

ANTHROPOGENIC INFLUENCE ON THE SEDIMENTARY REGIME  
OF AN URBAN ESTUARY — BOSTON HARBOR

by

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Michael G. Fitzgerald

Submitted to the Woods Hole Oceanographic Institution-Massachusetts Institute of Technology Joint Program in Oceanography on June 2, 1980, in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

Abstract

Boston Harbor (and its approaches) is a glacially carved, tidally dominated estuary in western Massachusetts Bay. Characterized by low river discharge and significant human impact, the harbor is typical of many bays and estuaries along the New England coast.

The sands and gravels that floor Massachusetts Bay and the harbor approaches are relict glacial sediments, but in areas of fine-grained sediments, Holocene sedimentation rates have averaged 0.015 cm/yr. In the harbor itself, modern organic-rich sediments are accumulating in several depocenters at an estimated rate of 0.2-0.3 cm/yr. The high organic matter content (greater than 10%) of these modern sediments is attributed in part to anthropogenic wastes. Decomposition of this organic material and subsequent production of methane gas render the sediment impenetrable to acoustic energy, facilitating the mapping of these modern deposits.

Wastes rich in trace metals are discharged into the harbor from the sewage treatment facility at Deer Island and from numerous point sources in the Inner Harbor. Organo-metallic complexes and iron oxide coating on suspended particles and bottom sediment appear important in the transport and retention of these metals. Calculations suggest that at least 33% of the metal discharged into the outer harbor is retained. Trace metal profiles in the bottom sediments reflect the increasing use and discharge of these metals during the past 100 years. Large variations in several cores may be related to circulation changes accompanying the closing of Shirley Gut in 1936.

In the water column, silt and clay sized mineral grains are suspended together in organically bound agglomerates. The organic film binding these particles is a by-product of biological activity and aids in the deposition of particulates and pollutants.

Tidal activity and differential settling apparently fractionate silt and clay agglomerates forming a very thin, soupy layer of organic, clay-rich material at the sediment-water interface, that carpets portions of the study area. This layer seems to form a transition between the more silty and less mobile subsurface sediments and the suspensates of the turbid water column.

The redistribution of natural sediments (resuspension/advection) is a key depositional process, accounting for as much as 70-80% of the material deposited in the harbor. Harbor circulation indicates that Massachusetts Bay may be an important source for this material. Human activity may enhance the ability of the harbor to retain this redistributed material by stimulating biological production (organic film) and supplying lipid-rich organic material through waste disposal.

Boston Harbor is an efficient sediment trap. Long flushing times and landward bottom drift aid in the retention of fine-grained wastes, whose impact on the biological and chemical environment of the harbor can be severe. Other estuaries along the coast of New England may operate in similar ways with respect to waste dispersal.

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Title: Associate Scientist

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## II. Scientific Objectives

This thesis reports the findings of a three-year study designed to establish and explain the past and present patterns of movement and accumulation of sediment in Boston Harbor, with particular emphasis on anthropogenic wastes and their influence on natural processes. Because of its small riverine input and extensive urban influence, Boston Harbor offers an opportunity to assess the nature of man's impact on depositional processes. Several basic (and related) questions outline the task: what types of sediment cover the harbor floor; where are they concentrated, and why; what are the sources of these sediments; do pollutants accumulate in the harbor and at what rate; how effective is the harbor at retaining these pollutants; by what mechanisms are these pollutants transported; how does the composition of suspended particulates compare to bottom sediments; how does the suspended particulate regime change with time (tidally and seasonally)? Answers to these questions are vital to harbor management schemes aimed at improving existing conditions and minimizing future adverse impact. Three main research programs address the questions raised: 1) determine the character, distribution, thickness, and sources of bottom sediments; 2) define the accumulation history of pollutants (trace metals) in the harbor; and 3) relate the suspended particulate regime to the recent sedimentary history of the harbor. These programs are the topics of the major divisions of this

thesis. The collected samples are stored in the Data and Earth Sampling Center of the Woods Hole Oceanographic Institution. The data on which this report is based will appear in a separate data file (Ellis et al., 1980).

### III. Introduction

Estuaries, a critical transition between land and the sea, exhibit a wide range of hydrographic and ecologic conditions. As such, the estuarine environment is far more important than its physical dimensions would imply. For example, estuaries form a major sink of modern fluvial, and marine sediments (Meade, 1972) as well as provide spawning grounds for many fish and invertebrates (Officer, 1976). However, because many major cities are located on or near estuaries, this fragile environment is exposed to a diversity of pressures: economic activities (such as fishing and shipping) often conflict directly with recreation (e.g., bathing and boating), as do engineering projects (such as dredging, mining, and sewage dumping). Unfortunately the complexity of estuarine processes often makes the effects and interactions of various anthropogenic forces more difficult to understand. Clearly, however, coastal management schemes must incorporate a knowledge of both the dynamic regime within the estuary and the effects of man's activities in order to maintain that estuary as a viable economic and esthetic resource.

a. Environmental Setting

Boston Harbor and its neighboring waters face environmental problems similar to many other harbors and estuaries adjacent to large urban centers. Man's activity, both on land and in the estuary itself, has greatly affected harbor configuration (through extensive landfill operations), freshwater runoff, and water quality.

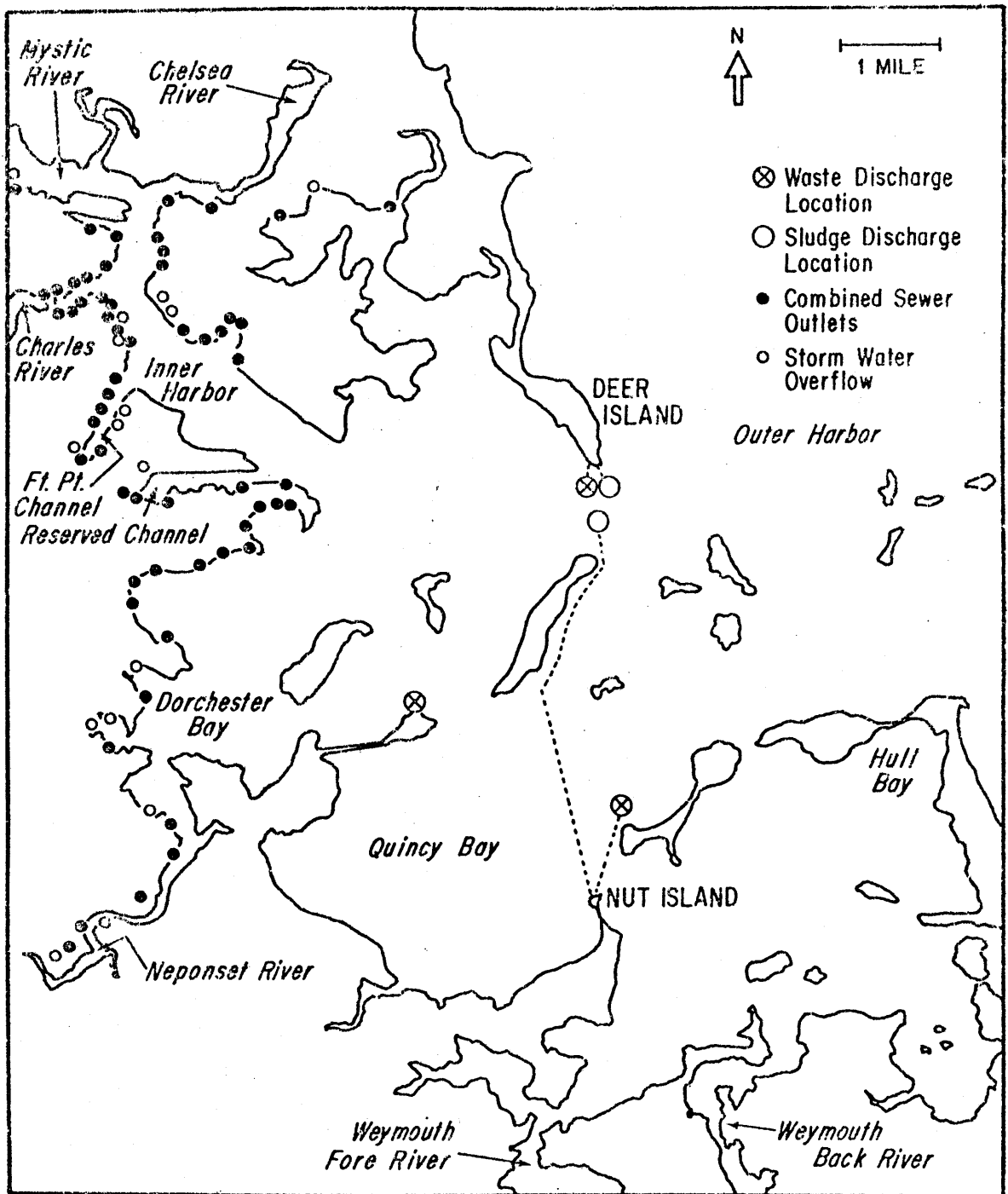
The discharge of domestic and industrial wastes into the harbor has made a major and lasting effect on this environment. The serious nature of this environmental contamination is reflected in the dramatic reduction in acreage open for shellfishing. Presently 9 sq. km of the harbor are closed to shellfishing with another 10 sq. km restricted (Boston Globe, December 10, 1979). The extent of the pollution of bottom sediments in portions of the harbor is shown by the character of the benthic communities in these areas (FWPCA, 1969; Stewart, 1968; Normandeau Assoc., 1975). Opportunistic polychaete worms and amphipods, typical of sediments stressed by human and industrial wastes, dominate the soft bottom community of the harbor. Five genera compose the polychaete assemblage: Polydora, Nephtys, Phyllodoce, Etcone, and Tharyx, and one species, Polydora ligni, predominates. Of the three genera (Ampelisca, Corophium, and Lysianopsis) comprising the amphipod assemblage, Ampelisca is the most common, often outnumbering even Polydora.

Boston Harbor receives the discharge of municipal wastes from the 43 communities served by the Metropolitan District Commission (MDC). Efforts to cope with the problem led to the construction of the two existing primary treatment plants, fed by 225 miles of interceptor sewers. Five of the older communities in the 36 square mile downtown area have combined sanitary and stormwater sewers that overflow into the rivers at hundreds of discharge points (Figure 1). Additional pollution sources include industrial waste discharges, shipping wastes, and debris from rotting dock facilities.

Municipal wastes discharged at the mouth of the harbor from outfalls at the twenty-five year-old Nut Island treatment plant and the eleven-year-old Deer Island facility carry a sizeable pollutant load. The Nut Island plant contributes 123 million gallons per day (MGD), and Deer Island over 329 MGD of chlorinated primary sewage to the harbor waters (MDC Annual Report, 1975). The flow from these two plants is equal to three-quarters of the average flow of all rivers emptying into the harbor. A third outfall, which discharged raw sewage from Moon Island for eighty years, contributed a considerable amount of material prior to its closing in 1969.

Figure 1. Map of sewer outfalls and storm-sewer overflows in Boston Harbor.





At present, approximately 100 tons of solid material from the waste treatment plants are flushed daily into the harbor at ebbing tide to enhance the dispersion of this material into Massachusetts Bay. Evidence suggests, however, that some of this sediment accumulates in the harbor (Bumpus et al., 1953), and McLeod (1972) has estimated that at least 20% of the sewage spoils are retained. In addition to the organic load, the sludge contains waste oils, trace metals, and chlorinated hydrocarbons. Waste oils make up 2% of the net weight of the organic material in the sludge, or some 1,360 kg per day (Gilbert et al., 1972). During September, 1979, Deer Island alone discharged some 200 kg of lead per day (MDC flow records).

Boston Harbor presents a managerial and environmental dilemma. Currently, local, state, and federal agencies are in the throes of a debate concerning a harbor cleanup plan and the 1 billion dollars allocated for it. To comply with the Federal Clean Water Act, Boston must upgrade its system to secondary treatment by 1983, unless MDC can secure a waiver allowing primary effluent to be pumped far out to sea. Decisions, hampered by the paucity of data on the harbor environment, are based solely on engineering and political considerations, and action is expected to be long delayed by litigation.

b. Geography

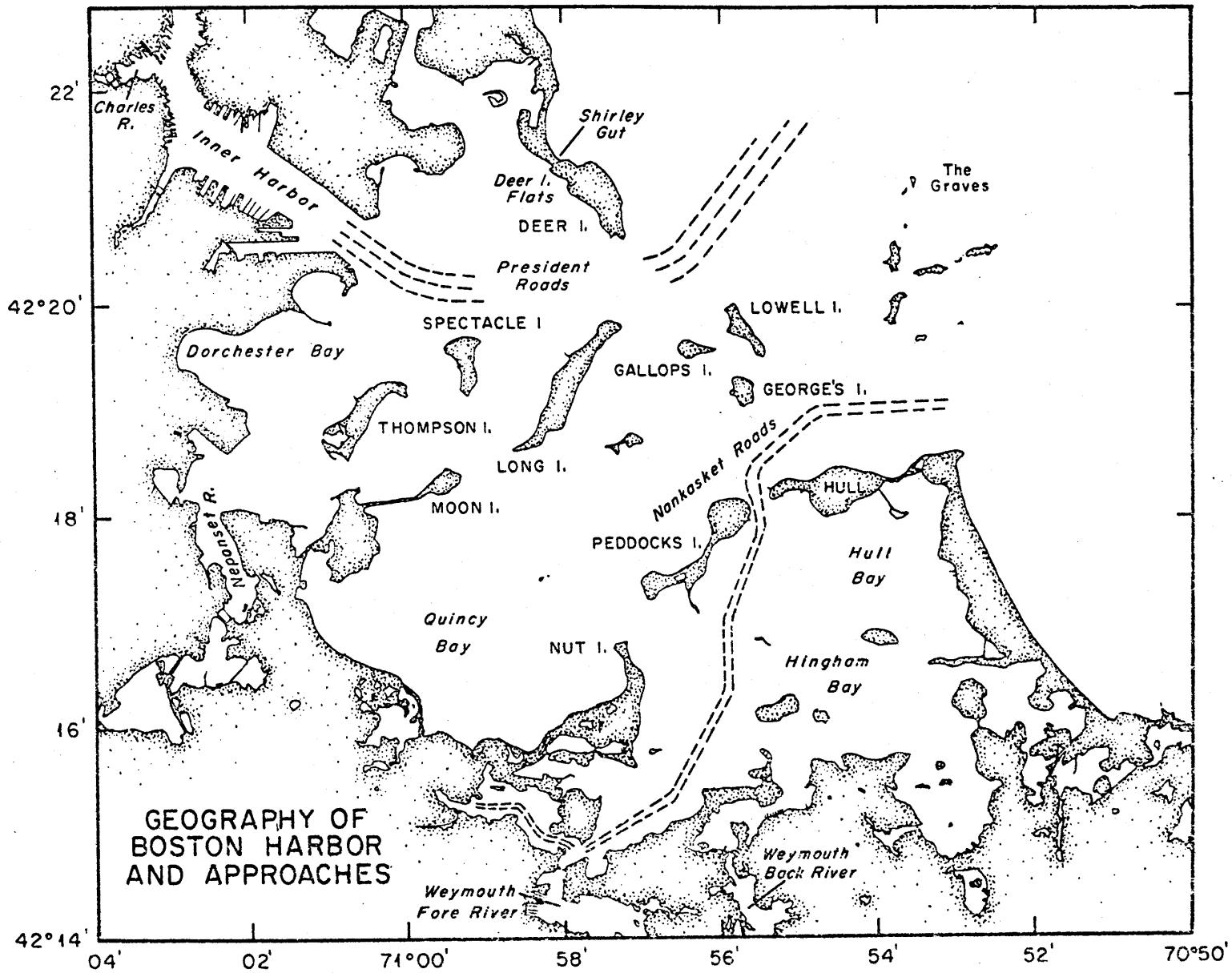
Boston Harbor and its 31 associated islands cover an area of 114 square kilometers in westernmost Massachusetts Bay (Figure 2). Draining into the harbor along its 190 km shoreline are the Charles, Mystic, Chelsea, Neponset, Weymouth Fore, and Weymouth Back Rivers. The natural configuration of Boston Harbor and the recent construction of causeways between various harbor islands have effectively divided the harbor into two major subdivisions: 1) the Inner Harbor, Dorchester Bay, Deer Island Flats, and President Roads to the north, and 2) Quincy Bay, Hull Bay, Hingham Bay, and Nantasket Roads to the south and east.

c. Hydrography

The harbor has little freshwater influx. The Charles, Mystic, and Chelsea Rivers contribute freshwater to the Inner Harbor at an approximate rate of 15 to 40 m<sup>3</sup>/sec (Karpen, 1974) - the Charles, though dammed, accounting for more than half of all freshwater flow into the harbor. Bumpus et al. (1951) estimate the flushing time for freshwater in the Inner Harbor at 2 to 12 days depending on river discharge, while the flushing time for the entire harbor is 42 days.

A thin wedge of water of less than 29 ‰ (4-29 ‰) occupies the surface layers from the Mystic River seaward throughout most of the length of the Inner Harbor.

Figure 2 Geography of Boston Harbor and its approaches. Dashed lines refer to shipping lanes.



This fresher water is underlain by water of salinity between 30.0 and 31.0 ‰. This intermediate wedge of water extends out across President Roads to Deer Island. In the approaches, salinities are generally greater than 32.0 ‰, though spring freshening (due to increased runoff) decreases salinities throughout the area.

From December through March the water column in Boston Harbor and Massachusetts Bay is virtually isothermal, reaching its minimum temperature in late February; surface temperatures during this period range between 0 and 6°C. In April vernal warming heats the surface layers, continuing through August, with surface temperatures reaching 18°C (Bumpus et al., 1953; Bumpus, 1974).

Semi-diurnal tides (mean range of 2.7 m) are primarily responsible for water exchange in the harbor (Bumpus et al., 1953; New England Aquarium, 1973). On a volume flow relationship, the residence time is slightly under two tidal cycles. However, because many areas have sluggish circulation, complete flushing presumably takes longer. Maximum current velocities approach 100 cm/sec between Deer Island and Long Island three hours after flood, but in most areas maximum surface velocities are less than 50 cm/sec (Folger, 1972).

Wave directions are predominantly from the SW through W in summer, NW and N to NE in winter, corresponding to the prevailing wind system (Bumpus et al., 1953). Wave heights

offshore usually range 1-2m from November through April and 0-1m the remainder of the year. Landward of the outer islands, lower sea states will prevail for SW, W, NW, and N winds due to limited fetch. Swells within the harbor are predominantly low, though occasional medium and high swells accompany NE and E winds.

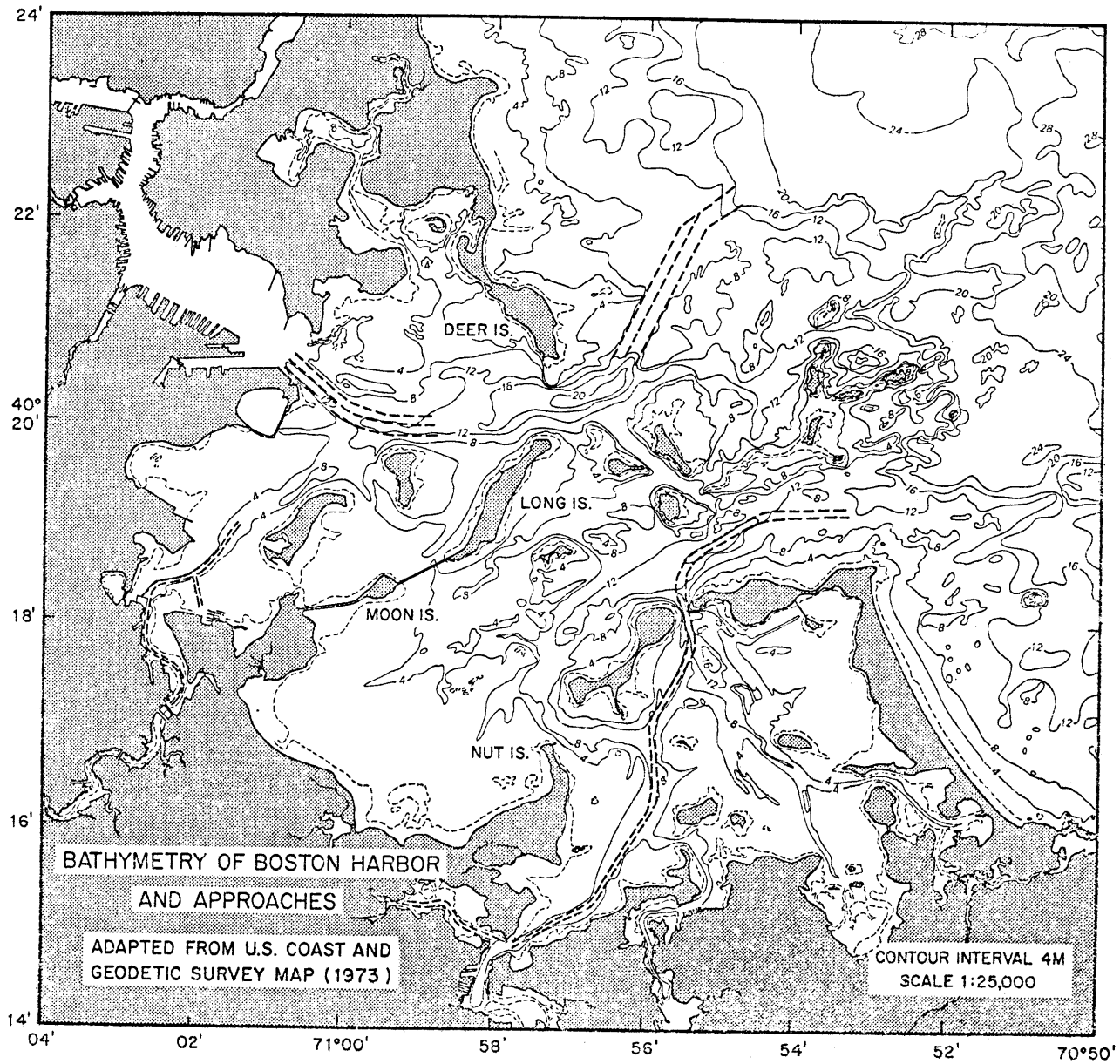
#### d. Bottom Topography

The submarine bottom topography of Boston Harbor and western Massachusetts Bay (Bumpus et al., 1951; Meisburger, 1976) is characterized by irregular (hummocky) terrain possessing considerable relief (Figure 3). The seabed includes a system of NE-SW trending, steep-sided, rough-topped, discontinuous rock ledges and troughs. Northeast of The Graves (Figure 2), the trend of the elevations changes to NW-SE, possibly indicating a change from bedrock to glacial sediments (Bumpus et al., 1951). Away from these rock ledges glacial deposition probably controlled the bathymetric characteristics. The majority of harbor islands owe their relief to the presence of glacial drumlins, whose long axes are oriented roughly in an E-SE direction (LaForge, 1932). Postglacial erosion and deposition (including man's activities) have modified bottom morphology throughout the harbor area.

More than three-quarters of the harbor has a depth (mean low water) of 3m or less. However, two major shipping channels provide Boston Harbor with effective connections to

Figure 3. Bathymetry of Boston Harbor and its approaches, contoured from 1973 U.S. Coast and Geodetic Survey chart.





Massachusetts Bay: President Roads, with a mean low water depth (MLW) of 12 m and Nantasket Roads, with a MLW depth of 9 m. Prior to its closing in 1936, Shirley Gut (Figure 1) also provided an important connection with Massachusetts Bay for tidal exchange.

e. Geologic Setting

Boston Harbor lies wholly within the Boston Lowland, a structural and topographic basin underlain by faulted and folded Paleozoic clastic sediments (Pre-Devonian) with interbedded andesitic volcanics of the Boston Bay Group (LaForge, 1932). Post-depositional erosion carved an irregular surface into the bedrock before the onset of Quaternary glaciation (Upson and Spencer, 1964). This old topography, which now forms the bedrock surface under the Boston Lowland, was later modified by glacial ice masses and subsequently buried by glacial drift, alluvium, and coastal deposits.

Basement rocks trend to the northeast and slope generally seaward. A few highs in the old topography outcrop on the seafloor and form some of the islets in Boston harbor and its approaches. Elongated, deep areas represent former drainage pathways. The apparent convergence of these valleys toward Point Shirley and the depth to basement (68 m below MLW) suggest a major outlet valley beneath the former position of Shirley Gut (Bumpus et al., 1951).

Except for bedrock exposures throughout the area, most surficial and shallow subsurface deposits consist of Quaternary glacial and glaciomarine sediments. In general, these glacial deposits lie directly upon the bedrock surface and are thickest in ancient bedrock valleys (see below). Holocene fluvial and coastal marine deposits are important only locally.

The record of Pleistocene glacial and interglacial stages in the Boston region is fragmentary (Table 1); however, the bulk of glacial deposits in the area are probably of Wisconsin age (Kaye, 1961). Presumably pre-Wisconsin continental glaciers deposited drift, though evidence of such past events has been largely obliterated by subsequent glacial erosion. During excavation under Boston Common, Kaye (1961) did find evidence of four, and possibly five, ice advances and three marine transgressions (pre-Wisconsin deposits). The oldest widespread deposit of Pleistocene age in the Boston area is a discontinuous drift layer (Drift III) which Kaye (1961) believed was deposited during the early Wisconsin-Iowan substage.

After retreat of the glacier associated with Drift III, the area was inundated, and a layer of glaciomarine clay (Clay III) was deposited. A second period of emergence followed the deposition of Clay III, during which this clay and exposed portions of older deposits were eroded.

TABLE 1 - Pleistocene Stratigraphy

Epoch	Kaye (1961) <sup>1</sup>	Judson (1949) <sup>2</sup>	Upson & Spencer (1964) <sup>3</sup>
Holocene		Upper peat Marine silt Lower peat	Estuarine deposits
Late Wisconsin (Cary)	Drift IV Mostly outwash (in Boston Basin)	Lexington Out- wash	Outwash
		Lexington Drift	
Mid Wisconsin (Tazewell)	Clay III	Boston Clay	Marine clay
Early Wisconsin (Iowan)	Drift III	Boston Till	Till
Illinoian	Drift II	Pre Boston Till	Bedrock
Illinoian or Yarmouth	Clay I		
Kansan or Nebraskan	Drift I		
	Bedrock		

1. Based on a section under Boston Commons, Massachusetts.
2. Based on excavations at Boston, Massachusetts.
3. Based on borings in fill of ancient valleys in the Boston Basin.

Another glacial episode (late Wisconsin) followed this period of erosion, depositing sediments consisting primarily of outwash. This last glaciation is dated at about 10,000 years B.P. (Kaye and Barghoorn, 1964).

Since that time, relative sea level has risen and estuarine and coastal sediments have been deposited -- modern sea level reaching a near standstill about 3000 years B.P. The rise of sea level to its present position over the past 3000 years at a rate of about 1 cm/year (Emery and Uchupi, 1972) has subjected glacial deposits to continuing marine reworking. This reworking has distributed a surface "skin" of marine sand and gravel over much of the area. Silts and clays, largely organic in composition, are now being deposited in sections of Boston Harbor.

## Chapter 1

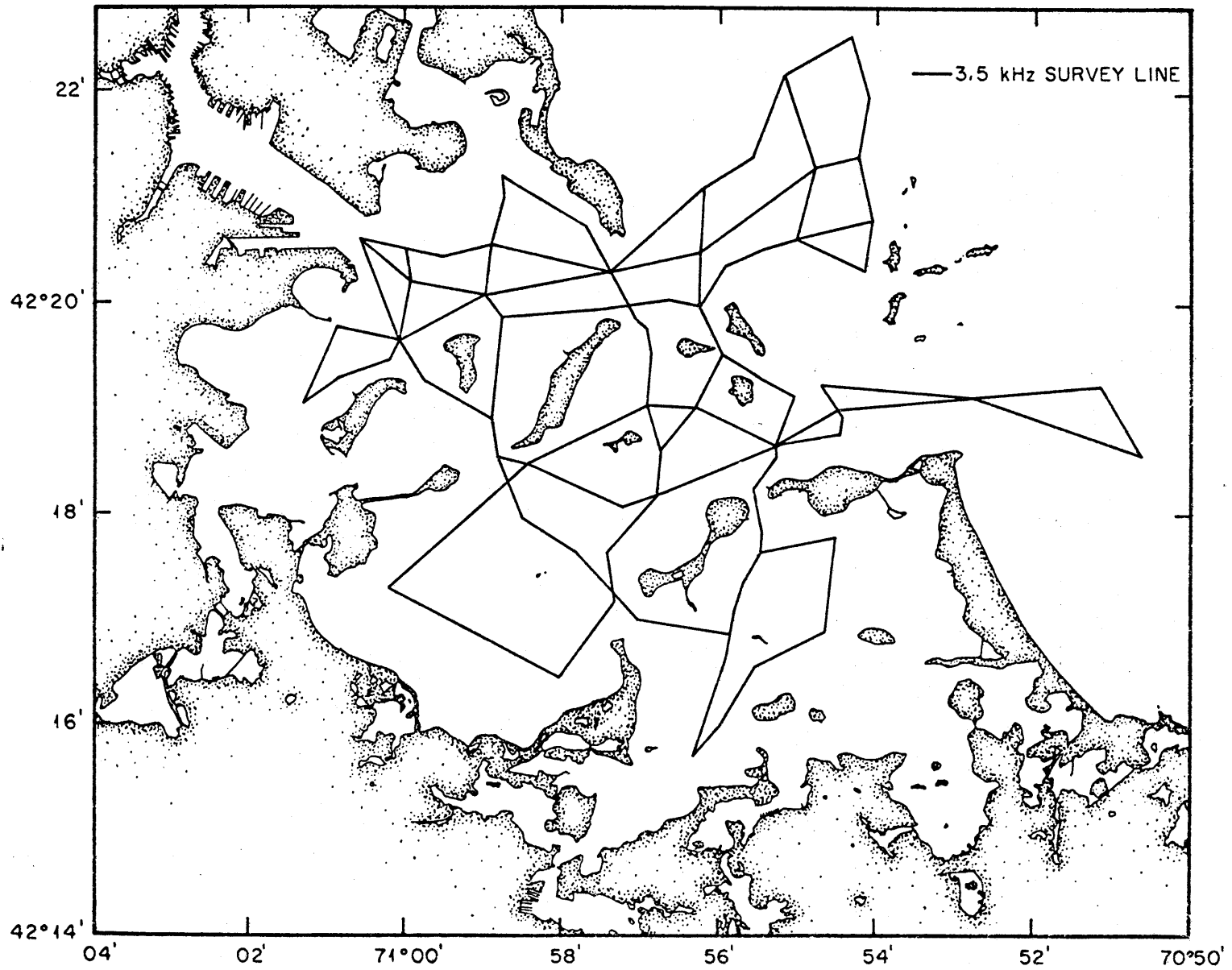
IV. Bottom Sediments

## a. Subsurface Geology

With the cooperation of the U.S. Geological Survey, seismic reflection profiling operations gathered data on the bottom morphology and shallow subbottom structure of Boston Harbor (Figure 4). Previous seismic operations within the harbor were very limited in scope (Edgerton, 1963, 1965; Yules, 1966). Profiling surveys of western Massachusetts Bay complement our own work and include the Massachusetts Coastal Mineral Inventory Survey, MCMi (Willett, 1972), and the Inner Continental Shelf Sediment and Structure study, ICONS (Meisburger, 1976). The paucity of deep borings in the harbor and the complexity of the basement topography preclude the correlation of internal reflectors. Thus, interpretation of the harbor's subbottom structure must be inferred from the detailed offshore seismic and coring surveys.

Relationships between bottom morphology and subsurface structure are fairly consistent in western Massachusetts Bay and Boston Harbor. Most topographic highs on the seafloor are associated with outcrops of the irregular bedrock surface or glacial till, while topographically flat or low areas occur where bedrock or till is buried.

Figure 4. 3.5 kHz seismic coverage





Oldale, Uchupi, and Prada (1973) inferred the existence of four discontinuous sedimentary units overlying the basement complex in the western Gulf of Maine and the southeastern Massachusetts offshore area. Defined largely on the basis of seismic reflection data, these units are: (1) coastal plain sediments of late Cretaceous to early Pleistocene age, (2) moraine deposits of Pleistocene age, (3) glaciomarine and marine deposits of Pleistocene and Holocene age, and (4) glaciolacustrine deposits of late Pleistocene age. The irregular acoustic basement was traced in many cases to within short distances of the shore, where crystalline and sedimentary rock of pre-Cretaceous age outcrop.

Two of these sedimentary units are found within western Massachusetts Bay (Oldale, Uchupi, and Prada, 1973). Unit 2, a glacial moraine, is present in only one place in the Bay, where it forms a large submarine hill. The other unit comprises glaciomarine deposits of Pleistocene and Holocene age. This unit, which Oldale, Uchupi, and Prada (1973) called the "transparent layer", outcrops throughout Massachusetts Bay alternating with outcrops of the basement complex (Meisburger, 1976).

### 1. Acoustic Basement

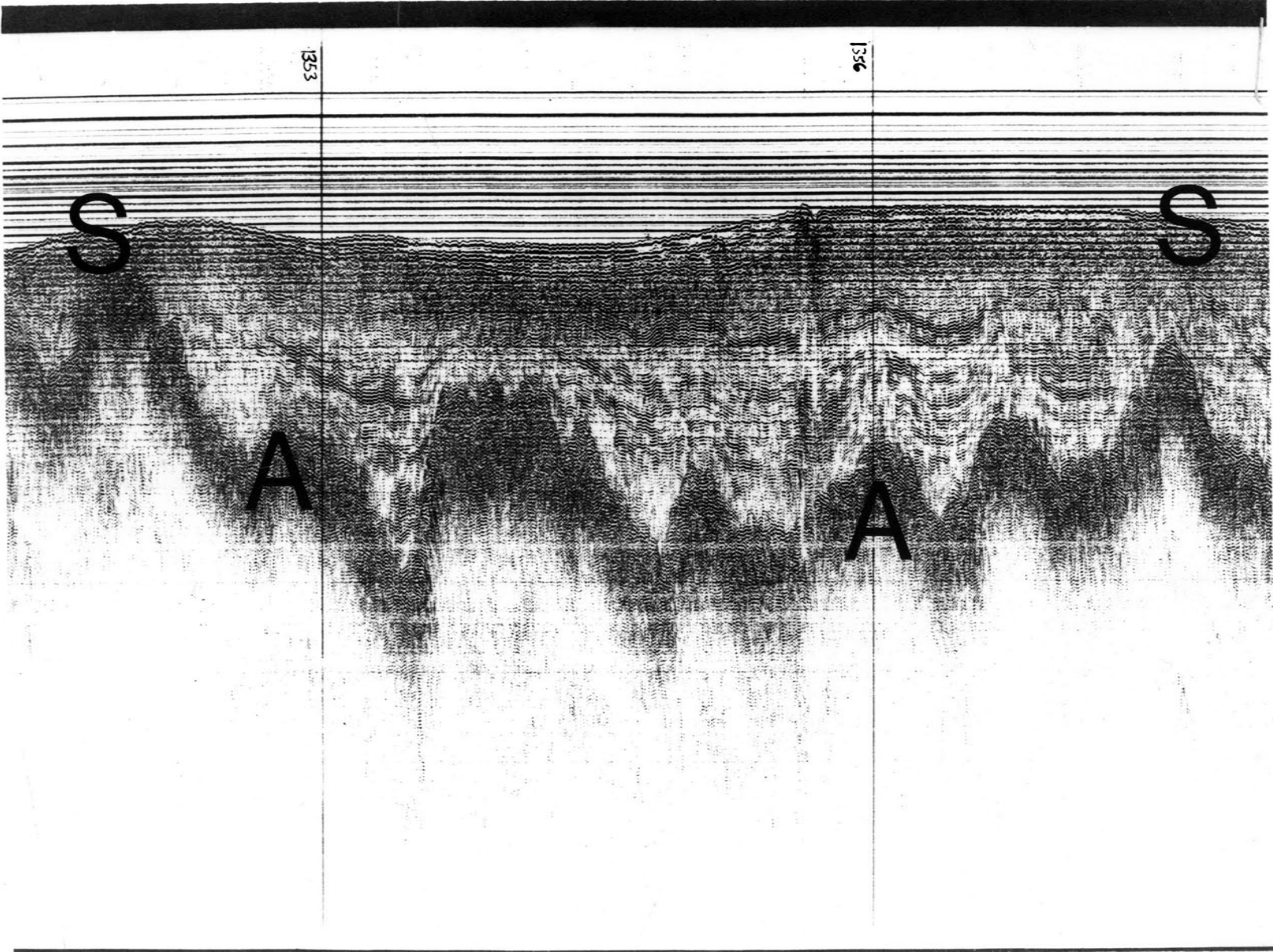
An acoustic basement containing no internal reflectors is evident on our 3.5 kHz records and the low frequency records (sparker and uniboom) of the ICONS and MCMI studies. This basement underlies the transparent unit and, in places, may outcrop on the sea floor to create topographic highs. It is likely that acoustic basement is not everywhere coincident with the top of pre-Cretaceous basement complex rocks, but includes overlying glacial deposits in places both in the harbor and its approaches (Meisburger, 1976).

The surface of the acoustic basement is highly irregular and complex (Figure 5). The basement topography consists mostly of elongate lows and irregular highs. The orientation of basement features is east to east-southeast offshore and northeast in the harbor proper (Figure 6).

### 2. Transparent Reflection Unit

Numerous reflectors can be seen in the transparent layer, and locally, reflectors defining cut-and-fill and slump structures are present (Oldale, Uchupi, and Prada, 1973). In some places, continuous internal reflectors are absent, and the record has a mottled appearance. The mottling is inferred to represent local deposits of coarser grained material, perhaps sand and gravel (Oldale, Uchupi, and Prada, 1973). Generally, the unit has a flat upper surface, and partly or completely fills topographic lows in the basement unit.

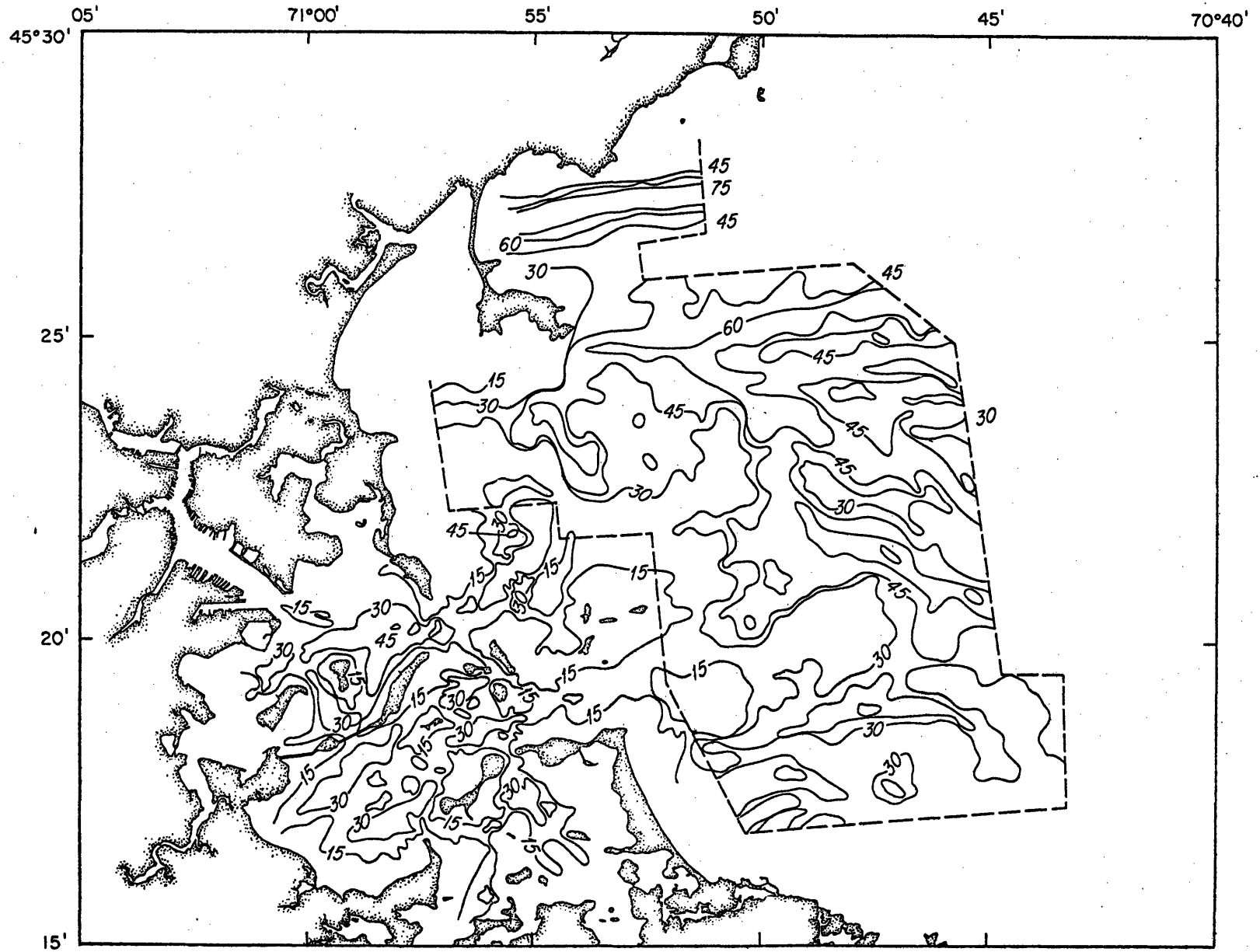
Figure 5. Selected 3.5 kHz profile showing the irregular and complex surface of the acoustic basement (A). Sediment surface (S) is indicated. Vertical scale is approximately 50 m (1/16 sec); horizontal scale 1 km.



1353

1356

Figure 6. Topography of the acoustic basement (relative to mean sea level). Offshore data taken from Willett et al. (1972). Boston Harbor data from this study.



Meisburger (1976) divides the offshore transparent unit into upper and lower subunits separated by an irregular reflecting surface. Meisburger (1976) suggests that this "blue reflector" is probably an erosional surface. Below this reflector, the transparent unit is reflectively featureless or possesses weakly defined reflectors with a horizontal or gently warped attitude. The upper transparent subunit has internal reflectors that are generally stronger, often discontinuous, and relatively steep. Offshore both subunits occur together throughout most of the area; where only one subunit is present it is usually the lower (Meisburger, 1976).

Though outer portions of the harbor display the subbottom character discussed above (Figure 7), large areas show strong reflectors (layering) throughout most of the sediment column (Figure 8). These layers drape over the acoustic basement, thereby suggesting a quiescent current regime, while overlying these parallel reflectors are discontinuous layers showing cut-and-fill structures, suggestive of the more vigorous current regime which exists today.

Boreholes in Boston Harbor show the upper part of the transparent layer to be Holocene silt and clay and the lower part to be glaciomarine silt and clay of late Pleistocene age (R.H. Burroughs, unpublished data); Oldale et al. (1973) inferred a similar correlation for the transparent layer

Figure 7. 3.5 kHz profile, taken near the outer islands, showing the acoustic character of the "transparent layer" as described by Meisburger (1976). Sediment surface (S), acoustic basement (A), and "blue reflector" (R) are labelled. Vertical scale is approximately 50 m (1/16 sec); horizontal scale .75 km.



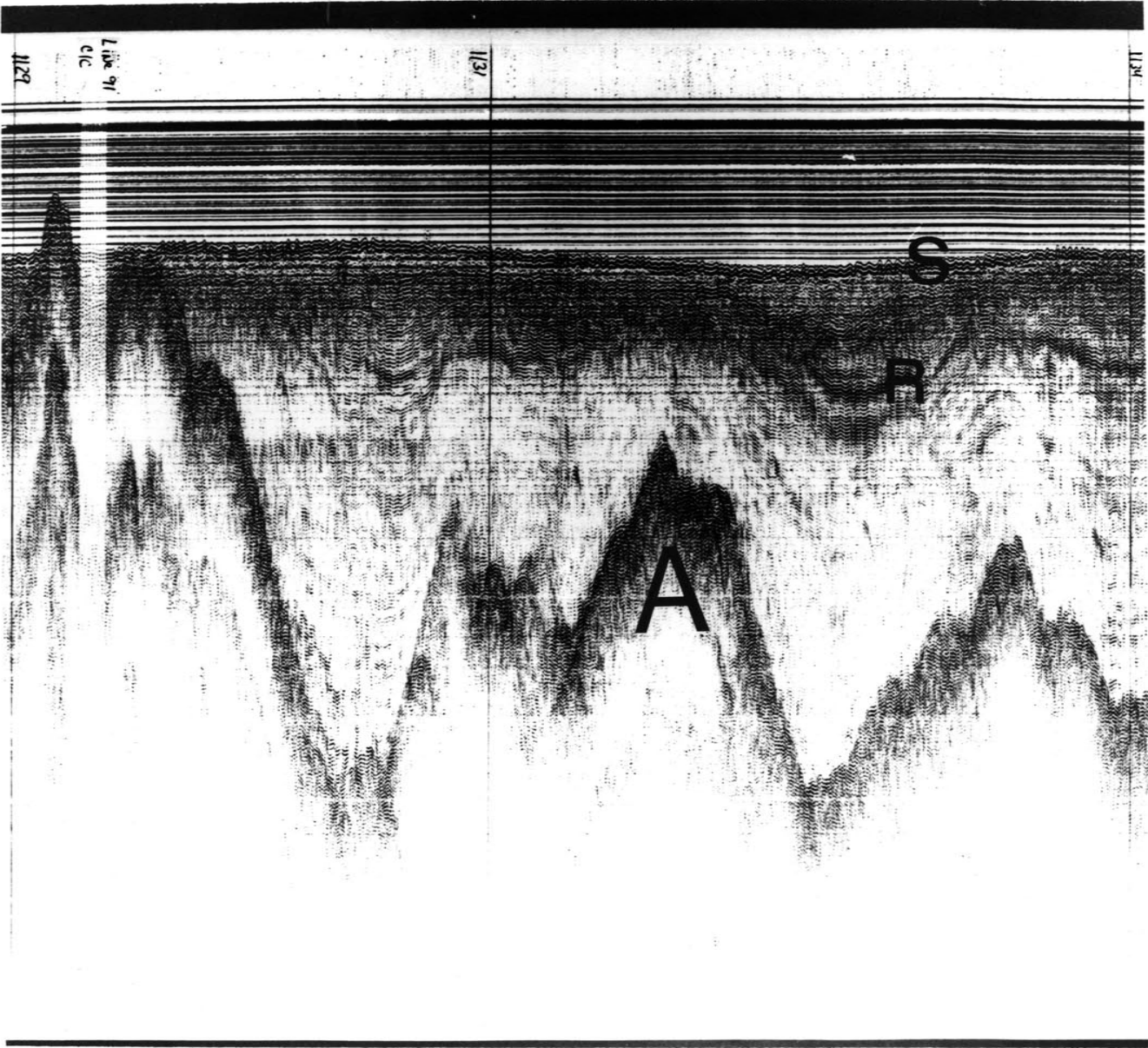
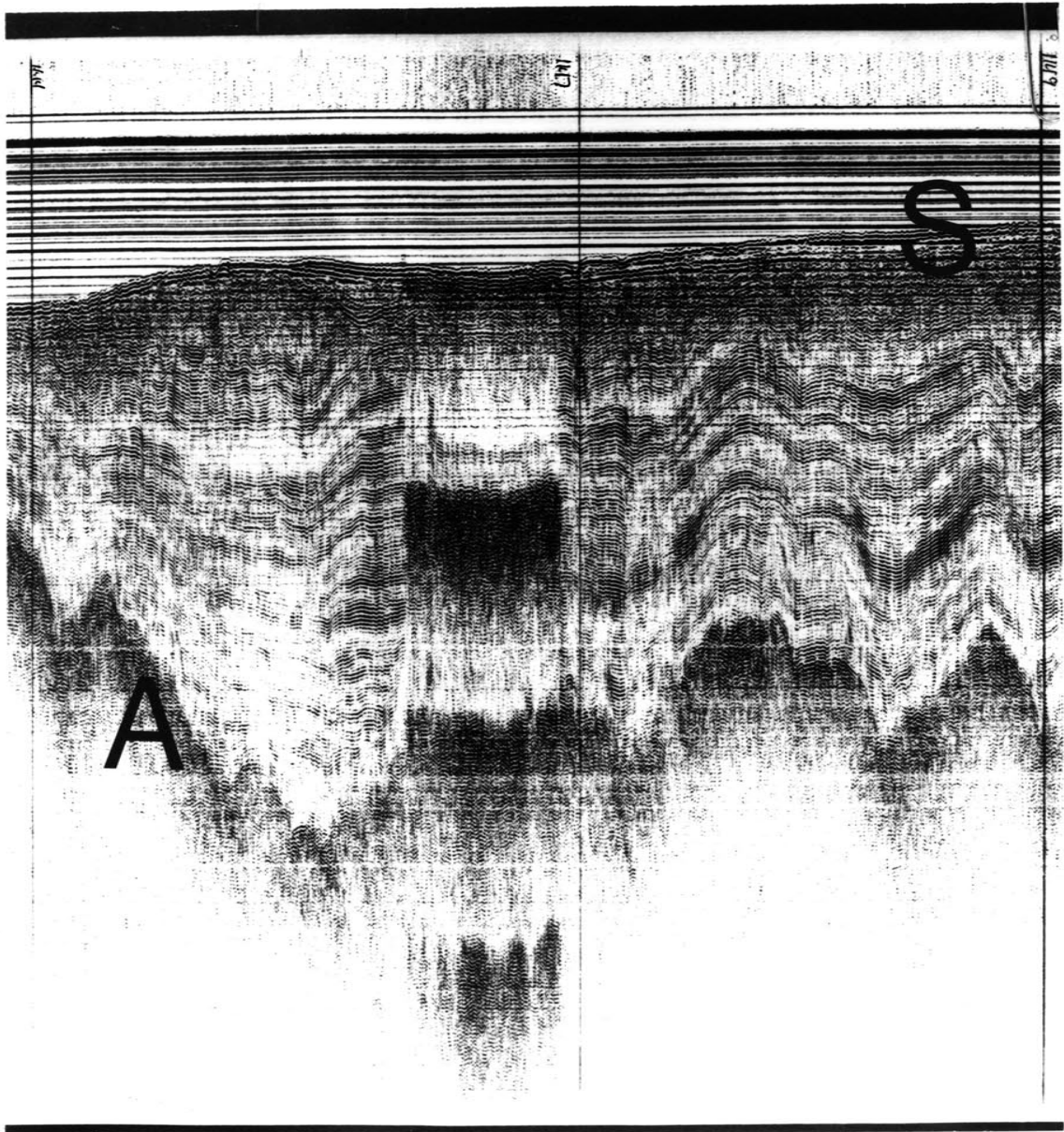


Figure 8. 3.5 kHz profile taken southeast of Long Island showing the extensive layering characteristic of much of the harbor. Sediment surface (S) and acoustic basement (A) are labelled. Vertical scale is approximately 50 m; horizontal scale .8 km. "Ringing" section is an acoustically turbid zone (see text).



offshore. No internal reflector within the unit, suggestive of an unconformity between the glaciomarine and Holocene marine deposits, could be identified. This fact suggests that in most places deposition has been continuous since the late Pleistocene.

The silt and clay represented by the transparent layer thus appears to have a complex origin. Presumably, most of the material consisted of glacial rock flour carried by melt-water streams and deposited in the basins. As the rising Holocene sea submerged the area, silt and clay were winnowed from glacial drift and carried into the basins (Oldale et al., 1973). Finally, the uppermost silt and clay deposit probably contains some material transported by modern streams.

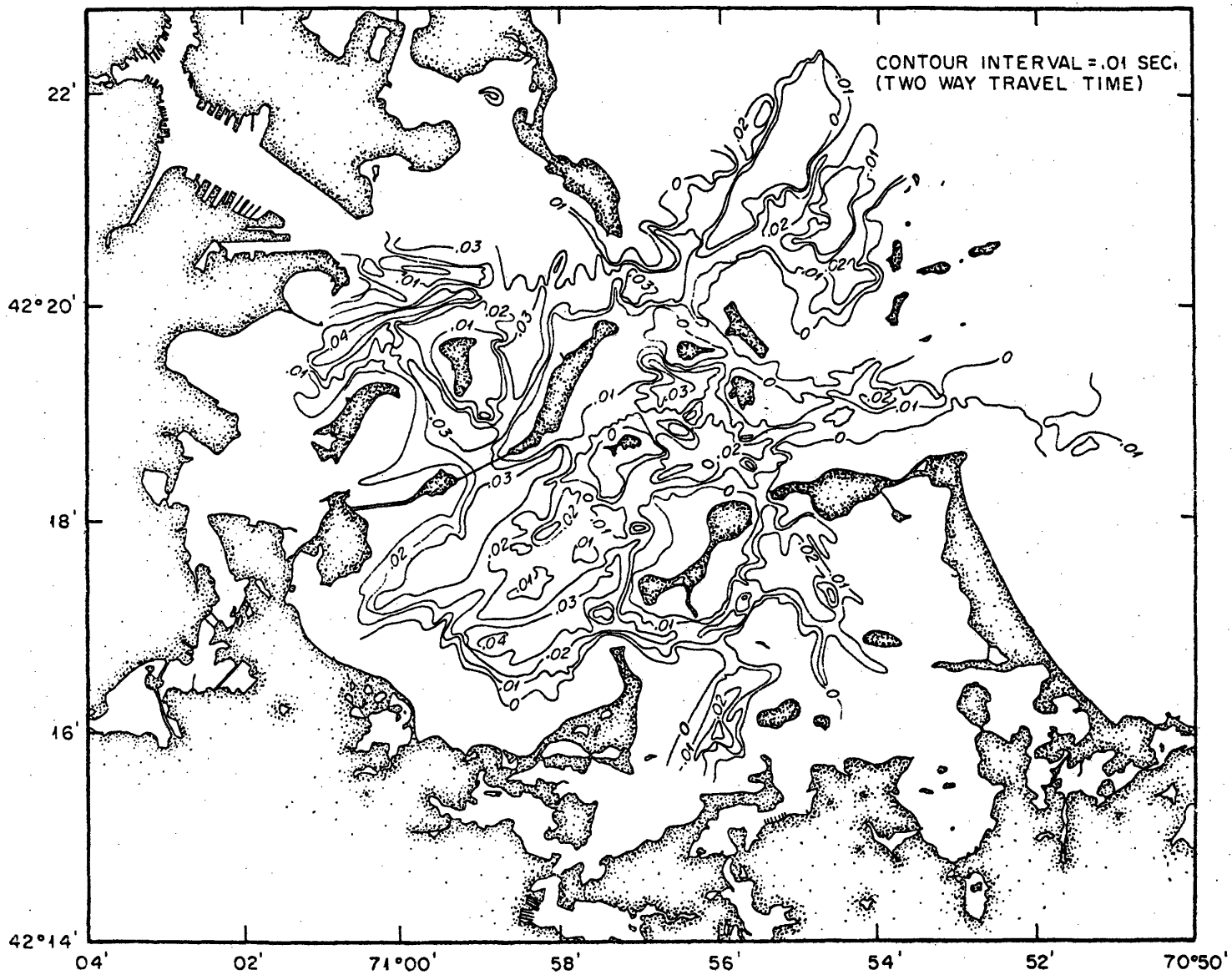
#### b. Bottom Sediment Thickness

Analyses of the 3.5 kHz profiles (Figure 9) shows the partial filling with sediment of the northeast trending bedrock valleys. Sediment is thinnest over topographic highs and thickest in troughs, where penetration reaches 45 - 50 milliseconds two-way travel time. Assuming a velocity of 1.6 km/sec, this time corresponds to 35-40 m of sediment. This is in good agreement with the thickness of Quaternary deposits on land (LaForge, 1932).

The isopach map highlights the historical loci of deposition in Boston Harbor: northeastern Dorchester Bay, President Roads, Quincy Bay, and the area surrounded by

Figure 9. Isopach map, contoured in milliseconds two-way travel time, of sediment over acoustic basement.

# ISOPACH MAP OF BOSTON HARBOR



Thompson, Spectacle, Long, and Moon Islands. Another thick wedge of sediment - not identified in our survey - lies in the Deer Island Flats at the former position of Shirley Gut (Bumpus et al., 1951). Comparing the locations of these historical depocenters with sites of modern deposition is important in assessing the modification of sedimentary patterns through time (see section on organic bottom sediments).

As stated earlier, the few deep test borings in the harbor show Holocene marine silt and clay overlying glaciomarine silt and clay of Pleistocene age. Unfortunately, these borings are too few to map the extent of these deposits and their horizontal relationships. Several shallow borings (6-9m) in the harbor by the U.S. Army Corps of Engineers, however, do provide some information on recent sediment relations (Bumpus et al., 1951). Soft mud areas are found in sheltered portions of the harbor such as Deer Island Flats and Quincy Bay. The greatest thickness of mud recorded is 12m in SW Dorchester Bay (Boston Society of Civil Engineers, 1961), but normal thicknesses of this mud run from 1.5 to 6 meters. The materials beneath these soft sediments vary from gravel to clay (Bumpus et al., 1951). Outside of these mud areas, few generalizations can be made regarding vertical sediment sequences, except that they are heterogeneous. Adjacent borings frequently show no correlation either in sequence or in thickness of individual types.

In the harbor, the most prevalent subbottom deposit is a blue-gray to slightly greenish-gray clay, which becomes yellow-brown when oxidized. This clay, generally called the Boston Blue Clay, may correspond to Clay III of Kaye (1961). This clay is often layered with fine sand or silt in beds of less than three centimeters to more than thirty (Mencher et al., 1968). The thicker layering may give rise to the parallel reflectors seen on continuous seismic profiling records in the President Roads and other areas (see above). From Fort Independence through President Roads to Deer Island, the Boston Blue Clay is commonly encountered at depths of 1 to 10 meters below the bottom. Overlying sediments vary greatly in thickness and composition within short horizontal distances (Bumpus et al., 1951).

#### c. Texture and Composition

The results of several studies, including this work, are utilized to fully describe the distribution and character of bottom sediments in Boston Harbor and its approaches (Bumpus et al., 1951; Mencher et al., 1968; Hathaway, 1971; New England Aquarium, 1972; Willett et al., 1977; Meisburger, 1976). Figures 10, 11, and 12 show the distribution of samples.



Figure 10. Grab sample locations used by Mencher et al. (1968).

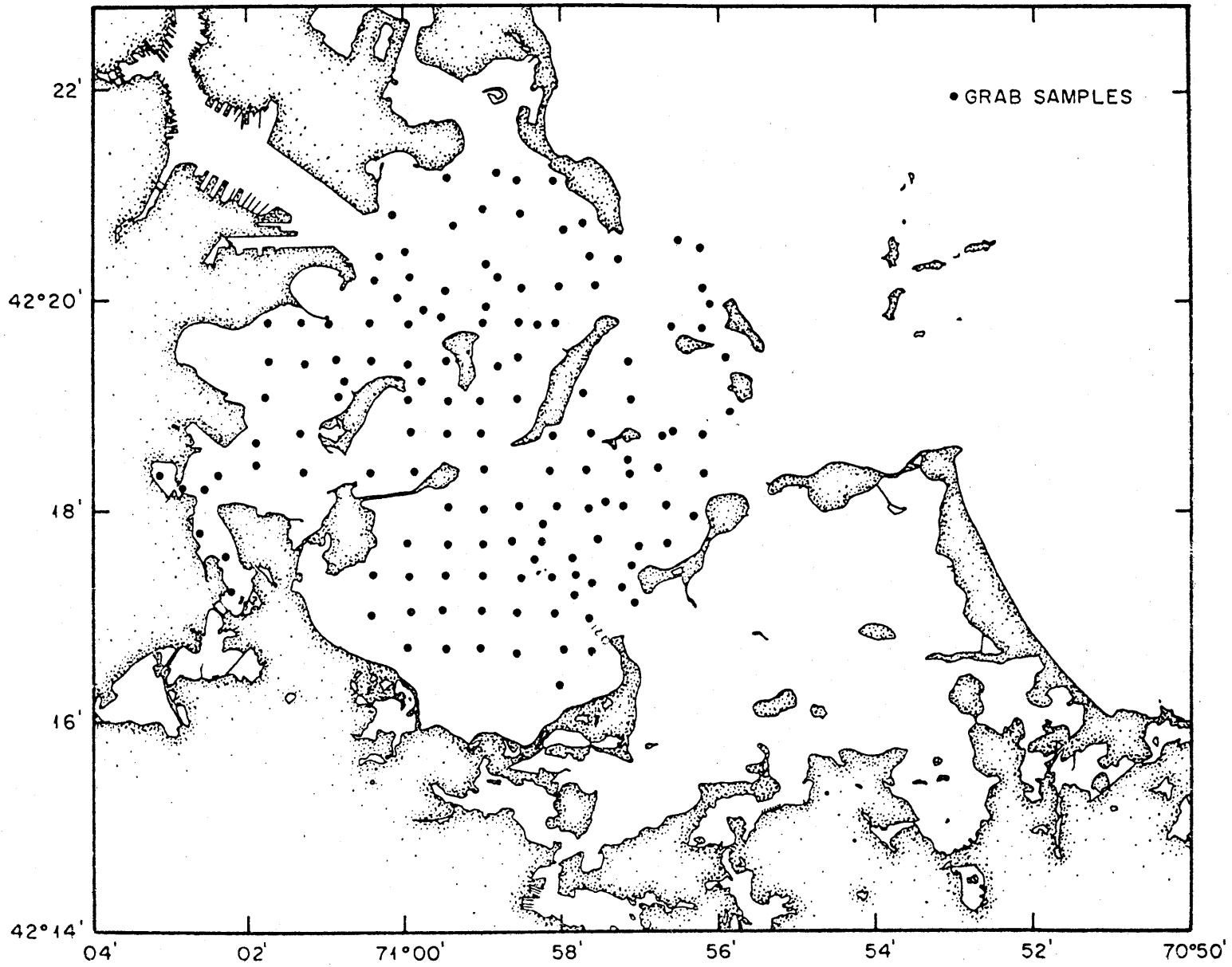


Figure 11. Bottom sample locations for the MCMI and  
ICONS surveys (see Willett et al., 1972;  
Meisburger, 1976).

