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TECHNICAL REPORT

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ABSTRACT

New Bedford Harbor and its approaches form the estuary of the Acushnet River in southeastern Massachusetts. The estuary is weakly stratified and only partially mixed because river discharge is very small. It appears to be typical of the inlets of the coast of New England, and is a branch of a larger estuary - Buzzards Bay.

Silt and clay are being transported into the estuary in suspension by landward-moving bottom currents that are driven by wave and tidal energy. These fine sediments come from Buzzards Bay, but may originate out on the continental shelf. Before the entrance to the harbor was almost completely blocked by a hurricane barrier, these sediments were accumulating in the harbor at rates of about 1-2 cm/yr in the deeps, and less than 0.5 cm/yr in the shallows. Construction of the barrier reduced the efficiency of tidal flushing, causing the rate of siltation to increase by a factor of 4-5. Outside the harbor, silt and clay accumulate in the drowned valley of the Acushnet and in related depressions at rates of 2-3 mm/yr.

In the water column, silt and clay sized minerals are suspended together in organically bonded agglomerates. During sediment transport, the silt and clay become partially fractionated, probably by differential settling of the agglomerates. Because fractionation is more effective where wave and tidal energy are strongest, there is a smaller proportion of clay relative to silt in the harbor than there is seaward. Nevertheless, the net transport of clay is still landward.

Fractionation due to differential settling also appears to have formed a very thin, soupy layer of clay-rich material at the sediment-water interface, that appears to carpet the study area. This layer seems to form a transition zone between the much more silty and less mobile subsurface sediments and the highly mobile suspensates of turbid near-bottom waters. Further study is needed to ascertain precisely the nature and persistence of this layer.

Wastes rich in metal are discharged into the waters at the head of the harbor, and rapidly become fixed in the bottom sediment throughout the harbor. Together, Cu+Cr+Zn, the three main contaminant metals, locally form more than one percent of the dry weight of harbor sediments. The metals are located in the very fine silt and clay fractions of the sediment. They migrate slowly out of the harbor, most probably by eddy diffusion in near-bottom waters and appear to have spread out over portions of Buzzards Bay in a carpet 10-20 cm thick. Calculations suggest that about 25 percent of the excess metal in the bay is derived by fallout from urban air that blankets the entire country. The remaining excess metal may represent 24 percent of what was discharged into the harbor and shows to what extent the harbor acts as a leaky sink for contaminants.

Organic wastes derived by discharge of sewage are deposited in the harbor, and close to the Clarks Point sewer outfall. Wastes appear to move away from these deponents in small amounts, under the influence of waves and tides. Organic waste material forms a significant part of the soupy, clay-rich layer that carpets the area. Assuming that organic waste is moved about in the same way that metal wastes are, then perhaps 24 percent of the organic particulates associated with sewage discharge end up in Buzzards Bay.

Clearly, New Bedford Harbor operates as a sediment trap. But it forms a somewhat inefficient trap for clay-sized particles and, as a result, acts as a "leaky sink" for organic and industrial contaminants (here we refer only to contaminants that move as part of the bottom sediment, not to those that remain in solution in the water column). Other estuaries along the coast of New England can be expected to operate in similar ways with respect to siltation and waste dispersal.

SCIENTIFIC OBJECTIVES

In this report we present the findings of a two-year study designed to establish and explain the past and present patterns of movement and accumulation of fine-grained sediment, human waste, and industrial waste in New Bedford Harbor and its approaches (Figure 1). This is the first large-scale multi-disciplinary study of its kind in this immediate area, most previous work having been focused on the nearby waters of Buzzards Bay. In this study we attempted to answer several basic and related questions: what types of sediment cover the sea floor; where are they most concentrated, and why; how are fine-grained sediments moved through the area at different times of the year and different parts of the tidal cycle; do fine sediments and industrial wastes accumulate in the harbor, or escape from it; what effect does sewage, treated or not, have on sedimentation, and how is it distributed away from input points; what has been the history of waste buildup in the sediments; if wastes escape from the harbor, do they reach and pollute the sediments of central Buzzards Bay; what has been the effect on the harbor of the 10 year old hurricane barrier that constricts its entrance. The answers to these and other related questions provide a scientific basis for solving several of the problems of coastal zone management in the New Bedford-Fairhaven industrial area, and for predicting with some degree of certainty some of the environmental effects of future changes that man may make. In spite of our focus on New Bedford, many of the questions we have discussed are common to many other estuaries and harbors, so our findings are important in a wider sense in giving insight into the flux of solids through the estuarine environment in general. To answer these basic questions, we carried out four main research programs on the topography, subsurface structure and sedimentary history; the character, distribution, thickness and origin of bottom sediments; the composition and distribution of heavy metals in bottom sediments; and the character, distribution, and dispersal of suspended sediment. These programs are the topics of the major sections of the following report. We will present the data on which this report is based in a separate data file (Ellis and others, 1977). The collected samples are stored in the Data and Earth Sampling Center of Woods Hole Oceanographic Institution.

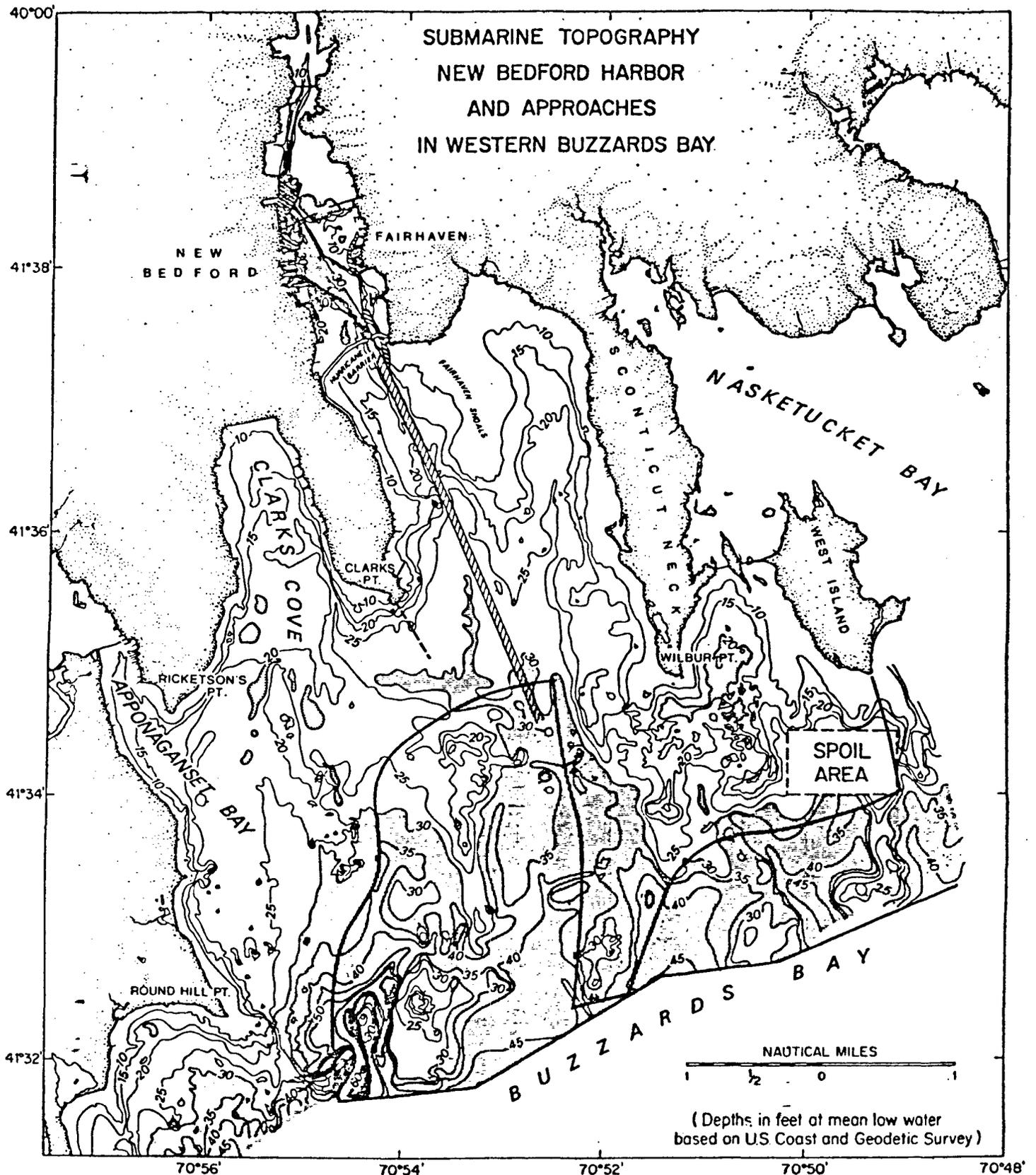


Figure 1. Topography contoured from 1935 USCGS surveys (No. 5880, 5881, 5882); except southern area (enclosed by black line), contoured from USCGS Chart No. 252. Stippling indicates depths over 30 ft. Dashed line indicates Clarks Pt. outfall.

INTRODUCTION

New Bedford, with a population of just over 100,000, is the largest coastal city in southeastern Massachusetts, and together with neighboring Fairhaven (population about 20,000) has a substantial impact on the waters of the Acushnet estuary. The Acushnet, one of the smaller New England Rivers, discharges into Buzzards Bay, one of the larger embayments of the eastern seaboard of the United States. It could be regarded as merely a branch of the larger estuary that forms Buzzards Bay (Bumpus and others, 1974).

During the 1820's New Bedford was the nation's leading whaling port. With the decline of the whaling industry, the economic base of the city shifted towards manufacturing, with service industries and fishing playing important roles. In 1968 the port handled 597,000 metric tons of cargo, a figure that is expected to rise to over 900,000 by 1990. This projected increase in harbor traffic provides impetus for a major expansion of the port, which will have an impact on the environment. In order to maintain the viability of the estuary as a port, much of it has been dredged to a depth of 30 feet (9 m), involving the removal of some 3 million cubic meters of sediment since 1839, when dredging first began (U.S. Army Corps of Engineers, 1972). Another major environmental modification was the construction of a hurricane barrier across the harbor entrance by the U.S. Army Corps of Engineers in 1964-1966.

Man has made a major and lasting effect on this environment through the discharge of human and industrial waste into the sea. The serious nature of environmental contamination in this area is reflected by the closing of Clarks Cove and Fairhaven Harbor to shellfishing in recent years. At present, most sewage from New Bedford is processed through a primary treatment plant, which became fully operational in 1974 and discharges effluent at Clarks Point outside the harbor (Figure 1) at an average daily dry weather flow of about 114 million liters. Discharge at Clarks Point is expected to increase to about 170 million liters a day by 1990 (Camp, Dresser and McKee, 1974). Human and industrial wastes of various sorts are

also discharged at other points, into the inner harbor, into the outer harbor north of Clarks Point and into Clarks Cove. Discharges into the inner harbor have caused its waters to be highly polluted and classifiable as untreated sewage (Hoff, 1971; Massachusetts Division of Water and Pollution Control, 1975). In part, problems in the inner harbor may be due to the construction of a hurricane barrier, which restricts tidal flow to a 150 ft. (45 m) wide, 30 ft. (12 m) deep navigation channel and two 64 inch (1.6 m) conduits (U.S. Army Corps of Engineers, 1972).

The waters of the harbor are known to contain substantial amounts of PCB's (polychlorinated biphenyls), considered an environmental hazard (E.P.A., 1976), and discharged by local industries. The Massachusetts Division of Water Pollution Control (1975) and the New England Division of the U.S. Army Corps of Engineers (unpublished data) find that the bottom sediments of the inner harbor and the navigation channel contain large amounts of heavy metals, oil, and grease. Clearly these sediments are heavily contaminated with industrial waste. After studying the geochemistry of sediments from nearby Buzzards Bay, Moore (1963) concluded that they were not significantly contaminated with industrial wastes. Farrington and others (in press), however, showed that sediments from central Buzzards Bay contained PCB's and organic components of industrial origin, and Bowen and others (1976) showed that they also contained fallout plutonium.

SETTING

Bottom Topography

Our study shows that the seabed is a drowned drainage system with NNW-SSE trending, steep-sided, rough-topped ridges and smooth-floored troughs. One of these troughs forms the drowned valley of the Acushnet River. It cuts across the study area from the harbor to Buzzards Bay, developing a north-south trend as the Bay is reached (Figure 1). East of the drowned valley is a steep-sided ridge that finds subaerial expression as Sconticut Neck. A drowned tributary of the Acushnet separates this peninsula from the smaller ridge that forms Fairhaven Shoals. West of the drowned valley is another steep-sided ridge, the subaerial part of which forms Clarks Point Peninsula. This last ridge is broken in two places; by a drowned tributary of the Acushnet that extends around Clarks Point and north into Clarks Cove, and by a deep, narrow gully about $2\frac{1}{2}$ miles (4 km) south of Clarks Point. Between this ridge and the western shore is a wide, rather shallow and flat-floored embayment which is divided into an eastern and western part by a low, discontinuous, NNW-trending ridge. The southern end of this western embayment is bounded by a high ridge through which are two very narrow, steep-sided gaps that are locally deeper than 60 feet (18 m). With the exception of these gaps, which appear to form part of a drowned channel system, the seabed is shallower than 45 ft. (14 m) throughout the study area.

Subsurface Structure and Geology

A 3.5 kHz echo-sounding system was used to obtain subbottom profiles along closely spaced track lines (Figure 2). The New England Division of the U.S. Army Corps of Engineers provided us with the unpublished results of 70 underwater test borings, made in or near the harbor, to assist in the interpretation of our profiles.

On most profiles we detect an acoustic basement reflector, which is most deeply buried beneath surface depressions, and approaches or reaches the surface at the crests of ridges (Figure 3). On the ridge crests, side-scan sonar detected what appeared to be scattered boulders. Large fragments of rock were usually recovered in grab

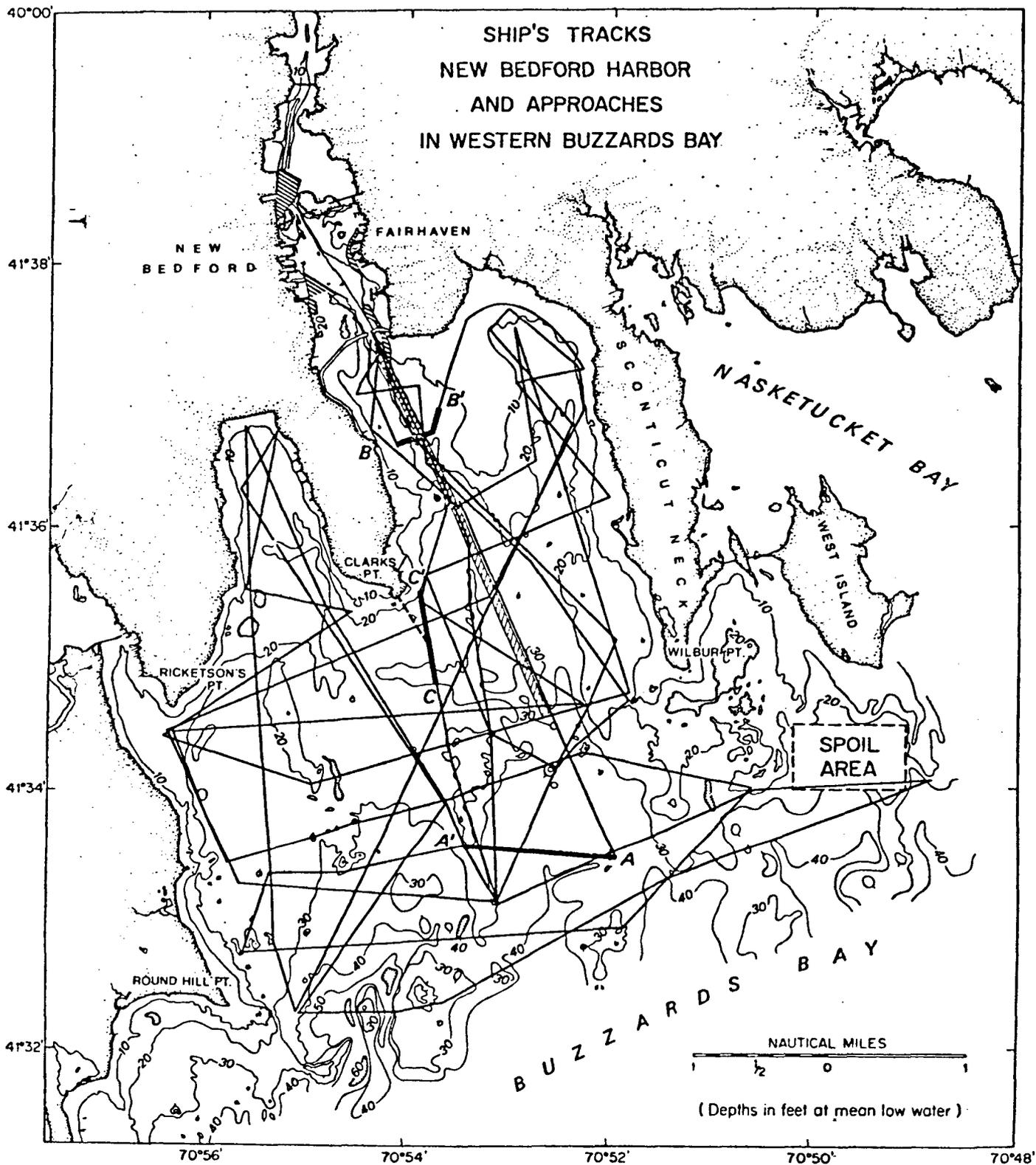


Figure 2. 3.5 kHz coverage (R/V CORSAIR, July, 1975). Heavy lines A - A', B - B' and C - C' indicate locations of profiles shown in Figure 3. Hatching shows recently dredged areas.

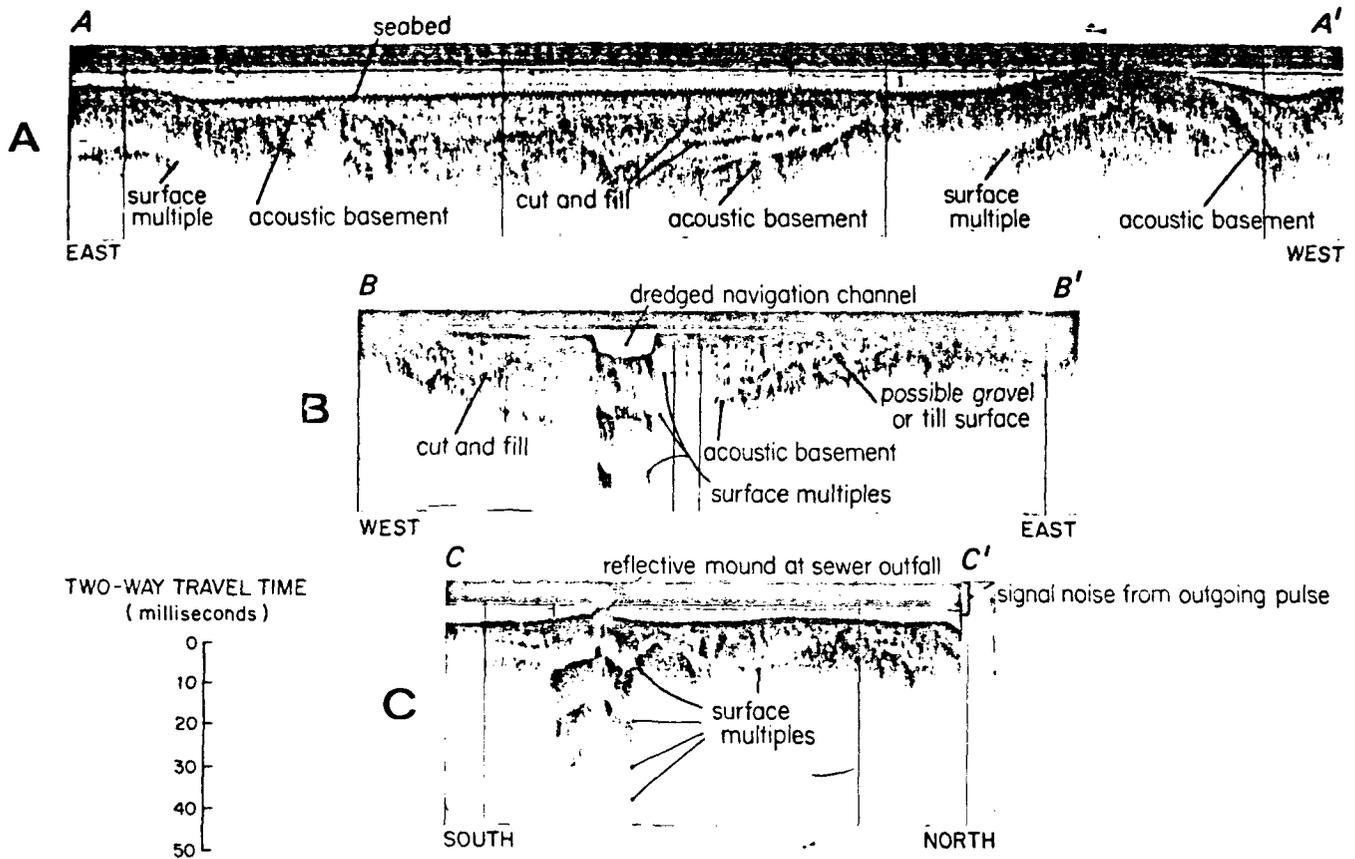


Figure 3. Selected 3.5 kHz echo-sounding profiles from the approaches to New Bedford Harbor. A - A': 2.5 km transect of the buried Acushnet River channel. B - B': 1.5 km transect of the buried Acushnet River channel. Note the location of the navigation channel with respect to acoustic basement. C - C': 1.4 km crossing of sediment mound at the Clarks Point outfall.

samples taken from these areas. We think that the acoustic basement may represent bedrock, or the gravel and till that immediately overlie bedrock in some places. Forty of the test borings made by the Corps of Engineers penetrated through sediment to bedrock, most of which is granitic gneiss that is probably pre-Mesozoic (Moore, 1963; O'Hara and others, 1976). Overlying bedrock there are usually 8-9 ft. (2.4-2.7 m) of glacial till and/or 6-9 ft. (1.8-2.7 m) of gravelly sediment, that are themselves buried by sands and silts (Figure 3).

