with the "before" and "after" values of DOC produced by resuspension of sediments from sites in the Pascagoula River System. Sediments from approximately half of the sites in this area created enlarged DOC levels after suspension

TABLE 10.

Sorption-desorption capacities of Mississippi Sound sediments.[1]

Site Name	Conditions[2]		DOC mg/ℓ		TOC mg/ℓ		NH_3 μg-at N/ℓ		NO_3 μg-at N/ℓ		NO_2 μg-at N/ℓ		TKN μg-at N/ℓ		PO_4 μg-at P/ℓ		SiO_2 μg-at Si/ℓ	
			Before	After	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After
Pascagoula River System																		
Paper Mill	Natural		12.9	—	18.1	167.0	90.0	340	—	—	1.37	0.87	290	260	3.1	9.4	—	—
Pogey Plant	Natural		7.79	—	7.70	86.2	50.0	563	—	—	0.13	0.14	39	83	0.10	2.1	59.0	76.0
Halter Marine[3]	5°C	6.5 ppt	10.8	7.44	9.16	33.0	29.2	447	40.9	309	0.470	7.93	145	278	0.924	2.44	73.7	60.6
Halter Marine[3]	5°C	15.0 ppt	10.8	8.77	9.16	19.5	29.2	356	40.9	29.8	0.470	0.470	145	286	0.924	0.232	73.7	94.4
Halter Marine[3]	30°C	6.5 ppt	10.8	12.4	9.16	27.2	29.2	450	40.9	158	0.470	0.439	145	345	0.924	0.171	73.7	75.1
Halter Marine[3]	30°C	15.0 ppt	10.8	9.49	9.16	21.5	29.2	375	40.9	18.2	0.470	0.409	145	394	0.924	0.148	73.7	95.1
Escatawpa River B.[3]	5°C	6.5 ppt	7.48	6.41	9.30	21.6	36.5	319	29.8	172	0.439	4.88	221	270	0.132	0.063	86.8	51.7
Escatawpa River B.[3]	5°C	15.0 ppt	7.48	6.52	9.30	25.6	36.5	305	29.8	26.0	0.439	0.409	221	278	0.132	0.094	86.8	149
Escatawpa River B.[3]	30°C	6.5 ppt	7.48	9.74	9.30	27.8	36.5	379	29.8	47.3	0.439	3.35	221	323	0.132	0.148	86.8	93.8
Escatawpa River B.[3]	30°C	15.0 ppt	7.48	12.7	9.30	35.8	36.5	376	29.8	—	0.439	—	221	406	0.132	0.148	86.8	56.5
McInnis Lake	Natural		3.50	8.00	3.64	455	ND[4]	119	14.9	12.1	1.12	0.744	2.75	84.1	1.84	2.85	153	105
Griffin Point	Natural		3.15	12.9	1.89	611	ND	51.7	16.5	33.0	1.01	1.66	8.08	33.6	0.757	8.90	257	297
Elevator Bayou	Natural		17.3	8.75	7.36	7.56	7.92	45.3	281	351	0.165	0.266	63.6	79.8	0.117	0.109	47.5	50.3
Lake Yazoo	Natural		15.9	7.87	5.75	9.19	4.49	55.2	447	600	0.195	0.256	120	124	0.063	0.078	39.2	19.2
Dead River[3]	5°C	0.0 ppt	1.62	3.10	1.79	27.4	4.07	232	26.0	44.9	0.363	2.86	24.7	55.4	1.39	0.873	388	591
Dead River[3]	5°C	15.0 ppt	1.62	0.992	1.79	8.07	4.07	171	26.0	39.6	0.363	0.767	24.7	347	1.39	0.184	388	347
Dead River[3]	30°C	0.0 ppt	1.62	8.25	1.79	34.2	4.07	195	26.0	36.3	0.363	1.65	24.7	318	1.39	0.959	388	464
Dead River[3]	30°C	15.0 ppt	1.62	7.60	1.79	10.6	4.07	263	26.0	16.9	0.363	0.877	24.7	368	1.39	0.271	388	253
Dead River[3]	LTI–1[5]		1.62	0.992	1.79	27.4	4.07	232	26.0	44.9	0.363	2.86	24.7	55.4	1.39	0.873	388	591
Dead River[3]	LTI–2		1.62	3.38	1.79	59.3	4.07	—	26.0	25.0	0.363	2.20	24.7	182	1.39	1.22	388	458
Dead River[3]	LTI–3		1.62	5.61	1.79	55.8	4.07	ND	26.0	23.6	0.363	2.60	24.7	46.4	1.39	2.51	388	234
Mary Walker Bayou	Natural		4.45	5.68	8.22	10.8	1.31	105	11.3	30.4	0.336	1.09	13.9	81.9	1.84	0.137	259	95.8
Bayou Pierre	Natural		0.199	4.70	0.959	26.0	6.71	84.6	28.7	41.3	0.950	0.987	65.3	22.3	8.53	1.56	486	549
Twin Islands	Natural		6.00	9.09	7.01	13.3	0.746	1.52	7.96	104	0.307	0.686	40.6	83.6	0.292	0.447	217	182
Chevron N. Dock	Natural		8.11	14.5	10.7	17.5	18.0	1800	8.64	10.9	0.468	0.334	43.9	606	1.06	10.2	76.6	190
Cooling Tower Canal I[6]	Natural		6.42	1.54	1.80	2.76	780	412	252	184	2.95	3.72	493	438	9.25	93.3	121	313
Cooling Tower Canal II[6]	LTI 22°C	5.0 ppt	—	—	0.335	7.38	93.0	1340	166	108	3.06	5.14	122	1360	4.60	28.7	94.8	307
Cooling Tower Canal II[6]	LTI 22°C	14.0 ppt	—	—	2.18	4.60	248	1240	517	441	10.1	10.2	288	1450	16.1	50.5	110	357
Cooling Tower Canal II[6]	LTI 30°C	5.0 ppt	—	—	0.335	11.9	93.0	915	166	29.4	3.06	16.8	122	626	4.60	64.0	94.8	264
Cooling Tower Canal II[6]	LTI 30°C	14.0 ppt	—	—	2.18	6.80	248	919	517	61.7	10.1	39.7	288	886	16.1	86.5	110	274
Cooling Tower Canal II[6]	LTII 22°C	5.0 ppt	—	—	0.335	2.88	93.0	440	166	32.9	3.06	2.95	122	499	4.60	37.4	94.8	197
Cooling Tower Canal II[6]	LTII 22°C	14.0 ppt	—	—	2.18	10.9	248	501	517	41.5	10.1	7.33	288	561	16.1	42.5	110	203
Cooling Tower Canal II[6]	LTII 30°C	5.0 ppt	—	—	0.335	5.20	93.0	289	155	34.7	3.06	7.03	122	376	4.60	26.8	94.8	87.9
Cooling Tower Canal II[6]	LTII 30°C	14.0 ppt	—	—	2.18	3.99	248	431	517	27.7	10.1	9.98	288	323	16.1	26.8	110	111
Cooling Tower Canal II[6]	LTIII 22°C	5.0 ppt	—	—	0.335	1.51	93.0	258	166	10.4	3.06	2.61	122	287	4.60	52.2	94.8	200

TABLE 10. Sorption-desorption capacities of Mississippi Sound sediments (continued).[1]

Site Name	Conditions[2]	DOC mg/ℓ		TOC mg/ℓ		NH_3 µg-at N/ℓ		NO_3 µg-at N/ℓ		NO_2 µg-at N/ℓ		TKN µg-at N/ℓ		PO_4 µg-at P/ℓ		SiO_2 µg-at Si/ℓ	
		Before	After	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After
Pascagoula River System (con't)																	
Cooling Tower Canal II[6]	LTIII 22°C 14.0 ppt	--	--	2.18	9.30	248	314	517	49.6	10.1	7.48	288	462	16.1	52.2	110	221
Cooling Tower Canal II[6]	LTIII 30°C 5.0 ppt	--	--	0.335	4.93	93	184	166	13.1	3.06	4.42	122	252	4.60	33.6	94.8	151
Cooling Tower Canal II[6]	LTIII 30°C 14.0 ppt	--	--	2.18	3.43	248	301	517	65.3	10.1	7.48	288	426	16.1	45.0	110	207
West Prong	Natural	0.927	0.754	2.60	2.62	2120	591	331	289.0	4.75	10.7	1140	667	4.37	40.1	242	298
MS Chem. E. Bank	Natural	2.46	4.91	4.17	24.8	178	190	--	--	0.170	0.230	80.0	78.0	0.700	0.700	47.0	53.0
Graveline Bayou	Natural	0.629	1.08	0.473	8.86	18.4	32.1	10.1	13.6	0.432	0.584	46.0	51.6	0.656	1.32	171	250
Biloxi Bay System																	
Hewchem Indus. Canal	Natural	18.3	37.5	9.18	32.5	9.24	446	14.0	18.5	1.30	1.34	44.6	396	4.42	27.0	216	561
Turkey Creek	Natural	1.29	1.12	2.72	20.3	42.7	277	13.5	14.9	4.92	0.983	65.8	346	16.3	14.9	247	344
Gulfport Lake	Natural	4.70	12.3	0.127	15.3	36.0	93.0	13.3	24.2	0.914	0.914	219	237	4.18	4.61	193	349
Industrial Seaway[3]	5°C 6.5 ppt	10.4	9.32	17.4	13.4	2.31	25.1	21.1	509	0.180	0.180	87.9	80.2	3.63	0.214	244	271
Industrial Seaway[3]	5°C 15.0 ppt	10.4	11.3	17.4	12.0	2.31	56.3	21.1	524	0.180	0.230	87.9	ND	3.63	0.370	244	400
Industrial Seaway[3]	27°C 6.5 ppt	10.4	12.8	17.4	10.7	2.31	57.9	21.1	146	0.180	0.300	87.9	28.6	3.63	0.060	244	201
Industrial Seaway[3]	27°C 15.0 ppt	10.4	8.57	17.4	10.2	2.31	38.5	21.1	46.4	0.180	0.730	87.9	28.2	3.63	0.290	244	158
Industrial Seaway[3]	LTI-1[5]	10.4	8.33	17.4	2.72	2.31	38.9	21.1	78.1	0.180	0.161	87.9	25.0	3.63	0.237	244	143
Industrial Seaway[3]	LTI-2	10.4	7.11	17.4	2.03	2.31	30.1	21.1	18.4	0.180	0.346	87.9	60.2	3.63	0.486	244	131
Industrial Seaway[3]	LTI-3	10.4	8.59	17.4	1.56	2.31	61.9	21.1	21.8	0.180	0.655	87.9	65.3	3.63	0.486	244	163
Reichhold Indus. Canal	Natural	7.97	14.5	1.70	14.4	20.4	449	22.2	34.3	0.803	0.970	68.5	573	5.65	27.9	199	429
Coley Island	Natural	1.98	1.89	1.09	0.592	25.5	64.1	8.16	13.3	0.358	0.393	53.9	147	1.05	0.796	137	227
Power Plant I[7]	Natural	3.36	3.42	6.80	6.21	1.26	6.49	5.94	11.1	0.080	0.115	48.8	101	3.51	0.457	168	166
Power Plant II[3,7]	5°C 8.0 ppt	7.42	11.6	8.13	38.5	6.27	23.1	11.3	538.0	0.130	0.370	79.1	22.8	0.450	1.53	169	507
Power Plant II[3,7]	5°C 15.0 ppt	7.42	8.53	8.13	41.2	6.27	40.2	11.3	15.8	0.130	0.400	79.1	58.3	0.450	0.440	169	306
Power Plant II[3,7]	27°C 8.0 ppt	7.42	11.8	8.13	34.8	6.27	21.8	11.3	140.0	0.130	1.23	79.1	73.5	0.450	0.760	169	214
Power Plant II[3,7]	27°C 15.0 ppt	7.42	10.6	8.13	44.2	6.27	23.2	11.3	50.3	0.130	0.160	79.1	135	0.450	2.46	169	432
Power Plant II[3,7]	LTI-1[5]	7.42	1.04	8.13	127	6.27	38.8	11.3	86.4	0.130	0.408	79.1	15.2	0.450	3.45	169	139
Power Plant II[3,7]	LTI-II	7.42	6.19	8.13	64.3	6.27	25.2	11.3	28.1	0.130	0.377	79.1	14.7	0.450	1.48	169	433
Power Plant II[3,7]	LTI-III	7.42	3.47	8.13	5.47	6.27	12.8	11.3	24.8	0.130	0.346	79.1	3.00	0.450	0.321	169	97.8
V.A. Hospital	Natural	2.16	0.035	1.89	7.05	20.8	62.5	65.4	63.0	0.365	0.890	50.7	77.7	1.38	3.63	337	444
Rhodes Point	Natural	13.2	2.66	3.47	2.89	1.37	35.4	57.9	58.7	0.249	1.90	9.14	49.9	0.989	2.15	203	480
Deer Island	Natural	1.44	1.13	1.92	0.489	269.0	41.3	9.18	11.1	0.072	0.413	128	118	1.39	0.539	290	301
Old Fort Bayou	Natural	0.342	2.01	2.19	3.23	ND	6.74	11.3	10.9	0.661	0.776	56.1	79.9	0.573	1.40	285	291
Davis Bayou	Natural	1.08	0.959	0.586	0.081	75.8	29.3	432	404	0.890	1.92	14.3	35.2	1.65	1.23	350	418
St. Louis Bay System																	
St. Louis Bay Bridges	Natural	1.52	3.05	0.675	3.91	0.769	34.3	5.34	6.50	0.034	0.110	48.8	82.4	0.455	0.793	128	223
Heron Bay	Natural	2.93	8.52	2.30	5.08	0.964	28.8	5.32	18.6	0.110	0.450	97.3	73.5	0.539	0.878	211	304

TABLE 10. Sorption-desorption capacities of Mississippi Sound sediments (concluded).[1]

Site Name	Conditions[2]	DOC mg/ℓ		TOC mg/ℓ		NH_3 μg-at N/ℓ		NO_3 μg-at N/ℓ		NO_2 μg-at N/ℓ		TKN μg-at N/ℓ		PO_4 μg-at P/ℓ		SiO_2 μg-at Si/ℓ	
		Before	After	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After
Mississippi Sound System																	
East Gulfport Channel	Natural	1.77	5.63	2.27	0.701	6.22	32.7	15500	11100	0.110	5.89	36.6	49.4	0.285	0.624	193	499
Ship Island	Natural	4.59	1.45	1.55	2.35	7.07	19.5	32.7	63.4	0.034	0.337	47.6	68.1	0.116	62.4	252	336
Horn Island	Natural	2.74	0.780	3.52	0.506	24.9	19.7	3.65	6.32	0.110	0.450	81.4	76.5	0.116	0.708	171	251
Open Gulf	Natural	4.35	5.29	4.55	6.97	12.23	67.6	4.98	6.19	0.161	0.130	0.840	36.9	0.156	1.23	29.9	151

[1] Except as noted conditions for simulated sediment exposure involved an initial analysis of filtered site water (the "before" value), addition of sediment in ratio 1:4 (wt. sediment:volume site water), agitation for 5 minutes, filtration (not for TOC "before" or "after") and a repeat analysis ("after").

[2] Temperature and salinity are as stated; "natural" indicates ambient temperature and site water salinity as collected.

[3] One "before" run with four exposure tests at temperature and salinity extremes normally encountered. Salinity adjusted by addition of ultrapure NaCl.

[4] Not detected.

[5] Long term impact study. At ambient temperature and natural salinity, two successive extraction tests were run on the same sediment with two batches of site water. The third extraction was conducted one week later.

[6] Tests run on sediment and two separate collections of site water. Cooling Tower Canal II had long-term impact extractions (as described in footnote 5) conducted at four temperature/salinity conditions.

[7] Power Plant I at cooling water discharge canal; II at intake canal.

whereas the other half reduced DOC thereby lowering the net organic material left in solution. This disparity does not seem to be related to pollution levels in the sediments but is an endemic feature of sedimentary composition. As expected from high organic carbon values in these sediments (see Table 4), TOC increased after resuspension in all cases. It was in regard to ammonia values that the effect of sediments on aqueous levels of dissolved constituents was most pronounced. After resuspending most sediments from the Pascagoula River System, very high levels of dissolved ammonia were released into the water column, five to ten times the amounts released by sediments from any other site in the Sound. Only Twin Islands and Graveline Bayou sediments failed to show a dramatic increase in dissolved ammonia.

Just east of the Pascagoula River in Bayou Casotte, tests at Cooling Tower Canal I and West Prong were conducted during a period when water pollution was at a very high level in the bayou. Using this polluted water as site water in the "before" and "after" tests underlined some very profound attributes of bottom sediments. These particular simulated resuspension studies show that in a sediment disturbance event, regardless of ambient levels of soluble constituents in the water, the sediment plays the dominant role in establishing the post-disturbance budget of soluble components in the water column. Bayou Casotte sediments behaved no differently than any other sediment studied in Mississippi Sound in this regard. Even the excessive loads of petrogenic hydrocarbons found at Cooling Tower Canal and West Prong (see Table 4) did not interfere with this "regulating" capacity of the sediments.

Cooling Tower Canal sediment was dispersed in two site water samples of entirely different composition (two different collections). Results of these two tests are depicted on Figure 17. (Temperature and salinity conditions of 22°C and 14 ppt, respectively, and the first of the 12 suspensions were chosen from Cooling Tower Canal II results in Table 10 for comparative purposes because these conditions duplicated those test conditions used for the Cooling Tower Canal I test.) In the earlier collection, free ammonia and DOC loads were reduced in the water after resuspension at Cooling Tower Canal (and West Prong) as seen in Table 10, whereas in the later collection, both variables were increased significantly as a result of sediment suspension. It was further documented that repeated resuspensions of this same sediment in successive batches of site water resulted in concentrations of these soluble components not too different from those found after the first suspension. Furthermore variations in temperature and salinity, although affecting the magnitude of water column change, did not affect the direction of change, i.e., increase or decrease.

These suspension studies also gave evidence of considerable loads of phosphorus and nitrogen in water and sediments of Bayou Casotte attesting to input from a nearby fertilizer chemical plant. The most critical observation was made on the exchange of DOC with sediment and water of Bayou Casotte. Dissolved organic carbon is known to facilitate the acceptance of aliphatic and aromatic hydrocarbons into the water column[1,12,13] and may prove to be an important factor in the control or release of toxic organic substances from sediments.

In most instances for Pascagoula River sites nitrate levels tended to increase by about the same order of magnitude as occurred with dispersal of sediments from other regions of the Sound. Most interestingly the largest relative increase of nitrate after dispersal occurred at Twin Islands, the area least subjected to pollutants of all sites in this region. Even though the nitrite values achieved after sediment dispersal were typically higher in tests using Pascagoula River sites than other Sound locations, the effect of sediments on the final level was not particularly pronounced. Some sediments caused slight reduction and others slight increase indicating that water masses in the Pascagoula River System would not be terribly affected by resuspending the underlying sediments.

Total Kjeldahl nitrogen showed an increase after suspending sediments from most sites, reaching values two to five times those found at other regions of the Sound. Serious departure from this generalization occurred only at Bayou Pierre, West Prong and Paper Mill sites, which all showed a slight decrease after sediment dispersal. The most pronounced increases occurred with sediments from McInnis Lake and Griffin Point, both locations near sewage outfalls which typically would be enriched in

nitrogenous waste products. Little significance could be attached to the random increases and decreases in orthophosphate effected by dispersal of Pascagoula River sediments in water. No relationship could be seen with known pollution levels, increases and decreases in other variables or presence of suspected sources with the aforementioned exceptions of stations in Bayou Casotte near a fertilizer plant.

An increase in silicate from 1.5 to 2.0 times background values occurred in samples from the Pascagoula River area. Only at Twin Islands, Mary Walker Bayou and Lake Yazoo did silicate decrease. No explanation is apparent for the behavior of sediments at these three sites.

Biloxi Bay System. In Biloxi Bay, DOC increased or decreased only slightly at most stations. The most notable changes occurred in experiments with sediments from V.A. Hospital and Rhodes Point, both in the eastern half of Biloxi Bay. Dissolved organic carbon dropped significantly after suspending these two sediments indicating a paucity of soluble organics in these samples. Of note also is the fact that Hewchem Industrial Canal sediments displayed the highest net DOC of any sediment tested after resuspension. In stark contrast with the Pascagoula River sediments, some Biloxi Bay sediments had lower TOC values after disruption, in particular Industrial Seaway, Coley Island, Deer Island and Davis Bayou.

Increases in ammonia content in the Biloxi Bay System were not nearly as dramatic as those for the Pascagoula River System. At Deer Island and Davis Bayou, at the eastern end of Biloxi Bay, the deposited sediments apparently are depleted in associated ammonia because levels dropped after dispersal of these sediments. At the western end of Biloxi Bay an equally impressive phenomenon took place with respect to nitrate levels. Most stations experienced little change in nitrate content, but the Industrial Seaway and Power Plant sites had tremendously increased nitrate values when sediments were dispersed. Nitrite values were little affected in the water column by dispersal of Biloxi Bay sediment, but TKN doubled at most sites and increased even more at Reichhold and Hewchem Industrial Canals, areas near industrial effluent release.

Sediments exert a random effect on overall orthophosphate levels in Biloxi Bay depending on the site with uniform increases being predicted at all sites for silicates.

St. Louis Bay System. Only two stations were measured in the St. Louis Bay area but the following trends seem to hold for this western Sound area. Dissolved organic carbon and TOC demonstrated substantial increases after sediment agitation but less than those found at Biloxi Bay and Pascagoula River. Ammonia behavior paralleled that of Biloxi Bay. Only at Heron Bay was nitrate much affected in a water column infiltrated with bottom sediments. Biloxi Bay and St. Louis Bay sediments were very similar in their potential effect on nitrite levels. Total Kjeldahl nitrogen showed opposite effects at both stations, but orthophosphate and silicate both increased as a result of sediment disturbances.

Open Mississippi Sound System. In the open Sound, sediments have sorption-desorption characteristics most like those of St. Louis Bay. Both are areas with low levels of pollution. Notable exceptions to this pattern of similarity occurred with respect to nitrate behavior at E. Gulfport Channel where ambient nitrate levels were astoundingly high before introduction of sediment. This sediment dropped the nitrate substantially, but final values were still very high. The other exception was orthophosphate behavior with Ship Island sediment-water mixes which resulted in very large increases in orthophosphate.

Salinity, Temperature Variations

Enhancement of TOC seemed to occur with lower salinities and increased temperatures which had only negligible effects on DOC levels produced by sediment dispersal. No consistency of any pattern attributable to salinity or temperature could be discerned at any site studied for ammonia level modifications by sediments. Even at the Cooling Tower Canal, long-term exposure trends are inconsistent in each of the sequential extractions. The effect of these physical variables on nitrate release-uptake is very predictable based on these studies. Both lower temperatures and lower salinities promoted release of nitrate into the water column with salinity tending to be the dominant factor. These lowered temperatures and salinities retarded uptake of nitrate as

observed in repeated suspensions of Cooling Tower Canal where original values of nitrate were very high and declined less as a result of sediment exposures at lowered temperatures and salinities.

A dichotomy of results occurred in nitrite uptake-release using variable temperature and salinity conditions. At Halter Marine, Escatawpa River Bridge and Dead River sites, nitrite was released in greater quantities at low salinity and temperature whereas greater release of nitrite at Cooling Tower Canal site occurred at high salinity and high temperature. At the two sites in Biloxi Bay, Industrial Seaway and Power Plant II, neither temperature nor salinity had any discernible affect on nitrite consumption or liberation by sediments. It may be concluded then that the predominant factor(s) controlling nitrite activity of sediments is not temperature and/or salinity. Total Kjeldahl nitrogen also showed somewhat the same erratic behavior with enhanced release occurring at lower temperatures during all suspensions at Cooling Tower Canal but with retarded release accompanying low temperatures at both Halter Marine and Escatawpa River Bridge sites. The two sites in Biloxi Bay also displayed opposing behavior, one with an increase at low temperatures and the other with increased release of TKN at higher temperatures.

No generalizations can be made on the temperature or salinity effects on orthophosphate behavior during sediment dispersals. Each station provided uptake and release that set no easily discerned pattern. Orthophosphate also tended to respond to other sediment and water conditions more than to temperature and salinity variations. These other variables seem to be well defined however, for as erratic as the results seemed at Cooling Tower Canal, the overall effects relating to orthophosphate were consistent in all suspensions. To a lesser degree silicate also seemed to react to salinity and temperature changes, but with other geochemical variables also playing a significant role that is specific for each sediment.

Successive and Periodic Disturbances

Studies to determine the effect of repeated or successive disturbances of sediments revealed some most intriguing information. The ability of sediments to substantially alter the chemical composition of overlying water during a disturbance incident is not significantly affected by repeated resuspensions regardless of whether these repeat episodes occur in quick succession, e.g., twice in one day or with greater time lapses between repeats, a week or longer. At Dead River site there was a slight decline in water enrichment of soluble components promoted by a second suspension of sediment and a somewhat smaller decline after a week elapsed before the third resuspension. Interestingly both DOC and orthophosphate were even more liberally released by these sediments in each successive suspension. Apparently the first suspension changed some chemical characteristic of the sediment so that the desorption mechanism was enhanced. These same phenomena were also noted for the Cooling Tower Canal site. At the Industrial Seaway site, very little difference in impact on water-soluble composition is expected due to repeated suspensions because little difference in the "after" values was noted for the successive suspensions. Power Plant site sediments behaved as originally expected with a slight depression in material leached from the sediment each time the sediment was suspended.

Although irrefutable evidence has been presented to confirm the dramatic impact that sediments would have on water column composition during a sediment disturbance event, the concept as it relates to the Environmental Stress Index is not as easily defined or understood. Therefore, rather than attempting to reduce this very complex data to a numerical rating, it is offered as ancillary information to be used with other factors fed into the index to more fully comprehend and judge the ultimate fate of environments exposed to natural or man-made dispersal of bottom sediments into the water.

Disturbance Probability

The occurrence and level of potentially dangerous compounds bound to the sediment in any given region of Mississippi Sound is certainly insufficient information to accurately assess the actual harm that any sediment poses to the surrounding environment. Because the greatest impact would occur during a disburbance, it is of utmost importance to know the likelihood of a disturbance. Although not

suitable for laboratory study, nevertheless this concept would have to be evaluated and numerically rated in as objective a manner as possible. Therefore, a panel of experts was chosen whose knowledge and field experience would permit them to assess all factors affecting the likelihood of disturbance. This team was composed of William Demoran and James Warren of the Gulf Coast Research Laboratory (GCRL), Ocean Springs, MS, and Ron Herring, Tom VanDevender and Chris Snyder from the Mississippi Bureau of Marine Resources. Among considerations for the one to five ranking were: water depth, density of boat traffic, dredging activity, tidal force, fish trawling, river flow turbulence, and benthic community composition. Each of the five panelists rated the 35 zones independently after group discussion, and the averages of their ratings are listed in Table 9. It is of interest that the range of rankings for any one station never exceeded one unit, showing a consensus of opinion and giving additional credence to the mean value used in the Environmental Stress Index. The importance of this factor can be illustrated by selectively examining index factors at two stations shown on Table 9. At Lake Yazoo, the highest rating was given in exposure mortality and in biota susceptibility (to be discussed later). However, the potential harm of these sediments is lowered because disturbance incidents would occur infrequently. Conversely, the fairly low mortality rating for the Escatawpa River Bridge site is magnified by an extremely high probability that these sediments will be disturbed and impact the resident organisms of the area.

Biota Susceptibility

The last area of concern rated addressed the question of organism community diversity throughout the Sound. Realizing that each species of organisms has a unique resistance and resilience to casualty from pollutants, an effort was made to provide a rating system to express the innate differences in this susceptibility or vulnerability of the entire community structure of each of the 35 zones. Again to be as objective as possible, a panel of three fisheries biologists from GCRL was enlisted to evaluate this factor. The biologists were Richard Waller, Harriet Perry and William Demoran, each with more than a decade of experience in conducting biota community surveys in the Sound. The criteria used in the rating decisions were: the ecological significance of resident organisms, the mobility of these organisms, presence of "escape" routes in the vicinity, the predominance of early life stages of organisms which are usually more vulnerable to chemical toxicants, the diversity of the community, if high, that would most likely be less adversely affected than monospecific communities, and the knowledge of the sensitivities of the various organisms to stress events in the environment. Averages of the individual ratings are contained in Table 9. Note that no station was rated at either the high or low end of the spectrum. The consistency of the ratings indicates that, although the composition of organisms is quite variable in different segments of the Sound, the susceptibility of these communities to an assault by a pollution incident varies little from one community to another.

Combined Index

In assessing the potential harm associated with polluted sediments in discrete regions of Mississippi Sound, each of the four rated categories, as well as the unrated factors of pollutant level and leachability, must separately be given careful scrutiny. A less rigorous approach may be taken, however, in giving an overall view of the entire Sound or in comparing one area to another. By giving equal weight to each of the four rated factors in Table 9 and realizing the compounding effect of one high rating upon another, an Environmental Stress Index, also listed in Table 9, becomes the product of these factors. This concept has been taken one step further to ease comparisons and dramatize differences in the Sound. The indices have been plotted in Figure 18 as circles with diameters directly proportional to the magnitude of the calculated index in Table 9. Trouble areas or "hot spots" are immediately apparent in Figure 18 as existing at the Pogey Plant in the Escatawpa River, at Lake Yazoo at the mouth of East Pascagoula River, and at Gulfport Lake in the Industrial Seaway of Bernard Bayou of western Biloxi Bay. Among those sites with an intermediate danger signal are Escatawpa River

Bridge, Mary Walker Bayou, Cooling Tower Canal, Rhodes Point, and Deer Island. An interest in the "whys and wherefores" of these danger zones leads back to Table 9 and reveals some interesting surprises. It might be inferred that the "hot spots" would be those sites with the most toxic sediments and for Lake Yazoo and Pogey Plant that is true. However, to be designated as a "hot spot" on Figure 18 requires relatively high ratings in at least three of the four categories; one or two high ratings is not sufficient. Furthermore, many of the zones of intermediate danger are not rated as such because of deadly toxic sediments but because moderately toxic sediments are either of such composition as to be efficiently resuspended, located where sediments are frequently distrupted, or found in regions where the resident organisms are imminently susceptible to any stress. If a rating of 4 had been given in all four categories to any site, the index would have produced a circle twice the size of any shown on Figure 18. Therefore, in the total concept, there is no station that would be classified as a disaster area.

Looking at the three river-bay systems along the coast, one notices from Figure 18 that the Pascagoula River System or eastern Sound, compared to other broad regions, has the greatest number of sites where polluted sediments may pose a significant threat. It is further observed, as was noted earlier in the transport and pollution distribution studies, that the regions of danger do not cover extensive tracts of waterways but are limited to relatively small regions within the Pascagoula River and upper Bayou Casotte. The central Sound around Biloxi Bay contains regions that pose significantly less environmental threat than the eastern Sound except those sites at the western extremities of Biloxi Bay, along Bernard Bayou whre indices are considerably elevated. Sediments of the St. Louis Bay System pose no real danger at the present time nor do the sediments offshore in the Open Sound and beyond the islands, all of which are described by relatively low environmental stress indices.

The idea of an environmental stress index was developed with no single user in mind but was envisioned to meet the very real need to have available a means to appraise the pollution problems of the various areas of the Sound. It is anticipated, however, the user groups will include those who may influence the use of lands bordering the waters of southern Mississippi. It has been gratifying to have agencies in the National Oceanographic and Atmospheric Administration (NOAA), other than Sea Grant, express interest in this index concept which may be developed by other investigative teams throughout the country. The U.S. Army Corps of Engineers (COE), Vicksburg District, has consulted with the principle investigators on a similar technique for use in Corps projects, and the COE, Mobile District, has solicited all of these data fed into the index system for use in their land use evaluation program. During a hearing in Gulfport, MS, to inquire about the feasibility of annexing land along Bernard Bayou in Biloxi Bay, the information packet pertaining to indices of the Biloxi Bay system was presented in evidence to show the present status of this system. The Mississippi Bureau of Pollution Control used the stress index in a hearing that brought about charges being filed against an industrial plant along Biloxi Bay. The completion of the index concept occurred late in this research program, but the reception by decision-makers and scientific personnel gave convincing proof of the need for this type of analysis in estuarine research. It cannot be emphasized too strongly, however, that this must not be construed as a static system. If dreding activity accelerates in some regions, if industry or municipalities are allowed to dump materials in previously "clean" areas, or if some regions are cleaned and renewed, the stress index would also change. The index is certainly not perfect because it must simplify an enormously complex system of interrelated environmental conditions. Nevertheless, this method can help remove much of the speculation and mysticism surrounding sediment pollution and promote a more informed and rational understanding of pollution impact for industry, coastal zone managers, and the public.

USE OF SCIENTIFIC INFORMATION

In a scientific investigation of the magnitude and scope of this study, the question arises, "How can such a massive body of data be presented so that the people who need it can use it?" Several experimental avenues were tried in an effort to convert the large data base into usable scientific information and to provide a means of communicating this valuable estuarine information to others. Some communication efforts met with acceptance only after several years, but continued persistence and questions from those who needed the pollutant data gave assurance of maximum usefulness. The user groups initially targeted were given the most consideration in the development of the varied data formats, but consideration was also given to a broader audience with unspecified interests and informational needs about pollution. In 1979, the program was envisioned ultimately to provide information to federal, state and local agencies, private enterprise, and interested individuals. User groups throughout the program have come from all of these disciplines. And now, although the active research phases of the study were completed in 1983, interest in the results has mushroomed again attesting to the benefit of persistent efforts to encourage use of these data.

User Groups

At the federal level this study has provided information to several agencies including the COE, Mobile District, which has used the information in proposal request preparations and in the design of dredge spoil disposal studies. As mentioned earlier, the core profiles were designed with COE's needs in mind. It is believed that these profiles have helped move the COE towards a posture on dredging impact statements based on stratigraphic sediment pollutant data rather than the present strategy of using homogenized cores to make decisions. The Vicksburg District of the COE has been aided in designing a hydrocarbon analysis program and also in the development of a sediment evaluation scheme using concepts included in the Environmental Stress Index. Requests for data to be placed in data banks have been received from several agencies including the Federal Toxic Water Watch. Following an estuarine research workshop in which the principle investigators (PIs) presented goals and accomplishments of this study, NOAA officials requested information on the Environmental Stress Index to help in the development of a similar guideline to be used on a national scale.

Officials of the U.S. Fish and Wildlife Service have contacted the principle investigators on more than one occasion to help evaluate biological effects of polluted sediments. The PIs have also made efforts to share the data base with the Environmental Protection Agency (EPA) laboratory at Bay St. Louis, MS and Gulf Breeze, FL. Although the former expressed high interest early in the program, this interest waned with administrative changes within the EPA. This was distressing because the communication gap with the EPA needed to be bridged because of the limited and sporadic sampling and analysis that EPA has been allowed to conduct in Mississippi Sound. This situation seems to have been resolved, however, by the keen interest shown in the last phases of this study by the Florida EPA laboratory. The National Marine Fisheries Service centers in Bay St. Louis and Pascagoula, MS, have requested help in designing sampling programs based upon results of the Pollutant Transport Study. Objectives of the two programs were sufficiently intermeshed that the PIs were able to add considerable insight into the selection of sample stations.

During the final year of this study a number of requests have come from the Mississippi Bureau of Pollution Control and other state agencies for information and advice concerning results of this study. The Mississippi Bureau of Pollution Control has, since its inception, devoted its field sampling and analysis exclusively to water samples, thereby ignoring sediment samples which now appear to be a much more powerful indicator of pollution problems. Through several consultations and data exchange programs, the Bureau has become aware of the value of sediment analysis and has requested help on several occasions. The area of most interest has been the Industrial Seaway of Bernard Bayou where two legal

disputes have been partially resolved by utilizing results of this study.

Requests have also been received from the Mississippi Research and Development Center to include the data of this program in their data bank, and by the Mississippi Highway Department for assistance in evaluating the environmental impact of a new bridge over the Escatawpa River. Another state agency, which has worked cooperatively with the principle investigators in the latter stages of this program, was the Mississippi Bureau of Marine Resources. This bureau exercises authority over the wetlands and has solicited help in interpreting possible damages resulting from dredging accidents and dredging permit violations in coastal waters.

Local officials and private industry have also shown an interest in study results. Representatives from International Paper Company located on the Escatawpa River have obtained information on our study results which are relevant to the operation of their plant. In a similar vein, Southern Corporation Services, representing several Mississippi power plants, has asked for data collected near power plants along the Mississippi coast. The principle investigators have had several data and informational exchange meetings with Chevron U.S.A. concerning operations of the oil refinery in Bayou Casotte. These meetings were aimed primarily at shedding light on all possible sources of the vast quantities of pollutants found in Bayou Casotte sediments. Several private consulting firms have contacted the PIs for help in writing and appraising dredging impact statements pertaining to Mississippi Sound waters. Private marina operators and numerous private citizens have contacted the PIs about particular problems to which solutions were provided by various findings of this study. A number of other scientific investigators have taken advantage of the knowledge and insight gained through this investigation. At least one foreign visitor has taken advantage of the study results. A representative of the French government visited the PIs in pursuit of further information regarding issues raised by the PIs at an international conference at which they presented results of this study.[67]

It has been primarily through the forum of scientific meetings and publications that this scientific information has been shared with colleagues, with scientists involved in closely aligned environmental studies, and with persons who desired data exchange and advice. Meetings at which poster and/or oral presentations were made include: the Mississippi Academy of Sciences annual meetings in 1979, 1980, 1982 and 1984; the American Chemical Society—New Orleans Discussion Group annual meetings in 1981 and 1983; the Southeastern Regional American Chemical Society meeting in Lexington, KY, 1981; the Southwest Geochemical Society Meeting in College Station, TX, 1981; Coastal Society 8, Baltimore, MD, 1982; a Sea Grant Symposium entitled "Mississippi Sound Symposium," held in Biloxi, MS, 1981; the Southeastern Water Pollution Biologists Association meeting, Biloxi, MS, 1983; Oil Spill Conference in San Antonio, TX, 1983; the American Chemical Society National Meeting in Seattle, WA, 1983; and a National Park Service Symposium held in Biloxi, MS, in 1983. Besides seminars given by the principle investigators at the GCRL campus, there have been formal talks presented at the University of Southern Mississippi in 1980, and at the University of Tampa, Tampa, FL, in 1982. The PIs have given papers and poster presentations at a NOAA estuarine workshop held in Newark, DE, in 1983, and at a Sea Grant workshop at the University of Florida, Gainesville, FL, in 1984.