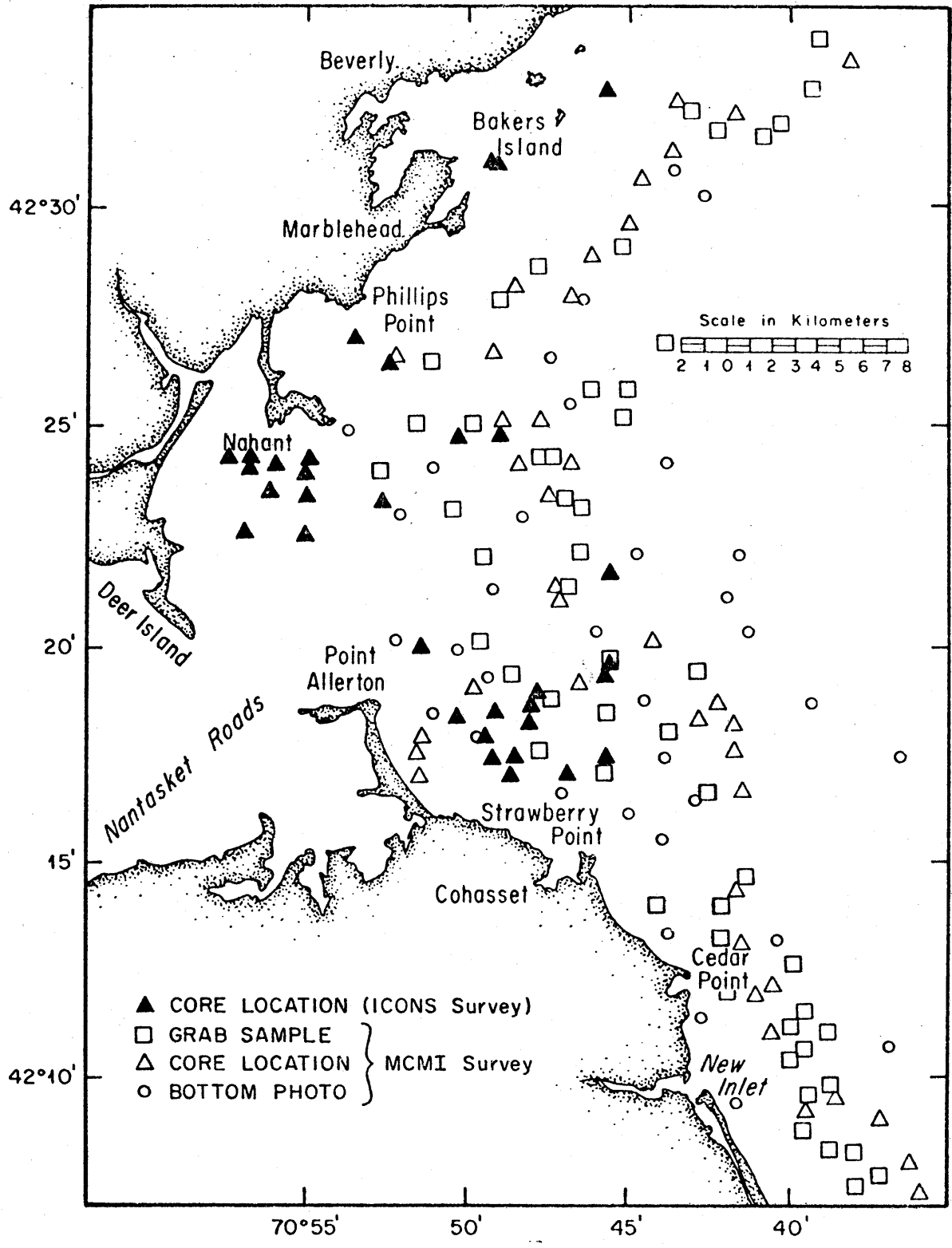
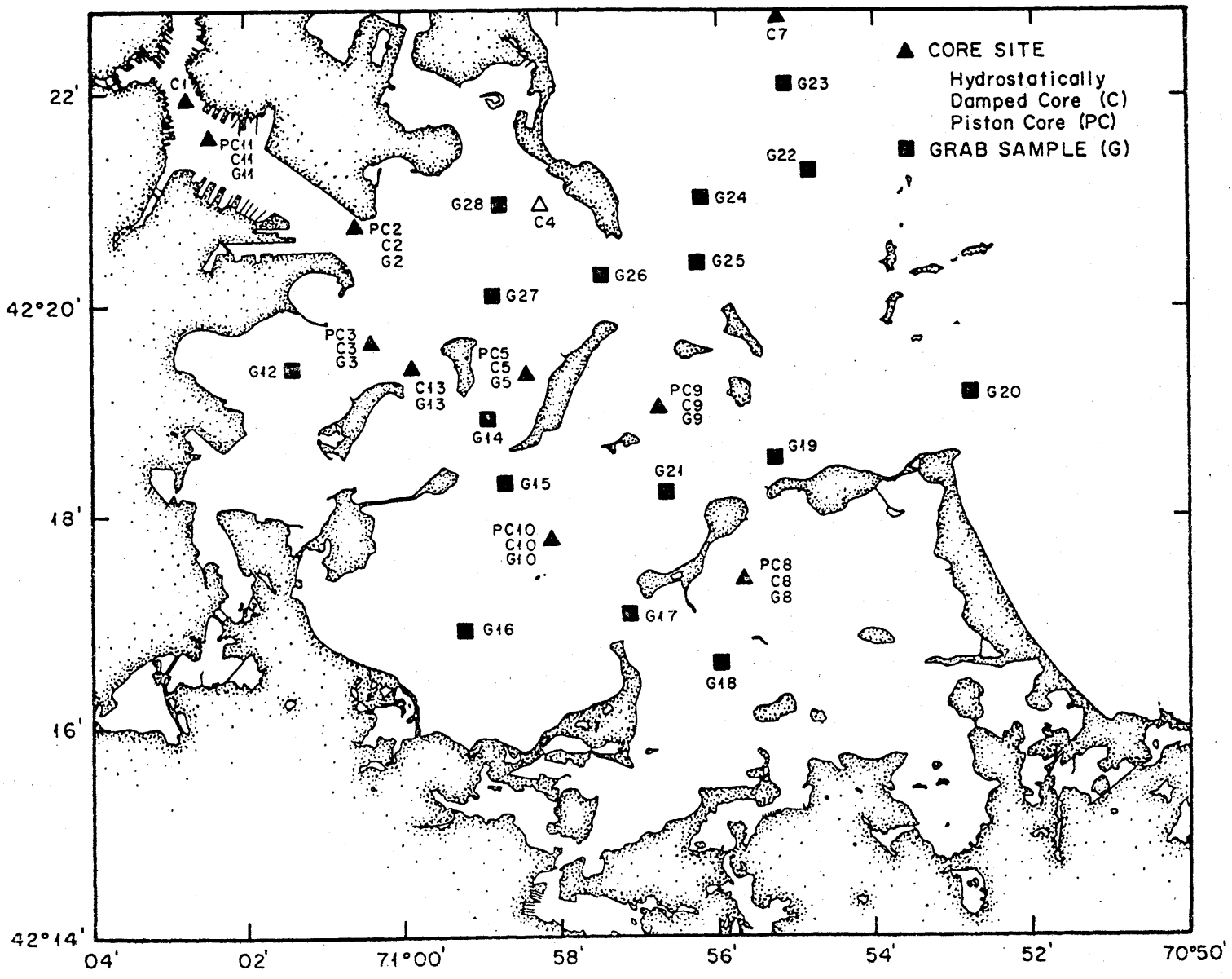


Figure 12. Core and grab sample locations (this study).



### 1. Size Distribution

Data from the 34 cores collected for the ICONS study (Meisburger, 1976), the 26 cores collected for the MCMI (Willett, 1972), and the 460 grab samples collected by Bumpus et al. (1951) provide information on surficial sediments in western Massachusetts Bay. Surface sediments in the harbor approaches are heterogeneous in character (Figure 13). In the region east and southeast of Boston Harbor, surface sediments are characterized by coarse gravels, while fine sands dominate northeast of the harbor. Coarse, gravelly sediments - similar to those found in the shipping channels - are interpreted as reworked glacial drift; the fine sand ascribed to modern progradation of sand from the shore and littoral zone (Meisburger, 1976).

Based on the 152 grab samples taken by Mencher et al. (1968) and the 27 samples taken during this study, muds (silt plus clay) within the harbor are concentrated in areas where dredging has not taken place and where tidal velocities are a minimum (Figure 14). Sands and gravels and mixtures of the two are found in the shipping channels and near the harbor islands (ridge crests). The major depocenters of mud correspond to the historical loci identified in the previous section. The muds in these areas contain between 25 and 35 percent clay. In the

Figure 13. Surficial sediments of Massachusetts Bay  
(from Willett et al., 1972).



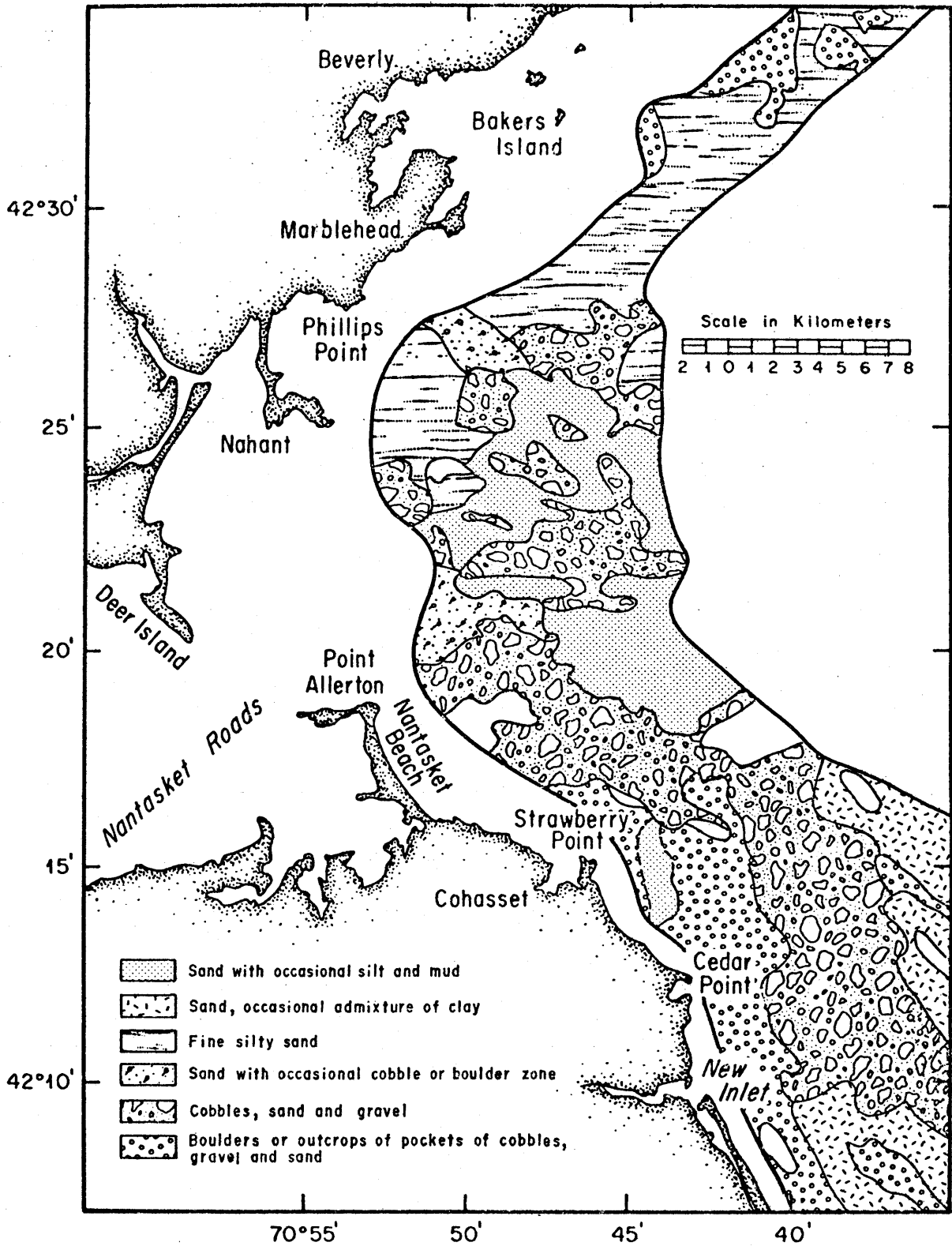
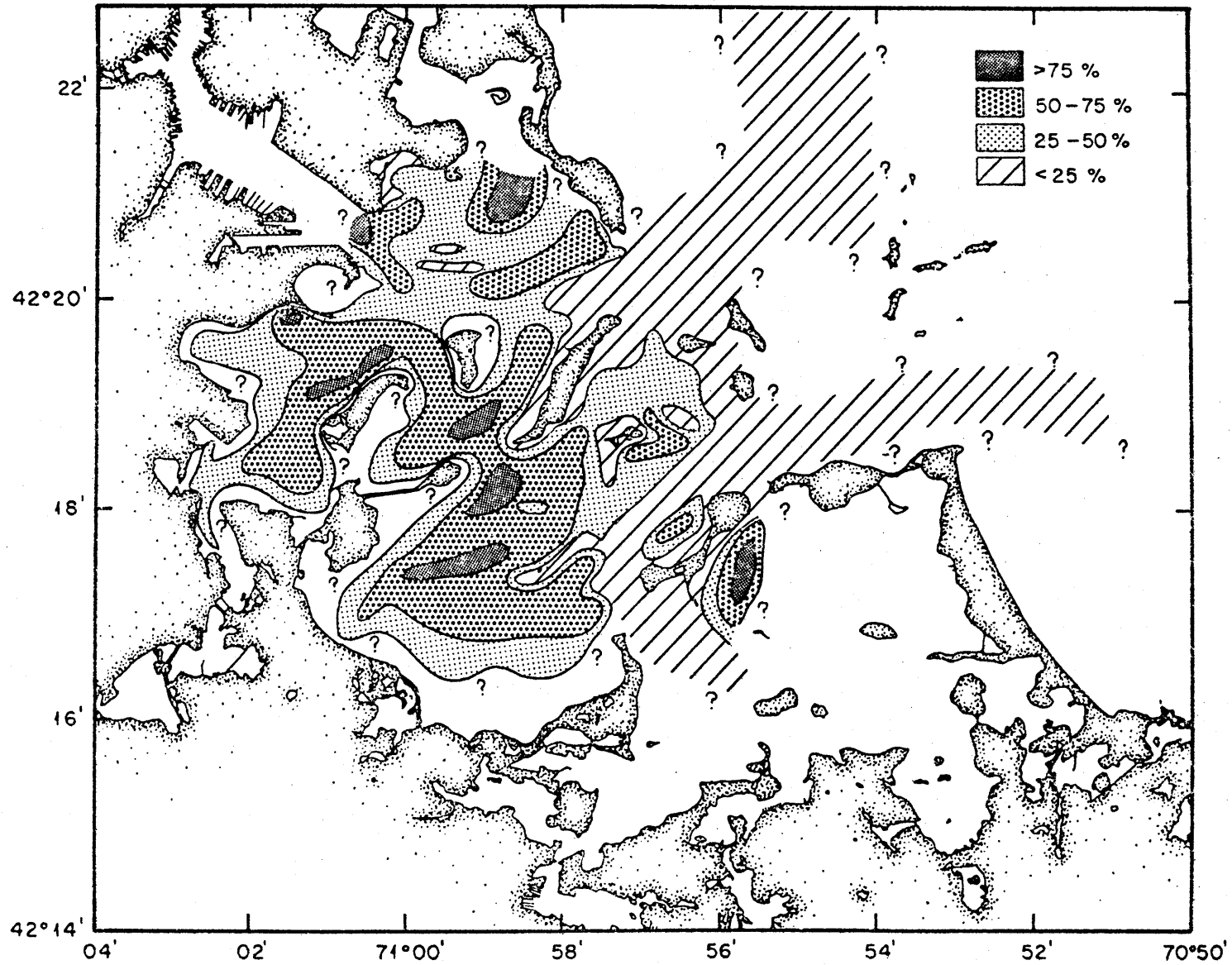


Figure 14. Distribution of mud, material finer than 62 microns. Based on samples from Mencher et al. (1968) and this study.

# MUD CONTENT OF BOTTOM SEDIMENTS



harbor, where the mud content exceeds 50 percent, the ratio of clay to mud is generally less than 0.40, indicating that these muddy sediments are dominated by silt-size material. In contrast, sands and gravels in the harbor (and its approaches) usually contain less than 5 percent clay and slightly less silt (ratio of clay to mud is greater than 0.50).

## 2. Bottom Sediment Composition

### a. Inorganic Sedimentary Components

The greater than 62 micron fraction of harbor sediments is fairly uniform. Constituents include: 1) angular to rounded, vitreous quartz (80-90%) with minor amounts of frosted quartz; 2) angular, glossy unburnt coal and black (burnt) wood shards (5-10%), most abundant near the navigation channels; 3) muscovite, feldspar, heavy minerals (15%); and 4) rounded rock fragments (<5%). Some samples contain iron-stained quartz grains.

In the harbor approaches, the dominant mineral constituent of the greater than 62 micron fraction is quartz. Rock fragments are common in coarser sands. Biogenic content is minor, consisting primarily of agglutinated foraminifera. Mica is generally present, but at low percentages.

Microscopic examination and x-ray diffraction studies of the 2-62 micron fraction (silt) show that harbor samples are dominated by angular quartz. Black carbonaceous material is

present in minor amounts. X-ray diffraction studies on oriented samples and powder mounts do show the presence of feldspar, 10 Å mica, illite, and chlorite. Offshore samples display a similar composition.

The mineralogy of the less than 2 micron fraction is dominated by illite. Chlorite and feldspar are secondary constituents, while quartz and kaolinite occur in trace amounts.

#### b. Calcium Carbonate

Both shelled and nonshelled organisms abound in the black muds and in the waters just above. Mussels are common, and shell fragments are frequent constituents of the mud. Other than these mussel banks, however, most sediments in the harbor contain less than 1.0 percent calcium carbonate and many contain less than 0.5 percent. The bulk of this carbonate consists of the remains of mollusks with subordinate amounts of benthonic foraminifera, echinoids, and barnacles. Molluscan shells dominated by the blue mussel Mytilus edulis (Linne), are most common in the fine muddy sediments of Dorchester and Quincy Bays.

Analyses of the samples from the harbor approaches by Willett et al. (1972), Meisburger (1976), and Hathaway (1971) show that calcium carbonate is a minor constituent of the

bottom sediments. Mollusk shells, where found, are usually fragmented; the majority are derived from the mussel, Mytilus edulis, and the quahog, Mercenaria mercenaria.

c. Organics

Organic carbon is most abundant in the fine-grained sediments of northern Quincy Bay and between the harbor islands (compare Figures 14, 15, and 16). In these areas, organic carbon in the surface sediments measures 4-5% by weight (LECO Analyzer). Away from these areas, most samples contain between 1.0 and 2.0 percent organic carbon, which are levels typical of estuaries along the eastern seaboard (Folger, 1972). Mencher et al. (1968) reported organic carbon values in excess of 15%, but these values appear at least three times greater than the ones reported here. Because of the wide-spread confidence in LECO methods and the errors possible in the "spectrographic" procedure employed by Mencher et al., it is assumed that the latter values are in error.

In the sandy and gravelly sediments of the harbor approaches and near the outer islands, organic carbon content is generally below 0.5 percent. Conover (1951) reported that the total organic matter content of the bottom sediments of Massachusetts Bay and the harbor approaches were generally below 2%, though some samples contained values in excess of 10%. (For comparison, Conover (1951) calculated a mean of 0.419 for organic carbon: total organic matter content.)

Figure 15. Percent organic carbon in surficial sediments (this study).

# ORGANIC CARBON CONTENT (%)

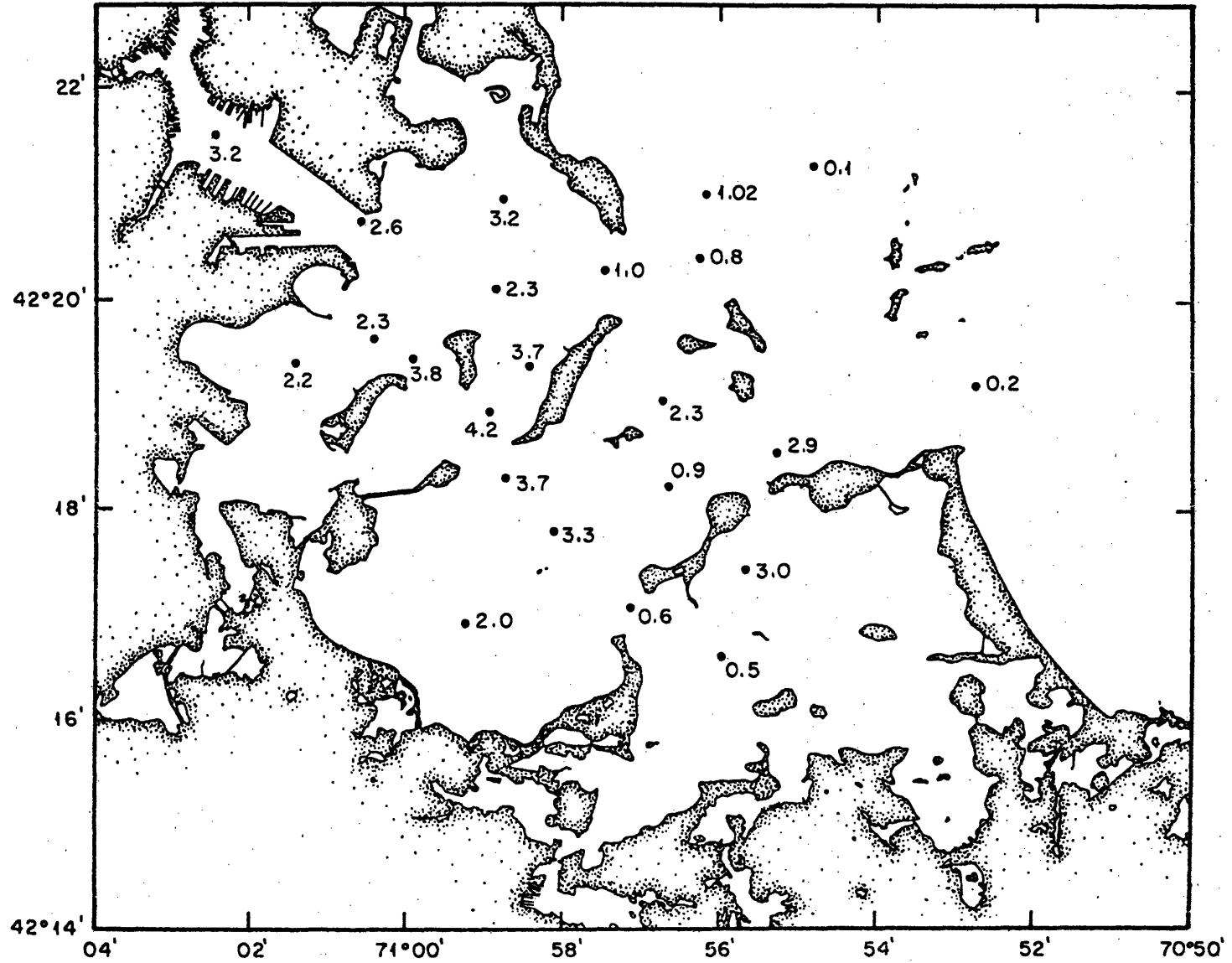
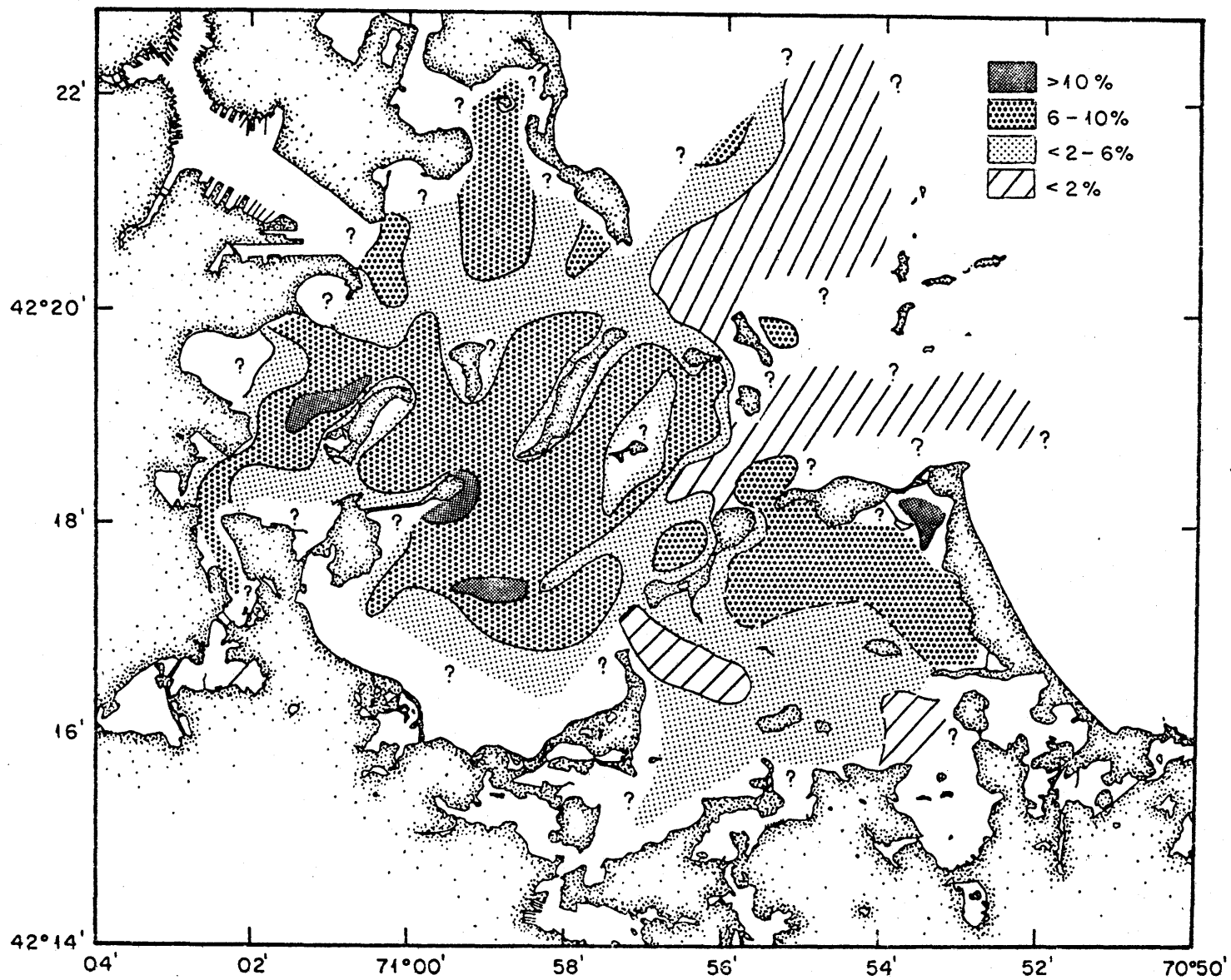




Figure 16. Distribution of organic matter. Based on samples from New England Aquarium, 1972, and this study.

# ORGANIC MATTER CONTENT



Organic carbon and clay show a direct relation (Figure 17). However, high carbon values do not merely reflect areas of fine grain size. In some samples (e.g. G25 and G26) very small clay contents are matched with dramatic concentrations of organic carbon. Analyses of the organic carbon content of the clay fraction for grab samples G2, G3, G5, G9, and G25 (Figure 10) show that the clay-size organic particles constitute under 20% of the total organic carbon content (Table 2), suggesting that silt and sand-size organic particles are also important. In fact, examination of the sand-size material in G25 shows that most grains are coated with an organic film.

Conover (1951) reported that the organic matter deposited in the sediments of the harbor approaches was derived largely from marine sources, the most important of which were phytoplankton. Conover (1951) did note, however, that some surface samples showed evidence of pollution from sewage, the highest values for organic matter content occurring near the North Channel and the Deer Island sewage outlet. Mencher et al. (1968) also concluded that a great part of the organic material in Boston Harbor proper was derived from sewage.

The composition of the organic material in grab samples G5, G12, G14, G15 was examined by Chevron Oil Company using microscopic organic analyses (Table 3). All four samples possess a mixture of pale and translucent, fibrous organic

Figure 17. Percent organic carbon versus percent clay in grab samples from Boston Harbor and its approaches. Triangles represent offshore samples taken by Hathaway (1971).

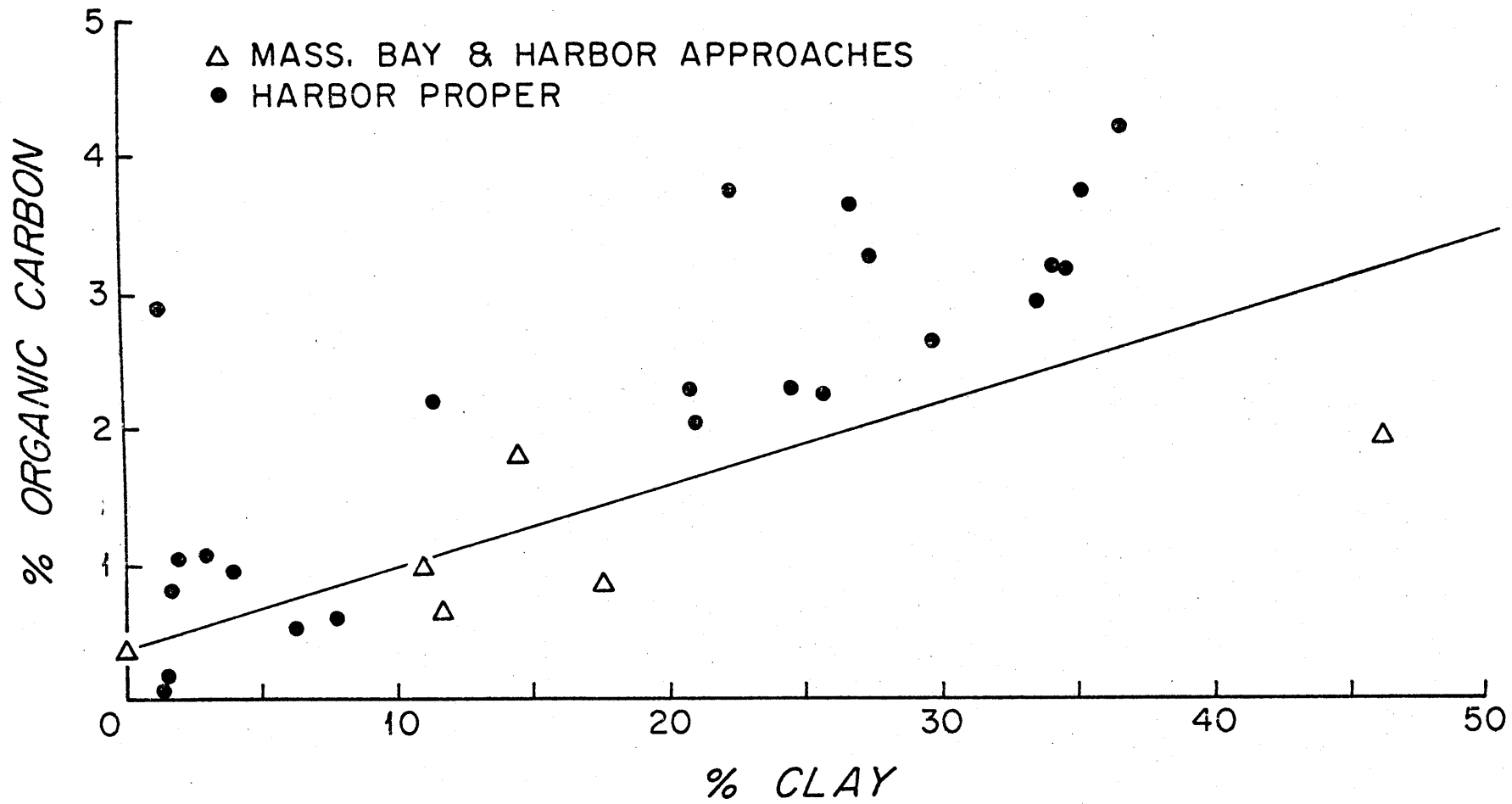


TABLE 2  
Size partitioning of the organic carbon

SAMPLE	BULK ORGANIC CARBON CONTENT (%)	PERCENTAGE OF TOTAL CARBON		
		SAND	SILT	CLAY
G2	2.64	27.7	62.6	9.7
G3	2.26	46.9	35.7	17.4
G5	3.65	43.2	49.3	7.5
G9	2.29	53.6	36.1	10.2
G25	0.81	79.8	12.0	8.3

TABLE 3  
Organic analysis of selected grab samples

SAMPLE	Wt.% CaCO <sub>3</sub>	Wt.% BFOC	Wt.% TOC	H/C	OIL-P OM (%)	Wt.% BIT	BIT/BFOC	TAI
G5	.23	4.02	4.48	1	75	.45	.12	1-1.5
G12	.41	2.00	2.08	0.6	50	.08	.04	1-1.5
G14	.11	4.34	4.91	1	80	.57	.13	1-1.5
G15	.35	3.67	4.06	1	80	.39	.11	1-1.5

BFOC - Bitumen-Free Organic Carbon  
 TOC - Total Organic Carbon  
 OIL-P OM - Oil-Prone Organic Matter  
 BIT - Bitumen  
 TAI - Thermal Alteration Index

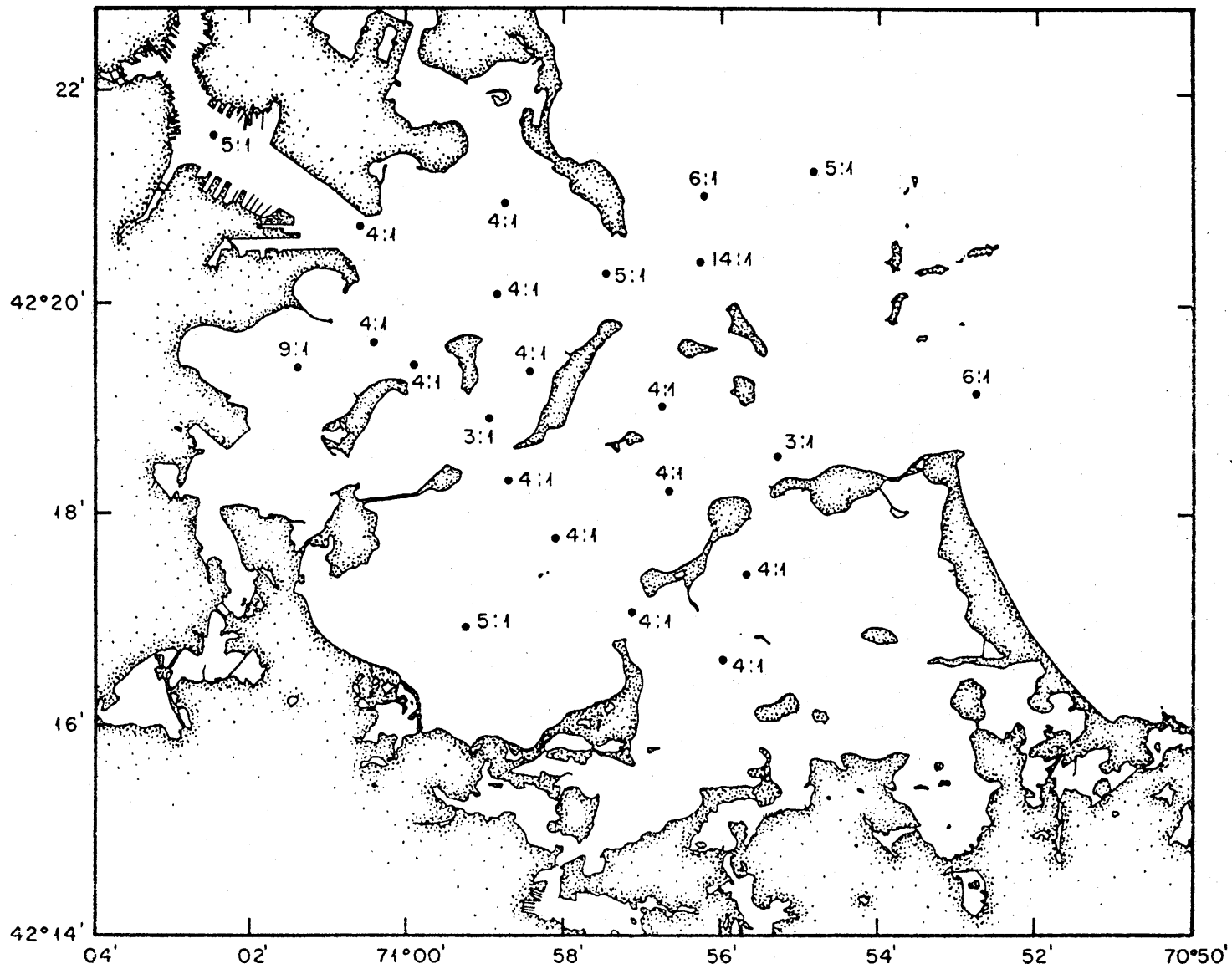
material which tends to bind particles together. The greater than 10 micron fraction of the organic matter has a heavy terrestrial influence which includes pollen, spores, humic and cuticular material. Amorphous algal material and occasional foraminifera linings are also in the greater than 10 micron fraction. The less than 10 micron fraction is predominately amorphous in all four samples. Much of this amorphous material is believed to be related to larger humic particles. Sample G12 is somewhat anomalous in that it contains significantly more pyrite than the others and appears more biodegraded. All samples possess numerous diatom and silicoflagellate fragments.

In general, the organically enriched muds of the harbor have C/N ratios of less than 4.0, while the sandy sediments of the topographic highs and navigation channels have C/N ratios in excess of 5.0 (Figure 18). These low values of C/N may be explained by the large nitrogenous input from sewage discharge and the severe fractionation of the sewage-derived organics (R. Vaccaro, personal communication). Yet, curiously, these C/N values do not reflect terrestrial origin. Differences between our C/N values and those calculated by others for the area (Hathaway, 1971; Stewart, 1968) are probably due to differences in nitrogen determination--i.e., Kjeldahl versus LECO.

Figure 18. Ratio of carbon to total nitrogen in grab samples (this study).



# RATIO OF CARBON TO TOTAL NITROGEN



Pockets of organic-rich sediment are often acoustically impenetrable to the energy from high-resolution, continuous seismic profilers. The cause of these acoustically turbid zones is ascribed to interstitial gas bubbles of methane and  $H_2S$  produced by the biochemical degradation of organic matter (Schubel and Schiemer, 1972). During our seismic survey of Boston Harbor, several such acoustically turbid zones were identified (Figures 19 and 20). For the most part, these zones are coincident with sediments of high organic content (compare Figures 16 and 20). While coring in these sediments, bubbles with a strong odor of  $H_2S$  evolved from the sediments. Acoustically turbid zones not associated with present areas of high organic content (i.e. those in Hingham Bay and the zone off Pt. Alerton) may represent areas where gas production occurs at some depth in the sediments. The acoustic records in these areas showed that the reflective surface was at a shallow depth below the sediment/water interface.

Figure 19. Acoustically turbid zone (location shown in Figure 20). Sediment surface (S) and acoustic basement (A) indicated for reference. Vertical scale is approximately 50 m (1/16 sec); horizontal scale is 1.5 km.

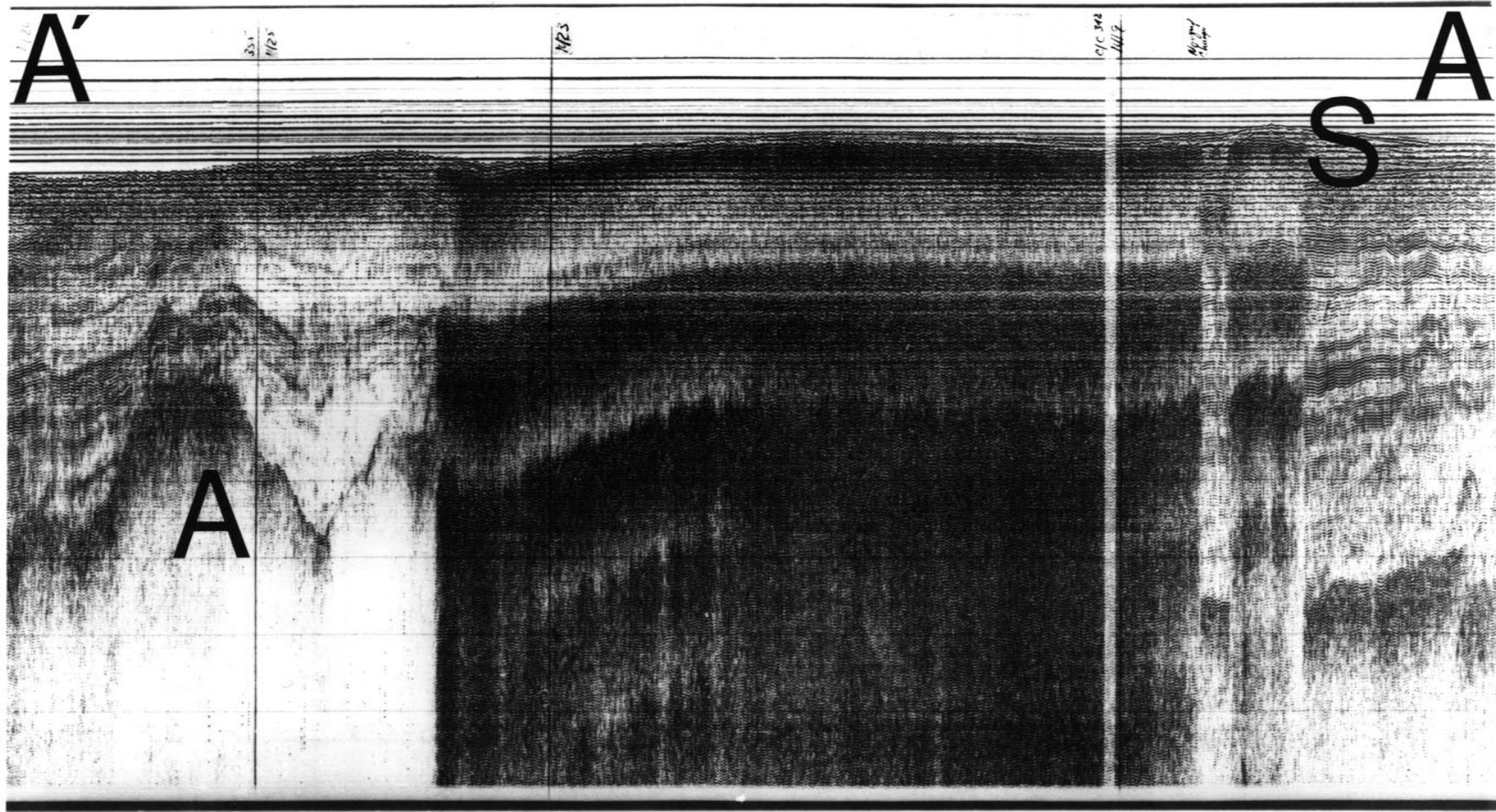
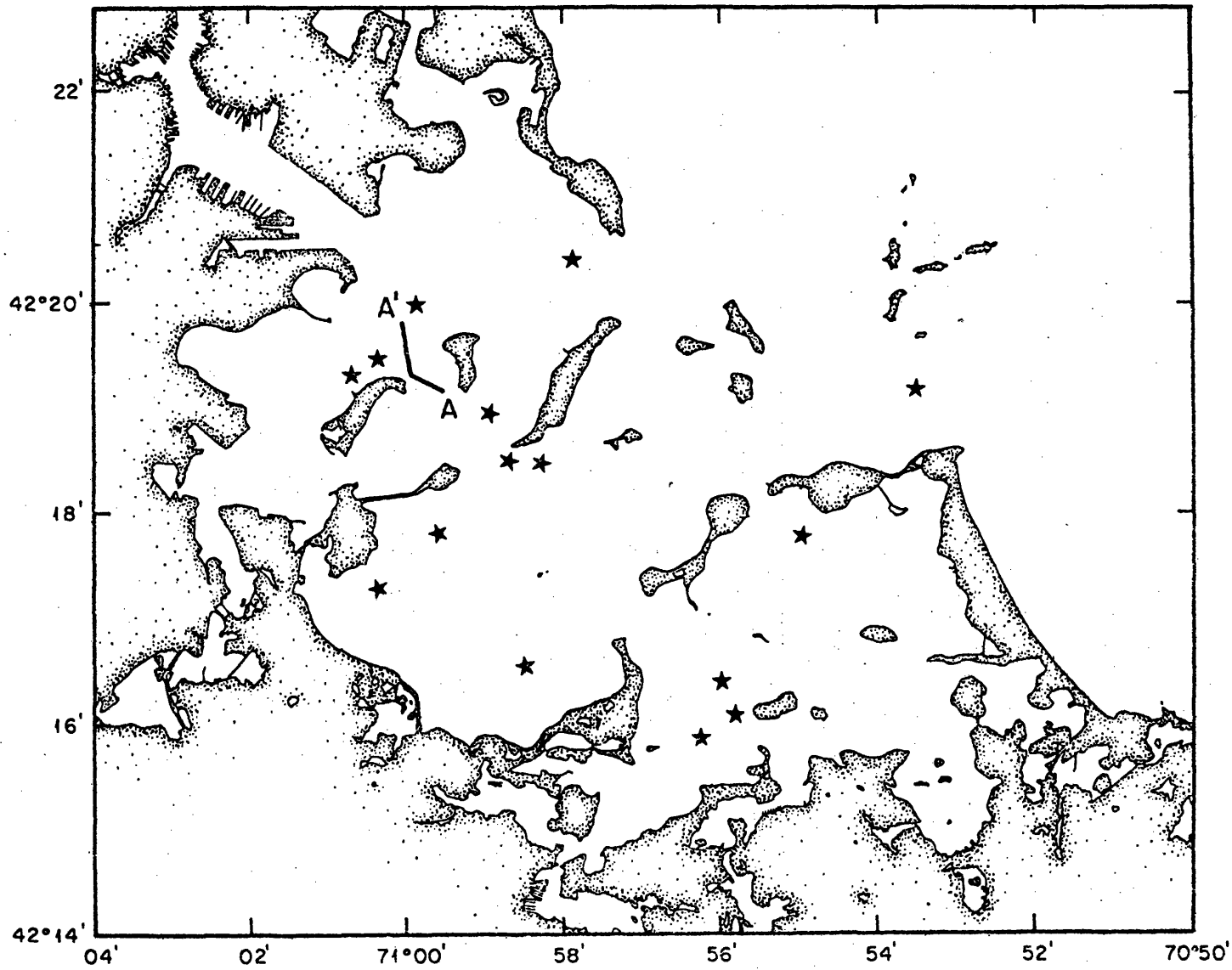


Figure 20. Distribution of acoustically turbid zones in Boston Harbor (indicated by ★). Heavy line A-A' indicates location of profile shown in Figure 19.

# DISTRIBUTION OF ACOUSTICALLY TURBID ZONES



## CHAPTER 2

V. Pollution History -- Trace Metal Accumulation

The intent of this chapter is to establish the recent sedimentary history of the harbor. The key to understanding the distribution of bottom sediments and the dispersal of fine-grained materials may lie in examination of the down-core distributions of various pollutants. Trace metal profiles and  $^{210}\text{Pb}$ -dating provide inference into historical changes in input or events (storms, changes in circulation, etc.) and lend insight into those factors responsible for the long-term retention of pollutants.

For a more extensive discussion of coring results and a detailed description of analytical techniques see Bothner et al., 1980 (in preparation).

## a. Surface Distribution of Trace Metals

## 1) Previous Work

Considerable attention has been given to the trace metal content of Boston Harbor sediments. The first detailed geochemical study of the harbor sediments (White, 1972) utilized 150 surface samples taken with a Peterson dredge. With atomic absorption spectrography, White determined 7 elements in his samples (Cd, Cr, Cu, Hg, Ni, Pb, and Zn), and found that although organic matter and trace metal concentrations varied considerably, definite distribution

patterns occurred throughout the harbor. In general, the metal concentrations decreased along a path extending from the Inner Harbor and western shore easterly toward Massachusetts Bay. Metal concentrations also decreased with distance from the Inner Harbor to Nantasket (Figure 21A & B). Comparison of the average harbor values with clean, background sediments (Table 4) reveals the significant accumulation of trace metals in the harbor.

White found that certain elements correlated with organic content. Nickel, lead, and copper had correlation coefficients with organic matter of 0.87, 0.85, and 0.84, respectively. On this basis, he asserted that organic matter was an important sea water-sediment exchange vehicle for these elements. Good correlations also existed between several of the different metals, with correlations between cadmium, copper, lead, and zinc having coefficients greater than 0.86. (Summerhayes et al. (1976) also reported good correlations among these elements in New Bedford Harbor.)

In 1972 the New England Aquarium reported on trace metal analyses of Cd, Co, Cr, Cu, Hg, Mo, Ni, Pb, V, and Zn from approximately 100 cores from the Inner Harbor and Outer Harbor (Gilbert et al., 1972). These results showed generally much higher concentrations in the Inner Harbor sediments, which were attributed to riverine input, commercial activity, and combined sewer outfalls. In the Outer Harbor, higher trace metal



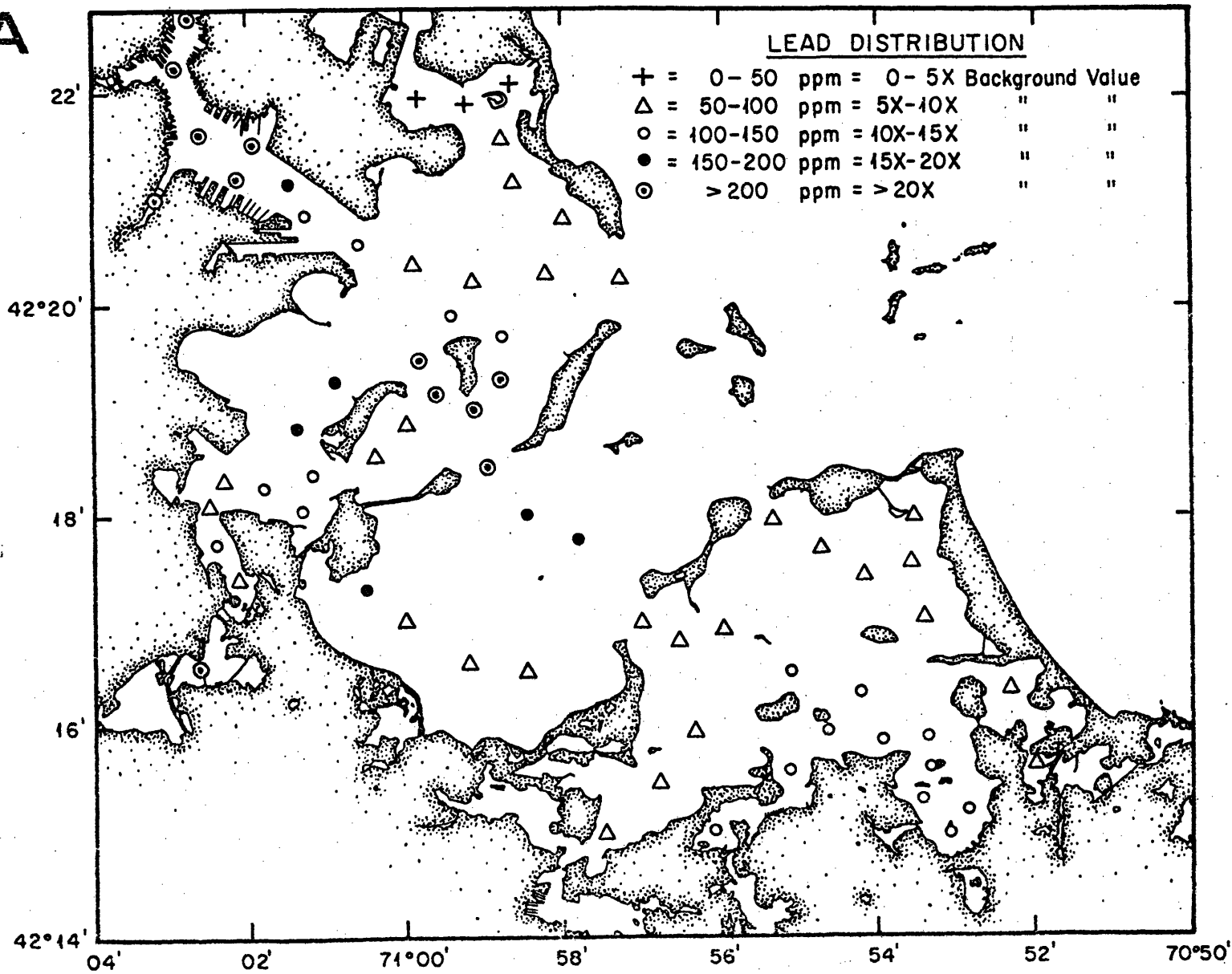
TABLE 4 Trace metal concentrations in the surface sediments of Boston Harbor

ELEMENT	RANGE (PPM)	AVERAGE BACKGROUND CONCENTRATION (PPM)	AVERAGE VALUE (PPM)	STANDARD DEVIATION (PPM)
Cd	0.3-17.5	0.7	2.8	2.4
Cr	20.0-437.0	7.5	164.1	119.6
Cu	8.0-625.0	5.6	106.9	88.0
Hg	0.2-9.4	0.2	2.3	1.6
Ni	8.0-129.0	4.3	29.9	13.9
Pb	12.5-500.0	10.2	148.7	111.4
Zn	32.0-1750.0	16.1	254.2	237.3

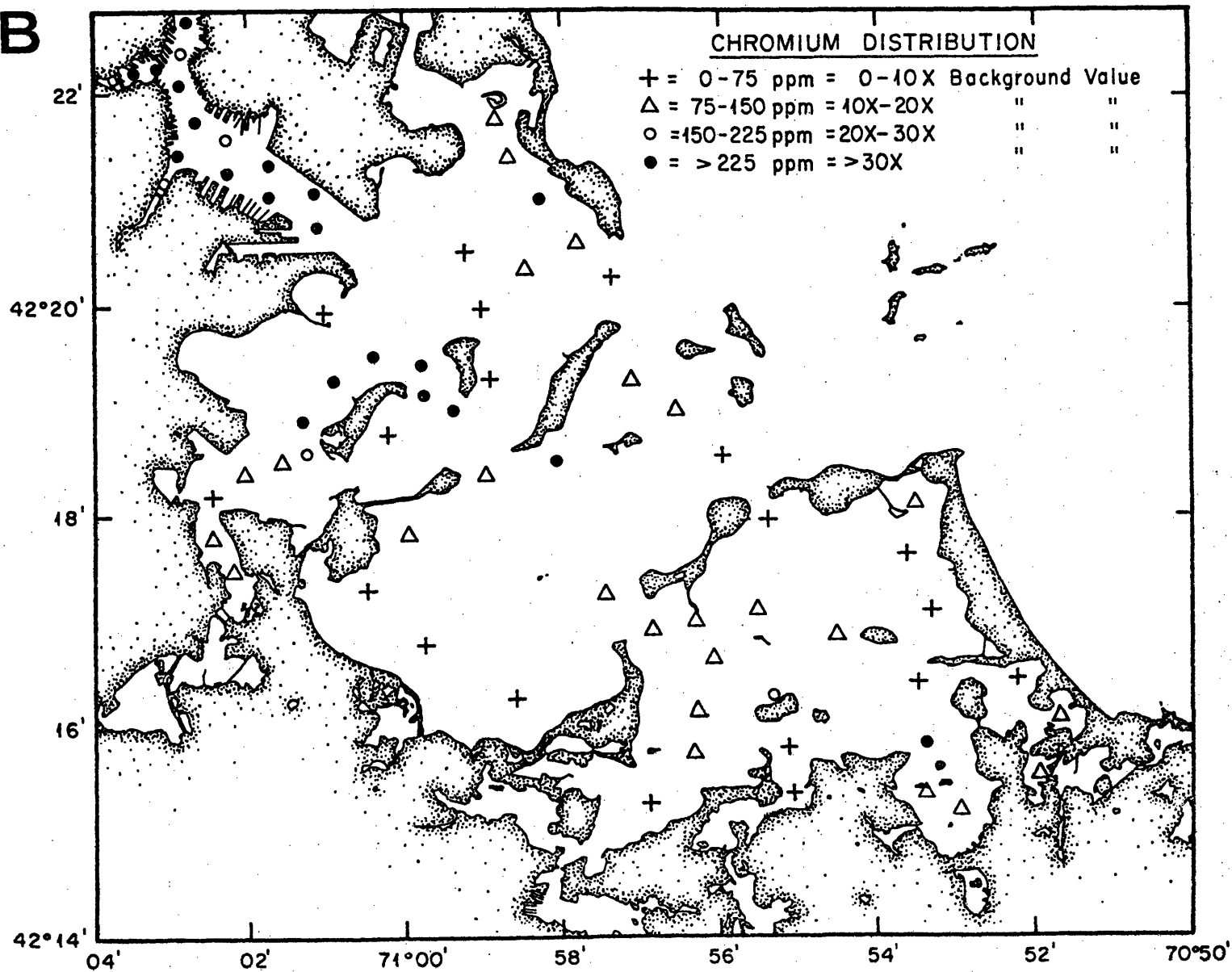
Taken from White (1972).

- Figure 21.
- A. Distribution of lead in the surficial sediments of Boston Harbor (taken from White, 1972).
  - B. Distribution of chromium in surficial sediments of Boston Harbor (taken from White, 1972).

A



**B**



values occurred in Deer Island Flats, northeastern Dorchester Bay, and along the western shore of Long Island. These locations are possible deposition sites for suspended solids emanating from the Inner Harbor and for the sludge and particulate effluent discharged at Deer Island. Sediments in the southern portion of the harbor had generally lower levels of trace metals; this was attributed to lower levels of industrial activity in the Quincy-Hingham area. Notable exceptions were ascribed to the former sewage facility at Moon Head or to the Nut Island treatment plant.

Subsurface samples in the Aquarium study showed a marked decrease in metal levels. Surface enrichment (and subsurface peaks) was attributed to increasing organic concentrations. In several areas, a significant portion of the organic content was reported to be petroleum products.