From the profiles, we can map the thickness of sediment over acoustic basement (Figure 4) and show that the drowned valley system is partly filled with sediment. Our interpretation of the seismic data is confirmed independently by five seismic profiles made in the same area by the U.S.G.S. (J. Robb, personal communication, 1976). Sediment is thinnest over topographic highs and thickest in troughs, where penetration reached 20-25 milliseconds two-way travel time. Assuming a velocity of 1.6 km/sec, this time corresponds to 50-60 ft. (15-18 m) of sediment. This is in good agreement with the thickness of sediment measured in test borings in the harbor, where bedrock is deepest; here, in areas away from the dredged portions of the harbor, there are up to 60 ft. (18 m) of unconsolidated sediment filling the buried channel of the Acushnet. Our seismic profiles show some irregular layering within the sediment column, and a complex history of cut-and-fill in the drowned valley of the Acushnet (Figure 3). Examination of test borings from the harbor shows that basal deposits are locally overlain, in the deepest parts of the buried channel, by up to 20 ft. (6 m) of silt and sandy silt, above which most of the sediment consists of sands with a few thin layers of gravel and some discontinuous lenses of silt. These last silt lenses, which tend to be gray, are no more than 10 ft. (3 m) thick and occur mainly near the axes of drowned channels. Sands are brown and were deposited in oxidizing environments. In test borings surface sediments are usually darker, finer-grained, shellier and contain more organic matter than the buried sediments, showing that the most recent depositional environment is more reducing than it was in the past. Surface silts are thickest near the head of the harbor, north of the New Bedford-Fairhaven Bridge,

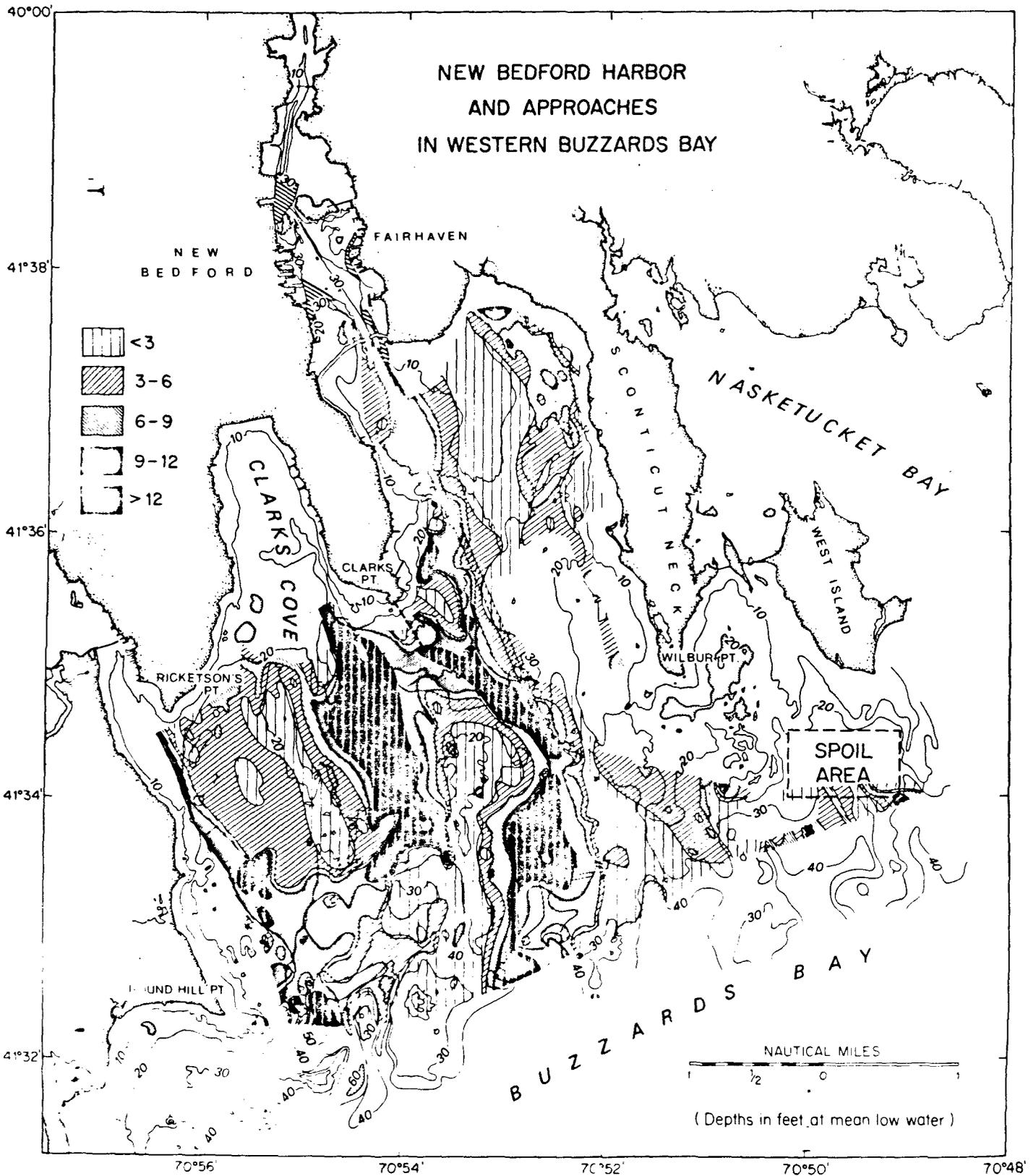


Figure 4. Isopachous map, contoured in milliseconds two-way travel time, of sediment over acoustic basement.

where there is up to 15 ft. (4.5 m) of dark, organically enriched silt. Our profiles across the navigation channel show that organic muds which occur there are highly reflective, and give rise to as many as six multiple reflections (Figure 3). We attribute this high reflectivity to the presence in the muds of substantial amounts of gas produced by the decay of organic matter. Similar organically enriched, highly reflective muds form a low mound around the sewer outfall off Clarks Point (Figure 3).

Sedimentary History

The drowned valleys that cross the study area are parts of a well-developed late Tertiary or Pleistocene drainage system that underlies much of the inner continental shelf in this region (O'Hara and others, 1976)*. Glacial till was deposited here until about 15,000 years ago, when the ice sheets began to melt and expose the old land surface (Strahler, 1966). The till was eroded locally by rivers and streams, and it seems likely that much of the gravel overlying buried channels was derived from the till by fluvial action. Except for the till and the most recent black muds, we do not know which of the buried sediments are marine and which are terrestrial or fluvial, so it is not possible to accurately reconstruct the geological history of valley fill. If the valleys contained almost no sediment, their seaward ends would have been flooded by rising sea level about 8,000 years ago, when sea level was about 100 ft. (30 m) below its present level. Sea level rose fairly rapidly until about 4,000 years ago, so the area now deeper than about 10-15 ft. (3.5 m) would have been flooded rapidly. For the past 3000-4000 years sea level has risen steadily at about 1 cm/year in this region (cf. Emery and Uchupi, 1972). If the valleys had not already been partly filled with fluvial sediment, they would have begun to fill with marine sediment during this transgression. The rising sea would have winnowed glacial till, supplying gravel on the one hand and suspensions of finer-grained sediment on the other. The fines would have tended to fill the drowned lower reaches of the river valleys, which may account for the 6 meters of silt that locally occurs beneath the main channel of the Acushnet. The sands, which form the bulk of the

* See also Schafer and Hartshorn (1965)

deposits, could be fluvial, or may have been deposited during the transgression. Sands tend to be widespread in inner continental shelf areas because sand grains tend to be moved landward on the inner shelf and because wave action tends to prevent the settling of fines. Thus the period of rapid transgression would be a high energy phase during which sand accumulation would be encouraged. As the sea continued to deepen, waves would have had less impact on the bottom, especially in depressions, allowing fine sediment to begin to accumulate slowly and form the most recent deposits. Borings taken in the harbor suggest that fine-grained sediments may have accumulated most rapidly in the quiet waters at the head of the harbor north of the New Bedford-Fairhaven Bridge.

SEDIMENTATION

The key to understanding both siltation problems and the dispersal of fine-grained wastes, may lie in the pattern of sediment movement through the water column by waves and tidal currents. We examined these patterns by studying the nature and properties of the water mass in the study area, and the distribution, size, and seasonal and tidal variations in the character of suspended particles, as well as the character of the bottom sediments themselves.

Previous Studies

Both Buzzards Bay and New Bedford Harbor are low energy microtidal estuaries in the sense of Hayes (1975), having a mean annual tidal range of 3.7 ft. (1.11 m) and a spring tidal range of 4.6 ft. (1.38 m) (measured in New Bedford Harbor: U.S. Army Corps of Engineers, 1970, 1971). Tidal currents in the Bay are generally less than 50 cm/sec. In the approaches to the harbor, they are generally less than 25 cm/sec, except over the shoals off Round Point and West Island, where velocities reach 46 to 50 cm/sec (Moore, 1963; Eldridge Tide and Pilot Book, 1976), and through the harbor entrance, where they reach 122 cm/sec (U.S. Army Corps of Engineers, 1971).

Wave energy is low in this area, the direct fetch into the study area being about 10 miles (17 km). Wind-driven waves, generally less than 6 ft. (1.8 m) in height, approach mainly from the south and southwest (U.S. Army Corps of Engineers, 1962). Most strong winds are

westerly. The highest winds, which are mainly from the WNW or NNW, may cause clockwise surface circulation in the study area.

Buzzards Bay is classified, on the basis of its salinity distribution, as vertically homogeneous (type C of Pritchard, 1955: see Bumpus and others, 1974). Freshwater discharge into the bay is estimated to be 27 cu.m/sec, most of it from the northern side, which gives rise in the bay to salinities of about 31 to 33^o/oo, with no significant annual cycle (Bumpus and others, 1974). Salinity decreases to as low as 20^o/oo in New Bedford Harbor (Massachusetts Division of Water Pollution Control 1971, 1975). The waters of the harbor contain coliform bacteria (up to 8000 counts/100 ml or more). Coliforms are much lower outside of the harbor, except near the Clarks Point sewer outfall, where they may be locally excessive (Hoff, 1971: Massachusetts Division of Water Pollution Control, 1971, 1975). In the open waters of Buzzards Bay they are as low as 5 counts/100 ml (New England Aquarium, 1973).

Surface waters in the harbor usually contain 1-4 mg/l of suspended matter (Massachusetts Division of Water Pollution Control, 1975), similar to the amount in suspension in Buzzards Bay (New England Aquarium, 1973), and in other Atlantic coastal estuaries (Meade and others, 1975). Bottom waters in the bay contain much more material in suspension, especially over muddy bottoms. In a series of reports, Rhoads (1963, 1967, 1973) and Rhoads and Young (1970) show that the bioturbated, top 2-3 cm of mud in the bay is easily resuspended by tidal currents and can give rise to a turbid layer of bottom water 2-3 m thick in which there may be up to 10-35 mg/l of material in suspension. Turbidity of near-bottom waters may also be increased by the ejection of particles into the water column by benthic organisms. Rhoads found that the turbidity of bottom water changes in intensity with tidal cycle, apparently being best developed on the ebb (at mean tidal velocities of about 8 cm/sec), and with season, being highest when benthic organisms are most active. Rhoads work was followed up in more detail by Roman (Roman, 1977; Roman and Tenore, 1977), who found that tidal resuspension increases the amount of organic matter in bottom waters on the flood and the ebb, thereby increasing primary productivity by more than 50 percent. Primary productivity increases most in spring and summer, when

resuspension of chlorophyll-a (resuspended phytoplankton) is greatest. Benthic primary productivity, bioturbation and resuspension are also greatest at this time (see papers by Rhoads).

Detailed studies of sediment distribution in Buzzards Bay in the 1930's by Hough (1940) and in the 1950's by Moore (1963), show that the deeper parts of the bay and depressions near the shore are floored with mud, while sands and gravels cover the shallow areas that are most exposed to waves and tidal currents. Nearly all of these sediments are terrigenous, very few of them containing shell remains; most of the sediments contain less than 1.5 percent of Ca (representing calcium carbonate skeletal fragments).

Moore found that most of the sands are either feldspathic (10-25 percent feldspar) or arkosic (more than 25 percent feldspar), and very few are quartzose (less than 10 percent feldspar). The gravels consist of locally derived granitic or gneissic rocks. The fine sediments, classified by Moore as protogreywackes, consist of silt, with up to 40 percent clay (Figure 5), the clay fraction being dominated by illite. These fine sediments contain about one percent of organic carbon (Hathaway, 1971), equivalent to about 2 percent organic matter (Hough, 1940).

Moore and Hough destroyed the natural character of their samples by disaggregating them before making size analyses. Subsequent work has shown that deposit-feeding benthic organisms like the polychaete Yoldia limatulina rework the top few centimeters of the mud deposits in Buzzards Bay, and in so doing, change the texture of the sediment by creating fecal pellets of fine sand to coarse silt size (31 to 125 microns in diameter), that form up to 20 percent of these deposits (Rhoads, 1963; 1967). Most reworking and pellet production takes place in the top 2-3 cm, below which pellets are destroyed (Rhoads, 1967). The pellet-rich surface sediments have a higher organic content, and are more oxidized because of prolonged contact with seawater (Rhoads and Young, 1970).

Too few samples were available to Moore and Hough to permit them to accurately map sediment distribution in our study area. Most information on this subject is

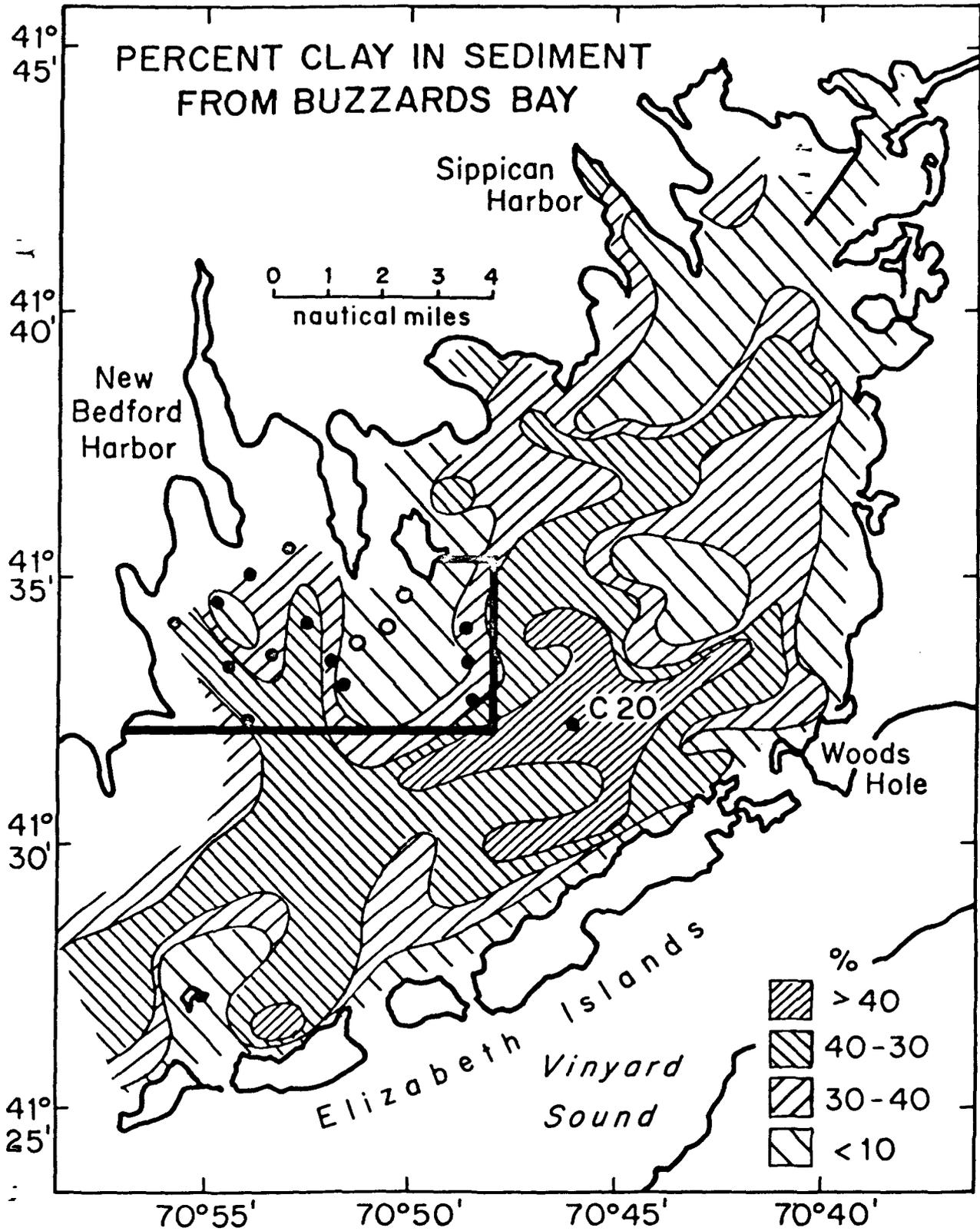


Figure 5. Clay in Buzzards Bay (data from Moore, 1963). Location of Moore's samples within the New Bedford study area denoted by open circles (size analyses) and dots (chemical and size analyses). C 20 from present study.

available in the form of unpublished chart notations made by the Coast and Geodetic Survey, which show that muds occupy the depressions and that there is sand, gravel, or rock on the ridges. In addition, the New England Division of the U.S. Army Corps of Engineers analyzed 15 cores collected from the harbor and navigation channel (Figure 6). All of the samples examined, bar three, were fine, black, organically enriched silt with more than 70 percent mud and up to 20 percent clay.

Water Properties

So that we could compare, through time, the changes that occur in different water properties with the changes that occur in the concentration and character of material in suspension, we made both seasonal and tidal measurement of water properties. Using a Hydrolab Surveyor model 6D, we measured temperature, salinity, dissolved oxygen, redox potential and pH, at 65 stations in November, 1975, and in January, March and April, 1976. The same measurements were made at the hurricane barrier and from I-195 in November and December, 1975 and March, 1976, as well as over a complete tidal cycle at two stations in the harbor in June 1976. Station locations are shown in Figure 7; summaries of the measurements are presented in table 1; all original measurements are presented by Ellis and others (1977). Our data show that tidally induced variations are subordinate to the seasonal changes.

(a) Seasonal Changes

The salinity structure of the study area is that of a weakly stratified, partially mixed estuary (type B, of Pritchard, 1955) and indicates that there will be a weak, net-landward movement of bottom water throughout the year. In the harbor, differences in salinity between surface and bottom waters exceed 1^o/oo in winter, dropping to 0.5 to 1^o/oo in summer (table 1), so landward movement of bottom water should be greatest in the winter. The same applies to the approaches to the harbor, although there the differences are smaller so movement should be less (table 1). The lowest salinity value detected in the harbor was 23.2 ^o/oo, showing the unimportance of freshwater discharge even in winter*.

Dissolved oxygen varies throughout the year,

* According to the U.S.G.S. (Dr. M. Frimpton, pers. comm., 1976) discharge of the Acushnet at Hamlin Road is .02 cu m/sec (7 day, 2 year low flow); discharge can be as high as .74 cu m/sec in winter.

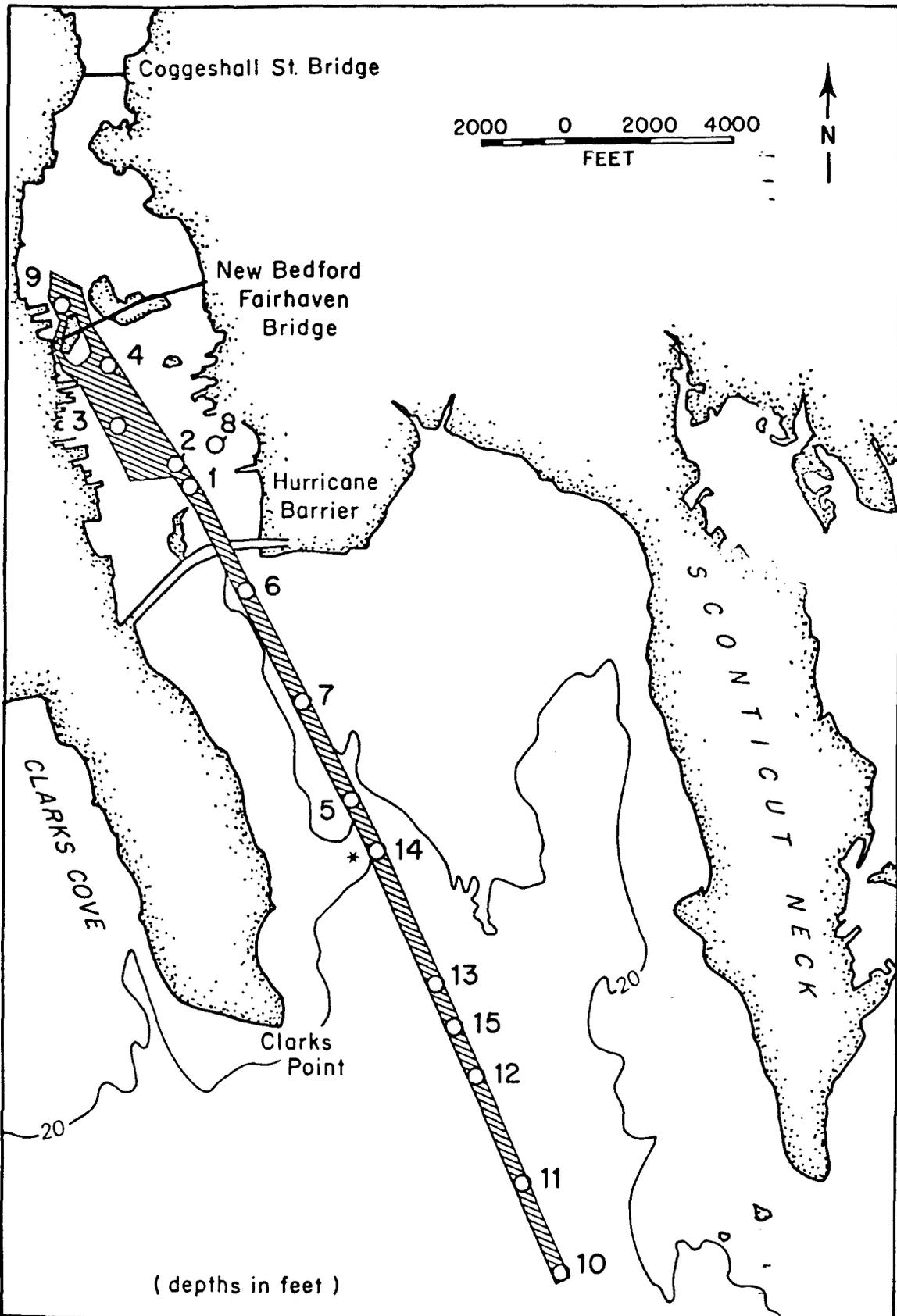


Figure 6. New England Division, Army Corps of Engineers cores in New Bedford navigation system (from unpublished report). Hatching denotes 30 ft. dredging.

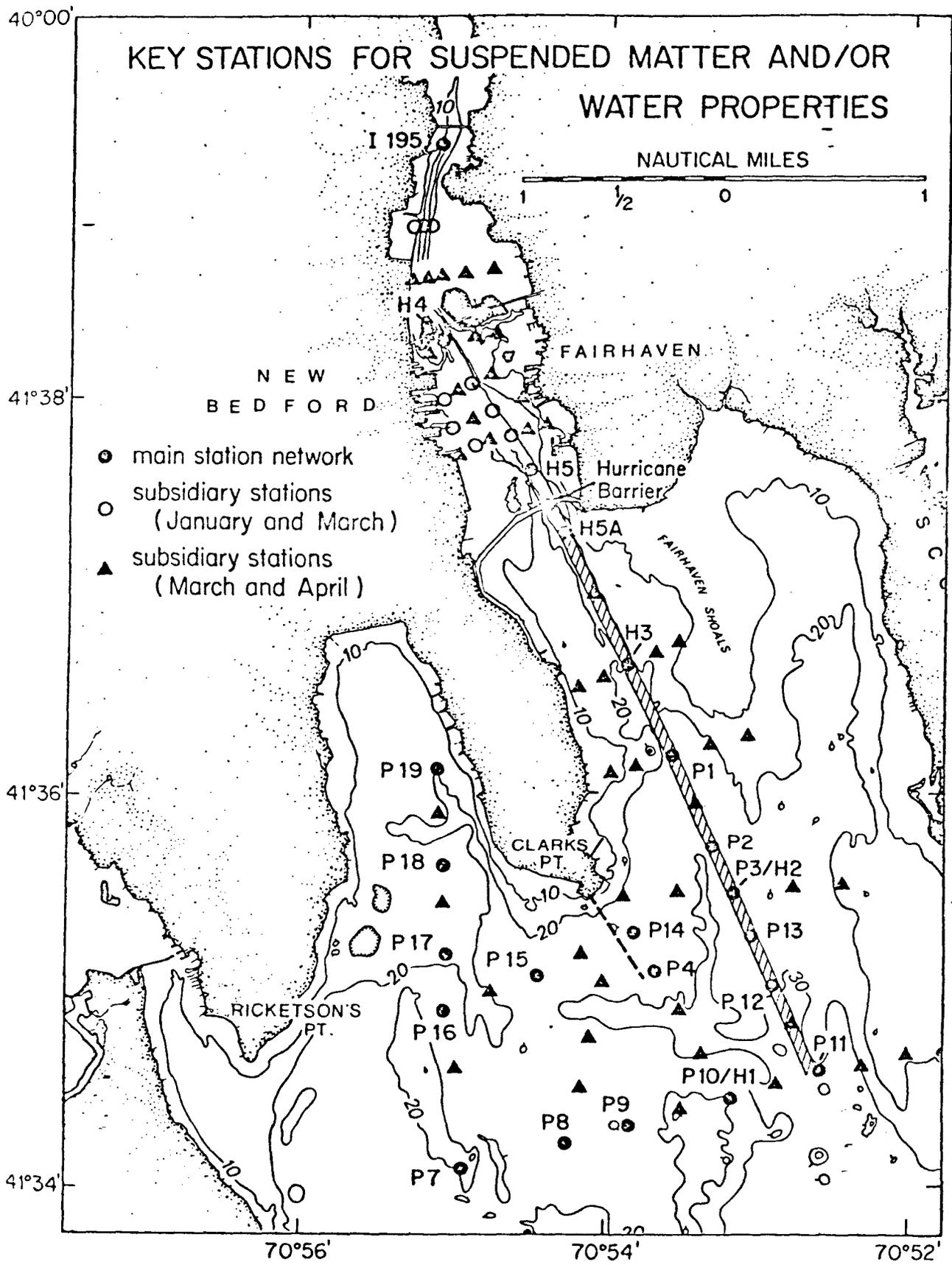


Figure 7. Oceanographic station locations. Main station network used during each seasonal survey, other stations used as noted.