A number of publications are in preparation at the time this manuscript goes to press covering in detail some of the aspects of this study only lightly touched upon in this report. Other publications that resulted at various stages of the study are listed below:

Lytle, T. F. and J. S. Lytle, *Interim Technical Report I: Pollutant Transport in Mississippi Sound,* Mississippi-Alabama Sea Grant Consortium, MASGP—79—032 (1981).

Lytle, J. S. and T. F. Lytle, *Pollution Impact in Mississippi Coastal Waters,* Mississippi-Alabama Sea Grant Consortium, MASGP—80—027 (1981).

Lytle, J. S. and T. F. Lytle, *Interim Technical Report II: Pollutant Transport in Mississippi Sound,*

Mississippi-Alabama Sea Grant Consortium, MASGP–80–028 (1981).
Lytle, T. F. and J. S. Lytle, "Monitoring pollutants in Mississippi Sound." Page 29 in *Symposium on Mississippi Sound* (Biloxi, MS), Mississippi-Alabama Sea Grant Consortium, MASGP–81–007 (1981).
Lytle, J. S. and T. F. Lytle, "Sedimentary record of pollution in the Pascagoula River," *Journal of the Mississippi Academy of Sciences* (Biloxi, MS) XXV (sup.) 20, Mississippi-Alabama Sea Grant Consortium, MASGP–82–041 (1980).
Lytle, T. F. and J. S. Lytle, "Phenolic compounds as chemical tracers of pollution migration," *33rd Southeastern Regional Meetings, American Chemical Society Abstracts* (Lexington, KY), p. 39, Mississippi-Alabama Sea Grant Consortium, MASGP–82–042 (1981).
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Lytle, J. S. and T. F. Lytle, "Pollutant transport in Mississippi Sound," Page 453 in *Proceedings Coastal Eight* (Baltimore, MD), Mississippi-Alabama Sea Grant Consortium, MASGP–82–046 (1982).
Lytle, T. F. and J. S. Lytle, "Potential damage of oil refinery wastes in coastal estuary sediments." Page 491 in *1983 Proceedings of Oil Spill Conference,* API, EPA, and USCG (San Antonio, TX), Mississippi-Alabama Sea Grant Consortium, MASGP–82–024 (1983).
Lytle, T. F. and J. S. Lytle, "Anthropogenic organic pollutants in sediments of Mississippi Sound." Page 103 in *American Chemical Society Extended Abstracts* (Seattle, WA), Mississippi-Alabama Sea Grant Consortium, MASGP–82–047 (1983).
Lytle, J. S. and T. F. Lytle, "Strategy of pollutant assessment in coastal waters." Page 51 in *Proceedings of the Northern Gulf of Mexico Estuaries and Barrier Island Research Conference* (Biloxi, MS), Mississippi-Alabama Sea Grant Consortium, MASGP–83–012 (1983).
Lytle, T. F. and J. S. Lytle, "An index system for evaluating the impact of sediment pollutants." *Journal of the Mississippi Academy of Sciences* (Biloxi, MS) XXIX (sup.) 10, Mississippi-Alabama Sea Grant Consortium, MASGP–82–048 (1984).
Lytle, J. S. and T. F. Lytle, "Pollutant profiles: A land management tool." *Journal of the Mississippi Academy of Sciences* (Biloxi, MS) XXIX (sup.) 11, Mississippi-Alabama Sea Grant Consortium, MASGP–82–049 (1984).

Education

An essential educational objective of this pollution transport study has been to let the public know how pollution affects Mississippi Sound, what the principle investigators of this

project have done to resolve this situation and what the public as private individuals can do to support corrective measures aimed at combating pollution.

The educational arm of this study has taken many forms. Several grammar school children have been directed in science fair projects involving pollution studies. Some of these projects have received awards beyond the local level and have aided in the dissemination of knowledge of the aims and goals of this project. One public seminar has been given, several talks have been made to civic groups, to high school and college groups and business groups visiting the GCRL campus and to the National Science Foundation Sea Grant Ecosystems' principle investigators who met at the Laboratory. Special posters and talks have been developed to give highlights of the projects to these groups. An open house at GCRL featured talks from both principle investigators concerning pollution on the coast.

The public has received bulletins of the progress and results of this study by several radio and television broadcasts, news releases in *Marine Briefs* (of GCRL), local newspapers and through informal encounters with various special interest groups. Videofilms were prepared that document all aspects of the sampling and analysis program. Geological descriptions of all the discrete sampling areas of the Sound have also been recorded on videotape for future reference by visiting groups. Pamphlets and manuscripts have been prepared and are available from the Mississippi-Alabama Sea Grant Consortium office on this project. In preparation now are two booklets to be followed by others giving a lay-language explanation of the Environmental Stress Index and sediment pollutant profiles. Enrichment groups from Long Beach and Ocean Springs schools have visited with the principle investigators for in-depth discussion of this project. A symposium sponsored by Sea Grant was also used as an outlet to distribute relevant findings to the public and scientists in attendance.

As a testimony to efforts made to convey this pollution information to the public, the Mississippi and National Wildlife Federation recognized the principle investigators with the 1983 Conservation Award in Water and Soil Conservation. Increasing the awareness of the public to pollution, raising its level of concern for the environment, and encouraging a more rational view of industry's obligation to control pollution have been among the principal missions of this total educational program which has continued well past the conclusion of the project.

Accomplishments and Benefits

This project was designed to be user-oriented and has accomplished that objective. A good data base of chemical and geological characteristics of bottom sediments has been generated and is complete for the entire Mississippi Sound and associated rivers and bayous. For the first time there are guidelines to assess the problem of polluted sediments and the possible environmental consequences of disturbing these sediments. Ratings of pollution troublespots have been mapped giving coastal planners pollution data in a form easily incorporated into the decision-making process. An active data exchange program has been inaugurated which should improve the credibility of all such research programs in the central Gulf and suppress needless duplication among those agencies with environmental responsibilities.

Several goals of this project have required cooperation and interworking with some state and federal agencies that have responsibilities congruent with objectives of this study. It has become apparent that many of these enforcement-regulatory agencies simply were unable to deal with all the pollution problems confronting them. Many of these problems have existed because the pollution data base was so very poor. Frequently decisions have been made by conjecture or were based upon economic considerations alone. This realization enabled the investigators to give some required redirection to this study which will give better scope and utility to the efforts of the enforcement-regulatory agencies. They all seem eager to accept this scientific input. The study has gone beyond just the generation of needed data. The project, by requiring input from other scientific workers at GCRL and other institutions of the Mississippi-Alabama Sea Grant Consortium, has formed the basis for better cooperative efforts of scientific teams in the two-state program. As a direct or indirect

result of this particular study and efforts to communicate coastal information, the public and scientific sectors have been brought into awareness of the severity of the pollution problems in Mississippi and their responsibilities to help combat the serious problems associated with development in the coastal zone.

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FIGURES 1 THROUGH 18

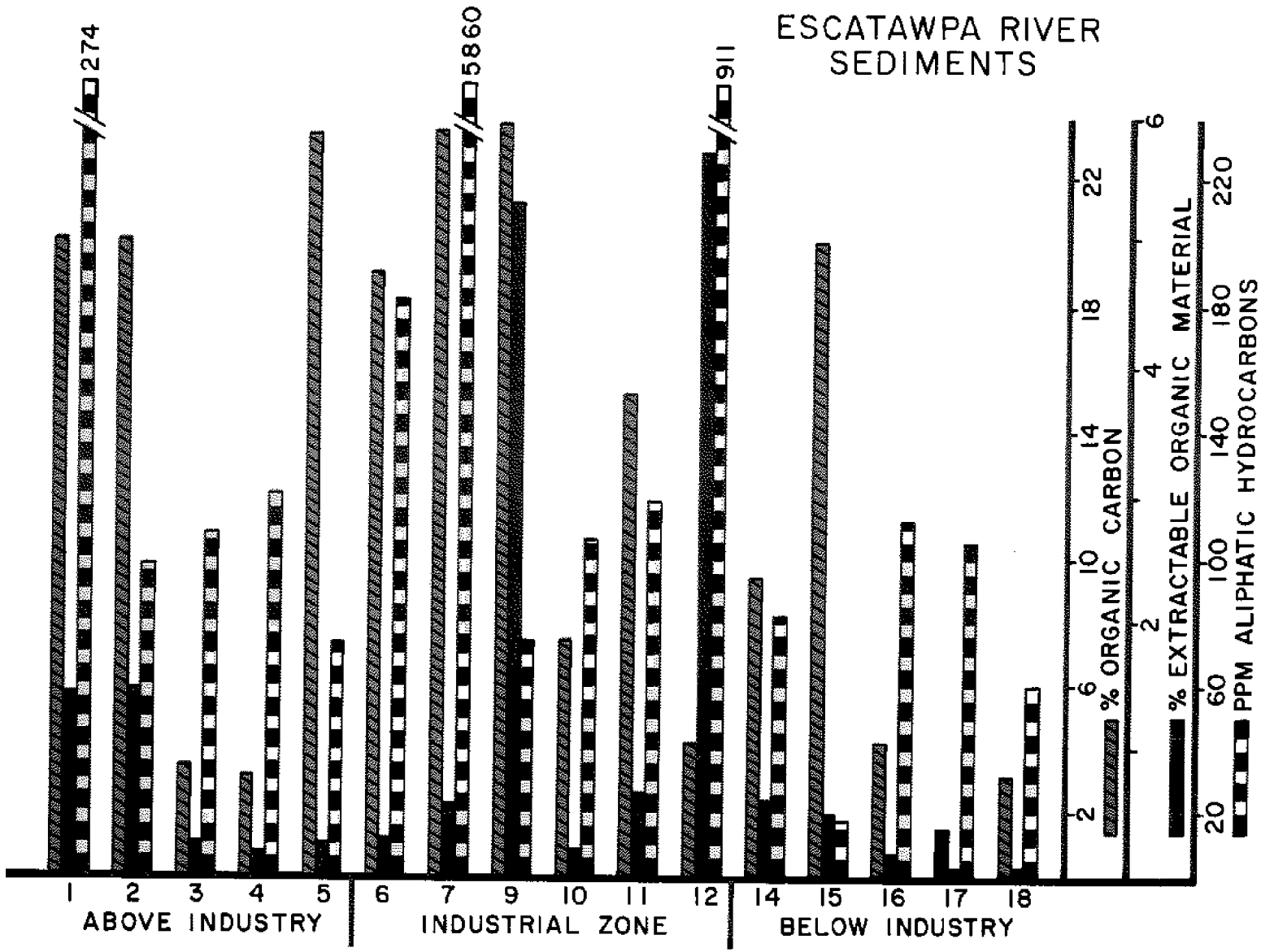


Figure 1. Gravimetric data from preliminary survey of Escatawpa River sediments. Numerical order of stations corresponds to the sequential placement of sites from upriver to downriver locations.

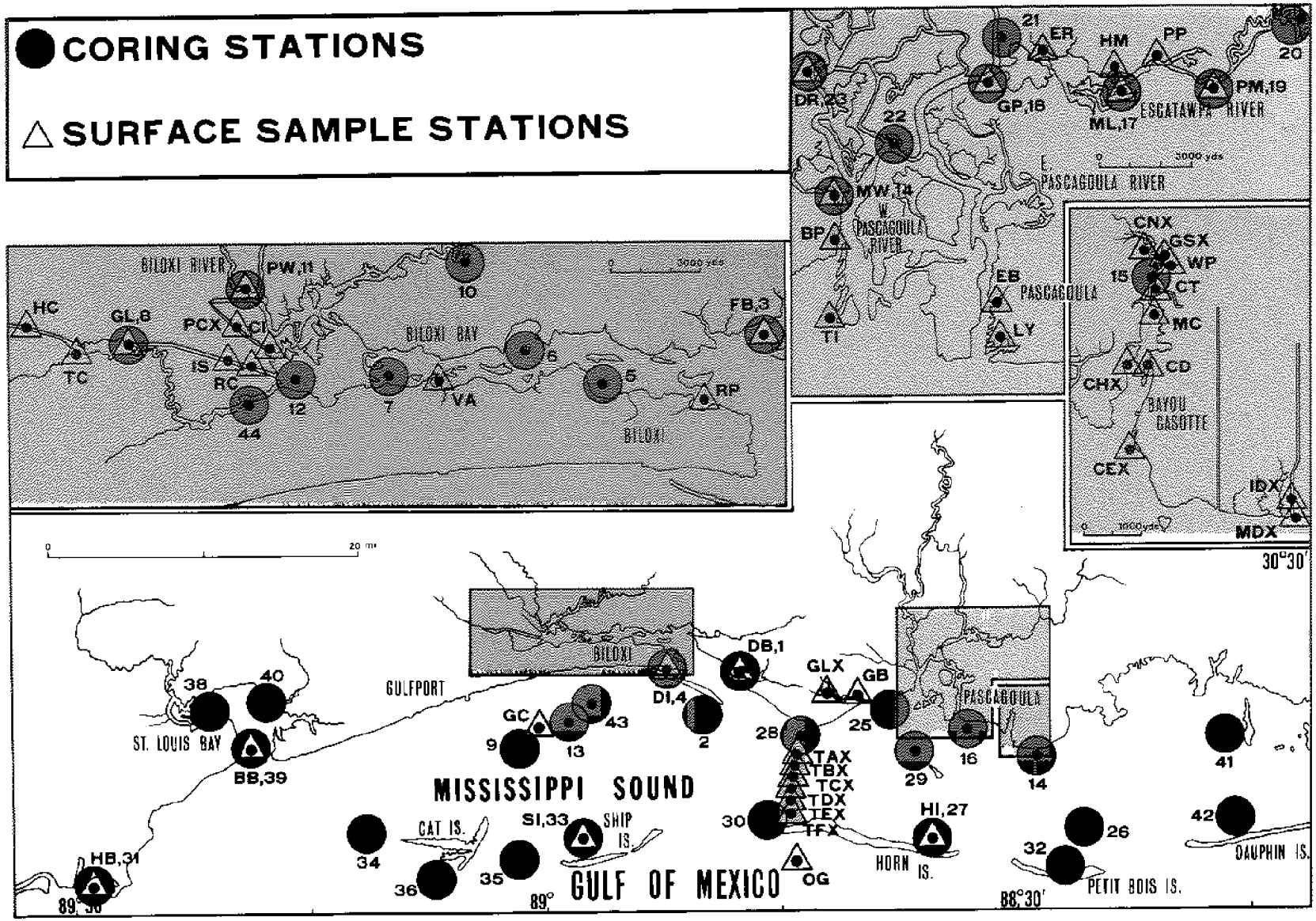


Figure 2. Sample site locations in Mississippi Sound. Location labels for the 43 core-sediment sites are fully explained in Table 2. The surface sample locations are described in Table 3.

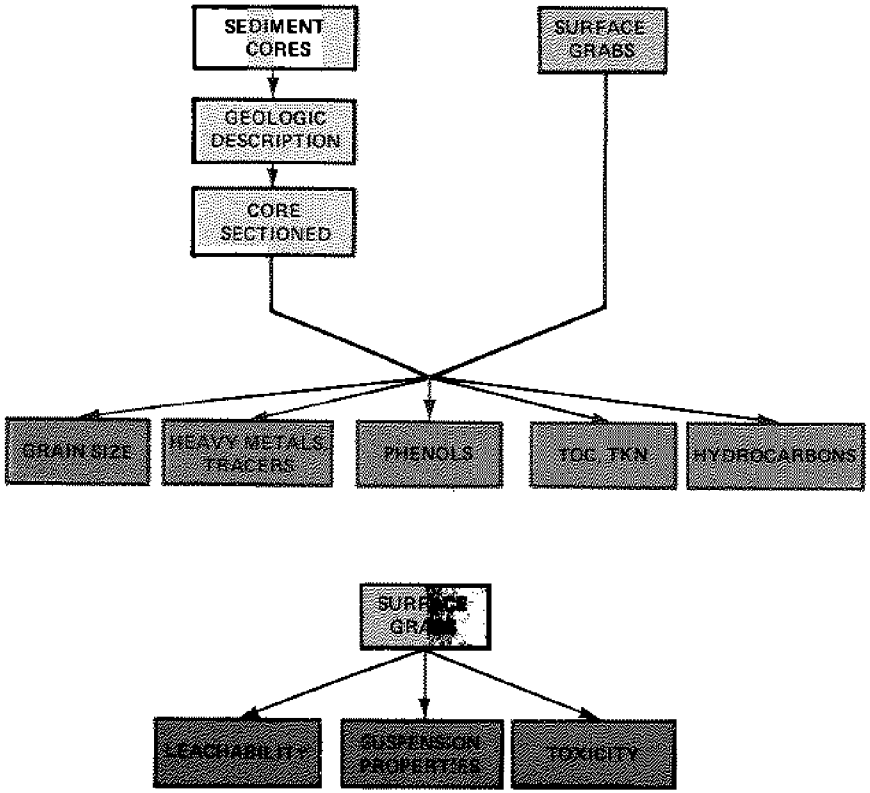


Figure 3. Sediment analysis scheme. After geological examination, sediment cores and grab samples were treated to the same analysis including grain-size distribution, trace metals (archived), certain chemical tracer techniques, total phenols, total organic carbon, Kjeldahl nitrogen and hydrocarbons. In addition surface grabs were characterized for leachability of nutrients, suspension settling rate properties and bioassay toxicities.

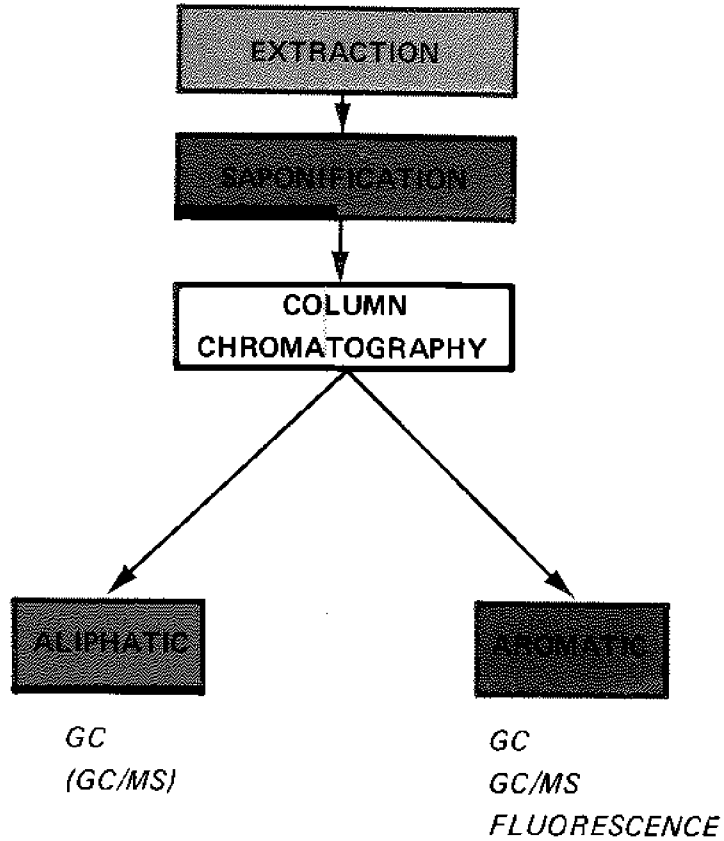


Figure 4. Hydrocarbon analysis scheme. Sediments were solvent extracted, the extract saponified to remove esters then chromatographed on silica gel/alumina to isolate aliphatic and aromatic hydrocarbons. Aliphatics and aromatics were identified by fused silica gas chromatography (GC) on a DB-1 column 15-m X 0.25-mm i.d., programmed at 90° to 250°C at 4°C per minute with a Perkin-Elmer (PE) 3920 or Sigma 2000 GC linked to a PE Sigma 10 data station. A few aliphatics and a considerable number of aromatics were further characterized by gas chromatography/mass spectrometry (GC/MS) at the GC/MS Center at the University of Alabama, Birmingham. Fluorescence scans were also obtained on all aromatic fractions with a PE MPF-44 fluorescence spectrophotometer.

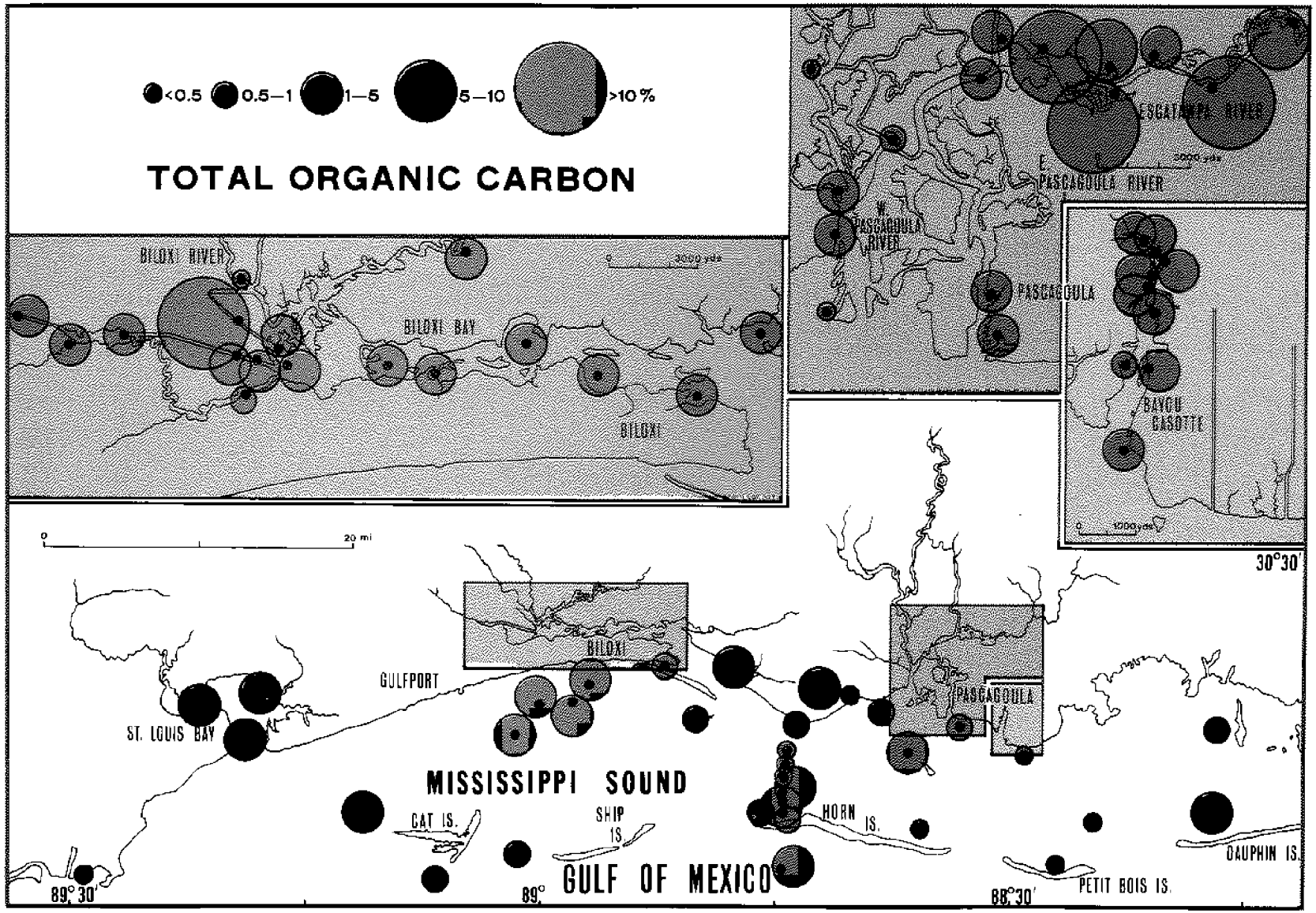


Figure 5. Total organic carbon in Mississippi Sound sediments. Values of organic carbon are depicted as concentration ranges of surface sediment secured from both surface grab samples and sediment cores. Precise values may be observed in Table 4. Station locations can be identified by referring to Figure 2 and Tables 2 and 3.

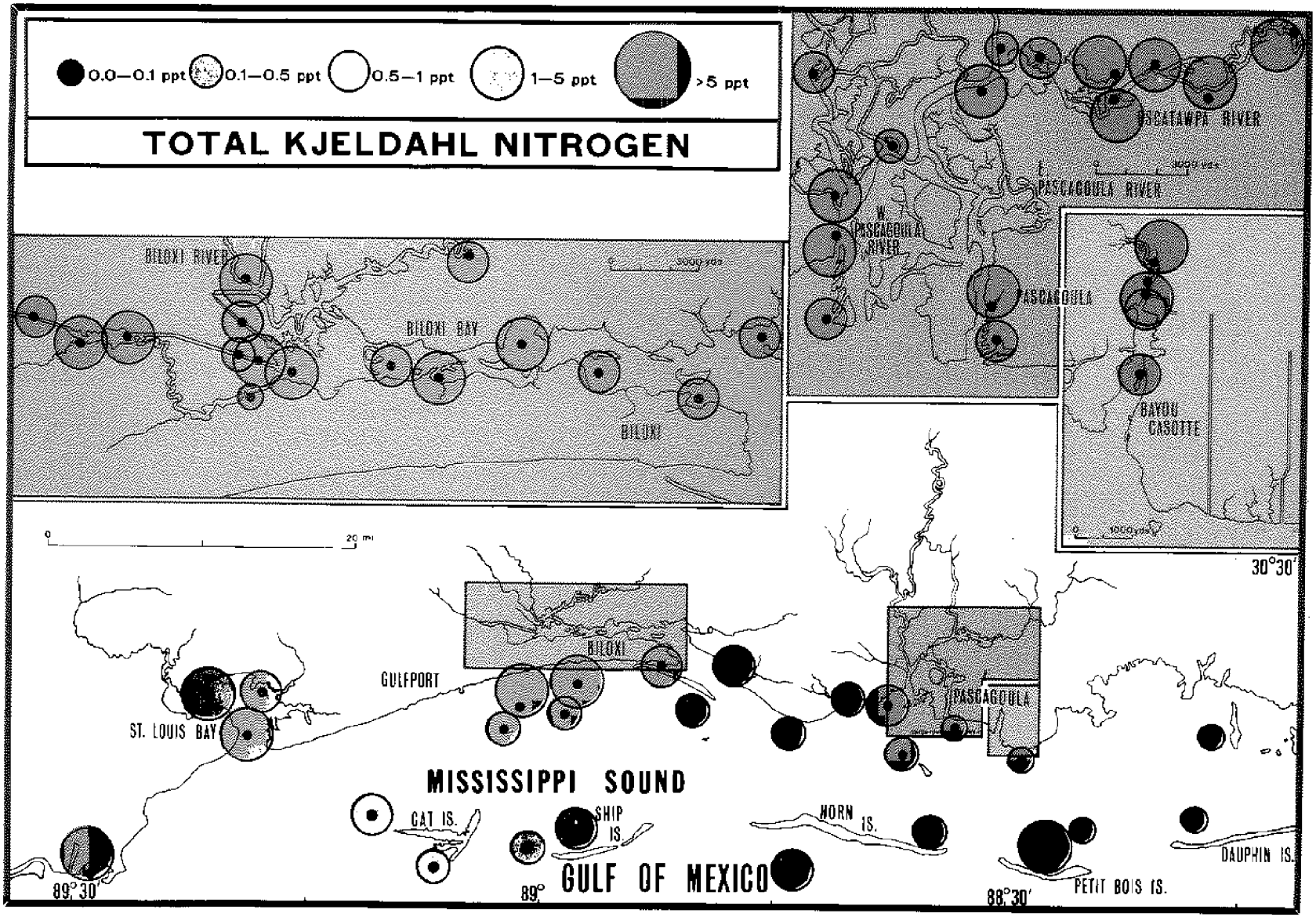


Figure 6. Total Kjeldahl nitrogen in Mississippi Sound sediments. Values of Kjeldahl nitrogen are depicted as concentration ranges of surface sediment secured from both surface grab samples and sediment cores. Precise values may be observed in Table 4. Station locations can be identified by referring to Figure 2 and Tables 2 and 3.

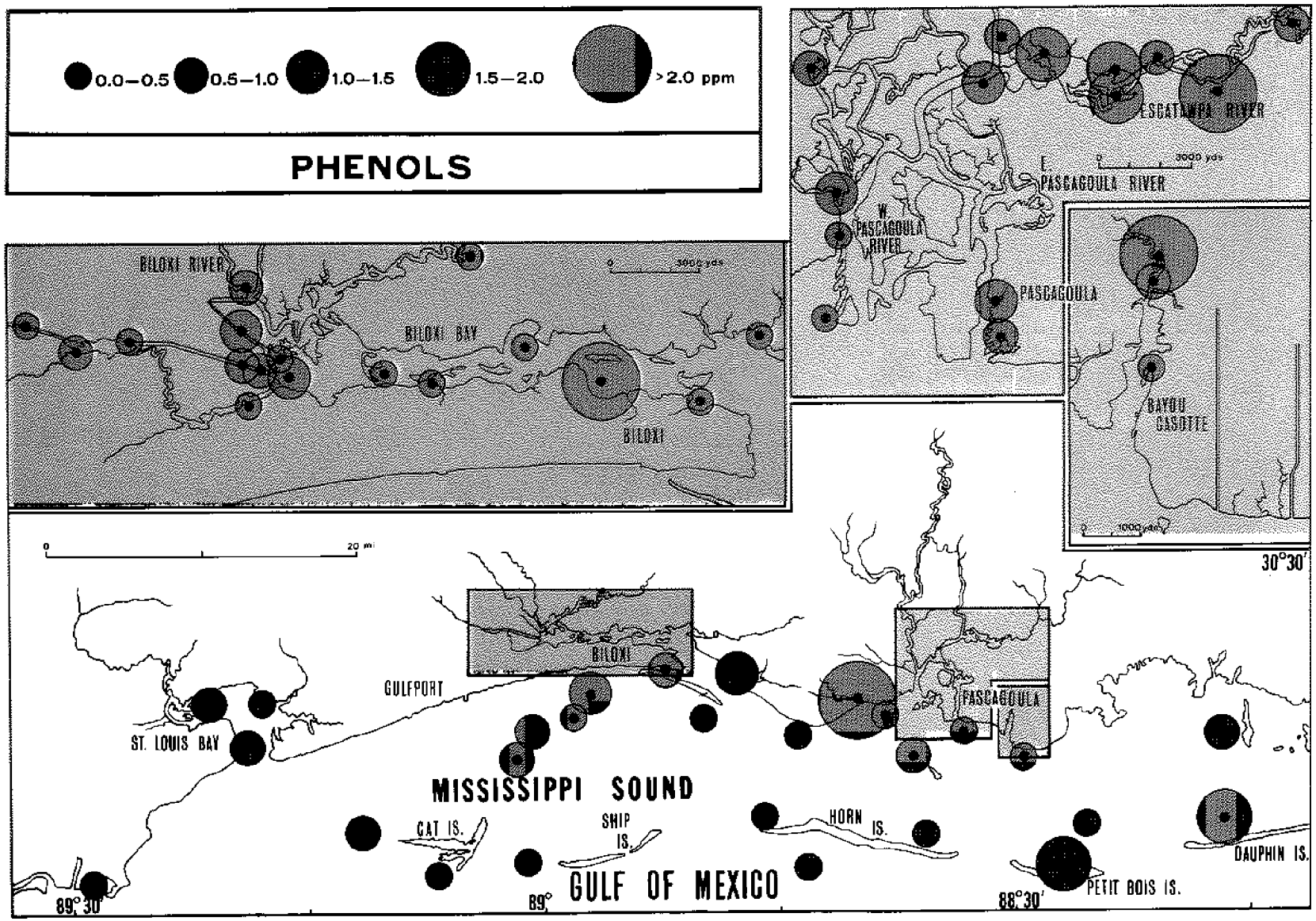


Figure 7. Total phenols in Mississippi Sound sediments. Values of phenols are depicted as concentration ranges of surface sediment secured from both surface grab samples and sediment cores. Precise values may be observed in Table 4. Station locations can be identified by referring to Figure 2 and Tables 2 and 3.

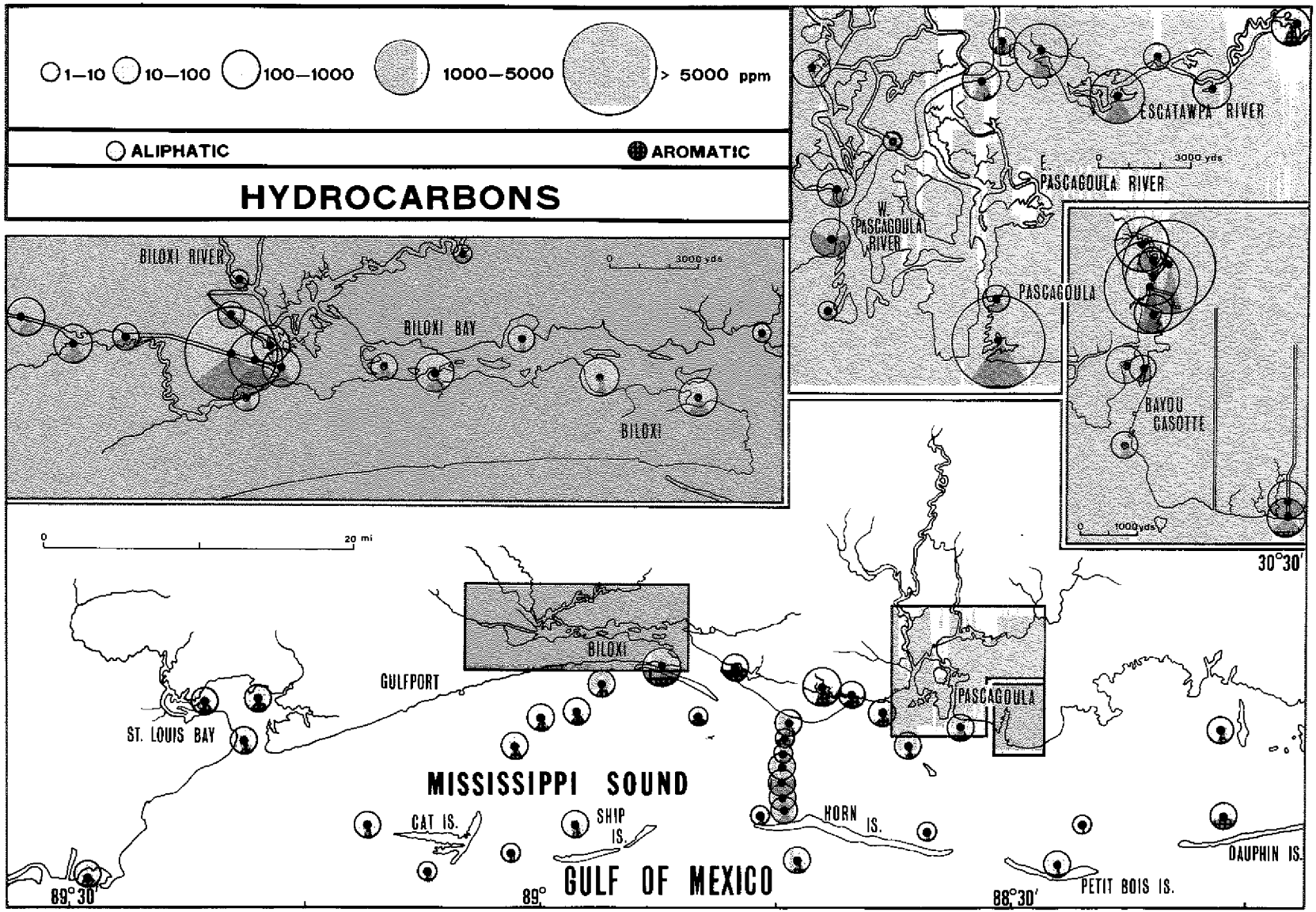


Figure 8. Hydrocarbons in Mississippi Sound sediments. Values of aliphatic, aromatic and total hydrocarbons are depicted as concentration ranges of surface sediment secured from both surface grab samples and sediment cores. Precise values may be observed in Table 4. Station locations can be identified by referring to Figure 2 and Tables 2 and 3.