## 2. Present Study

From the previous studies, it is clear that the sediments of Boston Harbor contain substantial quantities of trace metals. Input is dominated by the Deer Island and Nut Island treatment plants, the Inner Harbor, and the atmosphere. Little is known, however, of how these metals spread throughout the harbor. In an attempt to address this problem, we examined the horizontal distribution of trace metals, their vertical profiles in cores, and the relationships between these metals

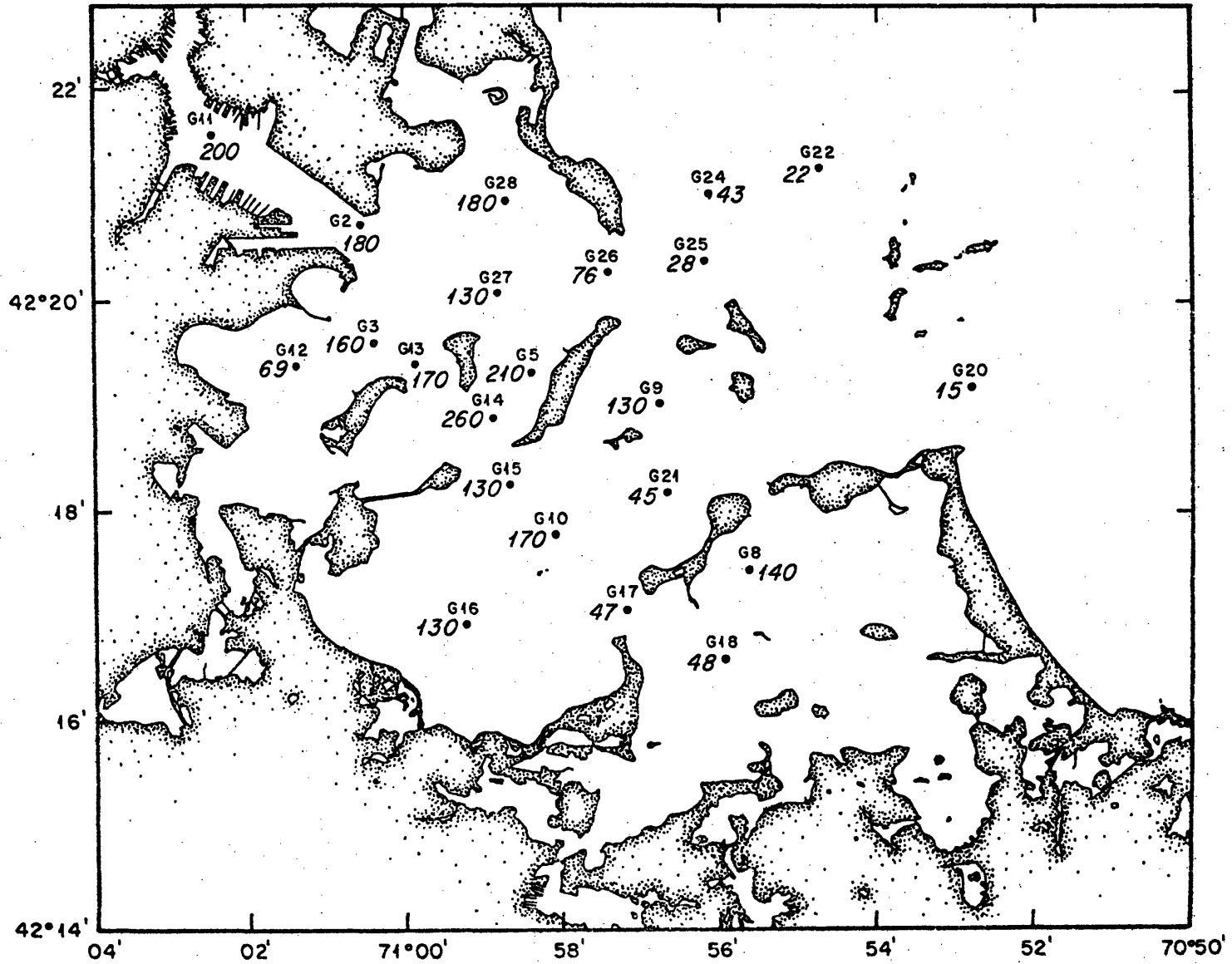
and sediment characteristics. This study involved sediment collected from 11 core sites and 24 grab samples (Figure 12). Bothner et al. (1980) discuss analytical techniques used and detailed results of this study. The following discussion is restricted to a preliminary description of the spatial and temporal distributions of metals and the implications of these distributions for the sedimentary environment.

The distribution of trace metals in the harbor closely follows the pattern outlined by earlier studies. Metals are concentrated in the Inner Harbor, northeastern Dorchester Bay, Deer Island Flats, and northern Quincy Bay (Figure 22). This regional distribution of metals coincides with regional concentrations of fine-grained sediments and organic matter (compare Figure 22 with Figures 13 and 16), though slight differences in mud or organic matter content can result in significant changes in trace metal concentration (Figure 23).

One way in which complex relations among many variables can be reduced to a smaller number of simple associations (which account for most of the variance in the original data) is through factor analysis (Spencer, 1966; Cooley and Lohnes, 1971). In factor analysis, the different variables (in this case geochemical data) are grouped on the basis of the degree of their intercorrelation (into factors). Mathematically, this process involves determining the eigen-structure of the

Figure 22. Concentration of lead (ppm dry weight)  
in the grab samples from this study.

# DISTRIBUTION OF Pb(ppm) IN SURFICIAL SEDIMENTS

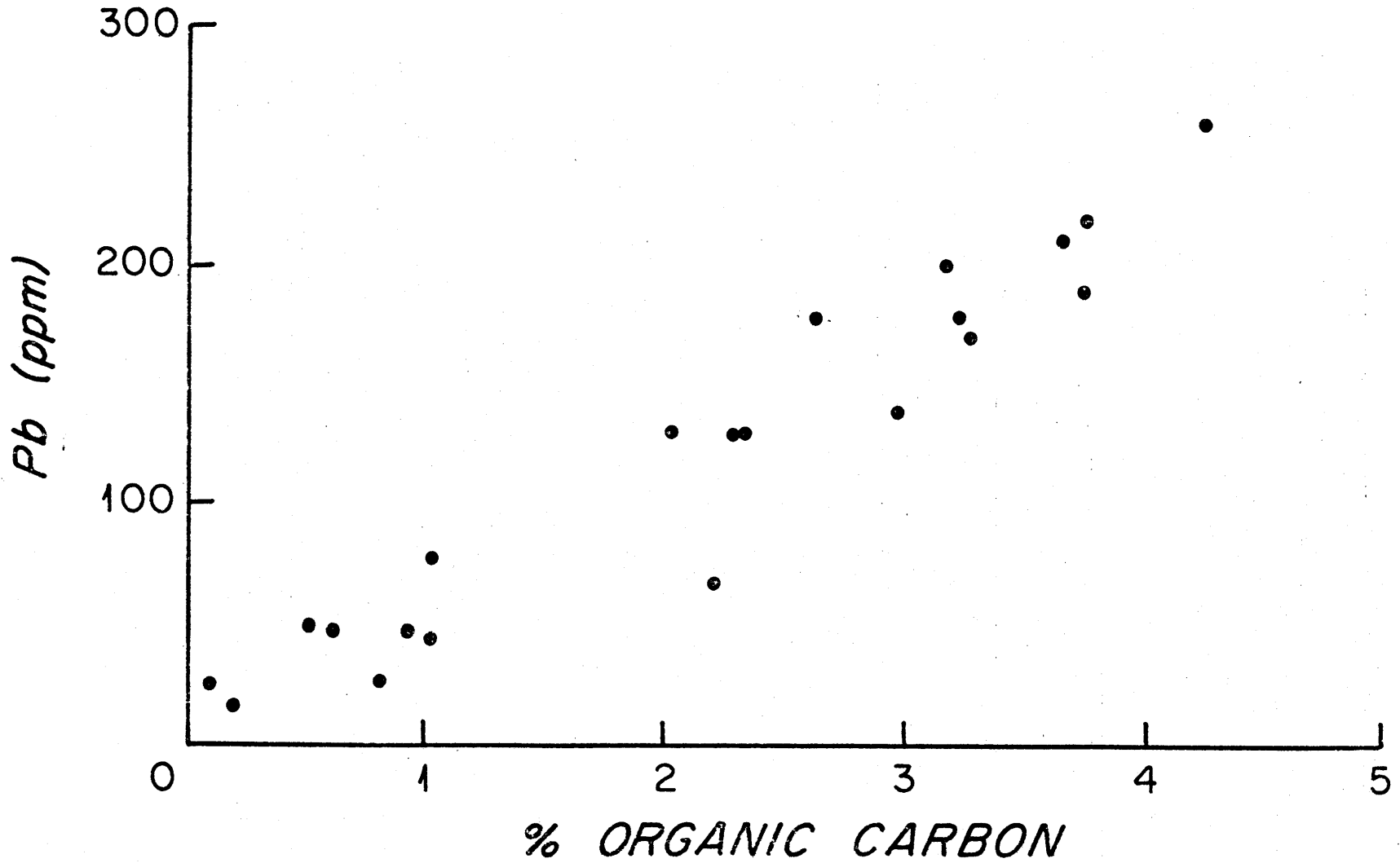




- Figure 23.
- A. LEAD VS. ORGANIC CARBON  
(in grab samples)
  - B. LEAD VS. CLAY CONTENT  
(in grab samples)

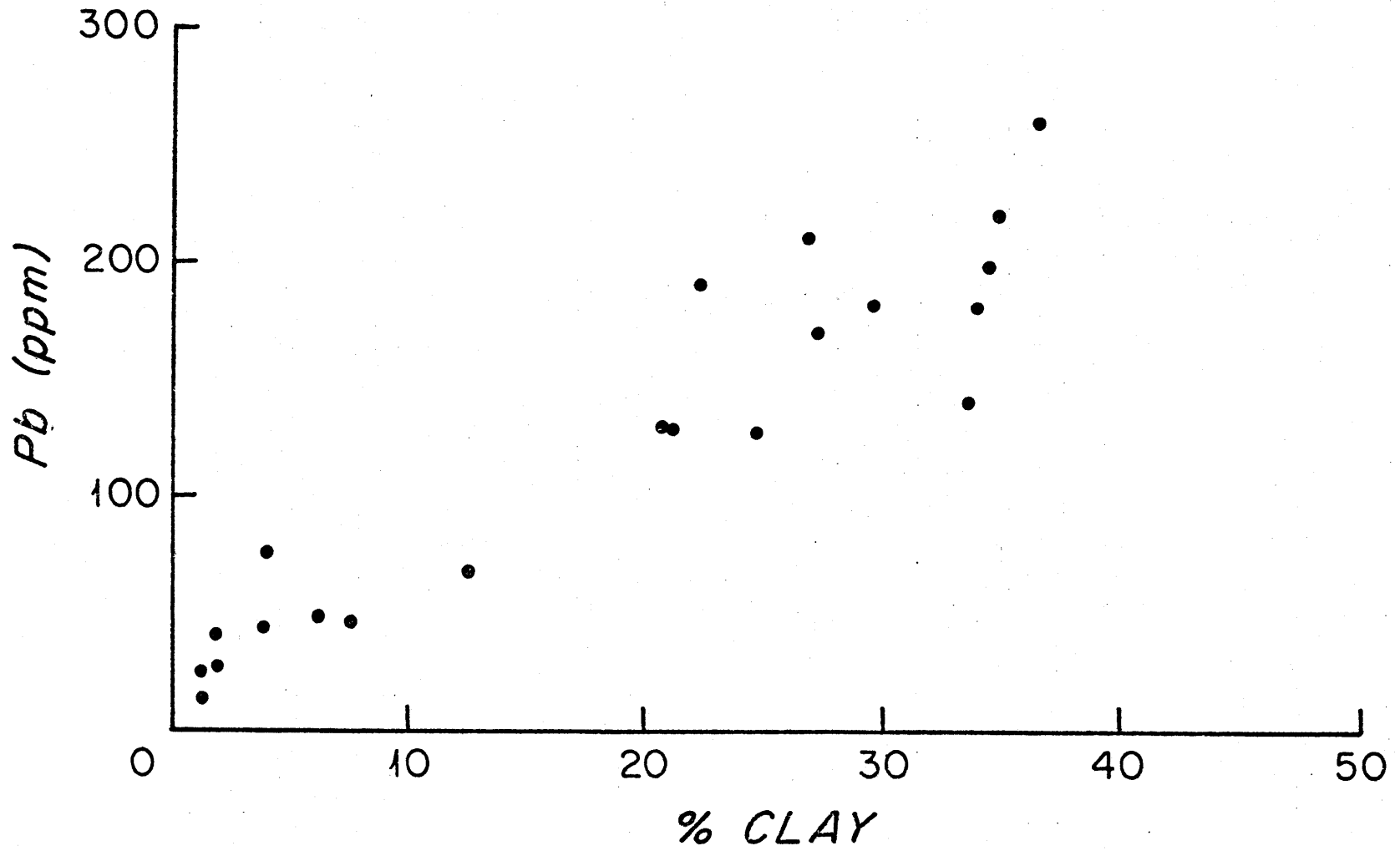
A

Pb (ppm) vs. % ORGANIC CARBON



**B**

Pb (ppm) vs. % CLAY



correlation matrix. The factors are statistically the most dominant features of data variation. The degrees of importance of each factor for a given sample are expressed as R-scores.

For the grab sample data (which include size data and organic carbon measurements), only two factors are statistically significant - i.e., eigen values greater than 1.0. Together they account for 85.7 percent of the total variance in the data (Table 5). Factor I, accounting for 79.0 percent of the variance, comprises a strong association among Cr, Ni, Pb, Cu, and Zn, V, As, and the fine-grained, organic-rich sediments. Factor II, accounting for 6.7 percent of the variance, associates Mn, Cr, Al, and Ba.

When the R-scores for factor I are calculated, the organic, metal-rich samples produce high positive scores, while the sandy, gravelly samples have negative scores (Figure 24). When the two factors are plotted against one another, the samples fall into three discernible categories (Figure 25). Highly contaminated (metal-rich), positively scoring samples and the less contaminated or negatively scoring samples are separated by the zero score for factor I. In addition, the contaminated samples from the Inner Harbor and Deer Island Flats are separated from the remaining contaminated samples by the zero score for factor II (categories 2 and 3, respectively, in Figure 25). Thus, there may be a discernible difference in

Table 5. Factor Analysis of Geochemical Data  
for Grab Samples showing:

- (1) Main factors controlling data variance
- (2) Percentage of variance explained by each factor
- (3) Factor loadings within each factor ( ).  
Factors have not been rotated.

FACTOR I	FACTOR II
79.0 %	6.7 %
Cr (.975)	Mn (.457)
Ni (.974)	Cr (.452)
Pb (.964)	Al (.394)
Cu (.958)	Ba (.352)
CLAY (.945)	
Zn (.943)	
Organic Carbon (.935)	
V (.930)	
Silt (.920)	
As (.912)	
SAND (-.941)	

Figure 24. R-Scores for factor I. Positive values are associated with the most highly contaminated samples.

# DISTRIBUTION OF R-SCORES FOR FACTOR I

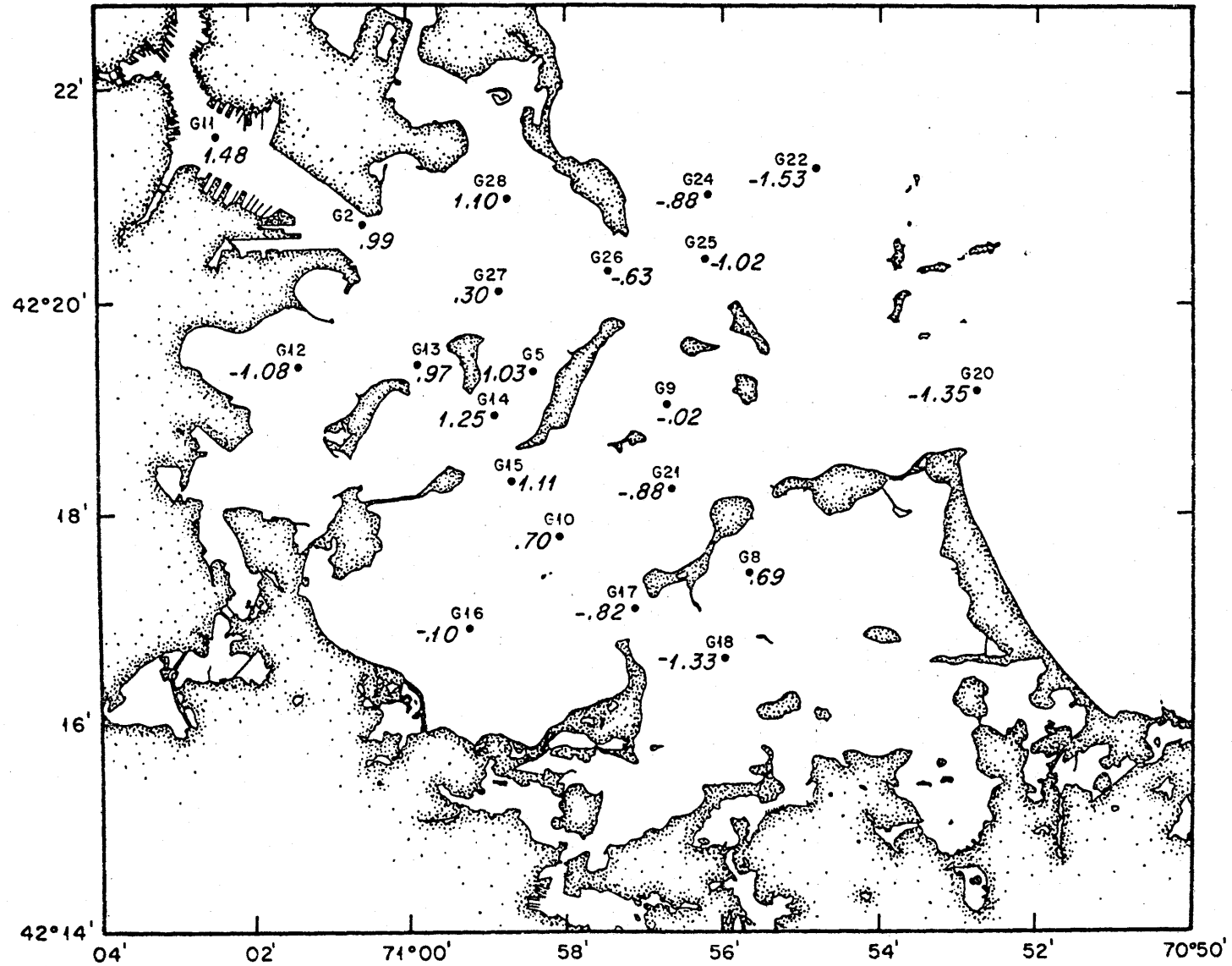
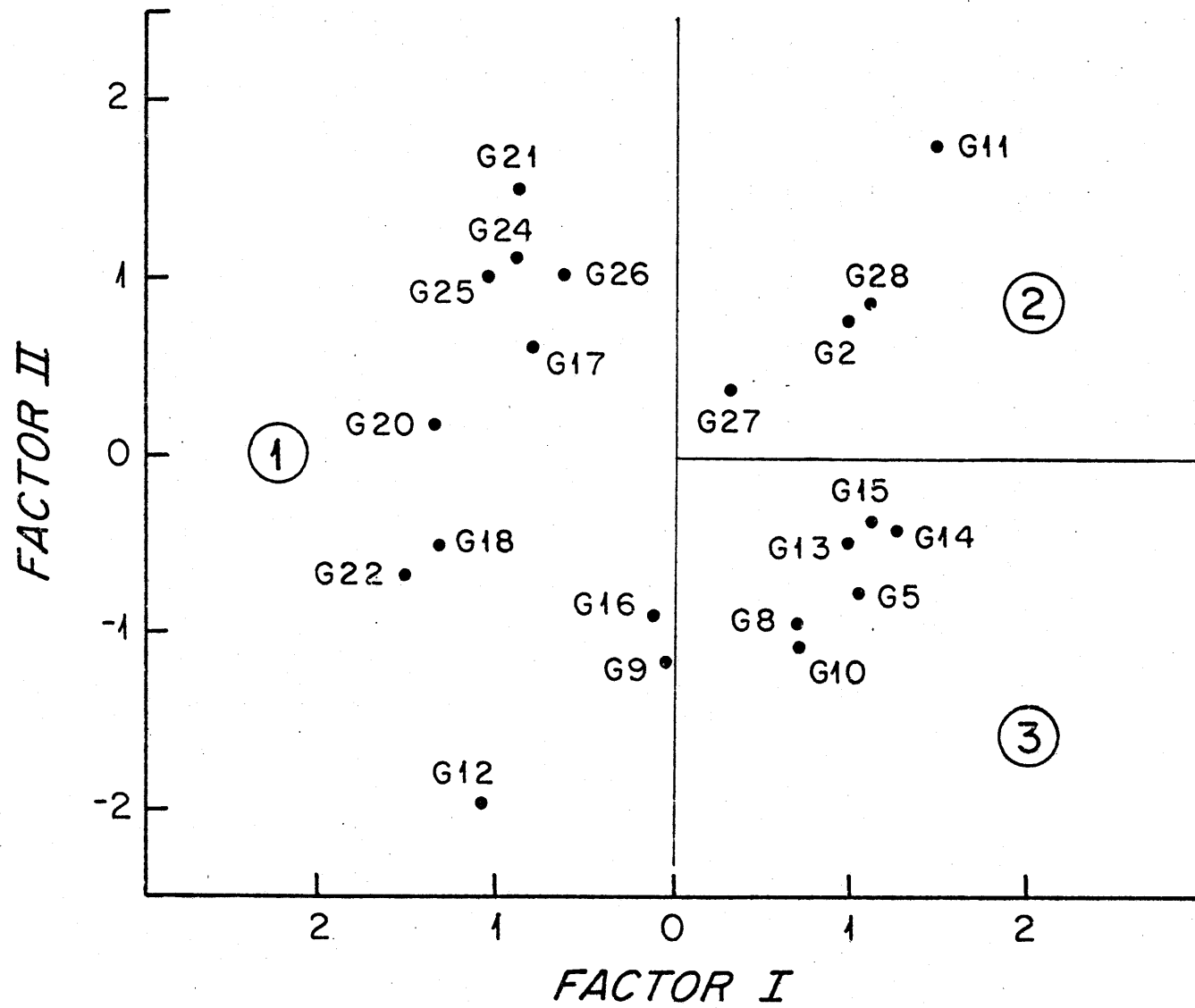


Figure 25. Factor I vs Factor II. Plot effectively divides samples into three categories (see text).



FACTOR I vs. FACTOR II



sediment chemistry between the inner and outer portions of the harbor, and the influence of the Inner Harbor on the sedimentary environment of the outer harbor appears limited to the area of Deer Island Flats and western President Roads.

Geochemical data show a greater intercorrelation (Table 6), than reported by White (1972). The close interrelation of this diverse suite of metals suggests common sources, modes of transport, and dispersal paths. The distribution of trace metals in the outer harbor and their association with organic-rich muds point to the treatment plants as the most likely source of these contaminants (in the outer harbor). The sheer volume of trace metals released by these treatment plants overshadows other sources. With its sluggish circulation and high sedimentation rates (see section V.c), the Inner Harbor is probably a secondary source of trace metals to the outer harbor. The impact of atmospheric input, however, can be significant for some metals (see section V.e).

Trace Metal  
Table 6. Correlation Matrix (GRAB SAMPLES)

	Al <sub>2</sub> O <sub>3</sub>	Cd	Cr	Cu	Fe <sub>2</sub> O <sub>3</sub>	Hg	Mn	Ni	Pb	Zn	As	Ba	Sb	V
Al <sub>2</sub> O <sub>3</sub>	1.000	.662	.776	.830	.744	.653	.548	.874	.720	.815	.655	.881	.590	.773
Cd	.662	1.000	.691	.766	.395	.435	.340	.673	.569	.824	.441	.689	.451	.599
Cr	.776	.691	1.000	.976	.801	.769	.487	.942	.962	.925	.882	.879	.836	.863
Cu	.830	.766	.976	1.000	.742	.770	.447	.941	.935	.949	.834	.866	.787	.867
Fe <sub>2</sub> O <sub>3</sub>	.744	.395	.801	.742	1.000	.565	.709	.875	.782	.773	.801	.895	.678	.759
Hg	.653	.435	.769	.770	.565	1.000	.460	.743	.790	.707	.796	.649	.934	.809
Mn	.548	.340	.487	.447	.709	.460	1.000	.565	.455	.568	.414	.667	.496	.452
Ni	.874	.673	.942	.941	.975	.743	.565	1.000	.917	.931	.868	.934	.807	.922
Pb	.720	.569	.962	.935	.782	.790	.455	.917	1.000	.884	.910	.802	.855	.894
Zn	.815	.824	.925	.949	.773	.707	.568	.931	.884	1.000	.813	.870	.743	.883
As	.655	.441	.882	.834	.801	.796	.414	.868	.910	.813	1.000	.770	.802	.900
Ba	.881	.689	.879	.866	.885	.649	.667	.934	.802	.870	.770	1.000	.675	.795
Sb	.590	.451	.836	.787	.678	.834	.496	.807	.855	.743	.802	.675	1.000	.800
V	.773	.599	.863	.867	.759	.809	.452	.922	.894	.883	.900	.795	.800	1.000

## b) Down-core Variations in Sediment Characteristics

To examine the accumulation history of pollutants (particularly trace metals) in the harbor, a coring program was initiated under the direction of Dr. Michael Bothner (U.S.G.S.). Eleven core sites were selected on the basis of our seismic survey to sample the entire range of accumulation rates and metal contamination (Figure 12). Core 11 from the Inner Harbor and core 7 northeast of Dear Island were hoped to represent end-members of this range for comparison (i.e., highly influenced by human activity and slightly influenced, respectively). At each site, multiple cores were taken using a piston corer, gravity corer, and a hydrostatic corer to provide samples for  $^{210}\text{Pb}$ -dating, trace metal analyses, and measurements of size, and organic carbon (see Appendix I for description of techniques).

### 1) Sediment Texture

Most of the piston cores taken in the harbor encountered sand or the Pleistocene clay (Boston Blue Clay) at depths in excess of 1 meter. Hydrostatic cores C2 and C11 from the Inner Harbor show low percentages of sand throughout the core, while C7 from the harbor approaches and C9 near the outer islands are dominated by sand-sized material (Figure 26). In other cores from Dorchester Bay, Quincy Bay, and between the harbor islands, there are considerable down-core variations in

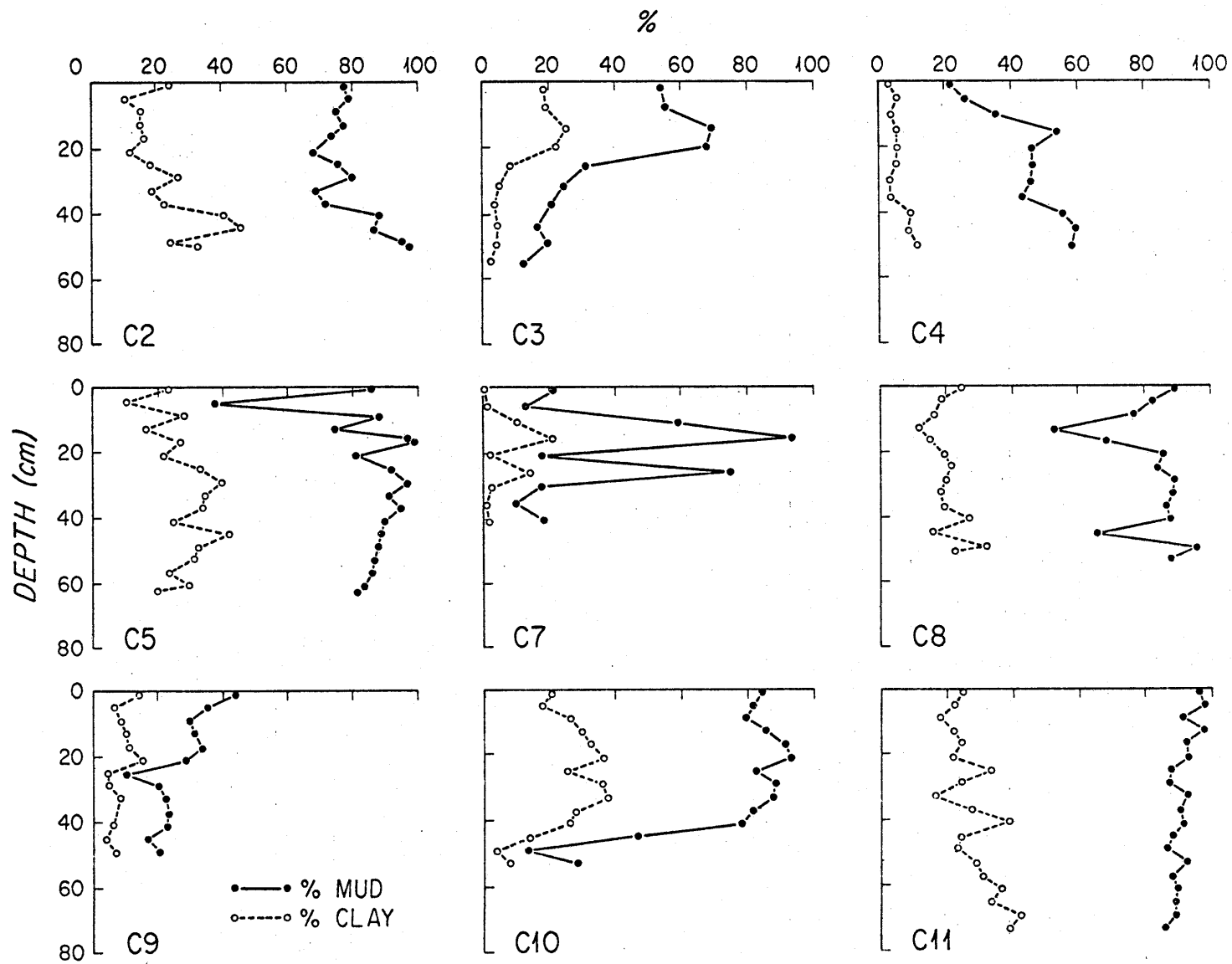
sediment size. Microscopic analyses of the subsurface sediments reveal a mineralogy consistent with that described earlier for surface samples.

For the most part, clay (finer than 4 microns) and mud (silt plus clay) co-vary down-core (Figure 26), but changes in the clay/mud ratios with changing mud content (within cores) can be considerable, and cover the entire range of values discussed for the surface sediments. Such variations may imply short-term changes in the depositional environment.

The clay/mud ratios in grab samples are much higher (greater than 0.10 difference) than the corresponding core tops. This apparent discrepancy may suggest that the surface layer of sediment consists of a soupy, clay-rich material which is trapped in grab samples; the coring process, however, may fail to sample this unconsolidated surface sediment (Summerhayes et al., 1977). Presumably, with its high water content such a layer is easily moved and forms, in effect, a mobile carpet. Such a layer would be of more importance and have greater extent in the quiescent areas of the harbor. Further evidence of this mobile carpet or "fluff" (Weil, 1976) will be presented later and its implications discussed.

Figure 26. Down-core variations in mud (silt plus clay) and clay ( 4 microns) for cores: C2-78, C3-78, C4-77, C5-78, C7-77, C8-78, C9-78, and C11-78.

# DOWN-CORE VARIATIONS IN MUD AND CLAY



## 2. Organic Carbon

In our cores from the harbor approaches and near the outer islands, organic carbon decreases slightly from top to bottom (Figure 27). However, cores taken in the harbor depocenters show large decreases in organic carbon with depth (except in cores 5 and 11, where the sedimentation rates are high). Sediments from the bottoms of harbor cores have amounts of clay and carbon similar to cores (tops and bottoms) in the harbor approaches, suggesting that these sediments were deposited under similar conditions. In contrast, sediments from the upper parts of harbor cores have carbon to clay relationships which correspond to grab samples from the harbor depocenters (Figure 28 and Figure 17). This increase in carbon relative to clay appears indicative of pollution (Summerhayes et al., 1976), and the core data suggest that this impact is increasing. However, there may be natural increases in carbon at the surface in unpolluted areas; Rhoads and Young (1970) observed that the bioturbated 2 to 3 cm thick surface layer of sediment in Buzzards Bay contain more organic matter than the subsurface sediment.

## 3. Metals

Analyses of down-core fluctuations of trace metal concentrates have been completed for five hydrostatic cores (C2, C3, C4, C5, and C7), and, hence, discussion will be limited to these cores. For an expanded discussion of results, see Bothner et al. (1980).



Figure 27. Down-core variations in organic carbon content.

## DOWN-CORE VARIATIONS IN ORGANIC CARBON

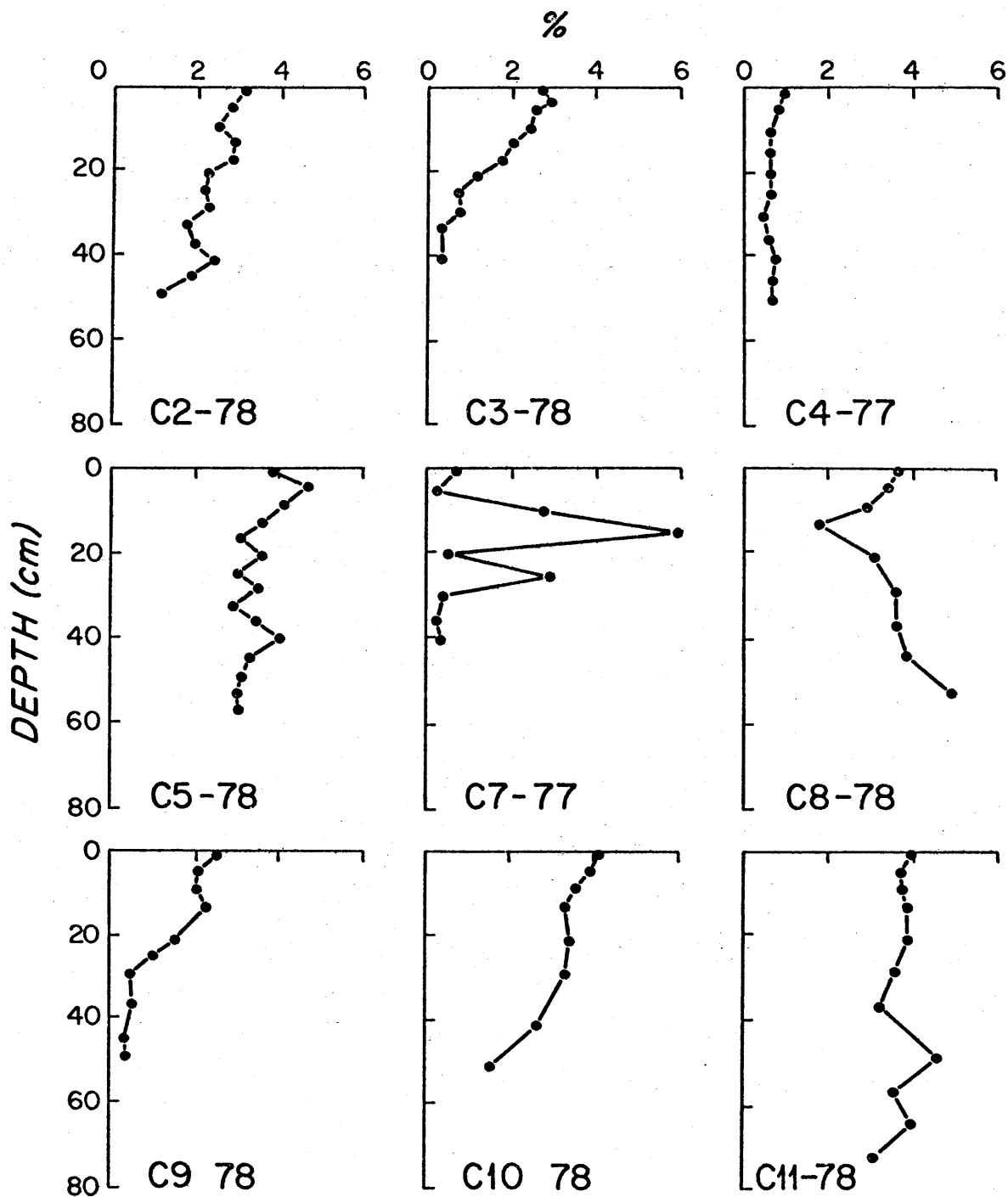
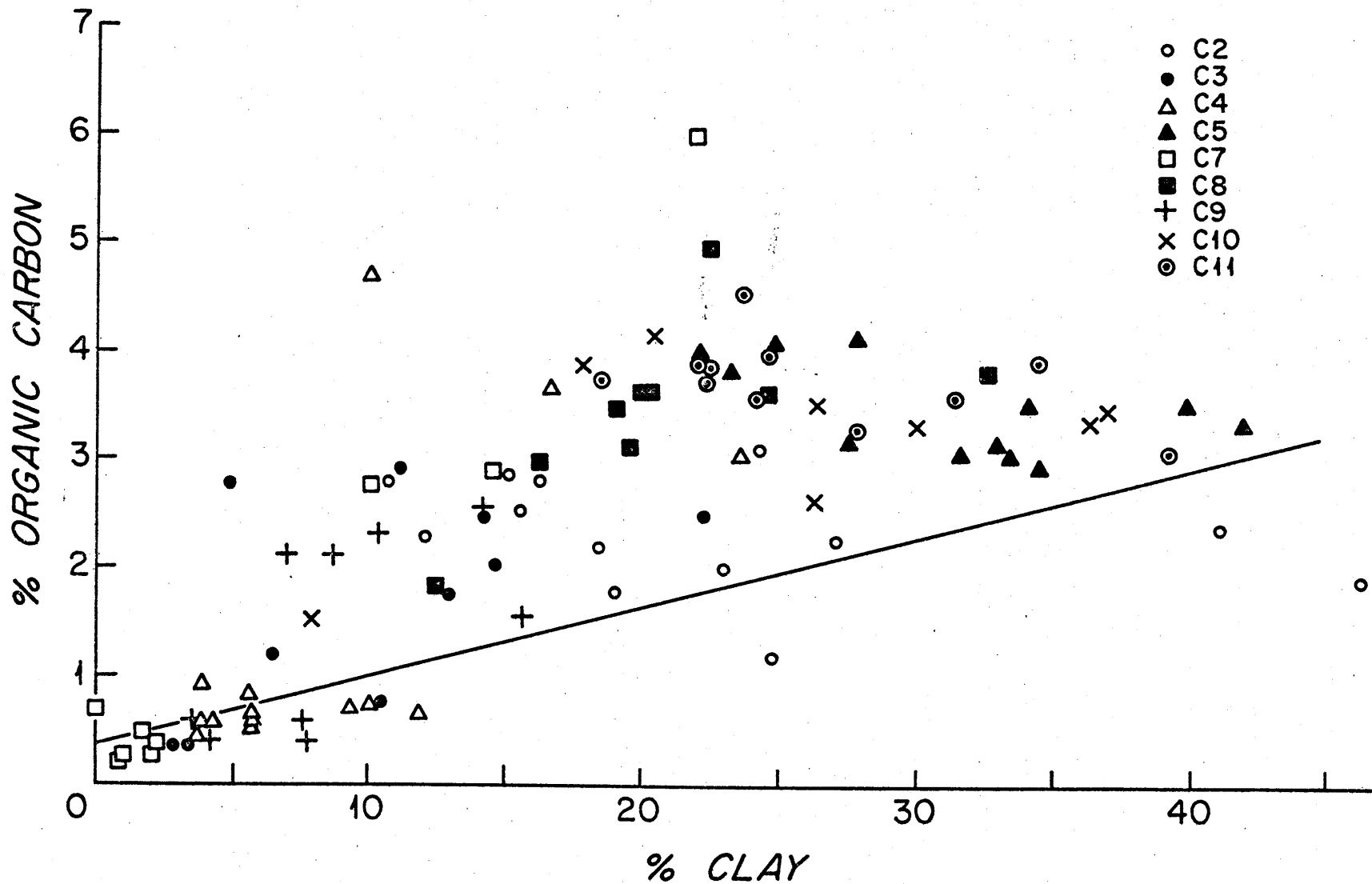


Figure 28. Organic carbon (%) vs. clay content (%) for cores C2-78, C3-78, C4-77, C5-78, C7-77, C9-78, C10-78, and C11-78. Line represents the carbon/clay relationship of grab samples from Massachusetts Bay (Figure 17).

% ORGANIC CARBON vs. % CLAY (in cores)



Trace metals show little down-core variation in C2 (Figure 29). Above 30 cm, there is a gradual increase in concentration for Cd, Cu, Mo, Pb, and Zn (and organic carbon), while the other metals maintain a relatively constant value. Note that White (1972) reported that several of these metals show considerable intercorrelation and an affinity for organic matter in the surface sediments.

In core 3 from Dorchester Bay, trace metals increase gradually in concentration above a depth of 38 cm (Figure 30). Silt, clay, and organic carbon show coincident increases.

Core 4 from Deer Island Flats shows a rapid increase in trace metal concentrations above 10 cm (Figure 31). Size analyses indicate that while the sediment is sandier near the surface (Figure 26), organic carbon content increases (Figure 27).

Trace metal concentrations decrease rapidly above 15 cm in core 5 (Figure 32). The large fluctuations evident throughout the core do not correlate with changes in size distribution or organic content, suggesting that some other factor (or factors) is responsible for the observed variation. In contrast core 7 (from the harbor approaches) shows large-scale variations in trace metal concentrations that are coincident with abrupt changes in size distribution and organic content (compare Figures 26, 27, and 33). Interpretation of these changes will be addressed in a later section.

Figure 29. Trace metal profiles for core C2-77.

C2-77

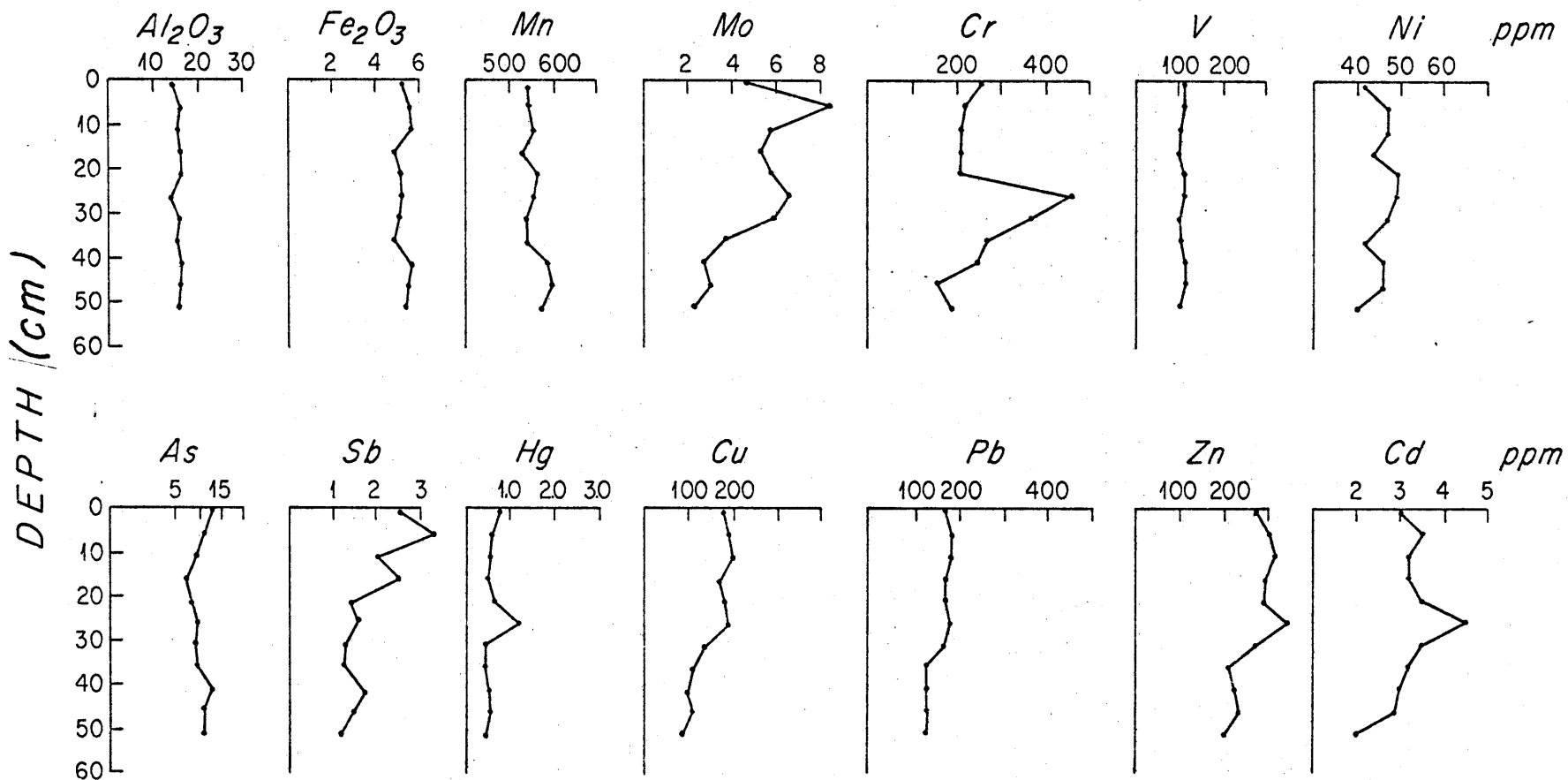


Figure 30. Trace metal profiles for core C3-77.



# BOSTON HARBOR C3-77 #1

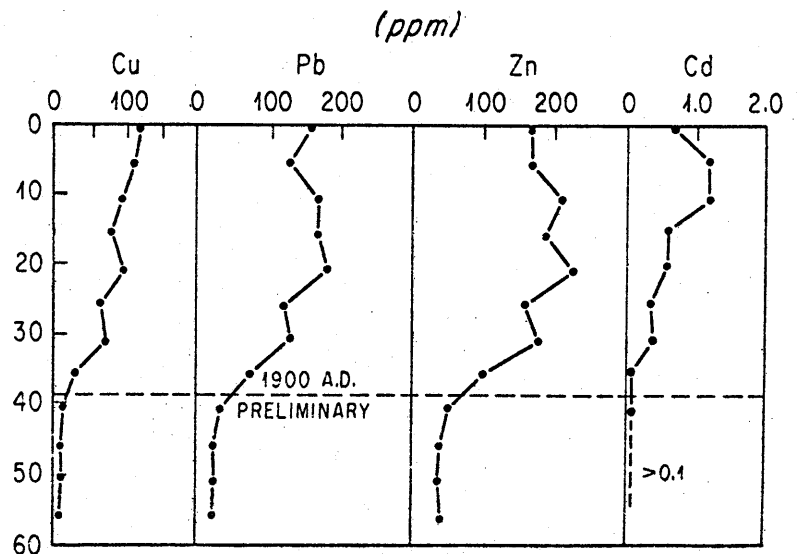
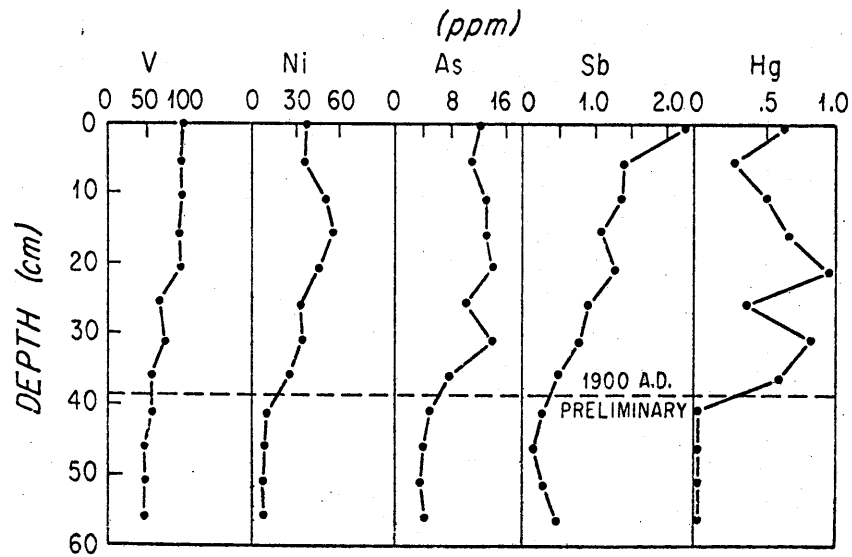
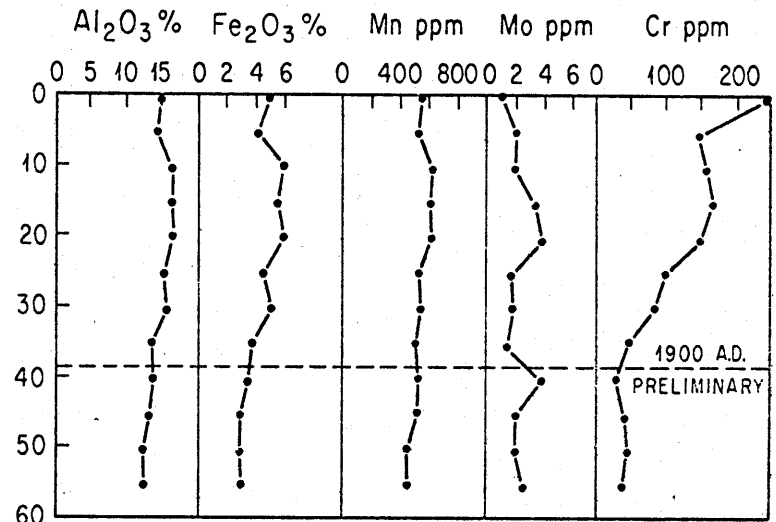
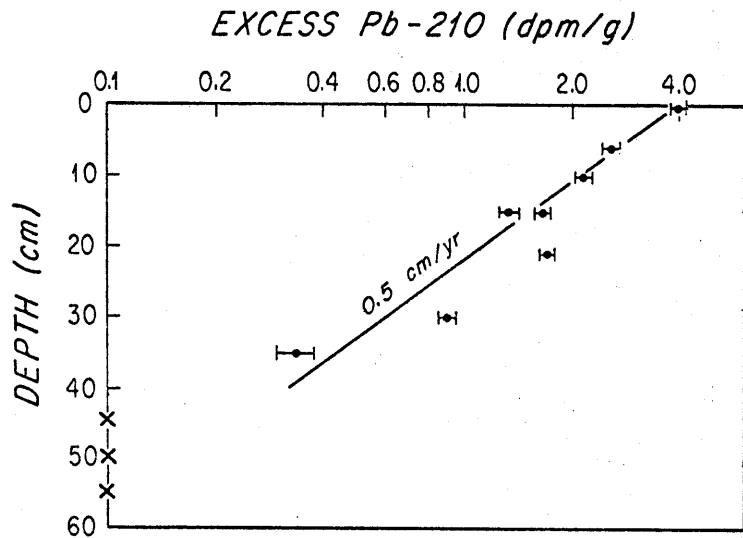


Figure 31. Trace metal profiles for core C4-77.

# BOSTON HARBOR C4-77 #2

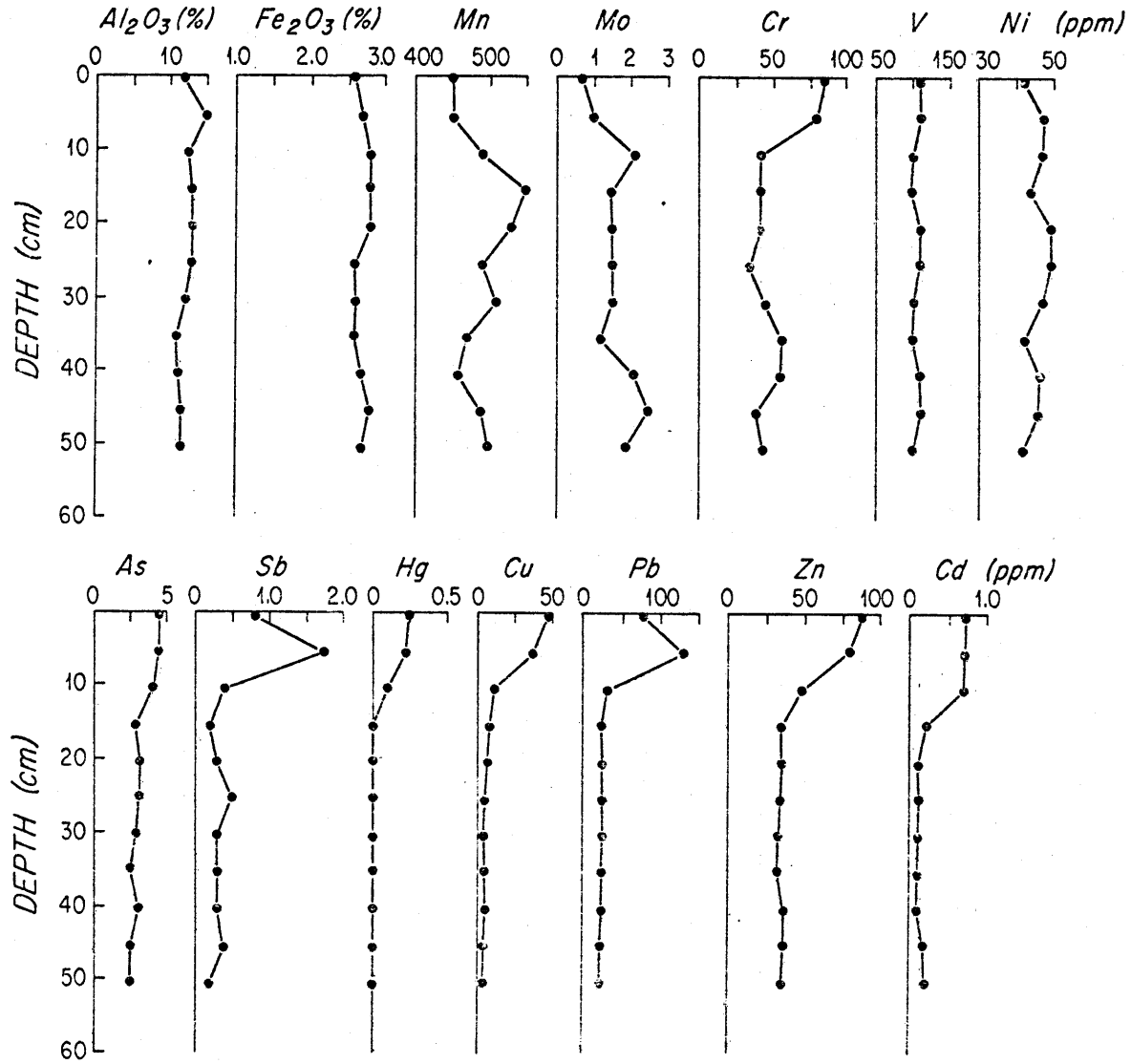


Figure 32. Trace metal profiles for core C5-77.

# BOSTON HARBOR C5-77#3

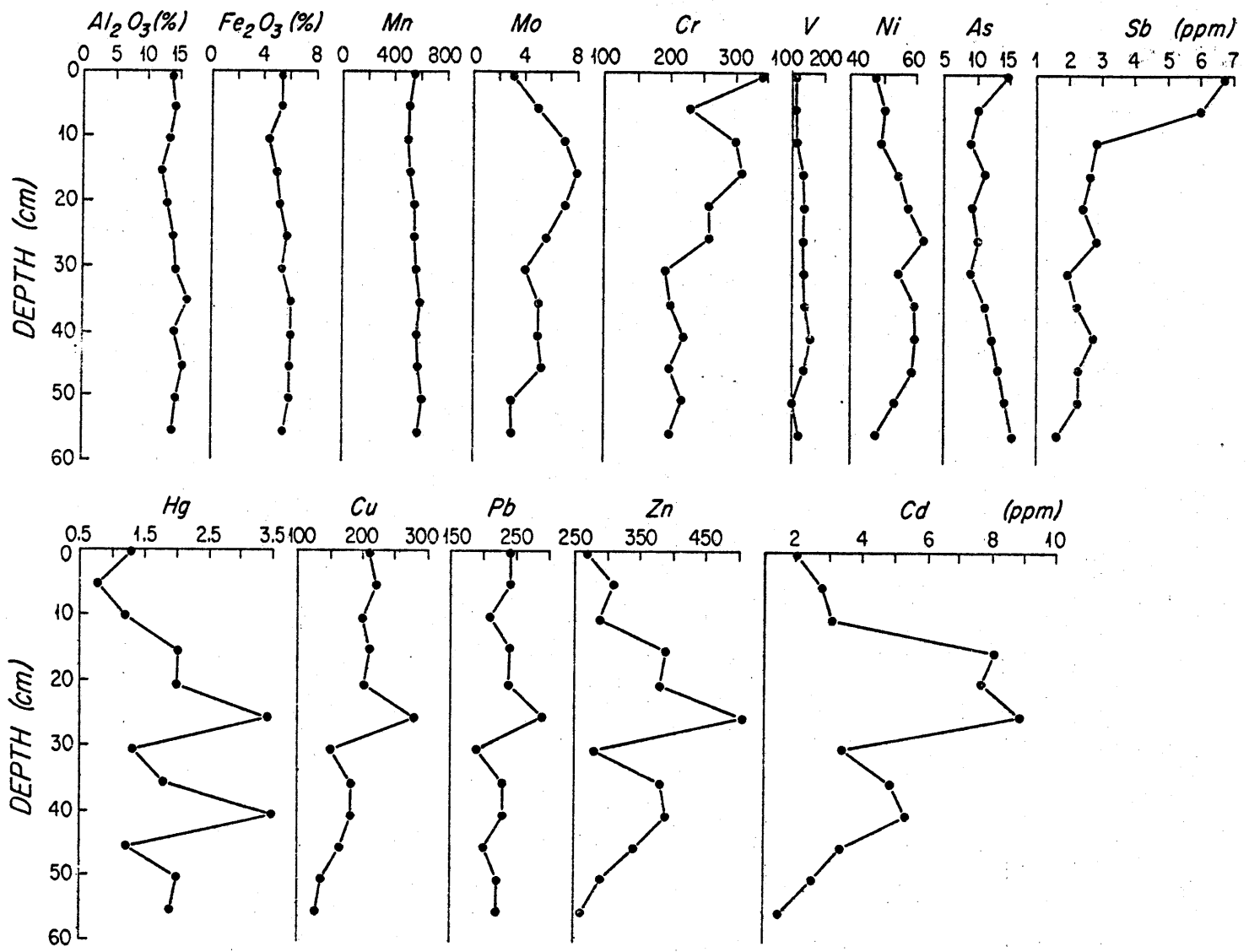
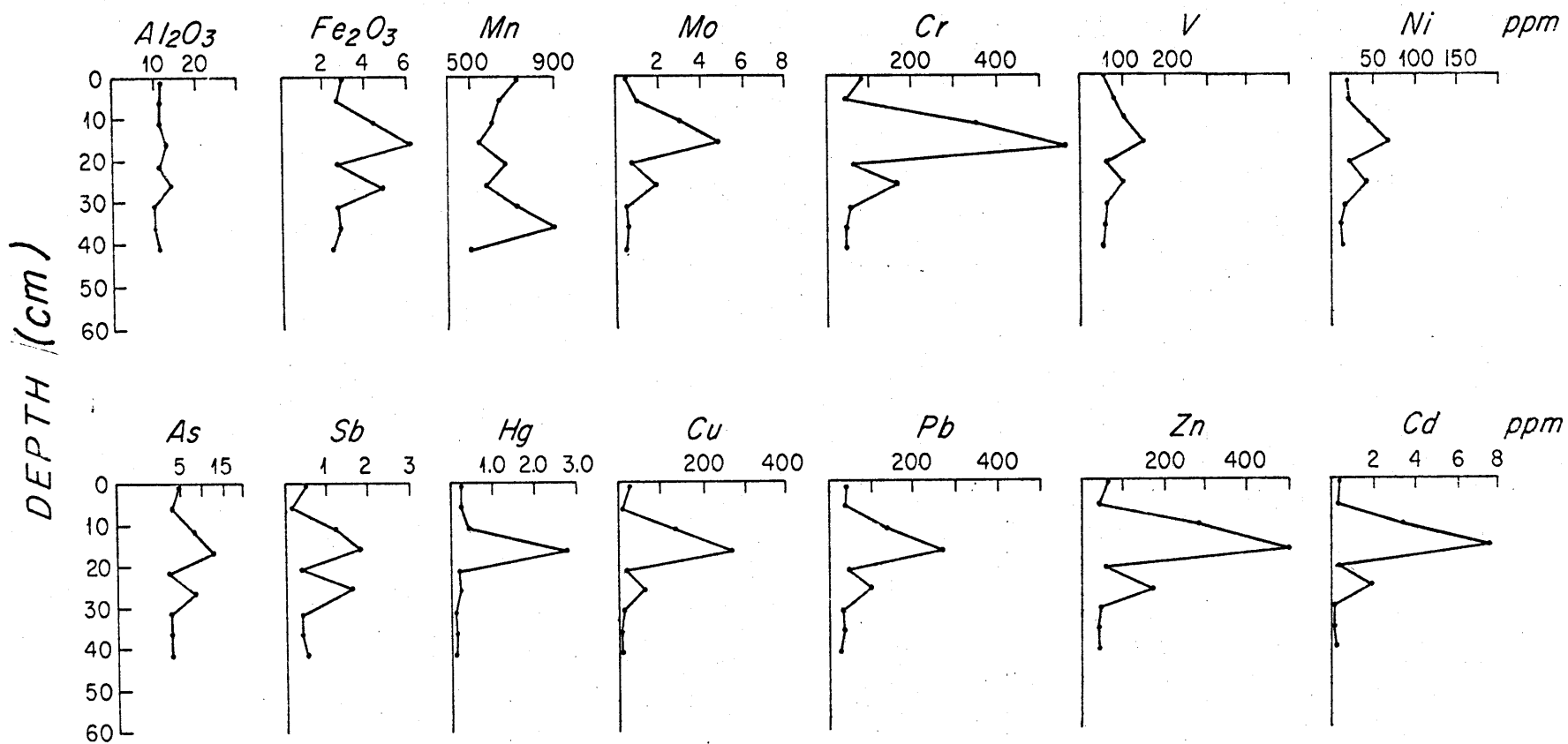


Figure 33. Trace metal profiles for core C7-77.