Table 1. Seasonal variations in properties of surface and near-bottom waters in the harbor and approaches to New Bedford. Means of measurements made at between 5 and 15 stations outside the harbor and from 3 to 10 stations inside the harbor, except in December, when the only measurement was made at the hurricane barrier, and in June, when we have used the mean values for tidal station H4. Measurements were made with a Hydrolab Surveyor; original data are presented by Ellis and others (1977). Bottom water was measured 0.5 m above the seabed.

| Month | Location | Salinity ‰ | | Dissolved Oxygen (ml/l) | | Redox Potential (mv) | | Temperature °C |
|-------|------------|------------|--------|-------------------------|--------|----------------------|--------|----------------|
| | | Top | Bottom | Top | Bottom | Top | Bottom | |
| Nov. | Harbor | 26.6 | 29.5 | 4.7 | 4.5 | 180 | 130 | 8.9 - 9.5 |
| | Approaches | 30.0 | 30.7 | 5.2 | 5.0 | 180 | 170 | |
| Dec. | HB | 23.2 | 30.5 | 6.2 | 5.8 | 200 | 205 | 1 - 2 |
| Jan. | Harbor | 26.8 | 28.8 | 7.1 | 6.8 | 180 | 170 | 0.5 - 2 |
| | Approaches | 27.5 | 28.3 | 7.1 | 6.8 | 240 | 220 | |
| Mar. | Harbor | 28.7 | 29.4 | 5.6 | 5.4 | 270 | 250 | 3 - 4 |
| | Approaches | 29.3 | 29.7 | 5.6 | 5.5 | 320 | 320 | |
| Apr. | Harbor | 29.5 | 30.2 | 4.3 | 4.3 | 130 | 110 | 10 - 9.6 |
| | Approaches | 30.4 | 30.7 | 4.8 | 4.9 | 220 | 220 | |
| June | Harbor | 30.4 | 29.6 | 3.7 | 2.7 | 150 | 70 | 17 - 19 |

ranging from mean values as low as 2.7 m/l in June, to 7.1 in January (table 1). Temperature changes seasonally, rising from lows of 0.5-1.0°C in winter, to highs of 19°C or more in summer (table 1). In the surface waters of the open Atlantic, dissolved oxygen varies directly with temperature (Broecker, 1974, Figures 5-8). Although the same happens in our study area, the surface waters always contain about 1.5 ml less of dissolved oxygen than open ocean waters (cf. Broecker, 1974, Figures 5-8). Dissolved oxygen is a non-conservative property of the water mass that is depleted where demand is large and may be taken as an indicator for the discharge of sewage effluent. There is little difference between the harbor and the approaches (table 1), probably because discharge points exist both inside and outside the harbor. Further depletion of dissolved oxygen in bottom waters, by up to 0.4 m/l suggests that demand is greater near the bottom than near the surface. We would expect bottom waters to contain more oxygen than surface waters, since the bottom waters are always 0.5 to 1.0°C colder.

We detected little significant change in pH, either with location, or with depth (Ellis and others, 1977). In contrast, the oxidation-reduction (redox) potential changes with season, being generally higher in winter than summer, tends to be higher in the approaches than it is in the harbor, and tends to be lower in bottom than surface waters, especially in the harbor where bottom waters can be very poorly oxidizing (table 1).

In summary, bottom waters are slightly cooler and more saline than surface waters, contain less dissolved oxygen, are more weakly oxidizing, and should have a net landward movement throughout the year.

(b) Tidal Changes

The only stations at which observations were made continuously throughout a tidal cycle, were H4 and H5, inside the harbor in June (Figure 8).

The Hydrolab Surveyor was used to measure water properties at 1 m intervals, and a Bendix model Q9 Savonius Current Meter to measure current velocity at 1.5 meter intervals at both stations (Figure 8).

At both stations the bottom waters were slightly cooler and more saline than surface waters and contained

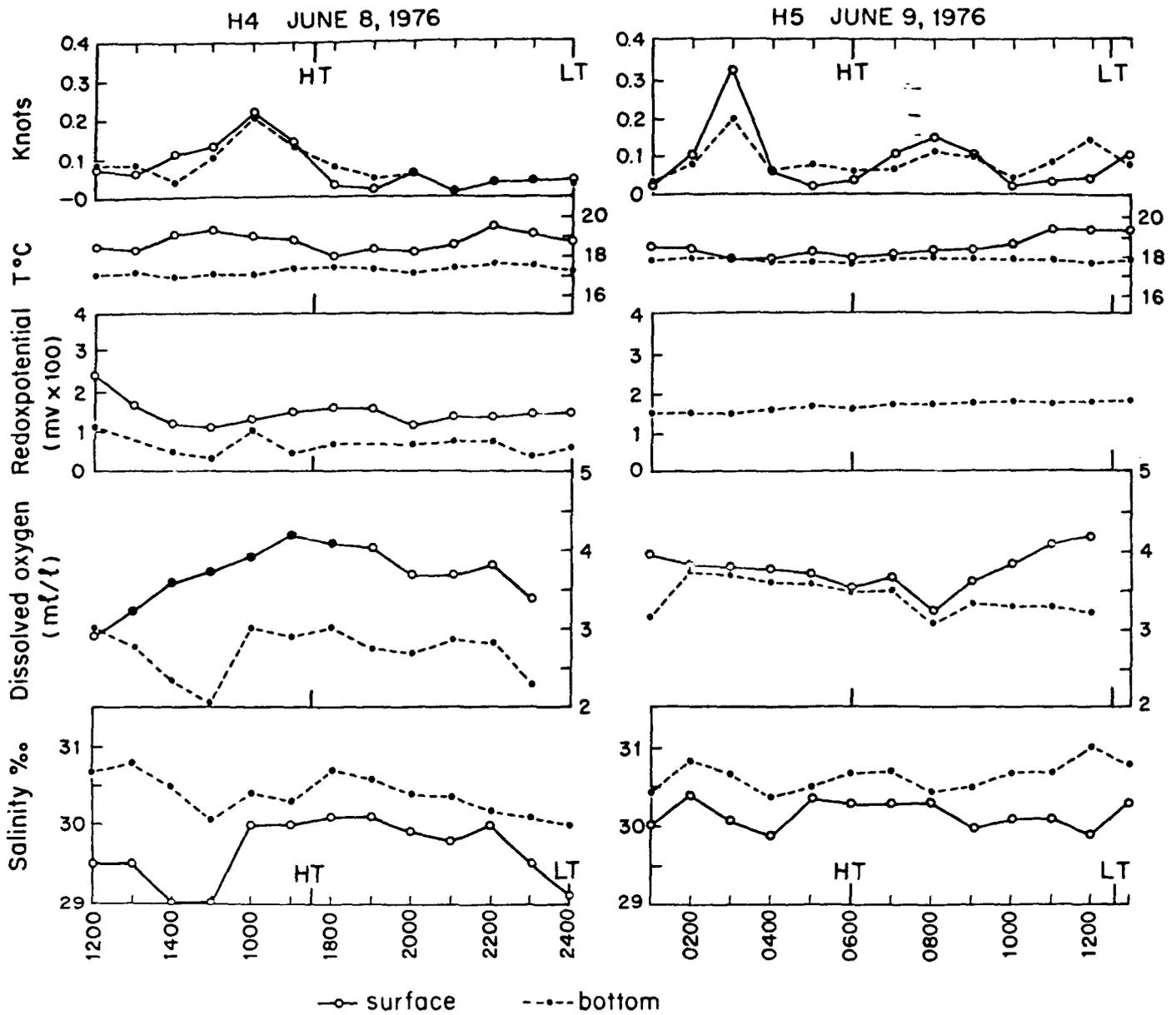


Figure 8. Variations in water properties and current velocities in surface and bottom waters for two stations (H4 and H5) through a complete tidal cycle.

less dissolved oxygen; only at H4 do they have a lower redox potential (Figure 8). Surface waters at H4 are slightly more brackish than those at H5. Bottom waters at H4 have about the same temperature and salinity as at H5, but contain less dissolved oxygen and have a lower redox potential. These various data suggest that the water column is much better mixed at H5, near the head of the harbor. This is hardly surprising in view of the velocity with which tides stream through the gap in the hurricane barrier.

We were able to make a limited number of observations of current direction that suggest that surface and bottom waters tend to move in more or less the same way during tidal changes. Surface and bottom waters clearly move with much the same velocities, that peak at 10-15 cm/sec during the flood, but are about 5 cm/sec or less at other times (Figure 8). These velocities are typical of much of Buzzards Bay (Rhoads, 1973).

Suspended Matter

Water samples for the extraction of suspended matter were collected from the surface and subsurface at most sites where water properties were measured (Figure 7). A polyethylene bucket was used to obtain surface samples and 10 l Niskin bottles for subsurface samples, which were taken 1 m, 2-3 m, and at some stations 4-5 m off the bottom. From each sample we stored a 1 liter subsample in a polyethylene bottle. A portion of some subsamples were analyzed for particle size (by Coulter Counter). All subsamples collected were filtered through weighed pairs of Millipore filters, to obtain particles greater than 0.45 microns in diameter. The total weight of the suspen- sate and the weight remaining after combustion at 550°C to remove non-skeletal organic matter were then obtained. The method is described in papers by Manheim and others (1970) and Summerhayes and others (1976); the raw data are recorded by Ellis and others (1977).

(a) Tidal Changes

We took our samples during a calm weather period when resuspension of sediment by wave action should have been minimal (see Figure 7 for station location). Our results show that on average, suspended matter is 1.5 to 2 times as abundant in bottom waters as it is in surface waters, with maximum suspensions occurring as the

flood tide decreases in velocity about 1 hour after the velocity maximum (compare Figure 8 and Figure 9). The surface and bottom suspensates follow each other more closely at H5 than at H4, probably because the water at H5 is better mixed than it is at H4.

The suspensates at H4 and H5 appear quite similar to one another, with a greater percentage of combustible matter being found near the surface than at depth (Figure 9, and table 2). At H5, there is a higher percentage of combustible material in the surface suspensate at slack tide than at peak flood or peak ebb when turbulent mixing is likely to be best developed (Figure 9). The picture is a little more complex at H4, but there is still a substantial decrease in the percentage of combustible material in surface suspensates when the bottom waters contain the most suspended matter. Visual inspection by petrographic microscope, shows that the incombustible fraction of these suspensates consists of discrete mineral grains, angular and irregular aggregates of sediment (probably resuspended), and diatoms.

We interpret these data to show that large amounts of sediment are carried into the harbor by the decelerating tidal currents, in agreement with Gordon's (1975) finding that decelerating tidal currents, because of vigorous fluctuations in turbulent velocity (Drake, 1976), should carry more sediment than accelerating currents. During both flood and ebb tide, sediment from the near-bottom turbid layer appears to be mixed with surface water, lowering the percentage of combustible material in surface suspensates. However, because of the low current velocities and lower total suspensate concentrations during the ebb, it appears that ebb tides are less effective than flood tides in transporting sediment through the harbor.

As there is little difference in total suspensates between samples taken 1 m and 2 m off the bottom at H5 (Figure 9, and table 2), the layer of turbid water here is probably quite thick and may be completely gradational with the surface water. There seems to be a thinner turbid layer of bottom water at H4, where there is a larger difference in total suspensates between samples from 1 m and 2 m off the bottom (Figure 9). These differences may be due to greater turbulence at the hurricane barrier near H5.

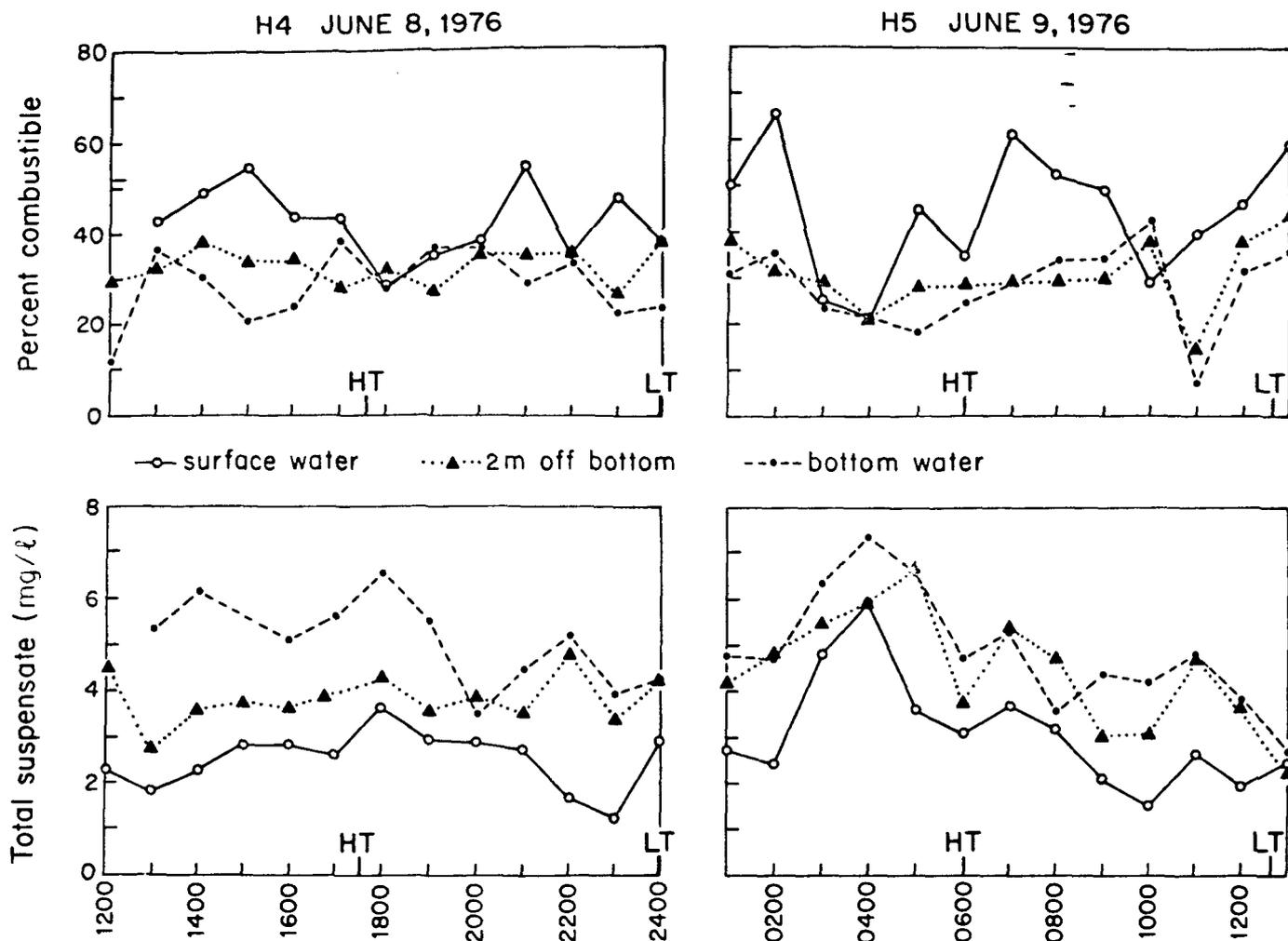


Figure 9. Suspended matter variations for stations H4 and H5 through a complete tidal cycle.

Table 2. Mean abundances of suspended matter, and contents of combustible material in suspensates collected at different times of the year and at different depths in the water column in the harbor and approaches. See Figure 18 for station locations. June values are the means for measurements made on samples collected throughout the tidal cycles (Figures 20a and 20b). August samples were collected at low tide on August 10 after passage of Hurricane Belle (at the I-195 Bridge and the hurricane barrier). Samples from the sewer outfall off Clarks Point were taken on January 6 and 7. River samples were collected 3 miles upstream from the I-195 Bridge, at Tarkiln Hill Road, on March 15 and 16.

| Month | Total Suspended Matter (Mg/l) | | | | Percent Combustible Suspended Matter | | | |
|-------------|-------------------------------|-------------------|------|------|--------------------------------------|-------------------|------|----|
| | Surface | Meters Off Bottom | | | Surface | Meters Off Bottom | | |
| | | 4-5m | 2-3m | 1m | | 4-5m | 2-3m | 1m |
| Sept.- | | | | | | | | |
| Nov. | 1.6 | 1.7 | 1.7 | 3.1 | 58 | 52 | 44 | 39 |
| Dec.- | | | | | | | | |
| Jan. | 1.4 | 1.2 | 3.7 | 4.9 | 46 | 46 | 34 | 34 |
| Mar. | 4.3 | | 4.5 | 6.0 | 39 | | 34 | 28 |
| Apr. | 2.4 | | 2.3 | 3.0 | 57 | | 63 | 46 |
| June (H4) | 2.5 | | 3.8 | 5.7 | 43 | | 33 | 29 |
| June (H5) | 3.1 | | 4.5 | 4.9 | 45 | | 31 | 30 |
| August (HB) | 13.2 | | | 18.7 | 32 | | | 30 |
| I-195 | 31.5 | | | 6.8 | 40 | | | 25 |
| Sewer | 13 | | | | 69 | | | |
| | 23 | | | | 60 | | | |

(b) Seasonal Changes

In general, the amounts of suspended matter in surface water samples taken at particular times of the year are scattered about a mean value. This scatter is similar to that for June surface suspensates at H4. The same applies to bottom suspensates taken at these times, with respect to the mean for June bottom suspensates from H4 (Figure 9). The scatter of points obscures any significant regional variation in abundance of suspensate that might have been produced by tidal change. By comparing the mean values of suspensate abundance for different seasons (table 2), we obtained some idea of the effects of changes in wave action, runoff and biological productivity on suspensates. We should add that there were no consistent differences in the character and abundance of suspensates between the harbor and the approaches, so all samples have been lumped together.

Surface water suspensates increase in abundance from lows of about 1.5 mg/l in winter to a peak of 4.3 mg/l in March, remaining moderately high in spring and early summer (April and June: table 2)*. Bottom waters show a similar pattern, with peaks of 6 mg/l one meter off the bottom and 4.5 mg/l two meters off the bottom in March (table 2)**. Mid-water samples 4-5 m off the bottom usually contain about the same amount of suspended matter as surface samples. Our data suggest that the water column is clearest in the fall, when water 2-3 m off the bottom contained the same small amount of material in suspension as surface water (table 2). At this time the near-bottom turbid layer could not have been thicker than about 2 m. The thickness of the turbid near-bottom layer increased to at least 3 m in winter.

In March and April, the entire water column became turbid and there was little difference between surface

* In making these calculations, we ignored three samples that were taken at or near the sewer outfall off Clarks Point.

** In making these calculations, we (1) ignored seven samples in Dec. and Jan. with abundances of less than 2 mg/l, that probably came from clear water above the near-bottom turbid layer, and (2) four samples in Dec. and Jan., one sample in Sept. and Nov., and eight samples in March, that had more than 10 mg/l in suspension and probably came from turbid clouds stirred from the bottom during sampling. These samples (extra low and extra high) were sufficiently different from the norms for these periods to be regarded as anomalies introduced by sampling mistakes.

water and water 2-3 m off the bottom. Although surface suspensates were highest in March, the river at this time contained only 2.6 mg/l, suggesting that runoff was not the source of the suspended material in the harbor (table 2).

The amount of combustible material varies inversely with total suspensate abundance, decreasing from fall and winter to spring, then increasing again in April and June, both at the surface and at the bottom (table 2). Examination by binocular microscope of selected samples from H5 shows that the increase in total suspensates and decrease in combustibles at surface is probably due to an increase in the production of diatoms during plankton blooms. Near-bottom suspensates commonly contain large irregular or angular aggregates (0.3 to 0.5 mm diameter), full of mineral detritus and amorphous organic matter, that appear to be resuspended bottom sediment. In the April sample, resuspended fecal pellets about 0.15 mm long were very common. Similar pellets are commonly resuspended in central Buzzards Bay (Rhoads, 1963, 1967).

We interpret these data to show that in the winter and early spring, storm waves cause more sediment than usual to be resuspended into water near the bottom. From early spring to early summer, production of organic matter increases giving rise to increases in the amounts of suspensates in the upper part of the water column; when diatoms are abundant, this increase lowers the proportion of combustible material in suspension. Resuspension of bottom sediment was also important in early summer, when benthic organisms are most active (Rhoads, 1963, 1967).

At the Clarks Point sewer outfall there is 10 to 20 times as much suspended matter as found elsewhere in the study area. This material drops rapidly out of suspension, and we never detected more than 5 mg/l of suspensates in surface waters further than 0.5 miles (0.9 km) from the outfall. Nevertheless, the presence of the outfall undoubtedly increases the amount of organic suspensates in the approaches to the harbor, both at the surface in the outfall plume, and near the bottom where organically enriched sediment deposited from the plume is resuspended by waves and currents.

The effects of severe storms can be assessed from August samples, which were taken at low slack tide at the

hurricane barrier and from I-195 on August 10, 1976, the day after passage of Hurricane Belle across the New England coast (table 2). River input was an order of magnitude higher than normal, and there was about 5 times as much suspended material in the outflowing river water as there was near the bottom at the I-195 bridge. At the hurricane barrier there was only half as much material in suspension at the surface as there was at the bridge, but there was three times as much material in suspension at the bottom as at the bridge. Resuspension of bottom sediment by waves in the approaches probably accounts for the near-bottom turbidity at the barrier, while runoff may account for much of the surface turbidity measured here at that time.

(c) Size of Suspended Particles

Numerous samples were analyzed by Coulter Counter to determine the size distribution of particulates. We present, as representative of the study area, the results of analyses of samples collected in November. Comparing surface, nearbottom and bottom waters, we find that there is a substantial increase in size in samples 1 m off the bottom and that there are more coarse particles in suspension near the bottom than above it (Figure 10). There are also larger particles in suspension in bottom waters as the flood tide decelerates than there are at slack tide or during the ebb (Figure 11). From later studies at H5, we know that the coarsest suspensions occur at periods of higher current velocity at each sample site. At the surface, we find no regional trend except around the sewer outfall, where there are much coarser particles in suspension than there are 0.5 miles (0.9 km) away from it (Figure 12). No attempt was made to accurately define the position or extent of the outfall plume.

In nearly all near-bottom samples, particles appear to be agglomerates of some sort. The agglomerates break down into smaller constituent particles when the samples are subjected to ultrasonic vibration [the treatment is mild, and involves setting the water sample, in its container, in an ultrasonic vibrating water bath for 2 minutes (W. Gardner, personal communication, 1976)]. Our preliminary investigations show that particle size distribution is usually polymodal, the most common modes being at 9 microns, 14 microns, and 28 microns. The average median diameter of untreated samples is 14 microns (fine silt). After

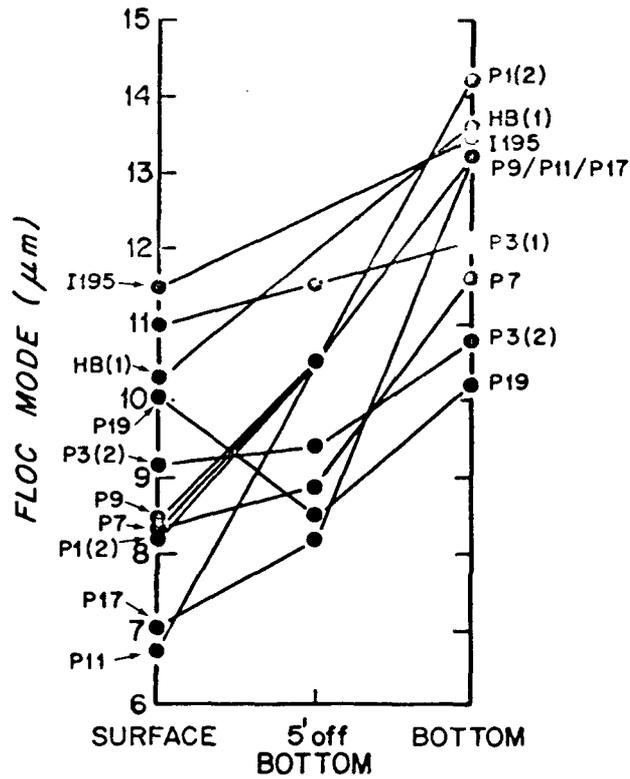


Figure 10. Floc mode (i.e. the modal size of suspended particles before ultrasonic disintegration) variation with depth. Note that horizontal scale is distorted since the distance between surface samples and those "5' off bottom" is 8 to 9 meters and between "5' off" and "bottom" is 1.5 meters. Actual size increase is exponential towards the bottom.

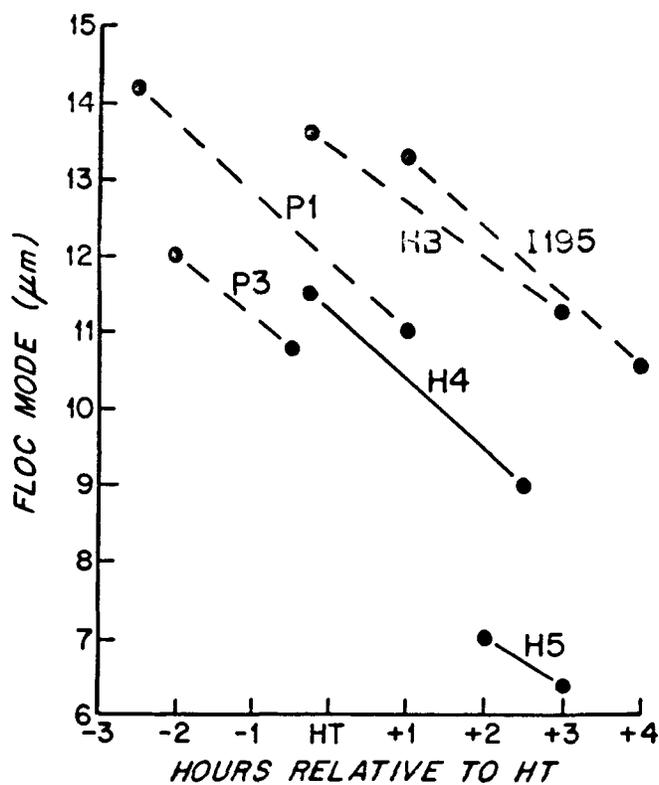


Figure 11. Changes in modal size (floc mode) of bottom water, suspended sediments for six stations in relation to tidal state.