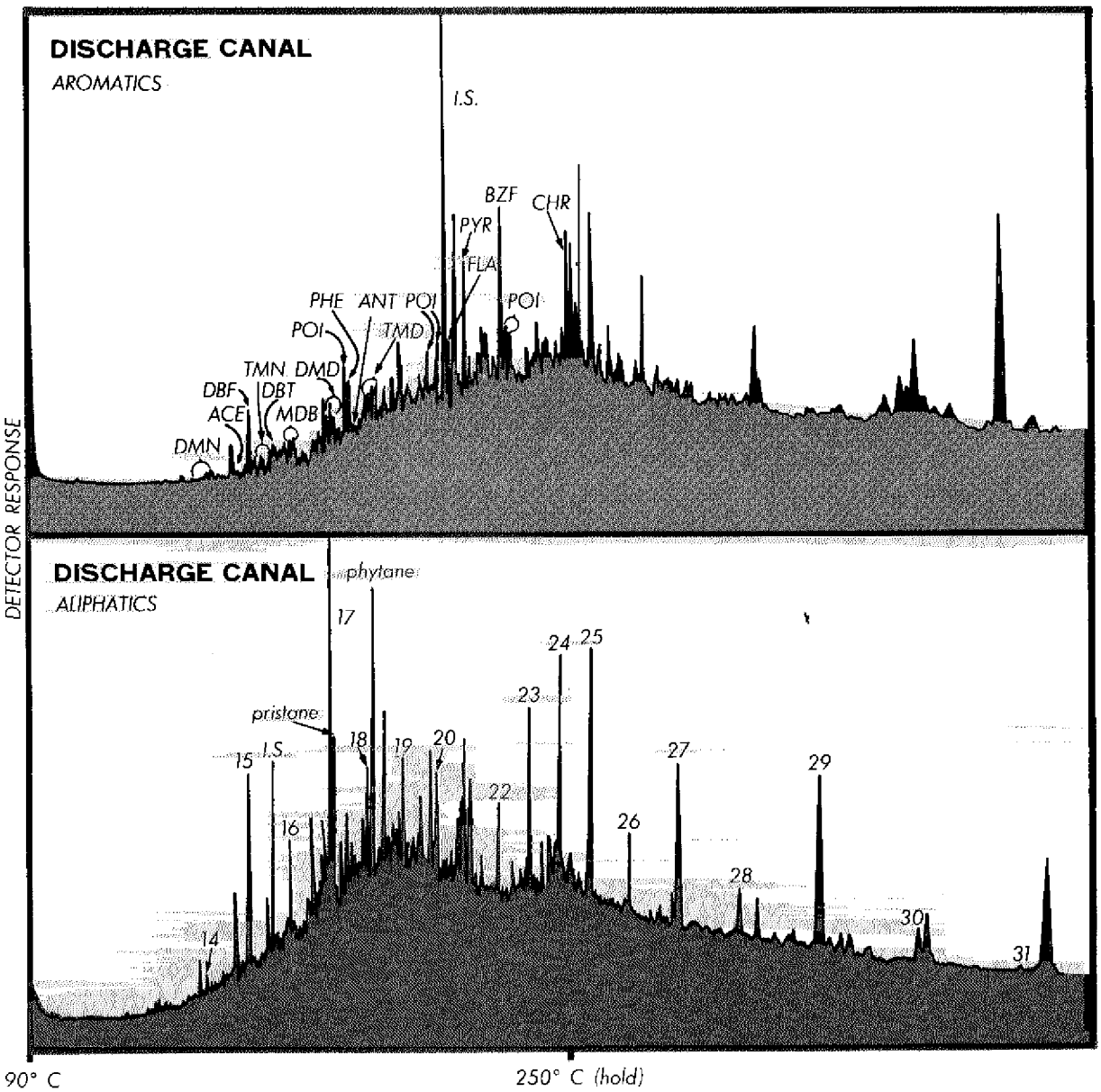


Figure 9. Gas chromatograms of aliphatic and aromatic hydrocarbons of surface sediments from Inner Discharge Canal. The sampling site is in the process water discharge drainage canal for an oil refinery in the Bayou Casotte region. The integers in aliphatic chromatograms refer to *n*-alkane carbon number. Other abbreviations are: Internal standard (I.S.) for aromatics, *n*-eicosane; I.S. (aliphatics), fluorene; 4MB, tetramethylbenzene; NAP, naphthalene; MNA, methylnaphthalene; DMN, dimethylnaphthalene; ACE, acenaphthene; DBF, dibenzofuran; TMN, trimethylnaphthalene; DBT, dibenzothiophene; FLU, fluorene; MDB, methyldibenzofuran; DMD, dimethyldibenzofuran; PHE, phenanthrene; ANT, anthracene; TMD, trimethyldibenzofuran; POI, polyolefinic isoprenoid; FLA, fluoranthene; PRY, pyrene; BZF, 2,3-benzofluoranthene; BZA, benz-a-anthracene; CHR, chrysene. Gas chromatographic conditions are described in the text.

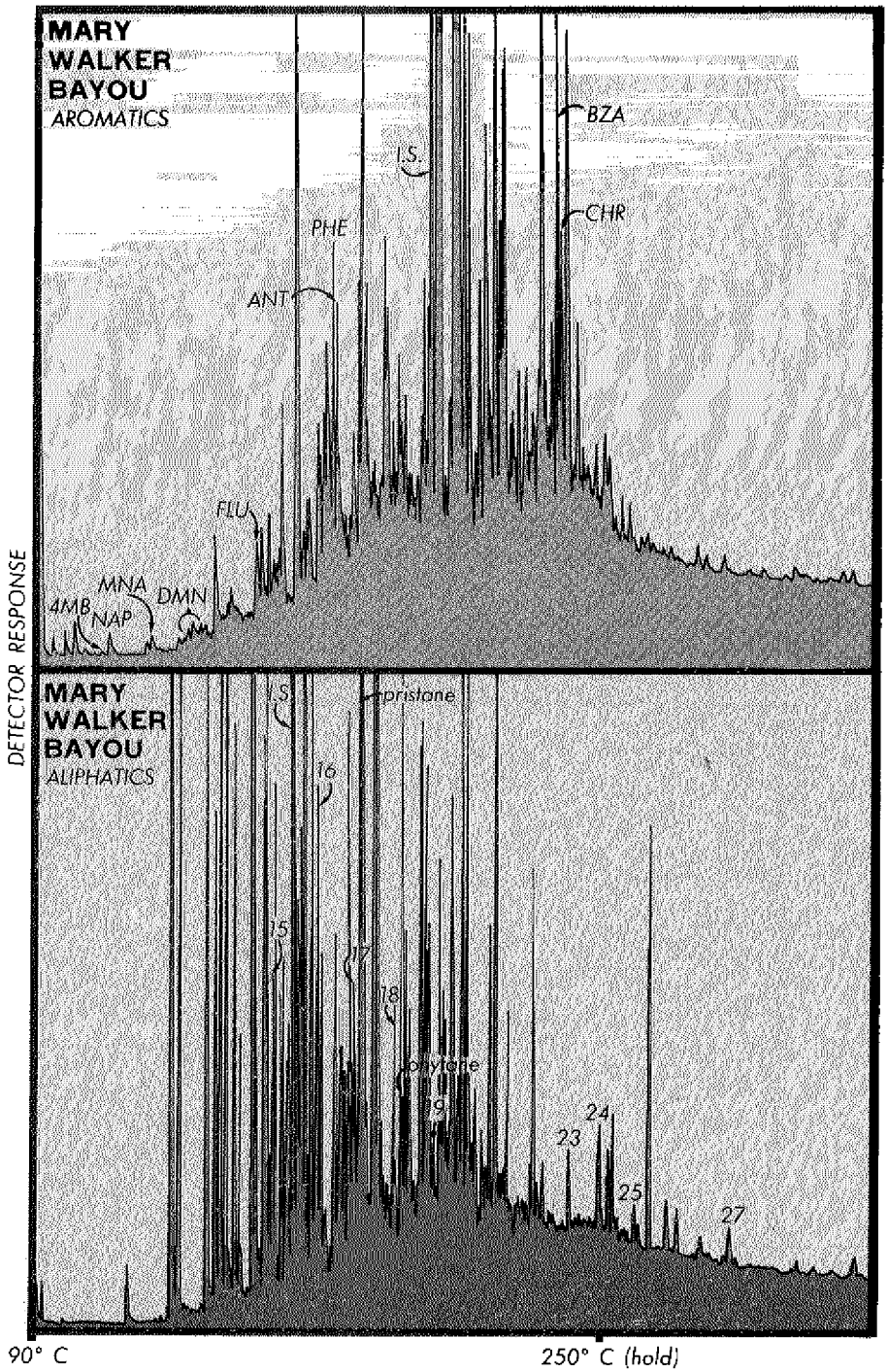


Figure 10. Gas chromatograms of aliphatic and aromatic hydrocarbons of surface sediments from Mary Walker Bayou. The sampling site is in the West Pascagoula River near several boat marinas. Abbreviations: Internal standard (I.S.) aromatics, *n*-eicosane; I.S. (aliphatics), fluorene; 4MB, tetramethylbenzene; NAP, naphthalene; MNA, methylnaphthalene; DMN, dimethylnaphthalene; ACE, acenaphthene; DBF, dibenzofuran; TMN, trimethylnaphthalene; DBT, dibenzothiophene; FLU, fluorene; MDB, methyldibenzofuran; DMD, dimethyldibenzofuran; PHE, phenanthrene; ANT, anthracene; TMD, trimethyldibenzofuran; POI, polyolefinic isoprenoid; FLA, fluoranthene; PRY, pyrene; BZF, 2,3-benzofluoranthene; BZA, benz-a-anthracene; CHR, chrysene. Gas chromatographic conditions are described in the text.

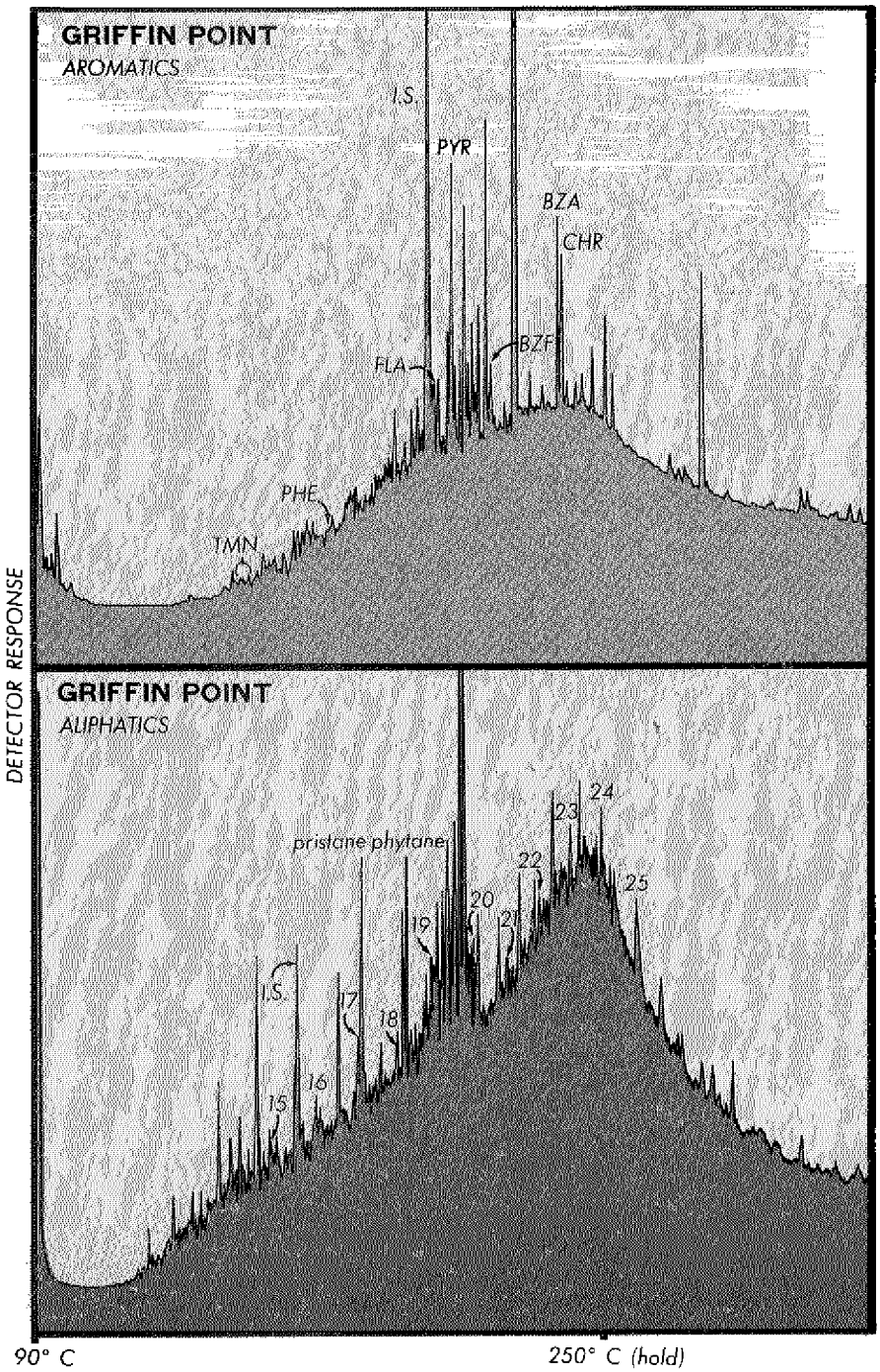


Figure 11. Gas chromatograms of aliphatic and aromatic hydrocarbons of surface sediments from Griffin Point. The sampling site is at the confluence of Escatawpa and East Pascagoula rivers and near a sewage outfall. Abbreviations: Internal standard (I.S.) aromatics, *n*-eicosane; I.S. (aliphatics), fluorene; 4MB, tetramethylbenzene; NAP, naphthalene; MNA, methylnaphthalene; DMN, dimethylnaphthalene; ACE, acenaphthene; DBF, dibenzofuran; TMN, trimethylnaphthalene; DBT, dibenzothiophene; FLU, fluorene; MDB, methyldibenzofuran; DMD, dimethyldibenzofuran; PHE, phenanthrene; ANT, anthracene; TMD, trimethyldibenzofuran; POI, polyolefinic isoprenoid; FLA, fluoranthene; PRY, pyrene; BZF, 2,3-benzofluoranthene; BZA, benz-a-anthracene; CHR, chrysene. Gas chromatographic conditions are described in the text.

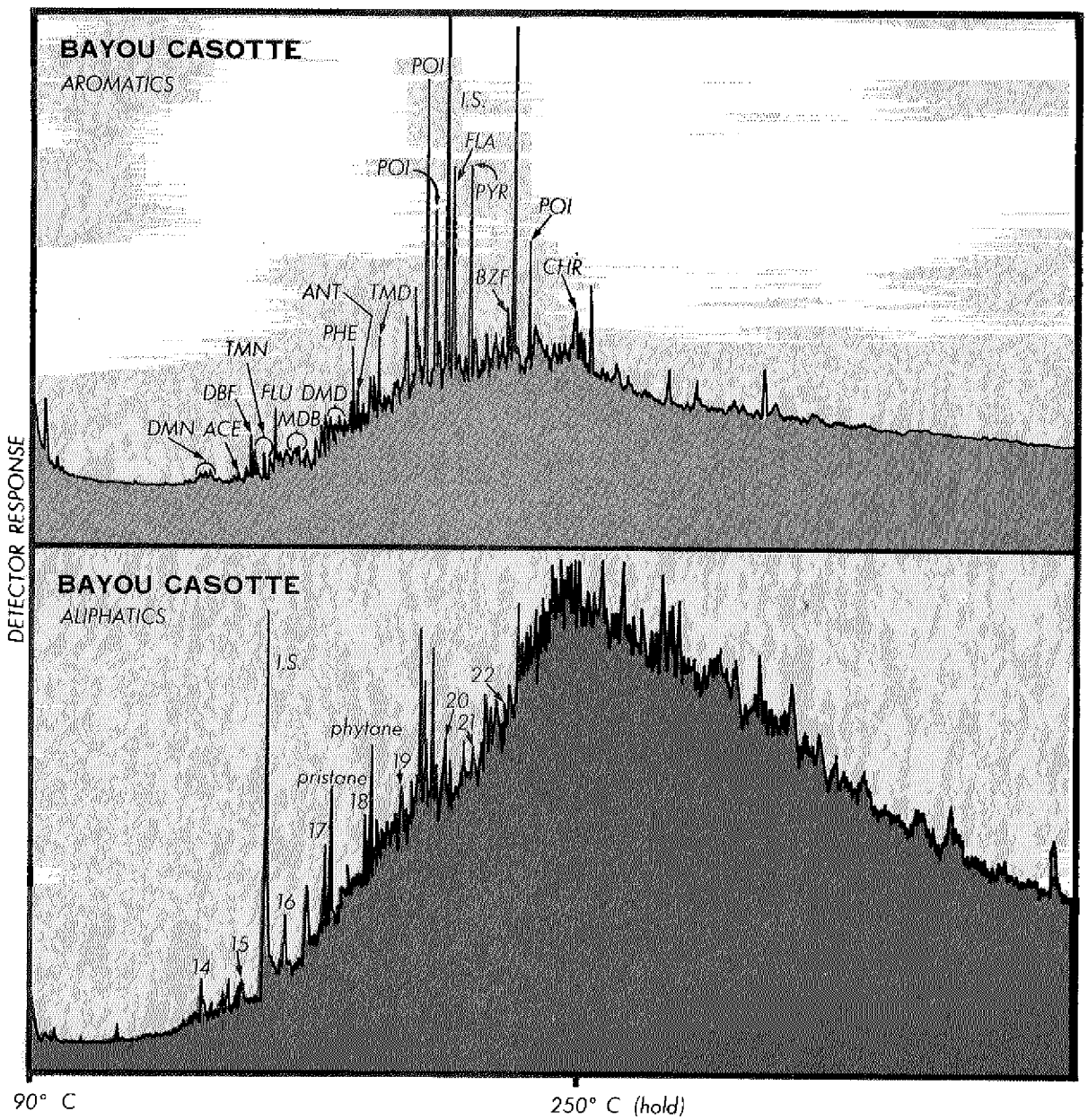


Figure 12. Gas chromatograms of aliphatic and aromatic hydrocarbons of surface sediments from Cooling Tower Canal in Bayou Casotte. Abbreviations: Internal standard (I.S.) for aromatics, *n*-eicosane; I.S. (aliphatics), fluorene; 4MB, tetramethylbenzene; NAP, naphthalene; MNA, methylnaphthalene; DMN, dimethylnaphthalene; ACE, acenaphthene; DBF, dibenzofuran; TMN, trimethylnaphthalene; DBT, dibenzothiophene; FLU, fluorene; MDB, methyldibenzofuran; DMD, dimethyldibenzofuran; PHE, phenanthrene; ANT, anthracene; TMD, trimethyldibenzofuran; POI, polyolefinic isoprenoid; FLA, fluoranthene; PYR, pyrene; BZF, 2,3-benzofluoranthene; BZA, benz-a-anthracene; CHR, chrysene.

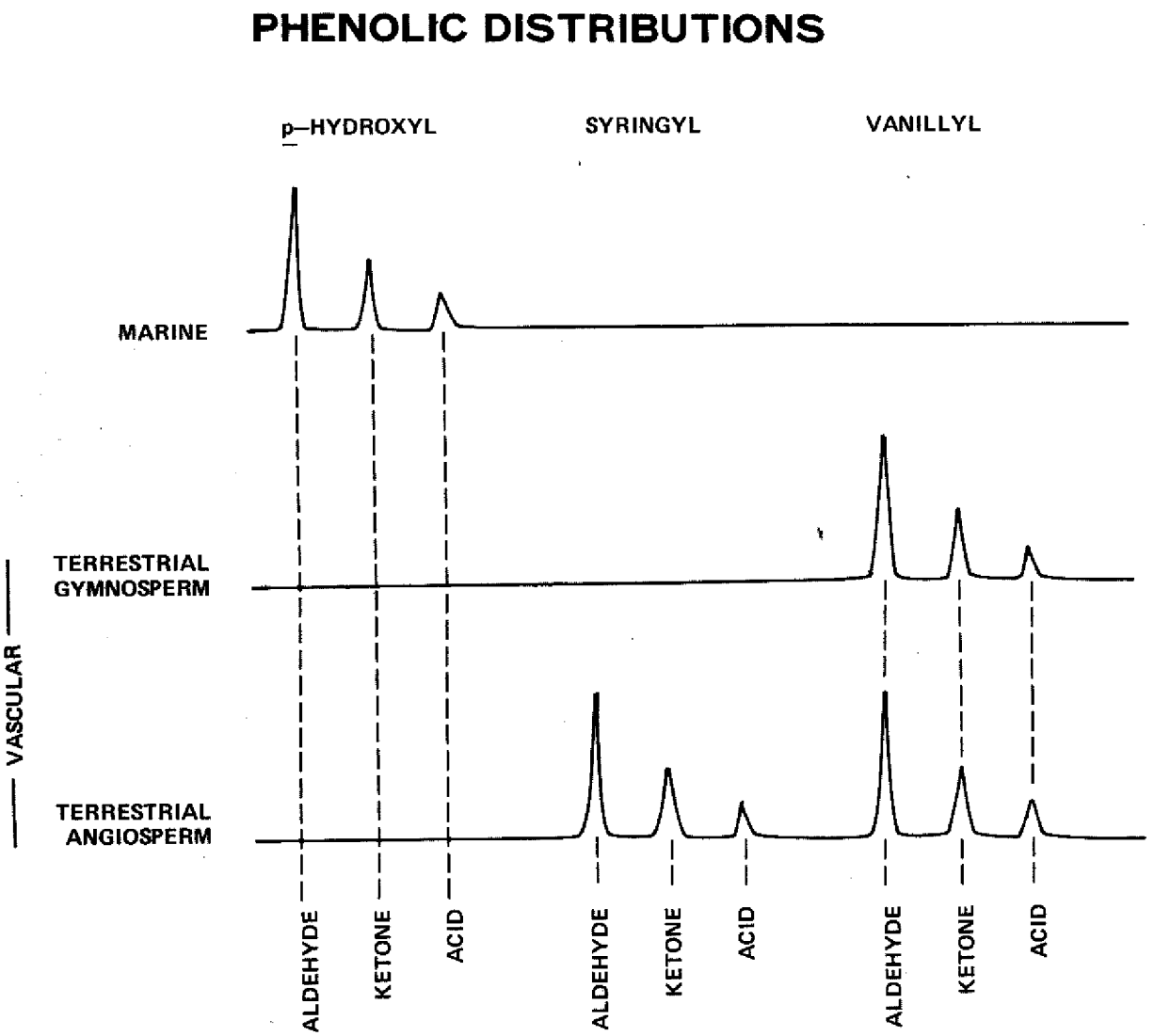


Figure 13. Stylized gas chromatograms of lignin structural units in vascular and nonvascular plants. The specific names within the three groups (*p*-hydroxy, syringyl and vanillyl) of aldehydes, ketones and acids are listed in the test and shown in Figure 15.

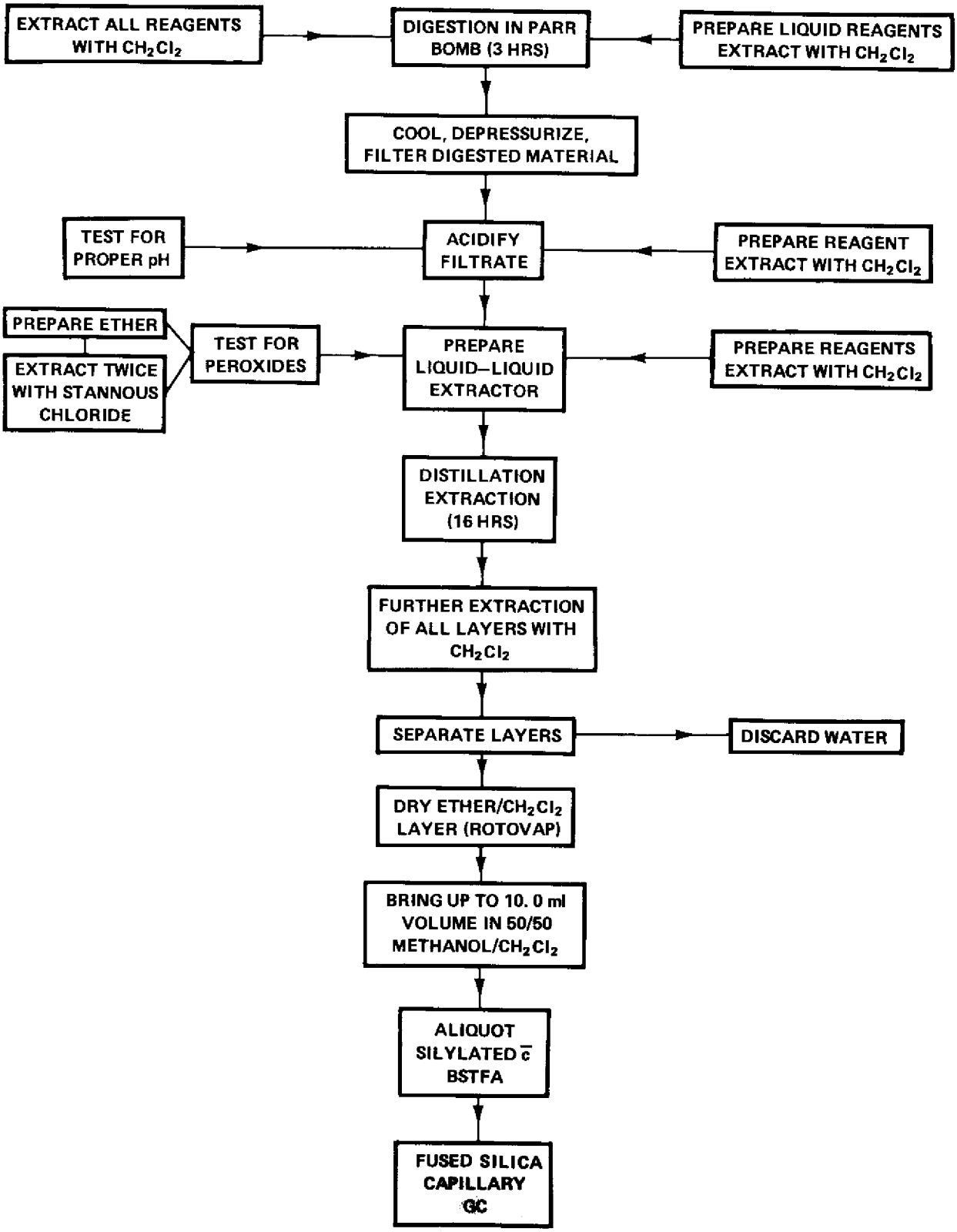


Figure 14. Analysis procedure for sedimentary lignin residues.

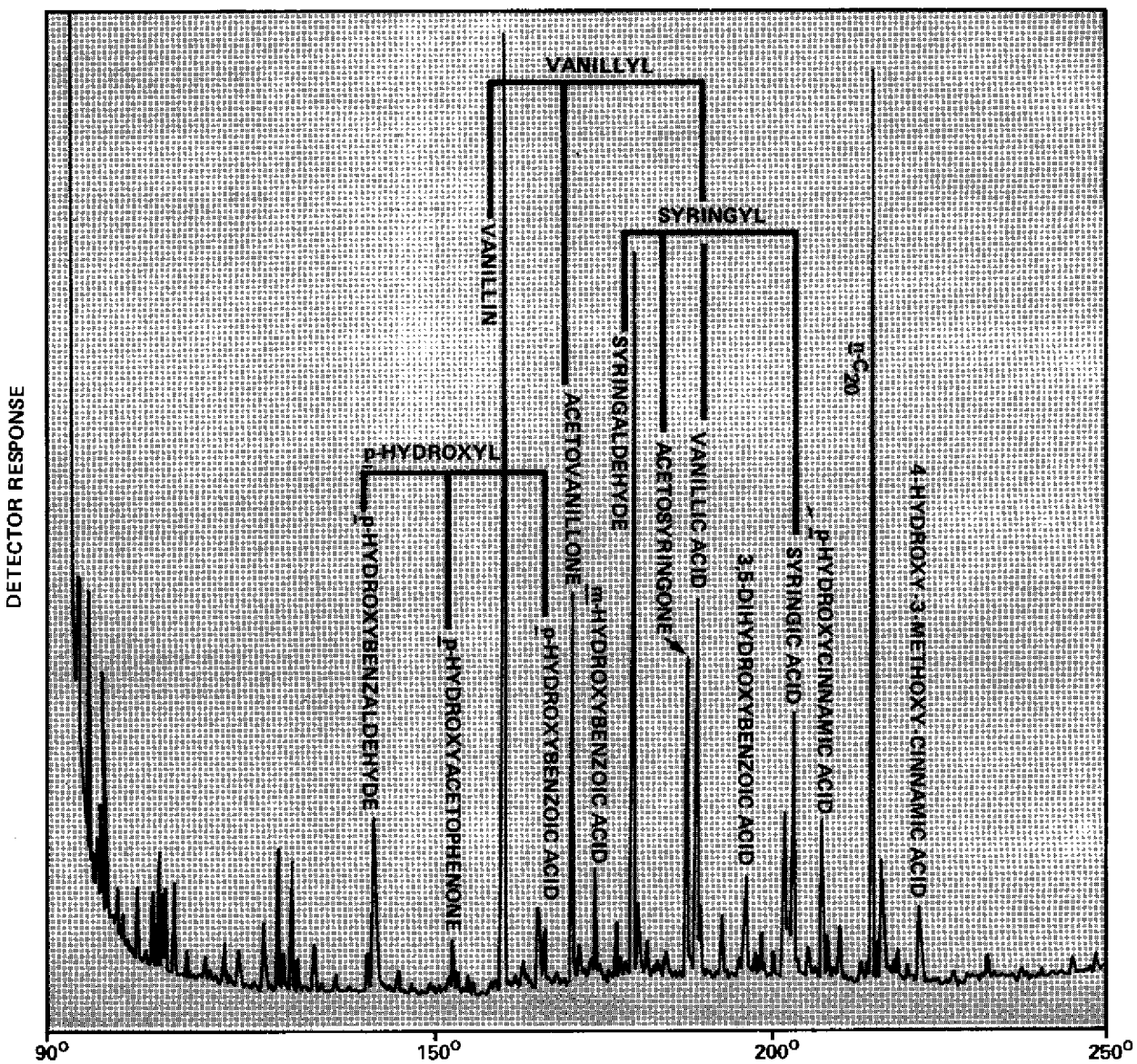


Figure 15. Gas chromatogram of lignin residues in surface sediments at Bellefontaine Point. The sampling site is in the path of Pascagoula River flow across Mississippi Sound. Gas chromatographic conditions are described in the text.

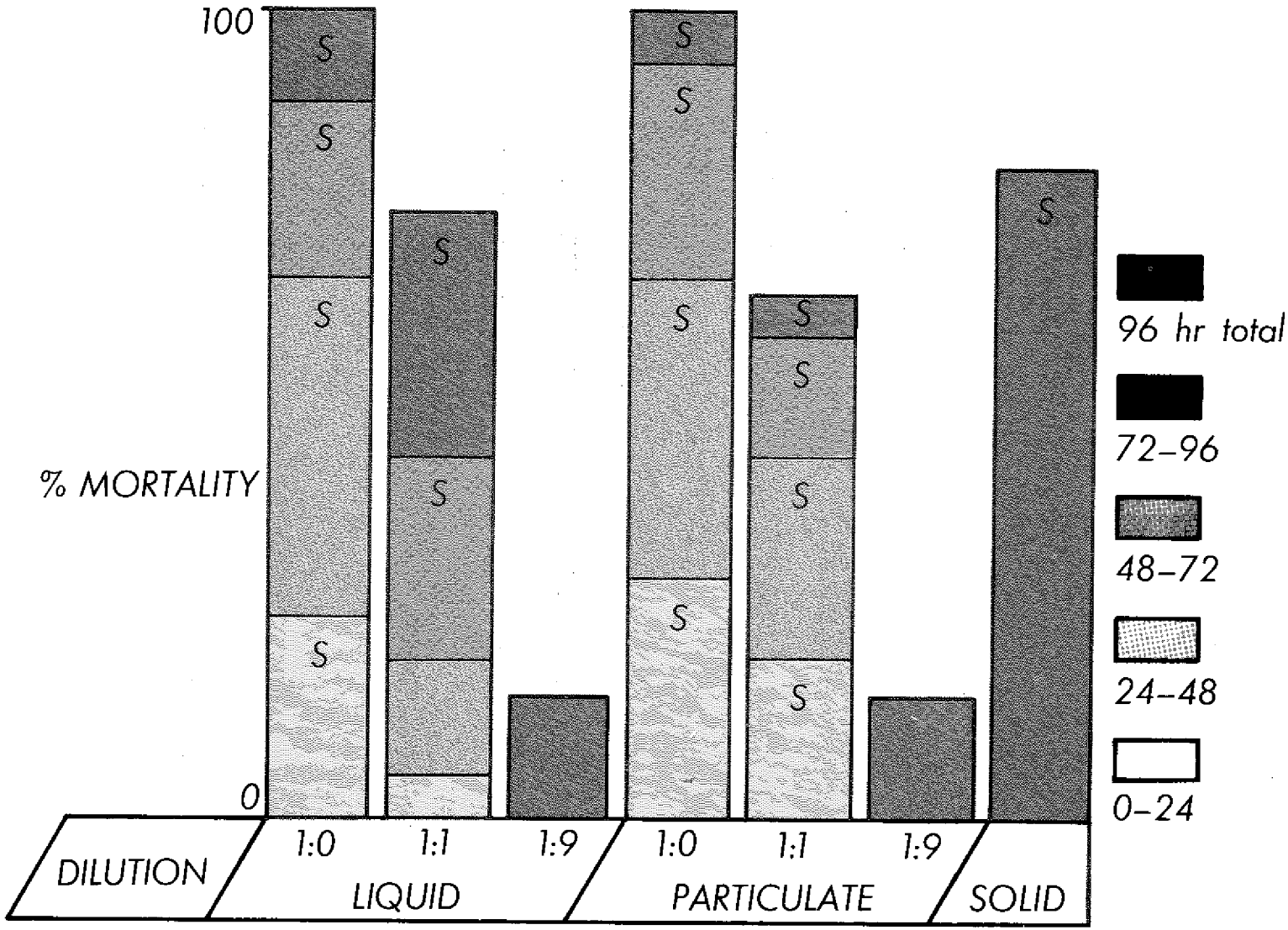


Figure 16. Bioassay mortalities of mysid shrimp exposed to Bayou Casotte sediment. Sediment was collected at the Cooling Tower Canal site. Percent mortalities are depicted at 24-hour intervals for the soluble fraction (liquid) and suspended plus soluble fraction (particulate) of sediment dispersed in diluted seawater. Exposure tests were run with sediment:water = 1:4 (V/V) with no further dilution (1:0) and with further dilutions with seawater of 1:1 and 1:9. Only one mortality reading was made for the exposure test to settleable material (solid). The "S" symbol indicates results were statistically significant compared with control organisms maintained in diluted seawater.

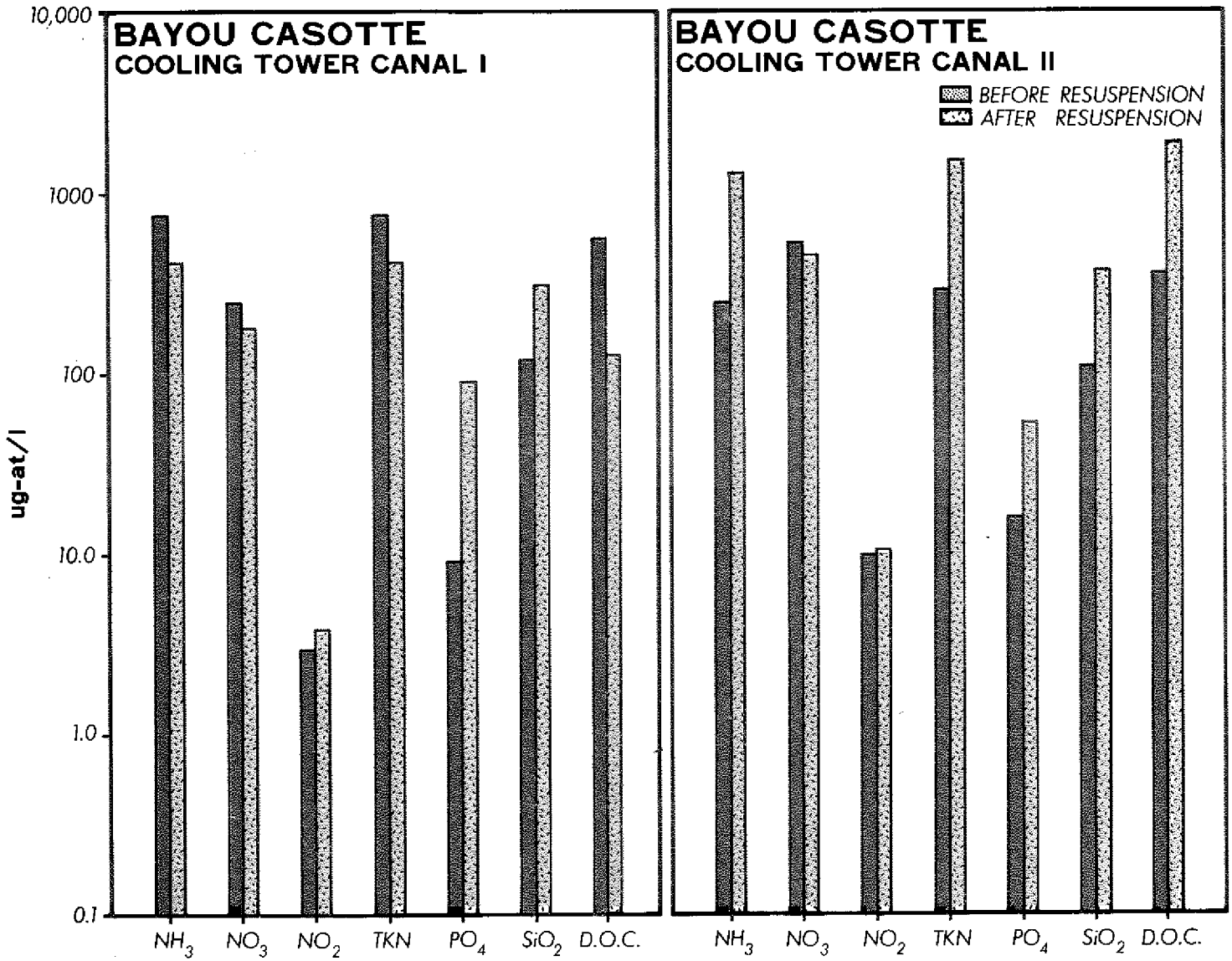


Figure 17. Effect of water soluble component concentrations after dispersion of Bayou Casotte sediment. Cooling Tower Canal sediment and water collected in March 1981 (I) and June 1982 (II); sediment: water = 1:4 (V/V); concentrations are in μg—at/1, N, P, Si and C.