C7-77



The harbor is an efficient trap for organic-rich sediment and their associated pollutants. The increases in trace metal concentrations with time reflect man's continually increasing metal usage. In the highly contaminated sediments of the harbor and the slightly contaminated sediments of the harbor approaches, the order of metal enrichment is  $Cu > Cd > Pb > Cr > Zn$  (Table 7), similar to that found in New Bedford Harbor (Summerhayes et al., 1976). Whether this ordering reflects the anthropogenic uses of these metals over the past century or is a function of immobility in the sediments is unknown.

Co-variance among the metals in the sediment cores is similar to that identified in grab samples (Table 8). Factor analysis of this geochemical data objectively examines the relationships between variables. Table 9 lists the three factors extracted from the data (accounting for 87.9% of the variance) and presents the loadings that characterize these factors.

Factor I comprises a strong association among Ni, Zn, Pb, V, Cu,  $Fe_2O_3$ , organic carbon, silt, and clay -- similar to the principal factor identified for grab samples. The high loadings for organic carbon and  $Fe_2O_3$  suggest the importance of organic matter and iron oxides in the transport and retention of trace metals with depth in sediments. The effectiveness of organic matter and iron oxide in binding heavy metals is well established. Summerhayes et al. (1976) found that in New Bedford Harbor sediments, for example, 20 percent



Table 7. Surface enrichment of trace metals in cores C2, C3, C4, C5, and C7

Metal	Average Nearshore Sediment (a)	Mean Background Boston (b)	Mean Surface Boston (c)	Enrichment
Cd	--	0.1	1.6	x16
Cr	100	38	203	x5.3
Cu	48	7	119	x17
Pb	20	25	145	x5.8
Zn	95	42	176	x4.2

All values are in ppm. Source: (a) Wedepohl (1960).

(b) From core C3 (Figure 30)

(c) Averages for these cores

Table 8. Correlation matrix for core data (55 samples)

	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	Mn	Zn	V	Cr	Ni	Cu	Mo	Cd	Pb	As	Sb	Hg	Sd	Silt	Clay	D.C.
Al <sub>2</sub> O <sub>3</sub>	1.000	.746	-.142	.511	.536	.326	.659	.469	.423	.269	.569	.733	.385	.291	-.702	.667	.710	.532
Fe <sub>2</sub> O <sub>3</sub>	.746	1.000	.154	.894	.919	.738	.962	.841	.670	.683	.906	.928	.653	.717	-.908	.863	.918	.897
Mn	-.142	.154	1.000	.070	.167	.050	.088	.019	-.139	.027	.071	.084	-.036	.084	.087	-.119	.002	.013
Zn	.511	.894	.070	1.000	.950	.854	.955	.869	.810	.911	.954	.763	.684	.852	-.848	.829	.823	.943
V	.536	.919	.167	.950	1.000	.850	.963	.923	.743	.843	.927	.821	.675	.782	-.850	.817	.834	.932
Cr	.326	.738	.050	.854	.850	1.000	.813	.871	.663	.778	.806	.681	.621	.655	-.717	.690	.701	.863
Ni	.659	.962	.088	.955	.963	.813	1.000	.910	.759	.802	.948	.862	.666	.788	-.903	.868	.887	.935
Cu	.469	.841	.019	.969	.923	.871	.910	1.000	.825	.873	.944	.726	.786	.775	-.825	.809	.773	.957
Mo	.423	.670	-.139	.810	.743	.663	.759	.825	1.000	.792	.733	.512	.583	.601	-.744	.747	.654	.747
Cd	.269	.683	.027	.911	.843	.778	.802	.873	.792	1.000	.804	.506	.539	.822	-.691	.685	.628	.792
Pb	.569	.906	.071	.954	.927	.806	.948	.944	.733	.804	1.000	.836	.780	.834	-.840	.805	.834	.948
As	.733	.928	.084	.763	.821	.681	.862	.726	.512	.506	.836	1.000	.623	.624	-.809	.750	.864	.829
Sb	.385	.653	-.036	.684	.675	.621	.666	.786	.583	.539	.780	.623	1.000	.528	-.663	.657	.602	.790
Hg	.291	.717	.084	.852	.782	.655	.788	.775	.601	.822	.834	.624	.528	1.000	-.667	.636	.670	.770
Sand	-.702	-.908	.087	-.848	-.850	-.717	-.903	-.825	-.744	-.691	-.840	-.809	-.663	-.667	1.000	-.987	-.917	-.870
Silt	.667	.863	-.119	.820	.817	.690	.868	.809	.747	.685	.805	.750	.657	.636	-.987	1.000	.843	.848
Clay	.710	.918	.002	.823	.834	.701	.887	.773	.654	.628	.834	.864	.602	.670	-.917	.843	1.000	.825
D.C.	.532	.897	.013	.943	.932	.863	.935	.957	.747	.792	.948	.829	.790	.770	-.870	.848	.825	1.000

Table 9. Principal factors identified from the geochemical data of cores showing:

(1) percentage of variance explained by each factor,

(2) factor loadings within each factor ( ).

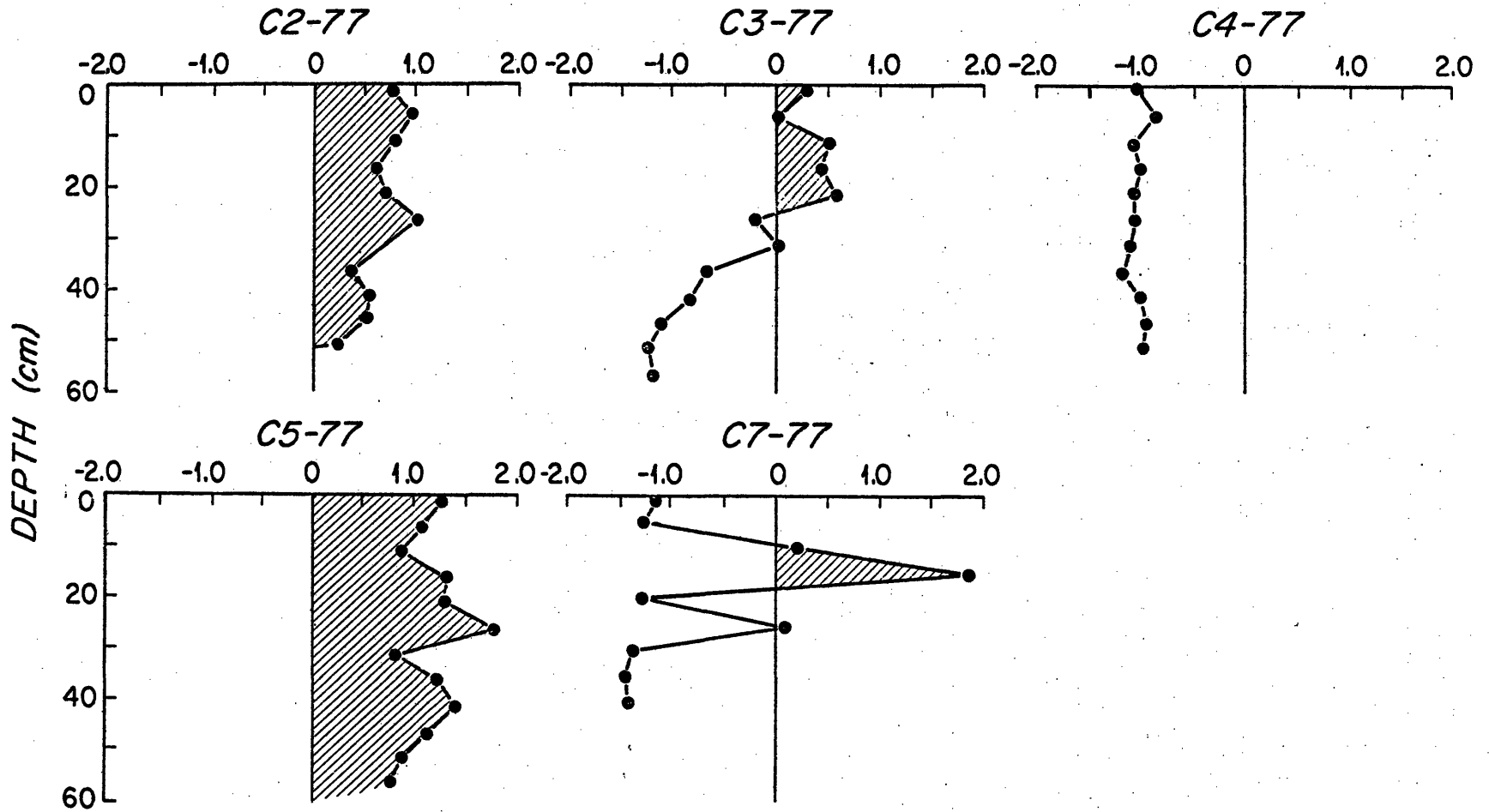
FACTOR I	FACTOR II	FACTOR III
74.2%	7.7%	6.3%
Ni (.980)	Mn (.466)	Mo (.348)
Zn (.972)	Cd (.398)	Mn (-.845)
Organic carbon (.967)	Al <sub>2</sub> O <sub>3</sub> (-.683)	
Pb (.966)		
V (.961)		
Cu (.954)		
Fe (.949)		
% SILT (.898)		
% CLAY (.989)		
% SAND (-.928)		

of the Cu and Zn was adsorbed onto organic and inorganic particles while another 20% formed organo-metallic complexes. In addition, Aston and Chester (1976) note that iron oxides are efficient scavengers of trace metals in the nearshore environment.

Down-core we find that positive scores for factor I dominate the organic-rich muds (compare Figs. 27 and 34); negative scores occur in the sandy sediments of cores 4 and 7 and at the base of core 3. These differences may represent differences in the sedimentary regime (and contamination) both laterally and through time -- these differences related to changes in organic matter input.

Figure 34. Profiles of Factor I for cores C2-77, C3-77, C4-77, C5-77, and C7-77.

DOWN-CORE VARIATIONS IN FACTOR I



### c. Sedimentation Rates

The broad areas of clean gravel which cover much of Massachusetts Bay (Figure 14) suggest that sediment accumulation over much of the bay has been negligible since glacial times. Rates are likely to be low on topographic highs and in the narrow channels scoured by tidal currents. Cores in the deep water east of The Graves (Bumpus et al., 1953) show 60 cm of sediment overlying the Boston Blue Clay. Following a period of subaerial exposure, this clay was submerged about 10,000 years B.P. (Kaye and Barghoorn, 1964), which translates into an average sedimentation rate of 0.006 cm/yr. Butcher (1951) calculated a rate of 1.2 cm/yr at the end of the President Roads shipping channel but concluded that this was probably a maximum rate for the approaches. Probably all gradations exist between the fastest and slowest rates mentioned depending upon the location within Massachusetts Bay, but for the most part, the sedimentation rate is likely to be low, perhaps on the order of 0.006 cm/yr.

Rates within the harbor proper are significantly higher than those estimated for the harbor approaches. Two cores (PC2 and PC11) penetrate the Boston Blue Clay in the harbor. Again using 10,000 years B.P. as the time of the clay's submergence, we arrive at rates of 0.014 cm/yr at PC2 and 0.016 cm/yr at

PC11. (Refer to Figure 12 for core sites.) These rates probably represent a minimum Holocene sedimentation rate in the harbor. This blue clay has been encountered at depths up to 10 m (Bumpus et al., 1951), giving an estimated maximum rate of 0.1 cm/yr.<sup>2</sup>

Radiometric methods ( $^{210}\text{Pb}$ ) were used to measure modern rates of sedimentation (over the last 150 years) from 9 sites in the harbor (Figure 35). Cores about 1 m in length were taken using a hydrostatic corer, which preserves the sediment/water interface (see Appendix I). After subsampling, the cores were analyzed for  $^{210}\text{Po}$  using the technique of Flynn (1968). The assumption of secular equilibrium between  $^{210}\text{Pb}$  and its granddaughter  $^{210}\text{Po}$  appears valid for coastal areas (Benninger et al., 1979; Nittrouer et al., 1979). The calculation of sedimentation rate from the profile of  $^{210}\text{Pb}$  is at present based on a level of supported  $^{210}\text{Pb}$  estimated from the  $^{210}\text{Pb}$  profiles. More accurate estimates of supported  $^{210}\text{Pb}$  levels will be made when  $^{226}\text{Ra}$  analyses are completed (see Bothner et al., 1980).

Bioturbation of the sediments creates a second limitation in estimating sedimentation rates from excess  $^{210}\text{Pb}$  profiles. The sediments in Boston Harbor are generally anoxic

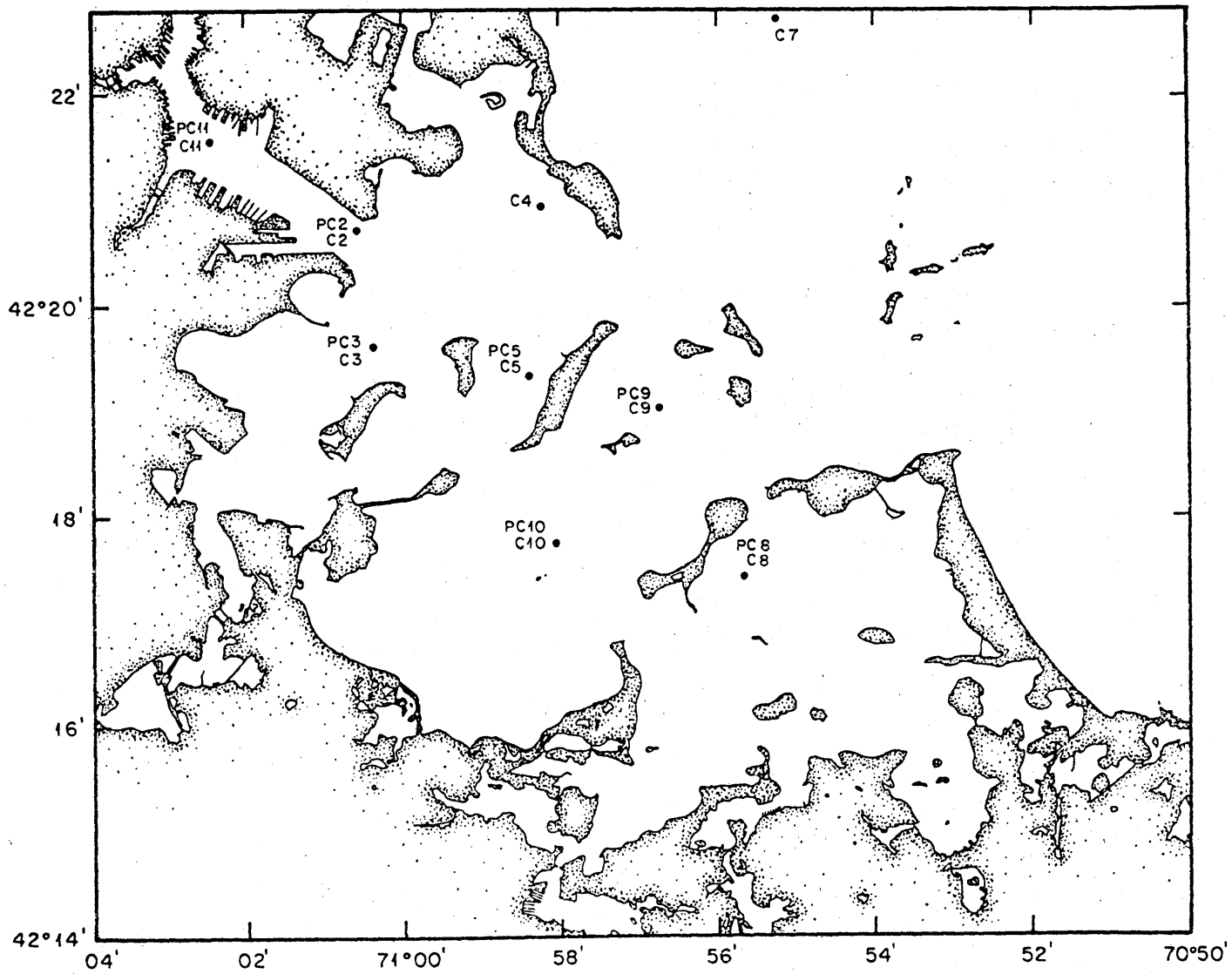
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<sup>2</sup>Unfortunately, the rough topography of the acoustic basement precludes the correlation of the blue clay between core sites, and thus the estimation of Holocene rates in these cores.



Figure 35. Cores selected for  $^{210}\text{Pb}$ -dating.  
Cores C2, C4, C5, and C7 were taken in  
1977. The remaining cores were  
collected in 1978.

CORES SELECTED FOR  $^{210}\text{Pb}$ -DATING



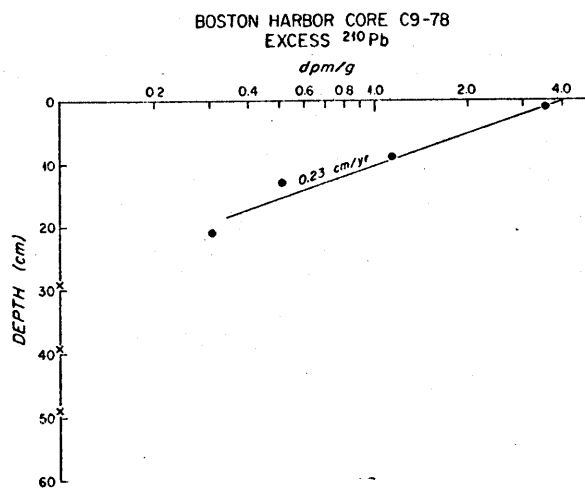
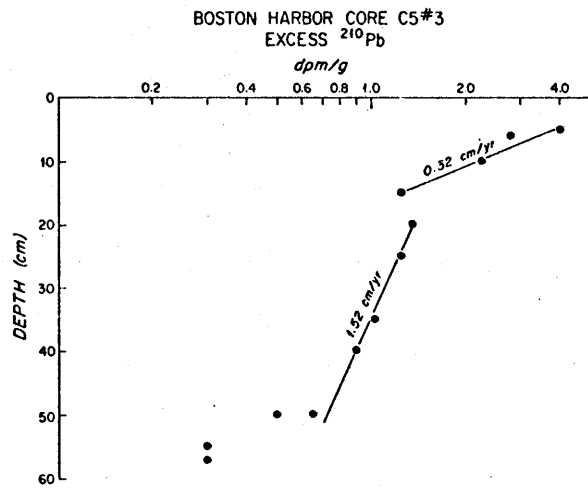
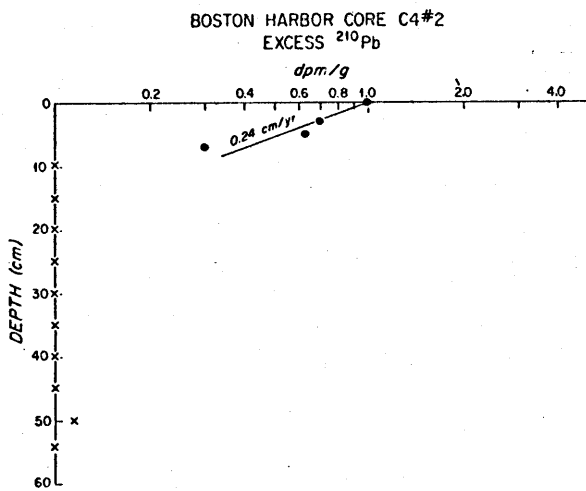
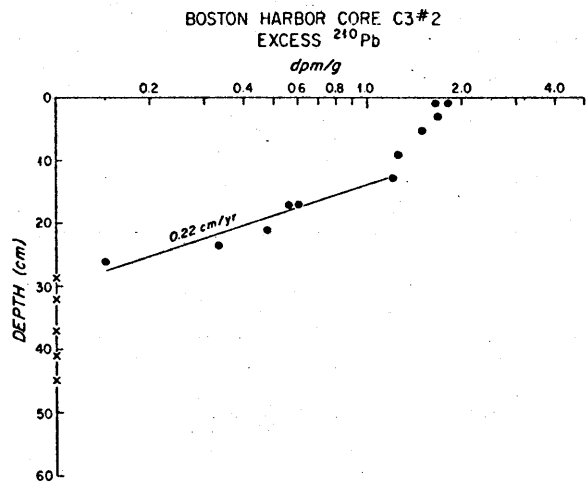
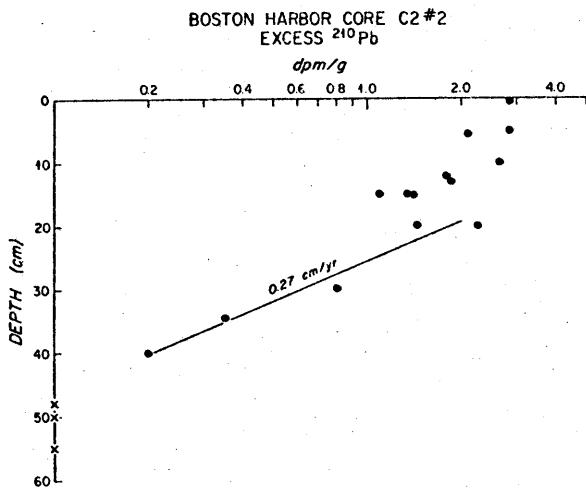
slightly below the surface but support a variety of organisms which are capable of sediment mixing. The effect of this mixing is to transport young sediment downward and old sediment upward, making the apparent  $^{210}\text{Pb}$  sedimentation rate too fast. Our preliminary estimates of accumulation rate are thus upper limits. Analyses of  $^{137}\text{Cs}$  (in progress) will hopefully resolve the issue of mixing. First occurrence of  $^{137}\text{Cs}$  at a sediment age of 1953 will indicate the absence of significant mixing (Smith and Walton, 1980).

The sedimentation rate calculated from the excess  $^{210}\text{Pb}$  profile for C2 is approximately 0.27 cm/yr (Figure 36). For comparison, the U.S. Army Corps of Engineers calculated an accumulation rate of 0.2 cm/yr for the Inner Harbor based on the volume of material collected between two dredging operations (1934 and 1950).

Rates in some sections of the Inner Harbor may be significantly higher due to the input of storm-sewer overflows. For instance, divers report a mound of waste some 2 meters high near the combined sewer under the New England Aquarium. The sedimentation rate calculated from the excess  $^{210}\text{Pb}$  profile for core 11 is 0.40 cm/yr which is significantly higher than rate at C2.

Core 3 from Dorchester Bay shows a rate of 0.22 cm/yr (Figure 36). The profile suggests that the upper 10 cm of the core form a mixed zone. The "Blizzard of '78" struck the

Figure 36. Profile of excess  $^{210}\text{Pb}$  for C2-77, C4-77, C3-78, C5-77, and C9-78. X's indicate samples assumed to have background levels of  $^{210}\text{Pb}$ .



Boston area prior to coring and may be responsible for this mixing. In fact, a core taken at this location a year earlier (Figure 30) does not show this shallow mixed zone.

The modern sedimentation rate measured at C4 in Deer Island Flats is 0.24 cm/yr (Figure 36). Assuming no sediment mixing, the 10 cm horizon in this core -- which defines the bottom of the sediment layer containing elevated trace metal concentrations -- corresponds to 1937, very close to the closing of Shirley Gut in 1936 (Figure 2). The close correspondence of the historical and sediment record suggests a possible change in sedimentary patterns due to the alteration of harbor configuration.

Core 5, between Spectacle Island and Long Island, is in an area of high organic and mud content (Figures 13 and 16). The excess  $^{210}\text{Pb}$  profile for this core indicates a change in sedimentation rate at about 15 cm (Figure 36). Below 15 cm, the rate is 1.52 cm/yr. Above this depth, the rate is about 0.32 cm/yr, a five-fold decrease, but very close to the modern rates estimated in other harbor cores.

The  $^{210}\text{Pb}$  profile for core 7 taken east of Deer Island shows erratic down-core variations. This is probably related to the highly variable texture in this core, which precludes the simple application of  $^{210}\text{Pb}$  for sedimentation rate estimates. The profile for core 8 in Hingham Bay is nearly vertical, which suggests that deposition of this sediment was

instantaneous. Uniform profiles have been found in dredge spoil dump sites in other harbors, though we have no knowledge of dumping in this area.

Sedimentation rates measured on cores 9 and 10 are .23 cm/yr (Figure 36) and 0.13 cm/yr, respectively. Both rates are close to those calculated for other cores in the harbor. The somewhat lower rate for core 10 is possibly the consequence of the more exposed location of the core site in Quincy Bay.

Several aspects of these data are significant (Table 10): the modern rate of sedimentation, over most of the harbor, averages about 0.2 to 0.3 cm/year; this rate is an appreciably higher than the estimated Holocene average, implying that the harbor is effectively trapping modern sediments; and the closing of Shirley Gut, north of Deer Island, in 1936 may have significantly altered depositional patterns in some areas of the harbor. Further analyses are needed to assess the importance of bioturbation (which could seriously affect calculated rates). These calculations, however, do provide us with a working model for estimating relative magnitudes of sedimentation in the harbor and its approaches.

TABLE 10. Summary of Sedimentation Rates

CORE	SEDIMENT COVER (m)	HOLOGENE RATE* (cm/yr)	PRELIMINARY MODERN RATE ( $^{210}\text{PB}$ ) (cm/yr)
2	25	.014	.27
3	30	--	.50
4	10	--	.24
5	30	--	.32
8	27	--	-
9	30	--	.23
10	17	--	.13
11	-	.016	.40

\*Based on Pleistocene Blue Clay (10000 yrs B.P.). These rates probably represent a minimum (see text). Maximum rate is estimated to be 0.10 cm/yr.



#### d. Interpretation

Large-scale changes in pollutant accumulation are attributable to several factors: changes in pollutant input, changes in circulation, and changes in sediment sources. In addition, post-depositional mobility of some metals may be influenced by the chemical environment which characterizes the sediment. In interpreting the pollution history of Boston Harbor as outlined by the trace metal profiles, two events appear to have had significant impact -- the initiation of sewage disposal at Moon Island in the 1890's (input) and the closing of Shirley Gut (Figure 1) in 1936 (circulation).

In core 3 from Dorchester Bay, trace metals, clay content, and organic carbon increase in concentration above a depth of 38 cm. Using 0.50 cm/yr (the rate measured on this core) as the sedimentation rate, this depth corresponds to the year 1900 -- in close agreement with the opening of the Moon Island plant. These increases likely reflect its influence.

As stated earlier, near-surface increases in trace metal concentrations in core 4 are coincident with the closing of Shirley Gut. This change in harbor configuration (and circulation) appears to have altered the sedimentary patterns over a broader area. Abrupt decreases in sedimentation rate and trace metal content occur at a depth of 15 cm in core 5 near Long Island. With a sedimentation rate of 0.32 cm/yr, this depth corresponds to the year 1932 -- suggesting possible

correlation with the closing of Shirley Gut in 1936. Note that positive scores for factor I in core 3 (Figure 35) occur above a depth of 20 cm (i.e., 1937), implying a change in sediment characteristics.

e. Trapping Efficiency

Knowledge of the areal distribution of trace metals, their input rate, and their accumulation rate enables one to make a geochemical budget for the area, and thereby estimate the trapping efficiency of the outer harbor. Because of the many assumptions, this estimate is rough, but it can serve as a starting point for discussing the capacity of the outer harbor to retain sediment and the associated pollutants.

Estimates of input rates were obtained by examination of Metropolitan District Commission (MDC) records (Table 11). Measurements of trace metals in both the sludge and effluent are infrequent and, therefore, only four records were available for the last two years. To eliminate problems with variations in input, differences in dispersal paths, and modes of transport, a suite of four metals was selected (Cd + Cu + Ni + Zn) -- all of which display an affinity for organic-rich particulates (Aston and Chester, 1976). The average yearly input of these metals (from discharge records) is  $5.08 \times 10^5$  kg.

The area of northeastern Dorchester Bay, Moon Island, and northern Quincy Bay appears to be the region most impacted by sewage discharge on the basis of trace metal and organic carbon concentrations. As stated earlier, Deer Island Flats (Winthrop Harbor), appears influenced by discharge from the Inner Harbor and is, therefore, excluded. Harbor circulation (see Chapter 3) and the discharge of Nut Island sludge near Deer Island (Figure. 1) preclude much of Quincy Bay, Nantasket Roads, and Hingham Bay as major depositories of these trace metals. The 50 percent mud isoline (Figure 13) is chosen to outline the major depocenter of trace metals in the outer harbor, encompassing approximately  $16.8 \text{ km}^2$ . Assuming that 40 percent of the mud consists of solid material with a density of  $2.65 \text{ gm/cm}^3$  and that the average concentration of Cd + Cu + Ni + Zn in these sediments is 470 ppm (as measured in grab samples), we can calculate the metal content in the top 1 cm of sediment:

$$\text{METAL CONTENT} = \text{AREA} \times \text{THICKNESS} \times \text{DENSITY} \times \text{CONCENTRATION}$$

$$\times (1 - \text{WATER CONTENT})$$

$$\underline{837000} \text{ kg} = 16.8 \times 10^{11} \text{ cm}^2 \times 1 \text{ cm} \times 2.65 \frac{\text{gm}}{\text{cm}^3} \times 470 \text{ ppm} \times .4 \frac{\text{cm}^3 \text{ dry sed.}}{\text{cm}^3 \text{ wet sed.}}$$

The sedimentation rate for the area ranges from 0.2 - 0.3 cm/yr. Thus, 1 cm represents a maximum of 5 years of accumulation. Dividing our estimated metal reserve by the 5-year input of these metals (Table 11), we arrive at an estimated trapping efficiency of 33%. The limited area

Table 11.

Input of trace metals (Cd+Cu+Ni+Zn) into Boston Harbor by the Deer Island Treatment Plant (including the Nut Island sludge).

DATE	EFFLUENT			SLUDGE			TOTAL METAL INPUT* (kg/DAY)
	Average Daily Discharge (x10 <sup>9</sup> ℓ)	Metal Concentration (mg/ℓ)	Metal Input (kg/DAY)	Metal Discharge (x10 <sup>6</sup> ℓ)	Metal Concentration (mg/ℓ)	Metal Input (kg/DAY)	
Aug., 1977	1.08	1.42	1534	1.37	100.3	137	1740
Nov., 1977	1.26	1.13	1424	1.30	27.3	36	1478
Feb., 1979	1.23	0.92	1132	0.82	42.2	35	1184
Sep., 1979	1.05	0.94	987	1.29	92.65	120	1167

Source: Metropolitan District Commission (MDC), Deer Island Plant Flow Records (Analyses by MDC Lab)

\*Inputs include Nut Island sludge estimated to be 50% of the Deer Island sludge load

AVERAGE INPUT = 1392 kg per day

YEARLY INPUT = 50.8 x 10<sup>4</sup> kg

FIVE-YEAR INPUT = 25.4 x 10<sup>5</sup> kg

considered and the effect of sediment mixing in reducing the surface concentrations of trace metals would make this trapping estimate too low. This error may be partially balanced; if mixing takes place, sedimentation rates are too high, overestimating the trapping.

The deposition of the digested sludge solids from the MDC treatment facilities in the harbor was estimated by Hydrosience (DiToro et al., 1973), using a two-dimensional model which incorporates the vertical settling velocity of solids, the longitudinal tidal velocity, and dispersive mixing, but excludes scouring. The proportion of discharged solids that eventually settle into Boston Harbor west of Deer Island was estimated at 15% to 20% of the total mass of solids released with the effluent (which is pumped continually), but the model ignored the possibility of resuspension and transport inshore. Nonetheless, in view of considering the assumptions involved, these two estimates are close.

If a similar budget calculation is made for lead (average input of 212 kg per day), we obtain a trapping efficiency of 96%. Measurements of dissolved and particulate trace metal concentrations in Boston Harbor waters (New England Aquarium, 1972) show that Pb possesses a much greater affinity for particulates than either Cd, Cu, Ni, or Zn, which may account for some of this discrepancy. In addition, the order of

stability for metallo-humic complexes is  $Pb^{+2} > Ni^{+2} > Zn^{+2} > Cd^{+2}$  (Schnitzer and Kahn, 1972), suggesting the enhanced ability of the organic-rich sediments to bind Pb.

However, the major contributor of lead to the harbor is most likely atmospheric industrial lead pollution, arising from incinerators and automobiles. Chow and Earl (1969) and Lazrus et al. (1970) found an average of 40 micro-grams Pb per kg of rain in cities. Using this figure and 40 inches as the average yearly rainfall in Boston, we can account for an additional 5-year input of 61,000 kg of Pb to the outer harbor of 16% of the calculated lead reserve in the bottom sediments from rain alone. The remainder is probably input into the harbor through land runoff. Lead input from lead-based boat paint is likely a minor contributor. The atmospheric input of other trace metals appears insignificant by comparison. (Atmospheric fallout of Cu, for example, is approximately  $0.5 \mu\text{g}/\text{cm}^2/\text{yr}$  (Bruland et al., 1974), or only 750 kg of Cu supplied to the outer harbor over a five-year period.)

According to MDC figures, the average output of solid material (from both sludge and effluent) is 200,000 kg per day. Using 33% as the trapping efficiency of the outer harbor,  $24.1 \times 10^6$  kg per year of sewage collects in the harbor. If we assume a water content of 60% ( $0.5 \text{ gm}^{\text{dry sed}}/\text{cm}^3_{\text{wet sed}}$ ), we can calculate a sedimentation rate for the area:

$$\begin{aligned}
 \text{RATE} &= \text{INPUT} \times (\text{AREA})^{-1} \times (\text{DENSITY})^{-1} \\
 &= 24.1 \times 10^6 \frac{\text{kg}}{\text{yr}} \times (16.8 \times 10^{11} \text{cm}^2)^{-1} \\
 &\quad \times (.0005 \text{kg}^{\text{dry sed}} / \text{cm}^3_{\text{wet sed}})^{-1}
 \end{aligned}$$

$$\text{RATE} = 0.029 \text{ cm/yr}$$

The measured (estimated) sedimentation rate for the area is between 0.2 and 0.3 cm/yr. Such a discrepancy might imply an underestimate of the trapping efficiency, or suggest the importance of material resuspended and redistributed in the harbor (as well as shoreline erosion).

## Chapter 3

VI. Suspended Sediments and Water Quality

In order to examine the pattern of sediment movement through the water column, a field program was conducted to determine water-mass properties in the harbor, the composition and tidal variability of suspended particles, the development of the Deer Island sludge plume, and the nature of particulates captured in sediment traps, and we compared these data to the character and distribution of the bottom sediments themselves.

## a. Circulation

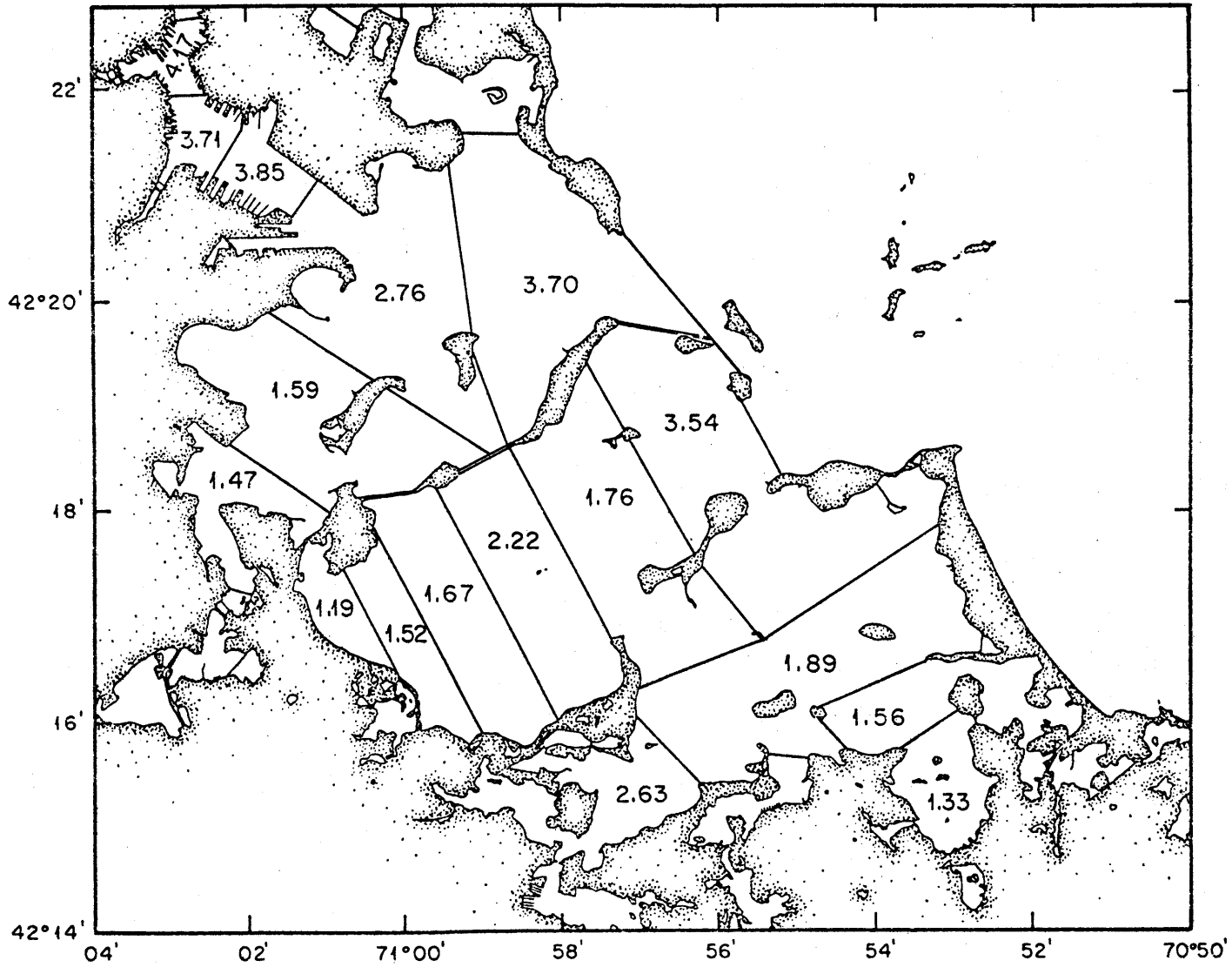
Any pollutant, whether dissolved or freely suspended in the water, is distributed landward and seaward of the outfall location by tidal circulation. Thus, a knowledge of harbor circulation is critical to the understanding of waste dispersal and the distribution of these wastes in the bottom sediments.

In accordance with the tidal flushing concept, Ketchum (1951) subdivided Boston Harbor into tidal excursion segments (Figure 37). Each segment is defined such that the volume it contains at high tide is equal to the volume of the tidal prism which enters through the seaward boundary on the flooding tide. If this entering water were to act as a piston, displacing landward the low tide water, the distance



Figure 37. Tidal excursion segments defined by Ketchum (1951). Numbers refer to accumulation factor, or flushing time (in number of tides), for each segment.

BOSTON HARBOR TIDAL EXCURSION SEGMENTS  
AND ACCUMULATION FACTORS



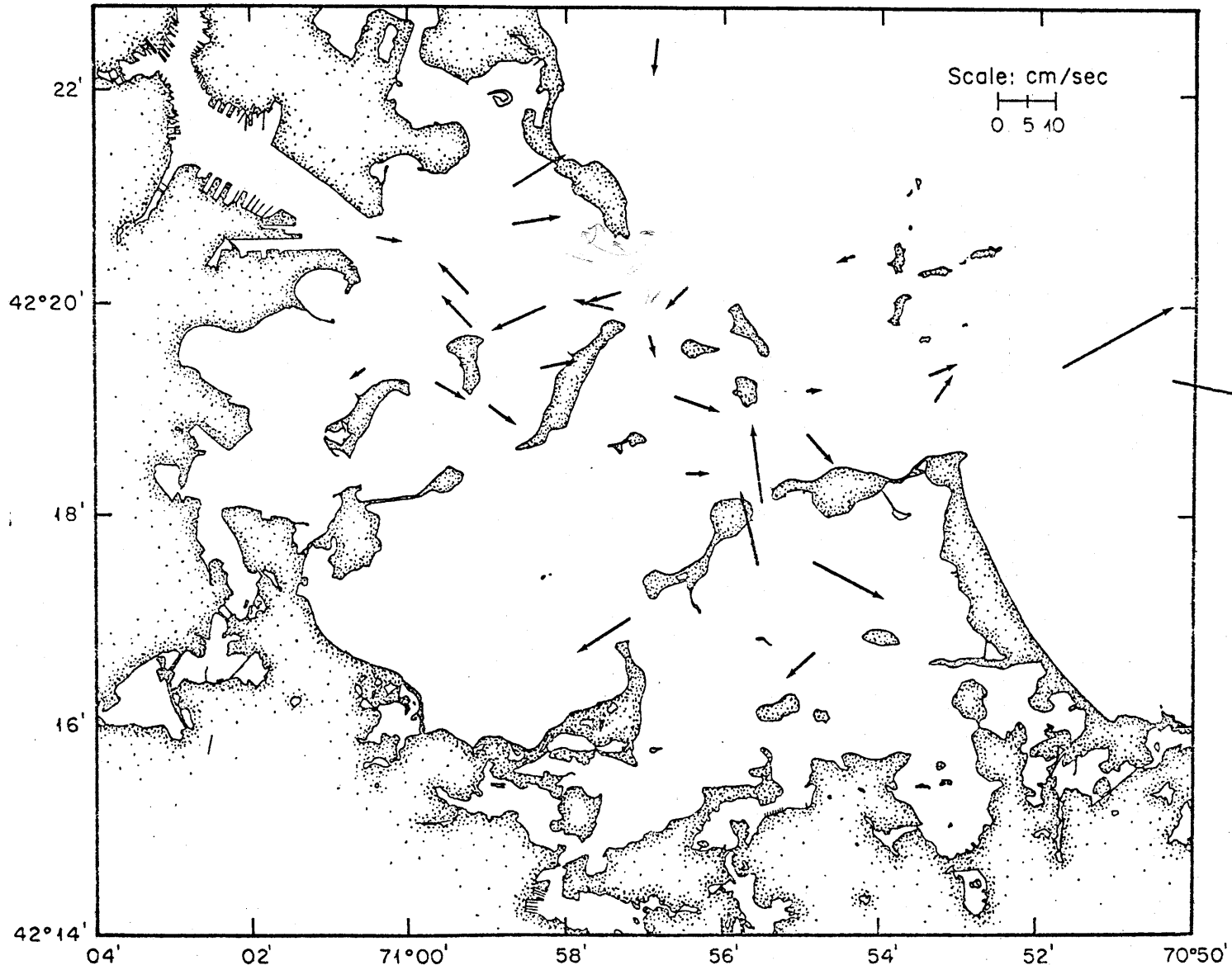
traveled would equal the average excursion on the flood tide. The low tide water displaced equals the volume of the tidal prism for the remainder of the estuary and fills the adjacent landward segment at high tide. Thus, the low tide volume of each segment equals the high tide volume of the adjacent landward segment. With each segment so defined, the intertidal volume is equal to the volume of water which permanently escapes on each tide (assuming complete mixing at high tide). This "escaping volume" is the water available for the dilution of pollutants introduced during a tidal cycle. For each segment, Ketchum (1951) calculated the exchange ratio (proportion of any material removed during a complete tidal cycle) and the accumulation factor (or the length of time required for a pollutant to move through the segment).

The Inner Harbor segments and that segment near the Deer Island outfall are characterized by long flushing times (Figure 37), which increase the potential for biological interaction and settling. These long flushing times, thus, may explain the restricted extent and influence of the outfall plume and Inner Harbor discharge noted in a later section.

In 1971 the National Oceanic and Atmospheric Administration (NOAA), utilizing a number of recording current meters, conducted a survey of harbor currents. Though the time scales of water movement (transient events, seasonality, etc.) are

Figure 38. Nontidal component of current meter record (averaged over an integral number of tidal cycles) at several harbor locations. Note general counterclockwise circulation. Data supplied by NOAA/Circulatory Surveys Branch.

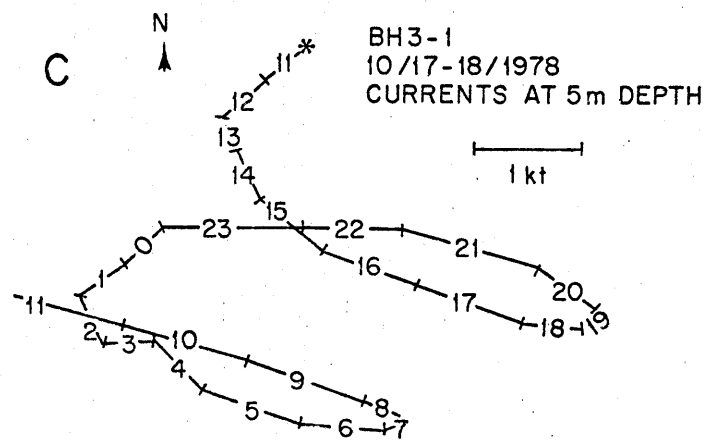
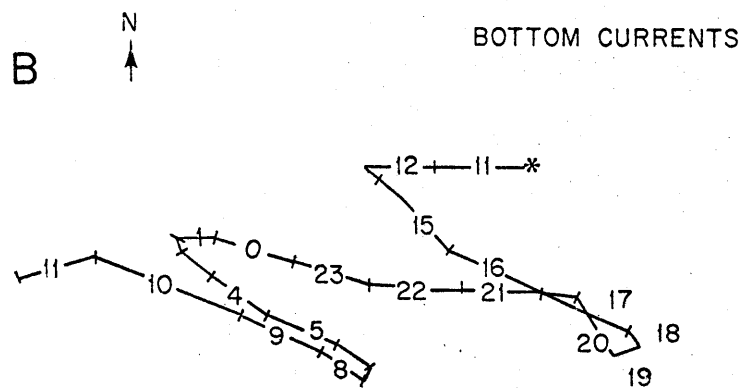
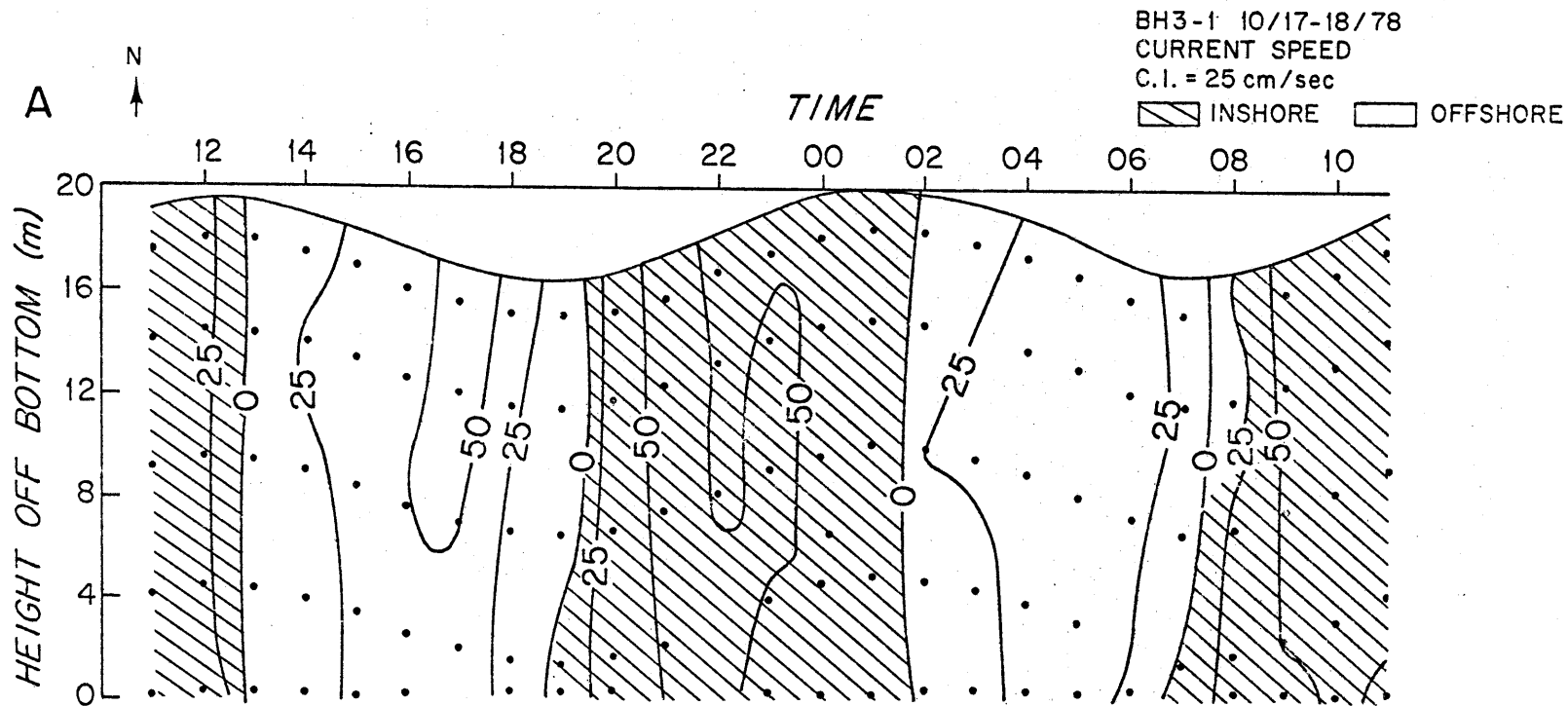
NONTIDAL COMPONENT OF CURRENT METER DATA (3m Depth)



poorly defined by these data, analyses of some of these records suggest dominant features in harbor circulation (Figure 38). Measurements display a general counterclockwise circulation, with water entering through President Roads, travelling landward and southward between the harbor islands, and finally leaving through Nantasket Roads. (Note: These data also may include errors due to meter drift and inaccuracy. Further processing is underway to lend more confidence to these data.)

Direct-reading current meters (ENDECO type 110), used during several cruises at stations BH1 and BH3 (Figure 41) provide records consistent with some aspects of the water movement described. Current measurements show a net landward displacement of water at Deer Island over two tidal cycles (Figure 39). In response to the strong NW winds associated with the major storm in February 1979, the near-surface waters did show a net seaward displacement, but bottom waters still moved landward. Recording current meter measurements near Deer Island, made for the Metropolitan District Commission (MDC) during the summer of 1979, also reveal a prominent landward movement (unpublished MDC report). At BH1 both near-surface and bottom measurements show a net seaward displacement. Near-surface waters were displaced northward into Deer Island Flats, while near-bottom movement was to the southeast.

- Figure 39.
- A. Tidal variations of current speed at station BH3 (in the shipping channel near Deer Island), October, 1978.
  - B. Progressive vector diagram of near-bottom currents (measured hourly with a direct reading ENDECO current meter).
  - C. Progressive vector diagram of surface currents.





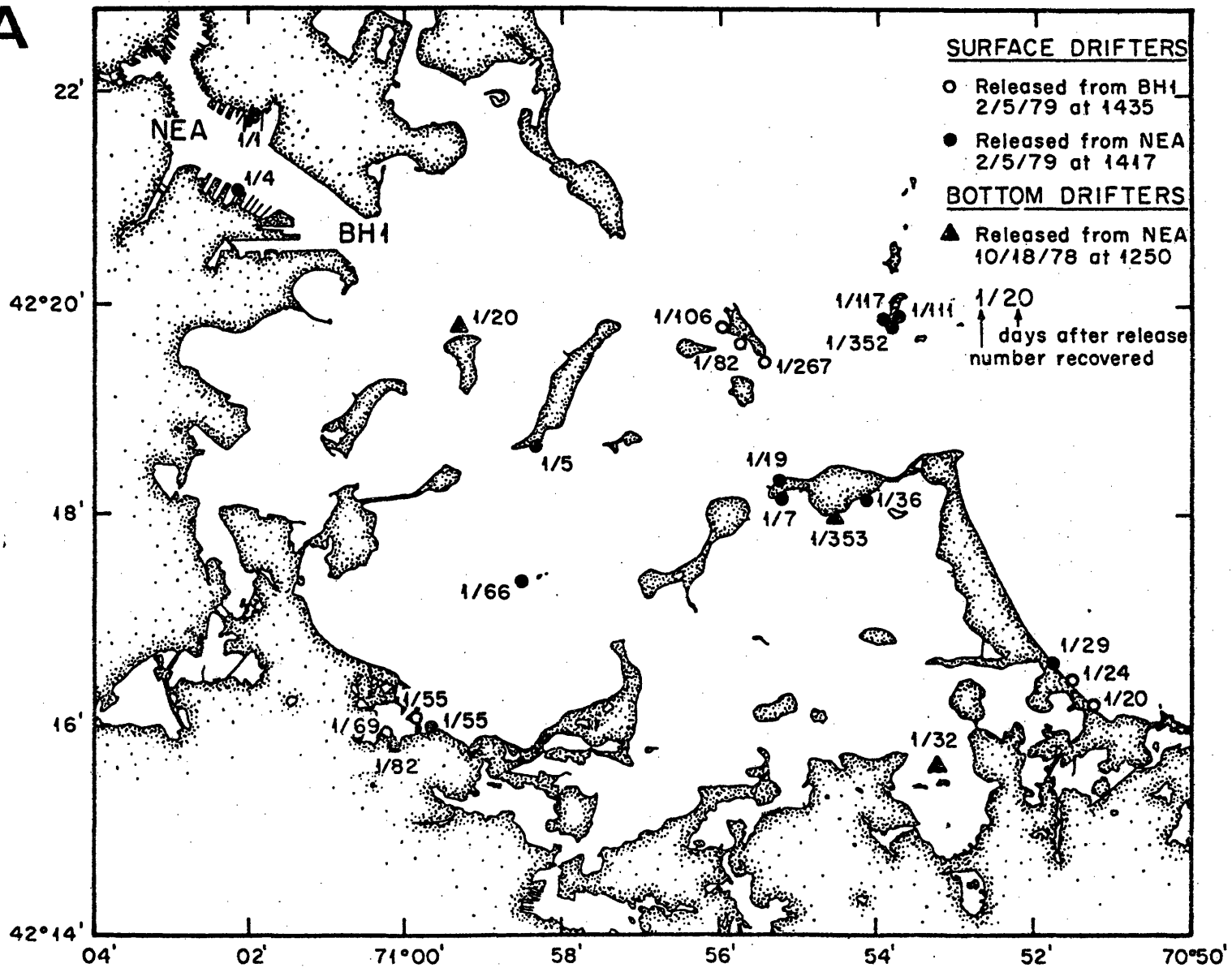
Surface and bottom drifters (10% recovery of bottom drifters and 30% for surface drifters), released at the New England Aquarium in the Inner Harbor and at the Deer Island outfall, lend some insight into long-term water movement (Figure 40A and B). These results, however, should be viewed only as supporting evidence. Water exits the Inner Harbor, mixes, and moves southward between the harbor islands, eventually to escape through Nantasket Roads. Some of this water apparently circulates through Hingham and Hull Bays. At Deer Island, water moves landward and southward between the islands. Once escaping through Nantasket Roads, water movement is southward along the coast, though some drifters appear to cross Cape Cod Bay. This landward and southward pattern of drift is consistent with the pattern outlined by Bumpus (1974) for the Massachusetts Bay region.

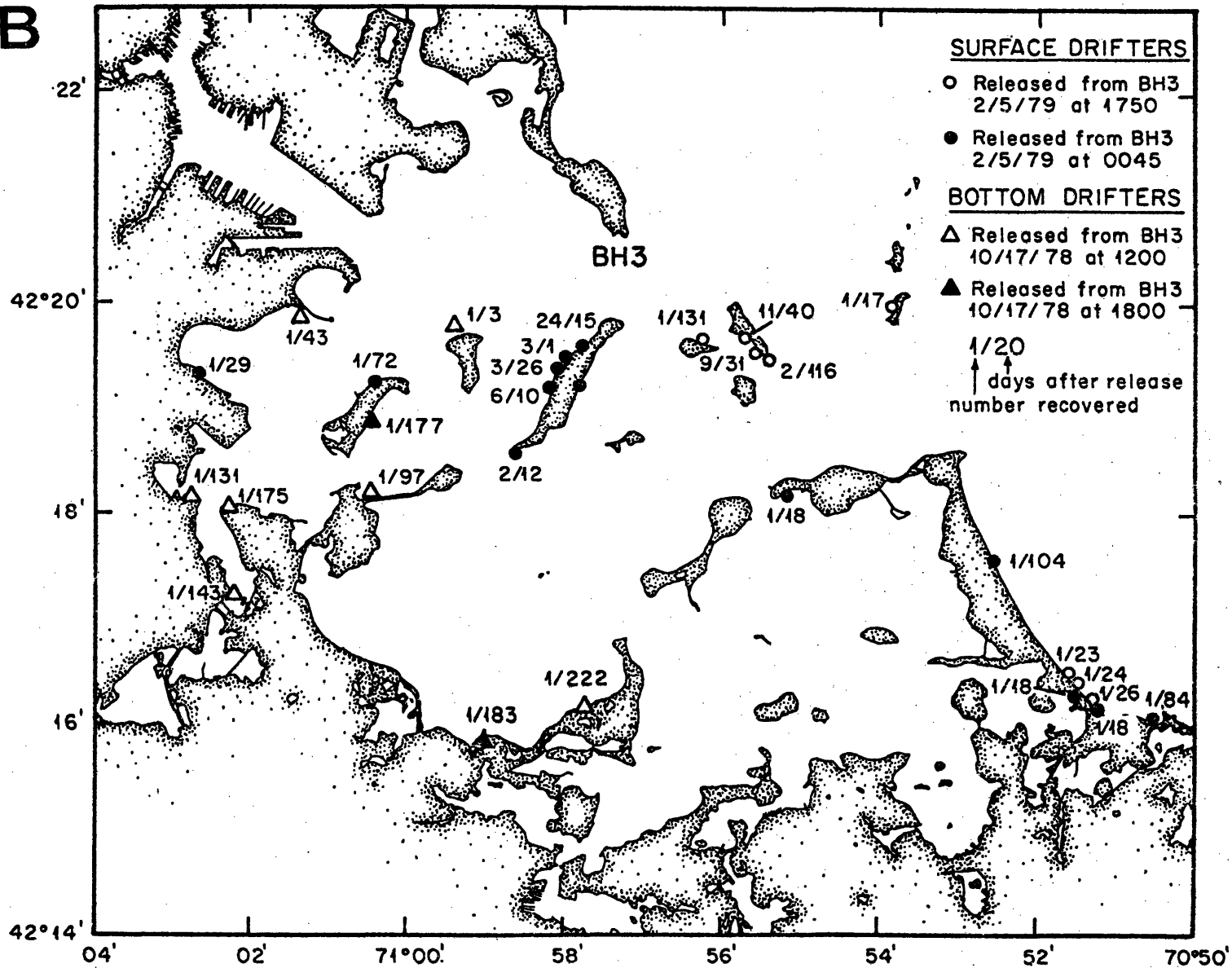
The circulation pattern described above may aid in the retention of fine-grained wastes. The long flushing time of the harbor segments and the general counterclockwise circulation would enable these wastes to settle from suspension. Patterns of long-term bottom drift also indicate that material from Massachusetts Bay may move landward and accumulate in the quiescent areas of the harbor. However, seasonal variations in circulation patterns (if they exist) and (particularly) storm events could significantly alter this scenario.