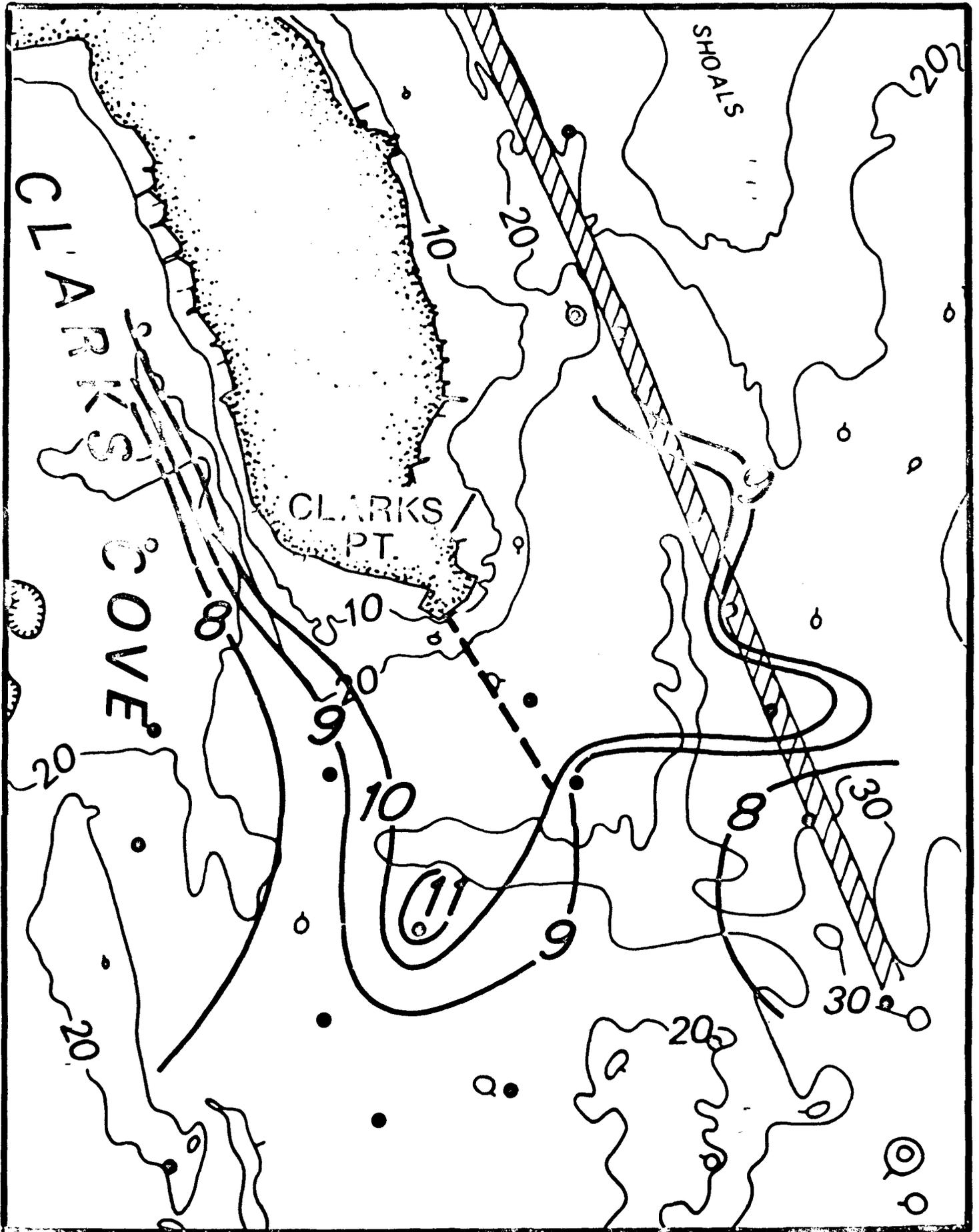


Figure 12. Distribution of surface water suspensates around the Clark's Point outfall as represented by floc mode. Contours are in microns, depths in feet; dots represent stations.

treatment, grain distributions are unimodal, the most common mode being 7.5 microns (very fine silt). The decrease in modal size cannot be interpreted simply as the change from floc mode to grain mode that is observed in other areas where flocculation causes the agglomeration of particles in the water column (Kranck, 1973), because some of the agglomerates are not flocs, but angular fragments of resuspended bottom sediment while others may be fecal pellets. As a result, it seems unlikely that flocculation is a prime mechanism of agglomeration in this area, especially in bottom waters.

Dispersal of Sediment

The harbor and approaches are low energy environments characterized by small waves, small tidal amplitudes, low velocity tidal currents and little river discharge. Because of the small discharge and weak tidal currents, the harbor is not flushed vigorously.

Tidal currents are stronger on the flood than they are on the ebb. Because there is more sediment in suspension on the flood than on the ebb, the net result must be landward transport of sediment. Most of this transport must occur near the bottom, where suspensate concentrations are highest. Net landward movement of suspended sediment in near-bottom water is common to both partially mixed and vertically homogeneous estuaries (Meade, 1972) and so probably occurs in Buzzards Bay itself, as it does in other similar embayments along the New England coast (Schnitker, 1974; Collins, 1976).

We can evaluate the amount of sediment transported along the bottom, by using the two-layer model of estuarine circulation that Oostdam and Jordan (1972) modified from Sverdrup's advective model of estuarine circulation (table 3). Using this model we calculate that there must be almost twice as much landward transport as seaward transport of suspended sediment, and that the rate of sedimentation in the harbor should be about 7 mm/yr. In view of the fact that the model is highly simplified, it does not take into account the diffusion of suspended sediments and ignores the input of sediment from the river (Oostdam and Jordan, 1972), the agreement between this value and the known rates of sedimentation, which are discussed in detail later in this paper, is gratifying.

Table 3. Calculation of estuarine circulation, suspended sediment transport, and sedimentation rate in New Bedford Harbor, based on the modification by Oostdam and Jordan (1972) of Sverdrup's advective model of estuarine circulation.

1. Water and Salt Balance:

Assume that the surface outflow (O) from the estuary = river input (R) plus bottom movement of salt water (I) as a function of the salinity structure of the estuary. Then, knowing the salinity of the outflow and inflow (S_o) and (S_i), and knowing river discharge (R), the model involves the calculation of (I) and (O) from

$$(a) \quad O = I + R$$

$$(b) \quad I = \frac{S_o R}{(S_i - S_o)}$$

We use November mean salinities (table 2) and use the low flow discharge measured in October ($0.74 \text{ m}^3/\text{sec}$): Thus $S_o = 26.6 \text{ ‰}$, $S_i = 29.5 \text{ ‰}$, and $R = 0.74 \text{ m}^3/\text{sec}$; it follows that: $I = 6.8 \text{ m}^3/\text{sec}$; $O = 7.54 \text{ m}^3/\text{sec}$

2. Sediment Transport

Assume that water movement (I) or (O) x total suspended matter (mg/l, table 3) = sediment transport.

$$(a) \quad \text{Surface transport} \\ = 7.54 \times 1.6 \times 10^{-6} \text{ m}^3/\text{sec} = 12 \times 10^{-6} \text{ m}^3/\text{sec}$$

$$(b) \quad \text{Bottom transport} \\ = 6.8 \times 3.1 \times 10^{-6} \text{ m}^3/\text{sec} = 21 \times 10^{-6} \text{ m}^3/\text{sec} \\ \text{Thus, excess landward transport of sediment in bottom} \\ \text{water} = 9 \times 10^{-6} \text{ m}^3/\text{sec} = T_i^{**}$$

3. Rate of Sedimentation

The average rate of sedimentation $S = \frac{T_i}{A}$ where A is the area of the harbor (4 km^2).

$$S = \frac{284 \text{ m}^3/\text{yr}}{4 \text{ km}^2} = 0.7 \text{ cm/yr}$$

*Oostdam and Jordan (1972) overlooked the fact that the term R in this equation was not included in the printed version of their paper.

**Note that even though outflow of water is larger than inflow, the greater suspended load near the bottom cause net landward transport of sediment over a tidal cycle (Oostdam and Jordan, 1972).

The suspensates tend to be very fine grained, in the fine silt to clay range. They exist in suspension mostly as agglomerates, that are chiefly irregularly shaped masses of amorphous organic matter containing dispersed mineral grains. Diatoms and fragments of diatoms are also common and may be parts of the agglomerates. Sand-sized quartz grains are also recognized and usually occur as discrete particles, as do fecal pellets and angular fragments of bottom sediment (both of which are types of agglomerate). Plant fibers are less common, but also occur as discrete particles.

As in other estuaries (Meade, 1972), the amount of organic matter in suspension is much higher than it is in the bottom sediments. Surface water suspensates in the study area usually contain more than 40 percent combustible organic matter, while bottom water suspensates contain more than 30 percent; both contain substantial amounts of incombustible skeletal material. In contrast, bottom sediments seldom contain more than 10 percent organic matter (5 percent organic carbon). Settling of this organic material during parts of the tidal cycle would change the organic content of bottom sediment, and through the activities of deposit feeding benthic organisms, could lead to the development at the sediment-water interface of an organically enriched layer of sediment, as implied from our studies of bottom sediments.

Our observations suggest that within the bottom 2-3 meters of the water column there is a well developed turbid layer, the density of which increases exponentially towards the bottom. By extrapolation, it seems that there may exist near the bottom a thin and very highly turbid layer of the 'fluff' that is common to many estuarine systems (cf. Meade, 1972; Weil, 1976). It remains to be seen whether this 'fluff' overlies, merges with, or is the equivalent to the 'carpet' of mobile sediment whose existence is inferred from our studies of bottom sediment later.

Seasonal fluctuations in the abundance of suspensates and their character are complex and probably have a variety of causes. Among the most important of these causes are: the effects of winter storm waves on resuspending bottom sediment and in mixing this through the water column; the effects of plankton blooms; and the changes in the patterns of activity of benthic organisms.

More work on the nature of the suspended material is required before the relative importance of these factors can be established with certainty. It appears that river runoff is not an important control of suspensates except during severe storms, when river-borne detritus dominates harbor suspensates, and even then, concentrations are not large. This is not surprising as the Acushnet is a small river draining only 9.3 km² of urbanized, glacial terrain. Furthermore, the river is dammed at two points along its course, the nearest dam to the harbor being located 8 km upstream from Popes Island, creating the New Bedford Reservoir. The river is tidal up to this lower dam, behind which most of the river's suspended load undoubtedly is trapped.

SEDIMENT PROPERTIES

Grain Size

(a) Sample Collection and Analysis

For purposes of our study we took 92 grab samples and 28 cores at 116 stations from the harbor and its approaches (Figure 13) and one core from the center of Buzzards Bay (Figure 5). Grab samples were obtained with a Smith MacIntyre Grab and cores with a 2 m long, 6.5 cm internal diameter gravity core. Samples from grabs were taken from the top 10 cm and, where there were pronounced differences between surface and subsurface sediments, from the top and bottom layers. Cores were sampled at 20 cm intervals, taking care to avoid the smear zone at the core wall. For size analysis, samples were treated with sodium hexametaphosphate and with an ultrasonic probe to ensure complete disaggregation. The silt and clay were separated from sand and gravel by wet sieving, silt from clay by centrifuge and gravel from sand by dry sieving. Splits of the samples were dried, powdered, and then analyzed for organic carbon and nitrogen and for calcium carbonate. Clay mineralogy, although not discussed here, was determined by x-ray diffractometry. Sand and gravel fractions of selected samples were examined by binocular microscope to determine their gross character. Analytical results are presented elsewhere by Ellis and others (1977); the methods are described by Milliman and Barretto (1975).

(b) Regional Distribution of Sediment

As nearly all of our samples were collected within

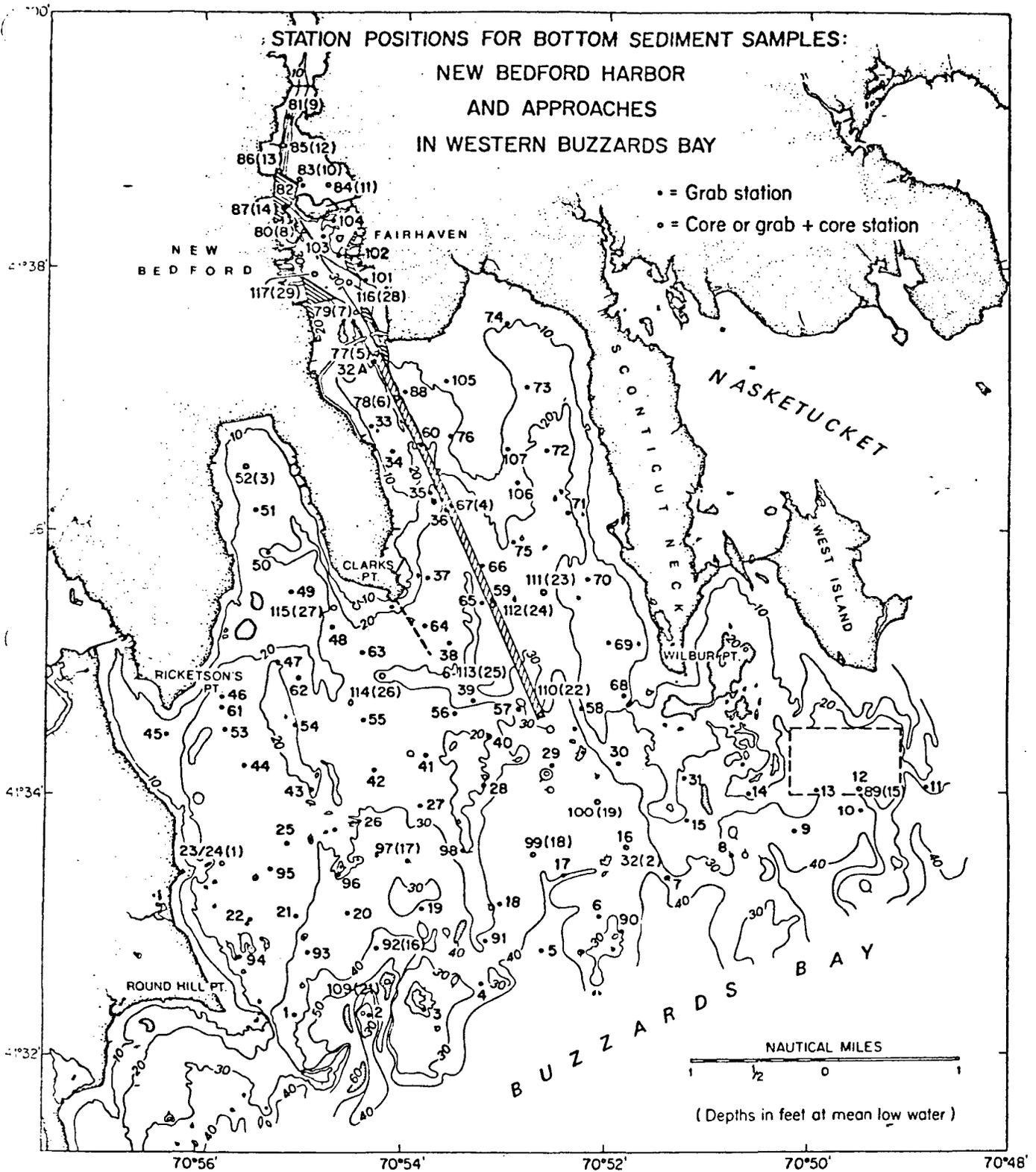


Figure 13. Core and grab sample locations (see Ellis, et al., 1977).

a few days of one another, during a period of consistently good weather (09/15-09/17, 1975), we are confident that our results give a synoptic picture of sediment distribution that is representative of the summer. Slight changes in these patterns may occur during winter, particularly outside the hurricane barrier.

Muddy sediments cover the floor of the drowned valley of the Acushnet, as well as the floor of the broad depression in the western half of the study area (Figure 14). These two deposits are separated by a sand-covered ridge. Where gravel-sized material is present in muddy samples, it is usually in the form of whole or fragmented mollusk shells. On the ridge crests and on the steeply sloping margins of the embayment, we find sands, gravels and mixtures of the two. These coarse deposits, and the muddy sediments flooring the depressions are separated in several places by narrow transitional zones in which we find varieties of muddy sand or muddy gravel. These transitional sediments take the place of muds in the depressions that run up into Clarks Cove and east of Fairhaven Shoals. Much of the navigation channel is floored with muddy sediment, except near the hurricane barrier where sandy sediments occur, probably because tidal currents are strong enough to prevent the settling of fines. In the deep narrow channels near Round Point we find gravelly muddy sands instead of sandy muds, probably because of tidal scour through the channels.

The map of mud (silt plus clay) distribution clearly shows the concentration of fines in depressions and the gradational boundaries between muddy depressions and sandy or gravelly topographic highs (Figure 15). The major depocenter of mud in the drowned Acushnet Valley is in the inner harbor. Although it is not clear from the map, the deepest samples in the harbor contain more mud than shallower samples. Smaller depocenters occur in the shallows in the lee of Butler Flats, at the seaward end of the navigation channel, and at depths greater than about 40 feet at the edge of Buzzards Bay (Figure 15). In the western depression, the major depocenter of mud lies close to the western shore where protection from the prevailing westerly winds is greatest.

The different types of mud in the depressions contain about 20 percent clay. In sediments seaward of the hurricane barrier, where the mud content is 40 percent or more, the ratio of clay to mud remains constant at

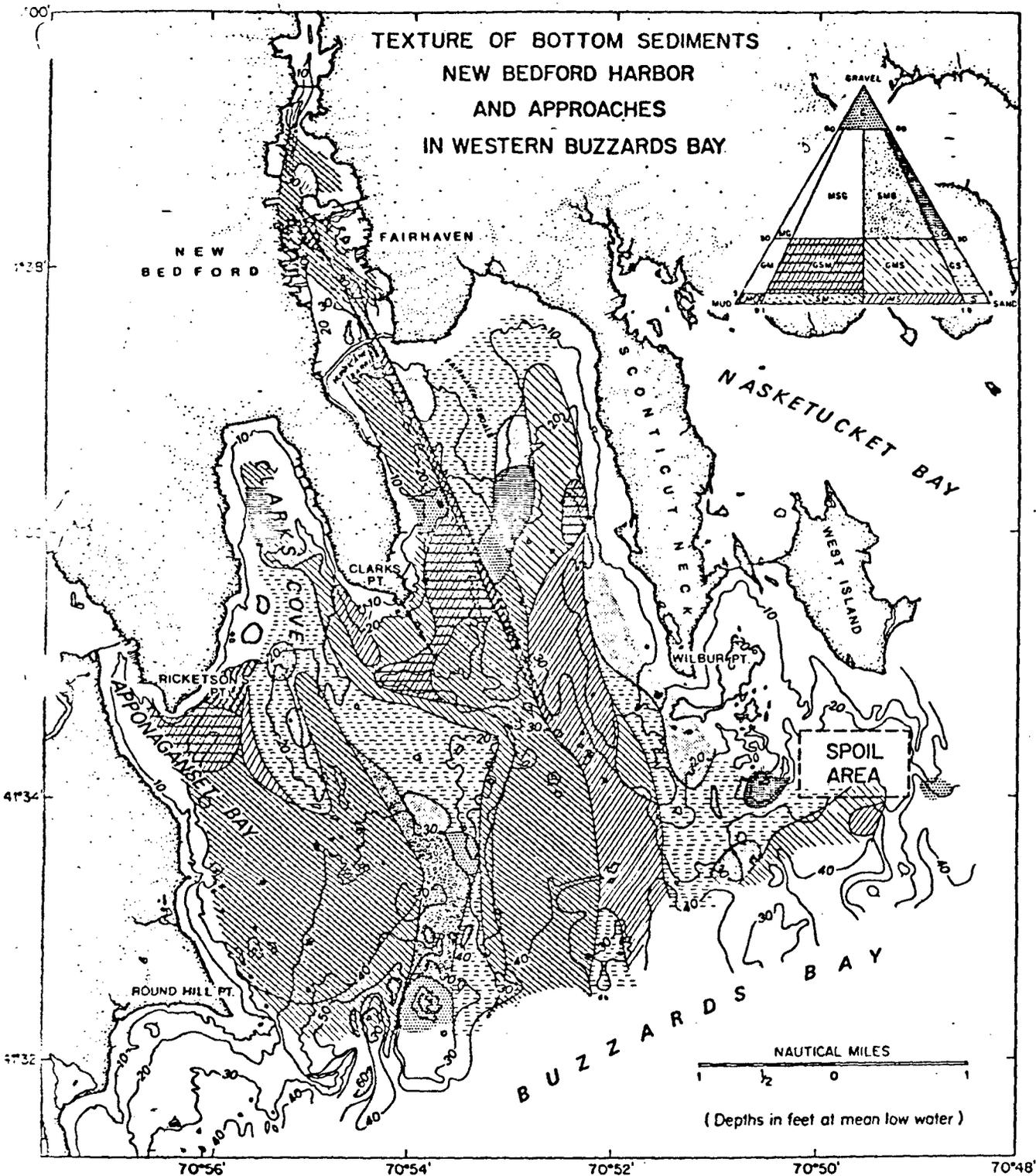


Figure 14. Textural classification of bottom sediments (after Folk 1968).

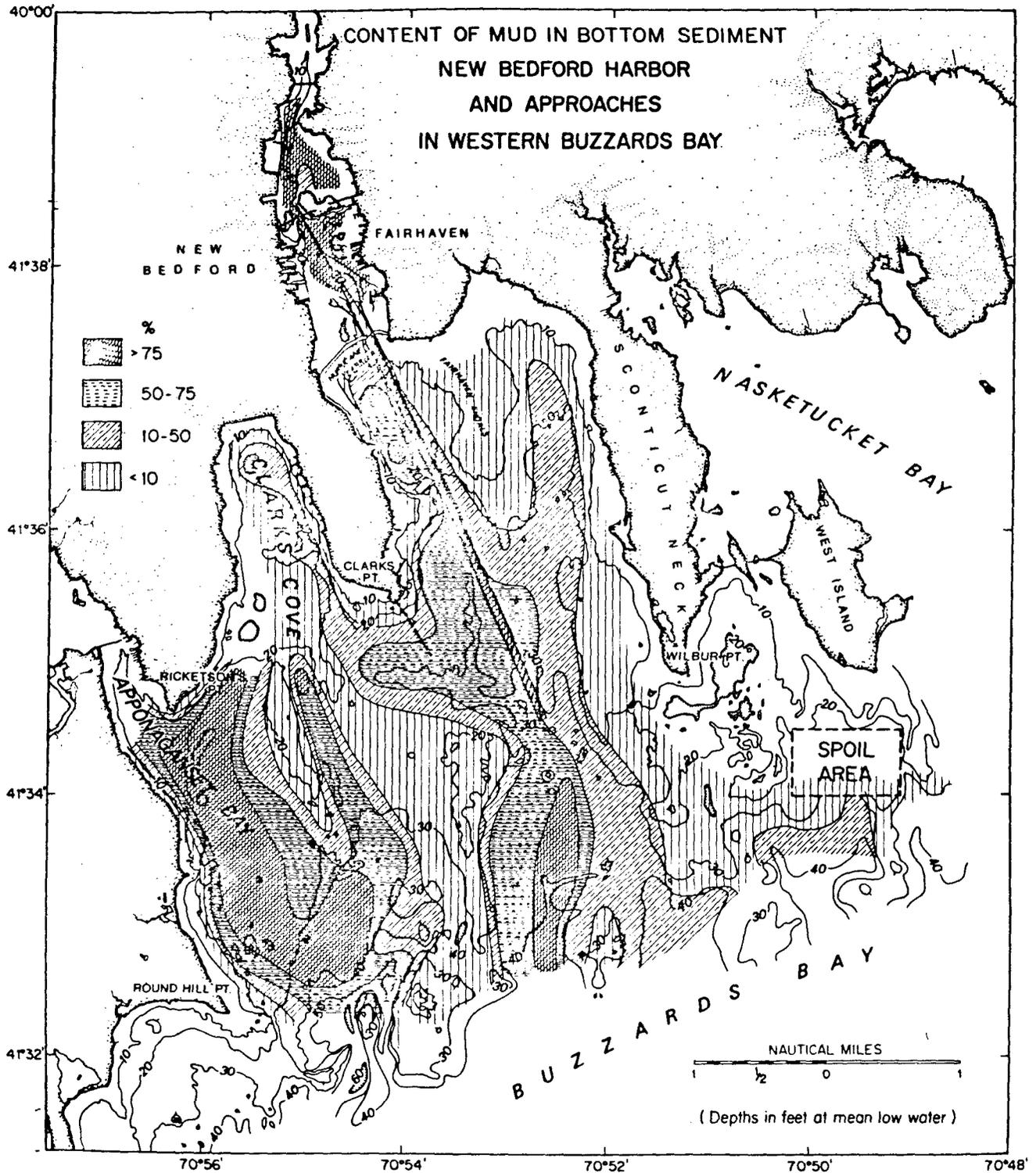


Figure 15. Distribution of mud (material finer than 63 microns).

about 0.28 (Figure 16). The ratio is higher (0.34) in muds from central Buzzard Bay, where Moore (1963) found the largest amounts of clay (Figure 5). In the harbor, where the mud content goes up to more than 40 percent, the clay content goes down to about 13 percent and the ratio of clay to mud averages only 0.18 (Figure 16). The muddy sediments in the study area are silts rather than clays, the siltiest being those from the inner harbor, while those from central Buzzards Bay contain the most clay.