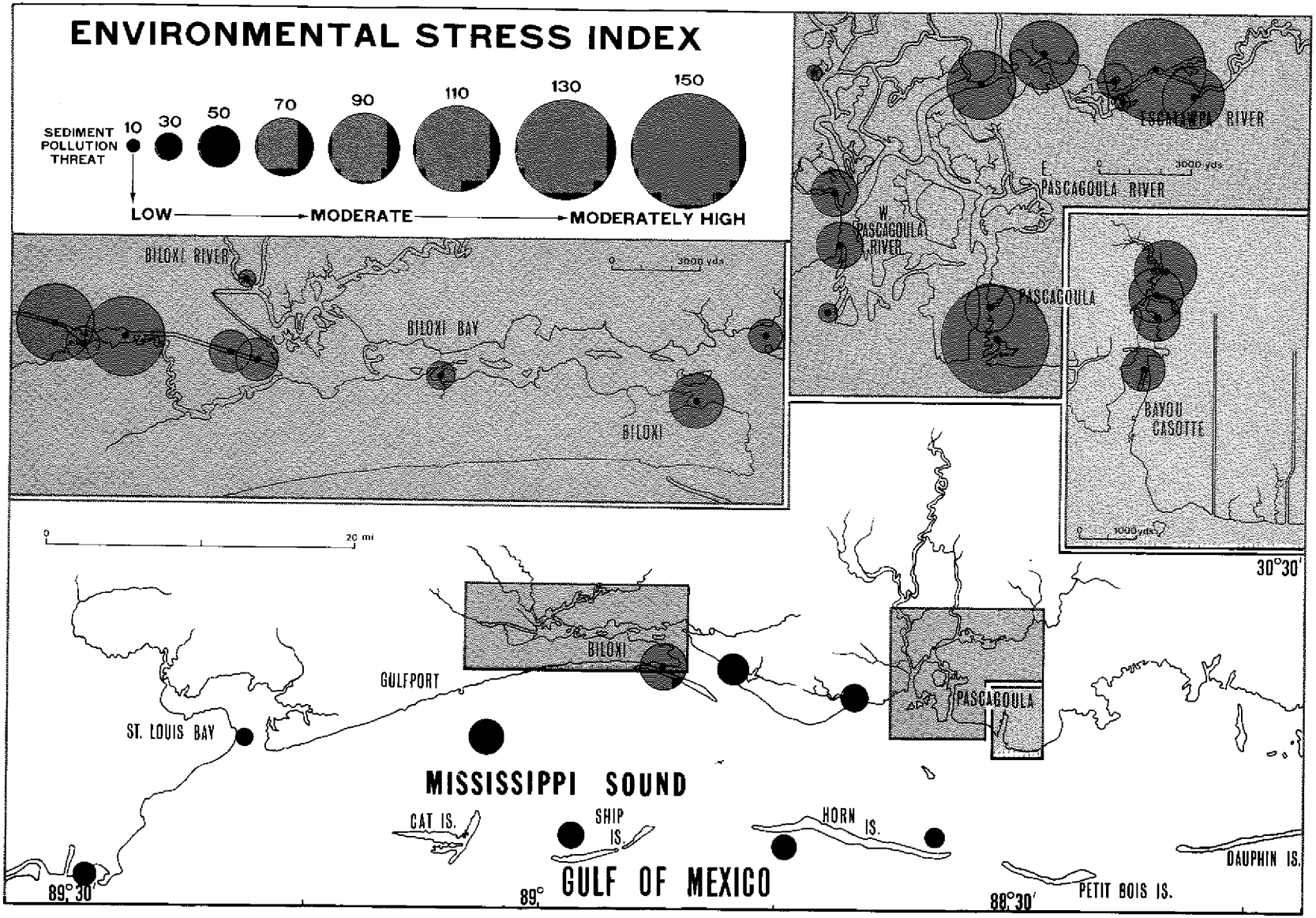


Figure 18. Environmental stress index for surface sediments of the Mississippi Sound. Circle diameters at each site are proportional to the product of all factors assimilated in the stress index including: toxicity, suspension stability, disturbance probability and biota susceptibility. Individual ratings and mathematical products are listed in Table 9.

APPENDIX I

VERTICAL PROFILES OF POLLUTANT AND GEOCHEMICAL FEATURES OF MISSISSIPPI SOUND SEDIMENTS

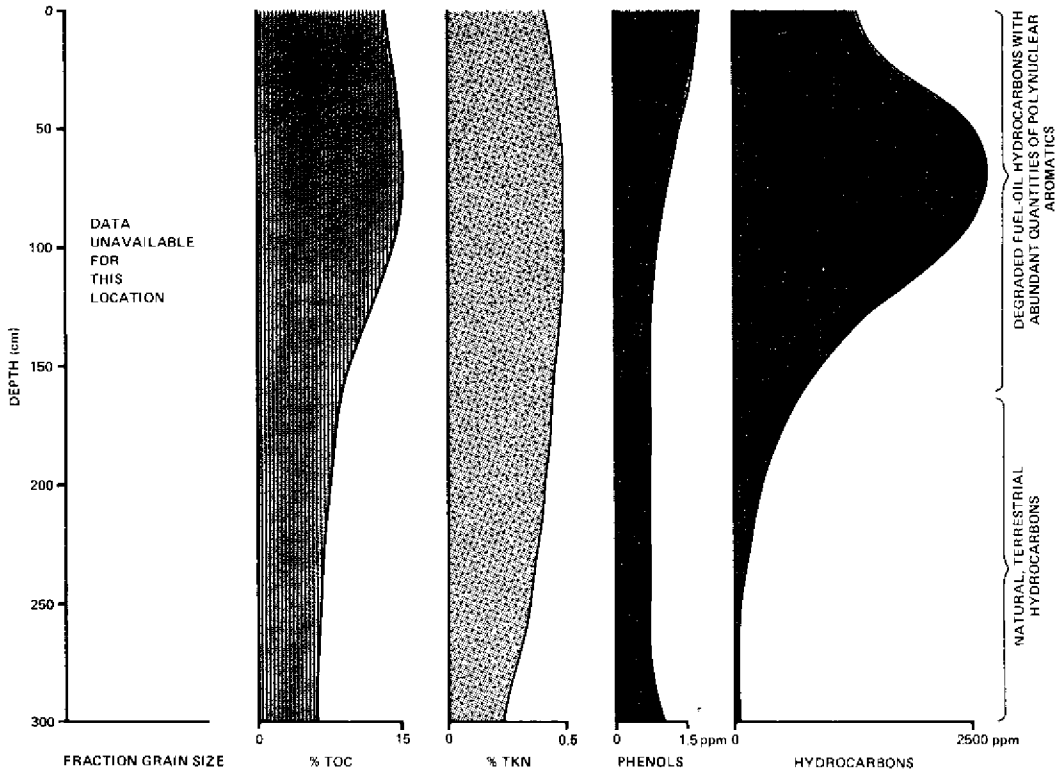
At 43 sites in Mississippi Sound, sediment cores of approximately 250 cm length were collected and analyzed at 10 to 20 cm intervals for grain size and the organic constituents: total organic carbon (TOC), total Kjeldahl nitrogen (TKN), total phenols, and total hydrocarbons. These geochemical and chemical features are depicted as a function of depth in the sedimentary strata. The width of each contour at any depth is directly proportional to the concentration of that component at that depth, and this concentration may be estimated using the scale for each component.

In comparing profiles, it should be noted that wide variations in sediment chemical composition throughout the Sound necessitated varying scales from one profile to another. Comments along the right margin of most profiles pertain primarily to hydrocarbon analysis (fluorescence, gas chromatography, etc.) that are significant in evaluating pollutant concentration with depth in the sedimentary column. Unless a geological boundary between Holocene and Pleistocene age deposits is noted, all deposits in a sequence are of Recent (Holocene) age. The profiles are arranged in the following order:

Figure Number	System
	Pascagoula River System
I-1	McInnis Lake
I-2	Paper Mill
I-3	Point aux Chenes
I-4	Mouth W. Pascagoula River
I-5	Griffin Point
I-6	E. Pascagoula I-10
I-7	Dead River
I-8	Mary Walker Bayou
I-9	Escatawpa River Control
I-10	Bayou Chemise
I-11	Round Island
I-12	Mouth E. Pascagoula River
I-13	Bayou Casotte
	Biloxi Bay System
I-14	Davis Bayou
I-15	Old Fort Bayou
I-16	Power Plant
I-17	South Deer Island
I-18	Popps Ferry
I-19	Deer Island
I-20	Gulfport Lake
I-21	Goat Island
I-22	Big Lake
I-23	Cedar Lake
I-24	Bernard Bayou
I-25	Keesler AFB
I-26	**St. Louis Bay System** St. Louis Bay Bridges
I-27	Heron Bay
I-28	Mouth Jourdan River
I-29	Mouth Wolf River
	Mississippi Sound System
I-30	D'Iberville
I-31	Horn Island
I-32	Gulfport Channel
I-33	Pass Marianne
I-34	Bellefontaine Point
I-35	Cat Island Channel
I-36	East Mississippi Sound
I-37	Petit Bois Island
I-38	West Horn Island
I-39	Bayou La Batre
I-40	Ship Island Pass
I-41	Edgewater
I-42	West Ship Island
I-43	Dauphin Island