Figure 40. Recovery locations of surface and bottom drifters.

- A. Released from New England Aquarium (NEA) and station BH1
- B. Released from station BH3

A



**B**

### b. Previous Studies

Previous investigations of the suspended matter regime of Boston Harbor are few and limited in scope, most focusing on water quality measurements (nutrient concentrations and coliform bacteria counts). Most measurements were made in the summer months, and few took into account diurnal/tidal variation.

The Federal Water Pollution Control Administration (1969) reported water quality data for Boston Harbor covering the period May - September, 1968. Plankton tows revealed a seasonal dominance of the diatom population by Chaetoceros sp. with some replacement by Rhizosolenia sp. and Nitzschia sp. in September. Nutrient analyses identified areas of high nutrient concentrations extending from Deer Island into Winthrop Harbor and from Nut Island into Hingham Bay. Data did not include suspended matter measurements.

Physical, chemical, and biological data collected from 1970-1972 have been reported by the New England Aquarium (1973). Dissolved oxygen and nutrient concentrations varied seasonally, with the greatest changes occurring in the spring and fall, apparently related to photosynthetic activity. Diurnal studies carried out at several stations revealed tidal variations rivaling seasonal fluctuations. For example, turbidity varied from 2.7 - 10.3 mg SiO<sub>2</sub>/liter over a tidal cycle.

Phytoplankton surveys undertaken by the Aquarium in 1970-71

identified the most frequently encountered species as:

Coscinodiscus sp., Nitzschia seriata, Chaetoceros sp.,  
Skeletonema costatum, and Thalassiosira nordenskioldii.

Additional water quality data are presented in an unpublished report prepared for the Metropolitan District Commission. Suspended solid concentrations taken under spring-tide conditions were generally less than 10 mg/liter, while under neap-tide conditions, seston concentrations were consistently greater at all stations. Nutrient determinations again showed the impact of the sewage outfalls but suggested that for the most part the harbor is well mixed.

### c. Water Properties and Suspended Matter

Data on the suspended matter regime of Boston Harbor were collected during nine cruises covering a period from August 1977 through September, 1979. The first five cruises - each lasting three to four days - focused on the tidal variations at eight stations (Figure 41), providing harbor-wide coverage. The desire to characterize the tidal variability and nature of the major seston sources necessitated a greatly increased sampling frequency, and, thus, the last four cruises concentrated on stations BH1 and BH3. Because of the voluminous amount of data generated, this discussion will summarize the tidal and seasonal variation at stations BH1, BH3, and BH4. A cruise-by-cruise examination of water properties and seston is presented in the Appendix II.

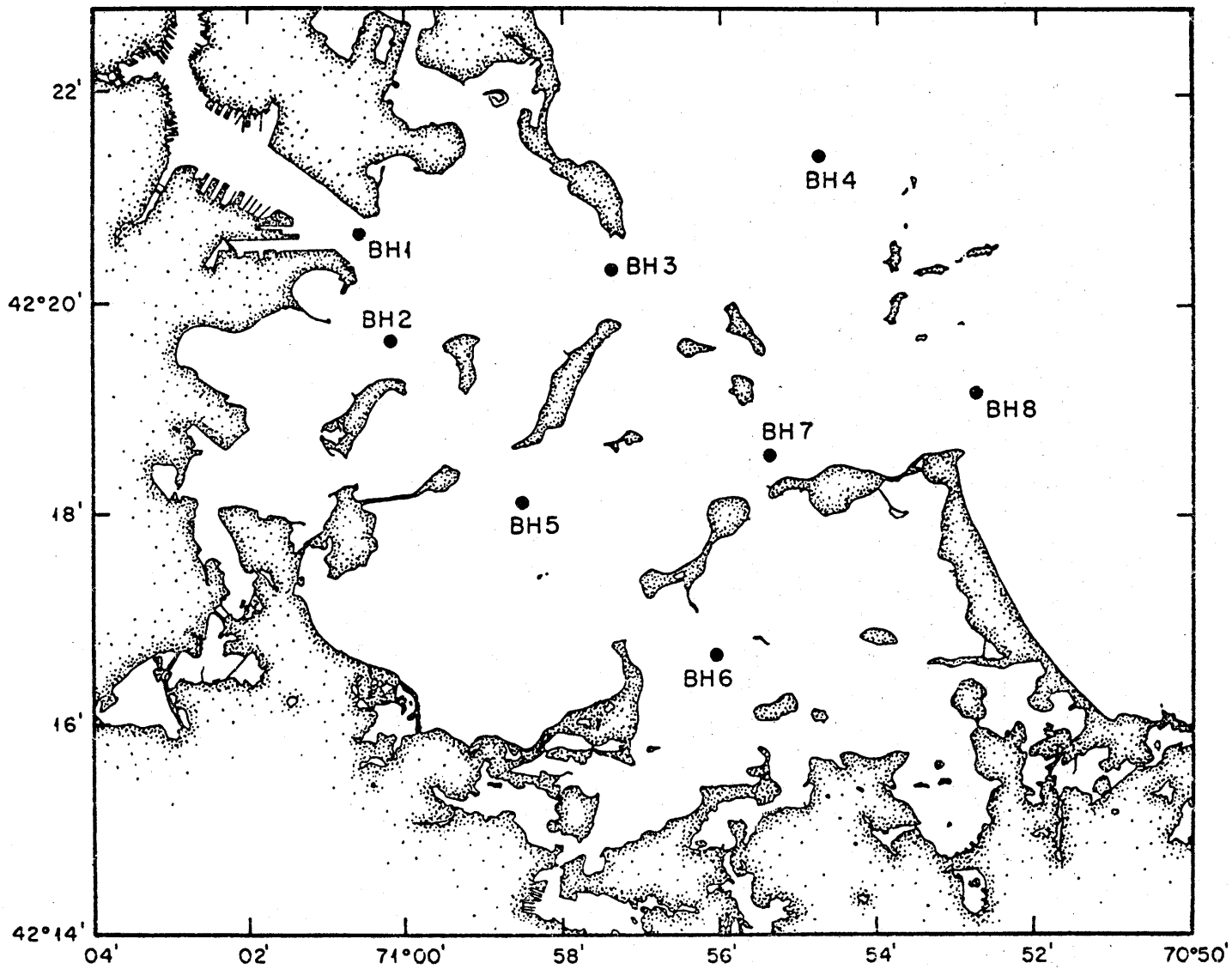
#### Summer

In summer months harbor waters reach their maximum temperatures (surface values  $>15^{\circ}\text{C}$ ), with the development of a strong thermocline (Figure 42). Tidal variations in temperature and salinity are most pronounced at stations BH1 and BH3 due to the influences of the Inner Harbor and Deer Island discharges, respectively. Massachusetts Bay water (colder and more saline) dominates the tidal fluctuations at station BH4 (Figure 42).

Figure 41.      Suspended matter and water quality  
                  stations.

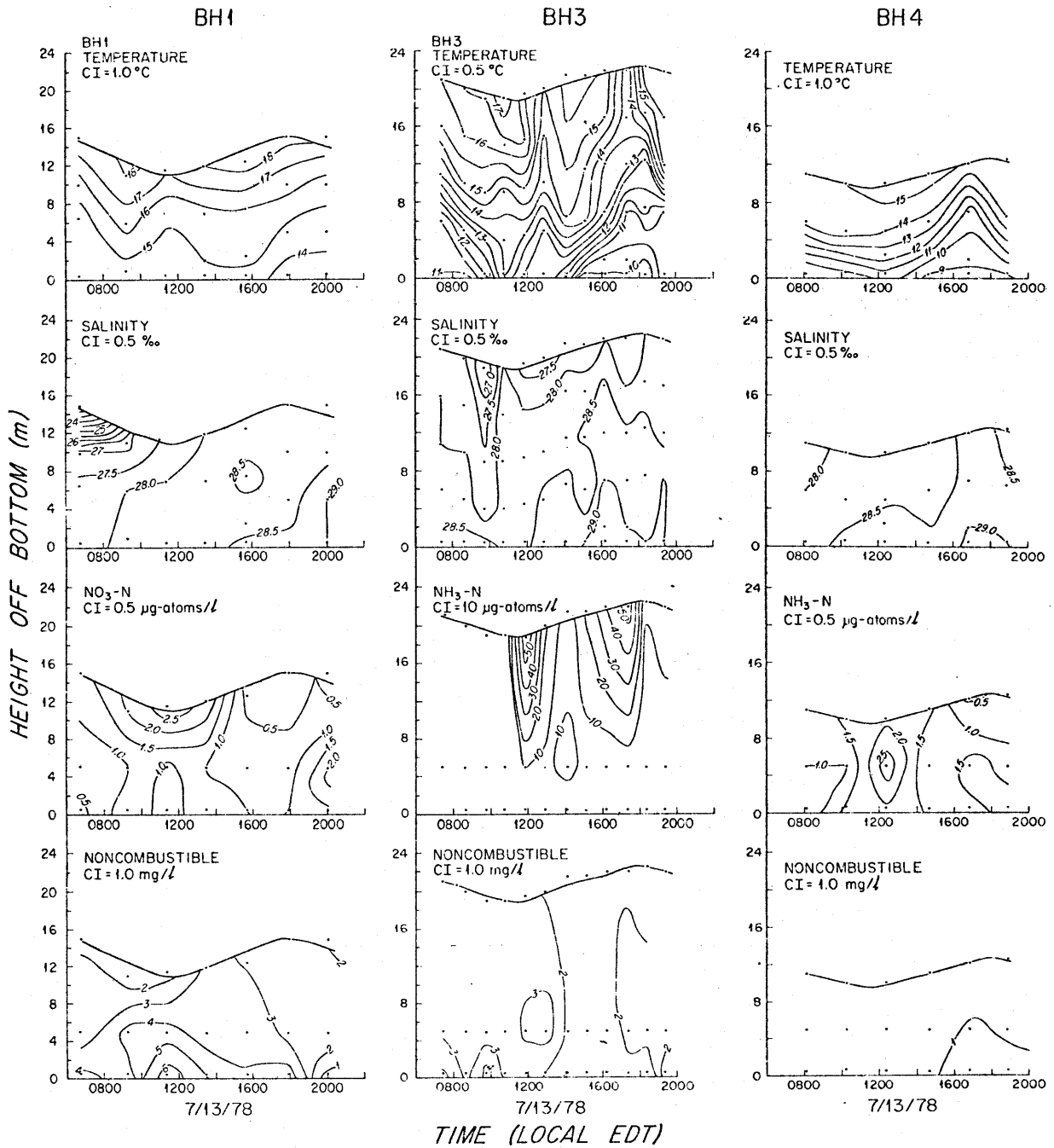


# SUSPENDED SEDIMENT STATIONS



- Figure 42. Tidal variations (summer):
- A. Temperature, salinity, nitrite,  
and noncombustible seston at BH1;
  - B. Temperature, salinity, ammonia,  
and noncombustible seston at BH3;
  - C. Temperature, salinity, ammonia,  
and noncombustible seston at BH4.

SUMMER



Warm temperatures, low salinities, and high concentrations of  $\text{NO}_2\text{-N}$ ,  $\text{NO}_3\text{-N}$ ,  $\text{PO}_4\text{-P}$ , and  $\text{SiO}_2\text{-Si}$  define the Inner Harbor water mass at BH1 (Figure 42) -- restricted to ebbing surface waters. Oxygen saturation values for this water mass are low especially in the early morning hours (see Appendix II).

Ammonia ( $\text{NH}_3\text{-N}$ ) and phosphate ( $\text{PO}_4\text{-P}$ ) profiles outline the Deer Island sludge plume at BH3 and define its temporal impact on water quality (Figure 42). The plume -- confined to mid and surface waters -- dominates the nutrient field but does not appear to adversely affect oxygen saturation values. The major tidal exchange between the harbor and Massachusetts Bay involves near-bottom water; surface tidal movement appears limited. A core of cold, saline Massachusetts Bay water, characterized by low ammonia values, intermediate nitrate values, and low concentrations of seston, represents the bulk of water transported in and out of the harbor. At stations inshore of BH3, this water mass is gradually obscured by mixing.

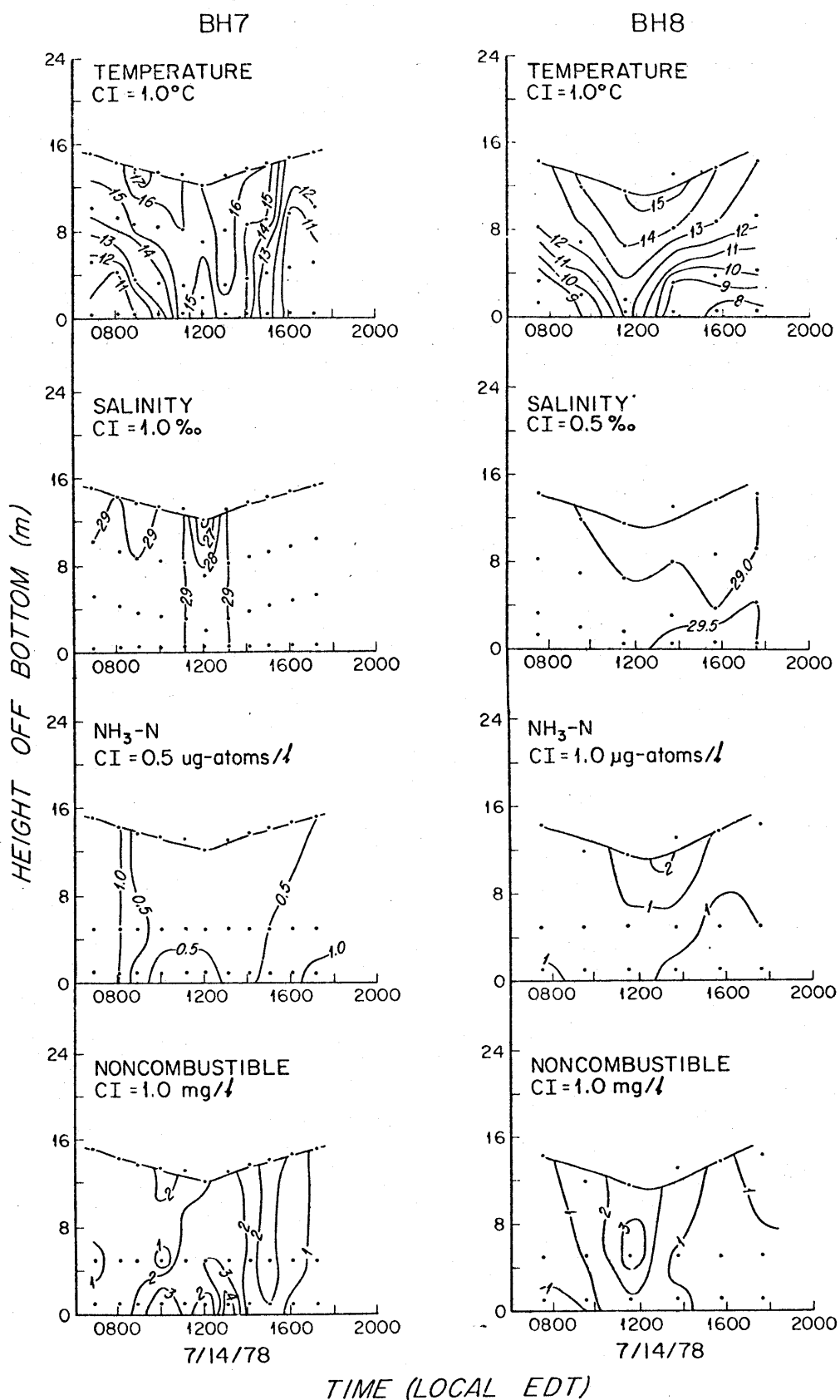
Temperature stratification is well defined at stations BH7 and BH8 in Nantasket Roads due to the intrusion of cold Massachusetts Bay water (Figure 43). However, tidal variations in salinity, nutrient concentration, and seston are small<sup>2</sup>.

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<sup>2</sup>Mixing greatly reduces tidal fluctuations in Nantasket Roads during other seasons.

- Figure 43. Tidal variations (summer) in temperature, salinity, ammonia, and noncombustible seston:
- A. at BH7
  - B. at BH8

## SUMMER



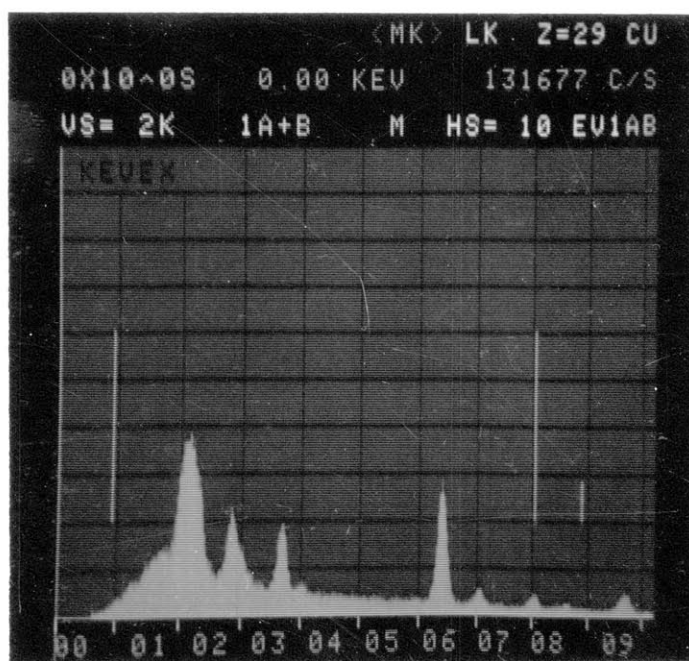
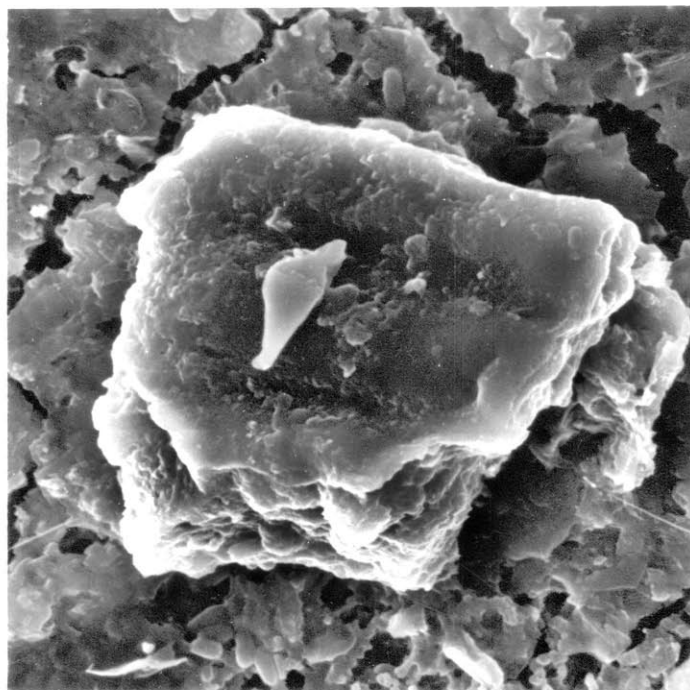
Near-bottom concentrations of noncombustible suspended matter are highest just before and after slack low water. Whether this increase is the result of local resuspension or horizontal advection is not clear. Mineral grains of quartz, mica, and clay minerals dominate the noncombustible fraction. Energy dispersive x-ray analysis of the particles (Figure 44) indicates relatively high concentrations of Fe. The importance of Fe as a scavenger of trace metals has been well established by other studies (Aston and Chester, 1976; Summerhayes et al., 1977; Eaton, 1979).

Combustible material (organics) averages 48% of the total seston in summer months, with much higher values in the surface waters of the Inner Harbor and in the Deer Island plume. This organic component is dominated by an organic film (described later) which blankets the filter and binds mineral aggregates. Such organic film has been reported from several shelf areas (Emery and Honjo, 1979), including Georges Bank (C. Parmenter, personal communication).

Plankton contribute significantly to the organic and inorganic fractions of the seston. However, the distribution of chlorophyll a is patchy, with the highest concentrations (over 40  $\mu\text{g}/\ell$ ) at BH1 and BH3 (associated with the outfall plume). The plankton assemblage (as inferred from these Niskin bottle samples) consists primarily of Thalassiosira sp.,

Figure 44. Photomicrograph of mineral grain from suspended matter sample. Back-scattering x-ray pattern reveals the presence of Cu (at 08) and Fe (between 06 and 07).





Coscinodiscus sp., and ebridians (Ebria tripartita).

Rhizosolenia sp., Pleurosigma sp., and Nitzschia sp. are secondary constituents. Fecal pellets (with pellicle) are common.

#### Autumn

By autumn, harbor waters have cooled significantly (10-13°C), and the water column is partially mixed. Tidal variations in temperature and salinity are small throughout the harbor (Figure 45). At BH4, temperature and salinity profiles outline the Massachusetts Bay water entering the harbor, but mixing obscures its signal further inshore.

Background concentrations of nutrients have increased over summer values, but tidal variations in the nutrient field are still dominated by the Inner Harbor and Deer Island (Figure 45). The Inner Harbor water mass is characterized by high concentrations of  $\text{NO}_2\text{-N}$  and  $\text{NO}_3\text{-N}$ , while ammonia profiles outline the Deer Island plume, which is restricted to mid and surface waters.

Near-bottom highs in the concentration of noncombustible material suggest the importance of resuspension/advection during ebb tide. Clay minerals, quartz, and mica are abundant, particularly in near-bottom samples. Scanning electron microscopy shows that particle aggregates are abundant, and

Figure 45.

Tidal variations (autumn):

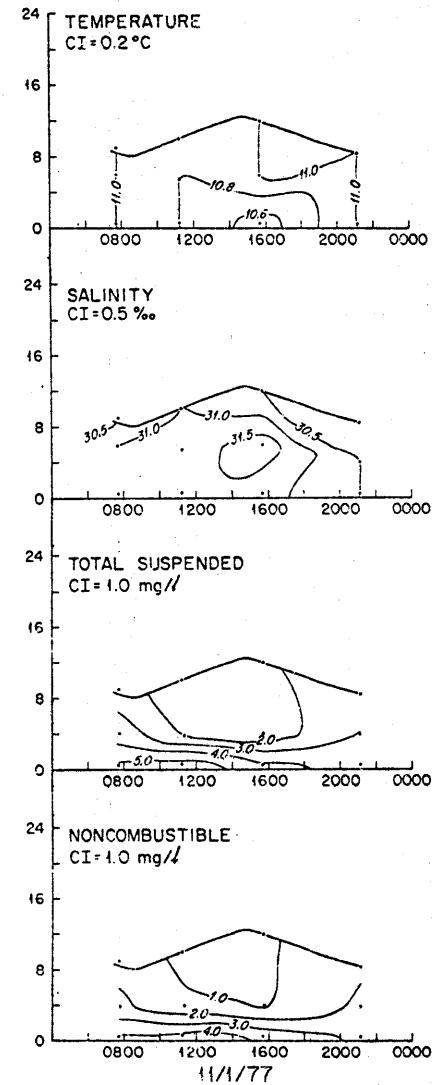
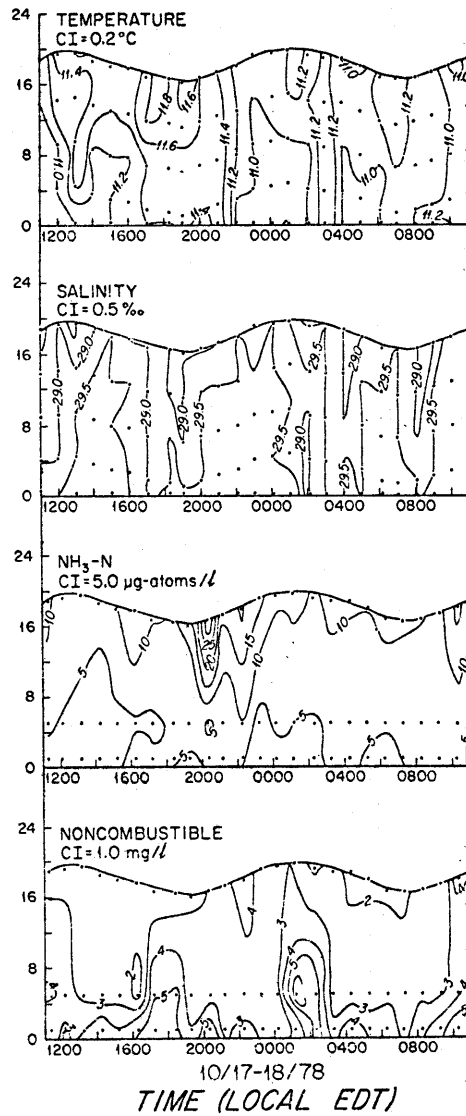
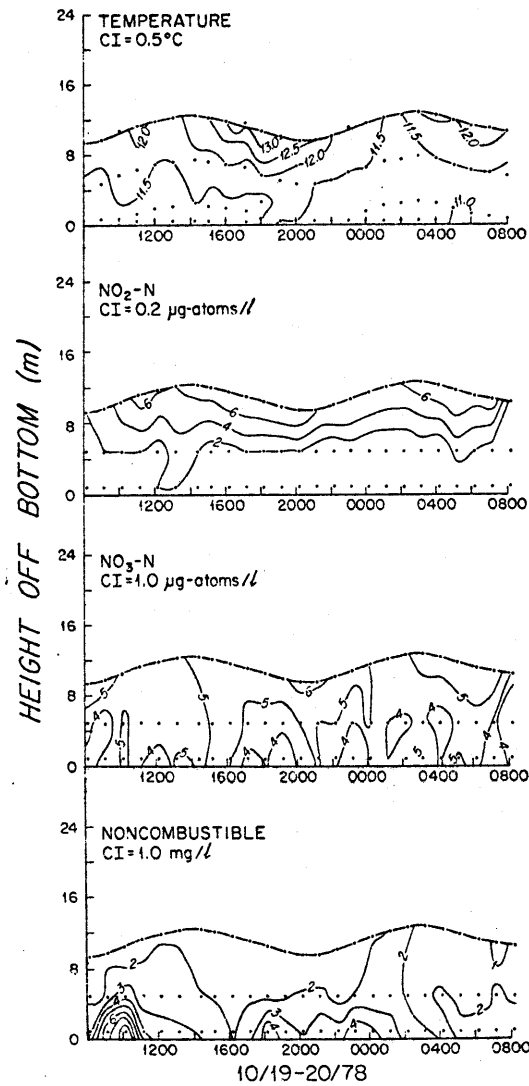
- A. Temperature, nitrite, nitrate, and noncombustible seston at BH1;
- B. Temperature, salinity, ammonia, and noncombustible seston at BH3;
- C. Temperature, salinity, total seston, and noncombustible seston at BH4.

# AUTUMN

BH1

BH3

BH4



KEVEX analyses indicate that iron is associated with most mineral grains -- if this Fe is in the form of an Fe-coating, then it is important in terms of trace metal transport.

Carbonate laths are visually prominent constituents of the seston. These "needles" (30-100 microns long and 2-10 microns wide) appear to come from the breakdown of mollusk shells (Figure 46). This degradation apparently begins with the breakdown of the organic material binding these carbonate bundles. Storm activity resuspends these bundles and enhances degradation (Fitzgerald et al., 1979).

In early autumn, organic film is still an important constituent of the seston, but as biological activity decreases, its importance is diminished (percentage of combustible material drops to 36%). Concentrations of chlorophyll a vary between 1 and 10  $\mu\text{g}/\ell$ , and its distribution is very patchy. Coscinodiscus sp., Skeletonema sp., and Thalassiosira sp. are important. Copepods and tintinnids are very abundant in early fall.

#### Winter

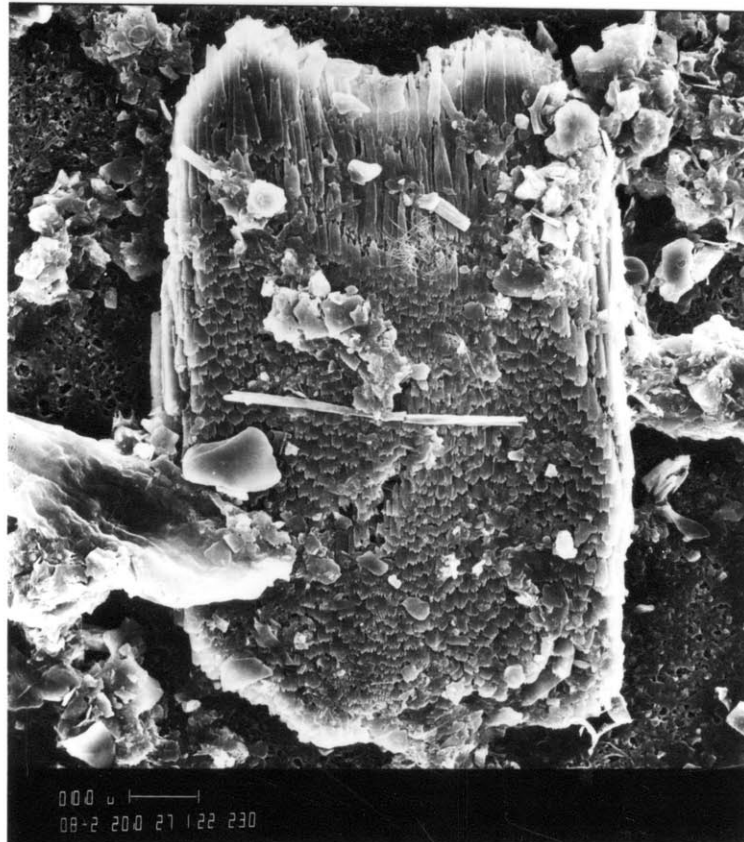
Water temperatures range between 0.5 and 2.5<sup>o</sup>C and the water column is very well mixed (Figure 47). High-salinity bottom waters at BH3 and BH4 outline the core of Massachusetts Bay water, but for the most part, tidal variations are small.

- Figure 46.
- A. Photograph showing carbonate laths (crossed-nichols)
  - B. Photomicrograph showing carbonate lath bundle.

**A**



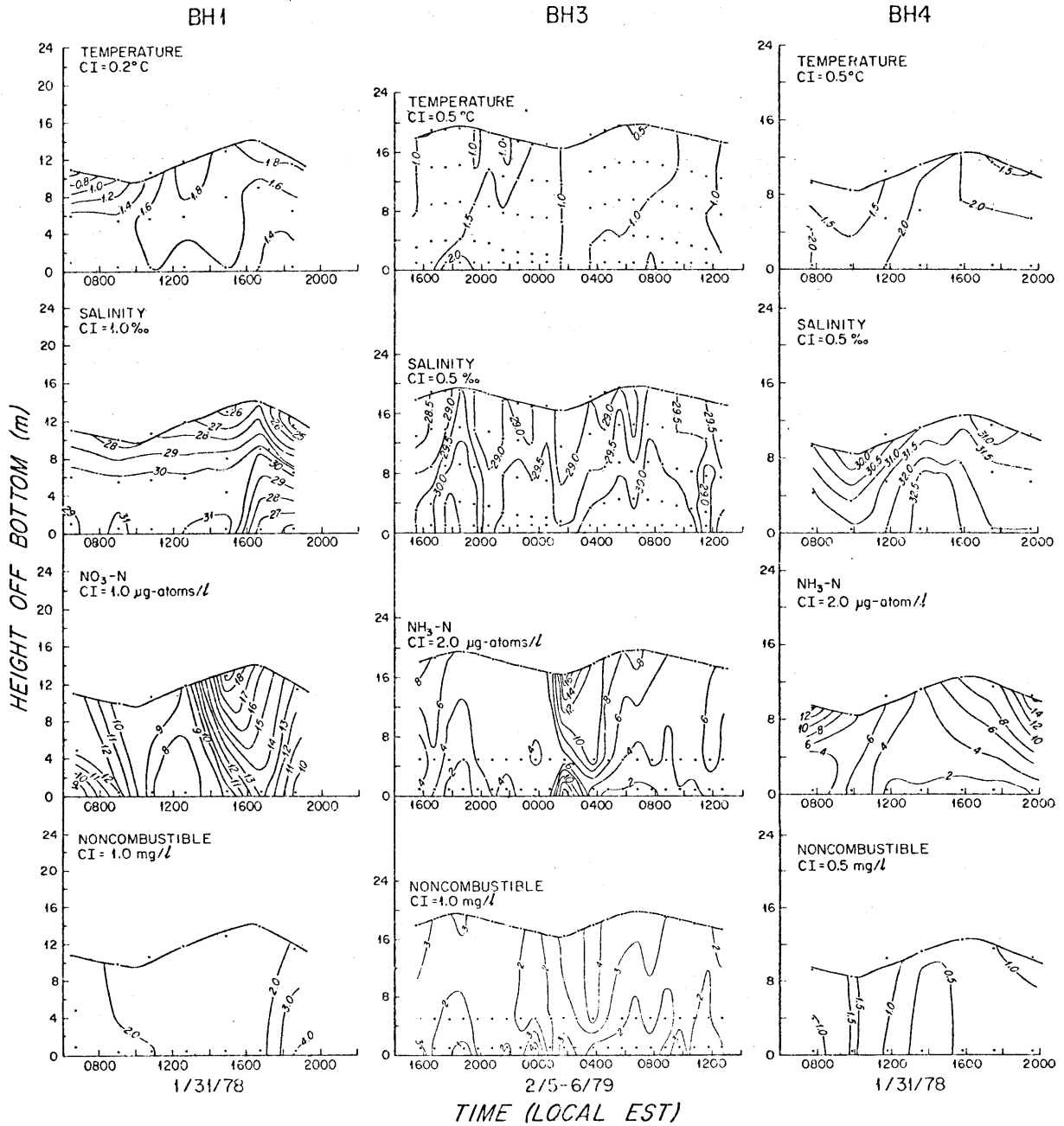
**B**



- Figure 47. Tidal variations (winter):
- A. Temperature, salinity, nitrate,  
and noncombustible seston at BH1;
  - B. Temperature, salinity, ammonia,  
and noncombustible seston at BH3;
  - C. Temperature, salinity, ammonia,  
and noncombustible seston at BH4.



WINTER



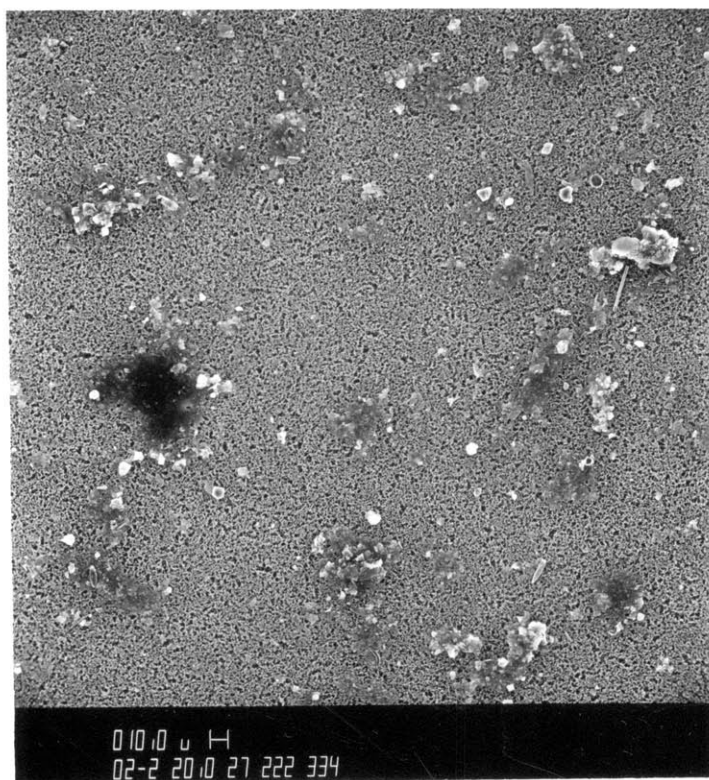
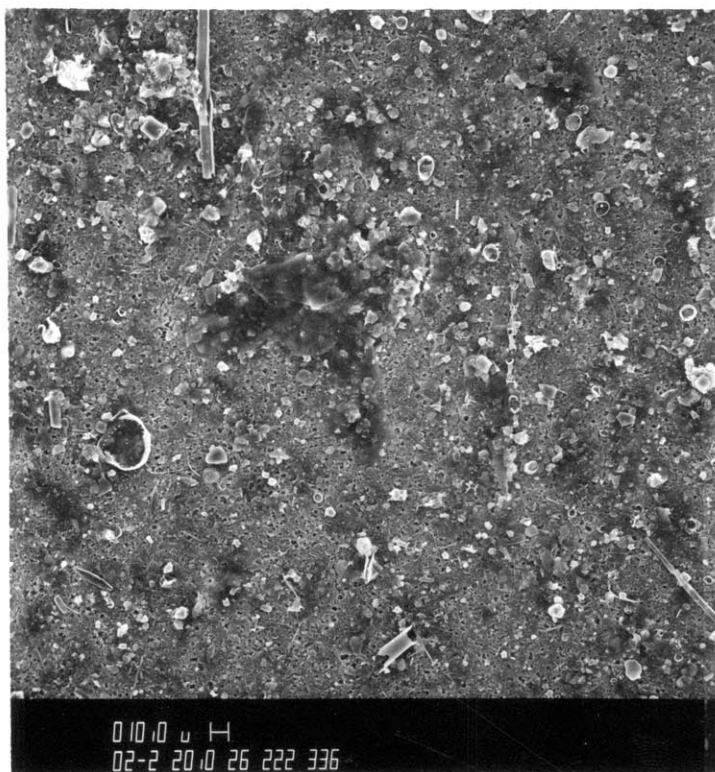
Background nutrient concentrations are high, with  $\text{NO}_3\text{-N}$ , for example, ranging from 7.0-14.0  $\mu\text{g-atom}/\ell$ . Yet, even during storm activity, the sludge plume dominates the nutrient field (see Appendix II). Ammonia and phosphate profiles define the impact of the Deer Island plume at BH3. Aided by a NW wind, the plume can extend as far seaward as BH4.

Suspended matter concentrations are lower overall than during other seasons, suggesting the importance of biological production on seston. Chlorophyll a concentrations are very low, ranging from 0.2 - 1.5  $\mu\text{g}/\ell$ . Organic material is not a major component except at BH3, and where present, appears in particulate form and not as a blanketing film (Figure 48).

Coscinodiscus sp., Rhizosolenia sp., Navicula sp., and Nitzschia sp. are the major constituents of the plankton assemblage.

Noncombustible concentrations, though fairly uniform throughout the water column, do show some increase during ebb tide. Single grains are the dominant particle mode, though organically bound aggregates can be important in the surface waters. Iron is ubiquitous in its association with mineral grains (quartz, mica, and clay minerals). Carbonate laths and bundles are very abundant.

- Figure 48.
- A. Photomicrograph showing abundance of organic film in autumn surface sample from BH1 (flood tide, September, 1979).
  - B. Photomicrograph showing paucity of organic material in winter sample from BH1 (flood tide, January, 1978).



### Spring

Salinities are much lower in both surface and bottom waters -- ranging from 24-29 ‰ -- at all stations both in the north and south as a response to the seasonal high in river discharge (Bumpus et al., 1953; Manohar-Mahara and Beardsley, 1973). Water temperatures range from 5-15°C, but stratification is not well defined except at station BH1 (Figure 49).

Background nutrient concentrations are much reduced from the winter values. Elevated concentrations of  $\text{NO}_2\text{-N}$  and  $\text{NO}_3\text{-N}$  profiles define the low-salinity Inner Harbor water -- limited to ebbing surface waters -- at BH1. At BH3 nutrient profiles reveal the strong influence of the sludge plume on water quality, though that influence is limited to the surface waters near BH3.

The importance of mineral grains as a seston component is diminished by the large biological contribution. Clay minerals, quartz, and mica are most prominent in near-bottom samples. Mineral grains are often agglomerated and continue to show traces of iron.

The profiles of chlorophyll a accent the increased biological activity. Values range from 3-20  $\mu\text{g}/\ell$ , with the highest concentrations in the Inner Harbor samples.

Thalassiosira sp., Coscinodiscus sp. and Chaetoceros sp. are the dominant diatoms. The microflagellate Calyceomonas sp. is

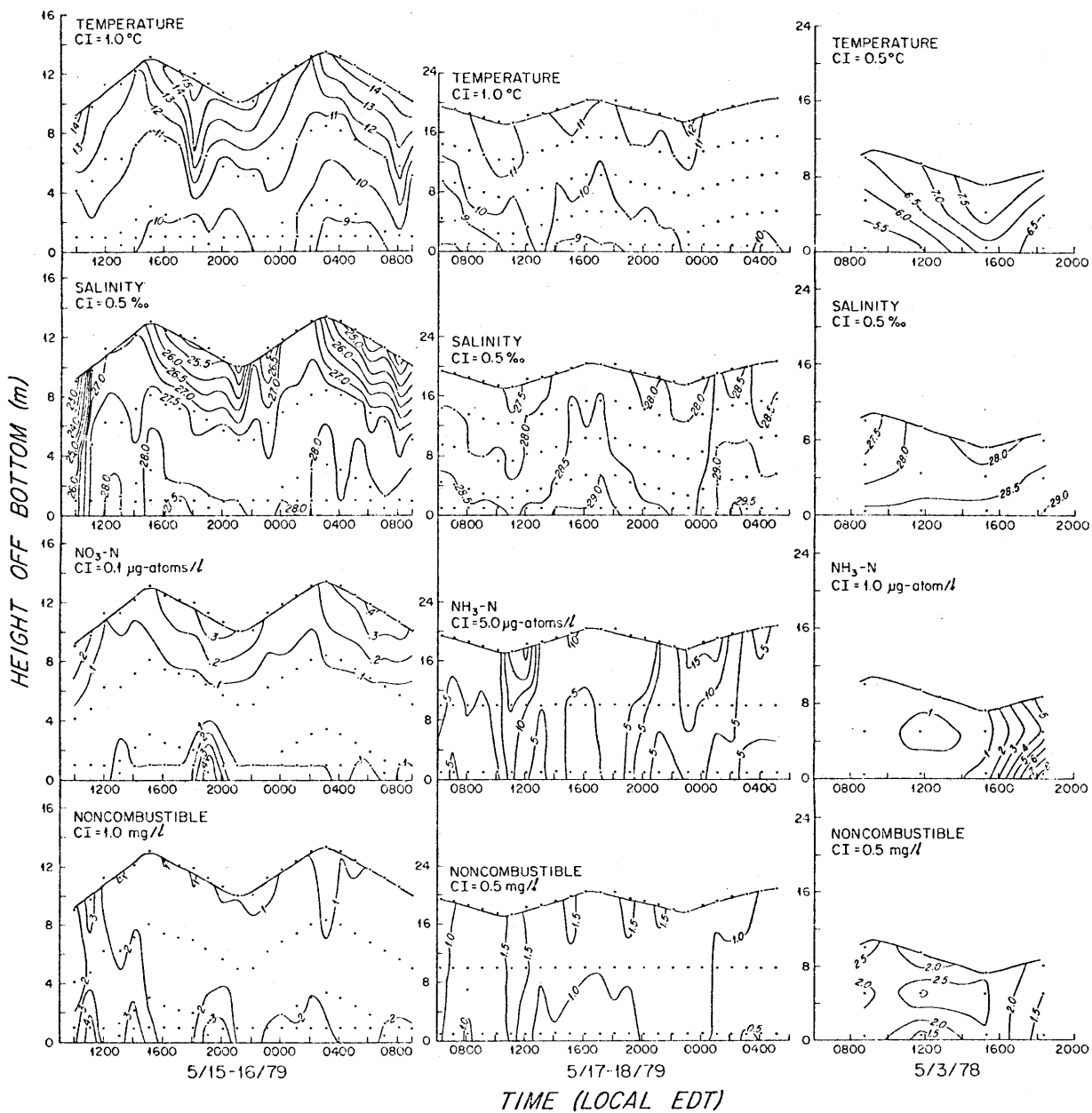
- Figure 49. Tidal variations (spring):
- A. Temperature, salinity, nitrate,  
and noncombustible seston at BH1;
  - B. Temperature, salinity, ammonia,  
and noncombustible seston at BH3;
  - C. Temperature, salinity, ammonia,  
and noncombustible seston at BH4.

SPRING

BH1

BH3

BH4



also important. Copepods Calanus sp. are locally abundant, and fecal pellets (with pellicle) are present in significant numbers. With this increased biological activity (percent combustibles averages near 50%), organic film is a prominent feature of the seston.

d. Statistics -- Characterization of Seston Sources

In an attempt to characterize objectively the principal seston sources, the scope of their impact, and their tidal and seasonal variations, the techniques of factor analysis were applied to the data on suspended matter and water quality. Factor analysis identifies those factors (sources) associated with the variation observed, and interstation comparisons define the spatial extent of those factors.

Analysis of summer (August, 1977; July, 1978), winter (January, 1978), and spring (May, 1978) water-quality data reveals three water masses that dominate tidal and seasonal variations in the harbor. Factors extracted from the data differentiate the waters of the Deer Island plume, the Inner Harbor, and Massachusetts Bay primarily on the basis of nutrient content. Interstation comparisons suggest that the direct influence of the Deer Island plume is restricted to the vicinity of station BH3, while Inner Harbor water extends into northeastern Dorchester Bay (BH2). Massachusetts Bay water



dominates the water column at the outer stations (BH4, BH7, BH8) throughout the year; the uniformity of this single water mass minimizes tidal variation. The character of the principal factors at stations BH5 and BH6 show some impact of the Nut Island plant.

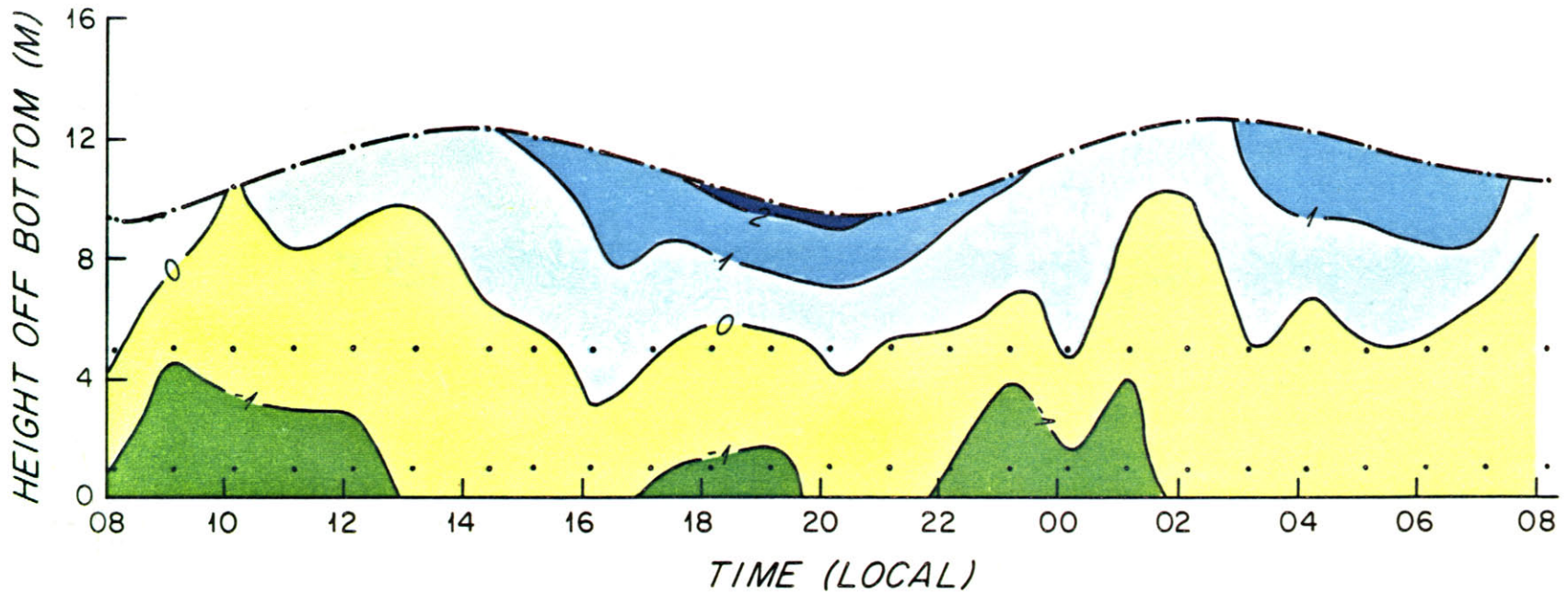
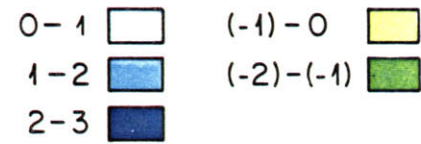
These data emphasize the importance of the Deer Island plume. Though its spatial extent is limited, the plume accounts for most of the tidal variation in water quality observed in the harbor throughout the year. The absence of its signature at station BH4 suggests that the plume tends to follow a more northeasterly route (the shipping channel), while inshore, mixing dilutes its signal. Waters from the Inner Harbor also appear to mix rapidly -- their zone of influence restricted to northeastern Dorchester Bay and possibly the western portions of President Roads. Stations in the southern cell of the harbor are not affected directly by the Inner Harbor or the Deer Island sludge, though Nut Island effluent may exert some influence.

Diurnal studies at stations BH1 and BH3 provide the sampling frequency necessary to observe tidal and seasonal changes in the characteristics of these water masses. At station BH1, factor I distinguishes between the nitrite/nitrate-rich waters of the Inner Harbor and particle-rich bottom waters (Figure 50). The components of

Figure 50. . . A, B, C, Tidal variations of R-scores for Factor I for station BH1: October (1978), May (1979), and September (1979), respectively. See Table 12 for description of these factors.

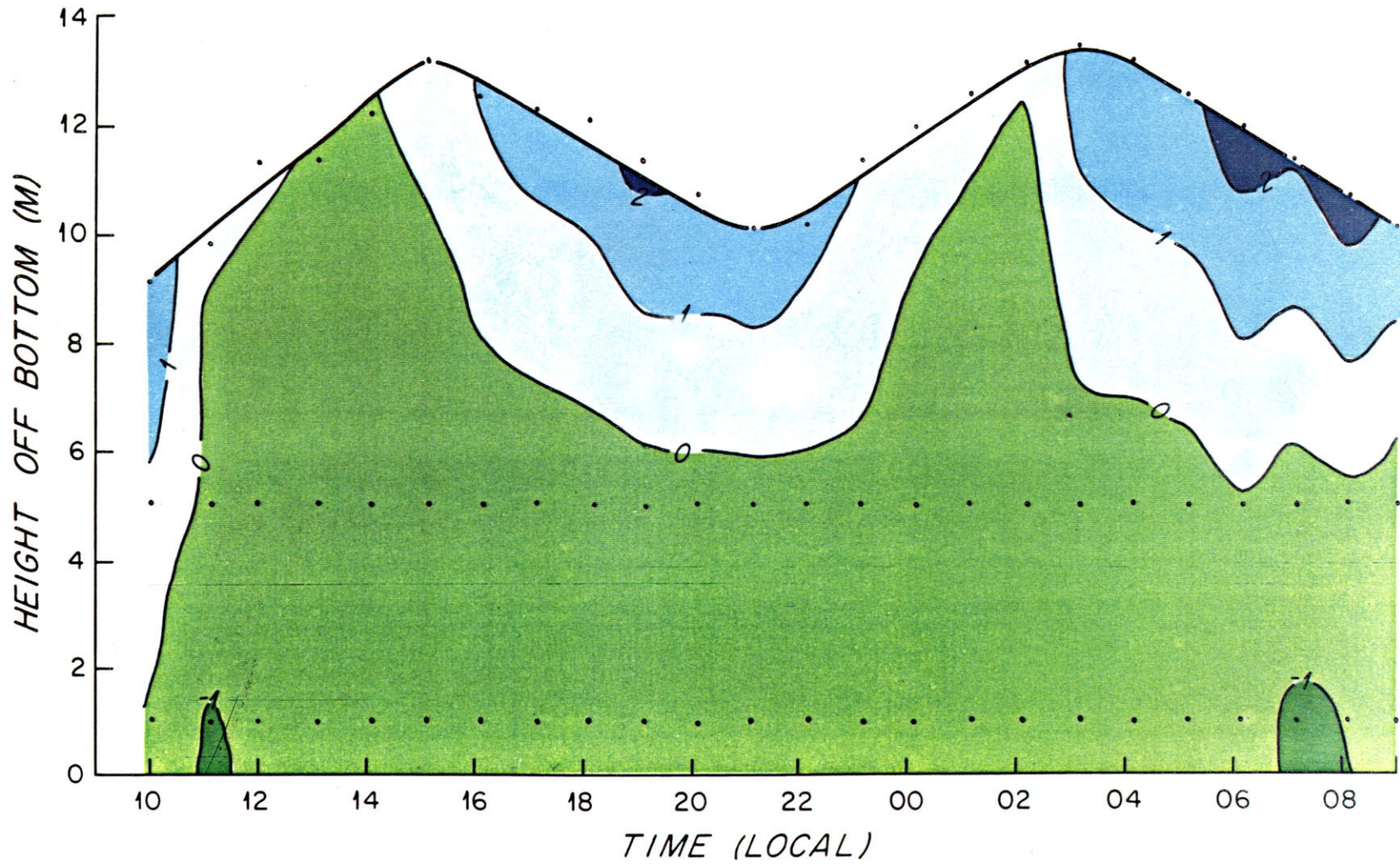
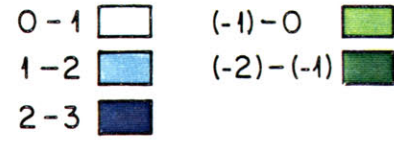
A

STATION BH1 - FACTOR I (50.5%)  
OCTOBER, 1978



**B**

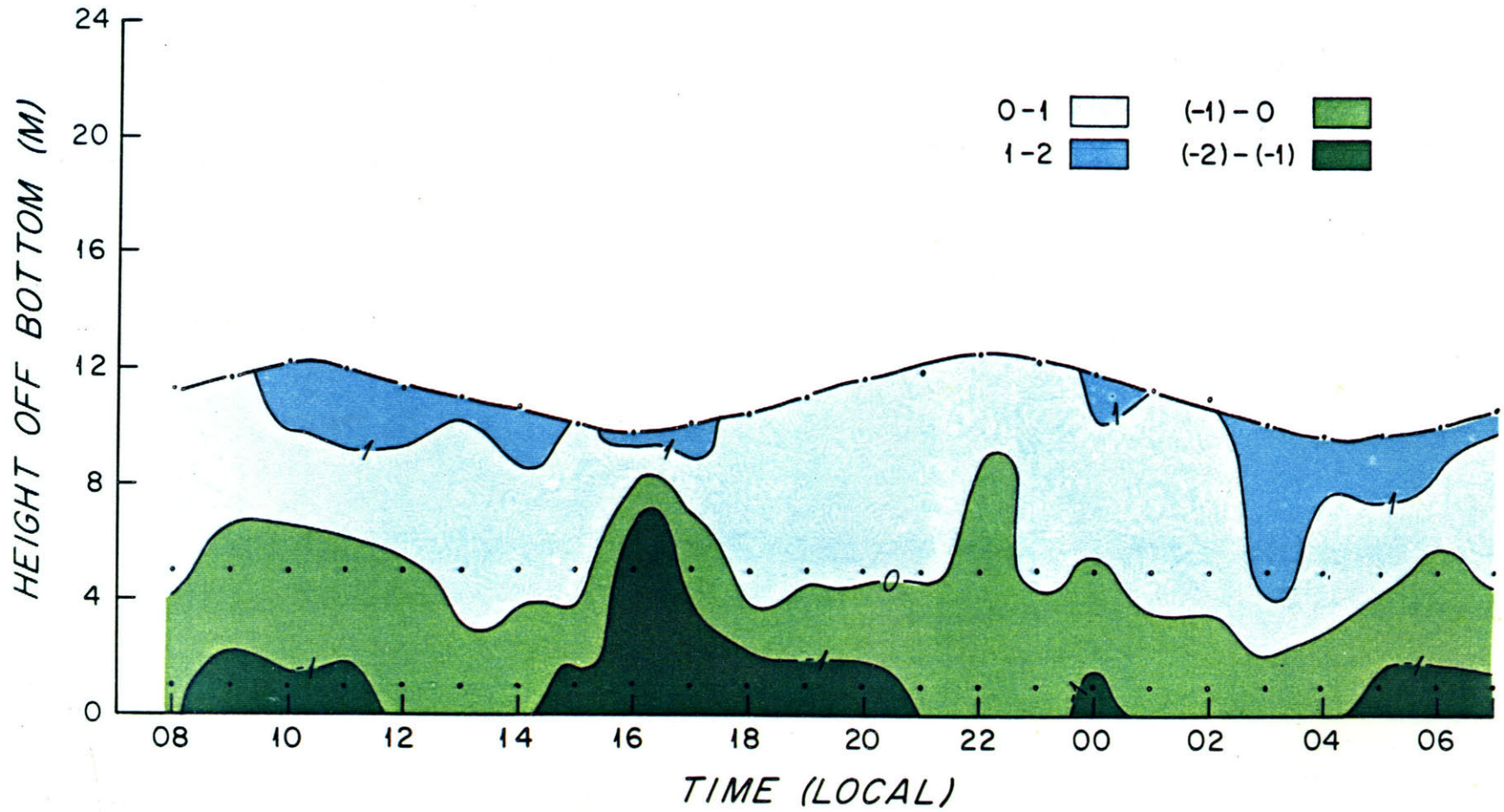
STATION BH1 - FACTOR I (48.7%)  
MAY 15-16, 1979





C

STATION BH1 - FACTOR I (42.5 %)  
SEPTEMBER, 1979



this factor vary in importance with the season (Table 12), but the identity of factor I does not. For station BH3 (Table 13), the principal factor differentiates the ammonia and phosphate-rich waters of the Deer Island Plume from the less turbid, saline bottom waters from Massachusetts Bay (Figure 51). This factor also maintains its identity through all seasons -- even during the February, 1979 storm. Thus, although the characteristics of these principal water masses (and seston sources) change seasonally, they retain a contrasting signature from the surrounding water mass.

e. Suspended Matter and Its Relation to Bottom Sediments

1. Dispersal of the Deer Island Sludge Plume

As reported earlier, sludge is released near Deer Island on the ebb tide to enhance its dispersal into Massachusetts Bay. But geochemical evidence suggests that at least 33% of the discharged material is retained in the outer harbor (Chapter 2, Vd). In July, 1978, under the direction of Dr. Marshall Orr (W.H.O.I.), a 200 kHz acoustic profiler was employed to delineate the development and dispersal of the Deer Island sludge plume.

The results of that survey show the spreading of the plume at the water surface and also the raining of material from suspension (Figure 52). Profiles show that the plume moves offshore, confined somewhat by the shipping channel. The plume does not reach the eastern extent of the shipping channel

Table 12 Factor analysis of water quality data for BH1  
(Diurnal sampling). (1) Main factors controlling variance.  
(2) Percentage of variance explained by each factor.  
(3) Factor loadings within each factor ( ).

October, 1978

I	II
50.5 %	13.1%
NH <sub>3</sub> (.870)	Total seston (.633)
SiO <sub>2</sub> (.845)	Combustible (.592)
NO <sub>2</sub> (.848)	Noncombustible (.512)
Temperature (.816)	
NO <sub>3</sub> (.789)	
PO <sub>4</sub> (.761)	
Noncombustible (-.723)	
Total Seston (-.700)	

May, 1979

I	II
48.7%	15.6%
NO <sub>3</sub> (.928)	Total (.943)
Combustible % (.815)	Combustible (.679)
NO <sub>2</sub> (.797)	Noncombustible (.611)
PO <sub>4</sub> (.785)	
Chlorophyll (.707)	
Salinity (-.932)	
pH (-.766)	
Noncombustible (-.537)	

September, 1979

I	II
42.5%	17.8%
NO <sub>3</sub> (.858)	SiO <sub>2</sub> (.726)
Temperature (.844)	NH <sub>3</sub> (.660)
NO <sub>2</sub> (.782)	PO <sub>4</sub> (.595)
PO <sub>4</sub> (.599)	
Total Seston (-.770)	
Noncombustible (-.766)	
Chlorophyll (-.730)	

Table 13. Factor analysis of water quality data for BH3  
 (Diurnal Sampling. (1) Main factors controlling variance.  
 (2) Percentage of variance explained by each factor.  
 (3) Factor loadings within each factor ( ).