Sands and gravels from the study area usually contain less than 5 percent clay. Where mud content is less than 40 percent, the ratio of clay to mud is much higher than in the depressions, averaging 0.40 (Figures 16 and 17). We re-examined Sanders (1958) data and found that the tendency for the ratio of clay to mud to be higher in coarse sediments was also true for central Buzzards Bay.

(c) Distribution of Sediment Down-core

Most of the cores taken in the harbor penetrated through muds into sands or gravels (Figure 18). In some cores the mud content was approximately constant above the sandy base. In others, from the channel and dredged areas, there were considerable, down-core changes in sediment type. Cores from harbor approaches and from central Buzzards Bay show little down-core variation in sediment type. Cores nearest to the Clarks Point sewage outfall are sandy sediments with a muddy top, some 10 to 15 cm thick (Figure 18), that suggests a recent change in depositional patterns in that immediate area.

Clay is distributed in much the same way as mud down-core, there being no significant change in the clay/mud ratio with changing mud content (Figure 19). The clay/mud ratio is different, however, in different parts of the area. Mean clay/mud ratios increase from a low of 0.22 in the harbor, through 0.25 in cores from shallower than 35 ft. (10 m) in the approaches, to 0.30 in cores from depths greater than 35 ft. (10 m) in the approaches and in central Buzzards Bay (Figure 19). Evidently, more clay accumulates outside than inside the harbor. The most clay accumulates in the deepest water, probably as a function of environmental energy. In the long cores of mud there is little change in the ratio of clay/mud down-core (Figure 19), which implies that there has been no long-term change in the depositional environment during the time represented by these cores.

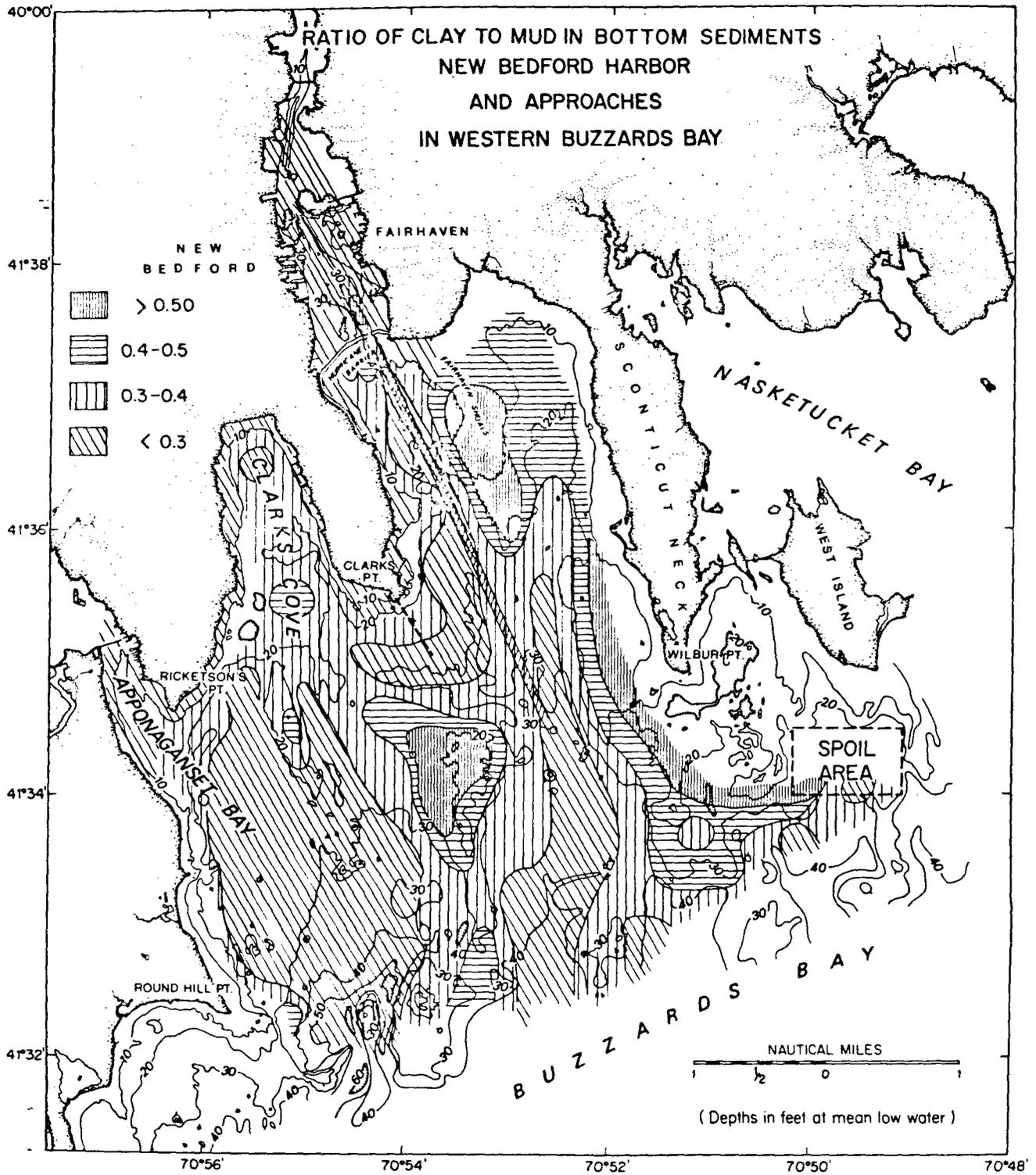


Figure 16. Ratio of clay (finer than 2 microns) to mud (all material finer than 63 microns).

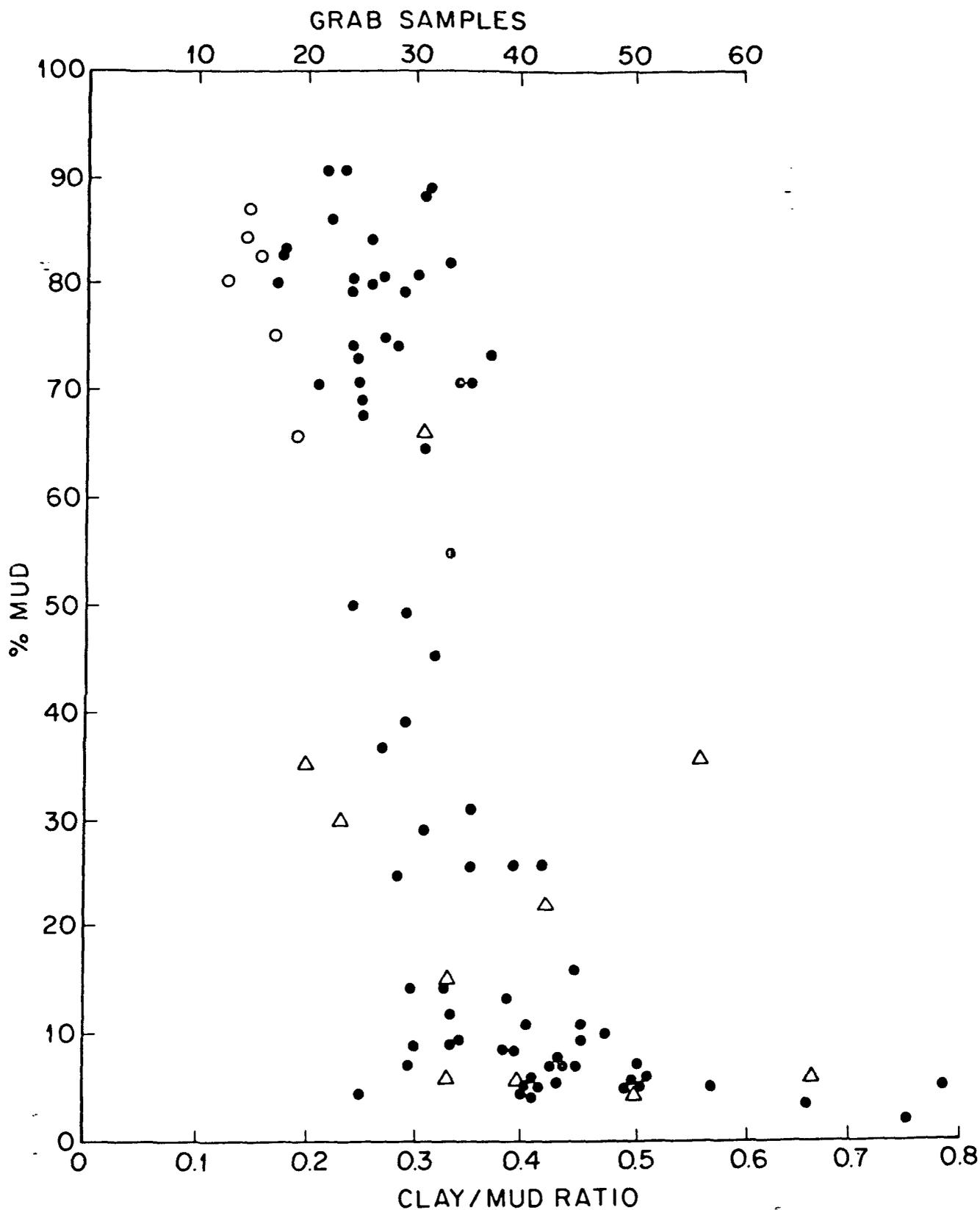


Figure 17. Ratio of clay to mud in grab samples from the harbor (open circles) and approaches (dots). Triangles are top and bottom samples from grabs (see table 1, page 20).

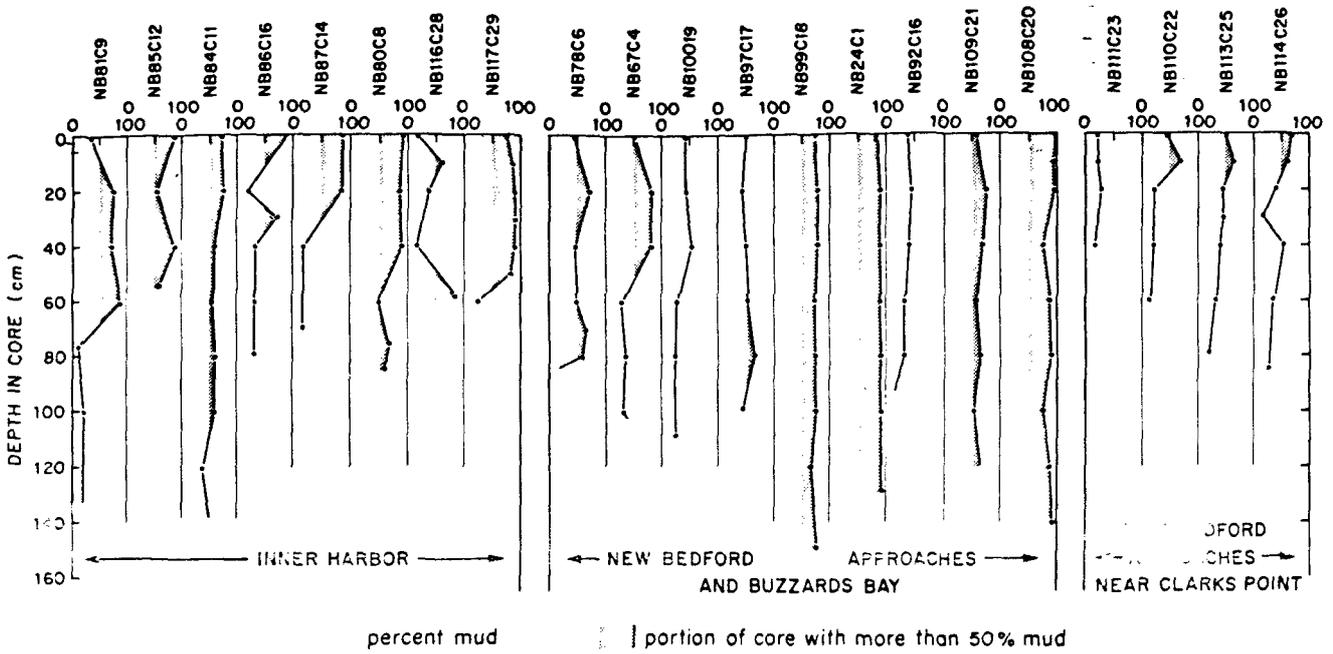
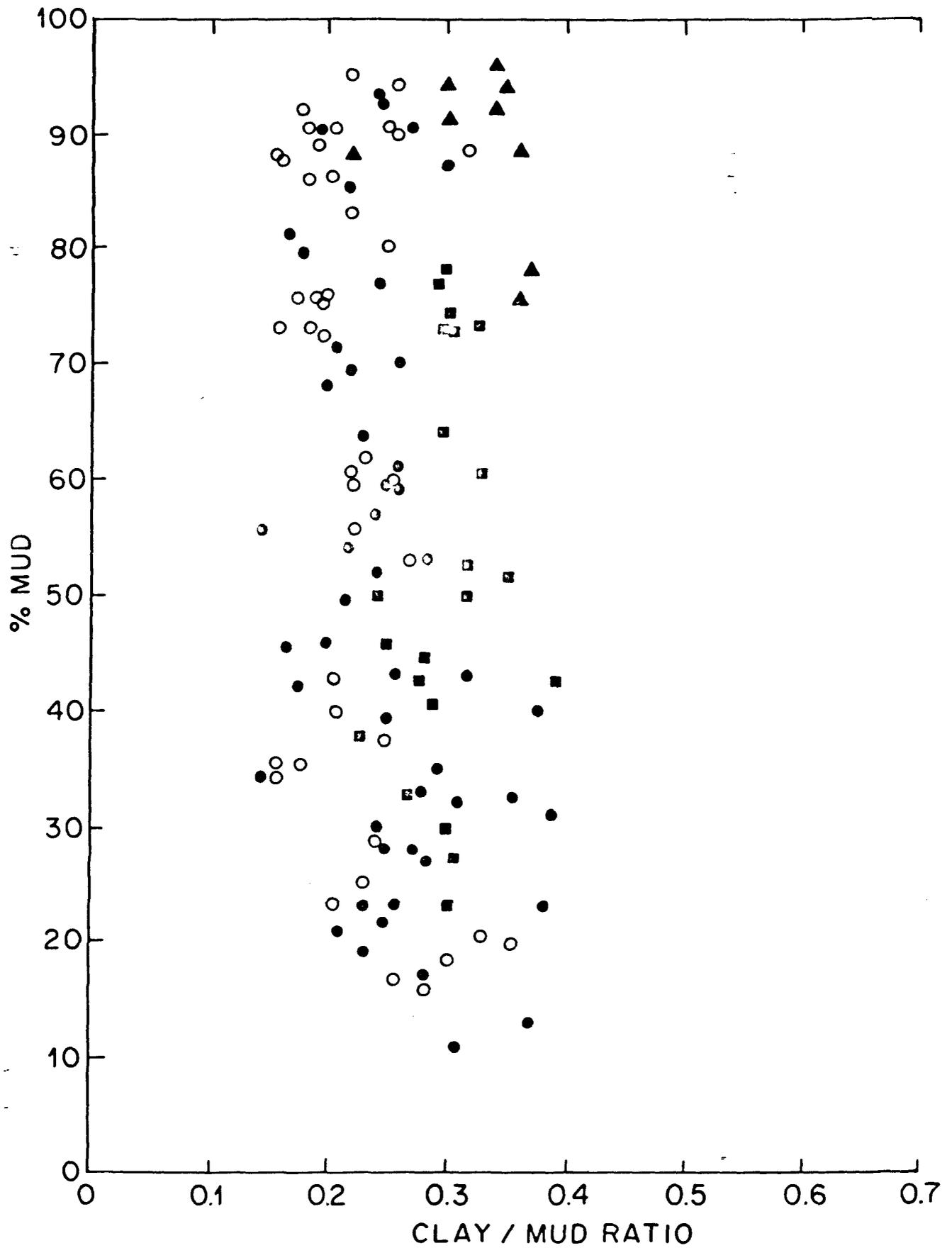


Figure 18. Percentage distribution of mud down core. Cores are, left to right, on a north-south transect. Cores 23, 22, 25 and 26 (far right) are on a west to east transect (see Figure 7).



The distribution of clay relative to mud is quite different in surface and buried sands and gravels. Coarse buried sediments in cores contain about the same clay/mud ratios as buried muds (Figure 17), but coarse surface samples have much higher ratios than either buried sands or buried muds (Figure 16, table 4). That surface enrichment in clay is not a function of grain size is illustrated by the fact that in two grab samples, the surface sediments were muddier than the subsurface sediments, yet had higher clay/mud ratios (table 4).

Table 4. Variation in sediment properties with depth
(0 to 5 cm and 5 to 25 cm) in grab samples

| <u>Sample No.</u> | <u>Percent Gravel</u> | <u>Percent Sand</u> | <u>Percent Mud</u> | <u>Percent Clay/Mud</u> |
|-------------------|---------------------------|-------------------------|------------------------|-----------------------------|
| NB 13 top | 19 | 75 | 6 | 66 |
| NB 13 bottom | 11 | 83 | 6 | 33 |
| NB 14 top | 55 | 41 | 4 | 50 |
| NB 14 bottom | 35 | 60 | 5 | 40 |
| NB 19 top | 37 | 48 | 15 | 33 |
| NB 19 bottom | 8 | 62 | 30 | 23 |
| NB 65 top | 15 | 20 | 65 | 31 |
| NB 65 bottom | 23 | 42 | 35 | 20 |
| NB 75 top | 8 | 55 | 37 | 56 |
| NB 75 bottom | 10 | 68 | 22 | 42 |

We also note that the mean clay/mud ratio in muddy grab samples from the approaches (0.28) is higher than it is in cores from the approaches (0.22 - 0.25). These apparent discrepancies may be explained by assuming that the surface centimeter or two of sediment throughout the area consists of a fine, soupy layer of very clayey material that is trapped only in grab samples. We sampled the top 5 cm of grab samples, obtaining composite samples in which the soupy, clayey surface was mixed with the less clayey subsurface, giving higher clay/mud ratios than we find in cores. It is well known that the coring process may fail to sample the surface sediment if that sediment

is so unconsolidated that the pressure wave in advance of the moving core barrel is capable of dispersing it. Furthermore, we know that the top 2-3 cm of muds in this area have a high water content and are very easily resuspended (Rhoads and Young, 1976), and so might be easily dispersed by the coring process. The key fact here is that the study area appears to be covered by a thin layer of clay-rich material that presumably is easily moved and forms, in effect, a mobile carpet.

Sediment Composition

(a) Inorganic Sedimentary Components

The sand fraction of most samples consists of angular to subangular grains of quartz and feldspar, with a few rock fragments. Many of the samples contain small amounts of gravel, which on topographic highs consists of rock fragments a few cm in diameter. About ten percent of the samples, nearly all of them from topographic highs and all of them coarse grained, have some weakly iron-stained sand and gravel.

Forty of our samples from the harbor approaches contain a few sand-sized fragments of coal, some as large as 1.5 cm. Coal was most abundant, forming up to about 1 percent of the sand fraction, in samples near the navigation channel.

(b) Calcium Carbonate

Most sediments contain less than 2.5 percent calcium carbonate, many contain less than 1.0 percent, and ten samples contain more than 10 percent (Ellis and others, 1977). The bulk of the carbonate consists of the remains of mollusks with subordinate amounts of benthonic foraminifera, echinoids, and barnacles. Molluscan shell remains are most common in the fine muddy sediments of the depressions. Visual appraisal of cores suggests that there is little change in carbonate content beneath the surface, although some cores contain one or two shell beds a few mm to a few cm thick.

(c) Organic Carbon and Nitrogen

Organic carbon is most abundant in the fine-grained sediments of the western depression and the drowned valley of the Acushnet (compare Figures 14 and 20). It is especially abundant around the sewer outfall off Clarks Point,

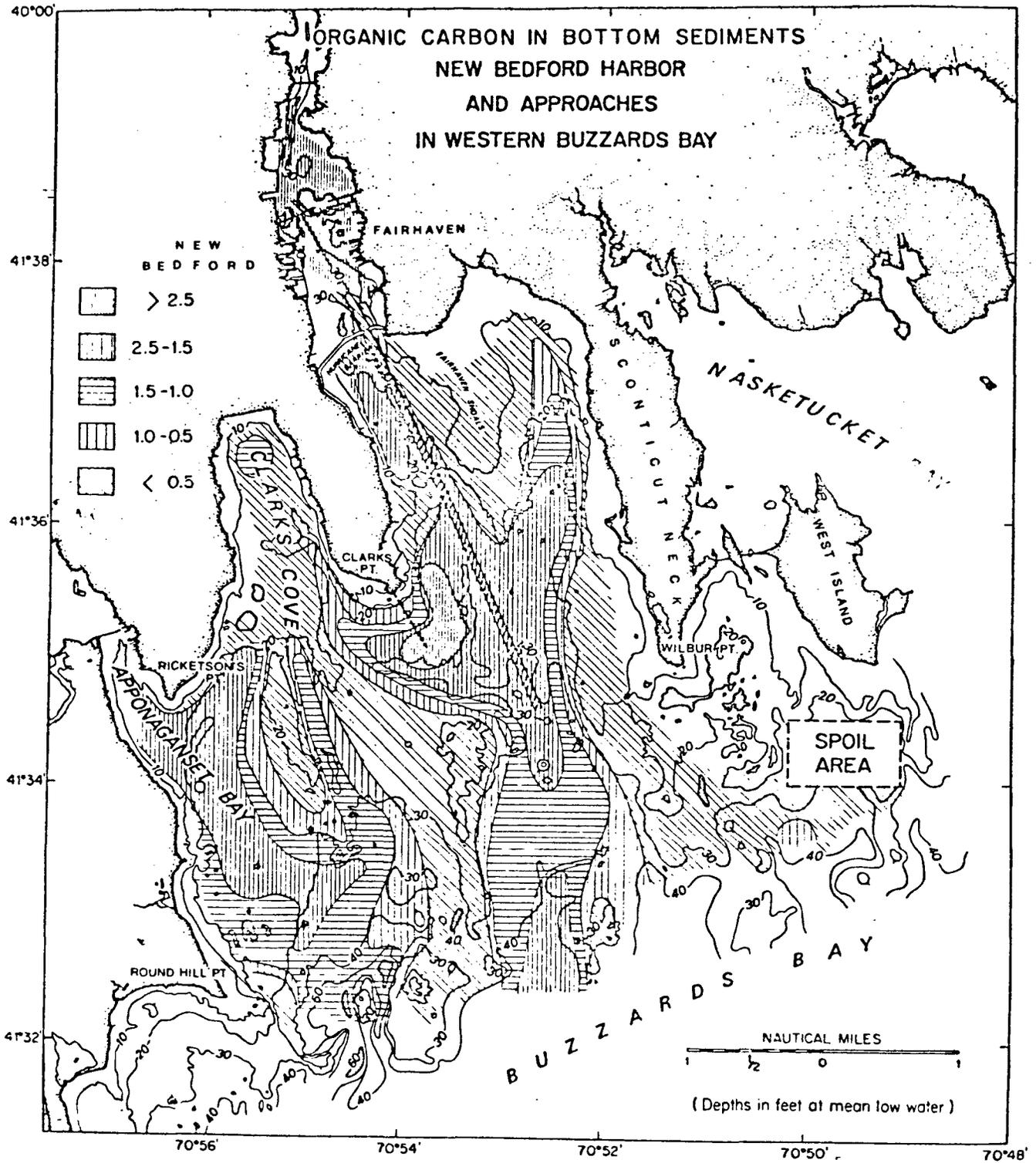


Figure 20. Percent organic carbon.

in the navigation channel seaward of the hurricane barrier and in the harbor. In the first two areas, organic carbon reaches 3.2 percent. In the harbor, surface samples contain from 4 to 7 percent; the highest organic carbon value measured is 9.6 percent, from a sample 20 cm down in core 9. Away from these three 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). The carbon levels of estuaries are much higher than those of continental shelves (0.5 percent), because of the high biological productivity of estuaries, which results in a high accumulation rate of organic matter, and the natural association of organic matter with fine-grained mineral detritus (Emery and Uchupi, 1972).