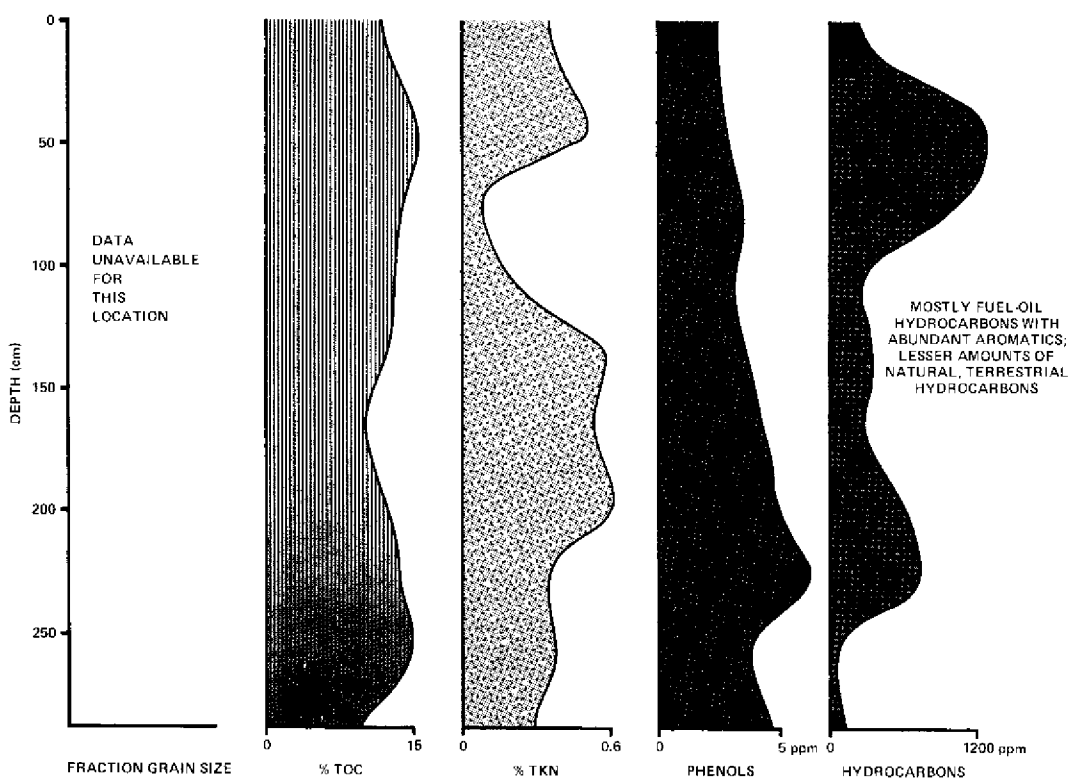
McINNIS LAKE

I-1



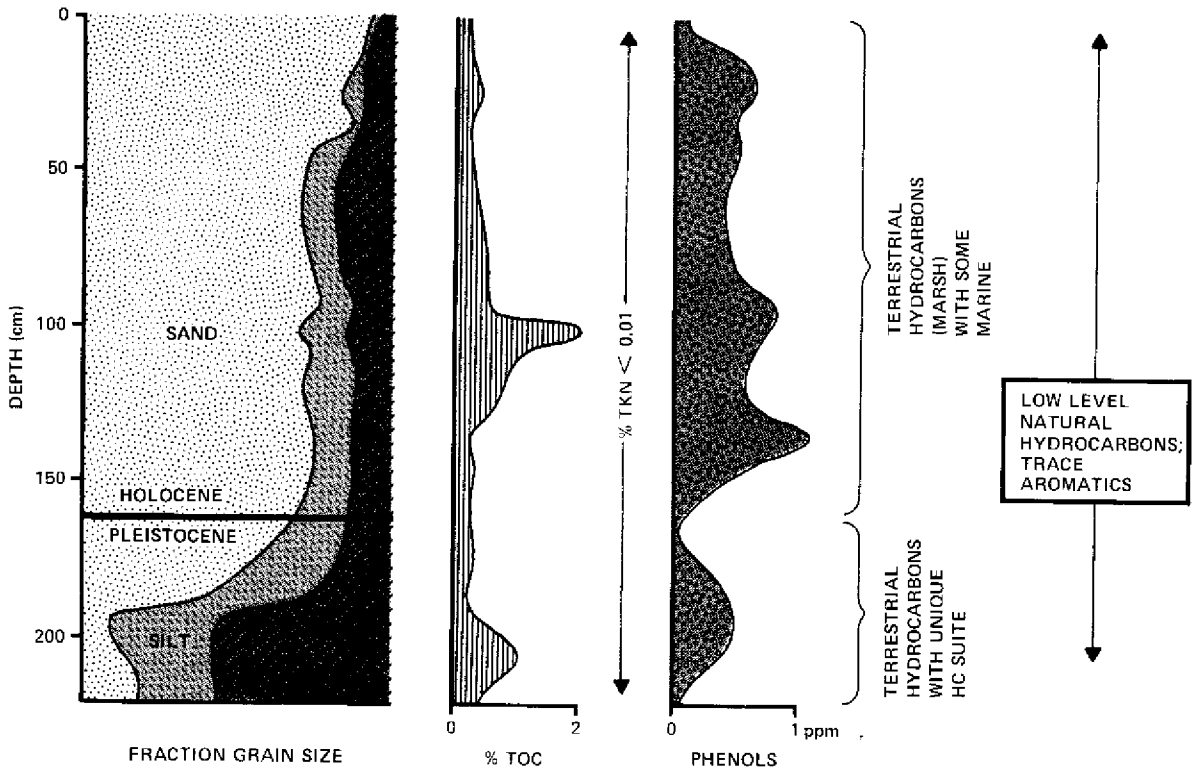
PAPER MILL

I-2



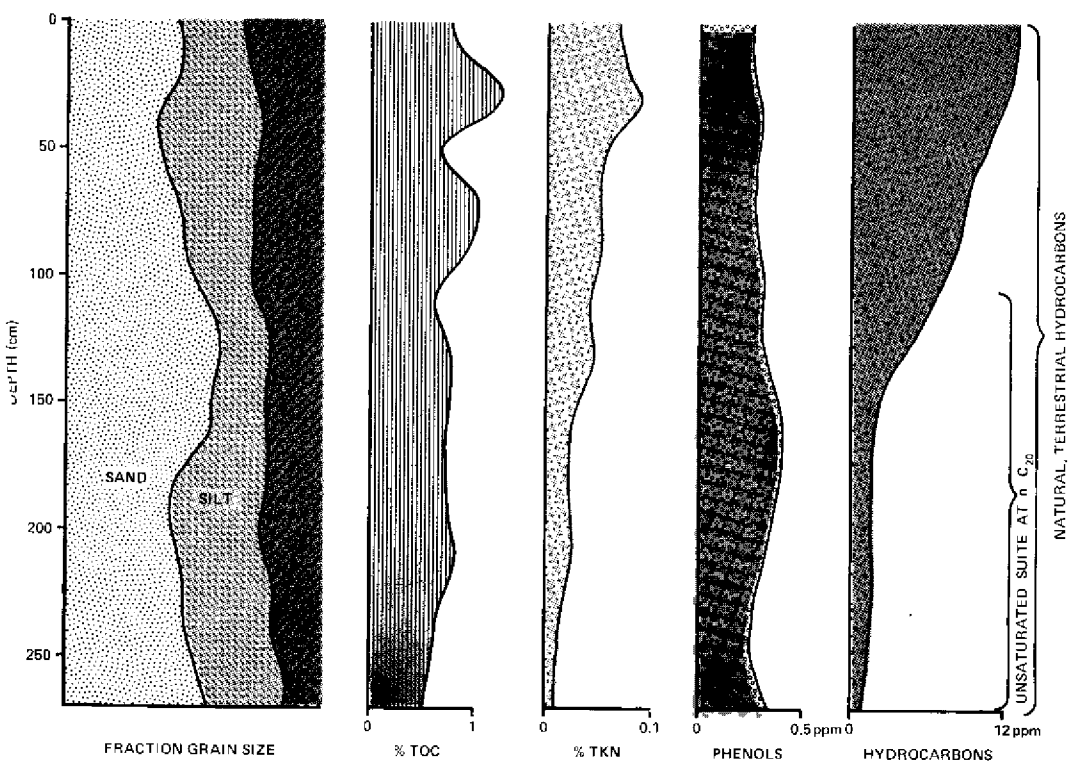
I-3

PT. AUX CHENES



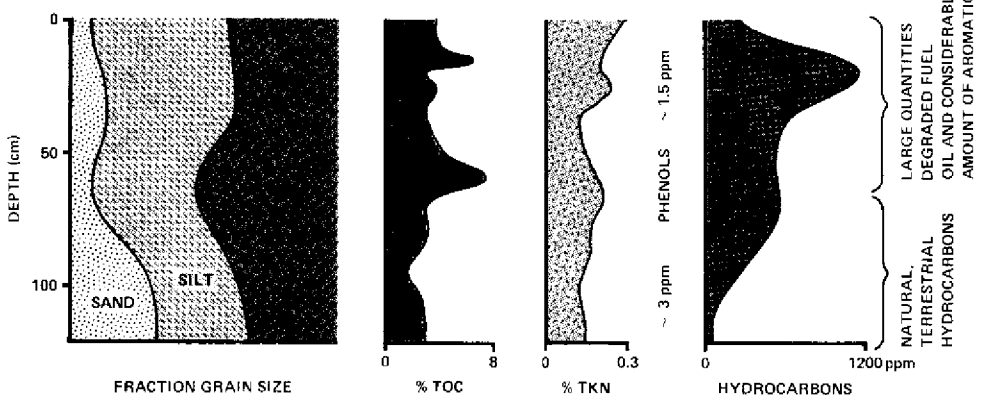
I-4

MOUTH W. PASCAGOULA RIVER



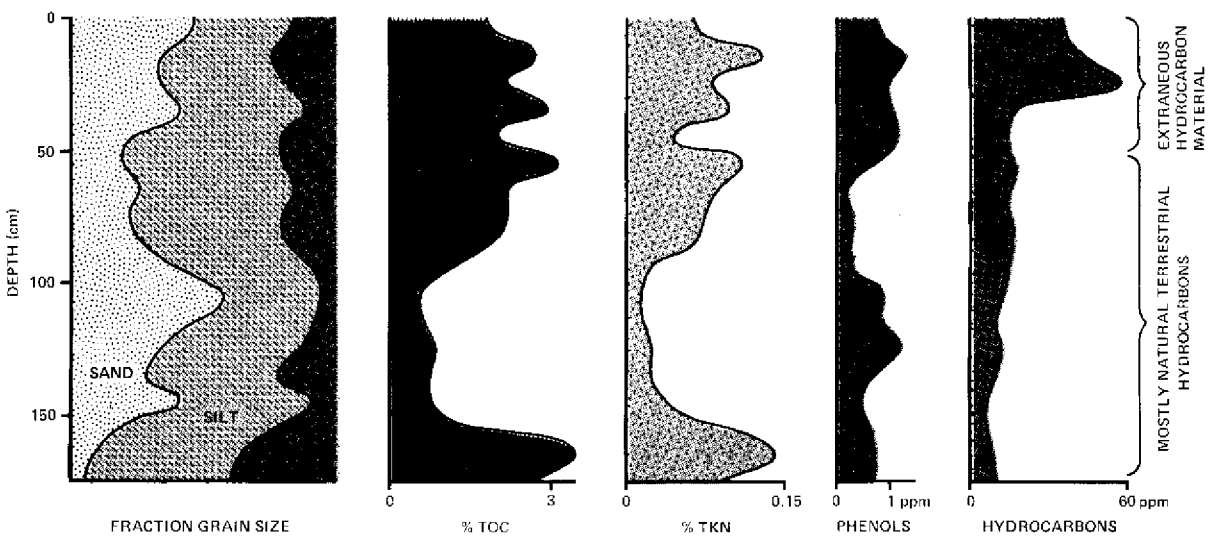
I-5

GRIFFIN POINT



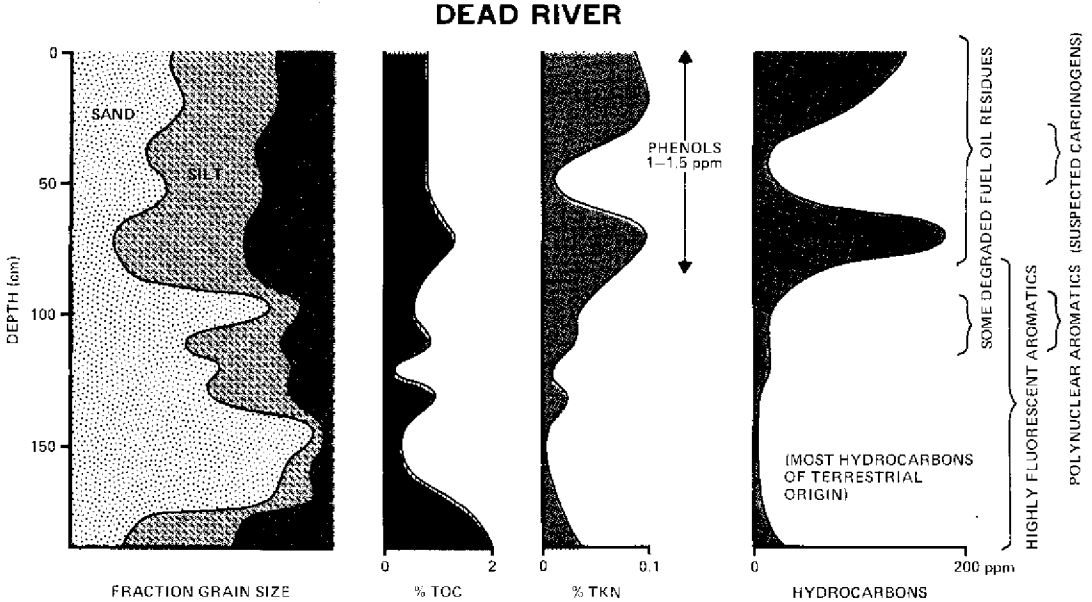
I-6

E. PASCAGOULA I-10



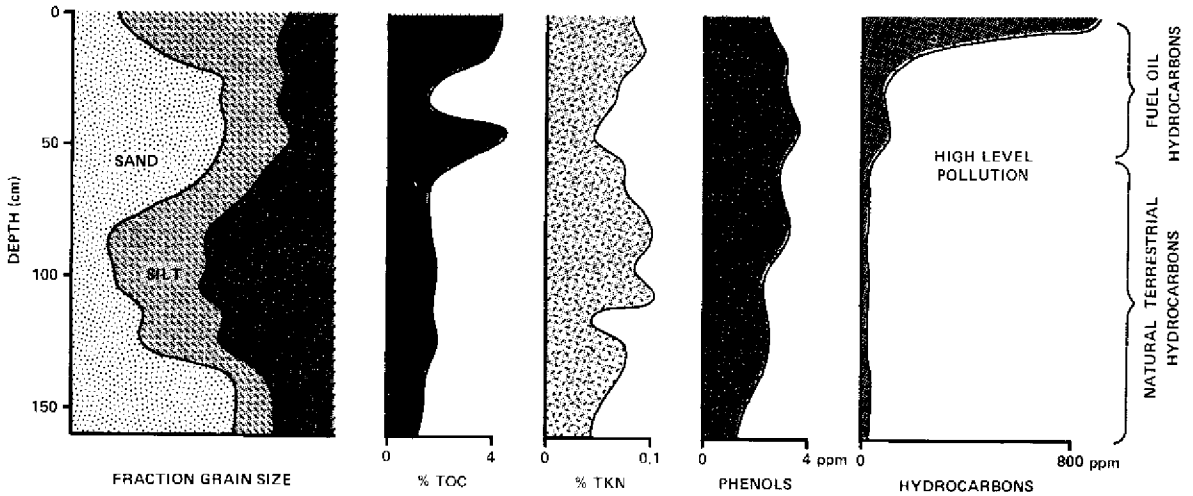
I-7

DEAD RIVER



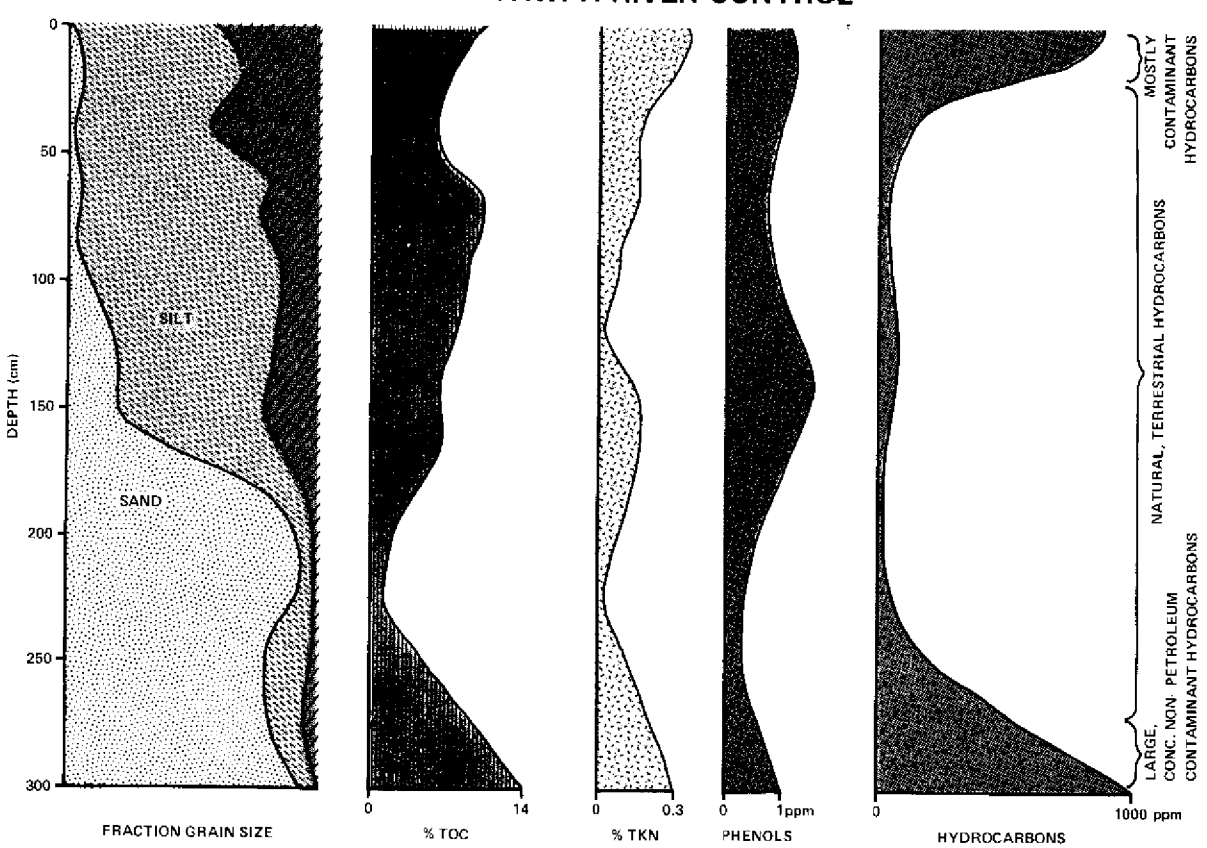
I-8

MARY WALKER BAYOU



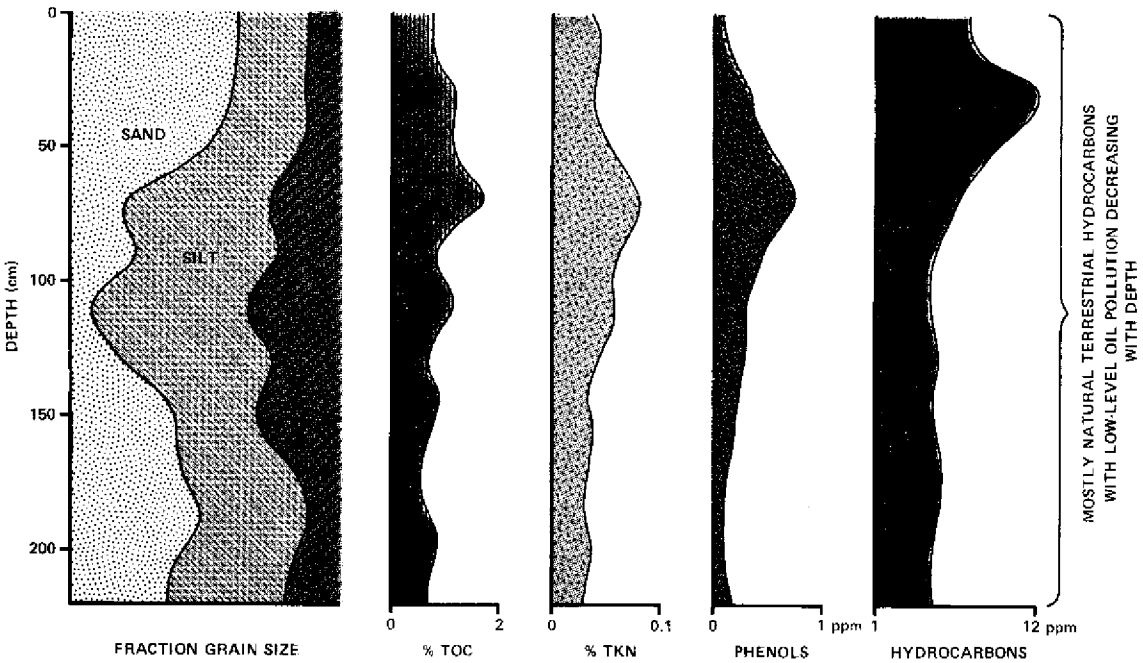
I-9

ESCATAWPA RIVER CONTROL



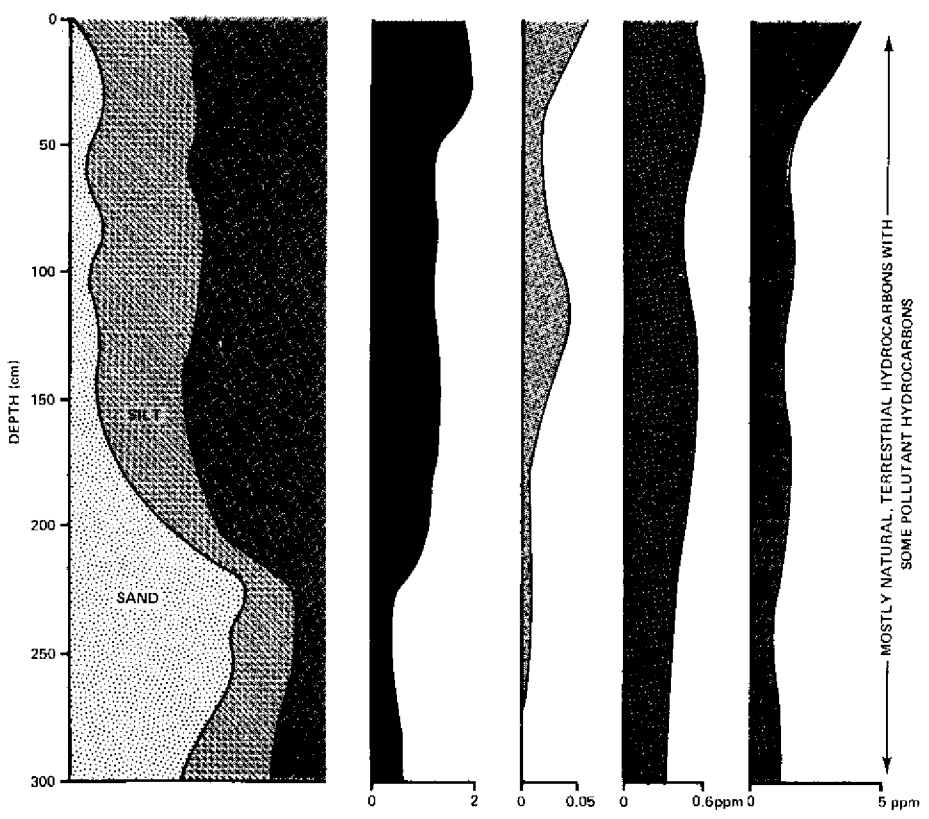
I-10

BAYOU CHEMISE



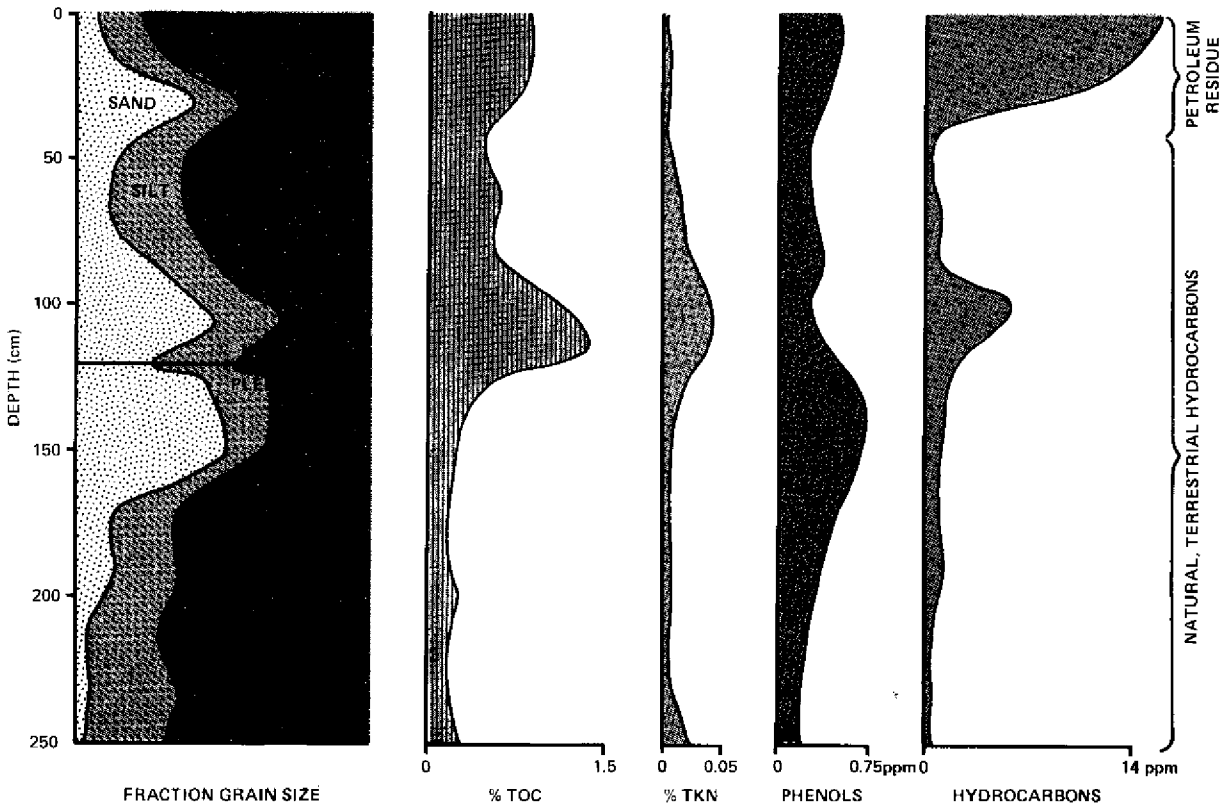
I-11

ROUND ISLAND



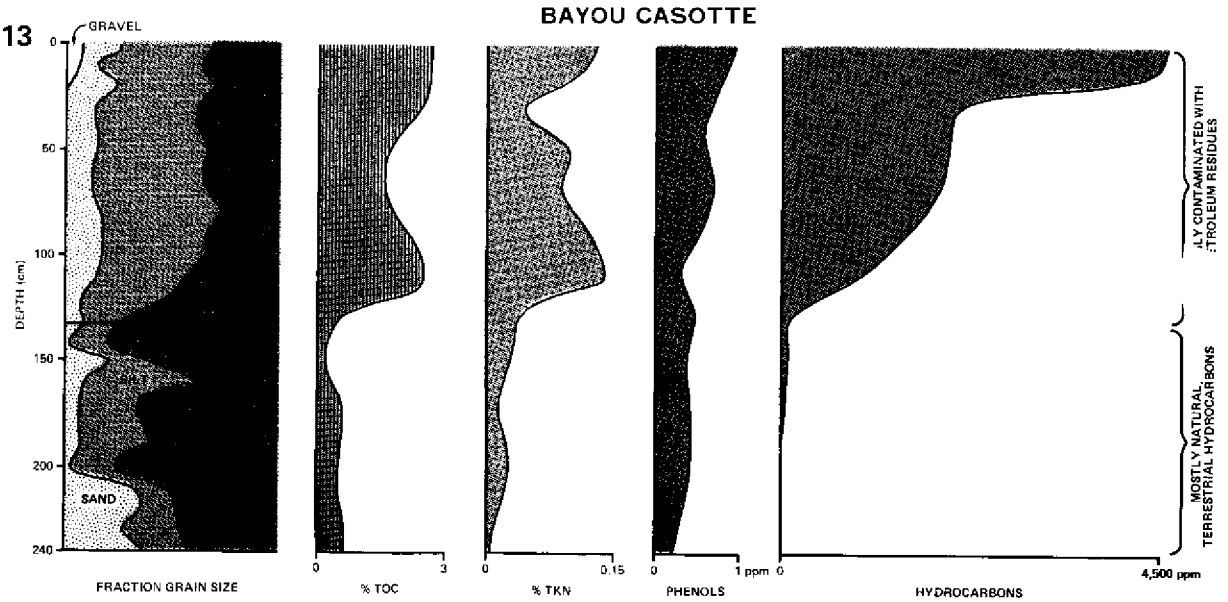
I-12

MOUTH E. PASCAGOULA RIVER



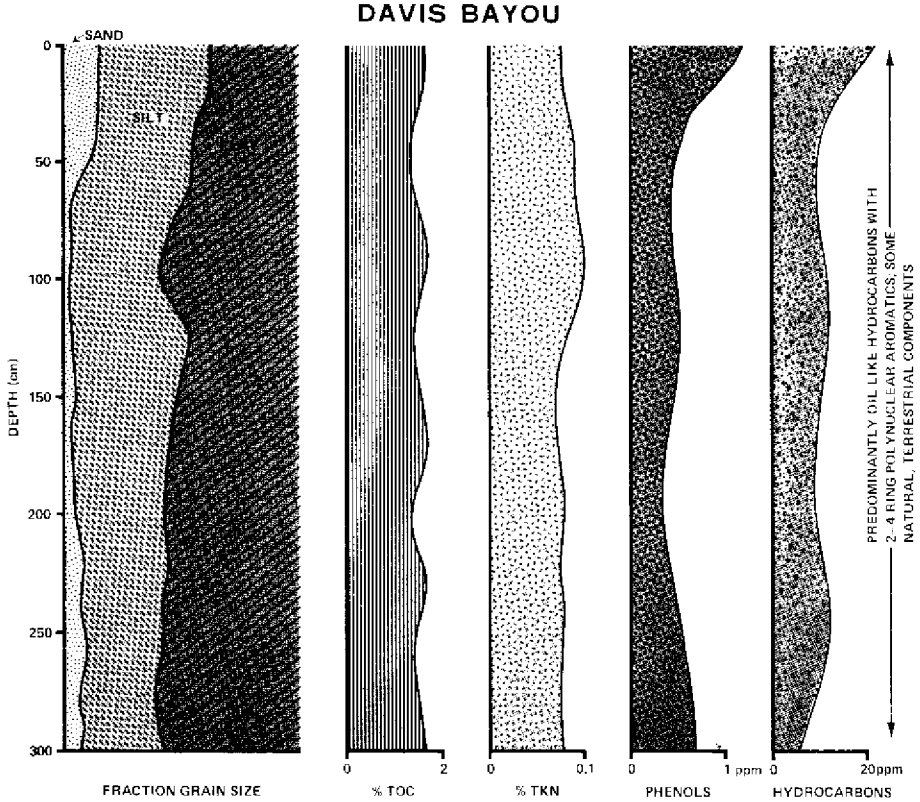
I-13

BAYOU CASOTTE



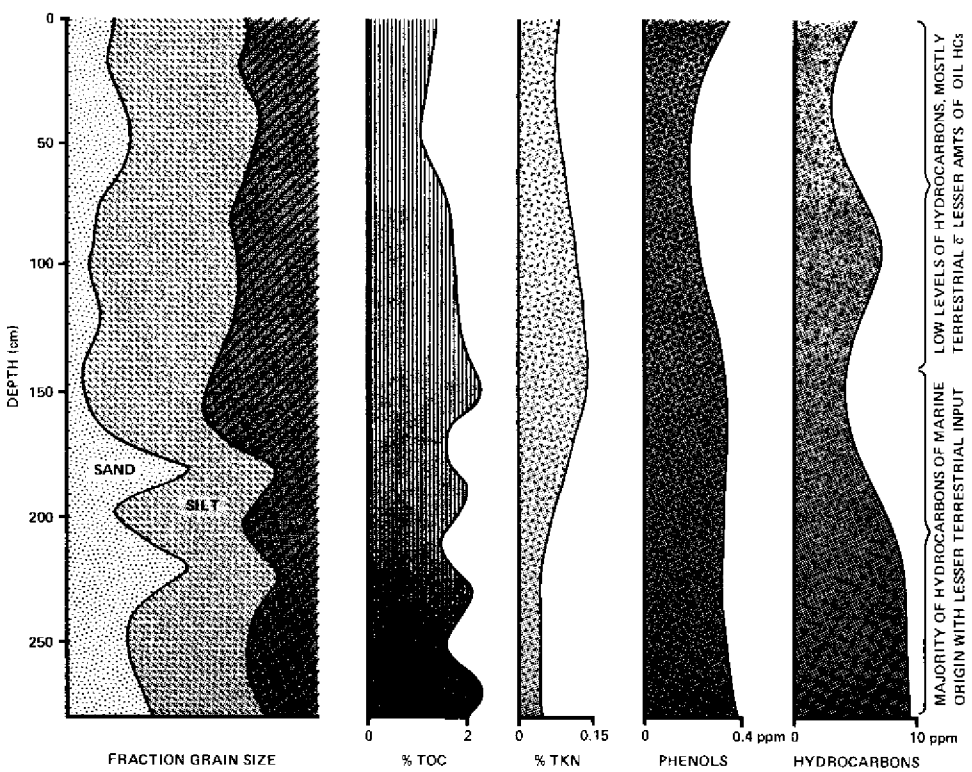
I-14

DAVIS BAYOU



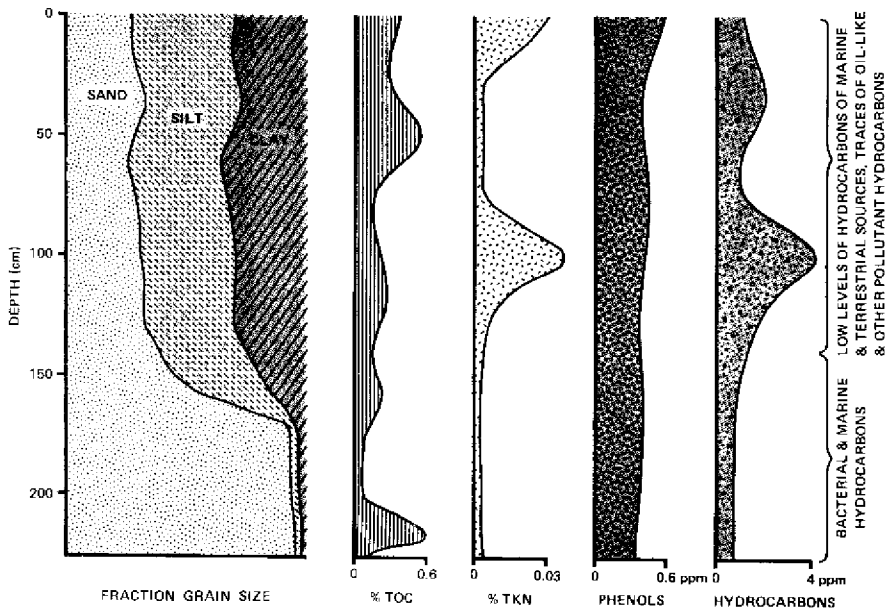
I-15

OLD FORT BAYOU



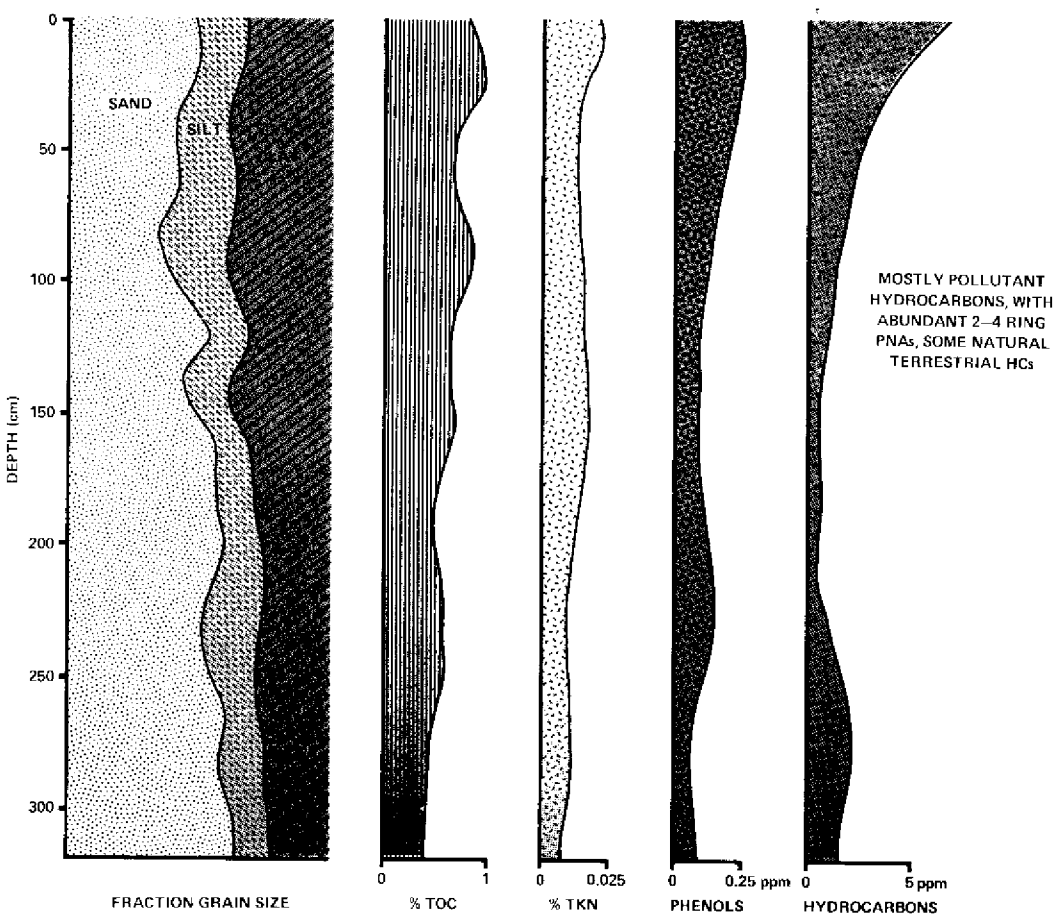
I-16

POWER PLANT



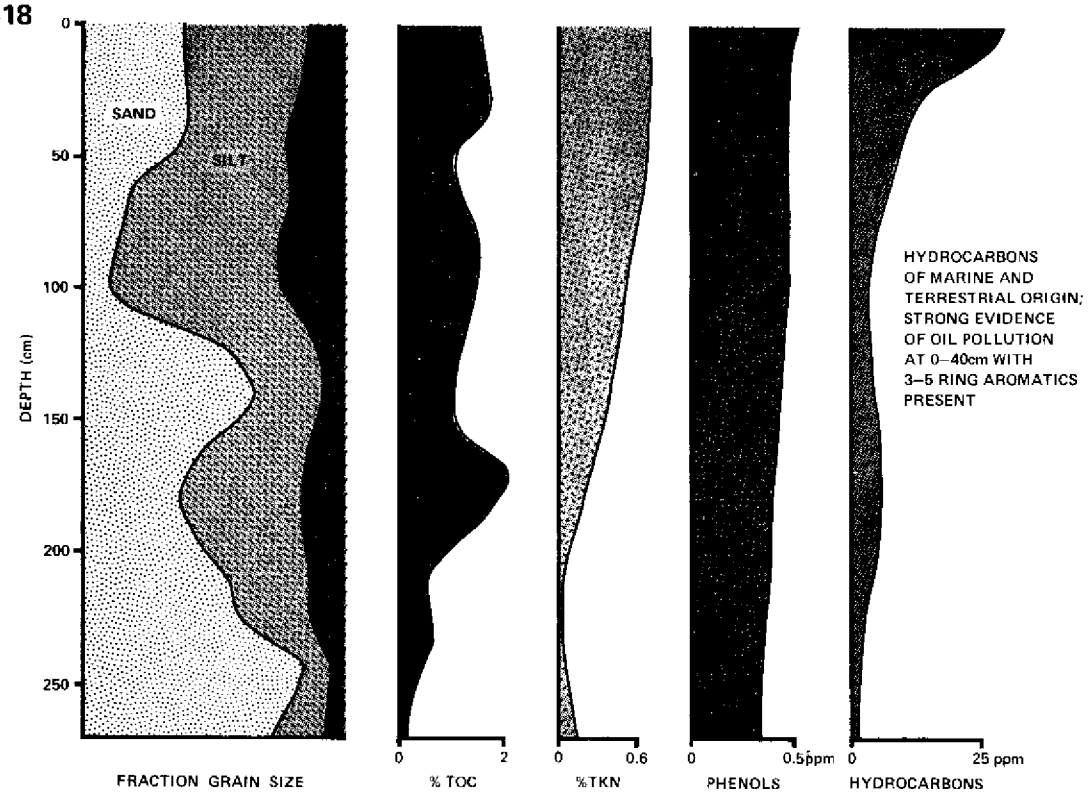
I-17

SOUTH DEER ISLAND



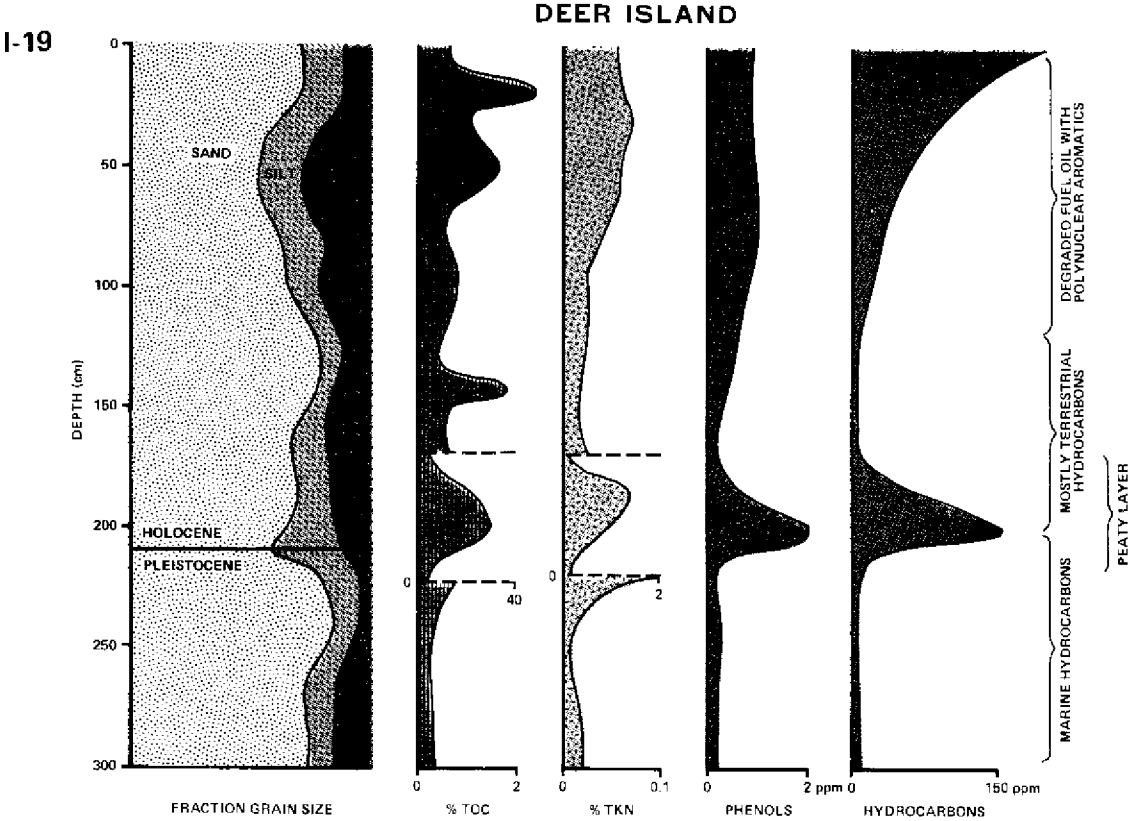
POPPS FERRY

I-18