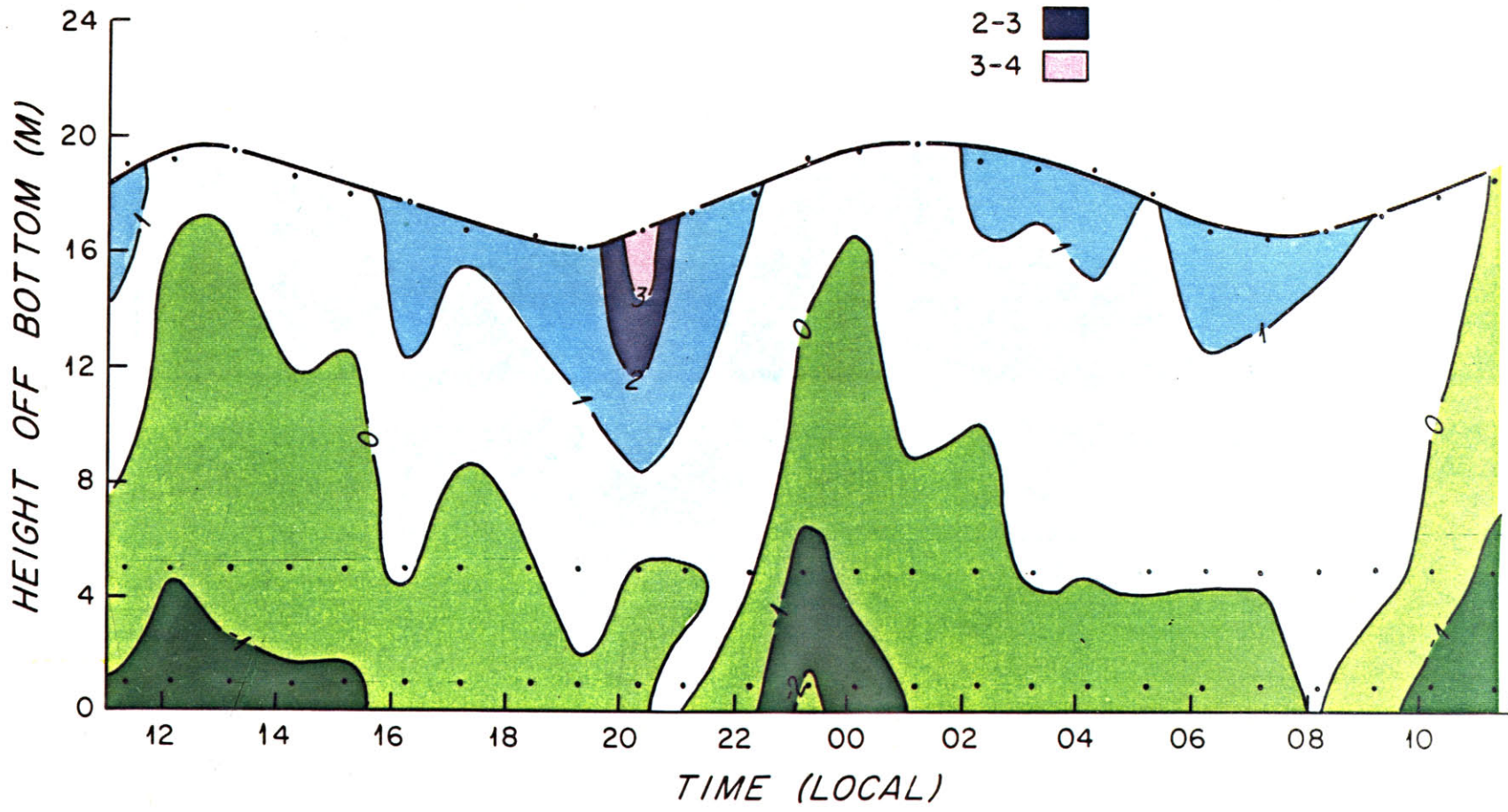
October, 1978		February, 1979	
I	II	I	II
26.8%	16.2%	43.5%	15.1%
NO <sub>2</sub> (.817)	Combustible (.916)	NH <sub>3</sub> (.899)	NO <sub>3</sub> (.632)
NH <sub>3</sub> (.816)	Total Seston (.687)	Total Seston (.865)	SiO <sub>2</sub> (.520)
PO <sub>4</sub> (.804)	Combustible% (.550)	Noncombustible (.801)	Combustible(-.642)
pH (-.616)		SiO <sub>2</sub> (.770)	Combustible%(-.707)
Salinity (-.536)		PO <sub>4</sub> (.758)	
		Combustible (.694)	
		NO <sub>3</sub> (.671)	
		Salinity (-.662)	
May, 1979		September, 1979	
I	II	I	II
37.7%	14.3%	32.9%	17.8%
Total Seston	Combustible% (.675)	PO <sub>4</sub> (.890)	NO <sub>3</sub> (.587)
PO <sub>4</sub> (.832)	Oxygen Sat. (.516)	Combustible (.869)	SiO <sub>2</sub> (.505)
Combustible (.790)	pH (.487)	Total Seston (.670)	Noncombustible (.500)
NH <sub>3</sub> (.758)	Chlorophyll(-.451)	Combustible% (.651)	Temperature (-.665)
Noncombustible (.666)		Salinity (-.696)	Oxygen Sat. (-.613)
Temperature (.549)		pH (-.660)	
Salinity (-.809)			
Oxygen Sat. (-.523)			



Figure 51. A, B, C. D. Tidal variations of R-scores for Factor I for station BH3: October (1978), February (1978), May (1979), and September (1979) respectively. See Table 13 for description of this factor.

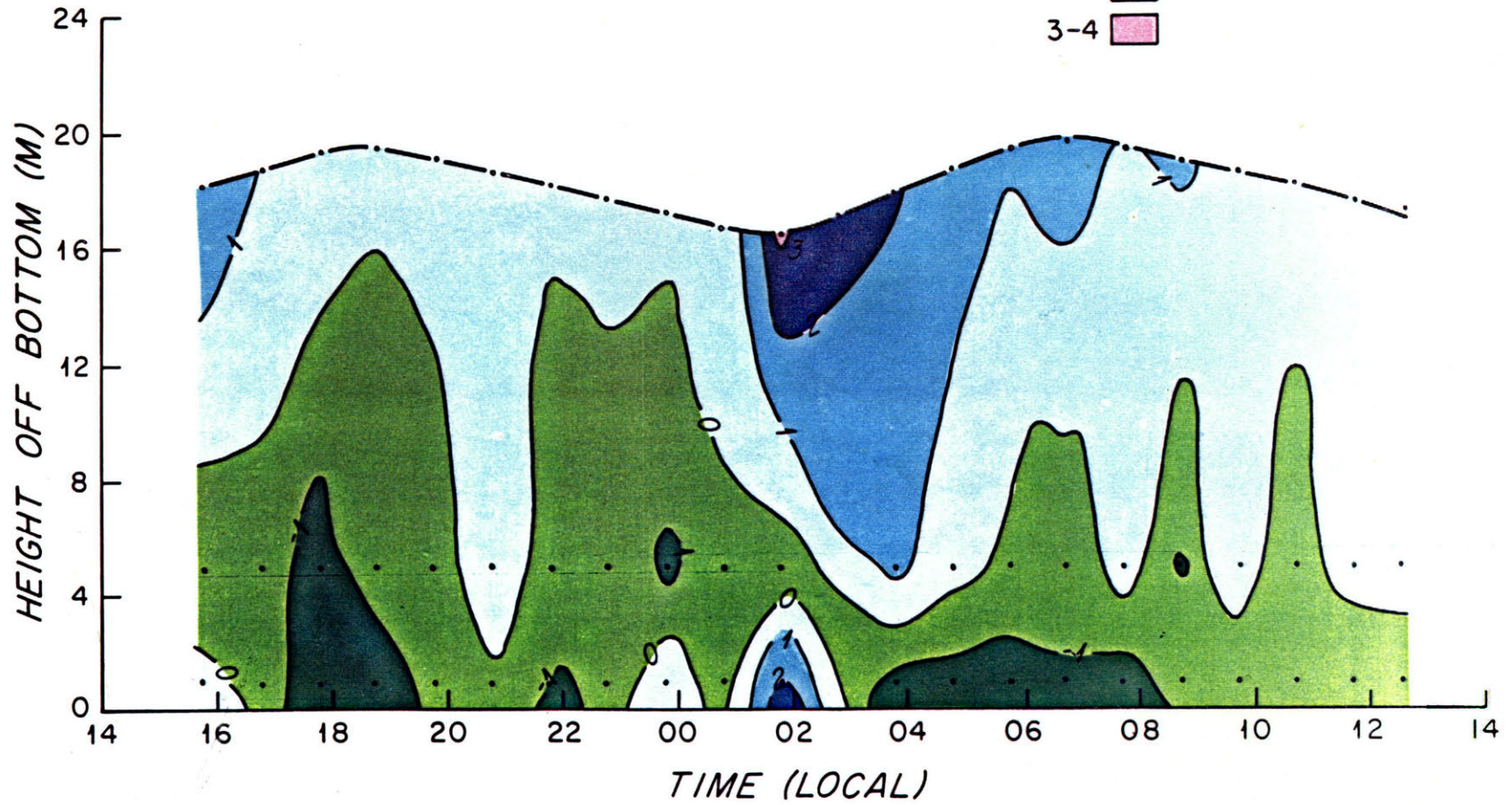
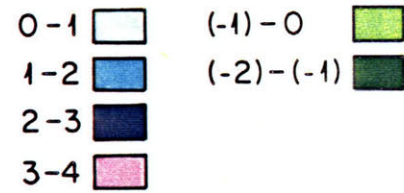
**A**

STATION BH3- FACTOR I (27%)  
OCTOBER, 1978



**B**

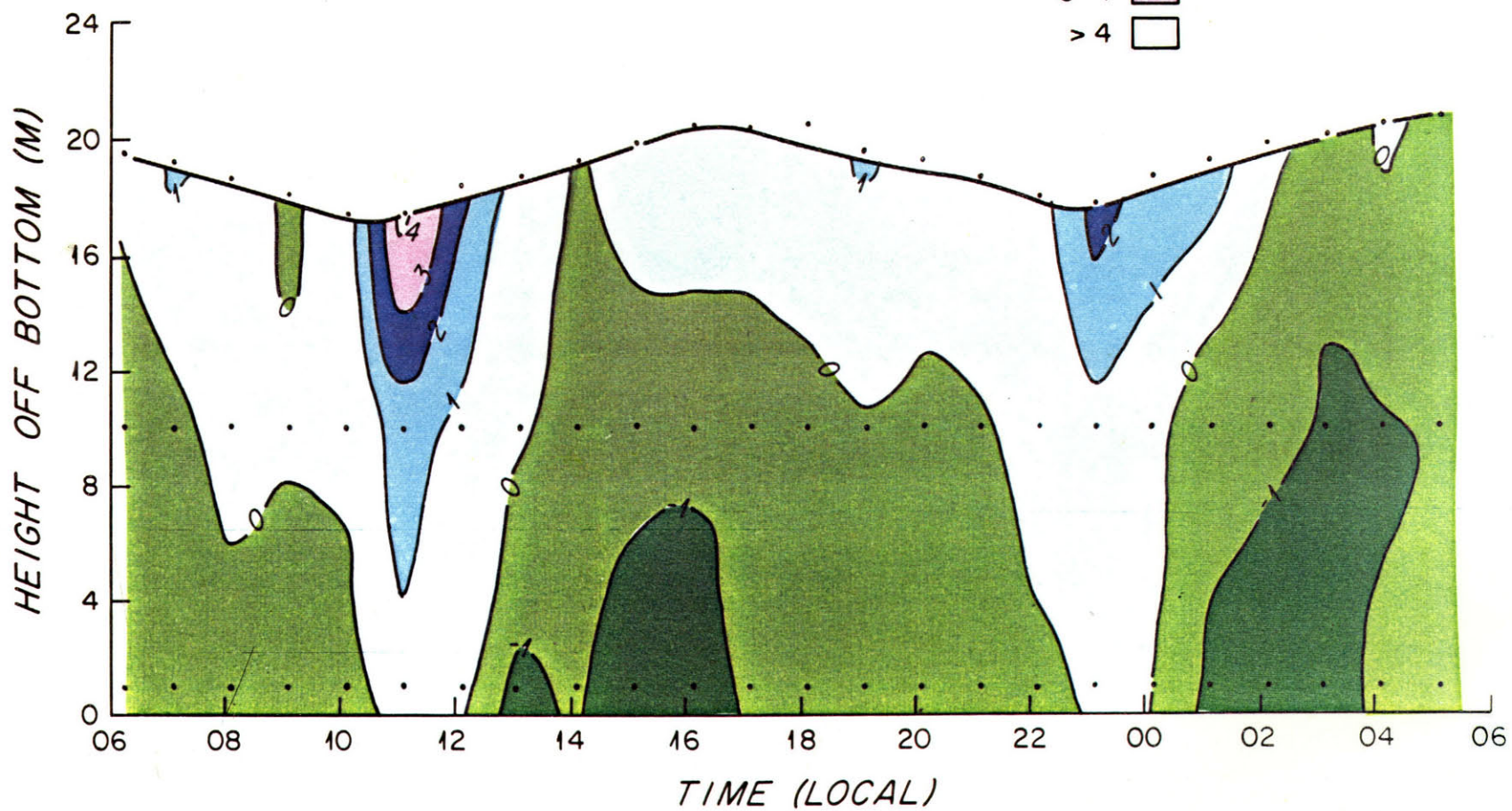
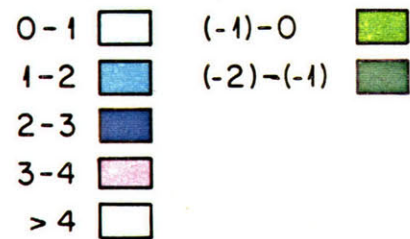
STATION BH3-1 - FACTOR I (43.5%)  
FEBRUARY 5-6, 1979





C

STATION BH3 - FACTOR I (37.7%)  
MAY 17-18, 1979



D

STATION BH3 - FACTOR I (32.9 %)  
SEPTEMBER, 1979

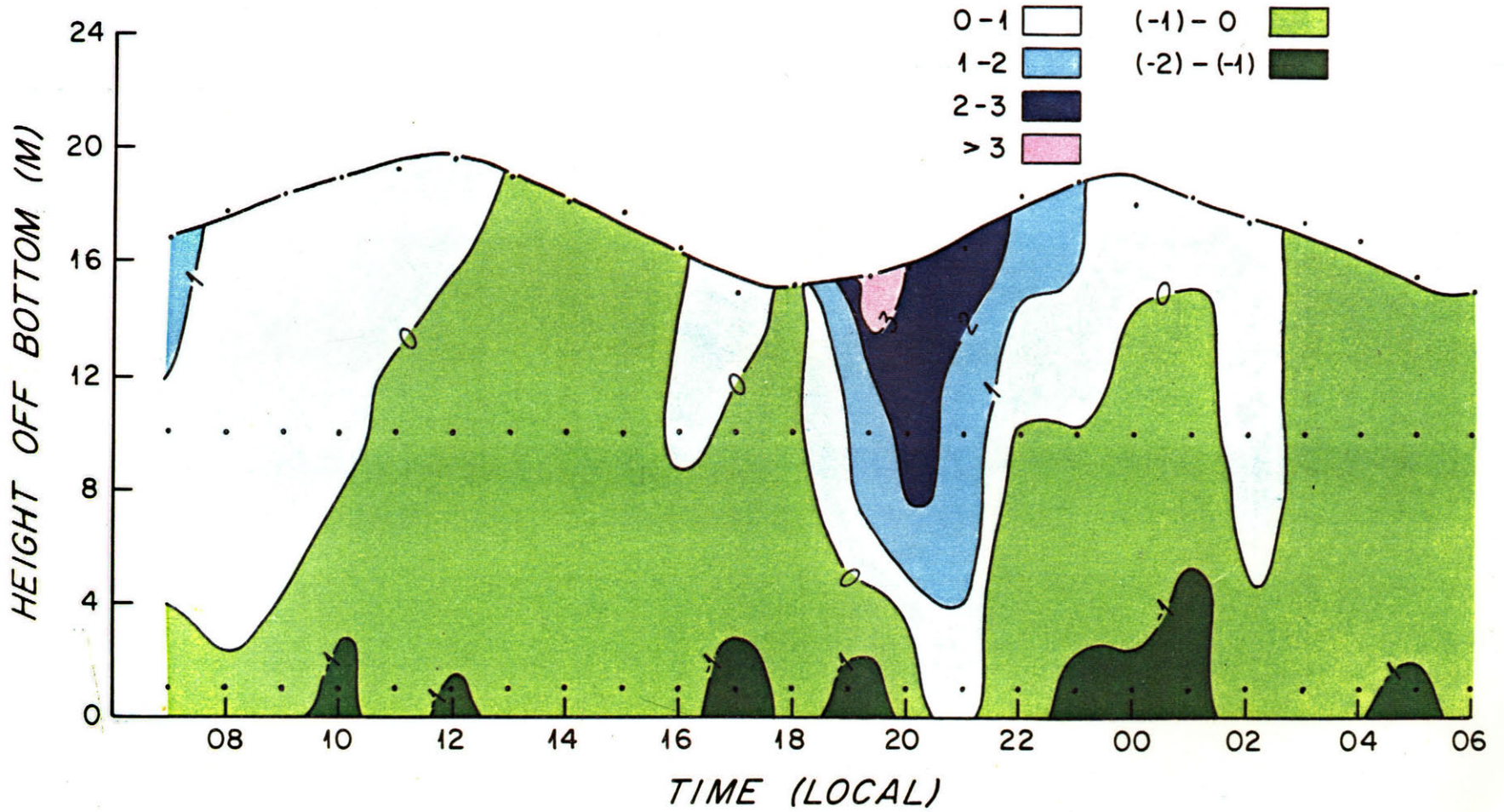
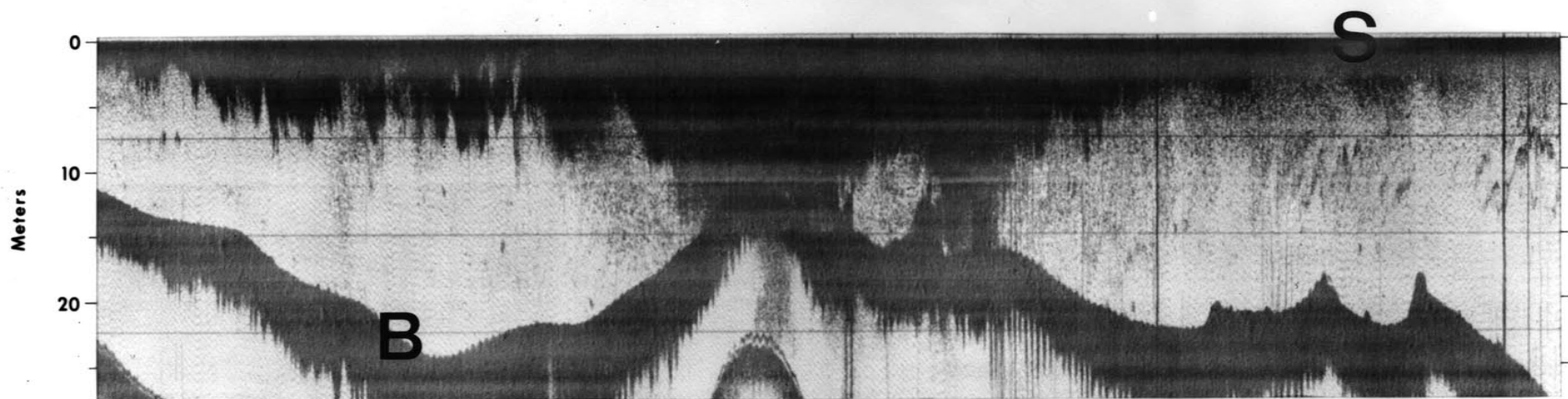


Figure 52. 200 kHz profile showing the Deer Island plume rising to the water surface and spreading. The water surface (S) and harbor bottom (B) are labelled.



before the tide reverses. Particle settling is intermittent, but increases with the approach of slack tide. As the tide reverses, the plume, maintaining its structure, moves landward into the harbor. The breakup of the plume is completed within a tidal cycle.

A drogue study conducted in October, 1968 (FWPCA, 1969) supports this description of the plume dispersal. A surface drogue was released in the "boil" created by the discharge of Deer Island sludge. A sustained 25-knot NW wind probably caused the drogue to drift southeastward. The drogue traveled out the South Channel and stalled with the approach of slack water (Figure 53). On the flood, the drogue returned to South Channel and moved westward into the harbor.

Temperature and salinity measurements seem to indicate that the major exchange of water with the bay involves bottom water. Because the plume is restricted to the surface waters, the plume stalls. In addition, intermittent particle settling, accompanied by landward bottom drift, may aid in retention of this material.

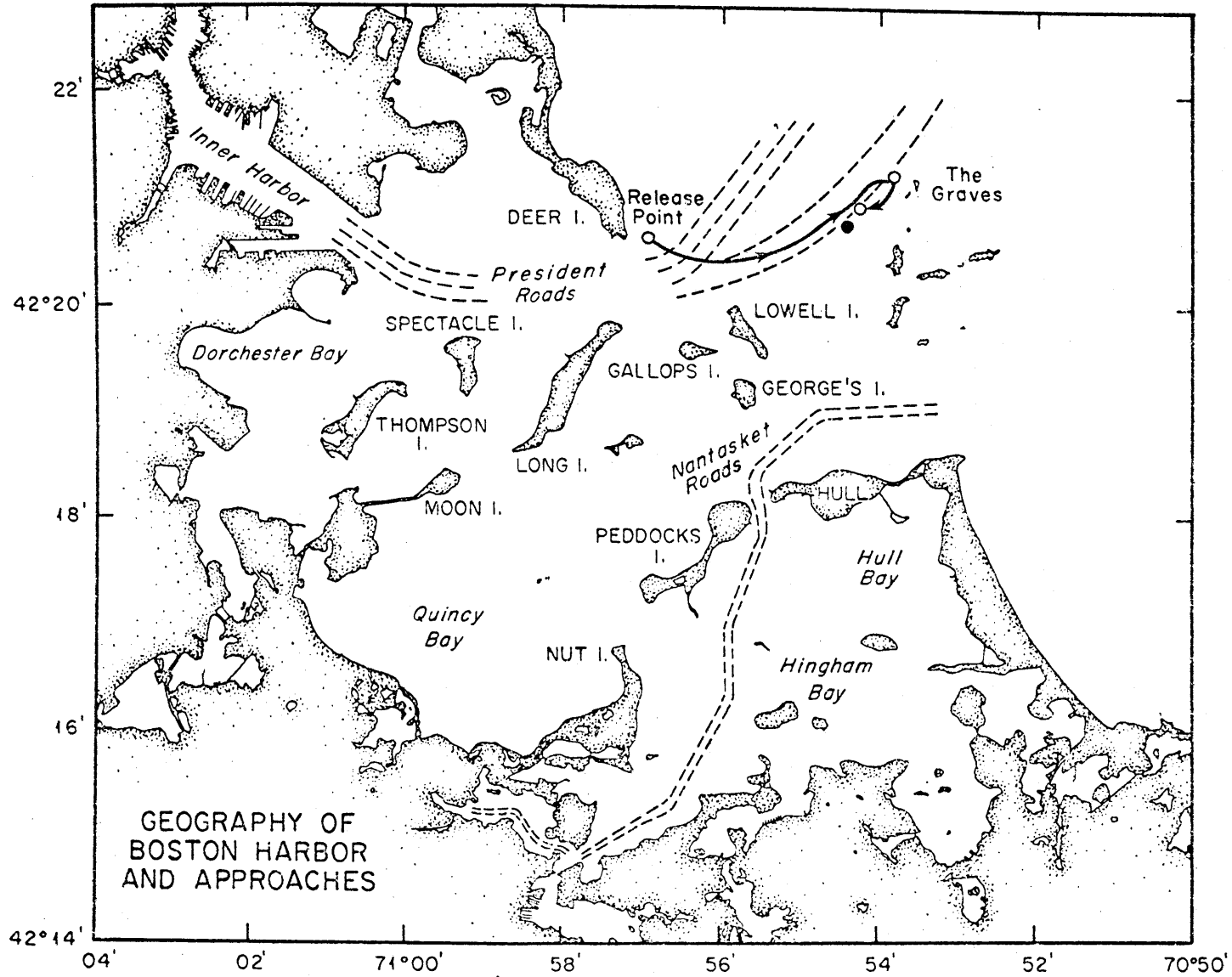
## 2. Organic film

The suspended matter sampling program has illustrated the importance and variability of the organic film that blankets the sample filter. These films contain many trapped or attached grains of skeletal debris and minerals (Figure 54) and, thus, may be important in the deposition of these



Figure 53. Path of surface drogue released in the "boil" of the Deer Island plume.

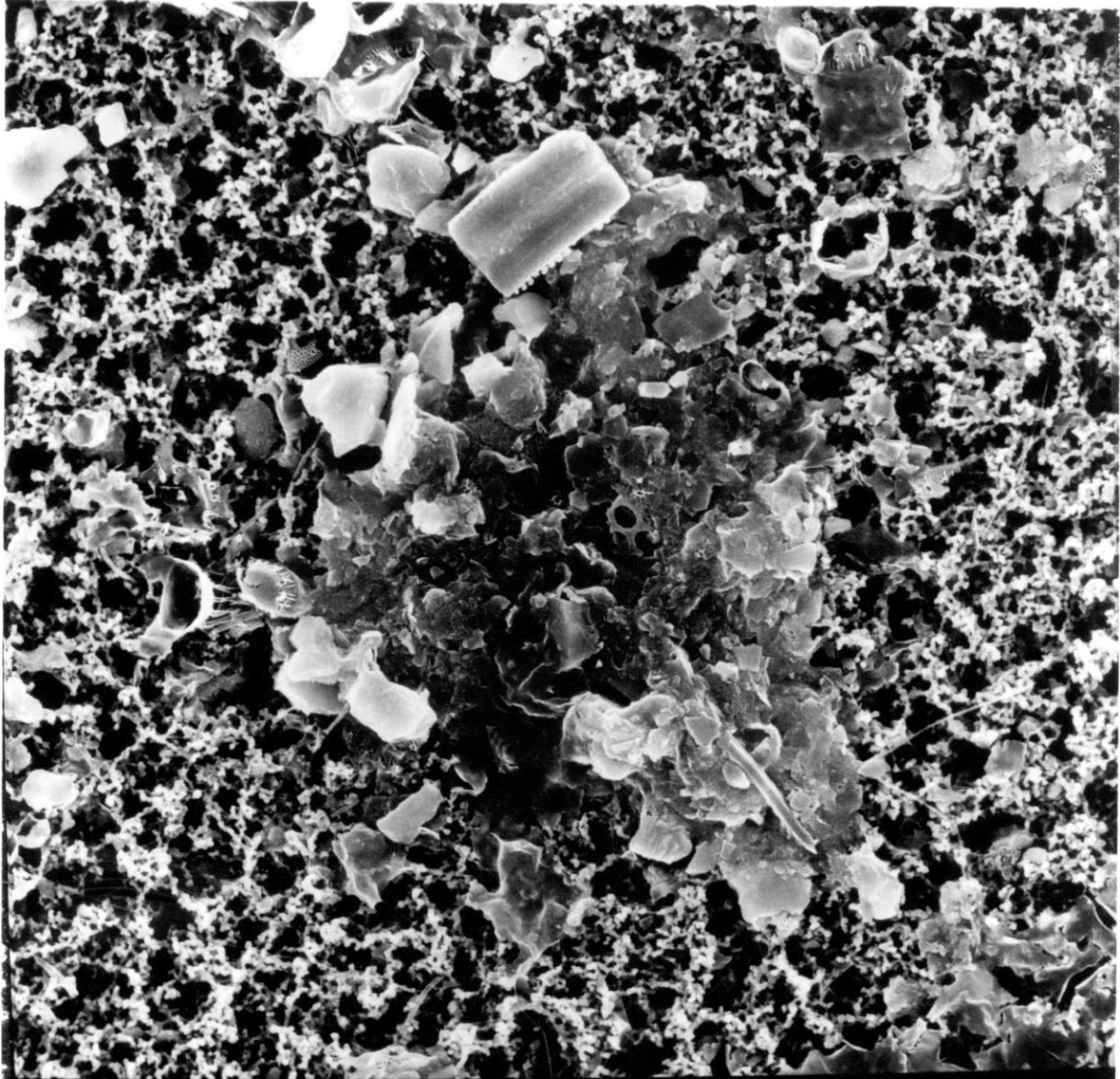
# DROGUE STUDY



materials. In addition, Emery and Honjo (1980) suggest that organic films enhance the role of fecal pellets in sinking grains below the surface, since particles are concentrated further within fecal pellets excreted by animals that graze upon the films. We might expect that the organic films in Boston Harbor play a similarly important role in the deposition of particulates.

Emery and Honjo (1980) report that organic films are found in various areas of the world ocean from which they have samples: off eastern Asia, off eastern North America, off western Africa, and the central Pacific. Thus, these films appear to be a major factor in marine sedimentation. In their work off western Africa, Emery and Honjo (1980) contrast the dominance of organic films (and aggregates) in upwelling areas with the relatively low amounts of organic film off river deltas (where the total organic content is much higher). On Georges Bank off New England, the presence of organic film corresponds with high concentrations of phytoplankton (C. Parmenter, personal communication). In Boston Harbor we noted earlier that the widespread occurrence of these organic films corresponds with increases in plankton concentration, and Sigleo et al. (1979) report that colloidal organic material in Chesapeake Bay is of marine biological origin. Thus, it appears that these organic films are a by-product of biological activity and important in sedimentary processes.

Figure 54. Photomicrograph of organically bound  
floc.



0 10.0  $\mu$  |—————|  
13-2 20.0 27 222 338

How does the discharge of organic-rich, fine-grained waste influence these films? As a source of organic matter and a source of nutrients for phytoplankton growth, sewage discharge most likely has considerable impact. Our sampling shows that despite the low chlorophyll a values for January and February, organic films may be a significant component of the seston near the Inner Harbor and Deer Island.

To learn of the composition of the organic matter in suspension, selected seston samples were examined by the techniques of thermal distillation - gas chromatography and pyrolysis - gas chromatography (Whelan and Fitzgerald, 1980). The technique involves heating a small, wet sample (0.5 - 50 mg) from 100° to 800 °C at 20 °/minute in a helium stream and measuring evolved hydrocarbons as a function of temperature. Unaltered adsorbed hydrocarbons evolve at 100° to 150 °C and cracked or pyrolyzed hydrocarbons at 500° to 800°C in two well separated peaks, P<sub>1</sub> and P<sub>2</sub>, respectively. The compounds in P<sub>1</sub> and P<sub>2</sub> are collected and analyzed further by capillary GC and GC mass spectrometry (Whelan and Fitzgerald, 1980). Analyses revealed that generally the P<sub>2</sub> peak is consistent between seston samples, implying that the organic matrix of these samples is of similar but complex composition. What does vary significantly between samples is the P<sub>1</sub> peak or the adsorbed organics. The Inner

Harbor water and the Deer Island plume give different  $P_1$  patterns. Samples from the Inner Harbor give GC patterns consistent with the presence of refined hydrocarbons (gasoline,  $C_8-C_{10}$ ). Analysis of a fecal pellet within the Inner Harbor water shows elevated levels of the "gasoline" peaks over the total suspended matter sample. In contrast,  $P_1$  peaks from surface samples near the sewage outfall show a different set of hydrocarbons ( $C_{14}-C_{16}$ ). In samples outside the plume and Inner Harbor water,  $P_1$  is low.

Apparently these organic films aid in the transport of wastes by binding particles and their associated pollutants and by adsorbing organic pollutants onto the organic matrix. In addition, these pollutants can be concentrated further by inclusion into fecal pellets excreted by animals grazing on these films -- enhancing chances of deposition. The discharge of human wastes contributes to the production of these films by supplying additional organic material and nutrients for biological uptake.

### 3) Sediment Traps

High horizontal tidal velocities in much of Boston Harbor (approaching 100 cm/sec) preclude accurate estimates of the vertical flux of particulates with sediment traps. However, two sediment trap arrays deployed for 3 days during later

cruises (Figure 55) give some insight into the importance of resuspension and the composition of settling material.

Locations were selected for their position relative to the Deer Island outfall and for local sediment type. The inner station, ST1, was located in 12 meters of water overlying a muddy bottom, while ST2 was in 10.7 meters of water over a sandy, gravelly bottom. Each array consisted of a mid-water (5 m depth) and near-bottom (1 m above) trap. Following the recommendations of Gardner (1976), the traps were 75 cm in length with an internal diameter of 30 cm. Baffling covered the trap opening to reduce turbulence.

Examination of the data reveals evidence of considerable resuspension/advection (Table 14). During 3 days in October, 1978, 318 gm of solid material collected in the bottom trap at station ST2; 87% of this material was sand size or coarser. If one uses the difference in weight between the bottom-trap and mid-trap contents as an estimate of resuspension/advection (Gardner, 1976), 94% of the bottom-trap material was resuspended (and/or advected). Similar calculations for ST1 (October, 1978), ST2 (May, 1979), and ST1 (September, 1979) yield 79%, 96%, and 73%, respectively. Though these numbers are consistent, there are large variations in total weight between the sampling cruises (Table 14).



Figure 55. Locations of sediment trap arrays.

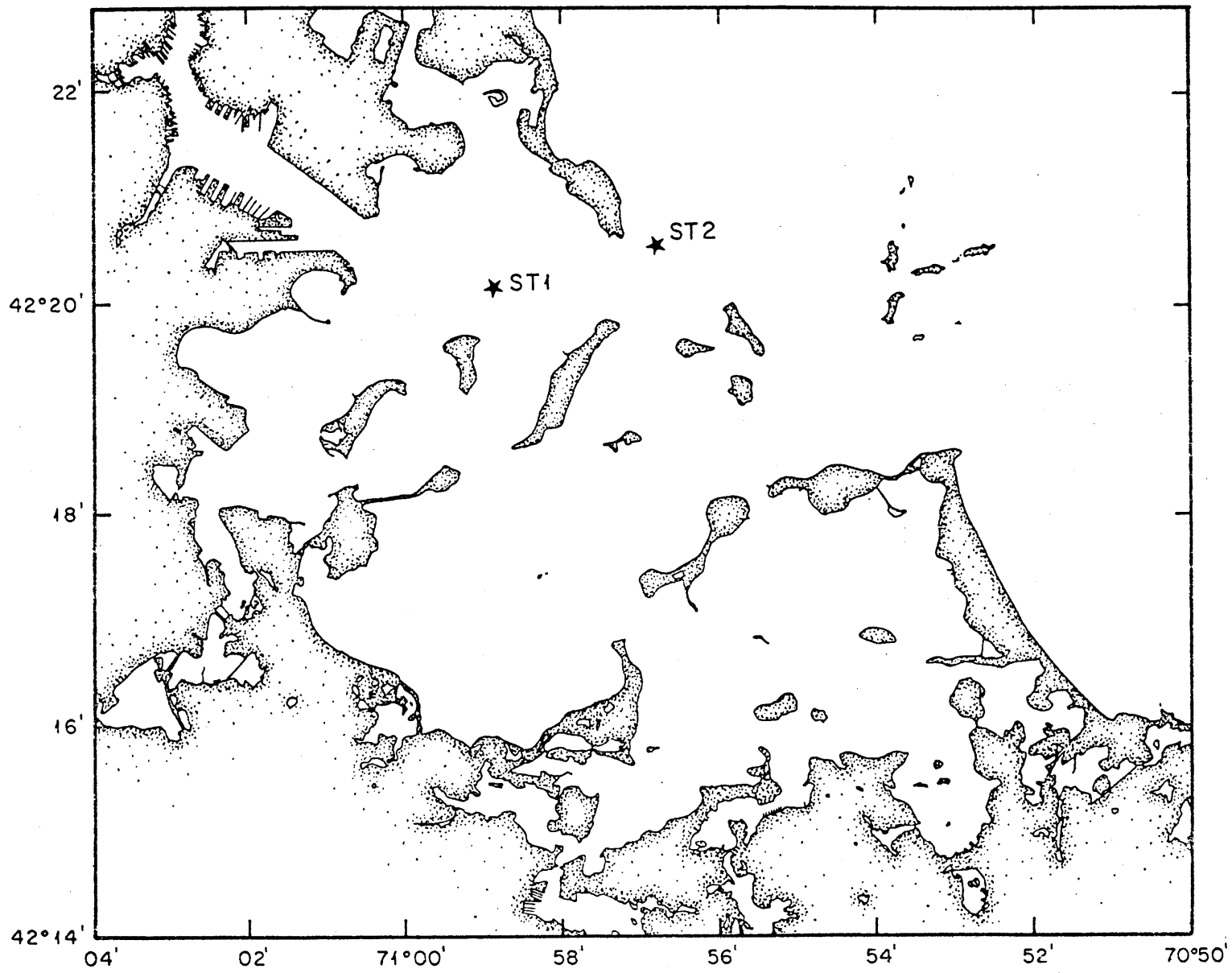


Table 14. Summary of sediment trap data

Date	Station Number	Depth	Size Fraction	Total Weight (gm)	% Sand (or coarser)	%Silt	% Clay (<2 $\mu$ m)	% Organic Carbon
October, 1978	ST1	Mid	<1 mm	5.2	28	29	43	3.1
	ST1	Btm	<1 mm	24.3	50	25	24	2.8
	ST2	Mid	>1 mm	1.2	100	-	-	-
	ST2	Mid	<1 mm	17.4	82	7	11	1.3
	ST2	Btm	>1 mm	80.8	100	-	-	-
	ST2	Btm	<1 mm	236.4	95	3	2	1.6
May, 1979	ST1	Mid	<1 mm	0.1	-	-	-	3.7
	ST2	Mid	>1 mm	.3	100	-	-	-
	ST2	Mid	<1 mm	2.2	76	9	15	2.4
	ST2	Btm	>1 mm	3.9	100	-	-	-
	ST2	Btm	<1 mm	55.1	94	3	3	3.1
September, 1979	ST1	Mid	>1 mm	.2	100	-	-	-
	ST1	Mid	<1 mm	1.0	23	37	40	7.4
	ST1	Btm	>1 mm	.4	100	-	-	-
	ST1	Btm	<1 mm	3.6	22	44	33	3.8

Note: Bottom trap for ST1 (May, 1979) lost during recovery attempt.  
 Array deployed in January, 1979 at ST1 lost during storm.

Comparison of trap data from the different seasons shows a consistency in the size distribution and organic carbon content (similar to local sediment type). The greater than 1 mm fraction consisted primarily of plant fragments, seeds, and aluminum foil. Microscopic and SEM examination of the less than 1 mm fraction reveal the predominance of mineral grains and fecal pellets. Many of the mineral grains occur in organically bound aggregates. The inorganic components consist of quartz, mica, feldspar, clay minerals, and shell fragments.

Thermal distillation-pyrolysis analyses of organic sediment trap material from October, 1978, and September, 1979 (Whelan and Fitzgerald, 1980), show that the  $P_2$  peaks (organic matrix) are consistent between trap samples and similar to the  $P_2$  peak of grab sample G27 (near ST1). Yet, these  $P_2$  peaks are very different from the  $P_2$  peaks recorded for suspended matter samples. The trap samples are more lipid-rich than the seston, implying that lipids may play an important role in the agglomeration and deposition of particulates. The  $P_1$  peaks - adsorbed material - show considerable variation between samples.

The higher organic carbon and clay content of the mid-water traps at ST1 may represent the "fluff" layer hypothesized above<sup>3</sup>. The slurry of fecal pellets and clay-rich, organically bound flocs found in the mid-water traps is similar to the mobile "fluff" reported by Weil (1976) in Delaware Bay and envisioned by Summerhayes et al. (1977) for New Bedford Harbor. Easily resuspended, this mobile carpet would be best developed in the quiet shallows of the harbor. Though these data hint at its existence, further sampling is necessary to confirm its presence.

f. Schematic Model of the Suspended Matter Regime

Trapping efficiency estimates (Chapter 2) indicate that anthropogenic wastes contribute only between 10 and 15% of the material deposited in the harbor depocenters. If biological production makes an equal contribution, then roughly 70-80% of the material deposited must come from other sources. Sediment trap data suggest that redistributed (resuspended/advected) material is the likely source. If man's contribution is so small in terms of volume, how then do we explain the apparent increase in modern sedimentation rates over the Holocene average?

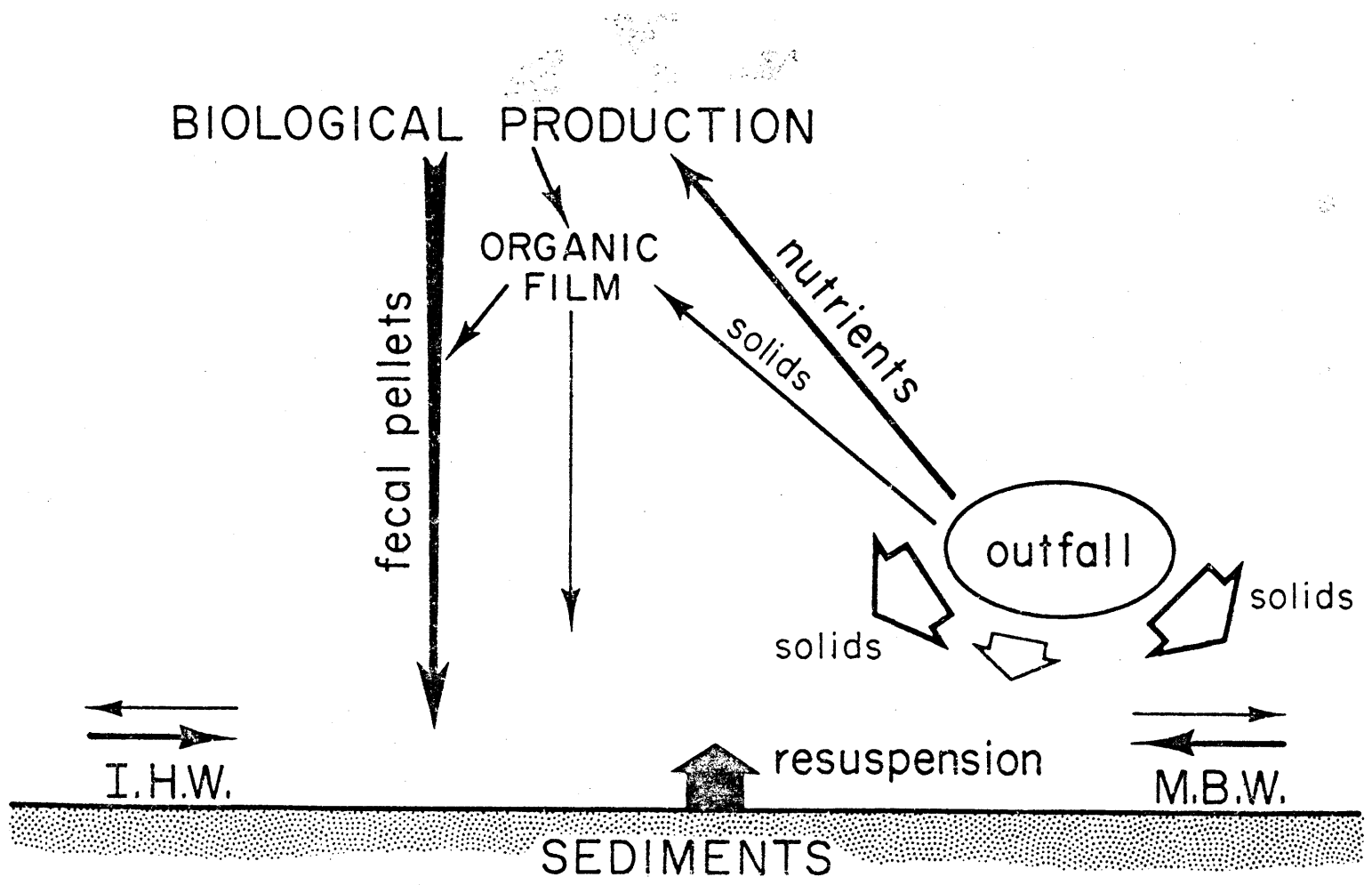
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<sup>3</sup>The material in the near-bottom traps is dominated by resuspended/advected material, which masks the character of the "fluff".

Superimposed upon the physical, chemical, and biological processes that shape the suspended matter regime of the harbor are man's activities (Figure 56). Biological activity produces an organic film that is important in the aggregation and deposition of particulates (Emery and Honjo, 1980). Sewage outfalls release nutrients into the harbor that stimulate biological production and thereby increase the abundance of this organic film. In addition, outfalls discharge significant quantities of solid material - both organic and inorganic - and associated pollutants. Organic pollutants are adsorbed onto the organic matrix of the aggregates, and trace metals are associated with the bound organic and inorganic particles. Organisms feed on these aggregates, further concentrating these pollutants into fecal pellets, which are deposited on the harbor bottom. (These fecal pellets and organic aggregates are probably cycled through the biological system several times before burial (Rhoads, 1963). However, the virtual absence of an oxidized layer in bottom sediments may limit this recycling and increase the potential for retention.) The sludge plume is not quickly dispersed, increasing the likelihood of biological interaction and particle settling. Tidal currents redistribute this sludge material along with natural sediments and deposit them between the harbor islands and northern Quincy Bay. (Seasonal changes in the circulation could alter this depositional pattern.)

Figure 56. Schematic model of suspended sediment regime.

INNER HARBOR | OUTER HARBOR | MASS. BAY





Perhaps the most important aspect of man's interaction, however, is the introduction of lipid-rich organic material. These wastes appear very efficient in the scavenging and rapid deposition of particulates. Natural material introduced into the system is quickly agglomerated and deposited (and effectively retained). Thus, though anthropogenic sources represent a small fraction of the material deposited, the types of material introduced aid considerably in the deposition and retention of natural sediment, as well as imparting a unique character to the bottom sediments -- i.e., heavily polluted!

## VII. Synthesis

The sources and sinks of modern sediment in the urban estuarine system are varied and complex. River discharge, shoreline erosion, onshore transport, biological production, and anthropogenic wastes represent the major inputs; tidal flushing, organic oxidation, and dredging the major losses. The interaction of these sources and sinks define the sedimentary regime, but that interaction is often blurred, and we observe only the end result. Boston Harbor, with its low river discharge and high urban impact, offers the opportunity to isolate the human factor and thereby assess man's role in the depositional processes of an urban estuary.

Outer Boston Harbor is the distal portion of a tidally dominated estuary. Consistent with the circulation pattern of a well mixed estuary (Pritchard, 1967; Schubel, 1971), harbor circulation (based on existing data) is generally counterclockwise, with water entering President Roads, travelling landward and southward between the islands, and leaving through Nantasket Roads. This pattern is aided by the landward and southward bottom drift prevalent in Massachusetts Bay (Bumpus, 1965, 1974).

Three distinct water masses -- Inner Harbor, Deer Island, and Massachusetts Bay -- can be characterized on the basis of water quality data. However, long residence times (Bumpus,

1953; Ketchum, 1951) limit the direct spatial impact of the Inner Harbor and Deer Island waters. Massachusetts Bay water dominates the outer portions of the harbor as well as Nantasket Roads.

Suspended matter concentrations in Boston Harbor range between 1 and 10 mg/liter, typical of many estuaries along the U.S. east coast (Folger, 1972). Tidal variations in concentration overshadow seasonal changes, and concentrations are generally higher during neap tides. The resuspension and/or advection of bottom sediments appears most vigorous during ebb tide, probably a function of tidal inequality. Similarly, Ludwick (1976) states that the intensity of erosion and deposition is greatest during ebb near the mouth of the Chesapeake.

Seston composition varies with the seasonal biological cycle. Suspended material consists of mineral grains (quartz, clay minerals, and mica), skeletal debris, and organic material. Iron, probably in the form of iron-oxide coating, is commonly associated with the mineral grains and may represent an important transporter of trace metals (Aston and Chester, 1976; Summerhayes et al., 1977). Organic matter content (loss on ignition) averages between 30 and 50 percent of the total seston depending upon the season -- higher than the year-round

average calculated for estuaries along the east coast (Biggs, 1978). Within the waters of the Deer Island plume and Inner Harbor, organic material can comprise 70% of the total suspended matter.

Organic film -- apparently the by-product of biological activity -- aids in the transport and deposition of particulates and their associated pollutants by agglomerating particles, which are subsequently ingested and transported to the bottom with fecal material. These organically bound flocs have been found in the seston from continental shelves worldwide (Emery and Honjo, 1979) and recognized as potentially important transport agents in other estuaries (Schubel, 1968; Meade, 1972). Fractionation of these clay-rich agglomerates by tidal currents seems to produce an organic-rich, clayey suspension or "fluff" similar to that found in Delaware Bay (Weil, 1976). This mobile carpet, easily resuspended in the shipping channels and exposed portions of the harbor, would form a transition zone between the silty, less mobile subsurface sediment and the suspensates of the turbid water column.

Black, anerobic, organic-rich (up to 5% organic carbon) muds are accumulating in several harbor depocenters at an estimated rate of 0.2 - 0.3 cm/yr -- higher than the average deposition rates in Narragansett and Delaware Bays (Biggs, 1978). These depocenters, located in northeastern Dorchester Bay, Deer Island Flats, Moon Head, and northern Quincy Bay, are often impenetrable to acoustic energy due to the presence of methane gas bubbles, similar to the organic-rich acoustically turbid zones of Chesapeake Bay (Schubel and Schimer, 1973). The organic material in Boston Harbor shows a large terrestrial influence which includes pollen, spores, humic and cuticular material.

These organic-rich muds are also metalliferous. The surface distribution of trace metals points to the Inner Harbor and Deer Island as the likely sources. Statistical analyses of bottom sediment data suggest that organic matter and iron oxide are important in the retention of trace metals (Presley et al., 1972; Aston and Chester, 1976) as seen in New Bedford Harbor (Summerhayes et al., 1977) and San Francisco Bay (Eaton, 1979). Down-core variation in metal profiles suggest that surface enrichment results from increasing input and that alteration of harbor configuration changes depositional patterns.

The importance of the different sediment sources varies spatially within the harbor. The influence of the Inner Harbor, with its large organic and trace metal load, appears restricted to northern Dorchester Bay and western President Roads. The dispersal of the Deer Island plume into Massachusetts Bay is incomplete; material settles; and bottom currents redistribute this material (and pollutants) about the quiescent portions of the harbor. In addition, the nutrient input from the Inner Harbor and Deer Island stimulate biological production in the northern region of the harbor.

Geochemical evidence suggests that the harbor retains at least 33% of the material discharged at Deer Island (or 10-15% of the sediment deposited in the depocenters). Redistributed material appears to be the most important sediment source in the depocenters, accounting for as much as 70-80% of the material deposited. Harbor circulation indicates that Massachusetts Bay may be a source of this redistributed (resuspended/advected) material (Meade, 1969; Drake, 1976; Swift, 1976). Ootsdam (1971), for example, reports a net contribution of shelf material in Delaware Bay.

Though sewage wastes represent a small fraction of the material deposited, anthropogenic impact must account for the apparent increase in sedimentation rate over the Holocene average. Yet, how do estuarine processes interact to produce the observed sediment patterns? Suspended clays adsorb trace metals, aided, perhaps by iron oxide coating. Biological

activity, stimulated by sewage discharge, produces an organic film that agglomerates the suspended particles and associated pollutants. Organisms feed on this film, further concentrating these particles into fecal pellets which are rapidly deposited. Organic, lipid-rich material released by the outfalls appears important in the aggregation and rapid deposition of particulates. Tidal currents resuspend bottom sediments, and long-term bottom drift moves this material landward. Long flushing times increase the likelihood of biological interaction and aggregation, and this material is deposited between the harbor islands. Once deposited, these aggregates may be cycled through the biological system several more times before burial. Thus, it would appear that man enhances the trapping efficiency of the harbor (and therefore sedimentation rate) by stimulating the biological production of "film" and through the discharge of lipid-rich organic material.

This study has focused on the impact of sewage discharge. Yet, other of man's activities also have influenced the harbor environment. Engineering projects, such as causeway construction and landfill operations, surely impact the sedimentary regime and may account for some of the modern increase in sedimentation rate. The closure of waterways (e.g. the Charles River dam and the closing of Shirley Gut) alter harbor circulation or sediment input and, thus, affect

depositional patterns. Shoreline construction and landfill operations also can change circulation as well as contribute to the sediment supply by increasing erosion and by introducing fine-grained sediment.

The data in this report relate the sinks of harbor sediment to "fair weather" sources. However, these conditions (or processes) cannot be assumed to dominate the long-term sedimentary environment. Major storms potentially can alter drastically depositional patterns through erosion, mixing, and redeposition. Existing information unfortunately is inconclusive, but the potential influence of storm events cannot be overlooked. Although trace metal and sediment profiles in harbor cores show no evidence of past storm events, three core sites reoccupied following the "Blizzard of '78" suggest erosion and mixing of sediment (Bothner et al., 1980). These data, however, are highly ambiguous due to the gross lateral heterogeneity of subsurface sediments (Bumpus et al., 1951).



### VIII. Recommendations for Future Work

This study investigated on a broad scale the geologic history of the harbor, the modern accumulation of pollutants, and the temporal and spatial variations in water quality. Given the present state of knowledge of the harbor environment, future efforts should concentrate on those problems defined but not delineated: the current regime and its temporal variability; the impact of storm events on the sedimentary environment; diagenetic processes and their implications for pollutant mobility; and the influence of storm-sewer overflows on the environment of the Inner Harbor.

Existing data on the current regime of Boston Harbor lack the seasonal coverage necessary to define adequately the circulation pattern and its influence on sediment distribution. A network of recording current meter arrays (surface and near-bottom meters) could outline the general circulation of the harbor and ensure proper delineation of the time scales of water movement (tidal and seasonal variability, storm events, etc.). Such information would aid greatly in understanding existing sediment data and in evaluating future harbor projects.

Storm events can alter significantly the sedimentary environment and thus pollutant distribution. Assessing the influence of these transient events is difficult but might be accomplished by utilizing a bottom instrument package -- camera, transmissometer, current meter, temperature and pressure sensors, sediment trap, and water samples (triggered by the transmissometer). Several of these packages (on tripods) deployed in the harbor approaches and in the depocenters would record the changes in water movement, wave climate, and sediment transport associated with storms as well as contrast the reaction of these two environments. Accurately located cores taken during deployment and after a storm event could integrate the effects of the storm on the sediments.

Toxic metals and organic pollutants are of grave concern to environmentalists, health officials, and resource managers. Once deposited, these pollutants are subject to biological interaction and widely varying chemical environments. Examination of the various diagenetic changes through which these pollutants proceed is necessary for understanding the capacity of the sediments to retain these materials. Analyses of cores need include measurements of sediment and pore water chemistry and of partitioning of pollutants among various phases.

Investigations to date have focused on the Outer Harbor and the impact of the sewage outfalls. Boston's Inner Harbor, however, remains poorly understood in terms of circulation, sediment (and pollutant) input and accumulation, and its contribution to the Outer Harbor. The Inner Harbor represents a very complex environmental problem because of the hundreds of pollution discharge points (storm-sewer overflows) and their sporadic input. Yet, assessing the impact of these overflows is essential to drafting an effective harbor cleanup plan. Studies should include monitoring of key discharge points, water and sediment chemistry (input and accumulation), water circulation, and sediment transport within the Inner Harbor itself.

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#### Publications

Fitzgerald, M.G., 1975, Stratigraphic trap potential of the Carrizo-Wilcox section in up-dip South Texas. Shell Oil Company Technical Report.

Summerhayes, C.P., Ellis, J.P., Stoffers, P., Briggs, S.R., and Fitzgerald, M.G., 1977, Fine-grained sediment and industrial waste distribution and dispersal in New Bedford Harbor and western Buzzards Bay, Massachusetts. Woods Hole Ocean. Inst. Tech. Rept. No. 76-115, 110 pp.

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## XII. APPENDIX I.

### a. Field and Laboratory Methods

Ten cruises in the study area aboard the R/V ASTERIAS (W.H.O.I.) and R/V EDGERTON (M.I.T.) from August, 1977-September, 1979, account for data collection. Cruise scheduling maximized seasonal coverage and facilitated coring and acoustic profiling operations.

#### 1. Seismic Operations

Seismic profiling operations (April, 1978) utilized equipment on loan from the Woods Hole Office of the U.S. Geological Survey. Richard Sylwester of the U.S.G.S. lent his technical expertise to the operation and maintenance of the acoustic gear.

Equipment included a 3.5 kHz fish with four transducers (Ocean Research Equipment), an O.R.E. 140 transceiver with a power output of 2.5-5 kw, and an E.P.C. recorder. Pulse length was set at 0.2 msec. Recorder sweep rate was 1/16 sec, which produced a record with a full scale of 50 m.

Survey lines were run between Coast Guard navigation buoys. Navigational control relied on line-of-sight and radar fixes on the buoys. It was assumed that buoy locations on Coast Guard charts were accurate. Survey line crossovers showed close agreement in water depth and sediment thickness, supporting that assumption.

## 2. Bottom Sediments

Sediment sampling included piston cores, gravity cores (2-3 m), Van Veen grabs, and hydrostatically damped cores, which recover the upper 50-70 cm of sediment . Core locations were selected to highlight areas of anomalous organic and heavy metal content (Mencher et al., 1968; White, 1972), historical depocenters (from seismic survey), and the "unpolluted" area of westernmost Massachusetts Bay. Grab samples filled the gaps in surficial coverage.

Two hydrostatic cores were taken at each site. One of these was immediately sampled to obtain profiles of Eh and pH. The remaining cores and grab samples were frozen for later analyses. Before subsampling, piston cores were split and photographed and the remaining hydrostatic core x-rayed to highlight downcore variations and to check for bioturbation (mottling and burrows).

Most analyses were performed on the hydrostatic core. These cores were subsampled at 4-5 cm intervals and dried to determine water content. Size analysis employed the Rapid Sediment Analyzer (RSA) of the U.S.G.S. for the sand fraction and Coulter Counter measurements of the 63 micron fraction (Schlee, 1966). Sediment lithology of the various size fractions were examined using light microscopy and x-ray diffraction (Phillips APD 3500). Powder mounts were used

for x-raying the silt fraction, while silver filters provided an oriented sample for clay mineral identification (Hathaway, 1971). The clay fraction was treated with 10% peroxide to remove organics.

Duplicate samples were analyzed for total carbon and organic carbon content using a LECO carbon analyzer. Samples for organic carbon measurements were treated for 4 hours with 2N HCl to remove the  $\text{CaCO}_3$ . Similarly, total nitrogen content was determined using a LECO nitrogen analyzer (triplicate samples). The LECO devices are precise to  $\pm 1\%$  and  $\pm 2\%$  of the carbon and nitrogen present, respectively. Reproducibility was generally within  $\pm 5\%$  for both carbon and nitrogen determinations.

The distribution and accumulation history of trace metals were examined under the supervision of Dr. Michael Bothner (U.S.G.S.). For grab samples, both bulk sample and clay fraction were analyzed, while only bulk samples were examined in cores. The following elements were determined for most samples:  $\text{Al}_2\text{O}_3$ , Cd, Cr, Cu,  $\text{Fe}_2\text{O}_3$ , Hg, Mn, Mo, Ni, Pb, Sb, V, and Zn. Statistical analyses identified those elements with significant covariance and enabled us to reduce



the element coverage in some cores.  $\text{Al}_2\text{O}_3$  and Mo were determined spectrophotometrically.  $\text{Fe}_2\text{O}_3$ , Zn, Mn, Cr, Pb, and Cu were analyzed using flame atomic absorption spectroscopy (AAS), and Cd, V, Ni, As, Hg, and Cu were determined using flameless AAS.