Organic carbon and clay tend to increase together (Figure 21), however, their interdependence is different in sediments from three different areas. In the harbor there is a dramatic rise in organic carbon with only a small increase in clay; in the navigation channel and around the sewer outfall there is a moderate but steady increase in carbon as clay increases; and in the approaches to the harbor there is a consistent and more moderate rise in carbon as clay increases, up to about 15 percent clay. Samples containing more clay than this seem to have a more or less constant carbon content. The sharp rise in carbon relative to clay in the harbor suggests that the harbor is a source of carbon. It seems more likely that the source is sewage and industrial waste, than that the carbon results from natural biological productivity, since there is no reason to suppose that the harbor is more productive than the approaches.

In our cores, organic carbon decreases from top to bottom by amounts which are very small seaward of the hurricane barrier (except in core 4 from the navigation channel), and very large in the harbor (Figure 22). Sediments from the bottoms of harbor and navigation channel cores have similar amounts of clay and carbon to those taken in the approaches, suggesting that these sediments were deposited under equivalent conditions (Figures 22 and 23). In contrast, sediments from the upper parts of cores from the harbor and navigation channel have carbon to clay relationships which correspond to grab samples from the sewer outfall and harbor. We submit that the carbon increases relative to clay are indicative of pollution. However, there also appears to be a small, natural increase in carbon at the surface in unpolluted areas as shown by the fact that grab samples (which contain the

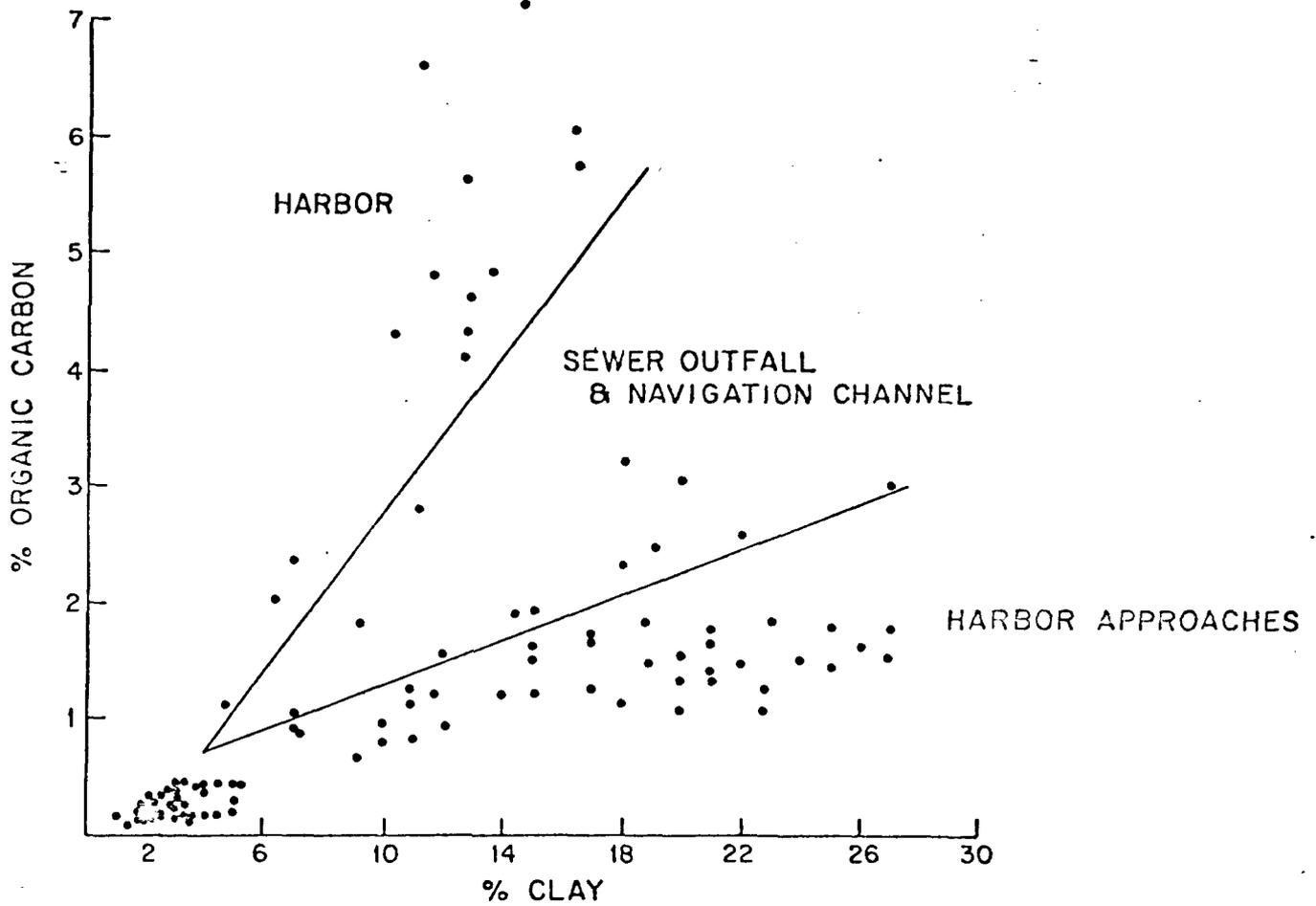


Figure 21. Relationship between percent organic carbon and percent clay in grabs and core tops. This relationship differs for three groups of samples: harbor, harbor approaches and sewer outfall plus navigation channel, as shown above.

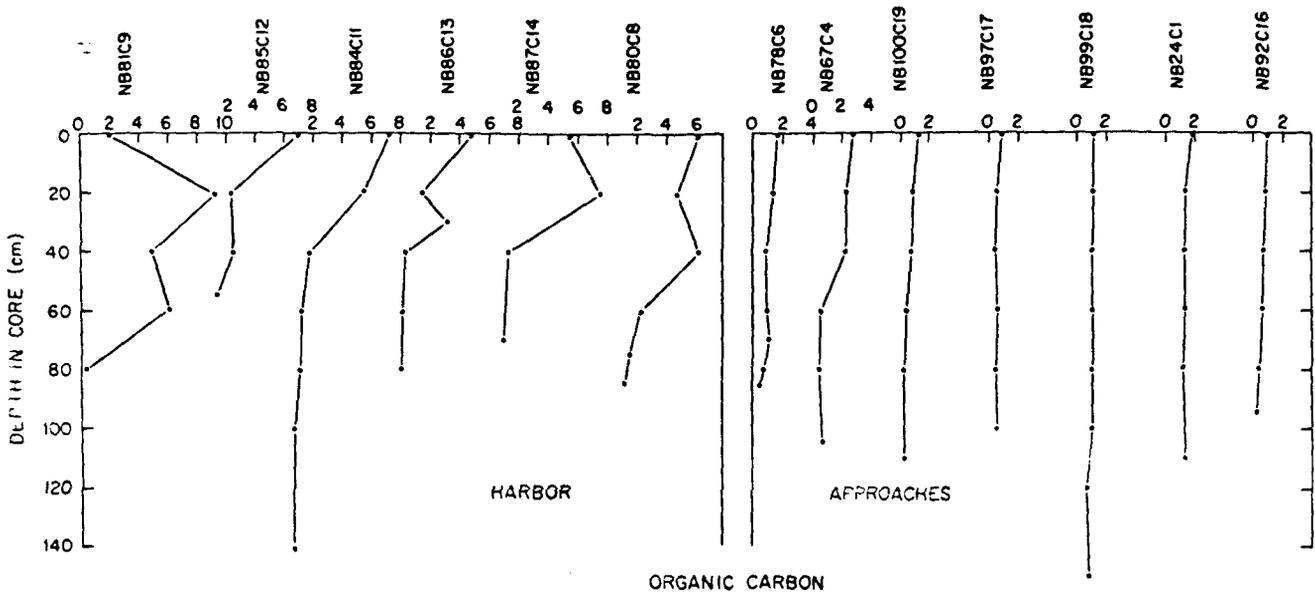


Figure 22. Down core abundance (%) of organic carbon. Cores, left to right, are on a north-south transect of the study area.

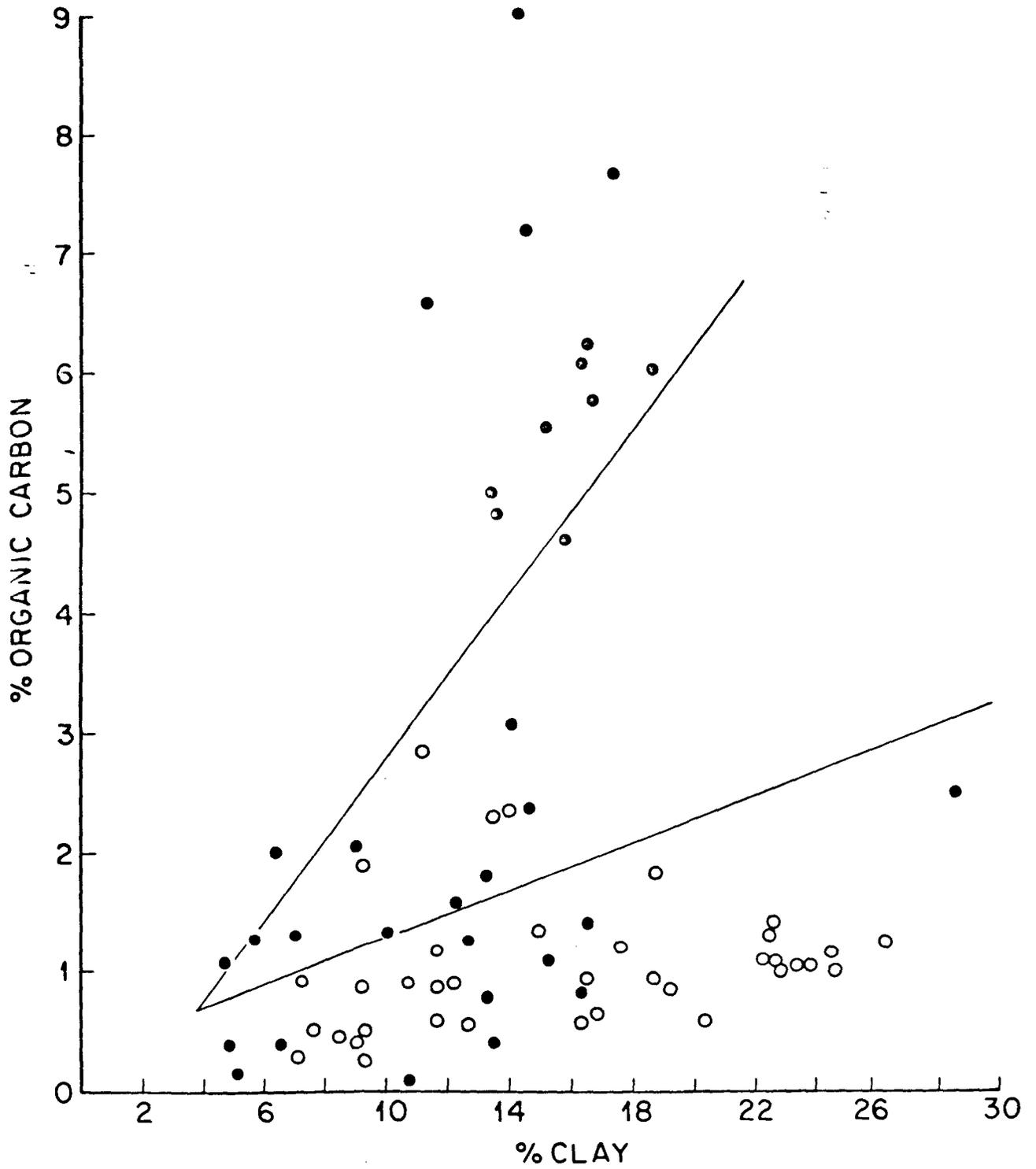


Figure 23. Percent organic carbon versus percent clay, down core, for harbor (dots) and approach (open circles) cores. Lines dividing the plot are the same as in Figure 15.

true surface) tend to contain more carbon than do subsurface core samples for the same amount of clay (compare Figures 21 and 23). Rhoads observed that the bioturbated 2 to 3 cm thick surface layer of sediment in Buzzards Bay contained more organic matter than the subsurface sediment (Rhoads and Young, 1970).

Ratios of carbon to nitrogen were determined to see if they were related to sources of effluent and might be useable as indicators of pollution (see data in Ellis and others, 1977). In general, the organically enriched muds of the harbor, the navigation channel and the Clarks Point sewer outfall (Figure 20) have C/N ratios of less than 5.0, as do the sandy sediments of topographic highs. Muddy sediments in the western and southern parts of the area have higher C/N ratios, between 5.0 and 6.0. We cannot discriminate between sands and muds on the basis of this ratio; it seems unlikely, therefore, that it has much value as a pollution index.

That the bottom sediments in the harbor, the navigation channel and around Clarks Point are polluted to some extent, is shown by the character of the benthic communities in these areas (Kelly, 1977). Using samples collected at our hydrographic stations (H4, H5, P1, P9, P17, and P19, Figure 7) Kelly finds that infaunal organisms are small, and that opportunistic polychaetes like Capitella capitata are abundant, suggesting that the benthic community is stressed. Pollution severely limits the abundance of infaunal organisms inside the harbor, where bioturbation of the sediment must, therefore, be much less than in the approaches.

RATES OF SEDIMENTATION

Radiometric methods were used to date samples from two sites in the harbor. Dr. M. Bothner (U.S.G.S.), using Pb210, measured the rates of sedimentation down a short core taken with a hydrostatic core at station NB 103 in 2.7 m of water. Below a depth of 17 cm in this core the rate of sedimentation was 2 mm/yr; above this depth it was 1.7 cm/yr. The change occurred in 1966, the year the hurricane barrier became operational.

Using C14, Teledyne isotopes dated mollusk shells from a shell horizon 75-83 cm deep in core 9 as 205 ± 85 years old, which suggests an average rate of sedimentation of 2.5 to 6.2 mm/yr. This core was taken in 17 ft. (5 m) of water at the edge of a channel that was dredged in 1920.

If the shells were exposed by dredging, then the overlying muds would have accumulated at a faster rate, up to about 1.5 cm/yr.

Using the assumption that the mud that buries sand in the deep dredged parts of the harbor was deposited after the sand was exposed by dredging, and knowing when the dredging was done, we can estimate the rates at which the muds may have accumulated. The berthing area was dredged in 1968-1969. At the top of core 14 (Figure 13) are 30 cm of mud (Figure 18) that were deposited since then at a rate of 4 cm/yr, more than twice as fast as the topmost muds in the core from station 103. The navigation channel and the 30 ft. (9 m) anchorage in the harbor, where cores 4, 8, and 29 were taken (Figure 13), was last dredged in 1953. At the tops of these cores there are 50 cm of mud (Figure 18) that were deposited since then at a rate of 2.0 to 2.5 cm/yr. The good agreement between these different estimates suggests that our assumptions are reasonably valid. Therefore, if the topmost muds from cores 8 and 29 accumulated at 4 cm/yr since 1966 when the hurricane barrier was completed (as in core 14), then the deeper muds in these cores accumulated between 1953 and 1966 at rates of about 1 cm/yr, five times as fast as the buried muds in the shallows at station NB 103.

In Buzzards Bay and probably in the approaches to the harbor, muds are accumulating at rates as low as 1 mm/yr (Bowen and others, 1976), or as high as 2.3 mm/yr (Hough, 1940) to 2.95 mm/yr (Farrington and others, 1976). These rates are typical of similar coastal areas, such as Chesapeake Bay (2 to 3 mm/yr; Schubel, 1968) and Long Island Sound (4.5 mm/yr; Thomson and others, 1975). Rates of sedimentation are likely to be negligible on topographic highs and in the narrow channels scoured by tidal currents.

Changes in the normal rate of sedimentation have been caused near Clarks Point, in response to the discharge of sewage effluent there. Around the sewer outfall is a 5-6 ft. (1.5-1.8 m) high mound that has probably grown since 1920 when the outfall was constructed. On the mound the rate of sedimentation may reach 3 cm/yr, but it diminishes rapidly to about 3 mm/yr within about 0.5 km of the outfall, where we find only 15 to 20 cm of organically enriched mud at the tops of cores 25 and 26.

The significant aspects of these data are: that the rate of sedimentation, over most of the area, is slow, probably averaging about 2 to 3 mm/yr; that there appears

to have been five times as much sedimentation in the deeps of the harbor as in the shallows, before the hurricane barrier was completed; and that construction of the barrier appears to have increased the rate of sedimentation in all parts of the harbor by factors of between x5 and x10. We caution the reader that further radiometric analyses are needed to test these hypotheses. For the present these calculations provide us with a working model for estimating relative magnitudes of sedimentation in the harbor and its approaches.

SUMMARY OF DEPOSITIONAL PATTERN AND RECENT HISTORY

Most of the sediments are terrigenous sands or muds containing less than 5 percent calcium carbonate. There are very few deposits of gravel. Most of the gravel is in the form of shell, and most gravel deposits are, in effect, shell beds. Commonly they are formed almost entirely by the mollusk Crepidula fornicata. Fine grained sediment is most abundant in the drowned valleys that cross the area. It consists largely of silt, but contains small amounts of clay that increase seaward. In deep water, these silt deposits are uniform in character down-core, suggesting that the same depositional conditions have prevailed here for some time.

At the seabed, it appears that there is a rather different type of sediment containing substantial amounts of water and clay-sized particles. Information from other sources shows that most of the clay particles are bonded together in aggregates of minerals and organic matter that are uncompacted fecal products of deposit-feeding benthic organisms (Johnson, 1974); a smaller proportion of the clay particles are similarly bonded in discrete fecal pellets (Rhoads, 1963, 1967). This surface sediment forms a layer 1 to 3 cm thick that is known to be easily resuspended by low-velocity tidal currents (Rhoads and Young, 1970; Roman, 1977). Because we find it trapped in the interstices of coarse sediments on topographic highs, as well as in muds from depressions, we think of it as a mobile 'carpet' covering the entire area. A similar thin layer mobile sediment, referred to as 'fluff' is widespread in Delaware Bay (Weil, 1976) and may be common in other estuaries and coastal embayments (Meade, 1972).

In the approaches to the harbor and in Buzzards Bay, muds are accumulating very slowly, probably at rates of 2 to 3 mm/yr and, until the hurricane barrier was built, the same applied to the shallows inside the harbor. Since the last century the harbor has been dredged from an average depth of 12 ft. (3.6 m) to 30 ft. (9 m); recently, the navigation channel has been dredged to the same depth (U.S. Army Corps of Engineers, 1970). Before the hurricane barrier was completed, the rate of sedimentation in these dredged deeps appears to have been about 1.5 cm/yr; now, it appears to be about 4 cm/yr.

To determine the flux of sediment through the environment we can make some simple calculations. If we assume that: (1) mud is deposited in the harbor at 1.5 cm/yr and in the Bay at 3 mm/yr; (2) harbor mud contains 13 percent clay and bay mud 30 percent clay; (3) mud particles have a density of 2.65 gms/cc and (4) the sediment is 50 percent water, then the flux of clay to the bottom in the harbor is $0.25 \text{ gms/cm}^2/\text{yr}$, twice as high as it is in the bay ($0.12 \text{ gms/cm}^2/\text{yr}$). If we assume further that harbor mud contains 72 percent of silt, and bay mud 60 percent, then the flux of silt to the bottom in the harbor is $1.4 \text{ gms/cm}^2/\text{yr}$, about six times as high as it is to the floor of the bay ($0.24 \text{ gms/cm}^2/\text{yr}$). Since construction of the hurricane barrier, tidal flushing of the harbor has been reduced, increasing the trapping efficiency of the estuary and leading to a flux to the bottom of $0.69 \text{ gms/cm}^2/\text{yr}$ of clay, and $3.26 \text{ gms/cm}^2/\text{yr}$ of silt, in its deep parts. Clearly, the landward transport mechanism discussed previously, is three times more effective for silt than for clay, which leads to size fractionation of the original sediment. It is this same fractionation mechanism which gives rise to the formation of a clay 'carpet' over a silt substrate throughout the area.

Like the muds from the center of Buzzards Bay, the muds from the seaward edge of the study area contain only 1 to 2 percent organic carbon (2 to 4 percent organic matter). The Acushnet estuary is like other estuaries along this coast in that as the harbor is approached, the carbon levels go up in direct response to the discharge of sewage (see Folger, 1972). Pollution of the bottom by accumulation of sewage waste is most important within 1.5 km of the Clarks Point sewer outfall, along

the navigation channel, and in the harbor, where carbon levels are high.

Our analyses show that organic carbon is highest in surface sediments and its concentration may be very high in the mobile 'carpet' of clayey material where fecal matter seems to be most concentrated (Rhoads, 1973; Rhoads and Young, 1970; Johnson, 1974). Organic material discharged from sewers is presumably moved about the area in this 'carpet', and if mixing is efficient, may be very widely dispersed from its source.

METALS: ORIGIN, DISTRIBUTION AND DISPERSAL

General Studies of Buzzards Bay

The first geochemical study of Buzzards Bay sediments was made by Moore (1963), using 150 grab samples collected in the 1950's. Fourteen of Moore's samples are from our study area (Figure 5). Moore used emission spectrography to determine the presence of 27 elements in his samples*. He discovered that certain of these elements appear to be correlated with clay**. Increases in metal concentrations with increasing clay are obvious in table 5.

Moore found that the Bay's fine-grained sediments smell of hydrogen sulphide, contain black hydrotroilite, euhedral crystals of pyrite, and abundant organic matter. Thus, while some metals may be found in the clay fraction, others may occur as sulphides, adsorbed onto organic matter, or bonded in organo-metallic complexes (Moore, 1963). Further work is needed to quantitatively establish the partition of metals between these different phases in the bay.

*Al, B, Ba, Ca, Co, Cr, Cu, Fe, Ga, K, La, Mg, Mn, Mo, Na, Ni, P, Pb, Sc, Sr, Th, Ti, V, Y, Yb, Zn, and Zr.

**Co, Cr, Cu, Fe, La, Mg, Mn, Ni, P, Pb, Sc, Th, Ti, V, Zn, and Zr.

Table 5. Mean levels of selected trace elements in different types of sediment from central Buzzards Bay, calculated from data presented by Moore (1963). Proto-graywackes contain more than 20 percent clay. Sands contain less than 20 percent clay. Sands with less than 10 percent feldspar are quartzose sands, with 10 to 25 percent feldspar are feldspathic sands, and with more than 25 percent feldspar are arkosic sands. We excluded from these calculations the highly contaminated sample ME 1 from the head of Sippican Harbor. All trace element abundances are given in ppm; clay abundance is given in percent.

| Sediment Type | Number of Samples | PPM | | | | | |
|-----------------------|-------------------|------|------|------|------|------|------|
| | | Cr | Cu | Mn | Pb | Zn | Clay |
| Protograywacke (P) | 47 | 61.6 | 22.9 | 240 | 45.4 | 65.0 | 34.3 |
| Quartzose Sand | 16 | 8.6 | 4.7 | 97 | 10.4 | 36.5 | 9.0 |
| Feldspathic Sand | 44 | 15.4 | 4.4 | 146 | 10.8 | 44.4 | 10.6 |
| Arkosic Sand | 16 | 21.1 | 8.4 | 175 | 18.0 | 39.9 | 13.8 |
| Mean of All Sands (S) | 74 | 15.0 | 5.4 | 145 | 12.5 | 43.0 | 11.2 |
| Enrichment factor P/S | | x4 | x4 | x1.6 | x3.6 | x1.5 | x3 |

Moore (1963) thought that all but four of his samples were not significantly contaminated, and that these four, might be slightly contaminated by Pb. One of the four (ME 1), from the head of Sippican Harbor, appears to be highly contaminated; it contains 109 ppm Pb, 784 ppm Cu and 5.6 ppm Mo. The other three samples, all from inlets on the shores of the Bay, contain much less metal.