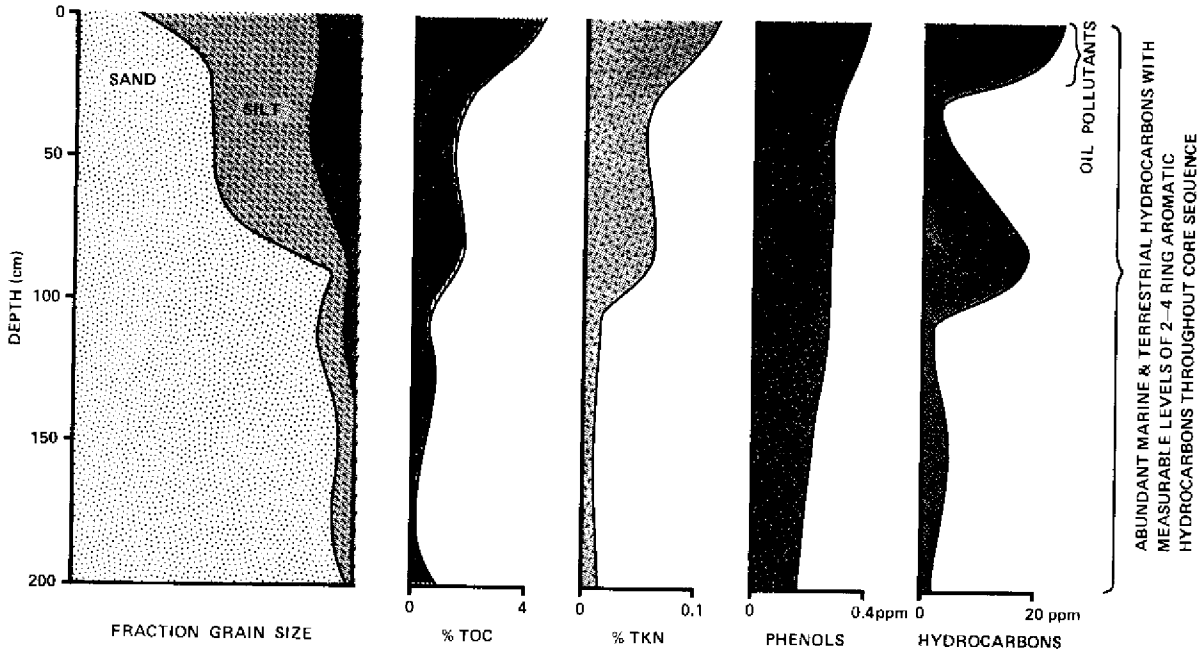
DEER ISLAND

I-19



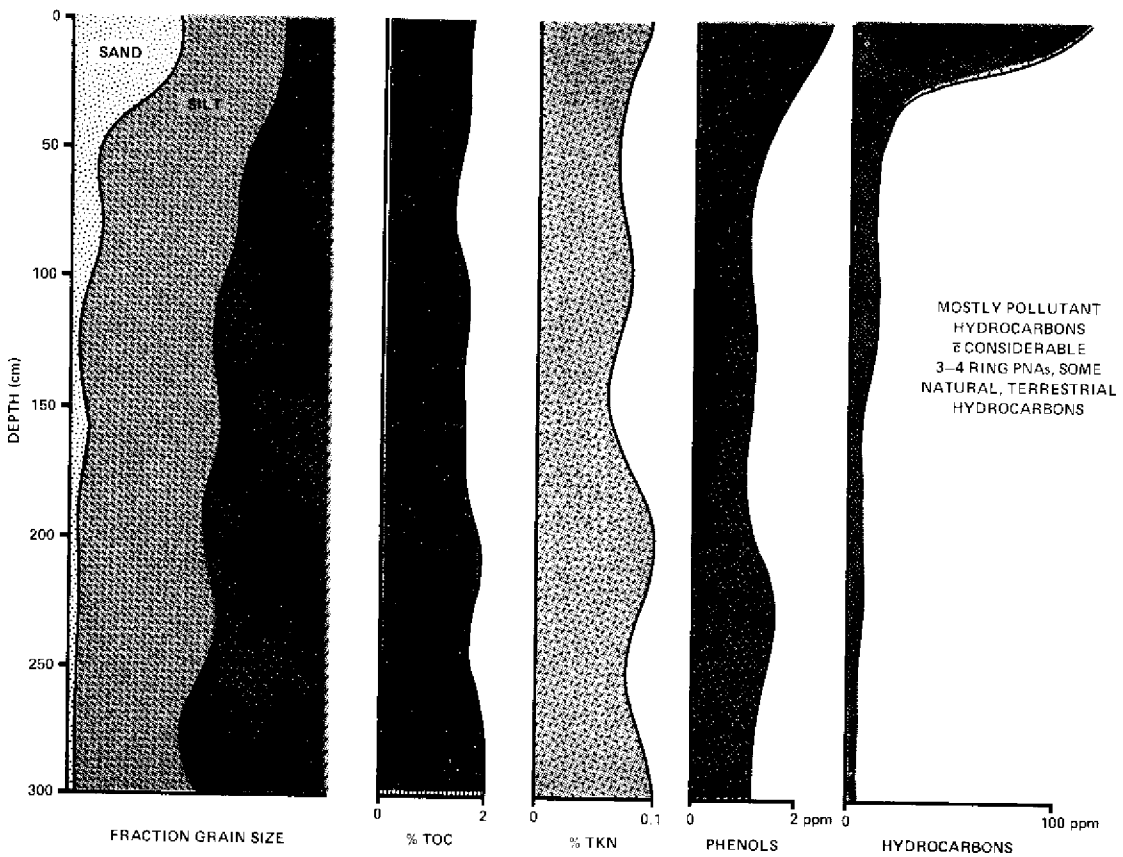
I-20

GULFPORT LAKE



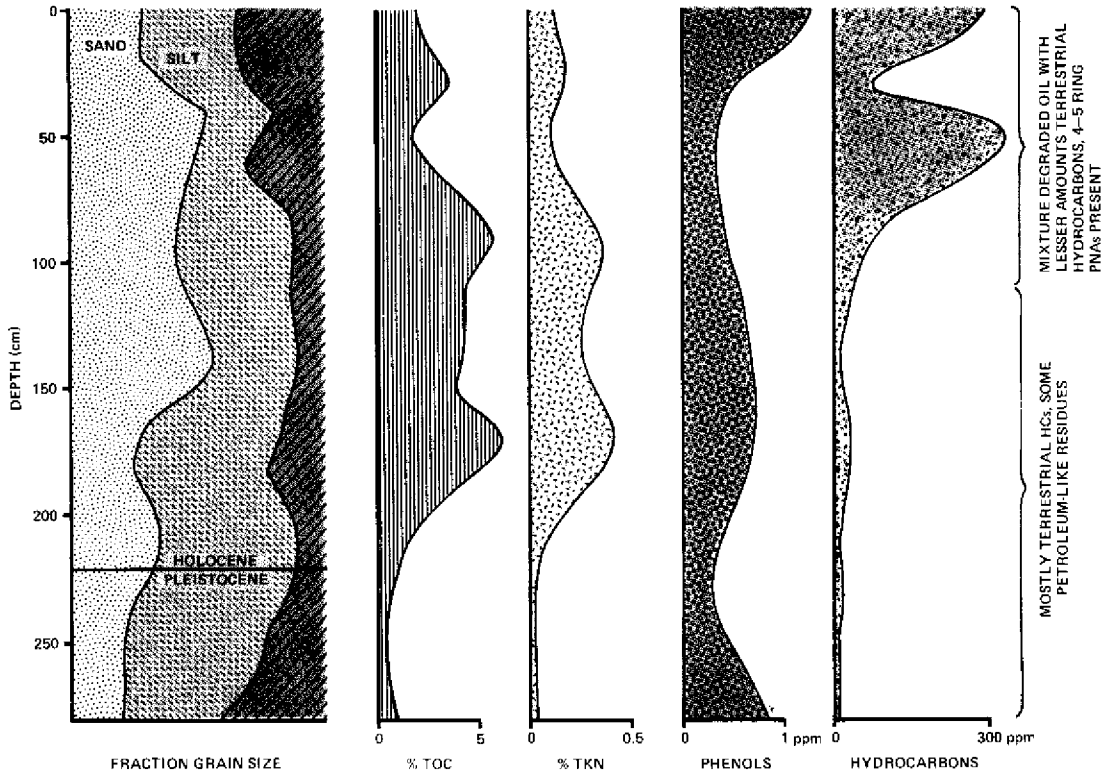
I-21

GOAT ISLAND



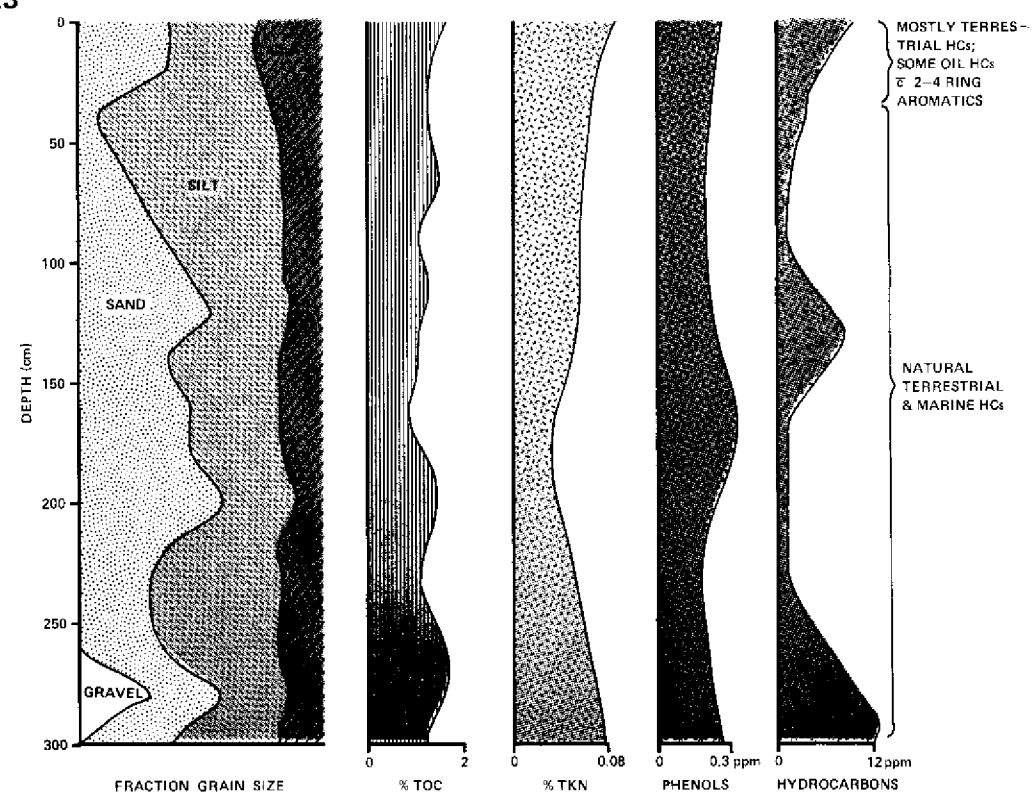
I-22

BIG LAKE



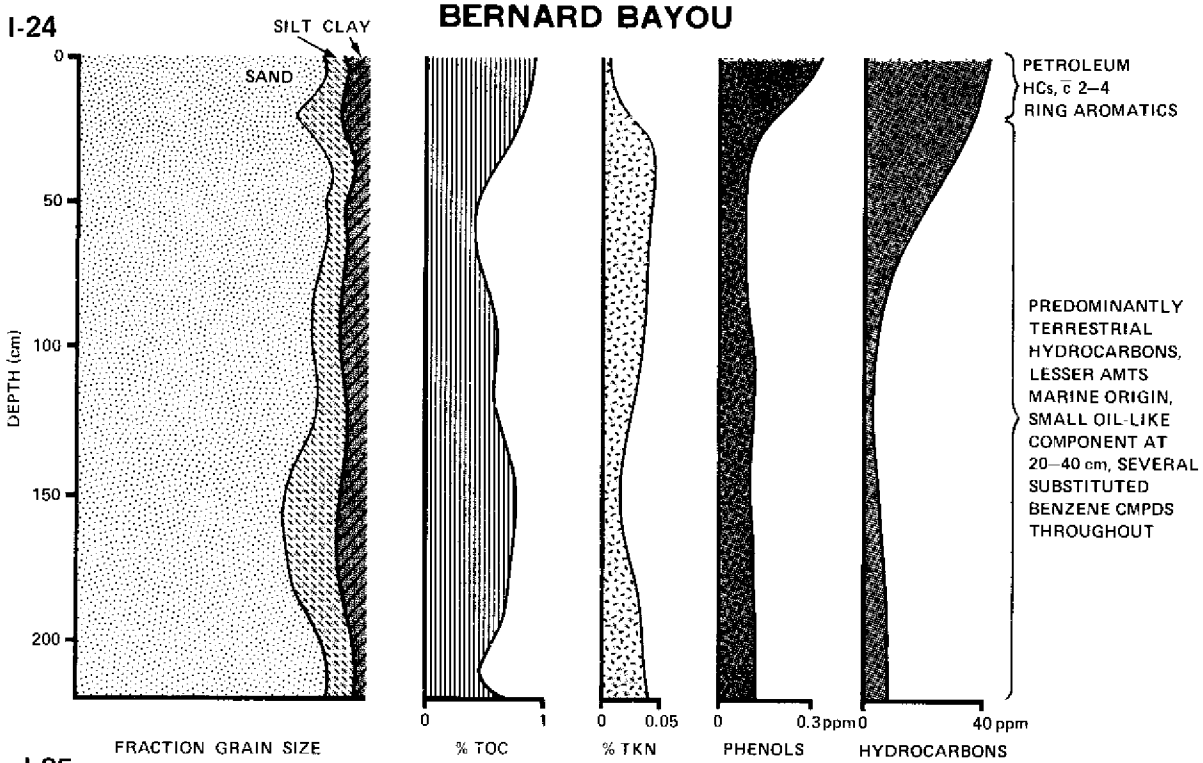
I-23

CEDAR LAKE



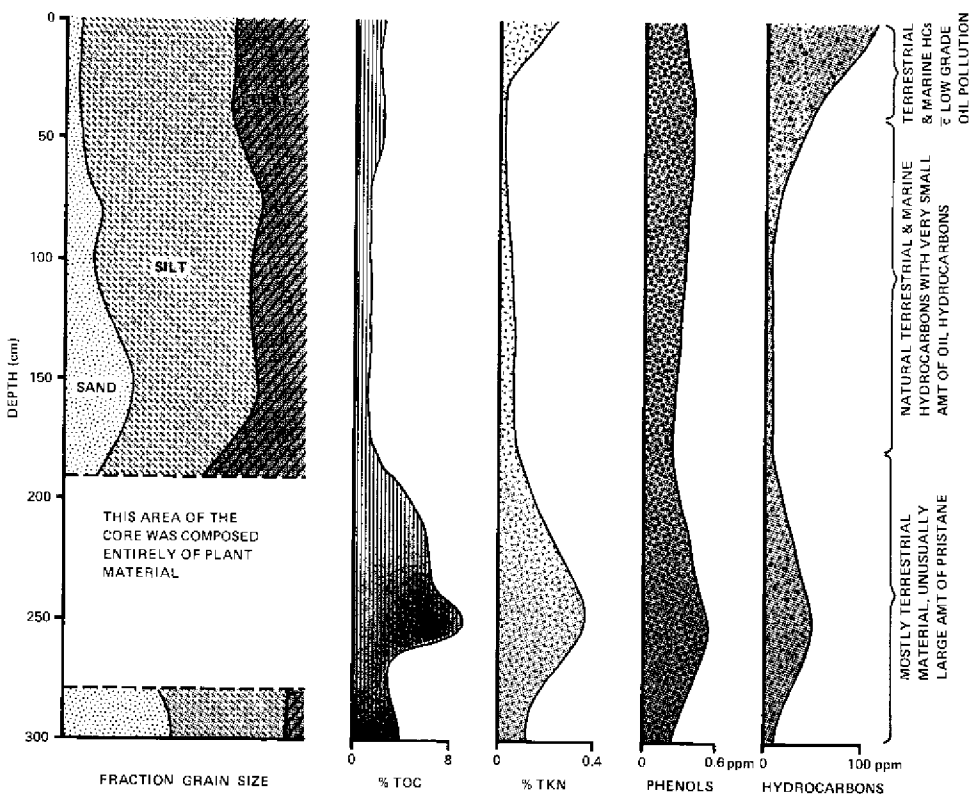
I-24

BERNARD BAYOU



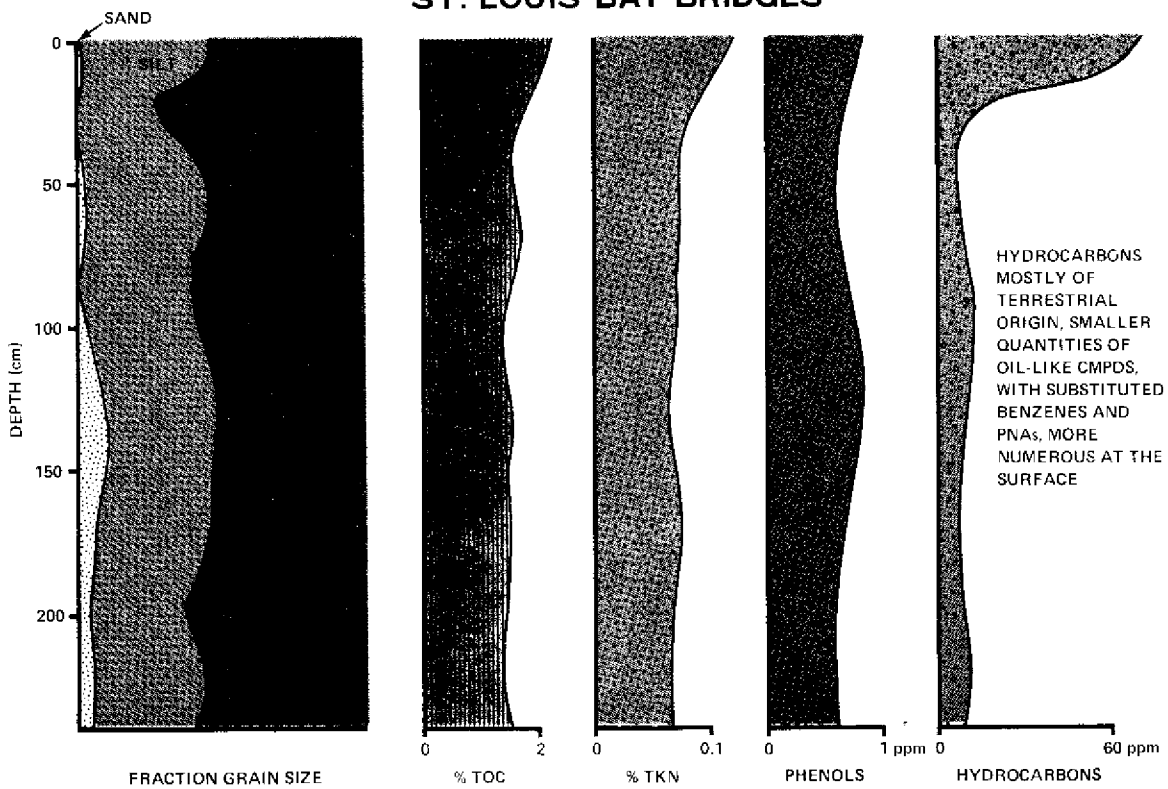
I-25

KEESLER AFB



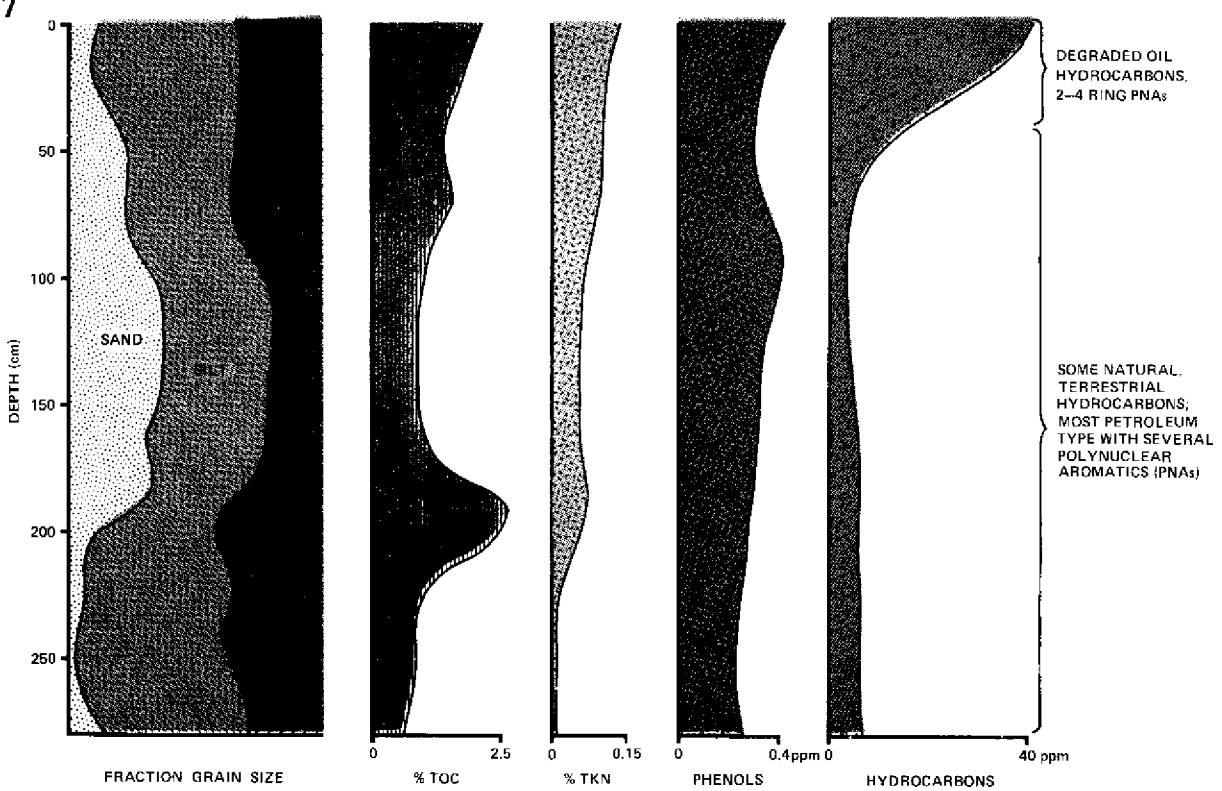
I-26

ST. LOUIS BAY BRIDGES

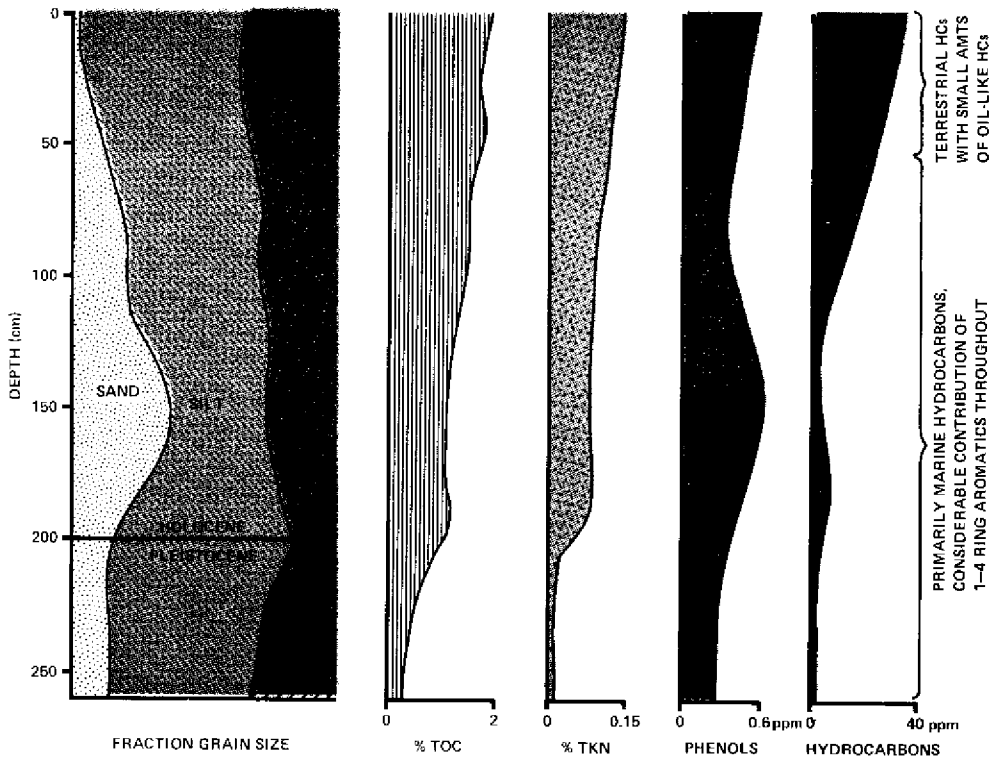


I-27

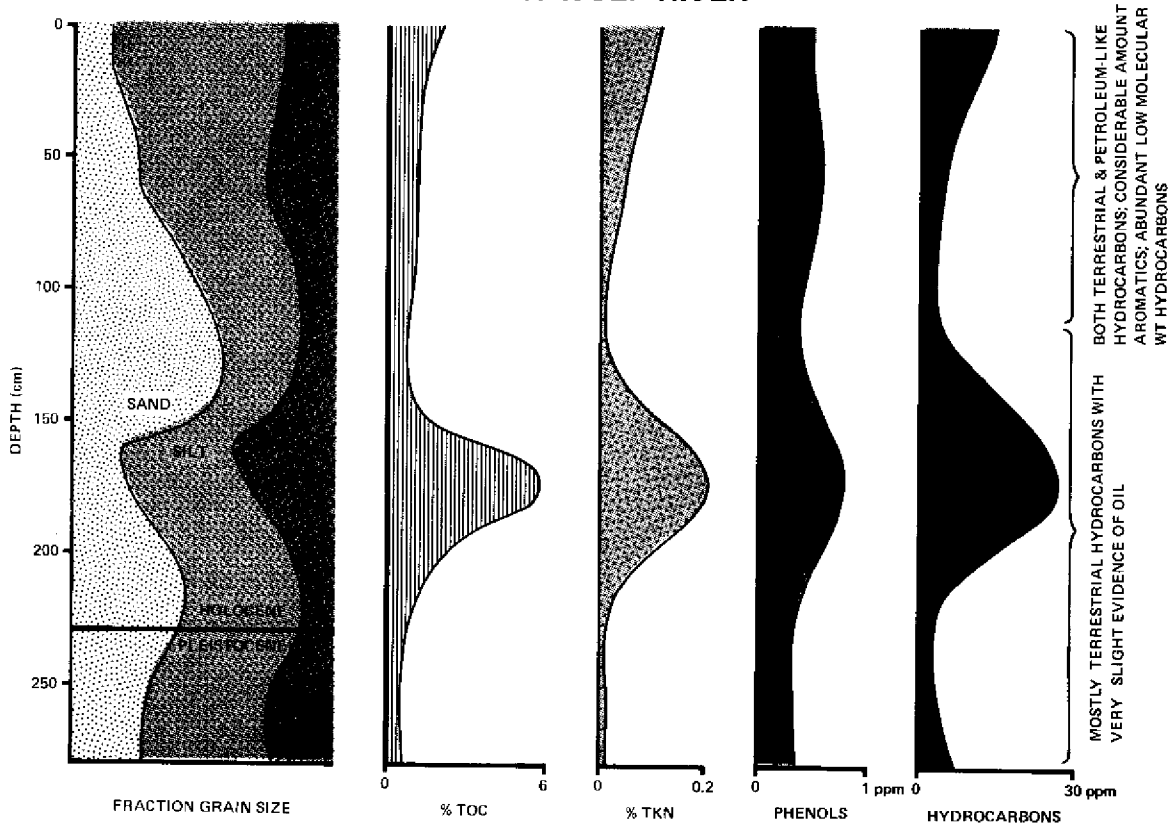
HERON BAY

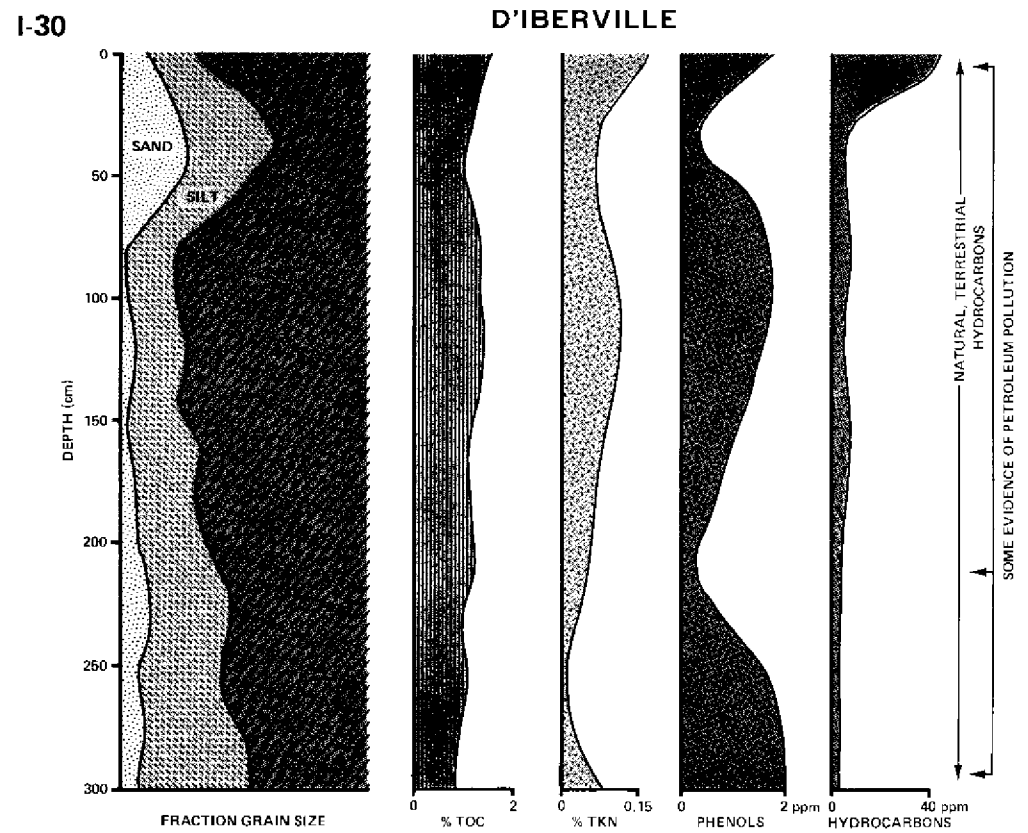


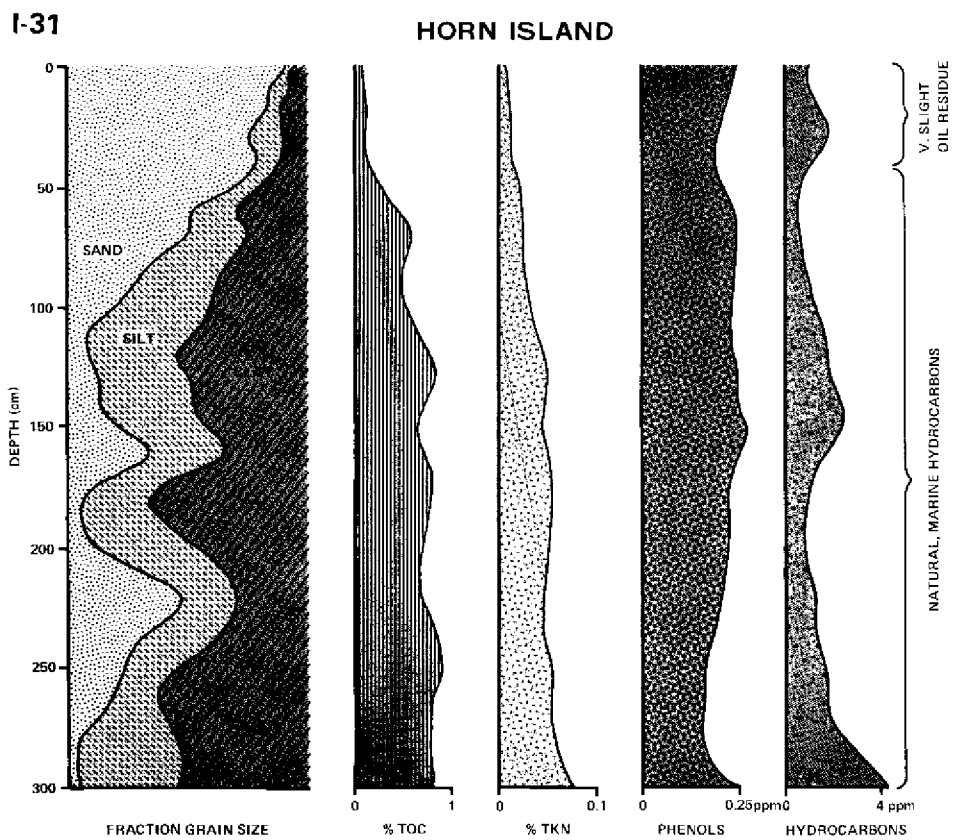
I-28 MOUTH JOURDAN RIVER



I-29 MOUTH WOLF RIVER

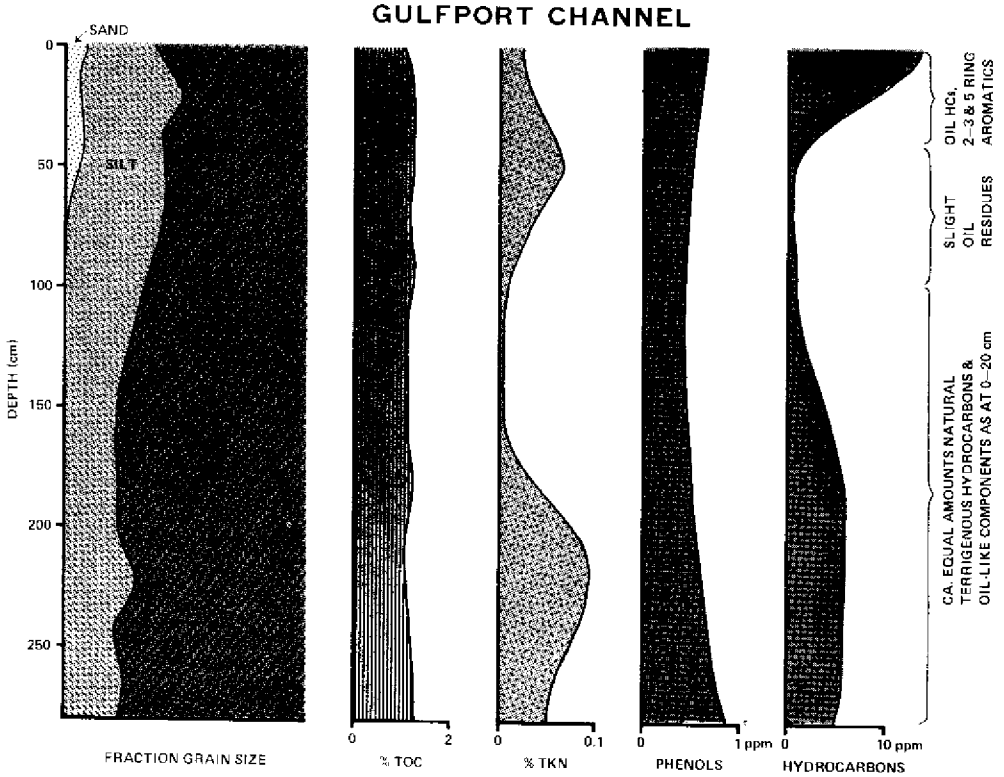



I-30
D'IBERVILLE
DEPTH (cm)
0
50
100
150
200
250
300
SAND
SILT
FRACTION GRAIN SIZE
0
2
% TOC
0
0.15
% TKN
0
2 ppm
PHENOLS
0
40 ppm
HYDROCARBONS
NATURAL, TERRESTRIAL HYDROCARBONS
SOME EVIDENCE OF PETROLEUM POLLUTION


I-31
HORN ISLAND
DEPTH (cm)
0
50
100
150
200
250
300
SAND
SILT
FRACTION GRAIN SIZE
0
1
% TOC
0
0.1
% TKN
0
0.25ppm
PHENOLS
0
4 ppm
HYDROCARBONS
V. SLIGHT OIL RESIDUE
NATURAL, MARINE HYDROCARBONS