Absolute rates of sedimentation were documented using methods of  $^{210}\text{Pb}$  determination (Bruland, 1974). Examination of  $^{210}\text{Pb}$  activity was carried out by analysis of the granddaughter  $^{210}\text{Po}$ , which is assumed to be in secular equilibrium with  $^{210}\text{Pb}$  (Nittrouer, 1979). Sample preparation followed the procedure of Flynn (1968). The alpha activity of the Po isotopes was determined by counting with silicon-surface barrier detectors connected to a multichannel analyzer. The activity of the  $^{208}\text{Po}$  spike was calibrated against a  $^{210}\text{Po}$  standard solution obtained from the Nuclear Regulatory Commission, Health and Safety Laboratory, New York, New York.

### 3. Suspended Sediments

#### a. Field Work

Water samples for suspensate and water quality analyses were retrieved using 5 liter Niskin bottles. After thorough mixing, subsamples were taken for suspended matter and dissolved nutrient determinations. Nutrient samples were immediately frozen using dry ice, and the one liter seston sample was fixed with 10 ml of Lugol's solution (iodine plus

potassium iodide) to halt bacterial action. Soon after collection, thirty to a hundred milliliters of water were passed through pre-ashed glass fiber filters for later measurements of chlorophyll a. These samples were preserved with  $MgCO_3$  and wrapped in aluminum foil before freezing. Additional water samples were saved for studies of dissolved trace element by the New England Aquarium.

Tidal variations in suspended load were observed by obtaining time-series samples at several stations (Figure 46) during each cruise for the first year. Diurnal studies of temporal variability - hourly sampling - at BH1 and BH3 were undertaken during the second year to characterize seston sources.

Horizontal control between stations was achieved on selected cruises using a 200 kHz echo sounder (also operates at 357 kHz and 500 kHz simultaneously). Capable of detecting particulate concentration differences greater than 1 mg/l, this ultrasonic acoustic profiler outputs a continuous profile of suspended particulate matter within the water column. Suspended matter samples calibrate the acoustic system. This unit was also employed to follow the development and dispersal of the Deer Island sludge plume and provided information on the net horizontal flux of particulates during our May, 1979 diurnal study. For details on the system's specifications and components see Hess and Orr (1978).

b. Laboratory Analyses

Measured volumes of water were passed through pre-weighed pairs of Millipore<sup>R</sup> filters (nominal pore size of 0.45  $\mu$ m). Thorough rinsing with filtered distilled water removed any salt. After air drying, filters were weighed using a Perkin-Elmer Autobalance Model AD-2 (accuracy  $\pm$  0.005 mg) to obtain total suspended matter concentrations. The bottom filter of the pair served as a corrected filter weight. Ratios of combustible to noncombustible material were derived by halving the filter pair and combusting each filter half in a pre-weighed platinum crucible at 500°C for one hour. After cooling, the crucible plus ash was weighed using the Perkin-Elmer. Determinations of total suspended matter and combustible-noncombustible concentrations were reproducible within  $\pm$  10%. A more complete description of techniques can be found in Manheim et al. (1970).

The remaining filter half served as an archive sample. Slides for microscopic analysis were prepared for each sample using Cargille Type B oil immersion, which renders the filter translucent. After thorough light microscopic examination, selected samples were inspected and photographed under the scanning electron microscope (S.E.M.). In addition to visual examination of the particulates, a semi-quantitative analysis

of elemental composition was obtained using the energy dispersive x-ray fluorescence unit (KEVEX) attached to the SEM (U.S.G.S. facility).

Concentrations of chlorophyll a were determined using the 90% acetone extraction method of Yentsch and Menzel (1963). Net percentage of fluorescence (chlorophyll a corrected for pheophytin) was measured on a Turner Fluorometer Model 110. Standards for calibration of the fluorometer were provided by the Environmental Protection Agency's Environmental Monitoring and Support Laboratory in Cincinnati, Ohio.

Dissolved nutrient concentrations were obtained by Dr. Zofia Mlodozinska (W.H.O.I.) using a Technicon Autoanalyzer II. Nutrients examined included  $\text{NH}_3\text{-N}$ ,  $\text{NO}_2\text{-N}$ ,  $\text{NO}_3\text{-N}$ ,  $\text{PO}_4\text{-P}$ , and  $\text{SiO}_2\text{-Si}$ . Samples were reproducible within 1-1.5%, 1-1.5%, 1-2.0%, 1-2.0%, and 1-2.0%, respectively for the nutrients listed. Methods for the automated analysis of nutrients were based on Wood, Armstrong, and Richards (1967) for nitrate, Bendschneider and Robinson (1952) for nitrite, Murphy and Riley (1962) for phosphate, Koroleff (1976) for silicate, and Solorzano (1969) for ammonia. Techniques are summarized in Technicon Company Industrial method papers (1973).

### XIII. APPENDIX II

#### a. Water Properties and Suspended Matter

Nine cruises covered a period from August, 1977 through September, 1979. The first five cruises to the harbor focused on the tidal variations at eight stations (Figure 57), providing harbor-wide coverage. The last four cruises concentrated on stations BH1 and BH3 --greatly increasing sampling frequency to characterize the variability and nature of the major seston sources. This section is a cruise-by-cruise examination of water properties and suspended matter.

August, 1977 (neap tide conditions)

Both the waters and seston in the outer harbor represent a mixture of several sources -- Inner Harbor, Massachusetts Bay, biological production within the harbor, outfall material, and resuspended bottom sediments. At station BH3, a core of cold, bottom water enters the harbor on flood tide (Figure 58). Characterized by relatively low dissolved ammonia values, intermediate dissolved nitrate values, and low concentrations of seston, this Massachusetts Bay water appears to represent the bulk of water transported in and out of the harbor. In contrast, the influence of the Deer Island outfall is reflected in high ammonia and total suspended matter content at 2120 hours. The high surface ammonia values during the previous

Figure 57. Suspended matter and water quality stations.

# SUSPENDED SEDIMENT STATIONS

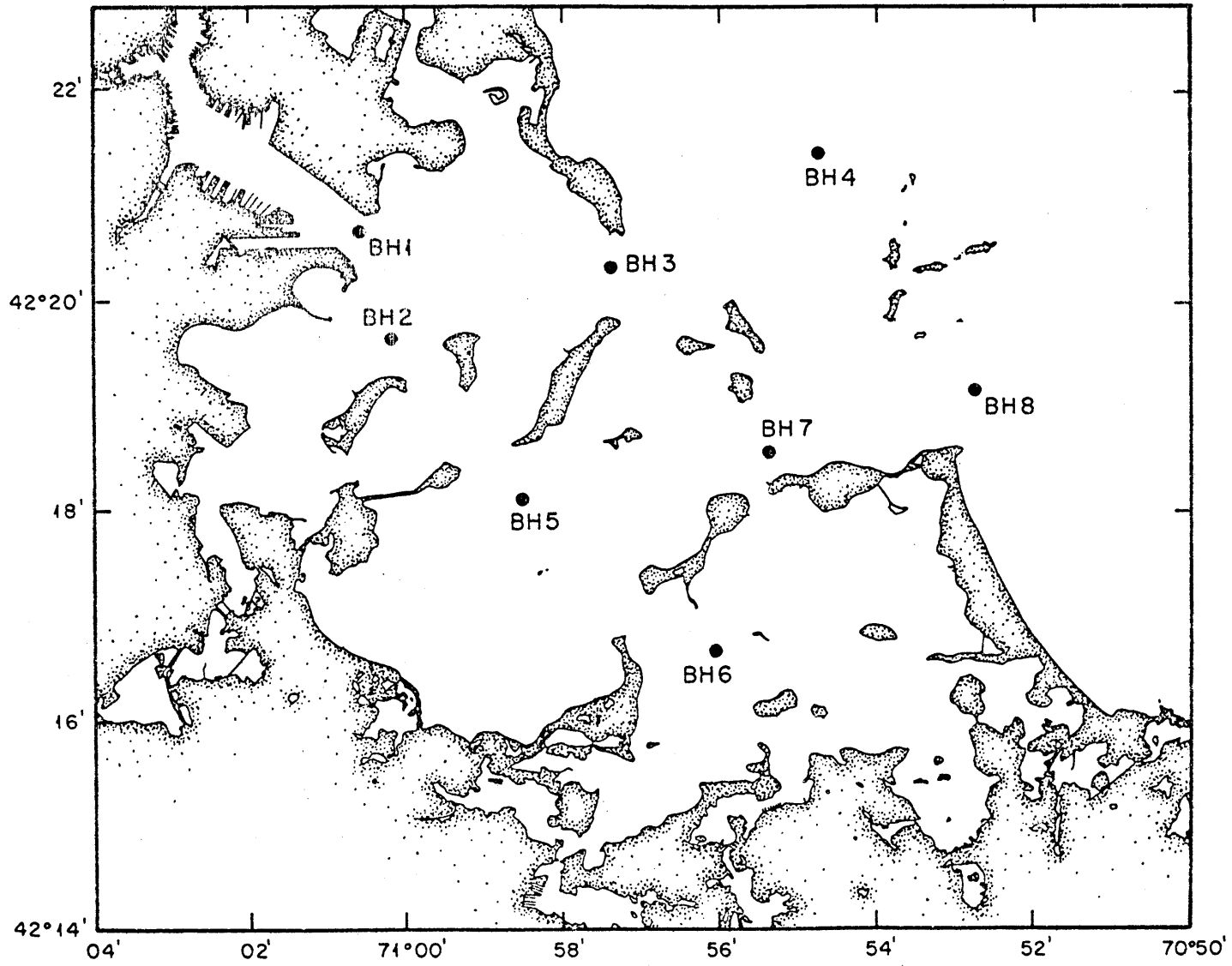
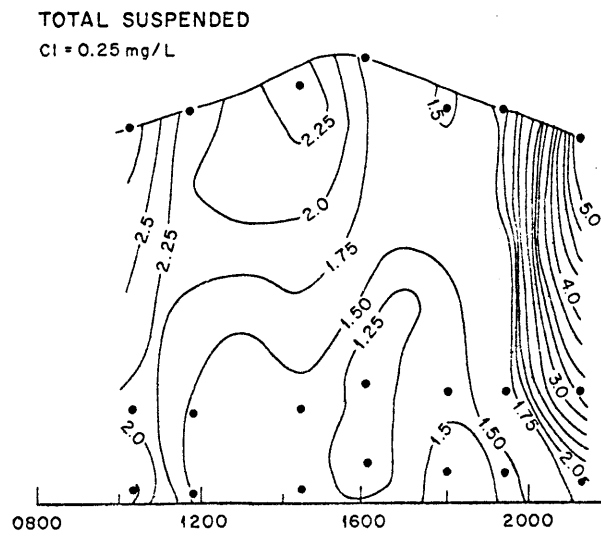
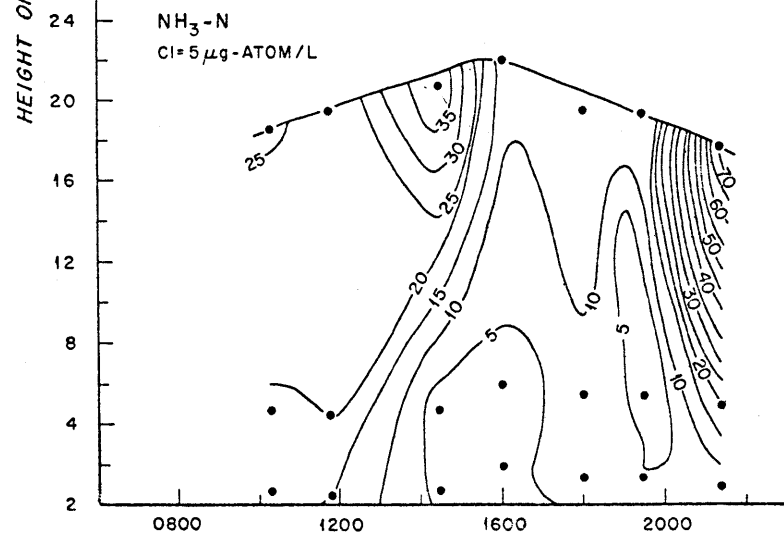
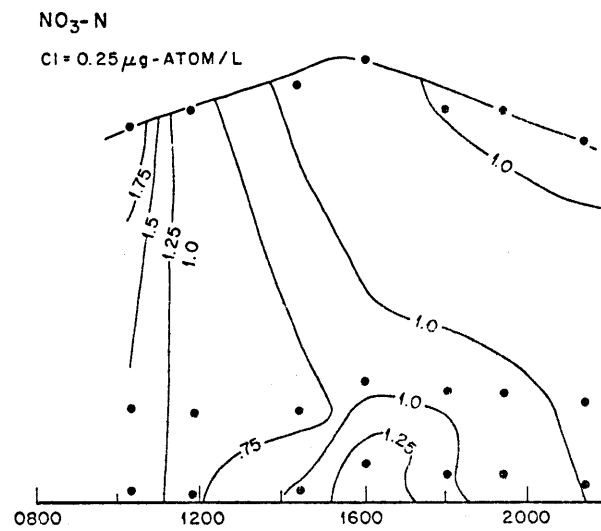
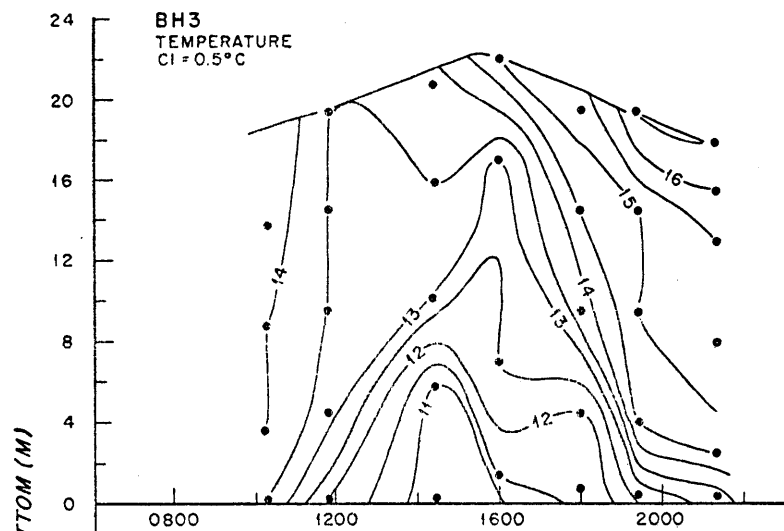


Figure 58. Tidal variations at station BH3, August, 1977.





TIME (LOCAL EDT)

incoming tide suggest that part of the preceding effluent plume had re-entered the harbor. These observations have important consequences for the dispersal of the Deer Island plume for if the major tidal exchange involves near-bottom Massachusetts Bay water, then surface tidal movement is limited and the plume does not disperse effectively.

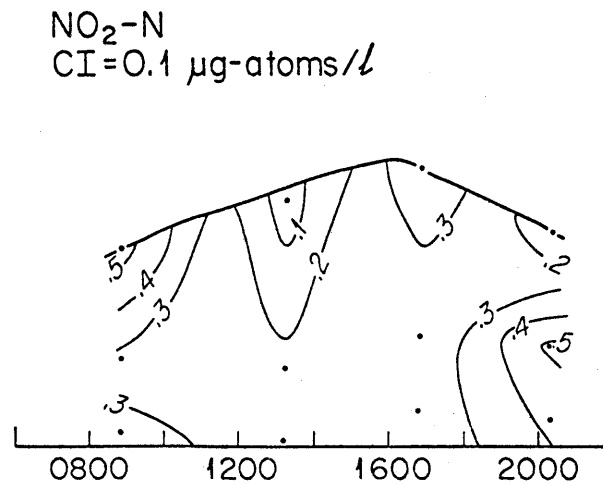
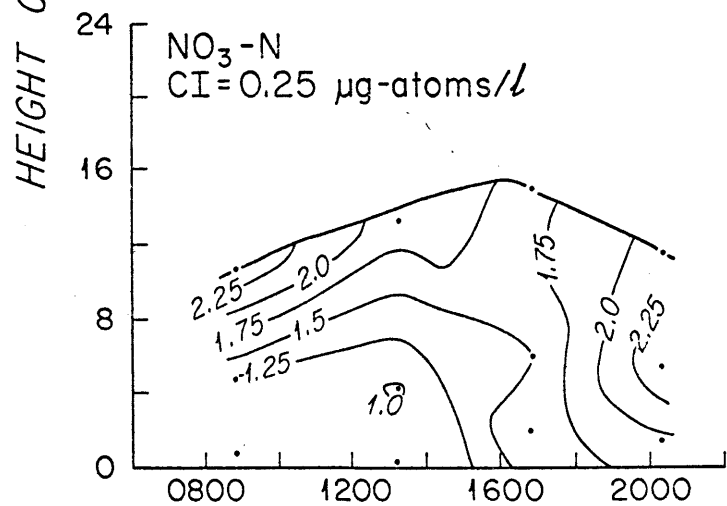
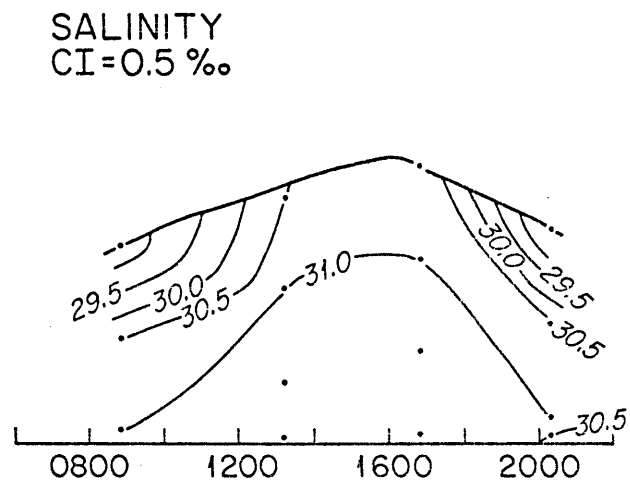
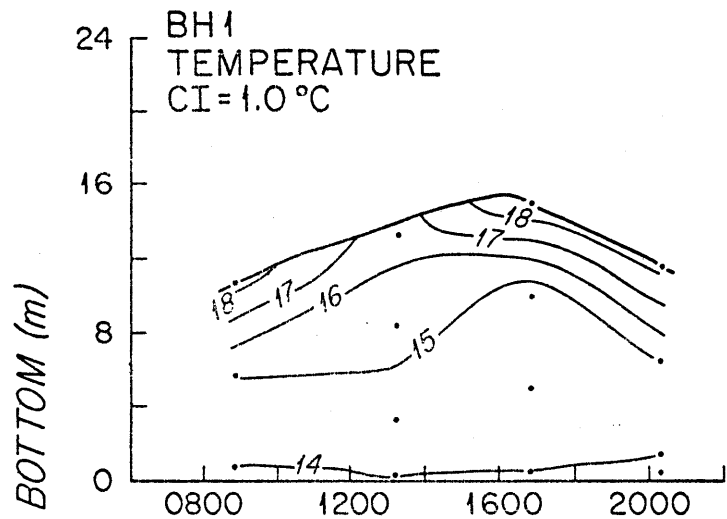
Station BH1 gives some evidence of the character of the waters in the Inner Harbor. Warmer temperatures, decreased salinities, and higher  $\text{NO}_2\text{-N}$  and  $\text{NO}_3\text{-N}$  concentrations reflect the influence of the Charles, Mystic, and Chelsea Rivers (Figure 59). Lower oxygen saturation values point to the high organic load in the Inner Harbor.

Stations BH7 and BH8 in Nantasket Roads show some temperature stratification, but for the most part, seston and nutrient concentrations vary little with depth or with tidal stage.

Near-bottom concentrations of noncombustible suspended matter are highest just before and after slack low water, suggesting that resuspension/advection is greatest with decelerating and accelerating current.

Seston is dominated by mineral grains -- quartz, mica, and clay minerals (noncombustible content averages 51.5%). Energy

Figure 59. Tidal variations at station BH1, August, 1977.



TIME (LOCAL EDT)  
8/77

dispersive x-ray analysis (KEVEX attachment to SEM) of these particles indicate that iron-coating -- an efficient scavenger of trace metals -- is common. In fact, several particles examined did have associated trace metals.

The organic component of the suspended matter is dominated by an organic "film" which blankets the filter, particularly for samples at stations BH1, BH2, and BH3. Such organic film has been reported for several shelf areas (Emery and Honjo, 1979), including Georges Bank (C. Parmenter, personal comm.).

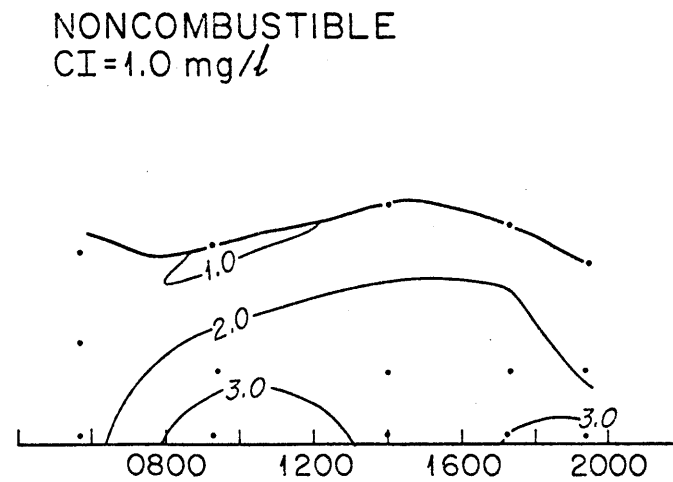
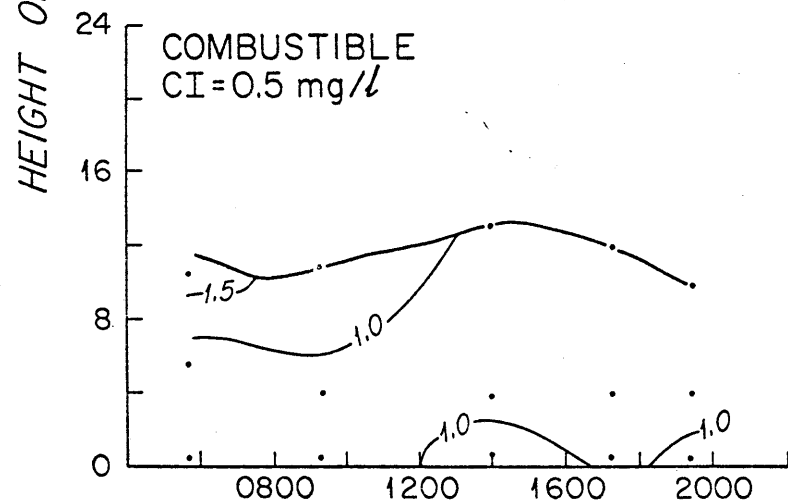
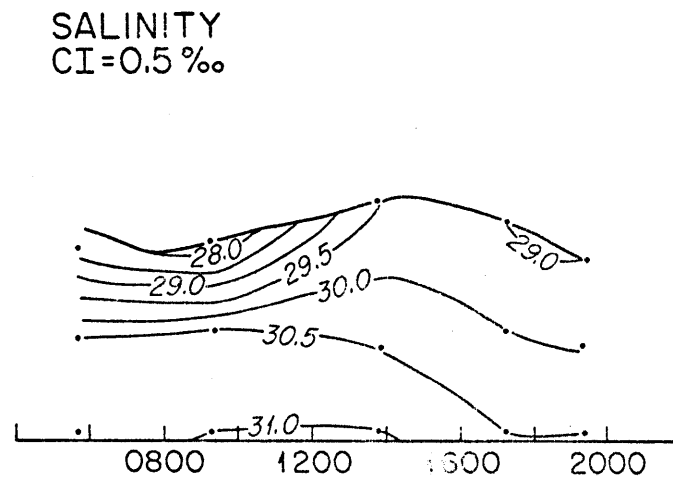
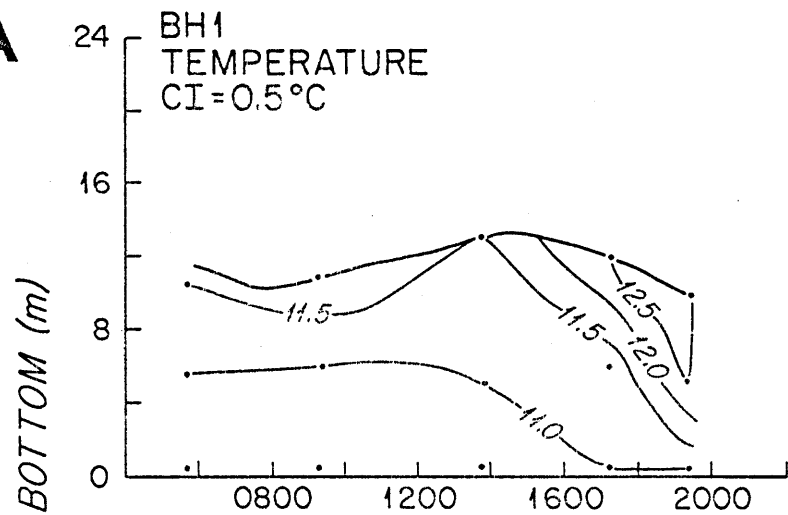
Plankton also contribute significantly to the organic and inorganic components. Diatoms fragments and frustules are prominent constituents. The plankton population (as inferred from these Niskin bottle samples) consists primarily of Thalassiosira sp., Coscinodiscus sp., ebridians, and tintinnids. Several genera of pennate diatoms are present, particularly in near-bottom samples, but represent minor constituents. Actual plankton counts are precluded by the extent and thickness of the organic film.

November, 1977 (neap tide conditions)

Water temperature has decreased and the temperature range (10.6-12.5°C) narrowed since August (Figure 60), with the water column becoming well mixed. Temperature and salinity profiles for station BH4 outline the Massachusetts Bay water entering the harbor, but harbor mixing obscures its signal further inshore.

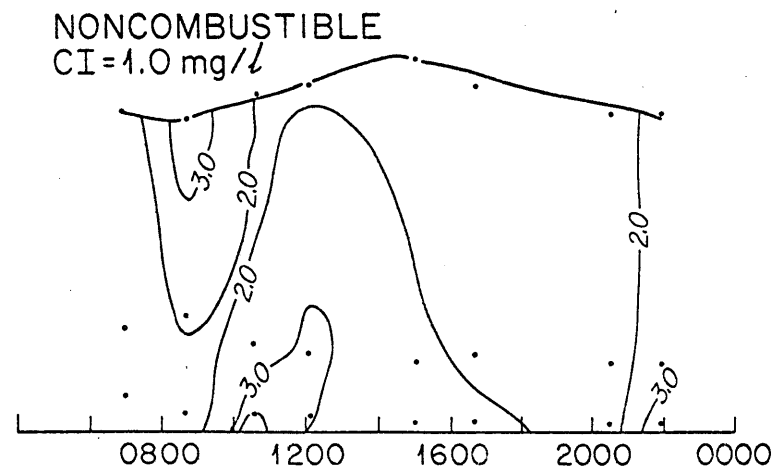
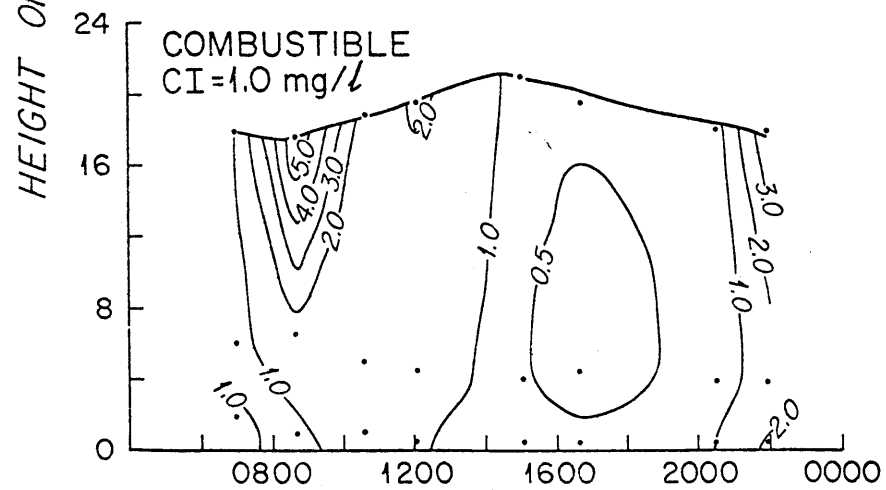
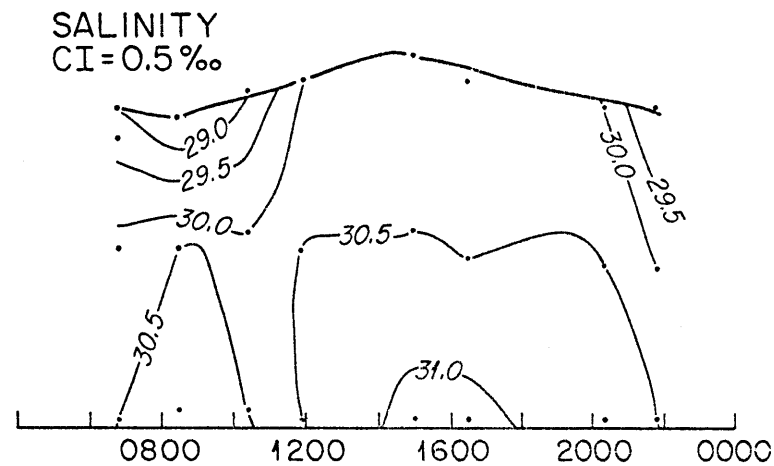
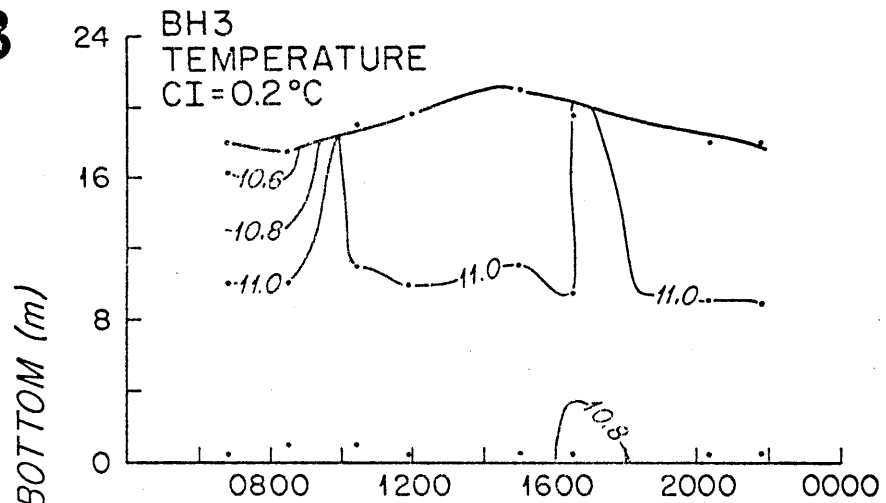
- Figure 60.
- A. Tidal variations at station BH1,  
November, 1977.
  - B. Tidal variations at station BH3,  
November, 1977.

**A**



TIME (LOCAL EDT)

11/1/77

**B**

TIME (LOCAL EDT)  
11/1/77



Nutrient samples were not collected, but the impact of the Deer Island sludge discharge is seen in the suspended matter profiles for station BH3 at 0845 and 2150 hours. The reappearance of the plume at this station at 2150 shows that the sludge plume does maintain its structure at least over a tidal cycle, which reflects the incomplete dispersal of this material.

Profiles of noncombustible material show the resuspension of bottom material near slack low water. Sediment trap samples, discussed in the text, give a better indication of the importance of resuspension.

Clay minerals, quartz grains, and mica dominate the seston in all samples. Many of these clay and silt-size particles are aggregated and iron-stained. Carbonate laths

- not observed in our August samples - are important constituents of the seston. These "needles" (30-100 microns in length and 2-10 microns wide) appear to come from the breakdown of mollusk shells (see text).

With the exception of station BH3 near the Deer Island outfall, organic particles are relatively minor. Even at BH3 organics are primarily in a particulate form rather than a film. This decreased importance is likely the result of reduced biological activity.

Whole plankton tests are greatly reduced over August samples. Pennate diatoms (Navicula sp. and Pleurosigma sp.) dominate near bottom samples. The silicoflagellate Distephamus sp. is fairly abundant and indicative of colder water. Skeletonema sp., Coscinodiscus sp., and Thalassiosira sp. are minor constituents. Tintinnids are quite abundant in some samples.

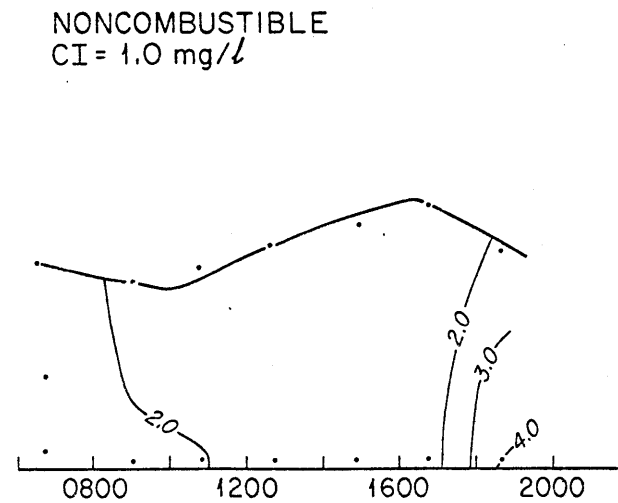
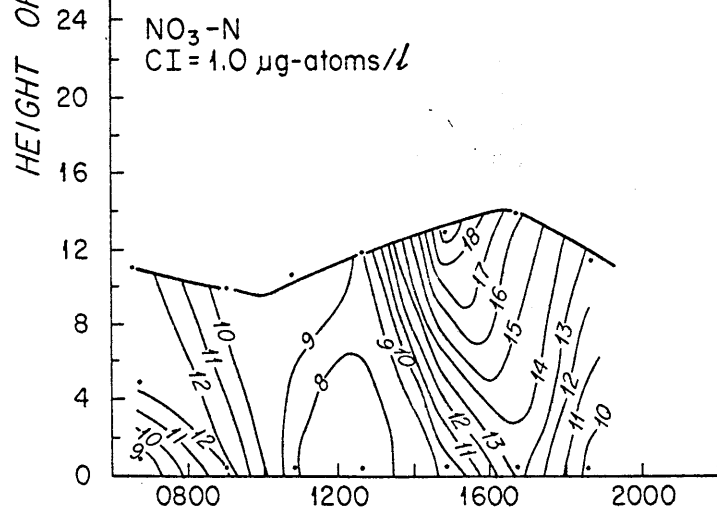
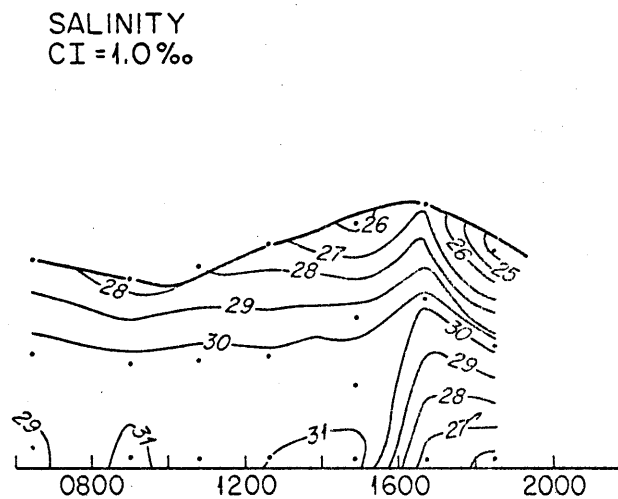
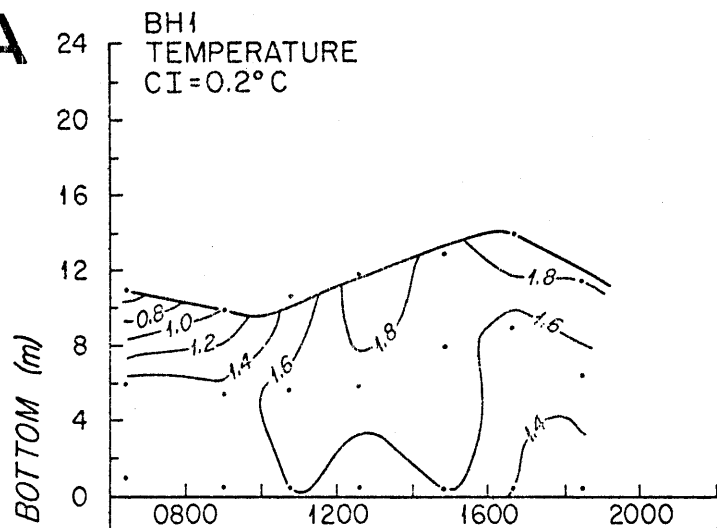
January, 1978 (neap tide conditions)

Water temperatures range between 0.5 and 1.5°C, and the water column is very well mixed (Figure 61). High-salinity bottom waters at BH3 outline the core of Massachusetts Bay water entering the harbor; profiles from the Nantasket Roads stations do not distinguish this water mass and generally display little tidal variation, suggesting rapid mixing. Nutrient concentrations - outside of the outfall plume - are quite high with NO<sub>3</sub>-N, for example, ranging from 7.0-14.0 μg-atoms/l.

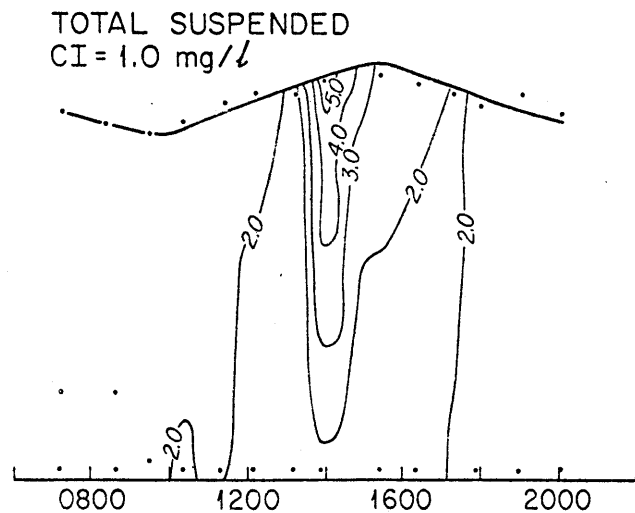
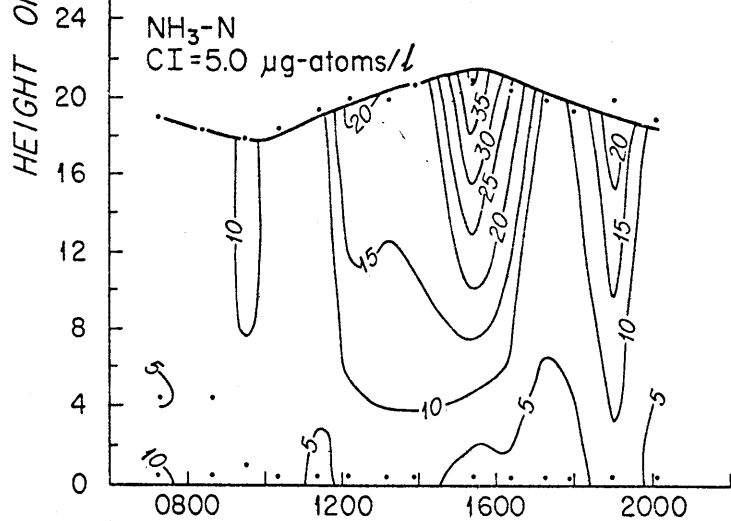
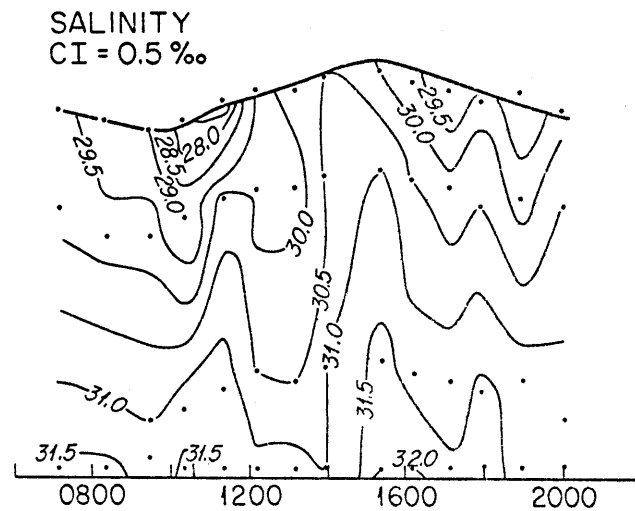
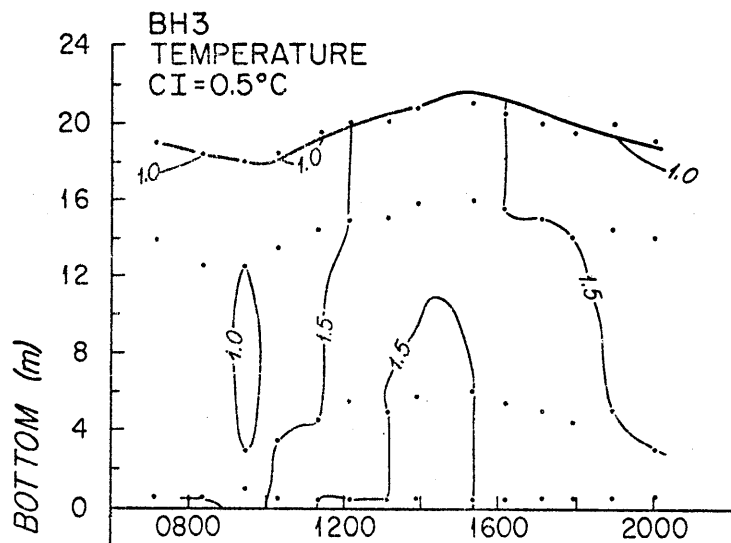
Suspended matter, ammonia, and phosphate profiles highlight the extent of the Deer Island sludge plume at station BH3 (Figure 61B). Data suggest that this plume extended as far seaward as BH4 on the ebb aided by a NW wind. Nutrient and combustible material profiles suggest that the Deer Island plume also influenced concentrations at BH1 (at 1450 hours).

- Figure 61.
- A. Tidal variations at station BH1,  
January, 1978.
  - B. Tidal variations at station BH3,  
January, 1978.

**A**



TIME (LOCAL EST)  
1/31/78

**B**

TIME (LOCAL EST)  
1/31/78

Suspended matter concentrations are lower overall than previous cruises, suggesting the importance of biological production on seston values. Noncombustible concentrations, though fairly uniform throughout the water column, do show some increase during ebb tide. Because of the low biologic activity, organic material is not a major component of the samples except at station BH3. Where present, organics appear as particulates and not as a blanketing film.

Individual mineral grains of quartz, mica, and clay minerals dominate the suspended matter. Aggregates are few. Back-scattering x-ray analyses show that iron and manganese are associated with most mineral grains. Pyrite framboids occur in some samples (primarily near bottom samples) and probably represent resuspended material.

Carbonate laths are a visually prominent component of the suspended matter. As stated earlier, these laths appear to come from the degradation of mollusk shells.

Navicula sp. dominate the pennate diatoms while Pleurosigma sp. and Rhizosolenia sp. are secondary constituents. Coscinodiscus sp. are the major centric diatom. Thalassiosira sp. are present but in minor amounts. Agglutinated forams collected in some samples are probably resuspended. Fecal pellets occur in significant numbers, usually without a pellicle.

May, 1978 (spring tide conditions)

Salinity is much lower - ranging from 26.0 - 29.0 ‰ -- at all stations both in the north and south as a response, perhaps, to the higher river discharge of New England rivers (Bumpus et al., 1953; Manoshar-Mahara and Beardsley, 1973). Water temperatures range from 5.0 - 10.0°C, but stratification is not well defined except at BH1 during ebb tide (Figure 62A).

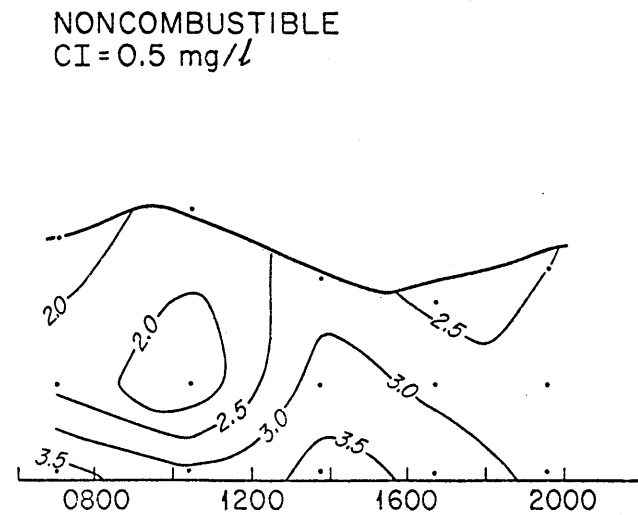
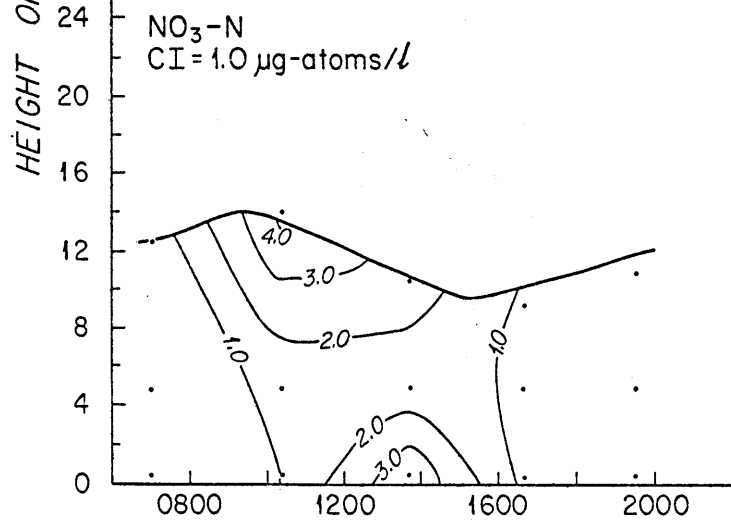
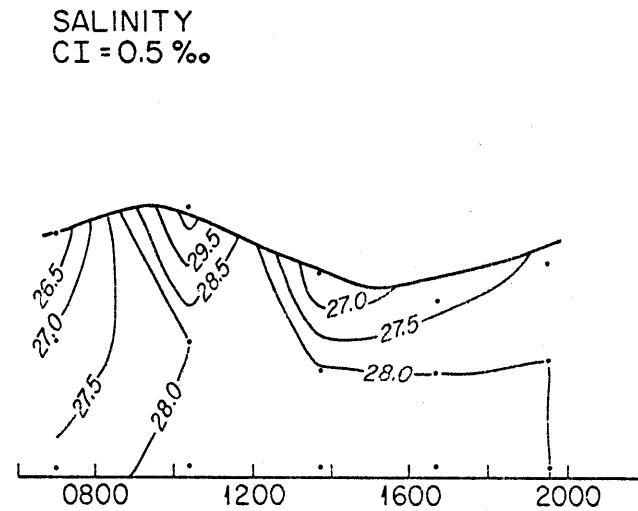
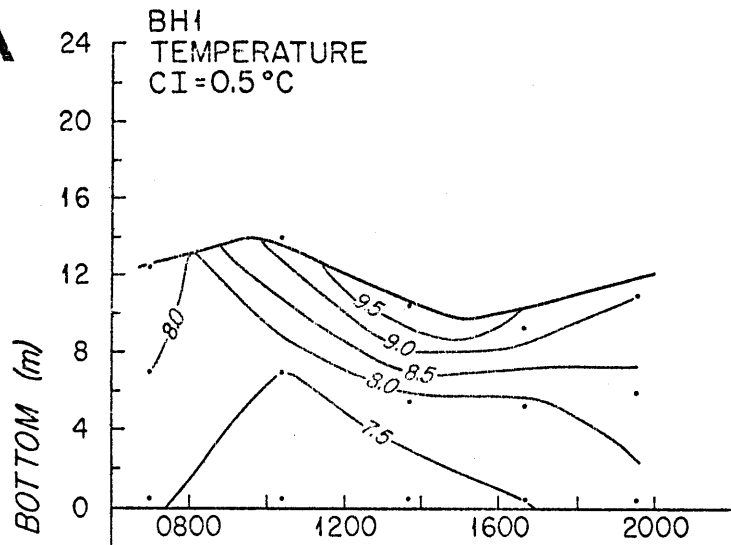
Nutrient concentrations are much reduced from the January highs. Nutrient values for BH1 reflect the high organic load of the Inner Harbor, while concentrations at BH4 and southern stations reflect the "cleaner" conditions of Massachusetts Bay and Nantasket Roads.

Suspended matter and nutrient profiles at station BH3 again reveal the strong influence of the sludge plume on water quality (Figure 62B). High  $\text{NO}_3\text{-N}$  values at 0930 hours appear related to the effluent discharge at Deer Island since no corresponding signal is seen in the values for combustible seston values. Stations BH1 and BH4 show no evidence of "contamination" by the plume.

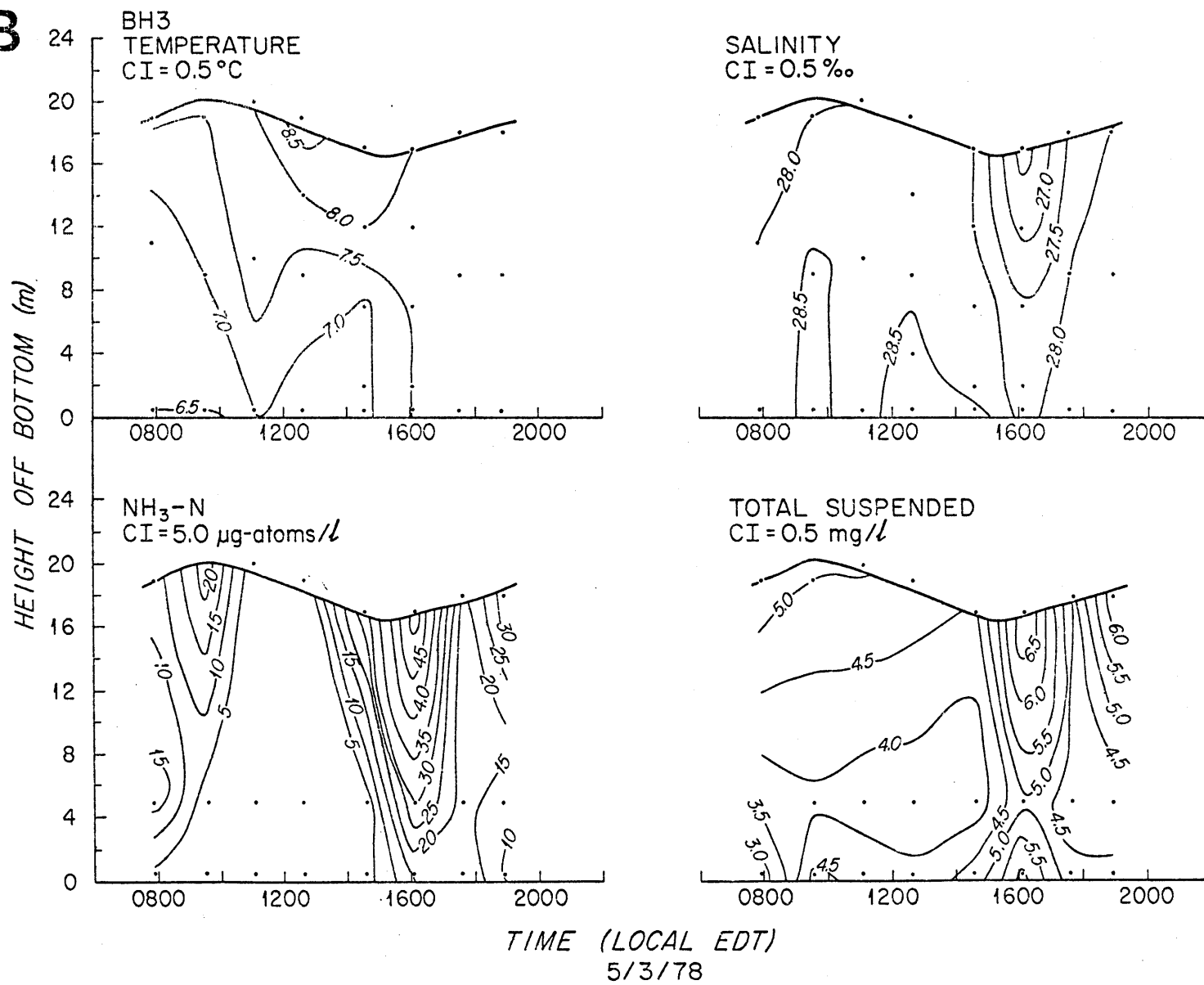
Resuspension/advection is again prevalent during ebb tide as seen in the profiles for noncombustible material. Most prominent in near-bottom samples, mineral grains are largely aggregated and show traces of iron and manganese (KEVEX).

- Figure 62.
- A. Tidal variations at station BH1,  
May, 1978.
  - B. Tidal variations at station BH3,  
May, 1978.



**A**

TIME (LOCAL EDT)  
5/3/78

**B**

Chlorophyll a profiles accent this increased biological activity. Values range from 3-15  $\mu\text{g/liter}$ , with the highest concentrations in the Inner Harbor samples. Thalassiosira sp. dominate the phytoplankton assemblage. Coscinodiscus sp. and Chaetoceros sp. are also numerous. Tintinnids, Asterionella sp., Thalassionema sp., and Nitzschia seriata are locally important. Fecal pellets (with pellicle) are present in significant numbers. With this increased biological input, organic film is again a prominent feature of the seston.

July, 1978 (neap tide conditions)

Temperature stratification is well established throughout the harbor. Values range from 8.5 - 18.5°C. Salinities average slightly higher than May values, ranging from a low of 23.5 ‰ at BHI to a high of 30 ‰ at the outer stations.

Nutrient profiles of  $\text{NO}_2\text{-N}$ ,  $\text{NO}_3\text{-N}$ ,  $\text{PO}_4\text{-P}$ , and  $\text{SiO}_2\text{-Si}$  define the nutrient-rich surface waters of the Inner Harbor ebbing past BHI (Figure 63A). Oxygen saturation values for this water mass are quite low, particularly in the early morning hours (Figure 64A). Together these measurements clearly distinguish this water mass from that entering the Inner Harbor at flood tide.

Ammonia and phosphate profiles outline the Deer Island sludge plume at BH3 and reveal the lengthy impact of this plume on water quality (Figure 63B). The plume appears confined to the surface waters, and does not appear to adversely affect oxygen saturation values (Figure 64B). Lower oxygen values near the bottom may reflect the reduced phytoplankton population of those waters or the oxidation of settling and resuspended organic material.

Mineral grains are a major constituent of the seston, particularly in near-bottom samples. Clay minerals, quartz, and mica are the dominant forms. Though most particulates are single grains, numerous organically bound aggregates are present.

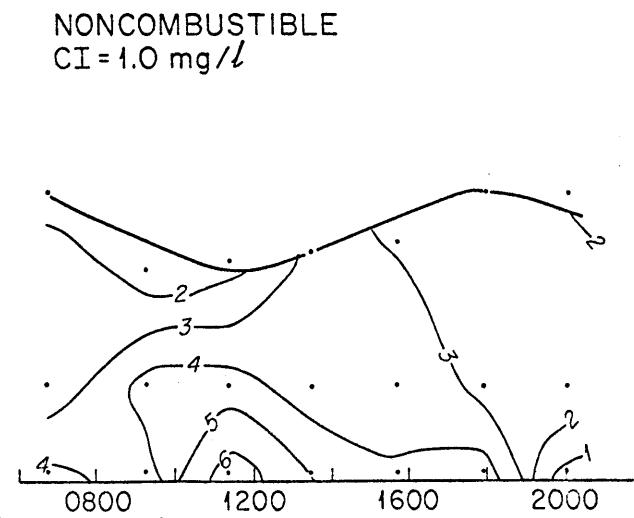
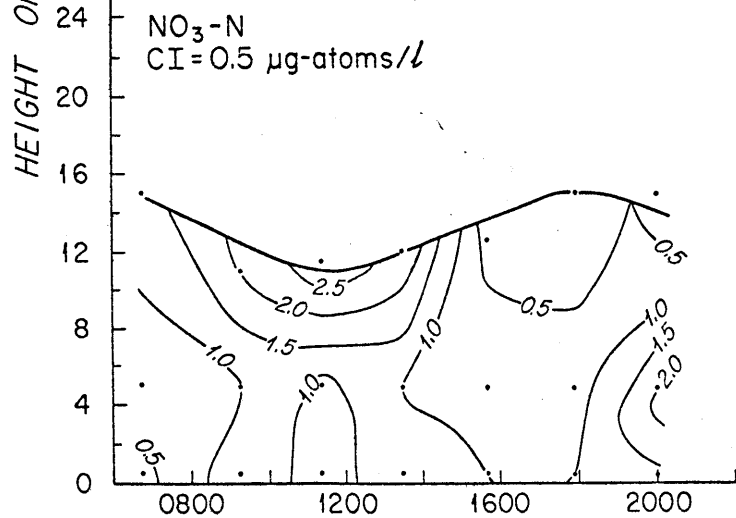
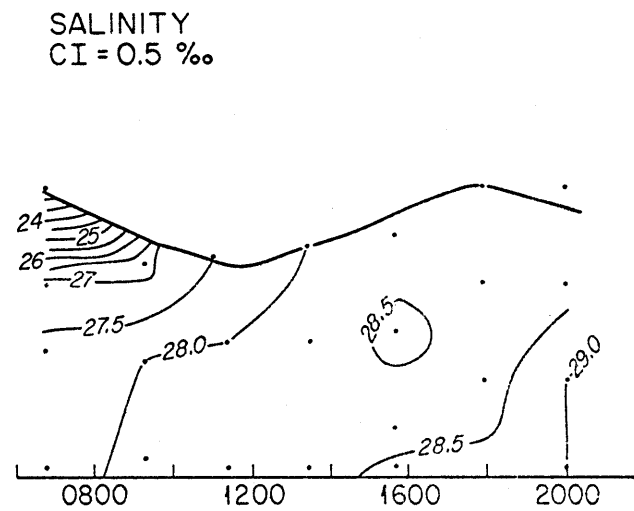
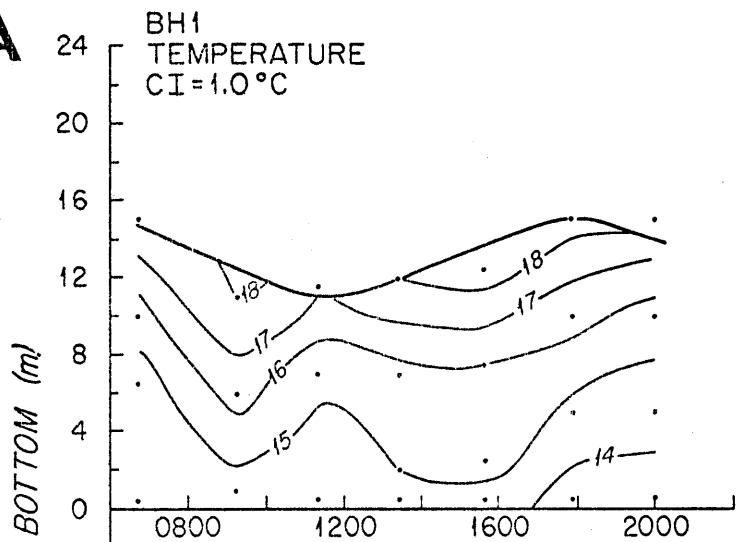
Chlorophyll a concentrations average slightly below the high values recorded for May, but several very high concentrations of chlorophyll a (up to 41  $\mu\text{g/liter}$ ) were noted at stations BH1 and BH3 (associated with the plume).<sup>4</sup>

Coscinodiscus sp. and Thalassiosira sp. dominate the plankton assemblage with Rhizosolenia sp., Pleurosigma sp., and Nitzschia sp. as secondary constituents. Tintinnids are locally abundant. Fecal pellets are common.