Using factor analysis, Spencer (1966) re-examined Moore's data in order to define more precisely the relationship between metals and mineralogy. Spencer's analysis confirmed that many of the minor elements are strongly correlated with clay (table 6). Most important of these, accounting for 40 percent of the variance, is a clay factor (No. 4, table 6). Also important are a feldspar factor (No. 5) and an apatite factor (No. 1), together accounting for 27 percent of the variance. The presence in factors 1 to 5 of elements like Ti and Zr, which are common in heavy minerals suggests to us that the feldspars and apatite are associated with heavy minerals, and the apatite is detrital, rather than authigenic. This would explain high scores for the apatite factor in sands around the edges of the bay, where some concentration

Table 6. Results of Spencer's (1966) factor analysis of textural, mineralogical, and geochemical data from 53 of the Buzzards Bay samples collected and analyzed by Moore (1963). Left is part of the correlation matrix listing, in order of correlation coefficient, the elements that correlate with clay. Right are the main factors that control the variance in the data within Spencer's sample set. Within each factor we show only those elements that have factor loadings greater than 0.3. Factor loadings are given in brackets. Percentage values at the top of each column show the amount of variance explained very small amounts of the variance and did not appear to be geochemically meaningful.

| Clay Correlation | | Major Factors | | | | | |
|------------------|-------|---------------|----------|----------|-----------|----------|----------|
| | | Factor 1 | Factor 2 | Factor 3 | Factor 4 | Factor 5 | Factor 6 |
| Ni | .9201 | | | | | | |
| V | .9068 | | | | | | |
| Co | .8997 | 11.66% | 4.78% | Current | 40.67% | 15.37% | 4.34% |
| Cr | .8793 | Zn(.83) | Sr(.87) | depth | Clay(.90) | Ba (.78) | B (.88) |
| Sc | .8749 | Yb(.79) | Ca(.71) | | Ni (.88) | Fel(.71) | Ti(.25) |
| Fe | .8657 | P (.77) | | | Sc (.88) | Al (.70) | |
| Ga | .8602 | Zr(.51) | | | Co (.88) | Ca (.68) | |
| La | .8400 | Ti(.47) | | | La (.86) | Mn (.61) | |
| Pb | .8129 | Cu(.39) | | | V (.85) | Na (.59) | |
| Na | .8507 | Mg(.37) | | | Pb (.83) | Mg (.54) | |
| Mg | .7972 | Y (.35) | | | Fe (.82) | Ti (.53) | |
| K | .7821 | | | | Cr (.81) | Zr (.52) | |
| Y | .7768 | | | | Ga (.80) | K (.51) | |
| Cu | .7713 | | | | Cu (.77) | Y (.50) | |
| Mn | .7399 | | | | Na (.71) | Ga (.52) | |
| Ti | .6940 | | | | K (.69) | Fe (.40) | |
| Al | .6496 | | | | Y (.67) | Cr (.39) | |
| | | | | | Mg (.67) | V (.31) | |
| | | | | | Mn (.62) | | |
| | | | | | Ti (.57) | | |
| | | | | | Al (.48) | | |

of heavy minerals would be expected. Relatively unimportant are factors 2 and 6, which probably represent control by carbonate shell remains (factor 2) and the heavy mineral tourmaline (factor 6, table 6). Spencer's analysis did not produce factors that might signify contamination by metalliferous wastes.

Recently, surface (0 to 5 cm) and subsurface (20 to 25 cm) samples from 14 core stations in the bay were analyzed in some detail by the New England Aquarium (1973) (table 7). Differences between these data and Moore's (tables 5 and 7) may be analytical rather than real. Compared with subsurface material, the surface samples are enriched in Cu, Hg, Pb and Zn, but not in Cd, Cr, Ni or V. Less than half of the samples were analyzed for As, so surface to subsurface variations for this element are not meaningful. Surface enrichment is accompanied by a decrease in clay and by an increase in sulphide, so it is not clear if the enrichment is the result of contamination or of natural processes.

Some degree of metal contamination is expected, since surface sediments from the bay are known to contain such materials as polychlorinated biphenyls (table 7 and Farrington and others, in press). The New England Aquarium also suggest that the hexane-soluble oil and grease measured in the sediments is a contaminant. This is only partly true, as some natural hexane-soluble hydrocarbons may exist in these sediments (Farrington, personal communication, 1976). According to Farrington and others (in press), many of the hydrocarbons in the bay are derived directly and indirectly through fall-out from urban air, rather than from shipping.

Previous Studies of New Bedford Harbor and Its Approaches

The New England Division, U.S. Army Corps of Engineers analyzed surface and subsurface samples from 15 cores, 6 from the harbor and 9 from the navigation channel seaward of the hurricane barrier (Figures 6 and 24). All of these organically enriched sediments were strongly reducing, with redox potentials ranging from -2.48 to -4.88 mv. The silts containing the least nitrogen also had the less strongly negative redox potentials, probably because they lie near the hurricane barrier, where tidal scour takes place (Figure 24). The pH of the sediments was slightly lower than that of seawater, averaging 7.5, and does not change significantly with location.

That harbor sediments are polluted is suggested by their oil and grease contents. Silts contain at least x10 and up to x80 more oil and grease than Buzzards Bay sediments (Compare Figure 24 and table 7). Pollution is evidently chronic at the head of the harbor, where oil and grease form more than 1 percent of the dry weight of sediment. Oil and grease are lowest in three sandy samples, presumably

Table 7. Means of concentrations of metals, sulphides, organic matter, PCB's, hexane-soluble oil and grease, and amounts of mud (finer than 63 microns), determined by New England Aquarium (1973), in 14 surface and 11 subsurface samples of sediment from central Buzzards Bay. Metals, sulphides, PCB's and oil and grease are given in ppm; organic and mud contents are given in percent; organic content was determined by loss of weight on ignition at 550°C so may include some structural water from clay minerals.

| | As | Cd | Cr | Cu | Hg | Ni | Pb | V | Zn |
|--------------------------|----------|-----|---------|-------|----------------|------|------|------|------|
| Surface (0-5 cm) | 2.0 | 1.4 | 29.0 | 13.2 | 0.30 | 21.1 | 26.7 | 48.0 | 83.8 |
| Subsurface (20-25 cm) | 3.6 | 1.9 | 29.3 | 8.7 | 0.13 | 19.0 | 19.0 | 47.0 | 66.5 |
| | Sulphide | | Organic | PCB's | Oil and Grease | | Mud | | |
| | 149 | | 4.2 | 0.193 | 195 | | 24 | | |
| | 80 | | | | | | | | |

Fallout, augmented by runoff, also contributes radioactive elements like plutonium, which are concentrated in the top 10 cm of Buzzards Bay sediments (Bowen and others, 1976; Livingston and Bowen, 1976). Reworking of the surface sediments by benthic organisms has caused some plutonium to be redistributed to depths of up to 20 cm; other evidence suggests that chemical processes within the sediment column cause some upward diffusion of this redistributed plutonium (Bowen and others, 1976; Livingston and Bowen, 1976). Other waste components may be similarly affected.

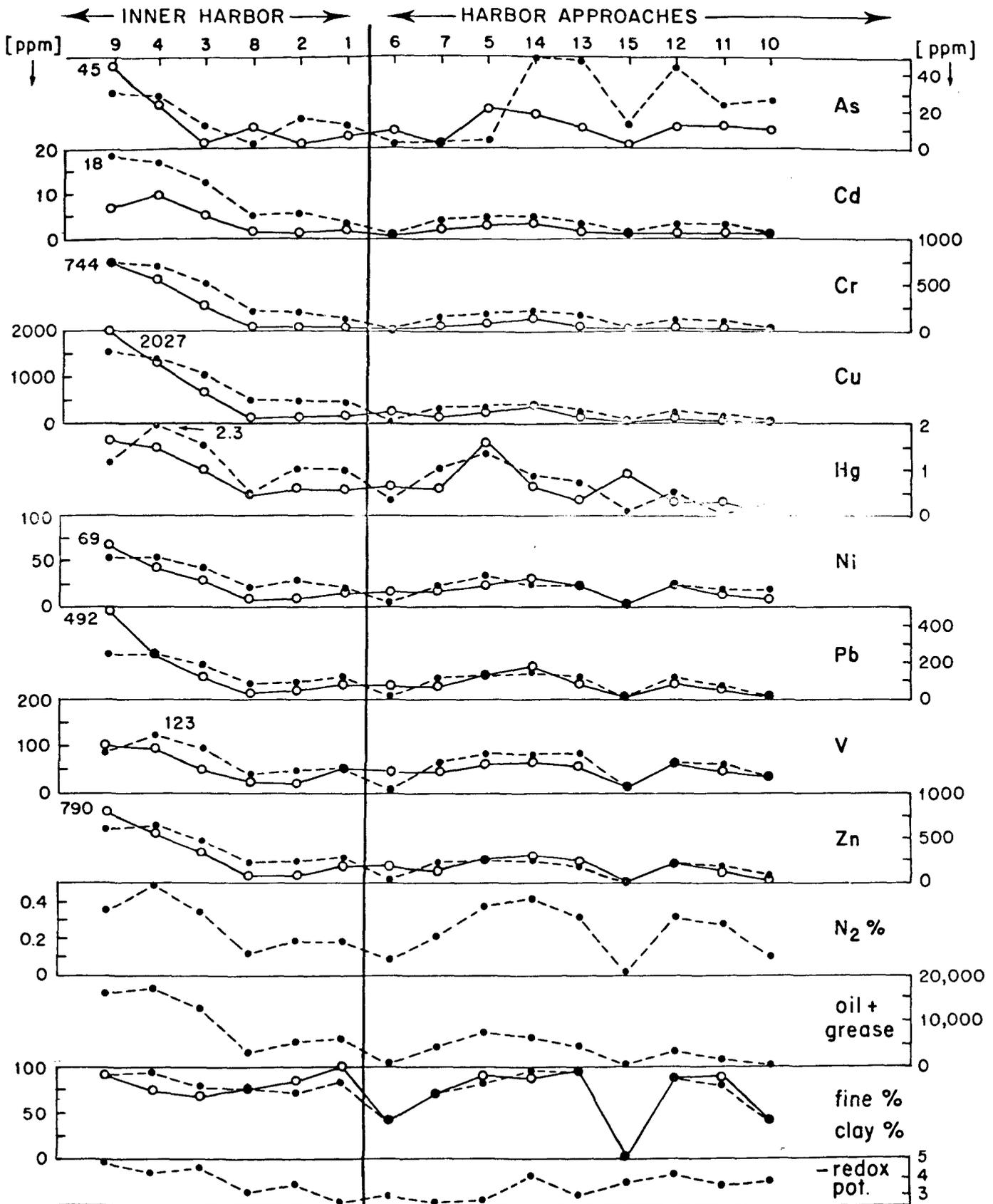


Figure 24. Geochemistry, Corps of Engineers cores (see Figure 6). Based on unpublished data. Samples: dots = core tops (3 cm) circles = subsurface (30 - 35 cm). Size: dots = 0 - 100% mud, circles = 0 - 20% clay. -redox potential is in millivolts.

because tidal currents prevent hydrocarbon accumulation at those sites (Figure 24).

Like oil, grease, and organic nitrogen, metals show a fairly close relationship to sediment size, being more abundant in silts than sands (Figure 24). Metals also tend to be higher in surface than subsurface samples. In comparison with surface sediments from central Buzzards Bay (table 7), most of the sediments from the harbor and navigation channel are enriched in metals (Figure 24): As, Cd, Cr, Cu, Hg, Pb and Zn are enriched in nearly all samples by factors of x3 to x5. In contrast, Ni and V are enriched significantly in only the three samples from the head of the harbor, where enrichment reached factors of x160 for Cu, x25 for Cr, x22 for As, x18 for Pb, x13 for Cd, x9 for Zn, x5 for Hg, x3 for Ni and x2 for V. Harbor metal levels are far higher than in average shales, deep sea clays, unpolluted coastal inlets (Saanich Inlet, British Columbia, and Poole Harbor, England), and diagenetically enriched sediment (Walvis Bay, South West Africa), but are similar to levels typical of mining districts or areas of industrial contamination (Conway Estuary, Wales and Sorfjorden, Norway, (table 8).

The Massachusetts Division of Water Pollution Control (1971, 1975) measured the amounts of metals in sediments from the harbor, navigation channel, approaches to the harbor and from the Acushnet River (Figures 25 and 26). This survey confirms that most metal (excluding Fe and Mn) occurs at the head of the harbor, the highest concentrations being in samples from A7 and A8, located respectively 0.5 miles (0.8 km) N and S of the Coggeshall Street Bridge (Figures 25 and 26). Muds from the navigation channel (NB 3) also contain abundant metal. Metals are depleted in the current-swept area near the hurricane barrier (NB 1). In approach samples collected away from the channel, there appears to be no significant enrichment in metal compared to sediments from central Buzzards Bay (compare Figure 26 and table 7). Upriver at site AR6, there are signs of slight contamination. The existence of salt water near the bottom at this site suggests that metals have been transported upstream along the bottom from AR7. Except for Fe and Mn, other river sediments contain little metal. Fe and Mn are known to decrease seaward in response to the change from relatively oxidizing and acid river conditions to relatively reducing and alkaline estuarine conditions (Krauskopf, 1967).

It is clear that the most metal occurs at site AR8, (Figures 25 and 26) where the sediment contains 1.17 percent Cr, Cu and Zn combined. At stations AR7 and AR8, the

Table 8. Abundances of metals in fine-grained sediments from different areas, including New Bedford Harbor. Fe given in percent, other metals in ppm. Nd = not determined. TR = trace. 1 = maximum values in New Bedford Harbor; 2 = average shale (Krauskopf, 1967); 3 = average nearshore shale (Tourtelot, 1964); 4 = average deep-sea clay (Turekian and Wedepohl, 1961); 5 = Saanich Inlet clayey silts (Gross, 1967); 6 = Poole Harbor muds (Thornton and others, 1975); 7 = Conway estuary muds (Elderfield and others, 1971); 8 = Walvis Bay mud maxima (Calvert and Price, 1970); 9 = Solfjordan muds (Skei and others, 1972). New Bedford Harbor data are maxima from either Corps of Engineers or Division of Water Pollution Control, except for Ag, which is from our analyses of the clay fraction.

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|----|------|-----|-----|------|-----|------|------|-----|-------|
| Ag | 40 | 0.1 | ND | 0.1 | ND | >0.2 | ND | ND | 35 |
| As | 45 | 6.6 | 13 | 13 | ND | 11 | ND | ND | ND |
| Cd | 76 | 0.3 | | 0.4 | ND | 1.0 | ND | ND | 80 |
| Cr | 3200 | 100 | 82 | 90 | 55 | 65 | 66 | ND | ND |
| Cu | 7250 | 57 | 27 | 250 | 34 | 12 | 34 | 129 | 2000 |
| Fe | 1.4 | 4.7 | | 6.5 | 2.0 | 1.1 | ND | ND | ND |
| Hg | 3.8 | 0.4 | | TR | ND | ND | ND | ND | ND |
| Mn | 180 | 850 | | 6700 | 311 | 340 | 1500 | ND | ND |
| Ni | 550 | 95 | 32 | 225 | 26 | ND | 48 | 455 | ND |
| Pb | 560 | 20 | 25 | 80 | TR | 104 | 205 | 32 | 8250 |
| V | 123 | 130 | 158 | 120 | 67 | 110 | 97 | ND | ND |
| Zn | 2300 | 80 | 104 | 165 | 64 | 60 | 900 | 337 | 15800 |

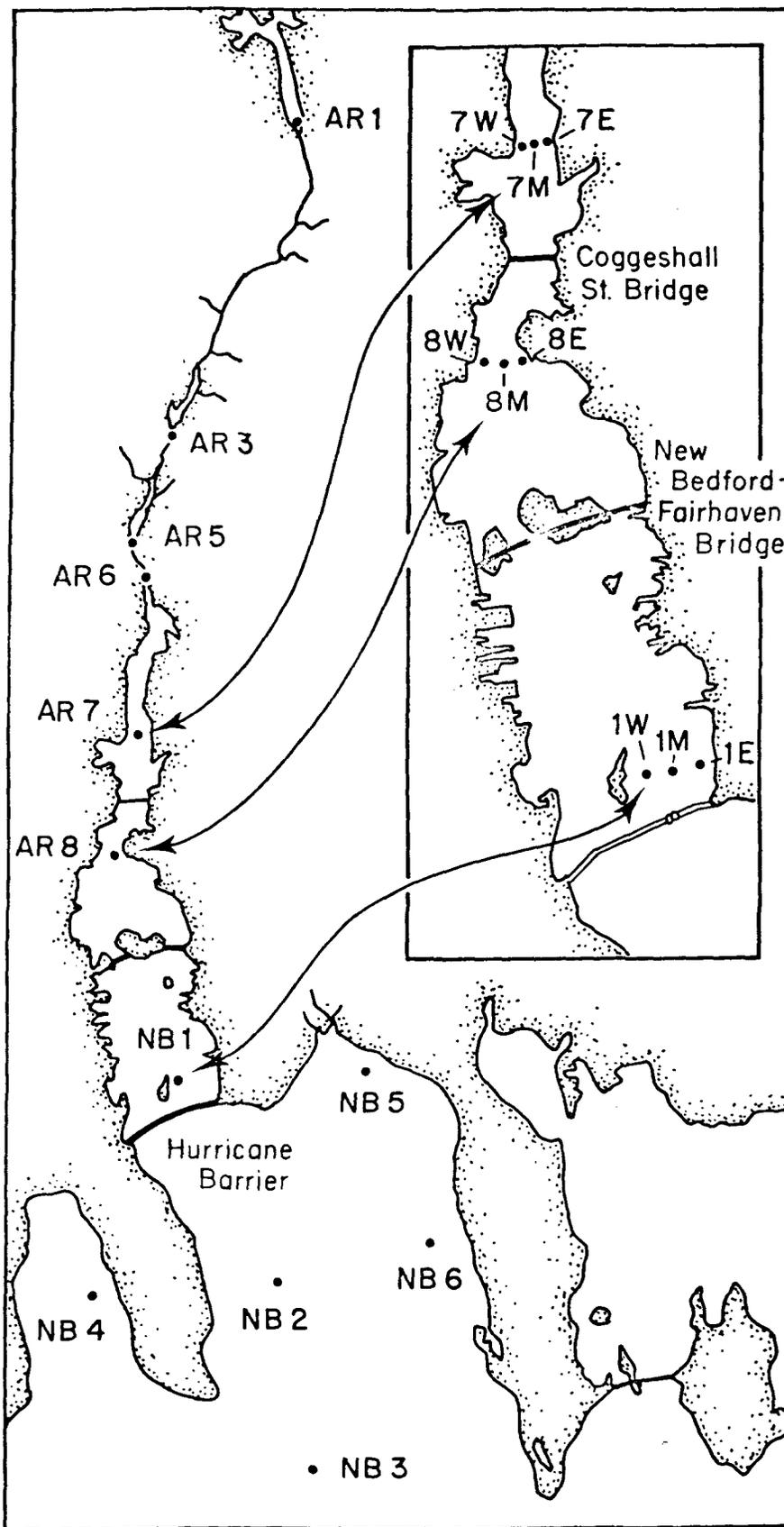


Figure 25. Massachusetts Division of Water Pollution Control bottom sample locations. "W", "M" and "E" refer to west, middle and east respectively.

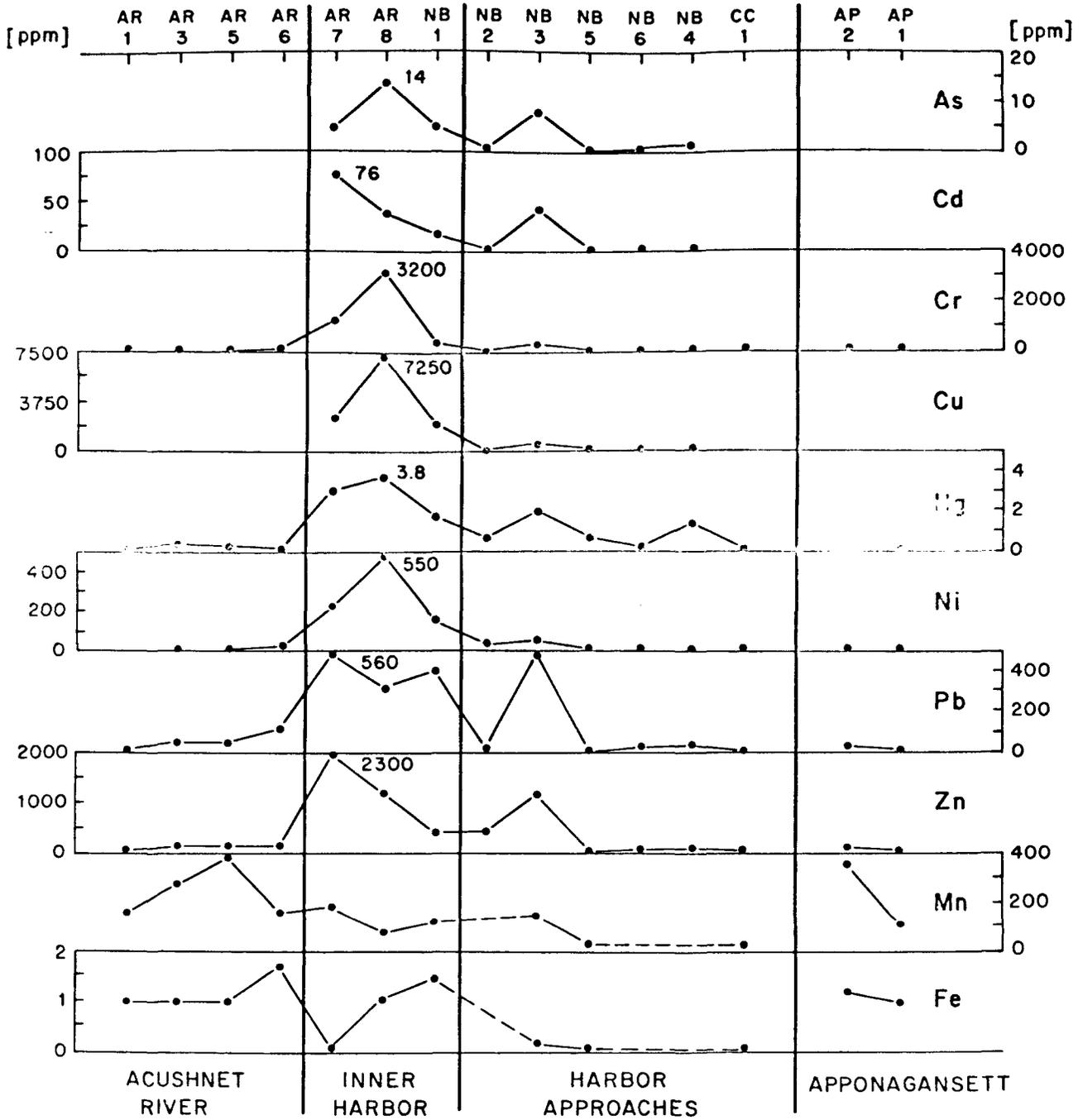


Figure 26. Massachusetts Division of Water Pollution Control bottom sample geochemistry. Fe given in percent, all other elements in ppm. CC 1 is from Clarks Cove and AP 1 and AP 2 from Apponagansett Bay.

Division of Water Pollution Control took three samples on east-west transects across the head of the harbor. The largest amounts of metal are in the samples nearest to the western bank, from which we deduce that a point source of metal lies on the western shore of the harbor very close to site AR8. Compared with sediments from central Buzzards Bay (table 7), samples AR7 and AR8 are enriched by factors of up to x500 for Cu, x100 for Cr, x40 for Cd, x30 for Zn, x25 for Ni, x20 for Pb, x13 for Hg and x7 for As.

Present Study of New Bedford Harbor

From our examination of previous studies, it was clear that the sediments of New Bedford Harbor and the navigation channel contain substantial quantities of metal, particularly Cu. Little was known, however, of how, or if these metals had spread beyond the navigation channel into Buzzards Bay. The mechanisms, dispersal paths, rates and amounts of metal dispersal were all unknowns. In an attempt to solve these problems we constructed maps of regional metal distribution, looked at the distribution of metals in cores, attempted to locate metal-rich fractions within the sediment, and statistically examined the relationships between different sediments from both the study area and central Buzzards Bay.

This study involved sediment collected from 106 sampling stations, 87 grabs and 19 cores. Samples were taken at 20 cm intervals down core and at 2 cm intervals in the top 10 cm. Care was taken to avoid the smeared sediment on the walls of the core liners. In Heidelberg, the clay fraction was separated by centrifuging, and analyzed for Ag, Cd, Cr, Cu, Fe, Mn, Pb and Zn and, in some samples, for Hg. Analyses were made with a Perkin Elmer 300B atomic absorption spectrophotometer, using a Perkin Elmer HGA 72 graphite furnace atomizer and, in analyses involving wave lengths smaller than 3000 Å, a deuterium background corrector. Analytical precision is within ± 2 to 5 percent at the 95 percent confidence level. The accuracy of the method is ± 5 to 8 percent, depending on the element analyzed. Detailed descriptions of the method are given elsewhere (Perkin Elmer, Analytical Methods, 1973).

(a) Chemical Analysis of Different Size Fractions

Compared with the sand fraction, which has amounts of metal similar to Buzzards Bay sediment, the silt and clay fractions of harbor sediments are enriched in metals (Figure 27). The fine clay fraction is the most enriched, by factors of about x300 in Cu, x150 in Cr and x25 to 30 in Cd, Pb, and Zn. There is slightly more Fe, Ni (x5) and Mn (x2) in the clay than in the sand fraction (Figure 27), but from 2 microns to <0.63 microns, concentrations of these three elements decrease.