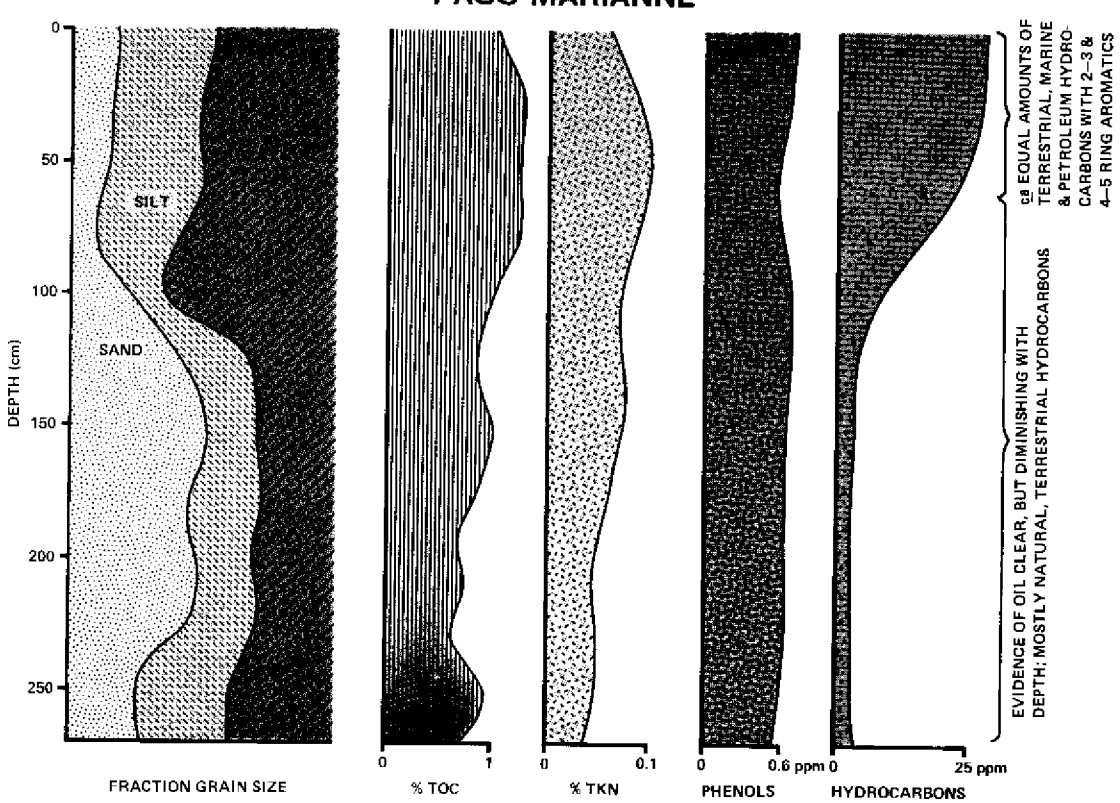
I-32

GULFPORT CHANNEL



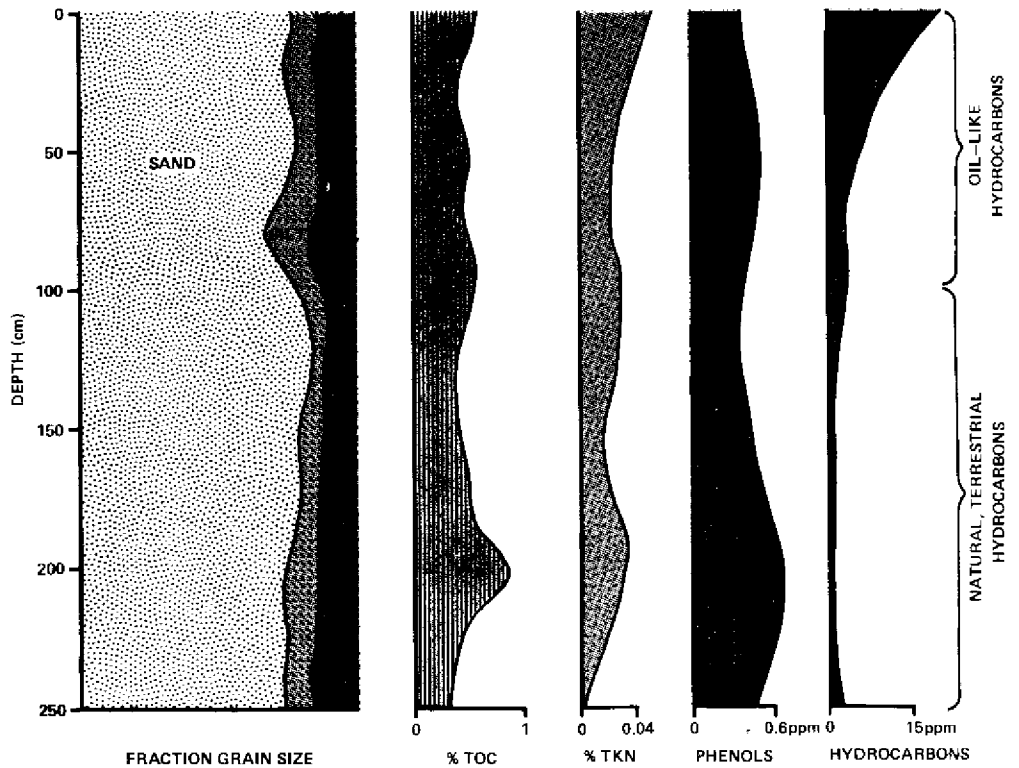
I-33

PASS MARIANNE



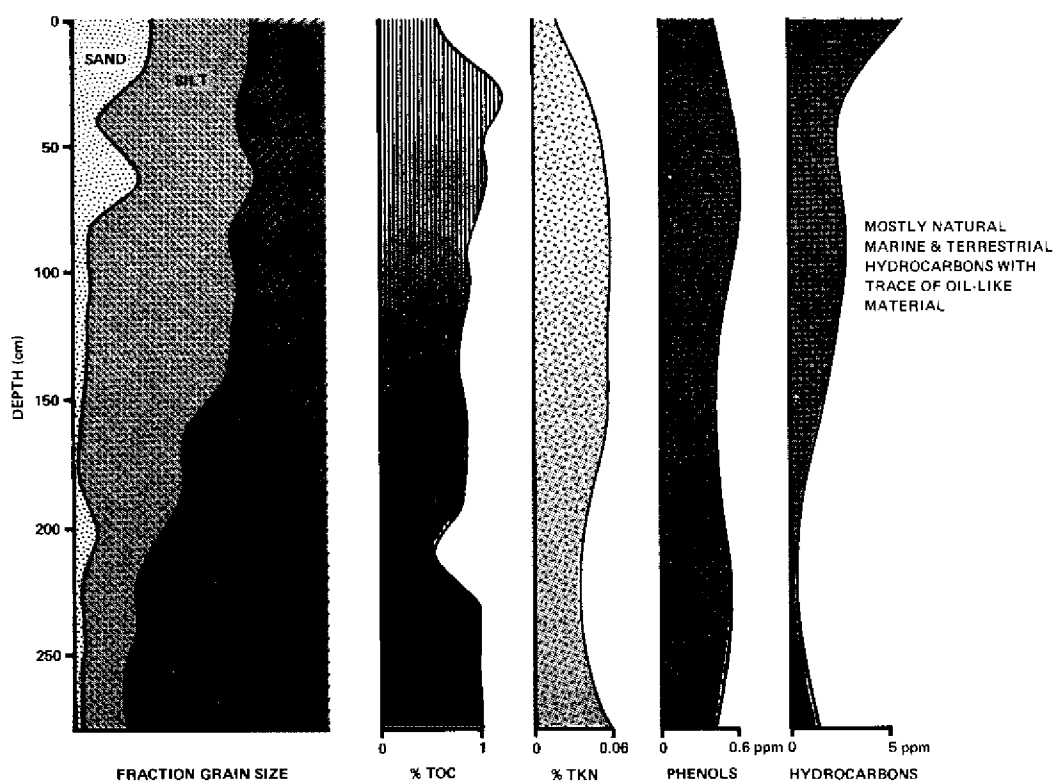
I-34

BELLEFONTAINE POINT



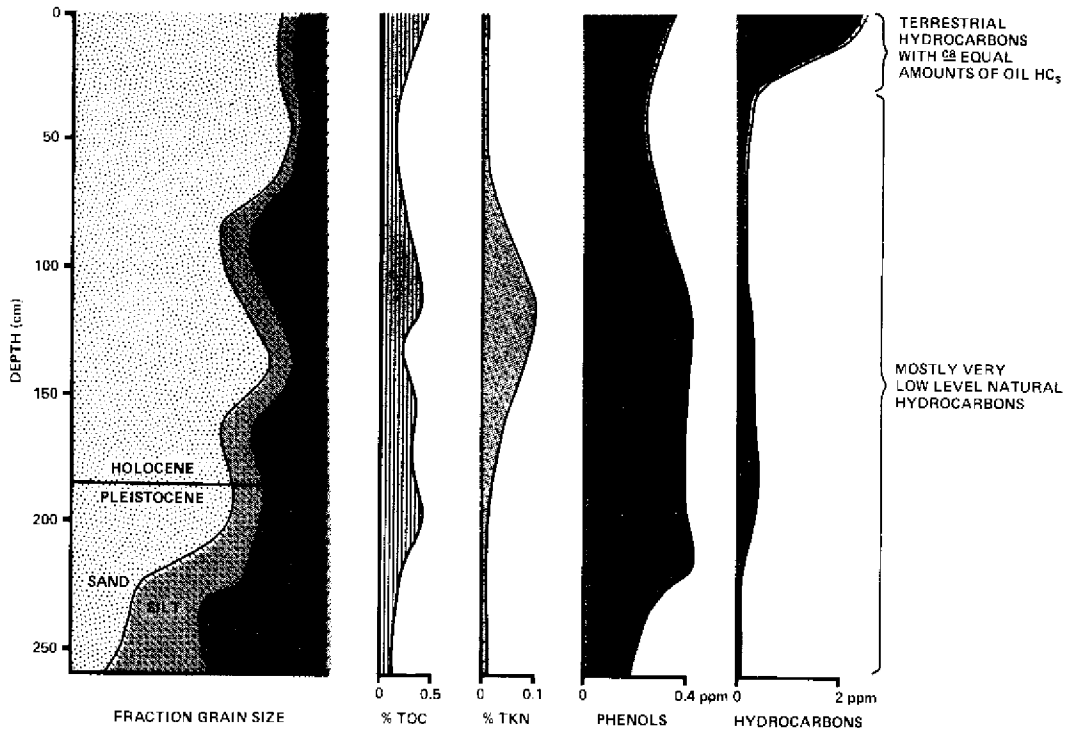
I-35

CAT ISLAND CHANNEL



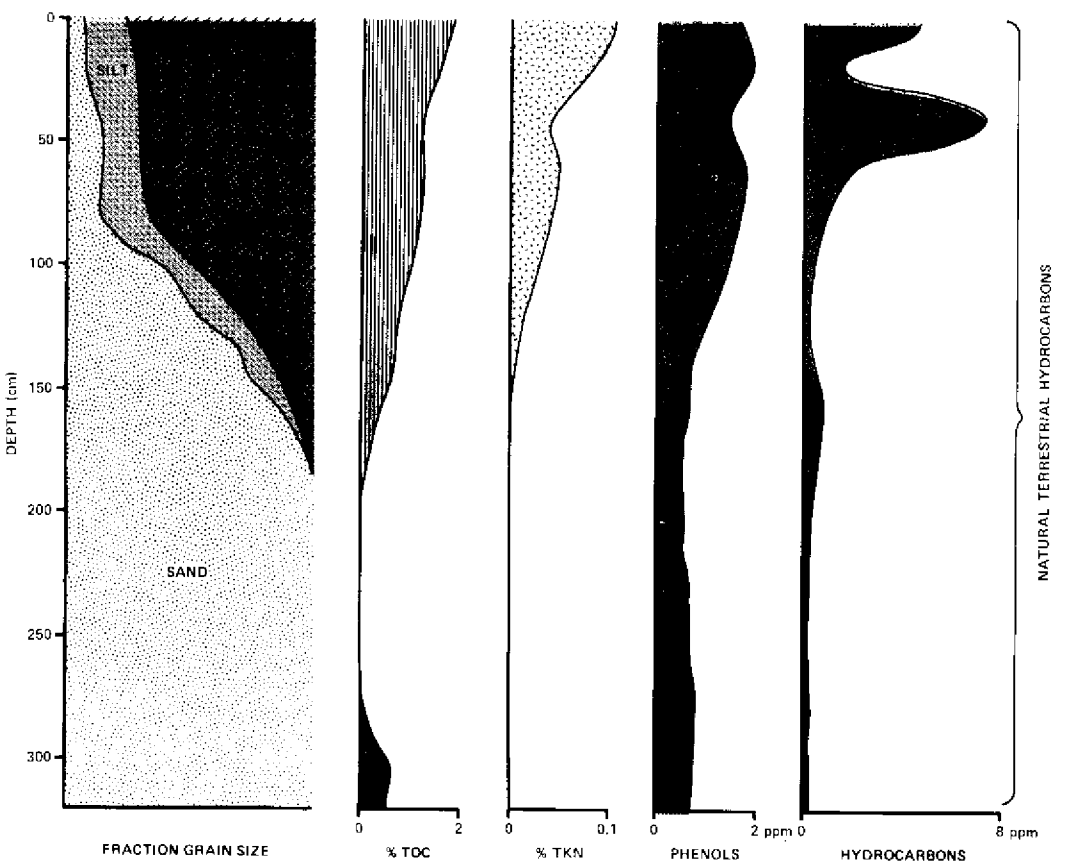
I-36

EAST MISSISSIPPI SOUND



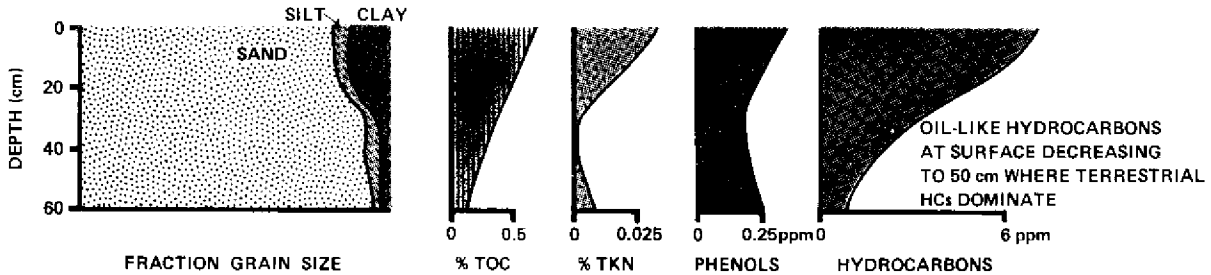
I-37

PETIT BOIS ISLAND



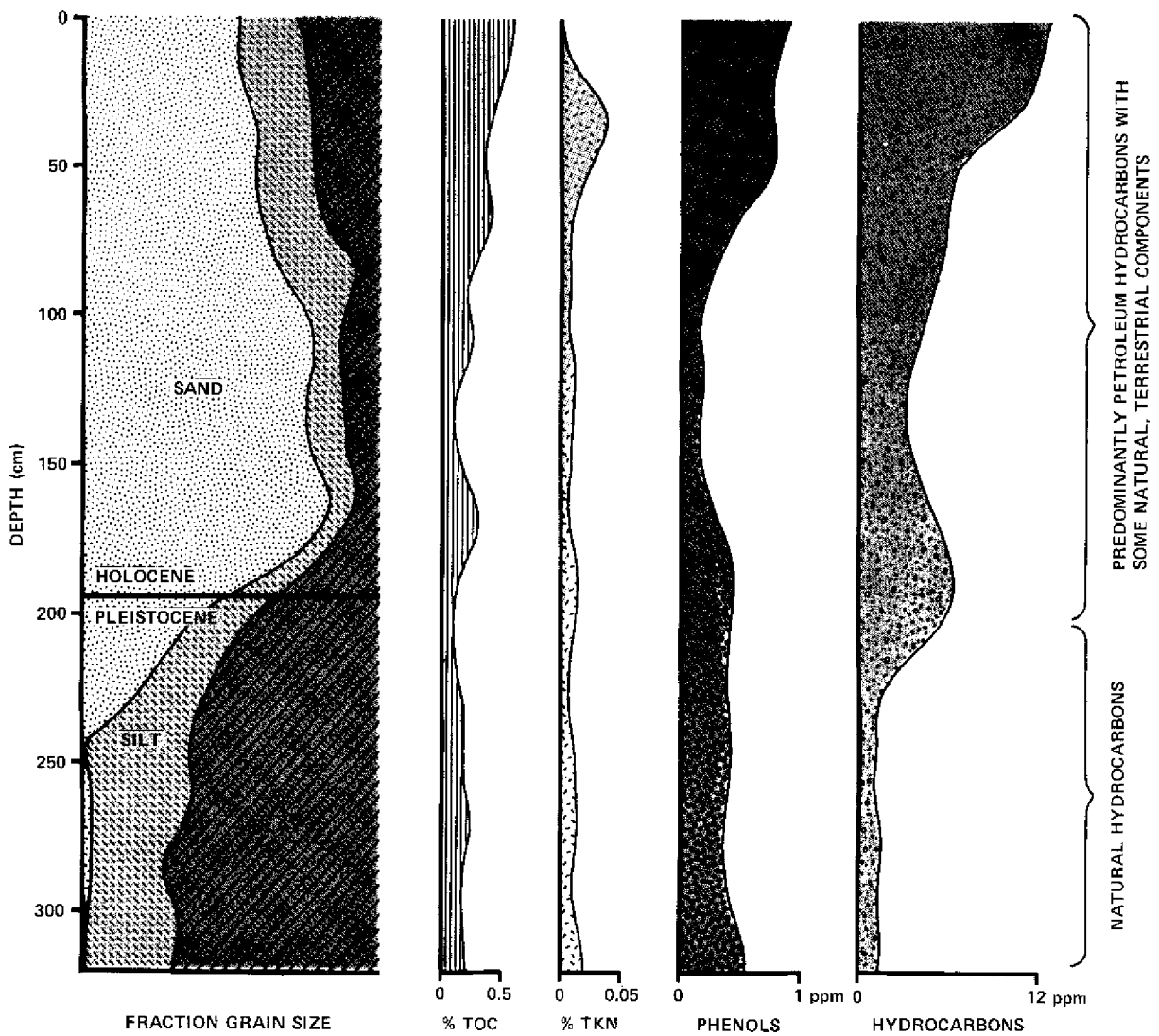
I-38

WEST HORN ISLAND

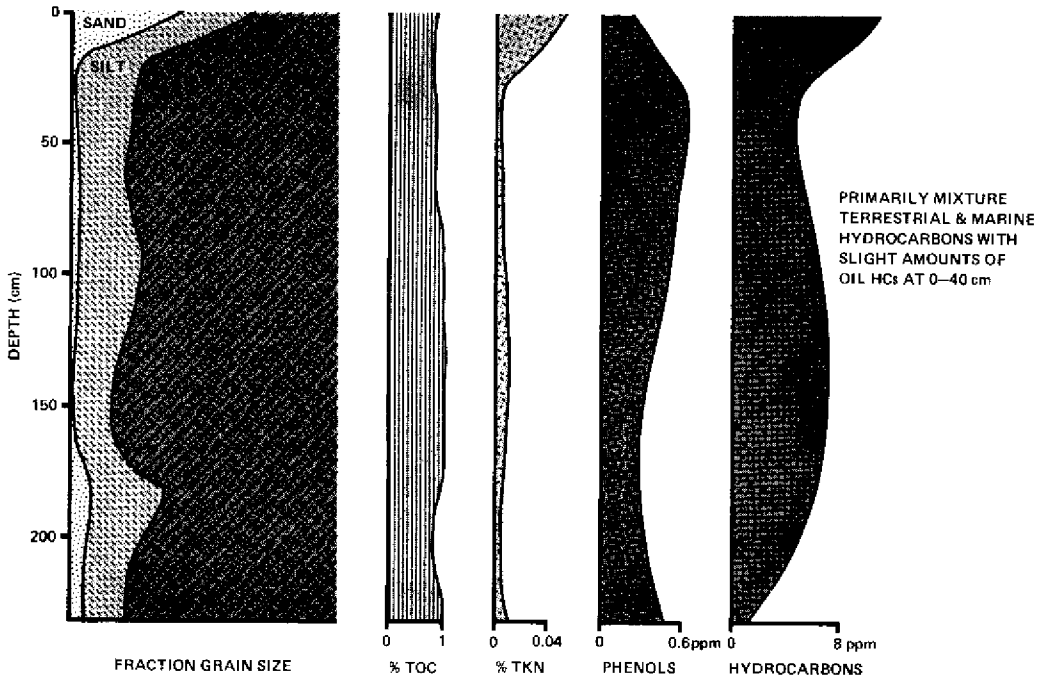


I-39

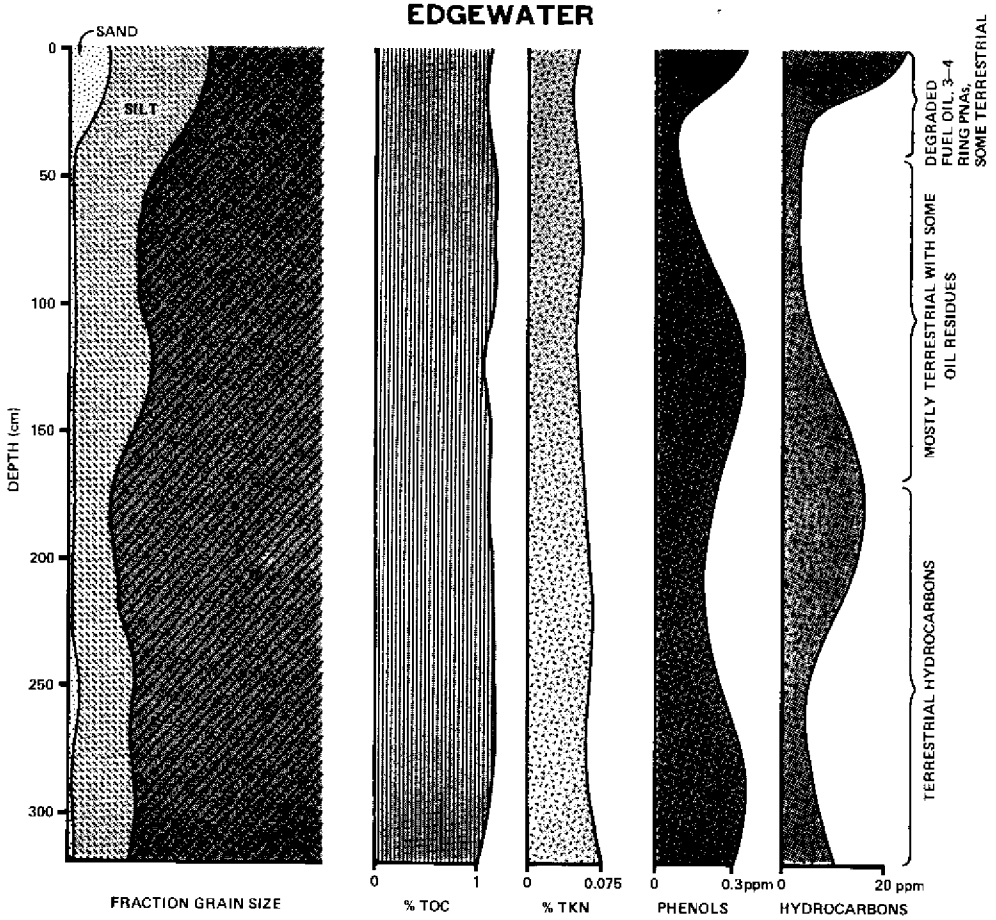
BAYOU LA BATRE



I-40 SHIP ISLAND PASS

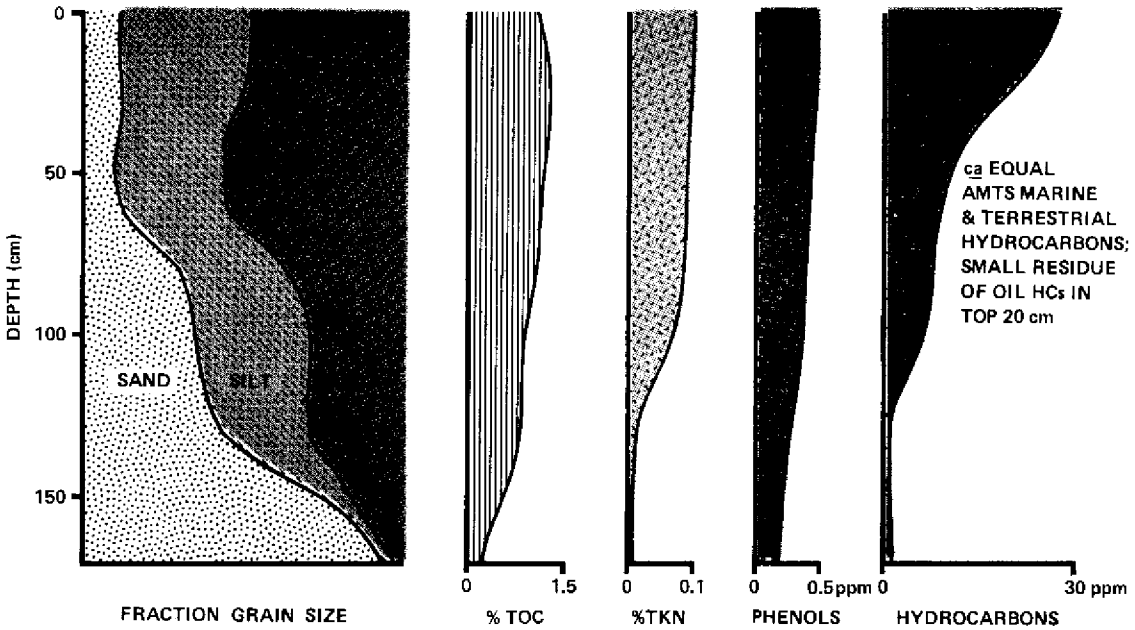


I-41 EDGEWATER



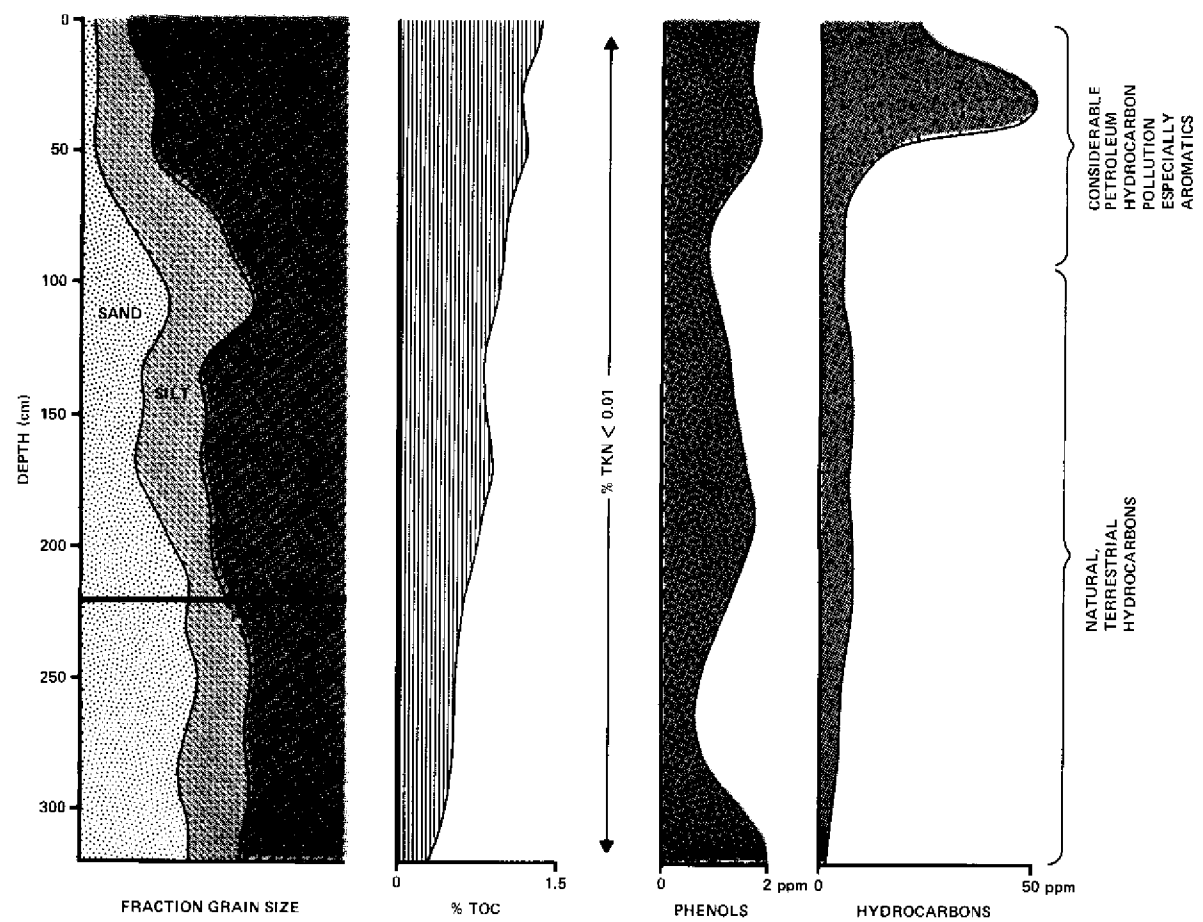
I-42

WEST SHIP ISLAND



I-43

DAUPHIN ISLAND



APPENDIX II

MISSISSIPPI SOUND SEDIMENT SETTLING RATE CURVES

To investigate the overall impact of resuspension of contaminated sediments from the Mississippi Sound, settling-rate characteristics were determined. Sediments from each sampling site in the Sound were suspended in water at a ratio of 1:4, V/V sediment and water. Approximately 250 g of sediment were dispersed in site water in one gallon jars using a platform shaker for disposal. At the end of a 5-minute shaking period, 1 minute elapsed before an initial 5-mℓ sample was withdrawn from 2 cm beneath the surface. After this initial collection, additional aliquots were withdrawn sequentially for 2,880 minutes. Suspended solids, measured gravimetrically, have been plotted as percent of the initial value versus time elapsed from cessation of dispersal. Points designated as $t_{1/2}$, $t_{1/4}$, and $t_{1/8}$ represent times at which suspended solids dropped to one-half, one-fourth, and one-eighth of initial values. The logarithmic x-axis gives proper definition to measurements made during short intervals immediately following the mixing process. Each of the settling-rate curves displayed may be described by one of eight settling descriptions as follows:

I. Very high initial suspended solids (15,000 to 35,000 mg/ℓ) dropping abruptly to background values.

II. Very high initial suspended solids (20,000 to 35,000 mg/ℓ) briefly maintained then dropping abruptly to background values.

III. Medium to high initial suspended solids (3,000 to 45,000 mg/ℓ) having steady gradual straight line decline with time to background levels.

IV. Medium high to high initial suspended solids (10,000 to 20,000 mg/ℓ), retained for long periods of time then slow decline to background values.

V. Very high initial suspended solids (> 75,000 mg/ℓ) with two-stage drop, abrupt in each case.

VI. Low initial suspended solids (< 1,000 mg/ℓ) abruptly dropping to background values.

VII. Low initial suspended solids (< 1000 mg/ℓ) with gradual, straight line decline.

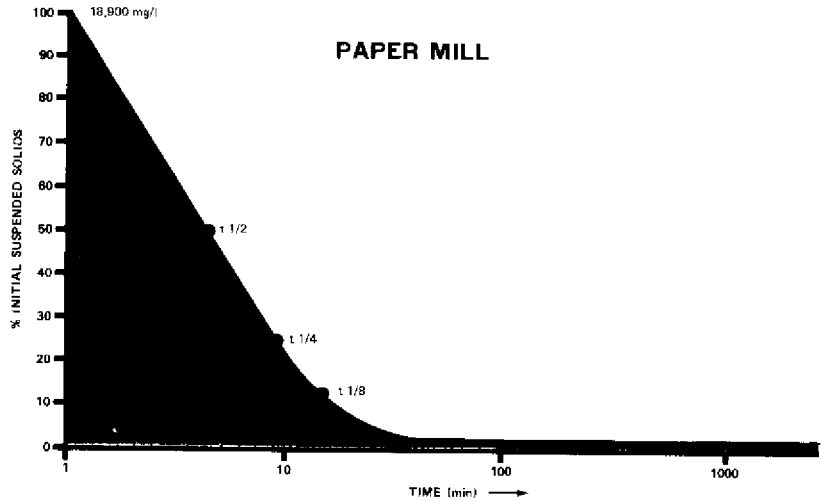
VIII. Low initial suspended solids (< 1,000 mg/ℓ) with decline in several plateaus indicating distinct fractions having varying suspension stabilities.

Mississippi Sound Sediment Settling Rate Curves

Figure No.	Sampling Site	Location Code[1]	Conditions		Class of Sediment Settling Rate							
					I	II	III	IV	V	VI	VII	VIII
Pascagoula River System												
II-1	Paper Mill	PM	N[2]				√					
II-2	Pogey Plant	PP	N					√				
II-3	Halter Marine	HM	N							√		
II-4	McInnis Lake	ML	N				√					
II-5	Escatawpa River	ER	15.0 ppt			√						
II-6	Escatawpa River	ER	6.5 ppt								√	
II-7	Griffin Point	GP	N				√					
II-8	Elevator Bayou	EB	N			√						
II-9	Dead River	DR	15.0 ppt				√					
II-10	Dead River	DR	0.0 ppt			√						
II-11	Lake Yazoo	LY	N			√						
II-12	Mary Walker Bayou	MW	N								√	
II-13	Bayou Pierre	BP	N								√	
II-14	Twin Islands	TI	N									√
II-15	Chevron N. Dock	CD	N			√						
II-16	Cooling Tower Canal	CT	N			√						
II-17	Cooling Tower Canal	CT	5.0 ppt	5°C		√						
II-18	Cooling Tower Canal	CT	5.0 ppt	30°C		√						
II-19	Cooling Tower Canal	CT	14.0 ppt	5°C		√						
II-20	Cooling Tower Canal	CT	14.0 ppt	30°C		√						
II-21	West Prong	WP	N		√							
II-22	Mississippi Chemical East Bank	MC	N		√							
II-23	Graveline Bayou	GB	N									√
Biloxi Bay System												
II-24	Hewchem Industrial Canal	HC	N		√							
II-25	Industrial Seaway	IS	15.0 ppt			√						
II-26	Industrial Seaway	IS	6.5 ppt			√						
II-27	Turkey Creek	TC	N				√					
II-28	Gulfport Lake	GL	N		√							
II-29	Reichhold Industrial Canal	RC	N		√							
II-30	Coley Island	CI	N		√							
II-31	Power Plant	PW	N		√							
II-32	V.A. Hospital	VA	N						√			
II-33	Rhodes Point	RP	N						√			
II-34	Deer Island	DI	N		√							
II-35	Old Fort Bayou	FB	N			√						
II-36	Davis Bayou	DB	N			√						
St. Louis Bay System												
II-37	St. Louis Bay Bridges	BB	N				√					
II-38	Heron Bay	HB	N					√				
Mississippi Sound System												
II-39	E. Gulfport Channel	GC	N			√						
II-40	Ship Island	SI	N			√						
II-41	E. Horn Island	HI	N			√						
II-42	Open Gulf	OG	N			√						

[1] Refer to Figure 2 (page 70) for site location.
[2] Natural, ambient conditions.

II-1



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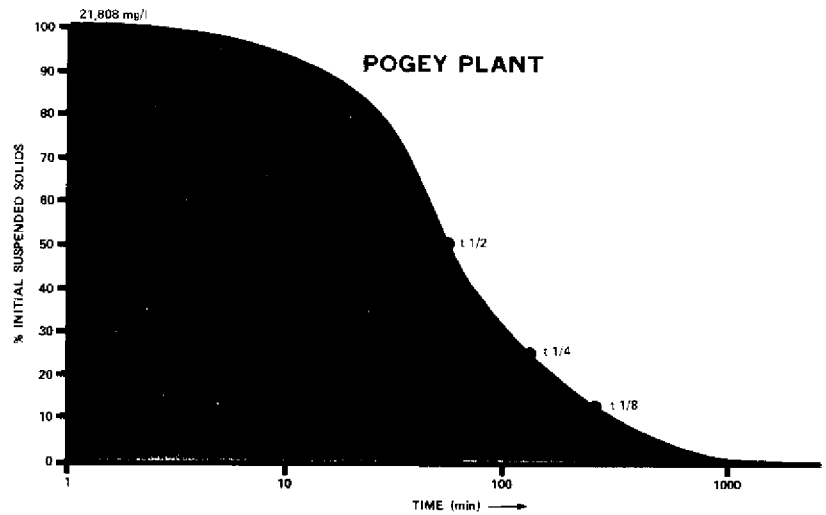

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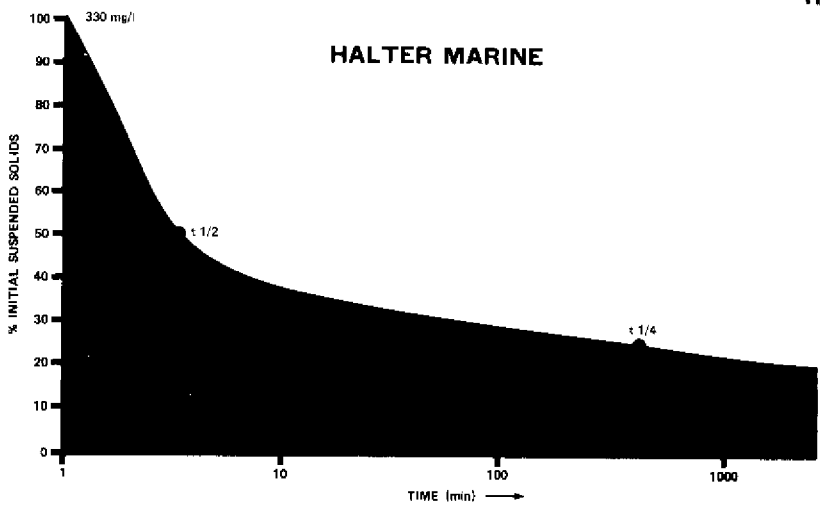

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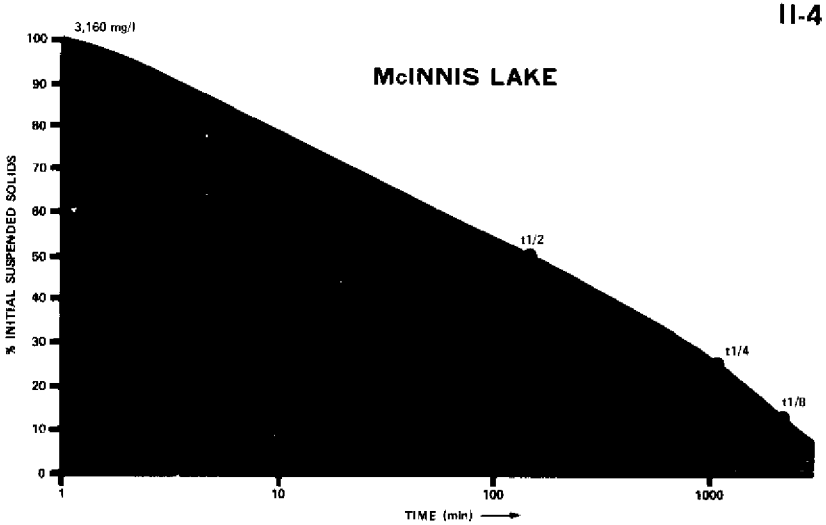

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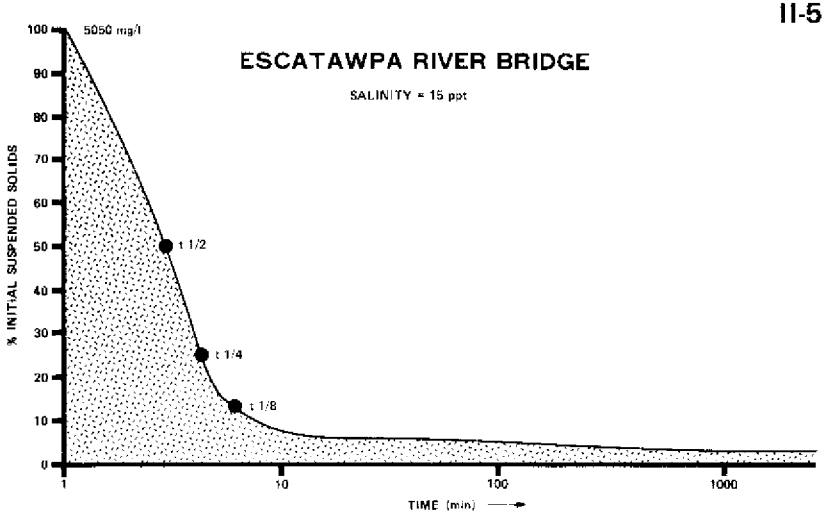

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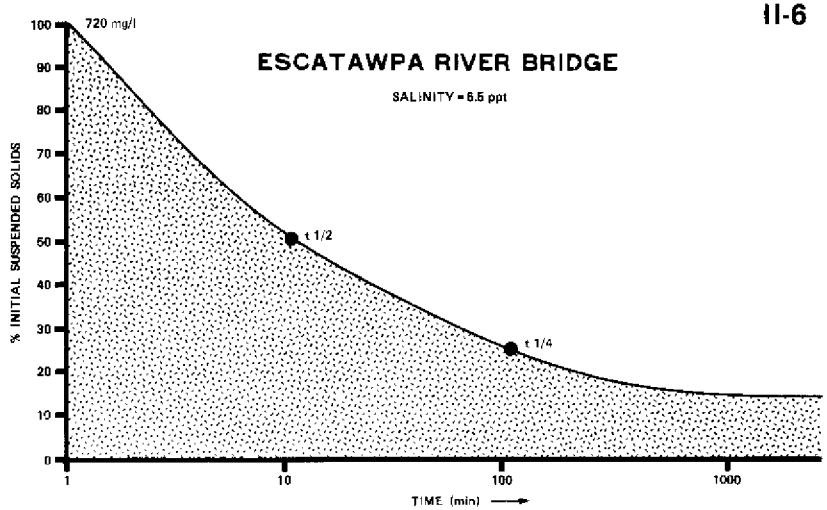

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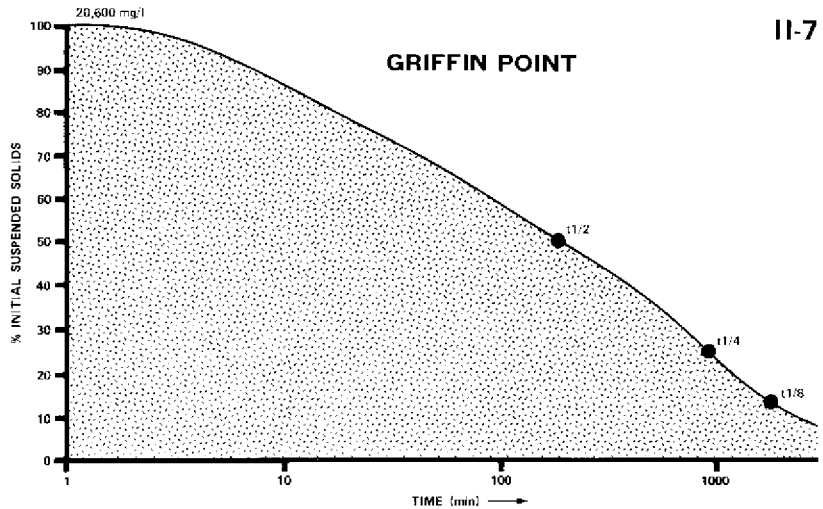

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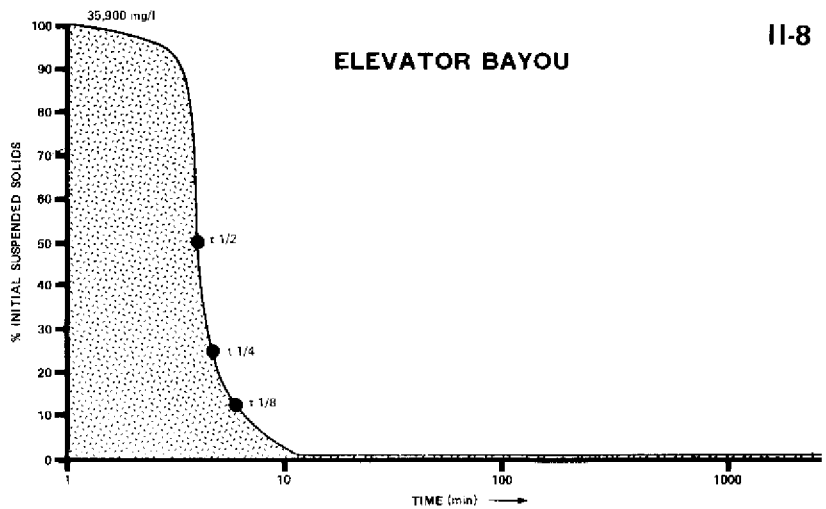

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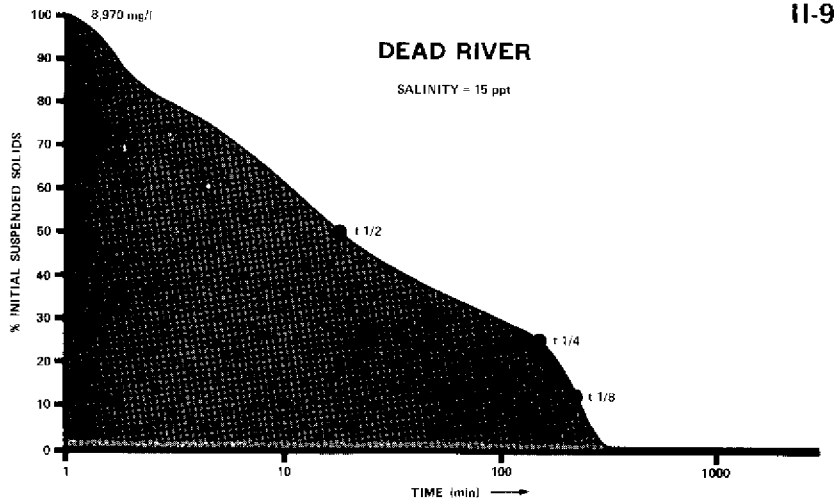

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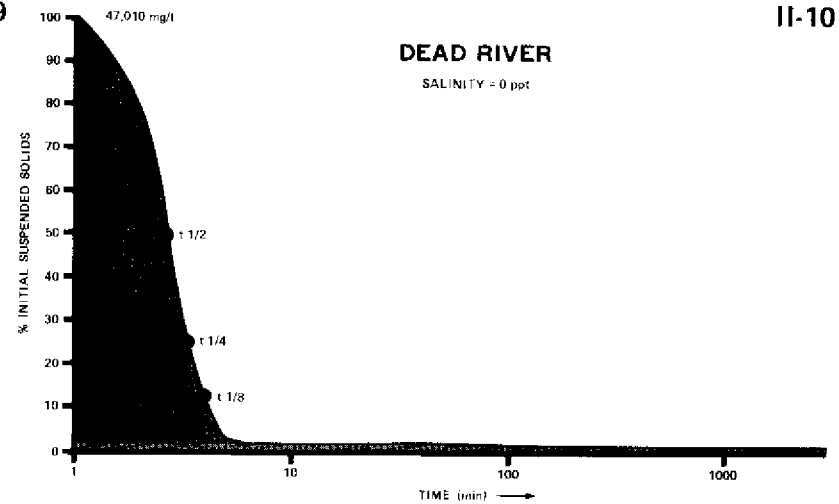

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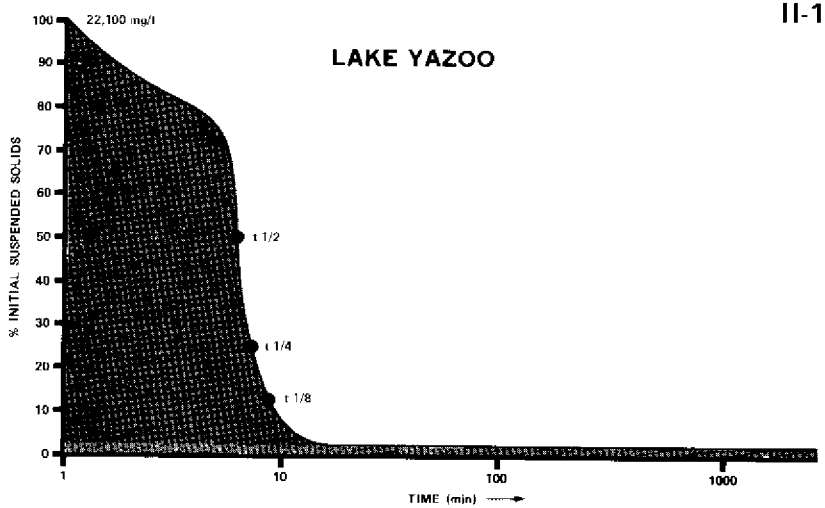

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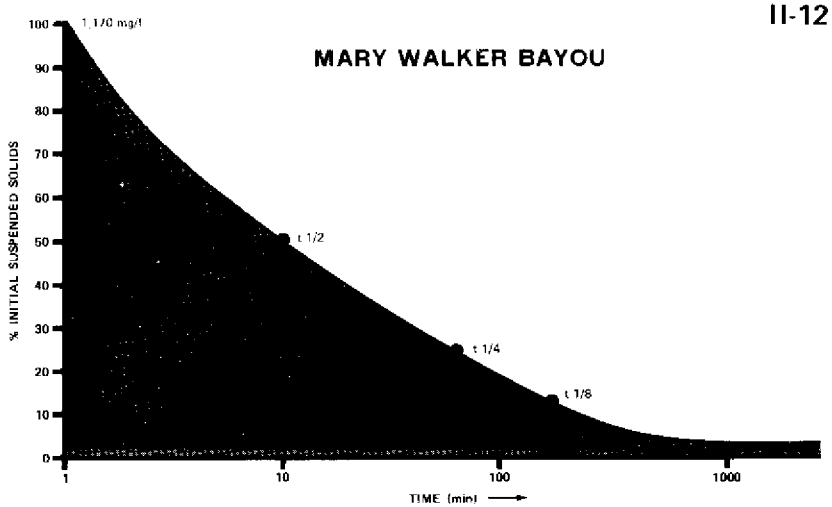

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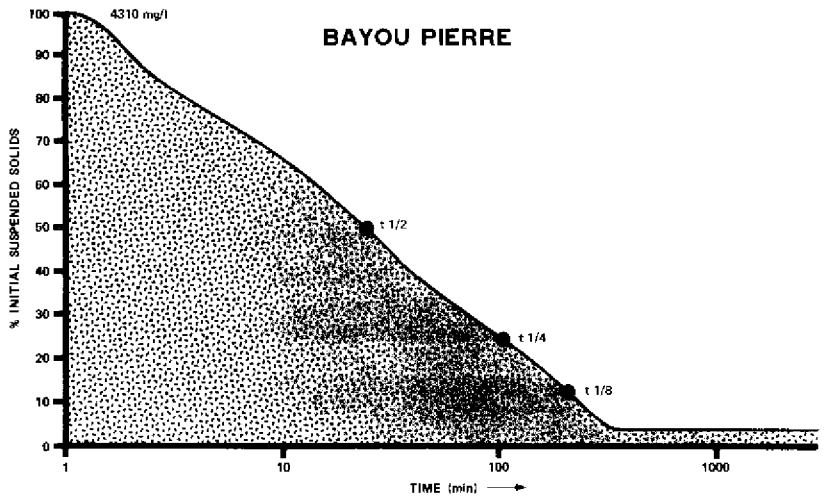

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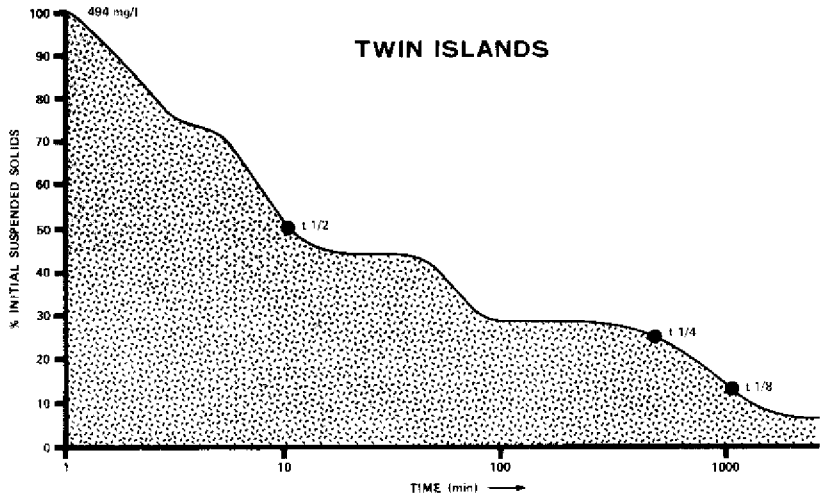

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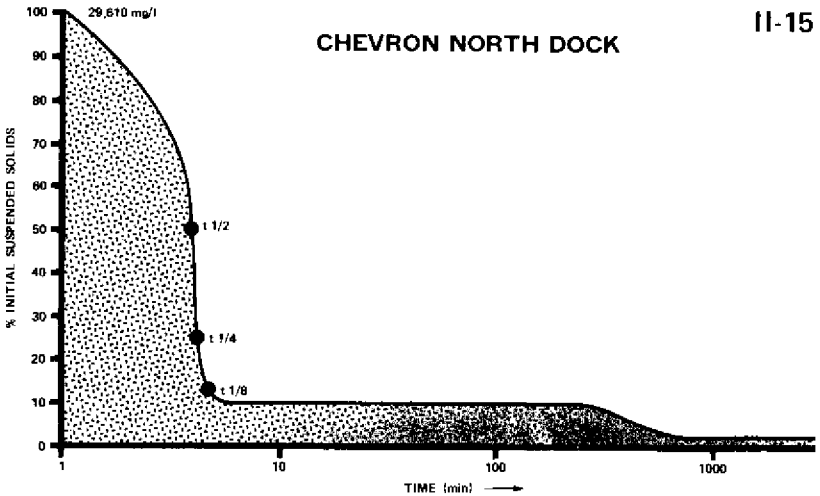

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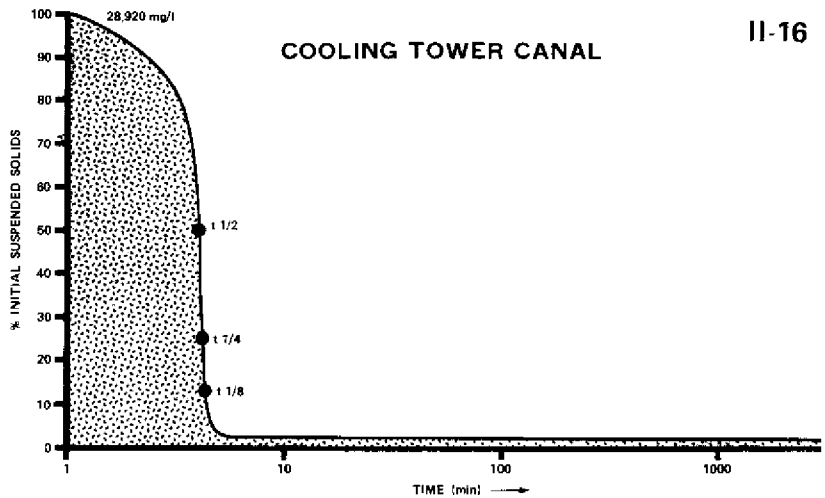

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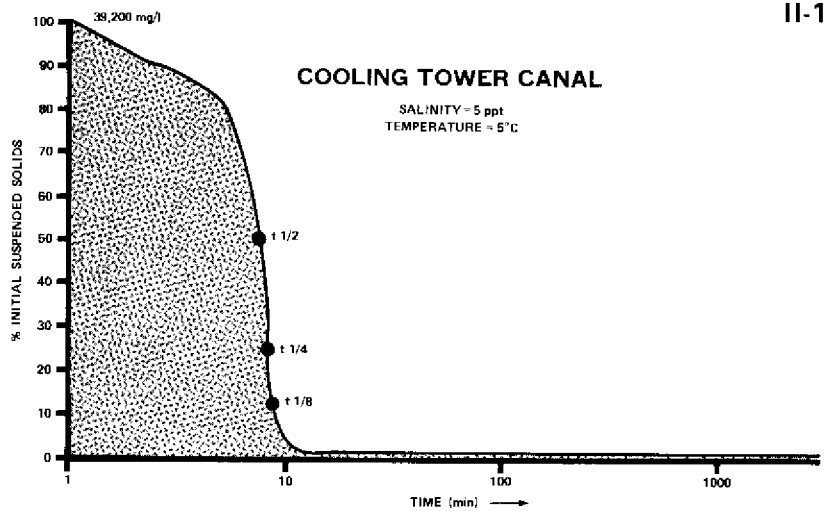