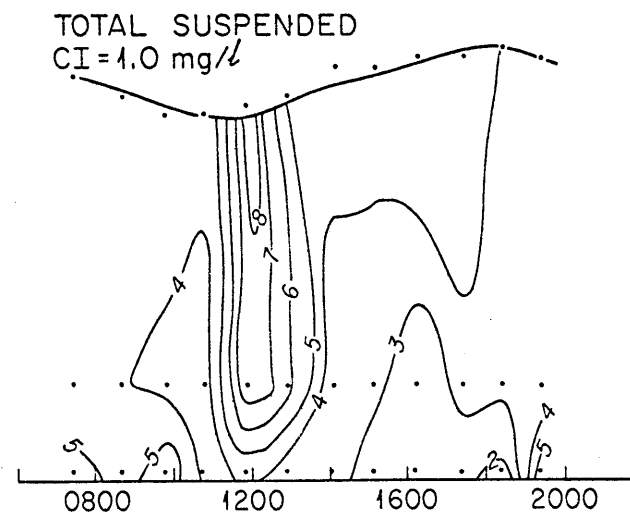
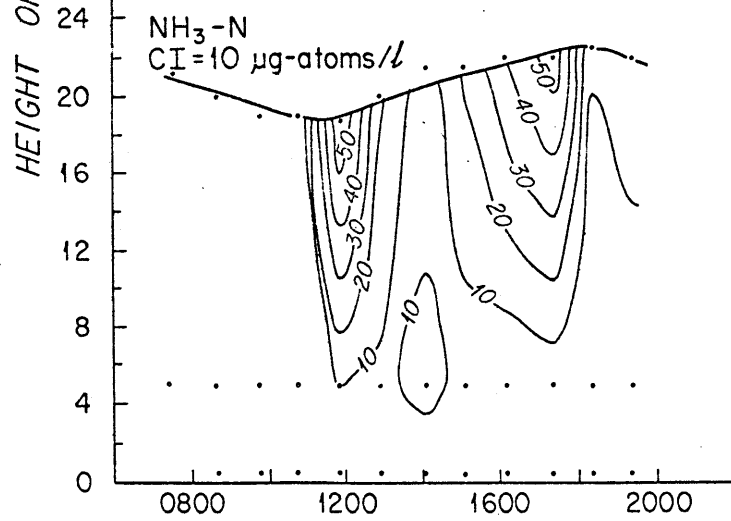
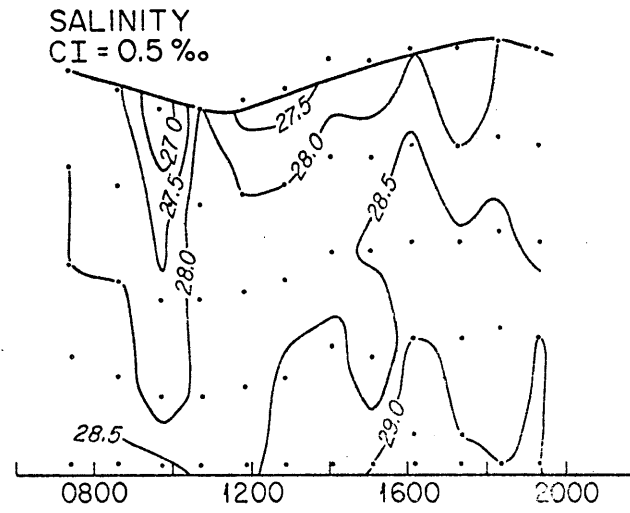
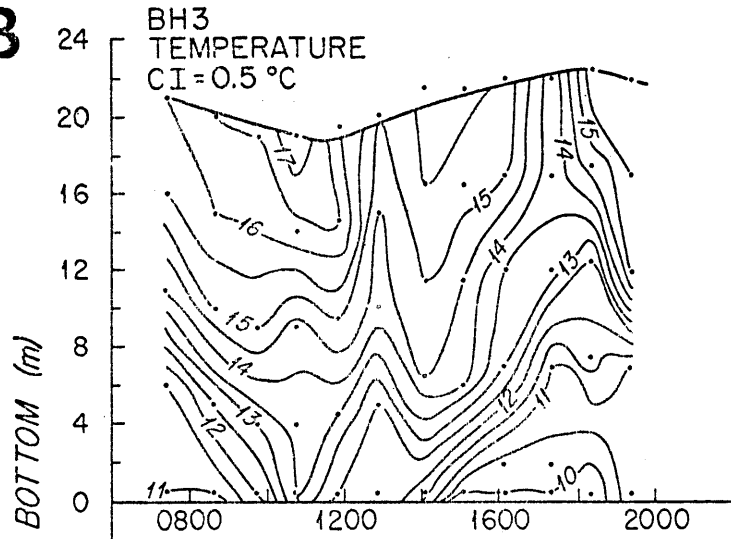
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<sup>4</sup>Chlorophyll a and the combustible fraction show a correlation of 0.5, improved over May.

- Figure 63.
- A. Tidal variations at station BH1,  
July, 1978.
  - B. Tidal variations at station BH3,  
July, 1978.

**A**

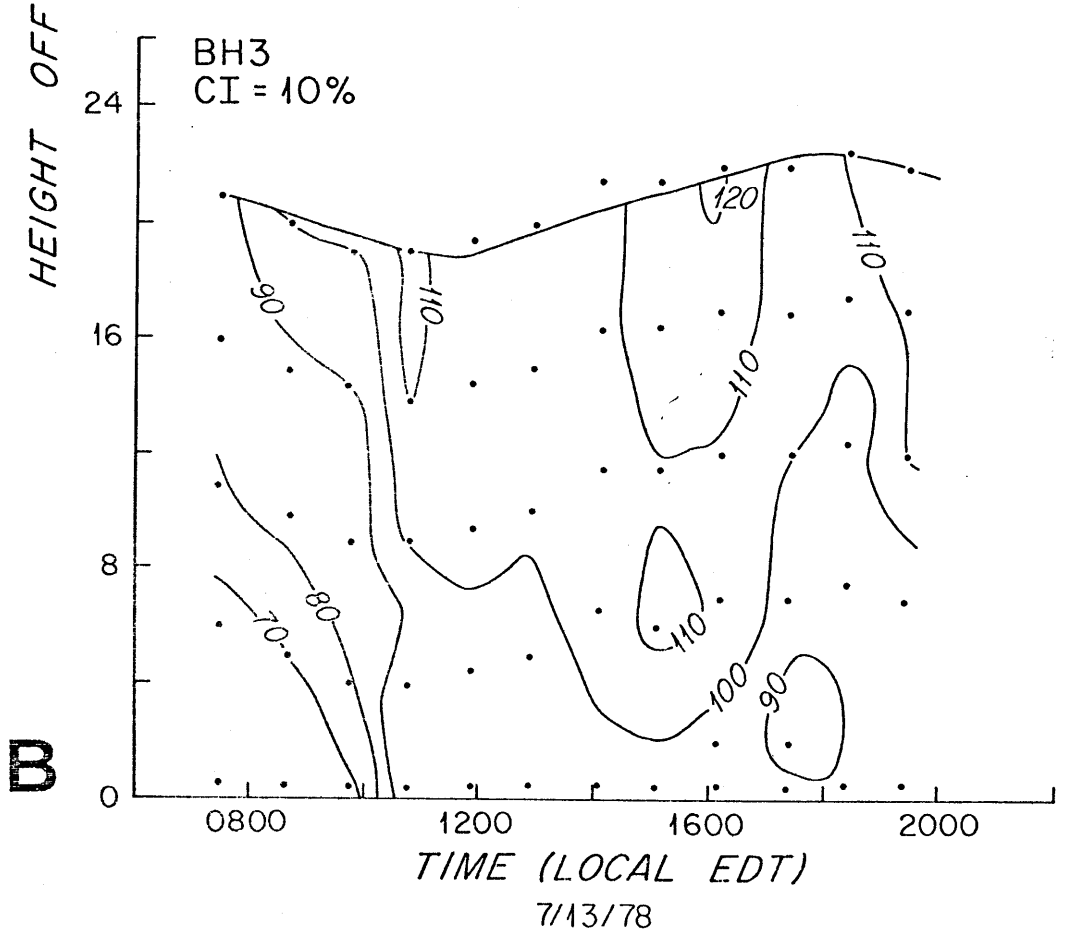
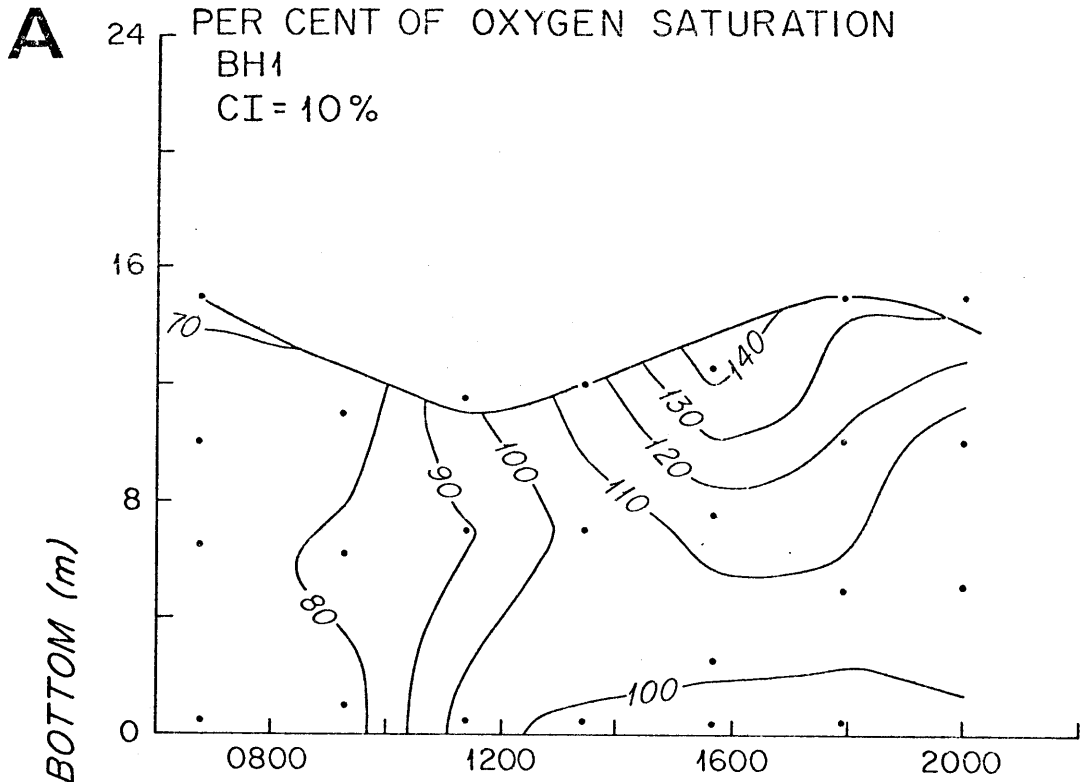
TIME (LOCAL EDT)  
7/13/78

**B**

TIME (LOCAL EDT)  
7/13/78

- Figure 64.
- A. Tidal variation of oxygen saturation at station BH1.
  - B. Tidal variation of oxygen saturation at station BH3.





October, 1978 (spring tide conditions)

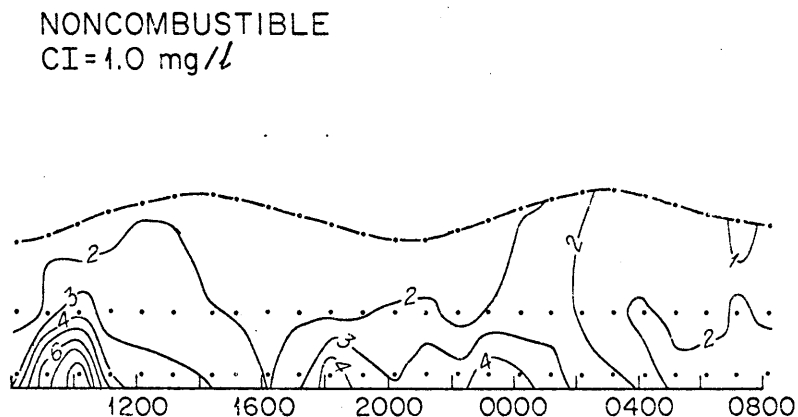
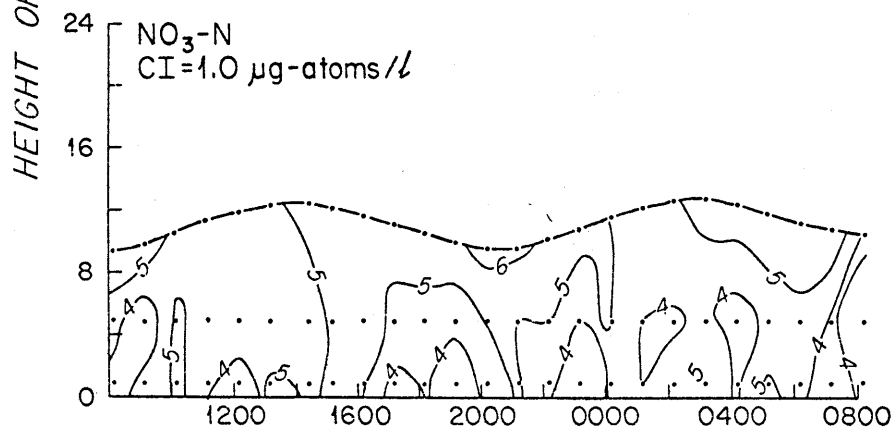
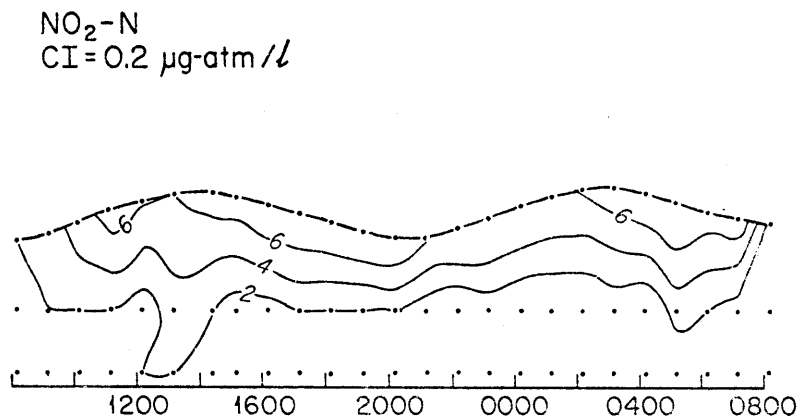
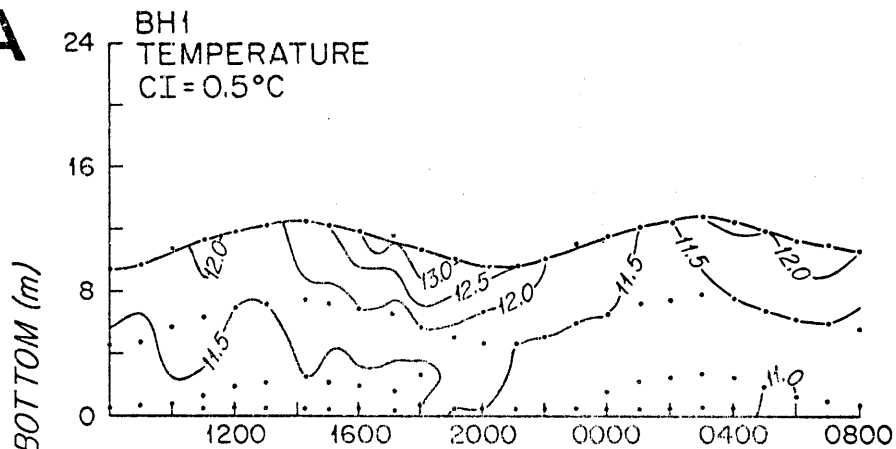
A more complete understanding of seston sources, their relative importance, and variability required greater frequency and duration of sampling. Hence, beginning with this cruise, attention was focused on stations BH1 and BH3. Samples were collected hourly over a twenty-four hour period.

At station BH1 temperature varies between  $11^{\circ}$  and  $13^{\circ}\text{C}$  and shows little change with depth except during ebb (Figure 65A). These warmer surface waters from the Inner Harbor are characterized by high concentrations of  $\text{NO}_2\text{ON}$ ,  $\text{NO}_3\text{-N}$ ,  $\text{PO}_4\text{-P}$ , and  $\text{SiO}_2\text{-Si}$ .

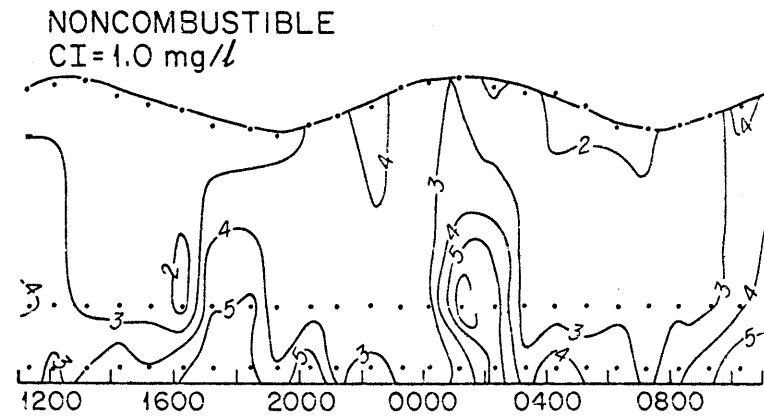
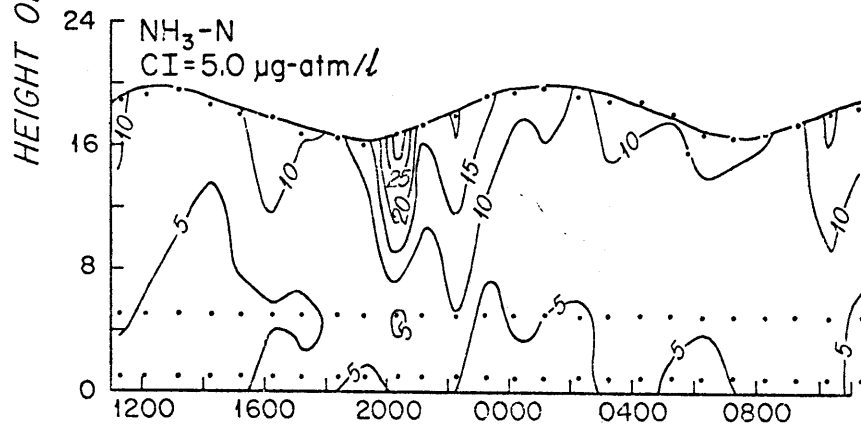
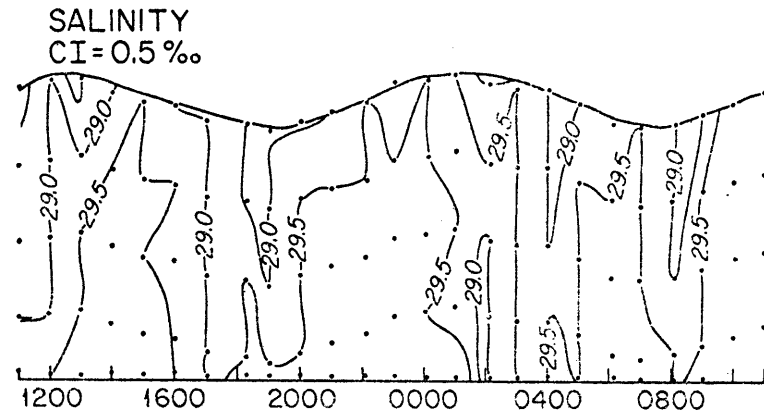
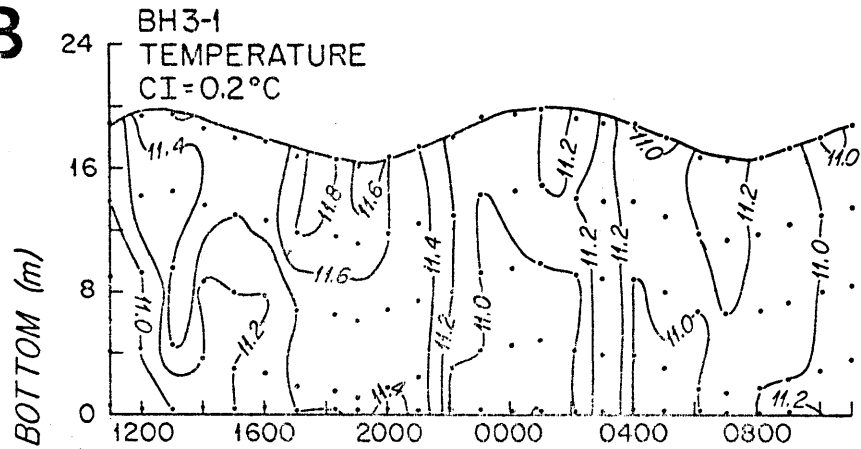
The water column at station BH3 is well mixed (Figure 65B), and temperature and salinity display little tidal variation. Temperature ranges between  $11^{\circ}$  and  $11.8^{\circ}\text{C}$ , while salinity varies between 29 and  $30 \text{ }^{\circ}/\text{oo}$ . The outfall plume -- restricted to surface waters -- accounts for most of the tidal variation. Ammonia profiles outline the plume at 2015 hours. Remnants of the plume linger and reappear at 1015 hours.

Noncombustible material shows near-bottom highs in concentration either side of slack low water, suggesting resuspension/advection. Clay minerals, quartz, and mica are very abundant, particularly in near-bottom samples. Iron is

- Figure 65.
- A. Tidal variations at station BH1, October, 1978.
  - B. Tidal variations at station BH3, October, 1978.

**A**

TIME (LOCAL EDT)  
10/19-20/78

**B**

TIME (LOCAL EDT)  
10/17-18/78

associated with most mineral particles. Particle aggregates are abundant, bound by an organic matrix. Carbonate laths are significant components of the seston, and lath bundles are common.

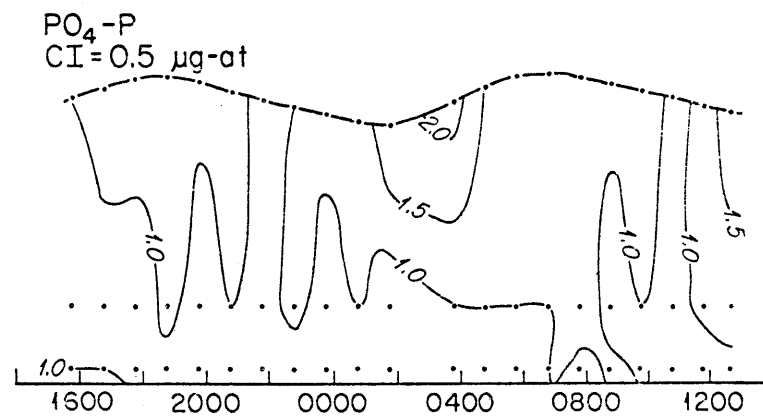
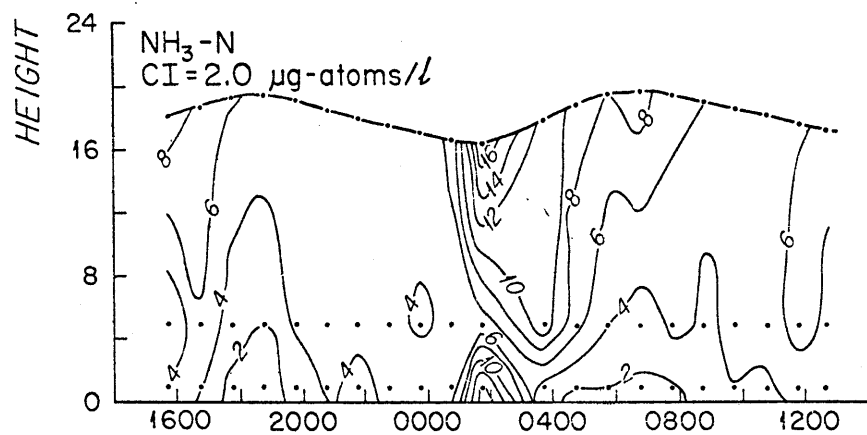
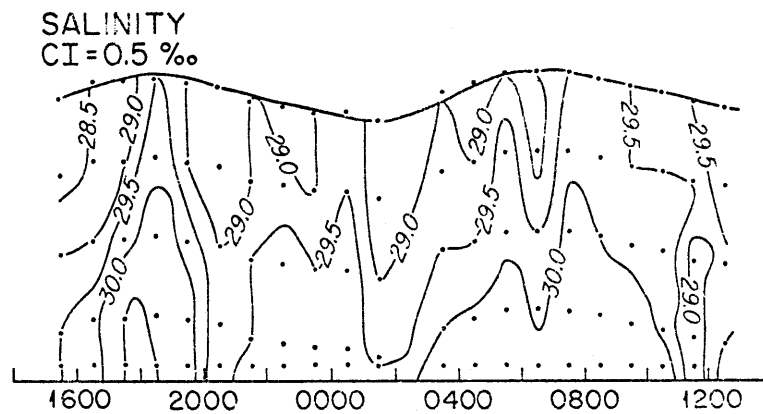
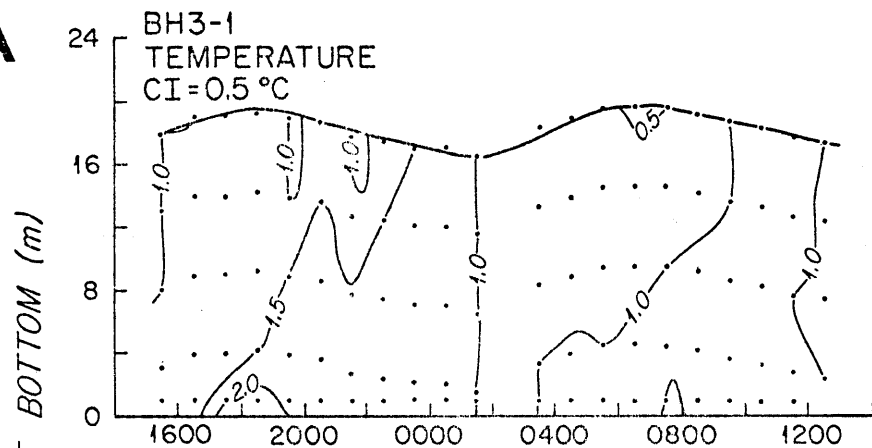
Biological activity is high in the harbor with chlorophyll a concentrations varying between 4 and 10  $\mu\text{g/liter}$ . Distribution is patchy. Organic film is an important constituent of the seston but shows poor correlation with chlorophyll a content (combustible material vs. chlorophyll a:  $r = 0.126$ ). Coscinodiscus sp. are by far the most abundant, followed by Skeletonema sp. Thalassiosira sp. are locally important. Copepods are found in several samples (Calanus sp.) along with abundant tintinnids. Fecal pellets are common constituents.

February, 1979

During this cruise only station BH3 was occupied, due to adverse weather conditions. Air temperatures hovered near  $-18^{\circ}\text{C}$  and winds gusted to 64 km/hr. Wave height in the harbor was 1-2 m. Thus, we were able to observe a portion of the suspended matter regime under storm conditions.

Water temperatures are very consistent throughout the tidal cycle (.4 - 2.2  $^{\circ}\text{C}$ ); warmer offshore water enters the harbor during flood (Figure 66A). Salinities show a bit more variation because of the lower salinity of the outfall plume and higher salinity of Massachusetts Bay water.

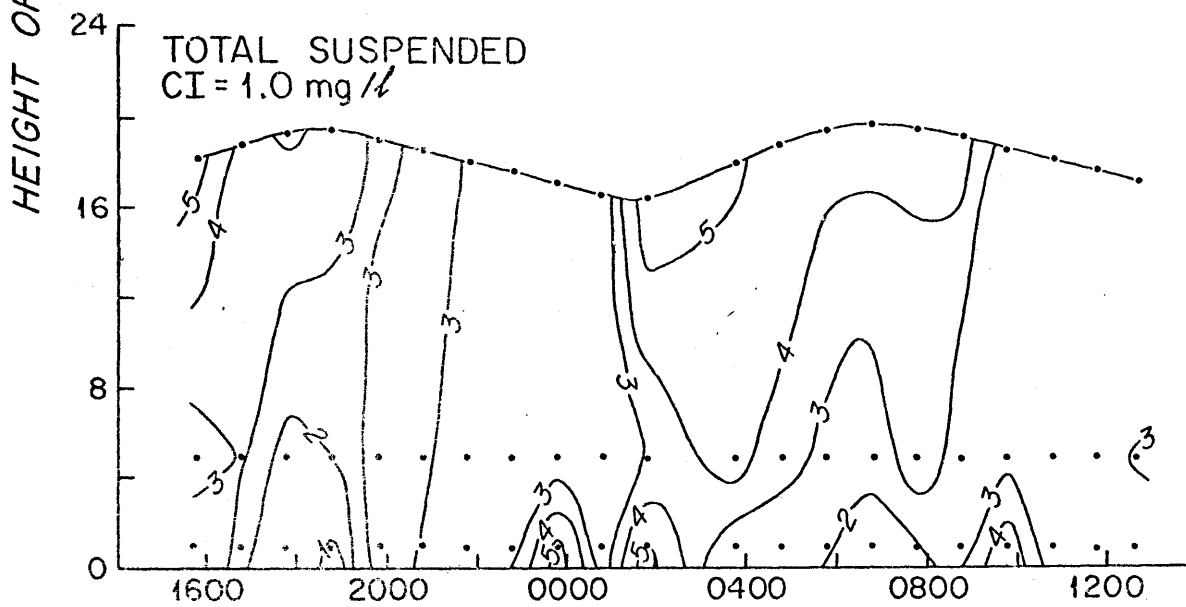
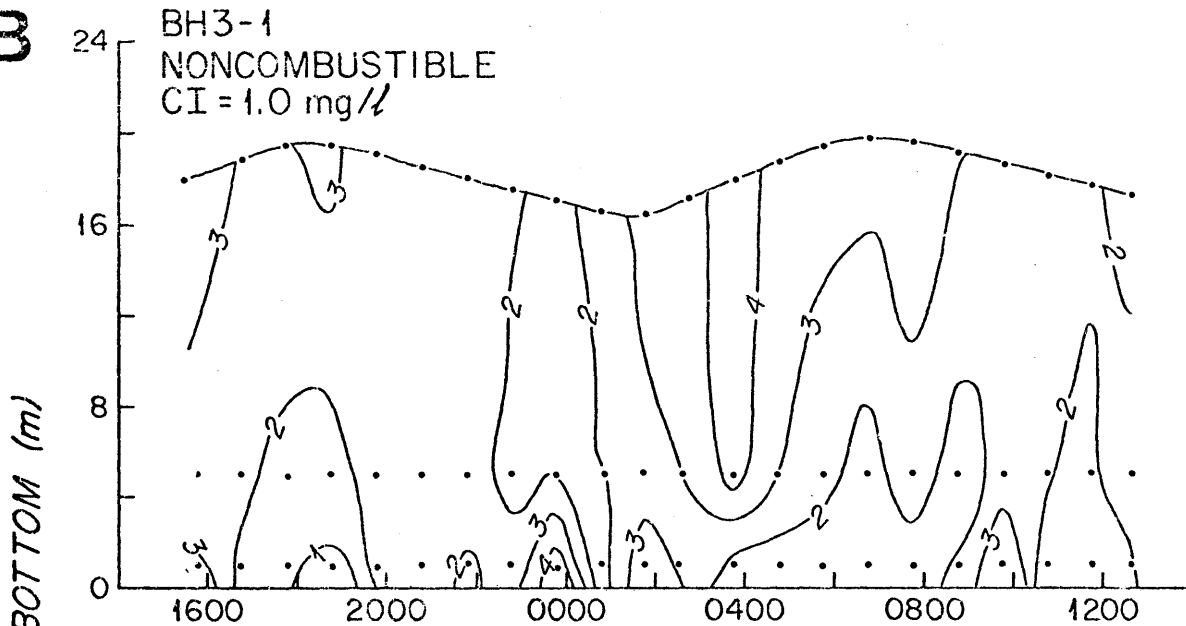
- Figure 66.
- A. Tidal variations at station BH3, February, 1979.
  - B. Suspended matter variations.

**A**

TIME (LOCAL EST)  
2/5-6/79



**B**



TIME (LOCAL EST)

2/5-6/79

Nutrient concentrations are high;  $\text{NO}_3\text{-N}$  values, for example, range between 7 and 12  $\mu\text{g-atom/liter}$ . Yet, the Deer Island plume accounts for most of the tidal variation observed. Outlined by ammonia profiles (at 0200 hours), the plume maintains its structure despite the storm activity.

Particulate concentrations average slightly higher than the previous winter (3.06 mg/liter compared to 2.33 mg/liter). Profiles of suspended matter (Figure 66B), however, show that the sludge plume dominates the seston regime. Concentrations of noncombustible material in near-bottom samples suggest resuspension/advection near slack low water.

Single grains are the dominant particle mode though aggregates bound by organic material are important in the surface waters. Iron appears ubiquitous in its association with mineral grains. Particles identified as calcium by back-scattering x-ray are common in the sludge plume. Apparently these particles are remnants of the lime added to the sludge to increase pH and could possibly serve as a tracer of outfall material. Carbonate laths are very abundant, and bundles of needles are quite common.

Chlorophylla a concentrations are very low even in the plume, ranging from 0.2 - 1.3  $\mu\text{g/liter}$ . Coscinodiscus sp., Rhizolenia sp., Navicula sp., and Nitzschia sp. are the major

components of the plankton assemblage. Distephenus sp., tintinnids, and dinoflagellates are minor constituents. Fecal pellets are not abundant.

Organic film and organic fibers are important in those samples taken in the sludge plume. However, because of the low biological activity, samples outside of the plume possess little organic matter.

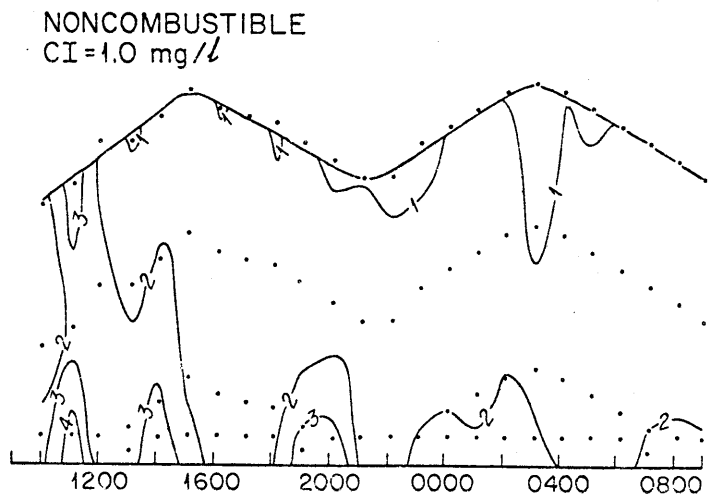
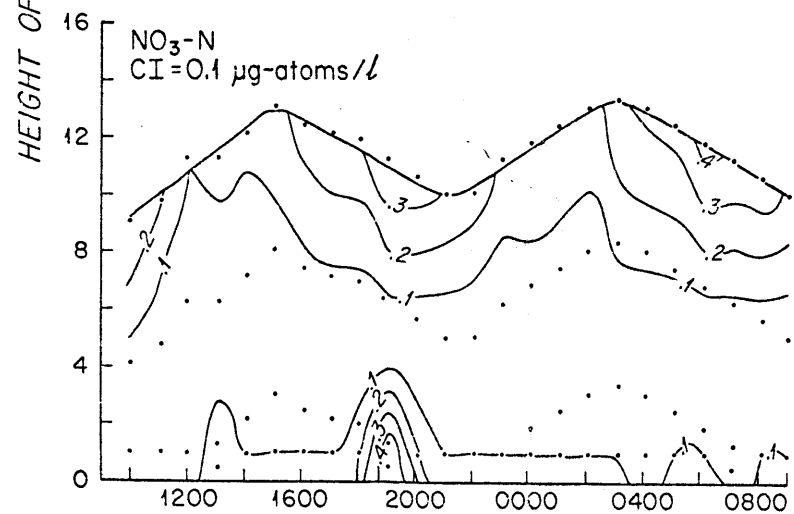
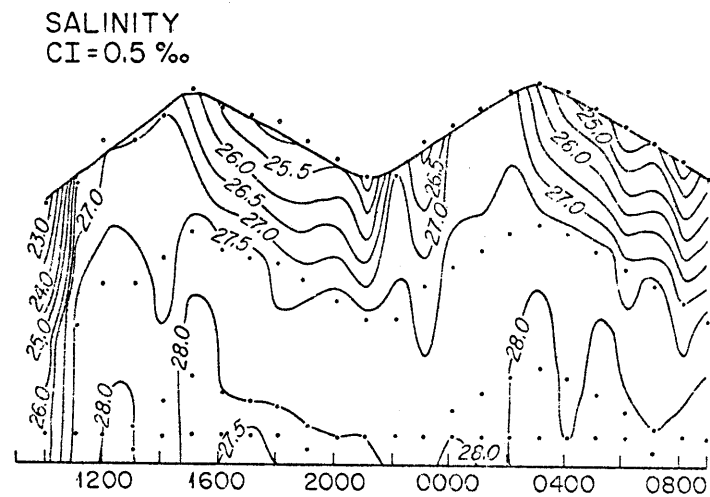
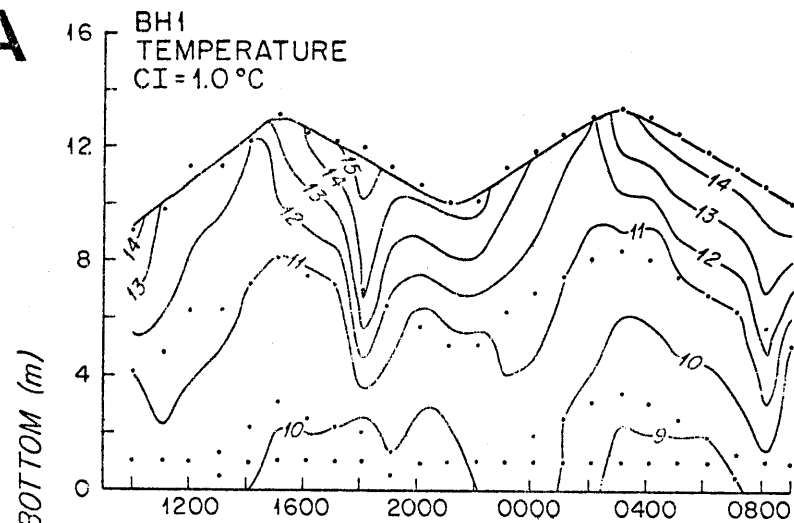
May, 1979 (neap tide conditions)

Temperature and salinity profiles for station BH1 show the effects of spring discharge on the water properties (Figure 67A). Stratification is well pronounced during ebb tide. Salinity dips as low as 23.7 ‰ at the surface, and the warming of the shallow Inner Harbor water is evident, with surface temperatures in excess of 15°C.

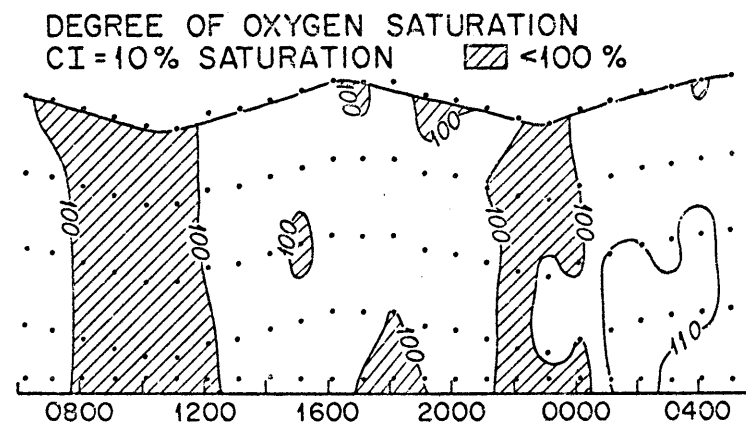
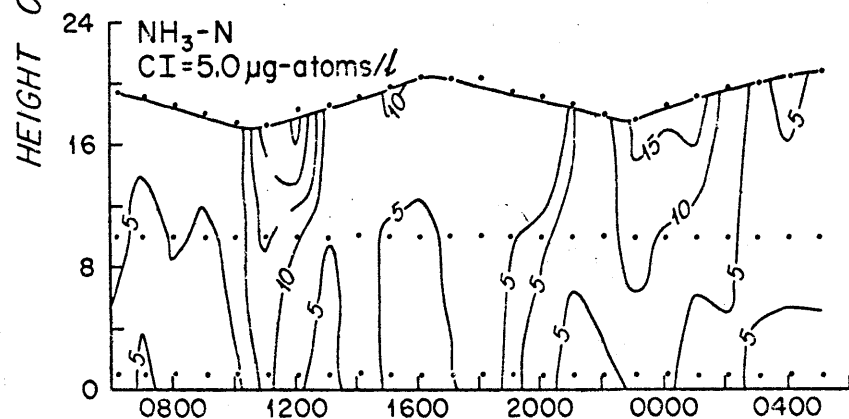
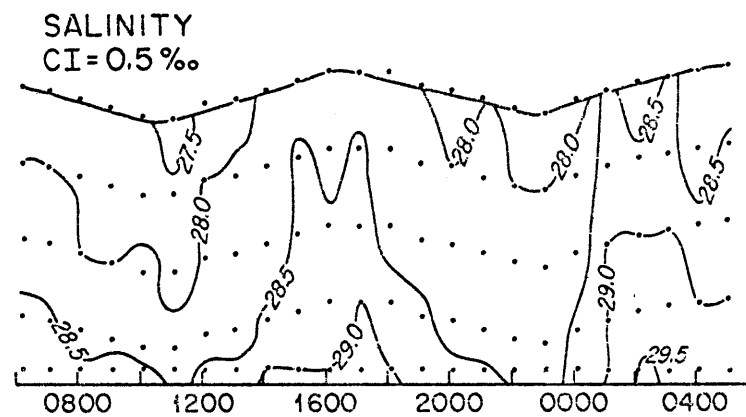
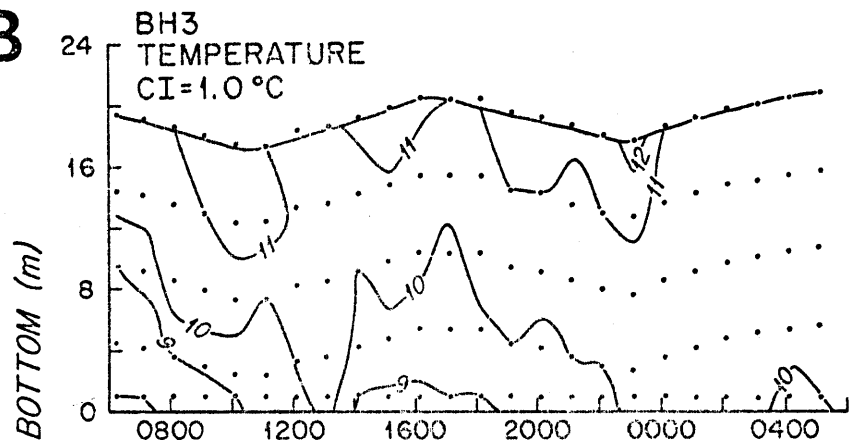
At station BH3 stratification is not well defined (Figure 67B). Tidal fluctuations in temperature and salinity reflect the influence of the Inner Harbor and Massachusetts Bay. The low salinity signal of the Inner Harbor (and of the sewage outfall) reaches BH3 at low tide, and during flood, cold, saline Massachusetts Bay water enters near-bottom.

Nutrient profiles at BH1 reflect the character of the Inner Harbor water mass -- defined by high concentrations of NO<sub>2</sub>-N and NO<sub>3</sub>-N and restricted to the near-surface. At BH3 the

- Figure 67.
- A. Tidal variations at station BH1,  
May, 1979.
  - B. Tidal variations at station BH3,  
May, 1979.

**A**

TIME (LOCAL EDT)  
5/15-16/79

**B**

TIME (LOCAL EDT)

5/17-18/79

sludge plume dominates the nutrient field between 1000 and 1200 hours. (Oxygen saturation values associated with the plume are lower than surrounding waters.)

Profiles of noncombustible material suggest the resuspension of mineral grains at both BH1 and BH3 near low tide. These mineral grains occur primarily as single grain clay minerals, quartz, and mica. Organic material, however, binds many grains into aggregates.

Chlorophyll a concentrations are highest (in excess of 19  $\mu\text{g/liter}$ ) in the ebb surface waters of BH1. Concentrations at BH3 are uniform, varying between 0.7 and 1.7  $\mu\text{g/l}$ .

Coscinodiscus sp. are the prominent diatom with Skeletonema sp., Thalassiosira sp., and Chaetoceros sp. as secondary constituents. The dinoflagellate, Ceratium sp., is a minor component, and tintinnids are only locally important. Copepods (Calanus sp.) are very abundant - as many as 30 per liter. Capturing so many in Niskin bottles suggests extremely large concentrations. The microflagellate Galycemonas sp. (2-5  $\mu\text{m}$  in long and 1-3  $\mu\text{m}$  wide) occurs in significant numbers<sup>5</sup>.

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<sup>5</sup>Spring blooms of microflagellates are not uncommon in the region. Furnas et al. (1976) report blooms of the microflagellate Olisthodiscus sp. in Narragansett Bay during spring and summer months.

September, 1979 (spring tide conditions)

At both BH1 and BH3 the water column is not stratified. Tidal variations in temperature and salinity are small and reflect the influence of the Inner Harbor at BH1 and of Massachusetts Bay at BH3 (Figure 68).

Nutrient profiles of  $\text{NO}_2\text{-N}$ ,  $\text{NO}_3\text{-N}$ , and  $\text{PO}_4\text{-P}$  characterize the nutrient-rich waters of the Inner Harbor. The sludge plume (characterized by profiles of ammonia and phosphate) dominates the nutrient field at BH3 and is restricted to surface waters.

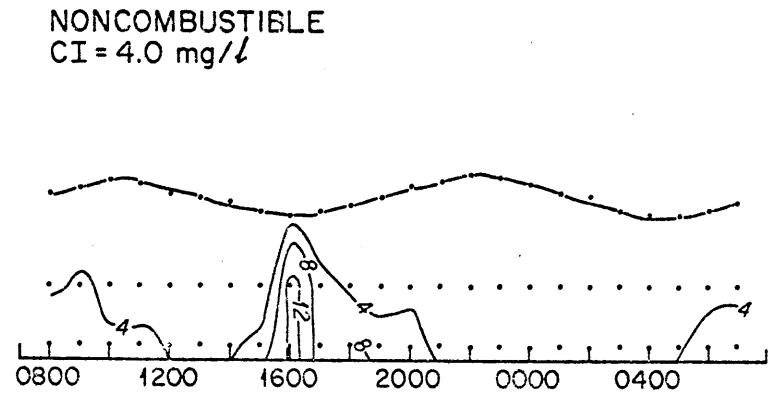
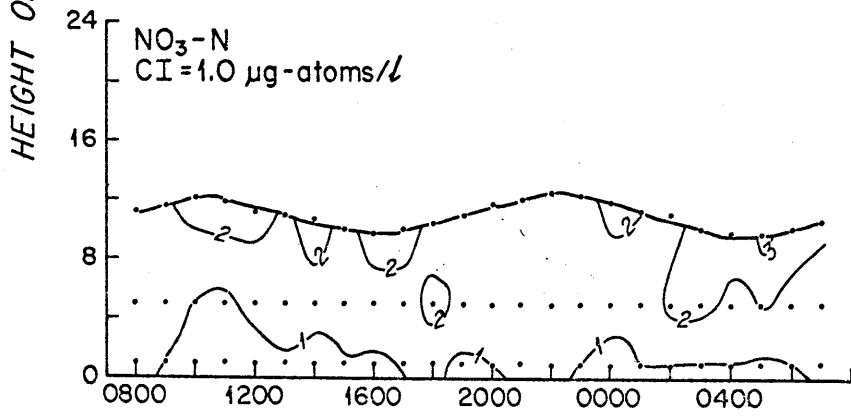
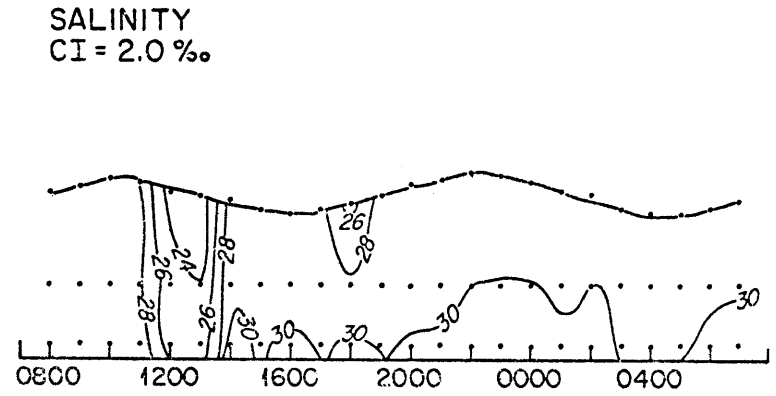
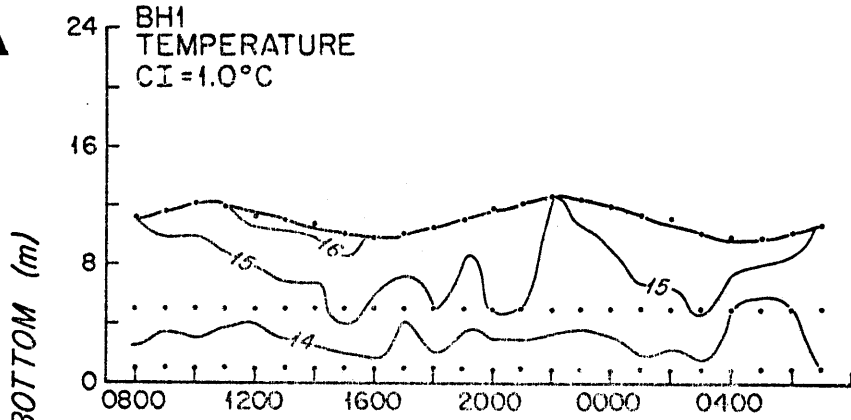
Noncombustible particulates are primarily single grain clay minerals, quartz, and mica -- most with associated iron. However, organics do bind numerous aggregates.

Chlorophyll a concentrations range from 1-8.5  $\mu\text{g/liter}$ , but do not display the patchy distribution noticed during other cruises (Figure 69). Skeletonema sp. and Leptocylindrus sp. are the secondary constituents. Ebridians are numerous in all samples as are tintinnids and the dinoflagellate Protocentrum sp. Copepods occur in significant numbers.



- Figure 68.
- A. Tidal variations at station BH1,  
September, 1979.
  - B. Tidal variations at station BH3,  
September, 1979.

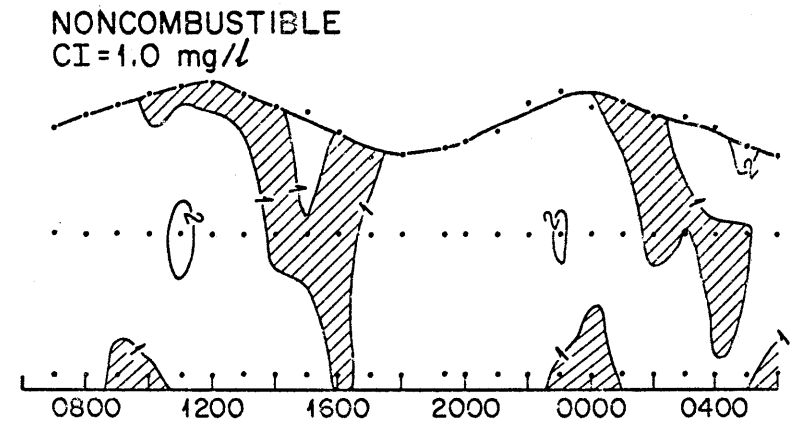
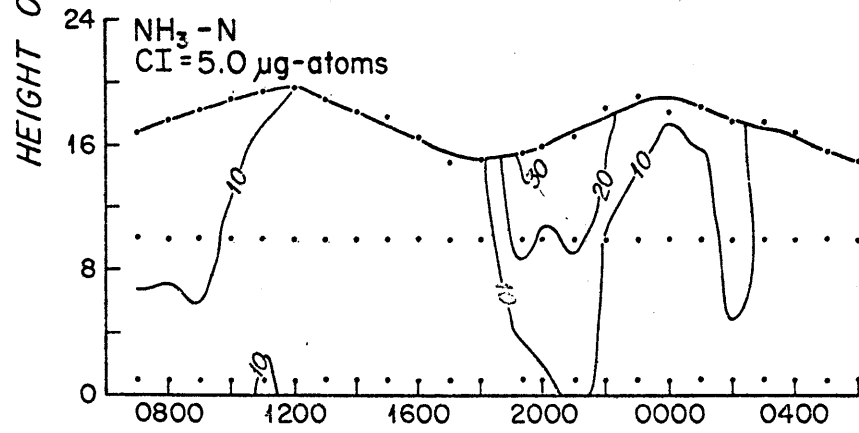
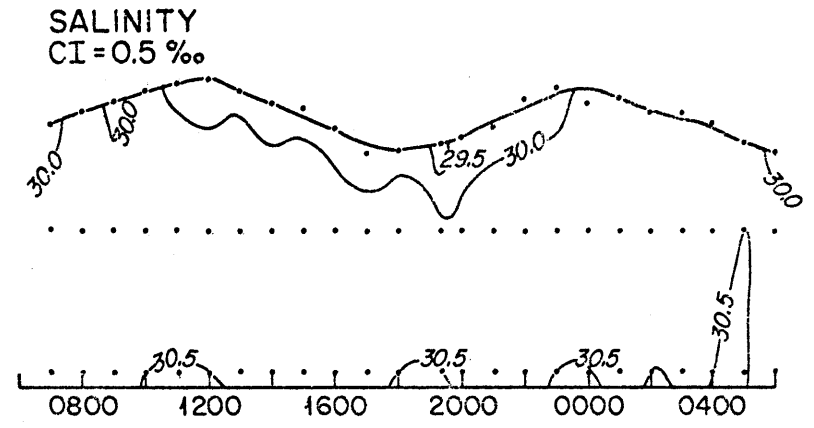
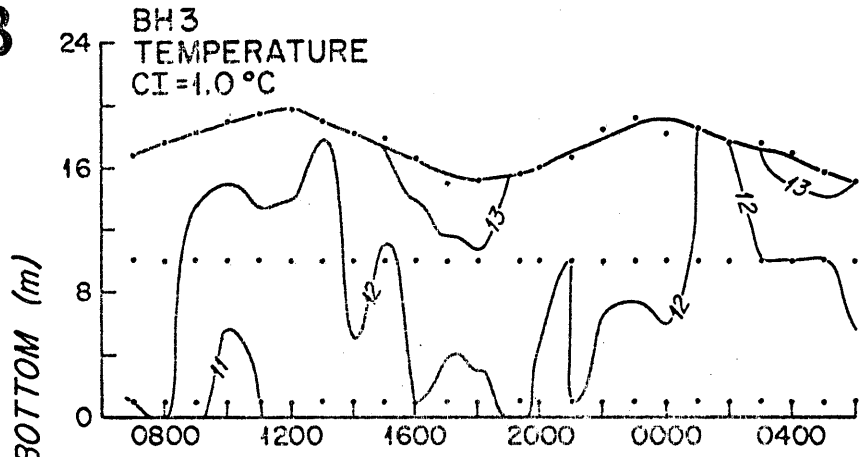
**A**



TIME (LOCAL EDT)

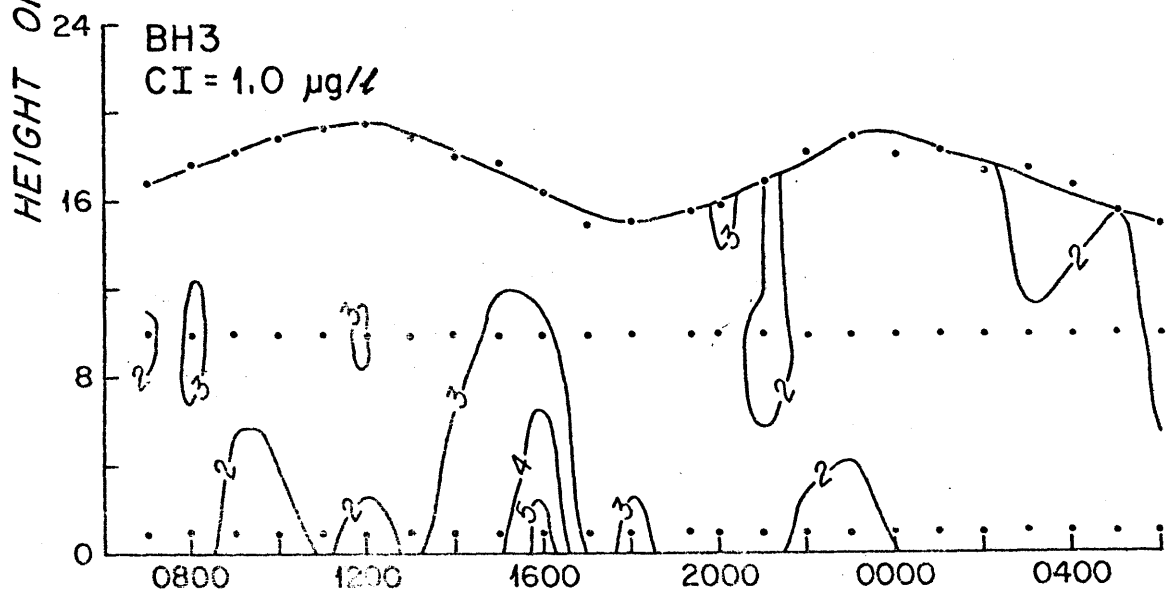
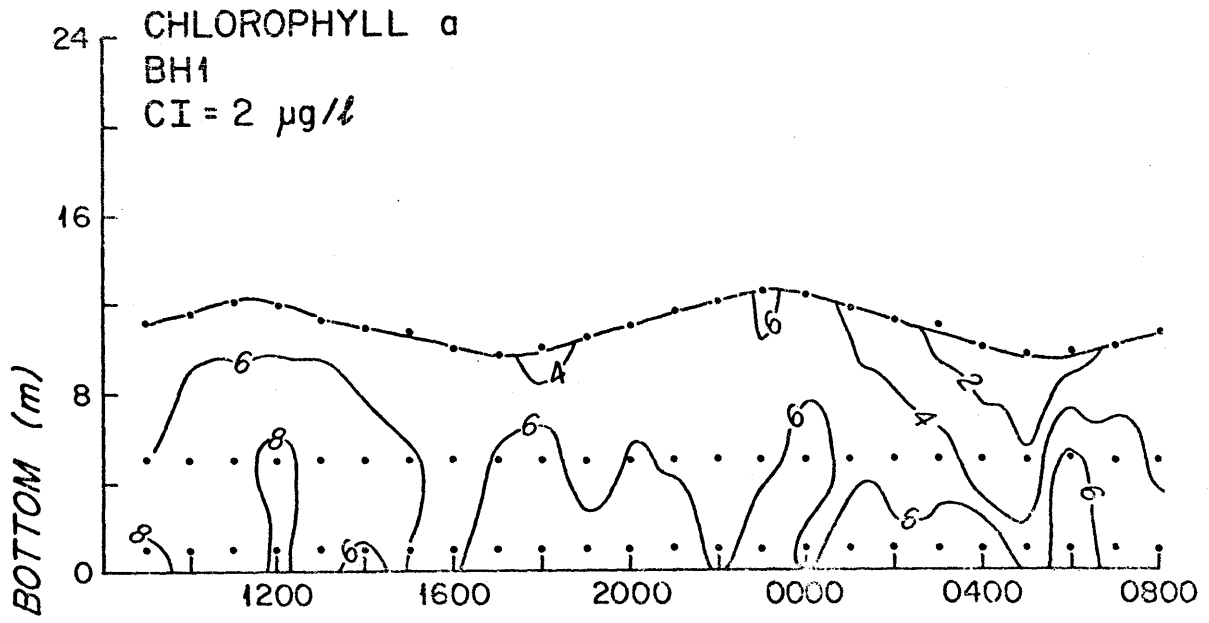
9/79

**B**



TIME (LOCAL EDT)  
9/79

Figure 69. Tidal variations of chlorophyll a at station BH1 and BH3.



TIME (LOCAL EDT)  
 9/79