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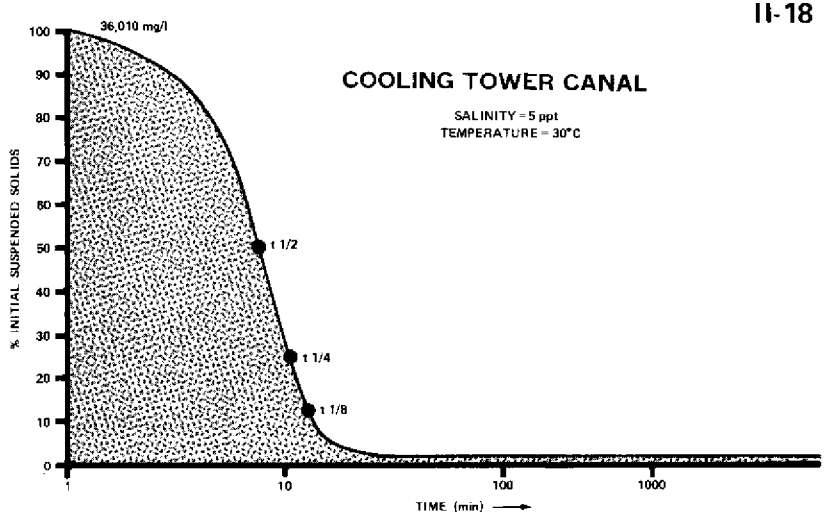

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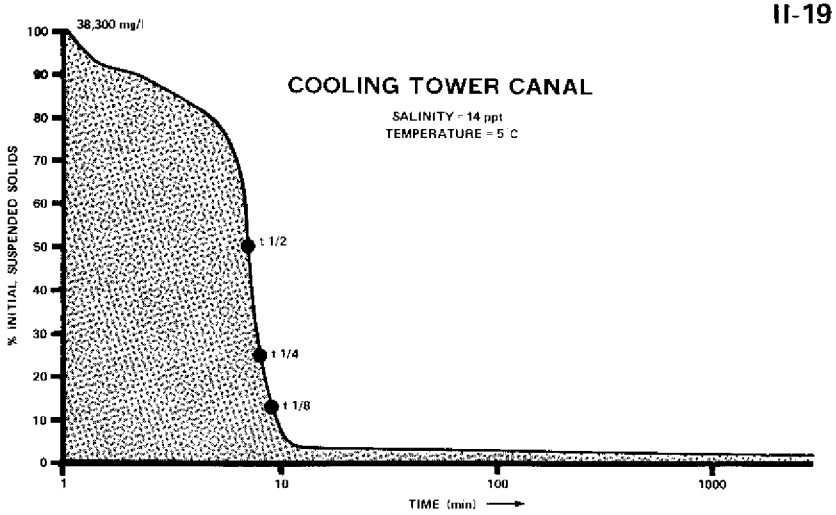

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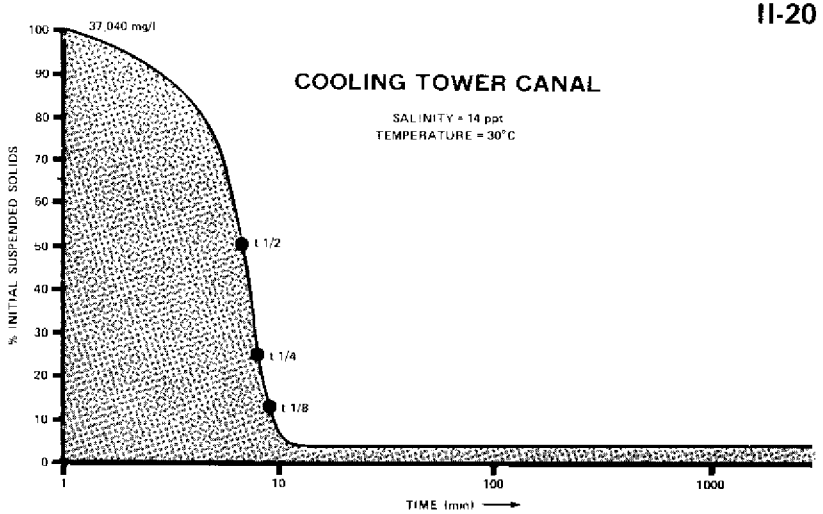

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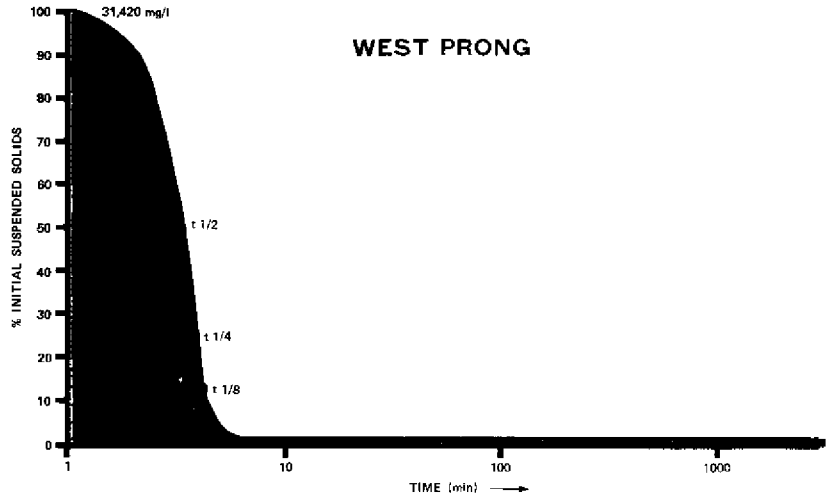

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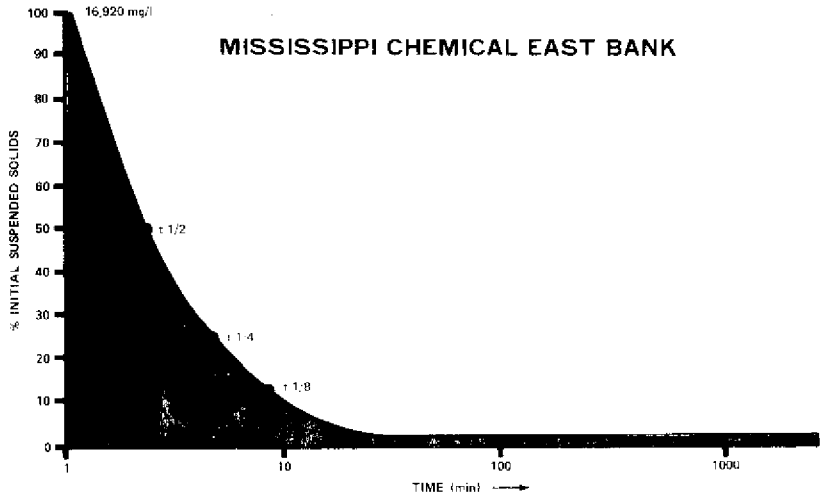

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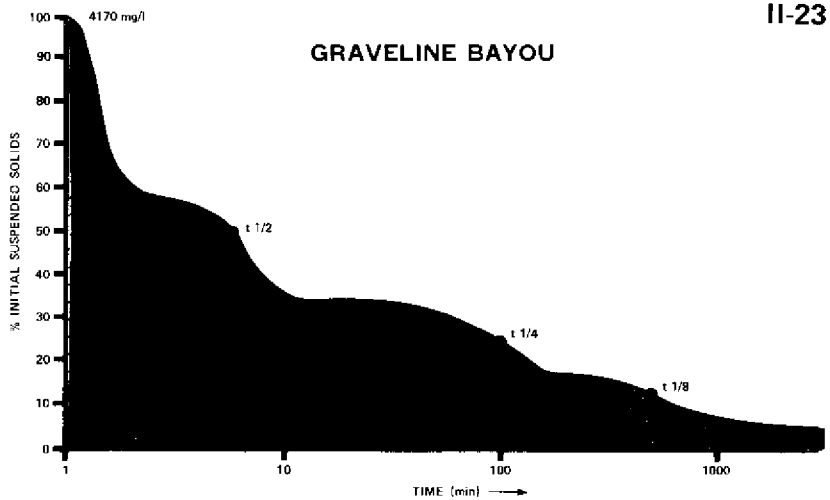

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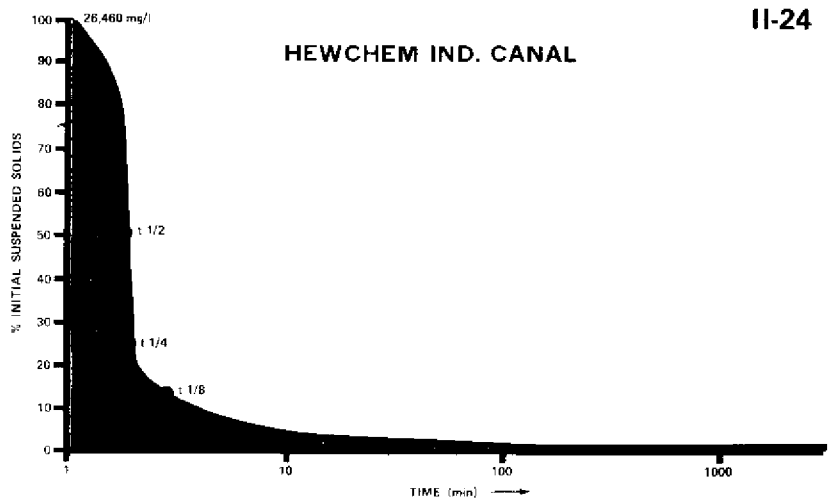

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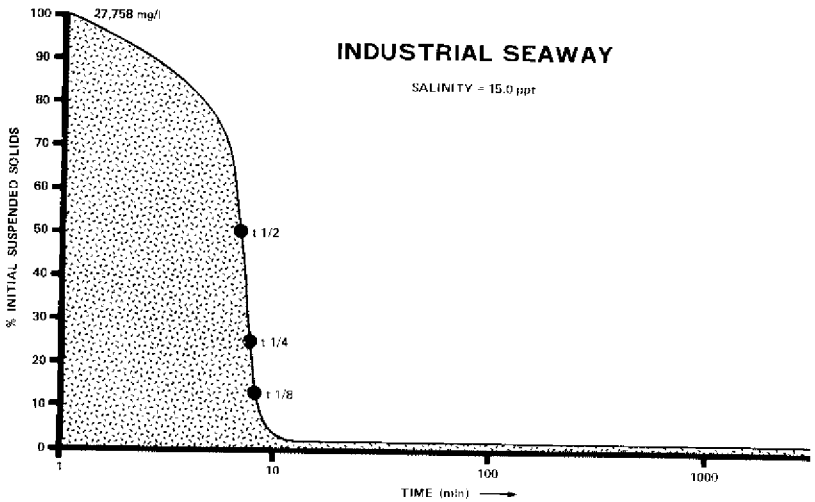

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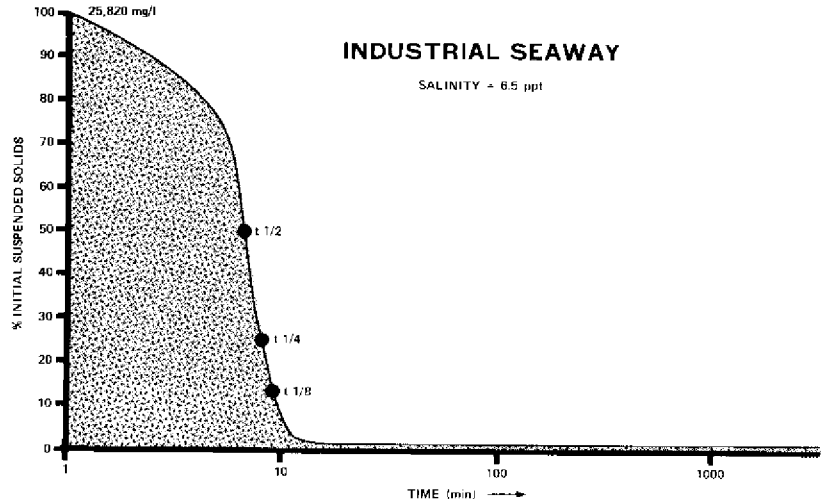

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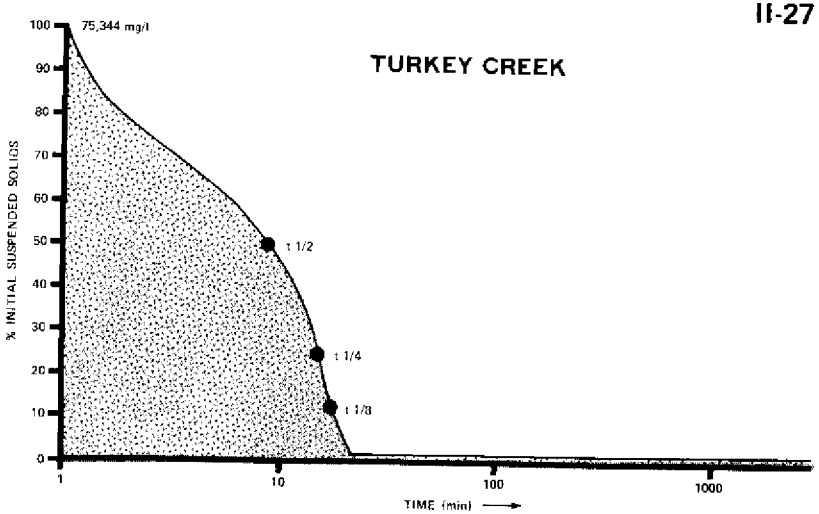

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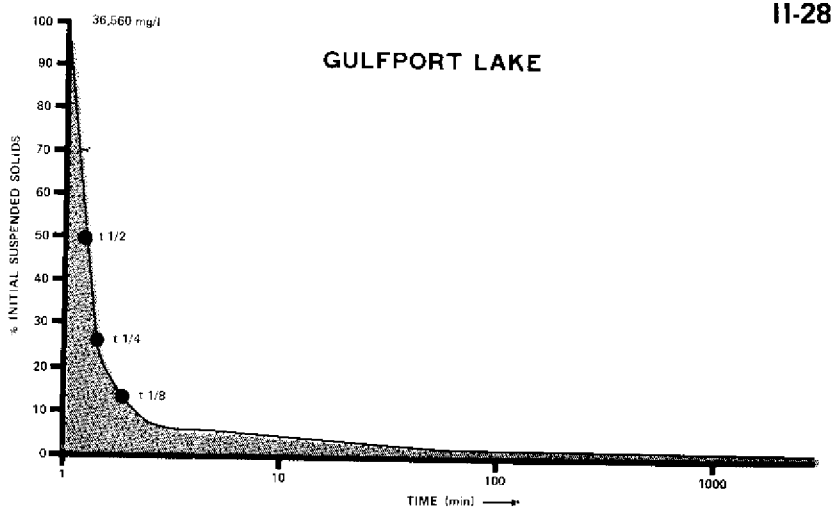

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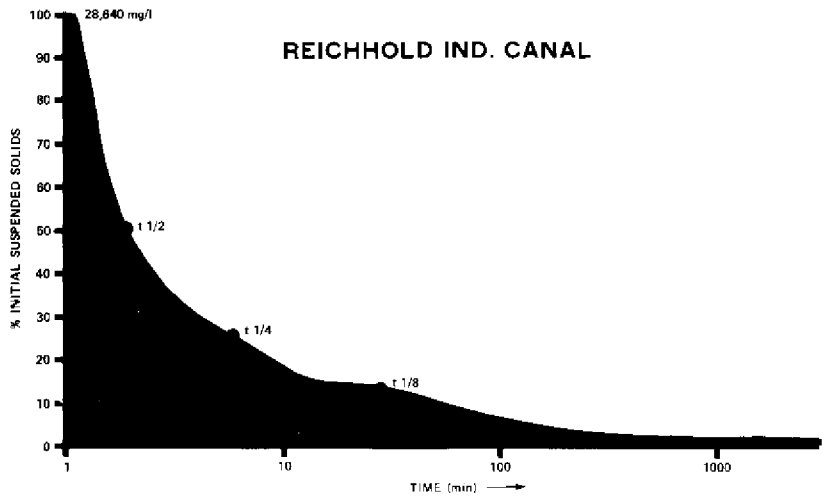

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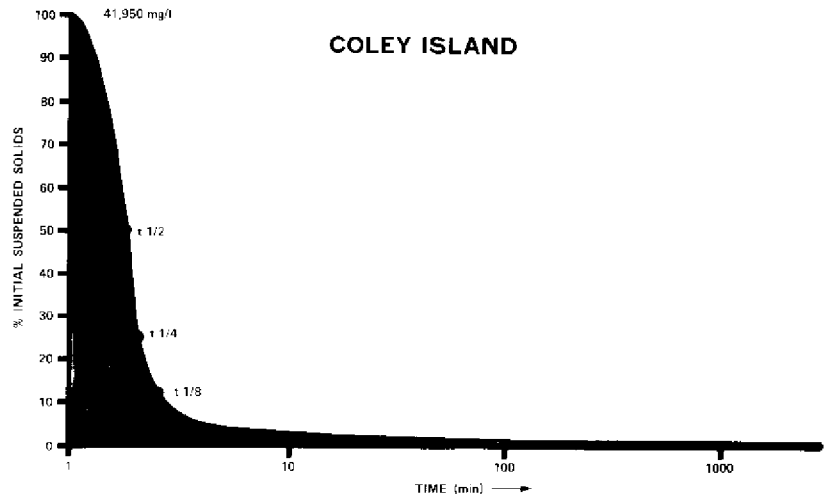

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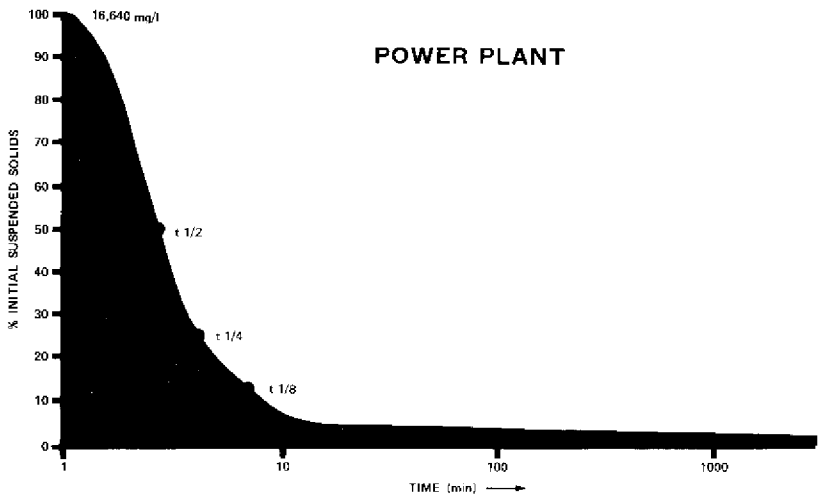

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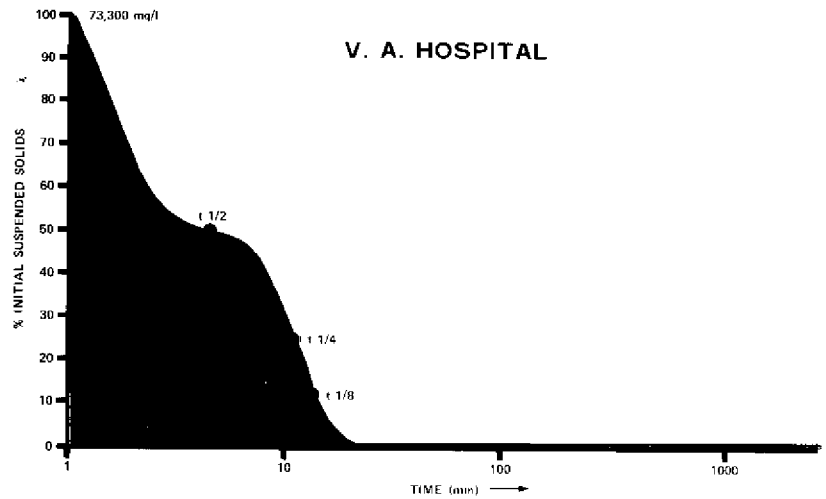

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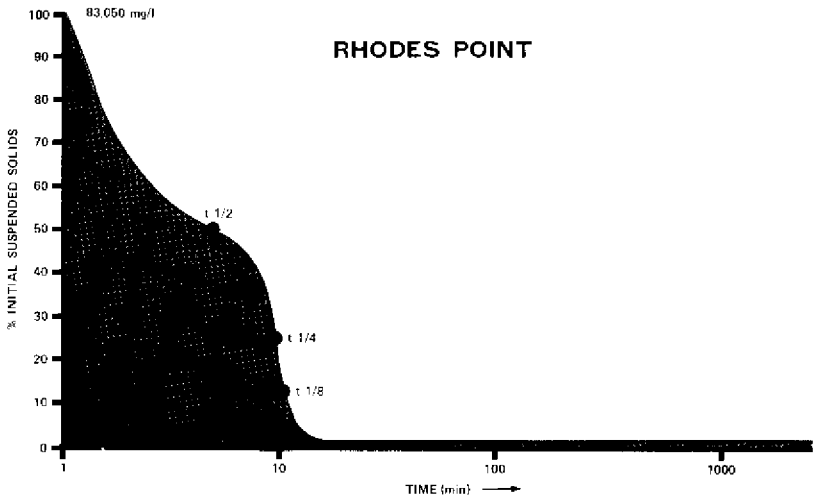

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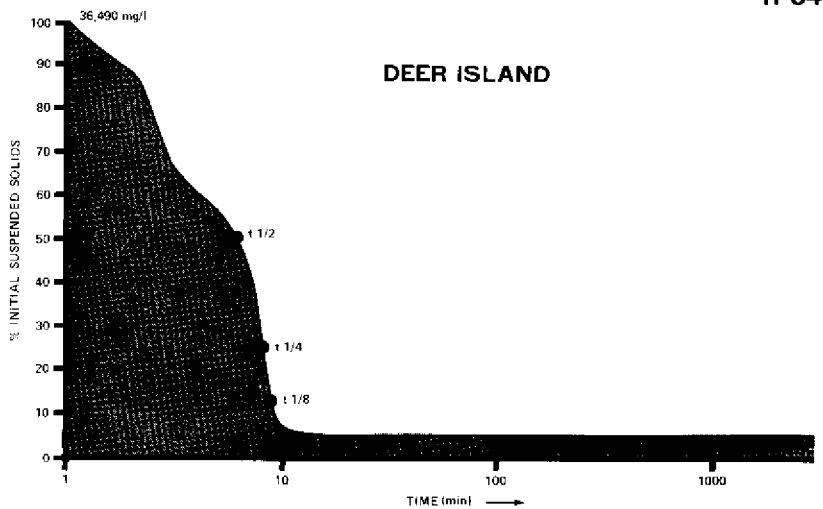

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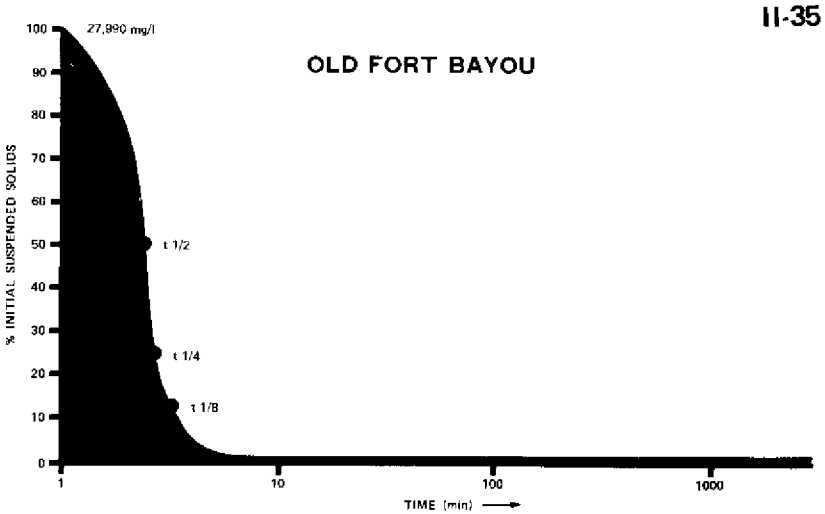

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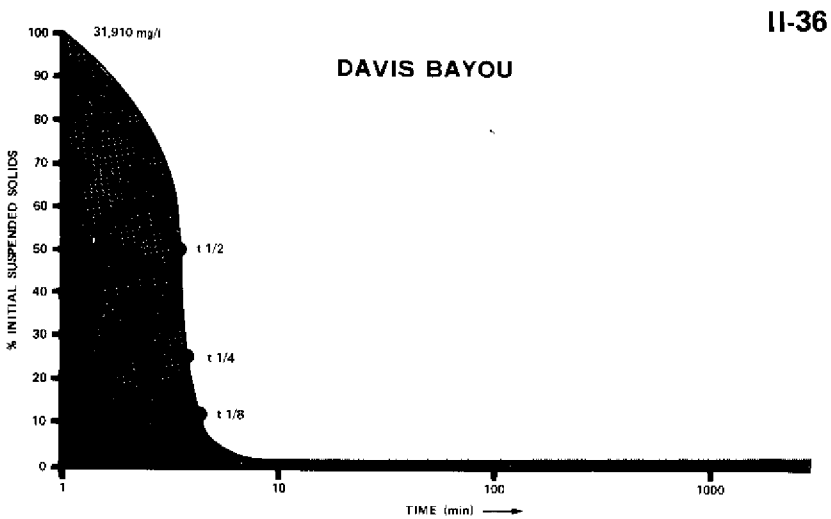

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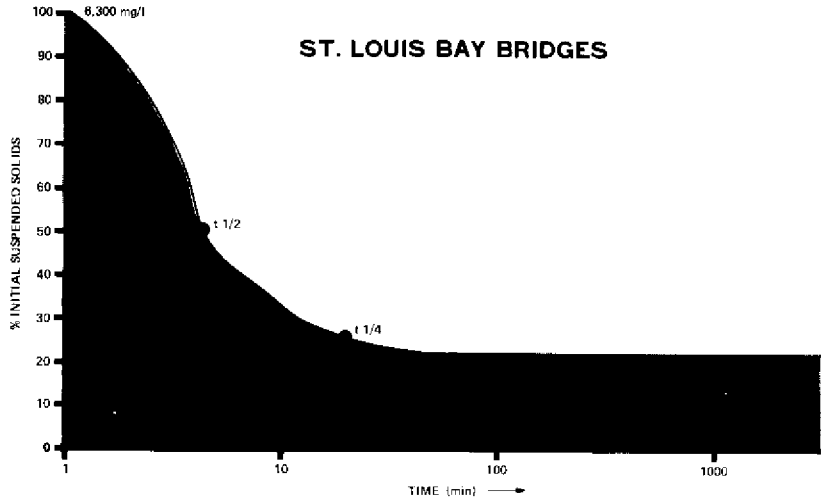

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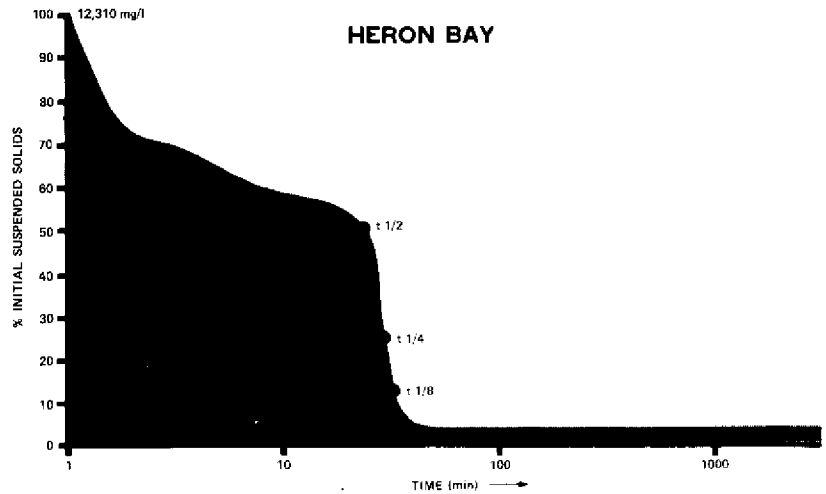

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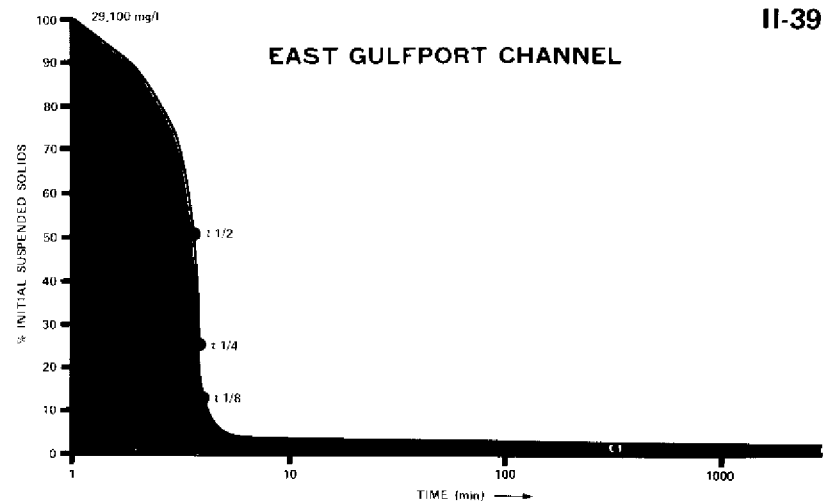

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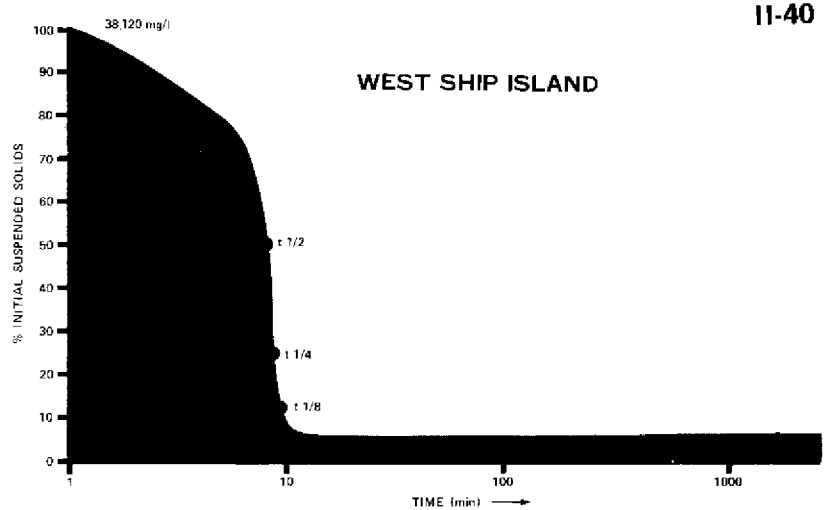

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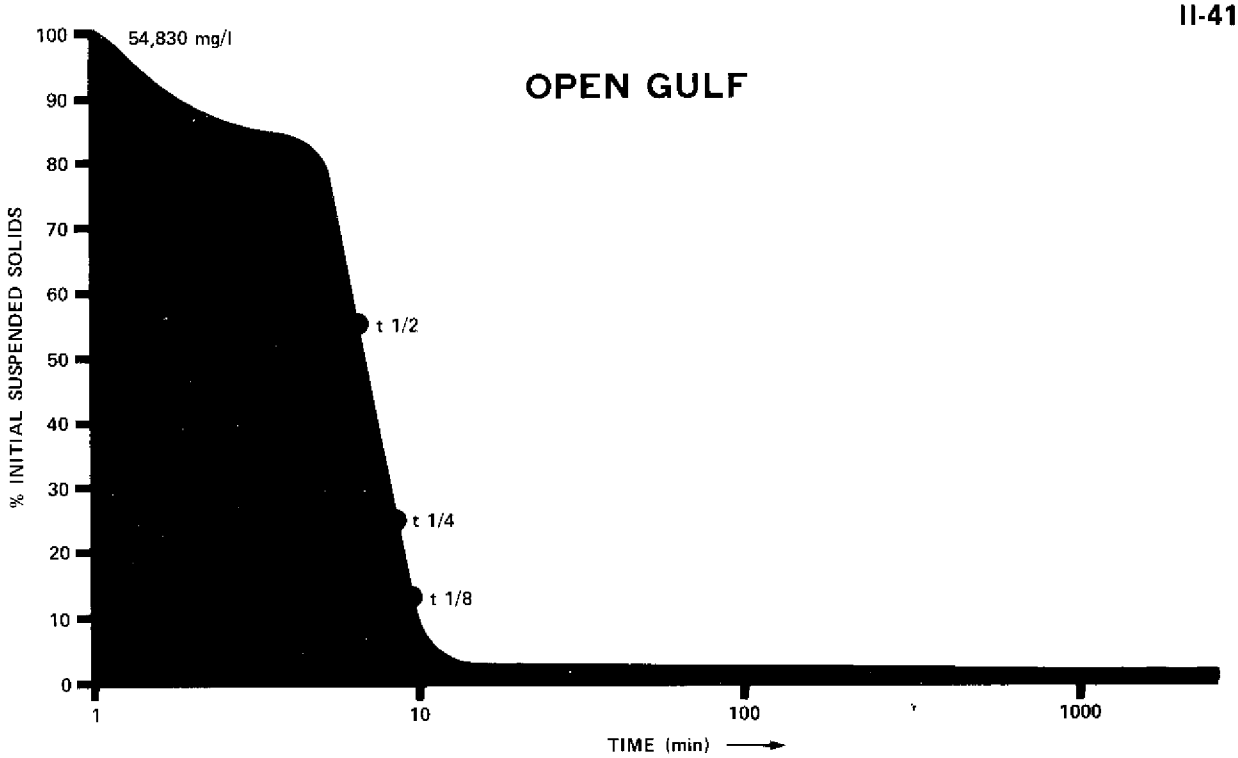
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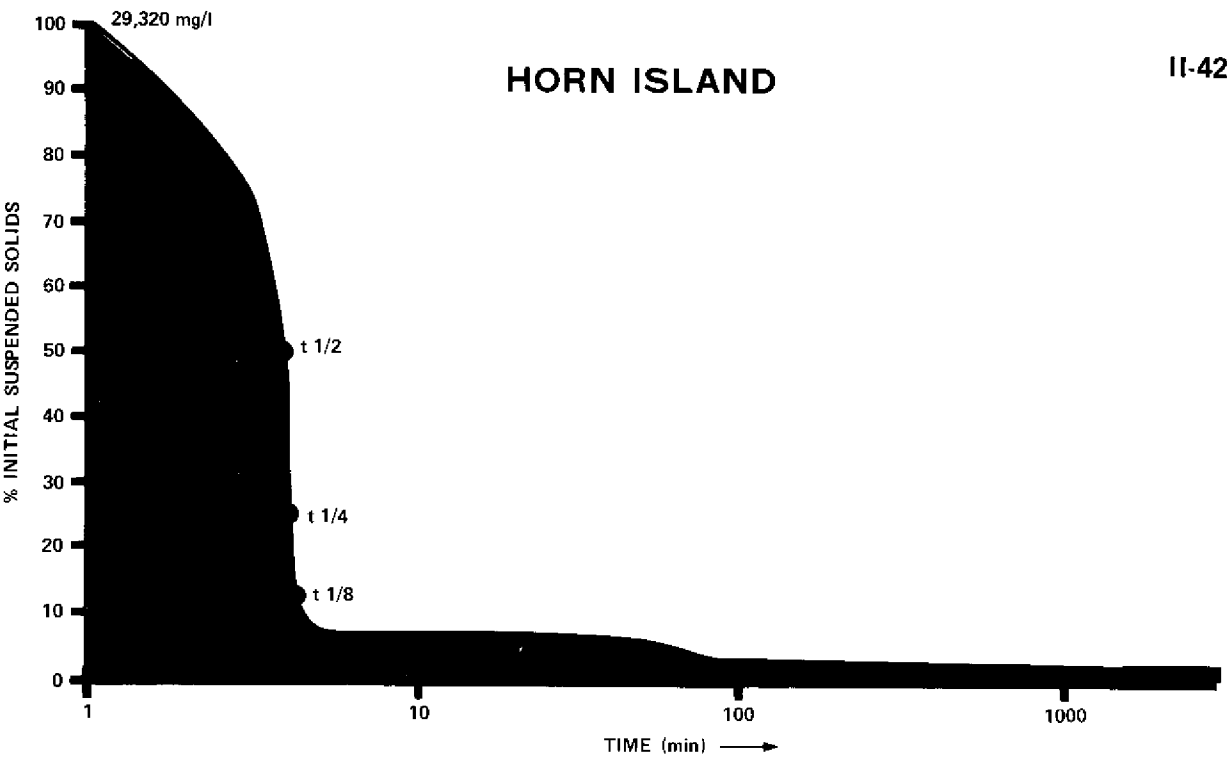
OPEN GULF
% INITIAL SUSPENDED SOLIDS
100
90
80
70
60
50
40
30
20
10
0
t 1/2
t 1/4
t 1/8
1
10
100
1000
TIME (min)

II-42


29,320 mg/l
HORN ISLAND
% INITIAL SUSPENDED SOLIDS
100
90
80
70
60
50
40
30
20
10
0
t 1/2
t 1/4
t 1/8
1
10
100
1000
TIME (min)

SUBJECT INDEX