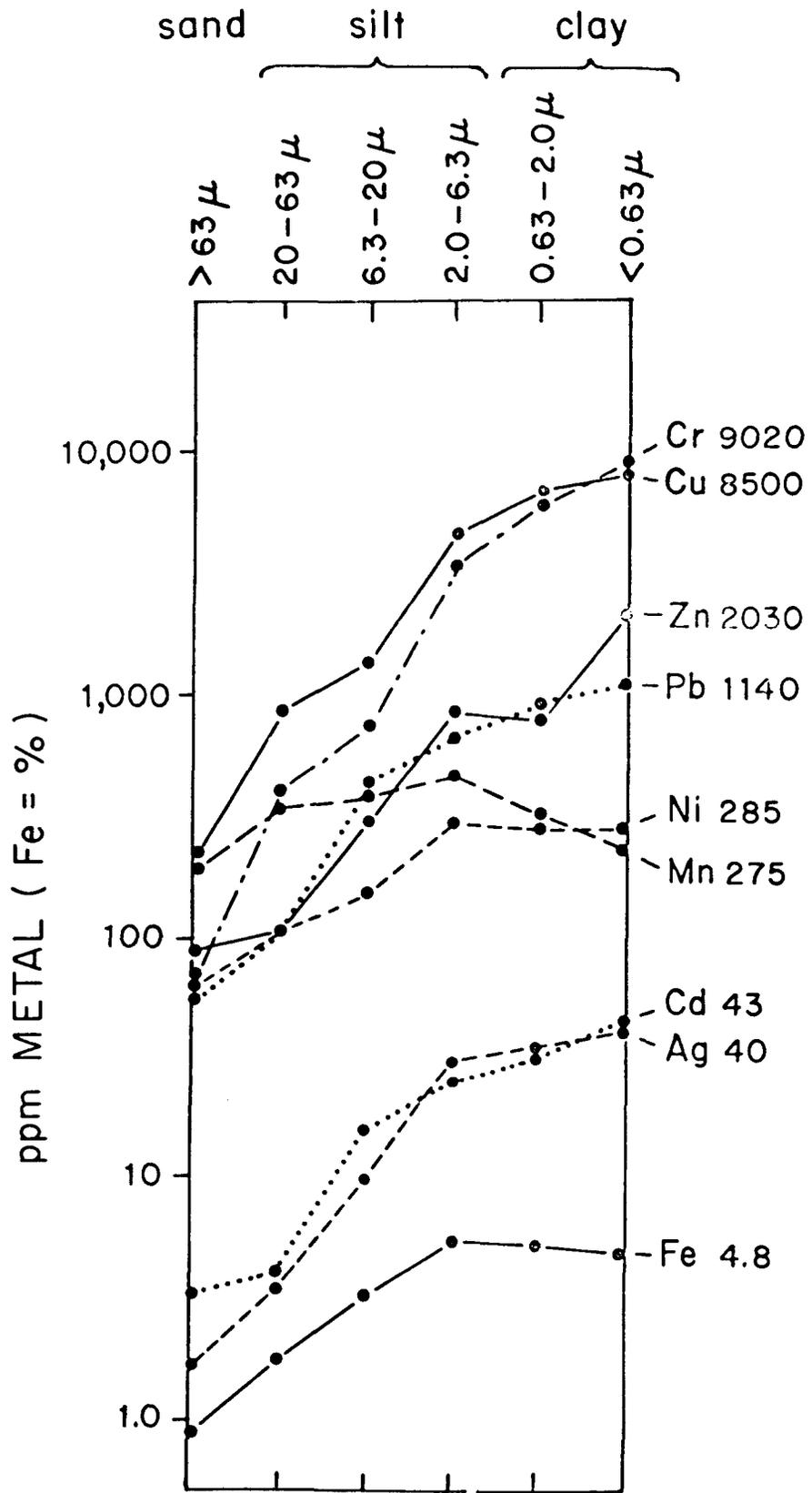


Figure 27. Metal abundance as a function of size in sample NB 85.

Massive increases in Ag, Cd, Cr, Cu, Pb and Zn are thought to be caused by the introduction of industrial waste, as has been shown to be the case in the Conway Estuary and Sjorffjord (table 8). The wastes are thought to occur either as fine solids or solutions from which metals are either scavenged by sorption onto fine mineral and organic matter, or are precipitated. Iron, Ni and Mn, do not appear to be significant waste products.

Examination of the different size fractions by scanning electron microscope and non-dispersive x-ray fluorescence confirms that Cu is associated with clay minerals. Moore (1963) and Spencer (1966) also found that clays and many metals are interdependent. We, therefore, analyzed only the clay fraction, thereby eliminating chemical variations that might be caused by size variations.

A representative sample from the inner harbor was chemically treated to determine within which phases of the sediment different metals are concentrated. Almost 40 percent of the Cu and Zn are located in insoluble mineral phases that are resistant to leaching (table 9). Another 20 percent of the Cu and Zn are located in an authigenic mineral phase, probably pyrite and/or hydrotroilite, that was leachable with a combined acid-reducing agent solution (table 9). A further 20 percent of Cu and Zn are sorbed onto the surfaces of organic and inorganic particles, from which they can be stripped by cation exchange. The remaining 20 percent apparently form organo-metallic complexes with fulvic and humic acids and bitumen.

Cr distribution is very different, (table 9), most of it (85%) being located in the authigenic phase that is probably dominated by iron sulphides. The remainder is split evenly between insoluble detrital minerals (8%) and organo-metallic complexes (6%). Whether or not Cr has a different source from Cu and Zn is unknown; clearly, more of it is introduced in the dissolved state (92% versus 60%).

(b) Regional Distribution of Metals

Copper is the main waste metal found in the harbor sediments. As it is strongly correlated with the other metals that were analyzed*, we chose to discuss metal

*Coefficients of correlation between Cu and other metals are: Cr (0.912), Pb (0.850), Cd (0.734), Zn (0.656), Ag (0.600), Mn (-0.402) and Fe (-0.330). Hg was measured in 47 grab samples and 31 subsamples from 10 cores: in the approaches to the harbor concentrations ranged from 0.4 to 3.6 ppm, increasing to 16.2 ppm in the harbor (core 9) and following Cu (see data in Ellis and others, 1977).

Table 9. Distribution of metals as a percentage of the total concentration for the clay fraction of sample 85A. Determined by chemical leaching techniques (S. Rao, Analyst). The method of Chester and Hughes (1967) was used for authigenic mineral extraction.

| Leaching Method | Cu | Cr | Zn |
|---|-------|-------|-------|
| Bitumen extraction, with 1:1 alcohol: benzene mix | 6.29 | 0.21 | 8.06 |
| Cation exchange, with 0.2N BaCl ₂ triethanolamine | 17.6 | 0.01 | 21.38 |
| Humic acid extrac- tion, with 0.1N NaOH | 1.36 | 1.57 | 0.2 |
| Fulvic acid extrac- tion, with 0.1N NaOH + H ₂ SO ₄ (pH3) | 17.28 | 4.86 | 4.28 |
| Authigenic mineral extraction with acid-reducing agent | 18.27 | 85.04 | 27.66 |
| Resistant mineral (residue after extractions completed) | 39.2 | 8.32 | 38.42 |
| Total concentration of metal in bulk sample (ppm) | 2500 | 1850 | 595 |

distribution mainly in terms of Cu (Figure 28). Copper is most abundant in the harbor, especially near the Coggeshall Street Bridge where as much as 8054 ppm Cu (0.8% was found in one sample. The abundance of Cu decreases exponentially with distance from the harbor, towards the center of Buzzards Bay where the Cu concentration in the top of core 20 was found to be 60 ppm (Figure 29). In the Cu-poor sediments in the southern half of the study area, there are local patches of Cu enrichment: next to the spoil area, where muds from the harbor were dumped in the past, and at station 92 in

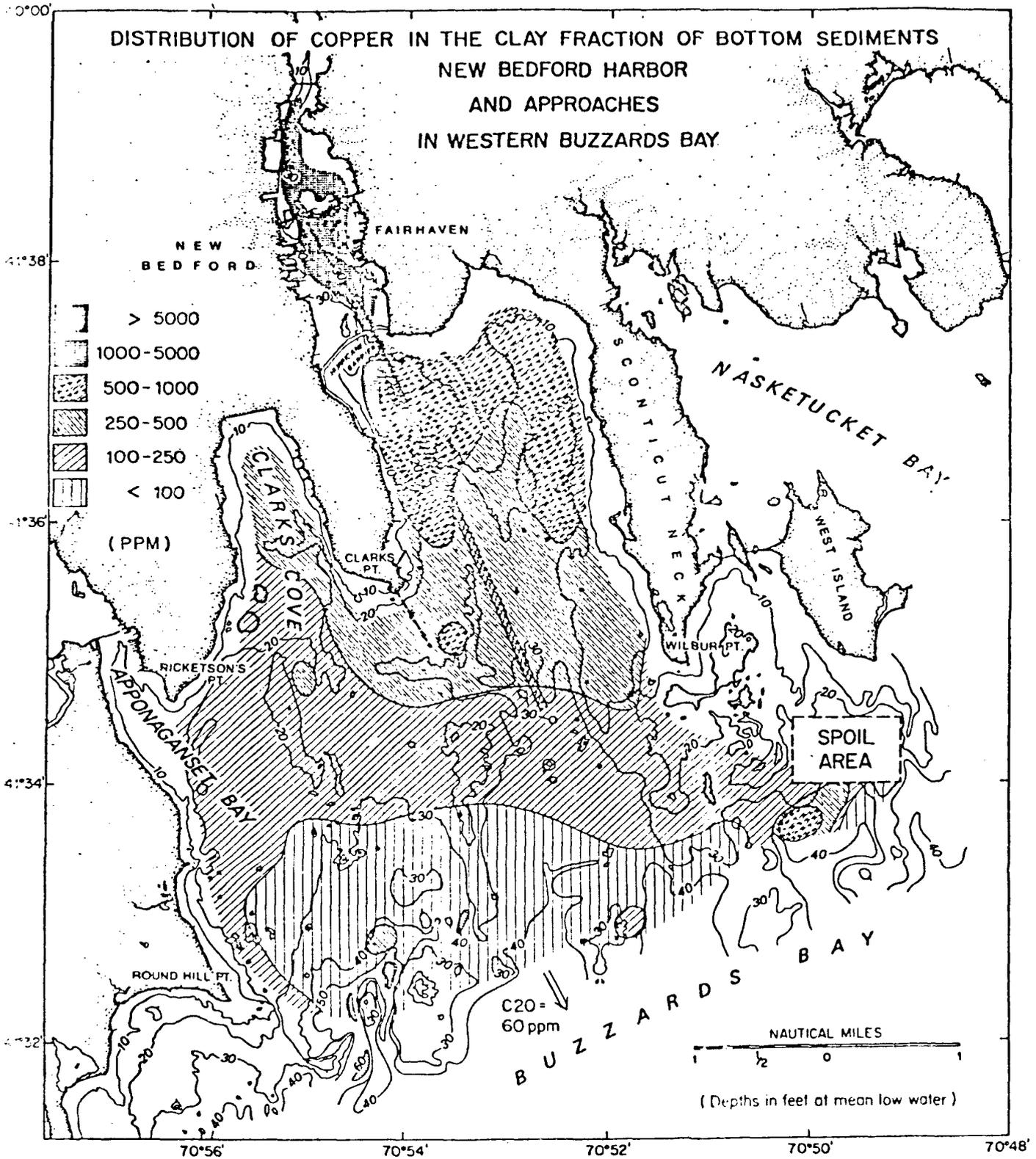


Figure 28. Regional Cu distribution based on surface sediment samples.

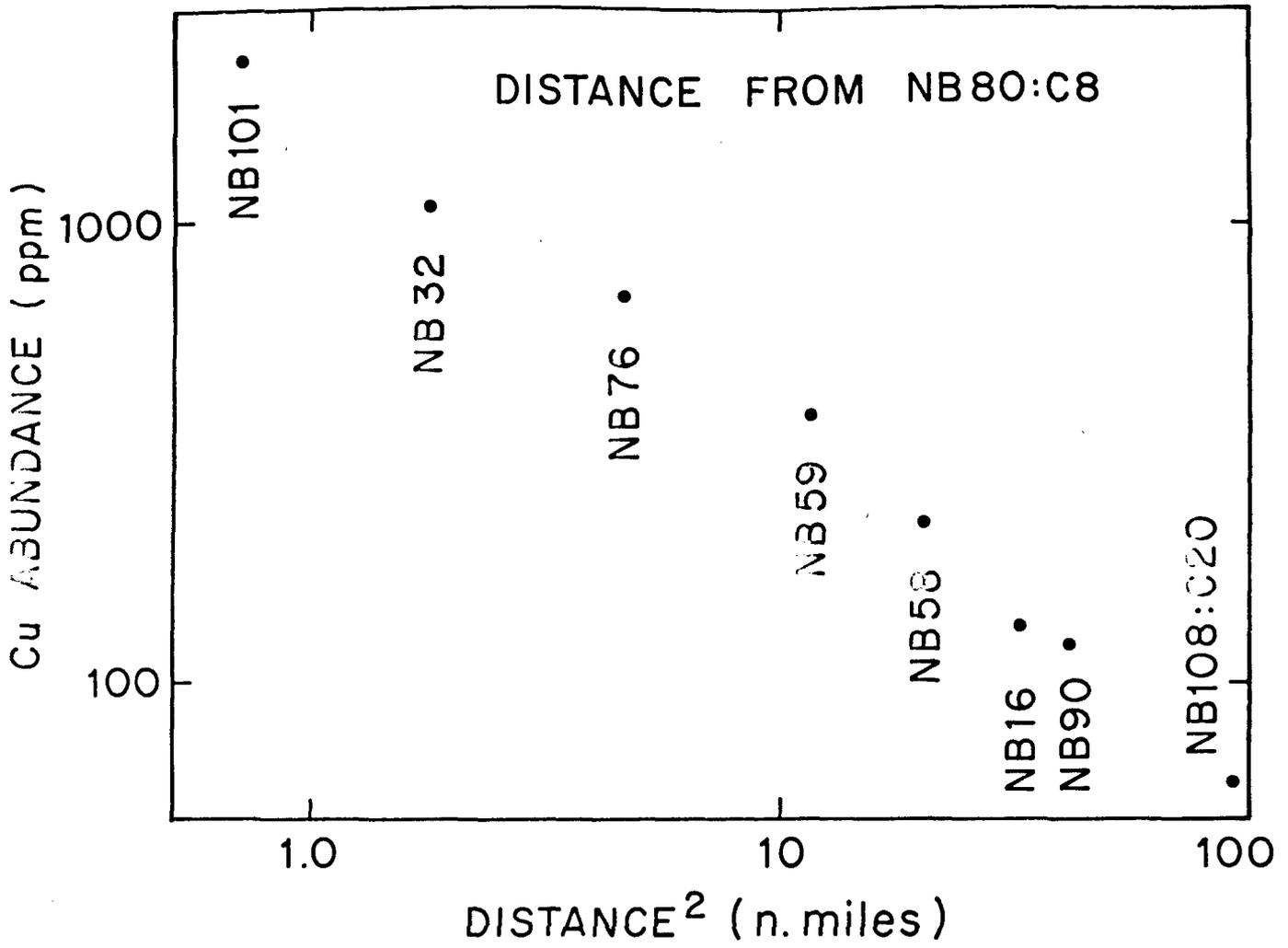


Figure 29. Cu concentrations in surface sediments as a function of the square of the distance from the head of the harbor (core 8). See Figures 5 and 7 for station locations.

the southwest corner of the area (Figure 28). The spoil area is swept by currents that may have moved the fine, metal-rich sediment dumped there. It is less easy to explain the Cu enrichment at station 92, which is far from both spoil area and harbor. At this site only the top 0 to 2 cm of core 16 were rich in Cu, and it is possible that a bargeload of dredge spoil was dumped here.

Even though metals have been found to be associated with the clay fraction, the regional distribution of metals appears to be independent of regional variations in clay and other properties of the sediment (compare Figures 15 and 28). For example, although harbor sediments have the highest concentrations of both organic carbon and Cu (Figures 20 and 28), the three samples richest in Cu, have significantly different amounts of organic carbon (2, 5 and 7%). Furthermore, in the harbor approaches, organic matter tends to be concentrated in north-south trending belts, while Cu zonation is east-west.

Manganese and Fe correlate closely with one another (Figure 30) and are distributed in a different way from Cu (compare Figures 28 and 31). Manganese is generally highest in the approaches to the harbor, reaching values of 500 ppm, and lowest inside the harbor, where no sample contains more than 350 ppm Mn, the average being 270 ppm. Within the approaches there is a tendency for Mn to be more abundant on sandy topographic highs than in muddy depressions (compare Figures 15 and 31), suggesting that the highs may be oxidizing while the depressions may be reducing environments. This is confirmed by the existence of weakly iron-stained sand grains in some sediments from the topographic highs and the absence of such grains from depressions. If Mn is seen as a redox indicator, then the harbor is the most highly reducing environment in this area.

Nearly all of the grab samples taken in harbor approaches had an olive to olive-grey oxidized surface layer, 1 to 2 cm thick. This feature has also been detected in sediments from central Buzzards Bay (Rhoads and Young, 1970). Beneath this surface layer, muddy sediments were obviously chemically reduced. In the harbor, all samples, including those from the surface, were black or grey, smelled of hydrogen sulphide and appeared chemically reduced, except at the bottom of some cores where brown oxidized sands were recovered.

The down-core profile of Mn (Figure 32) is also representative of Fe, (Figure 30, $r = 0.725$). Manganese tends to increase down core, although this trend is not as well developed in the highly contaminated harbor and navigation channel muds as it is in cores from the approaches to the harbor (Figure 32). It seems likely that this pattern, as well as the regional distribution of Mn, are related to the redox potential of the depositional environment (Figure 31) and may signify a gradual increase in the degree of

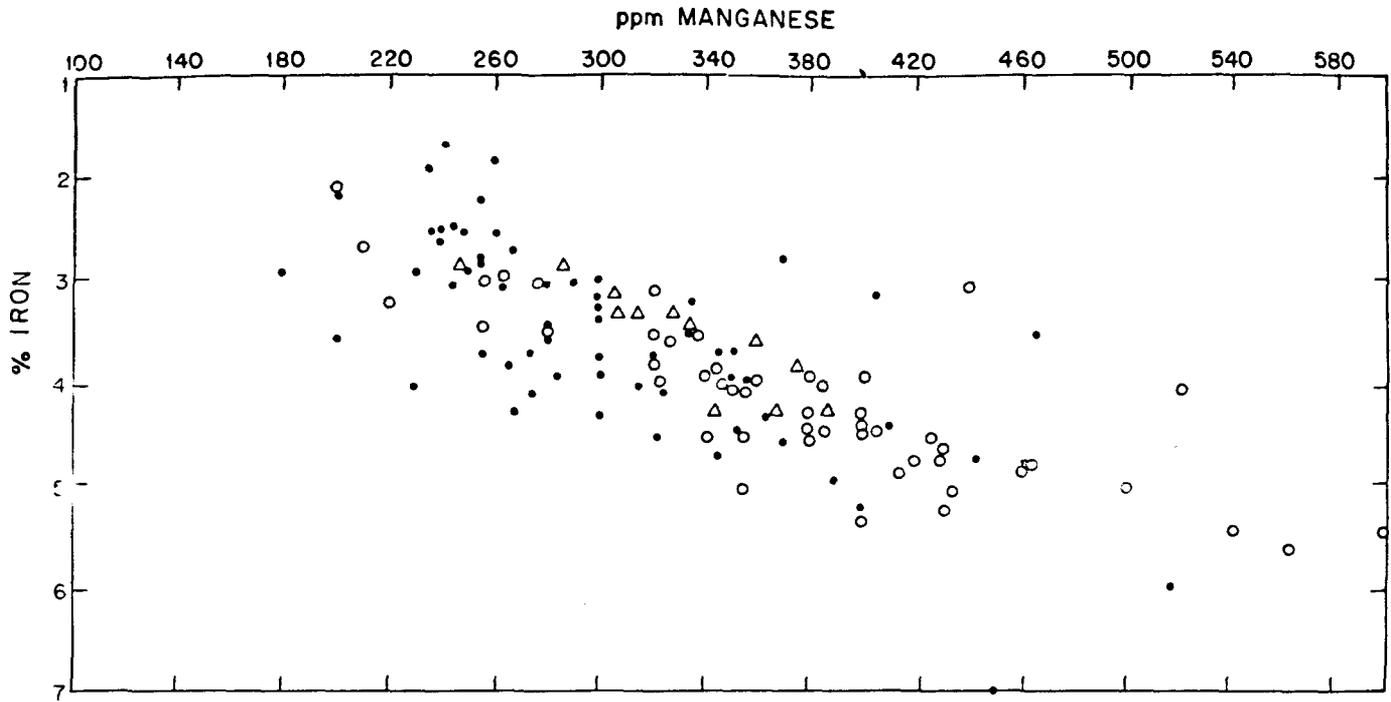


Figure 30. Relationship between Fe and Mn in cores from the harbor (dots), its approaches (open circles) and from core 20 (triangles).

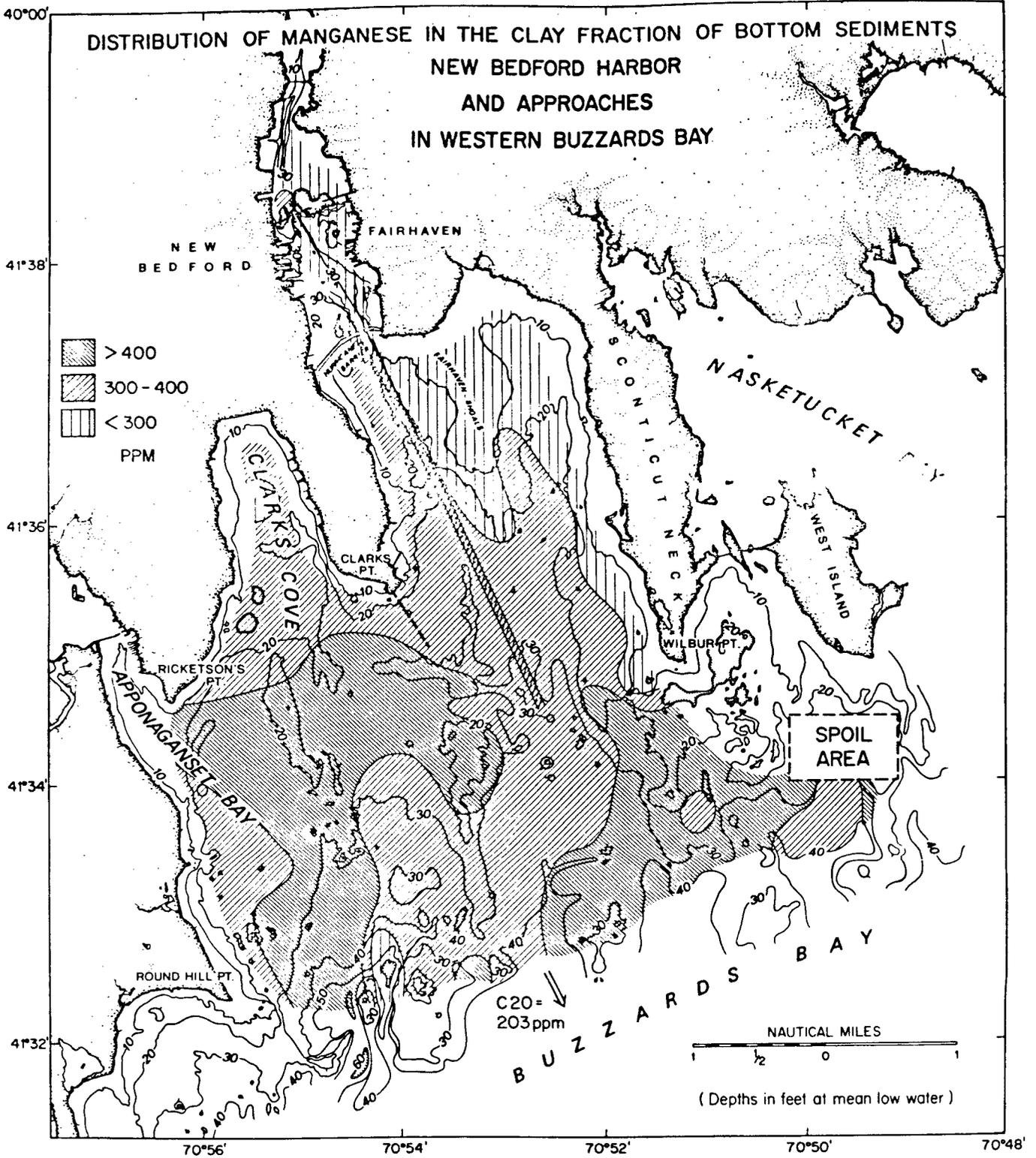


Figure 31. Regional distribution of Mn in surface sediments.

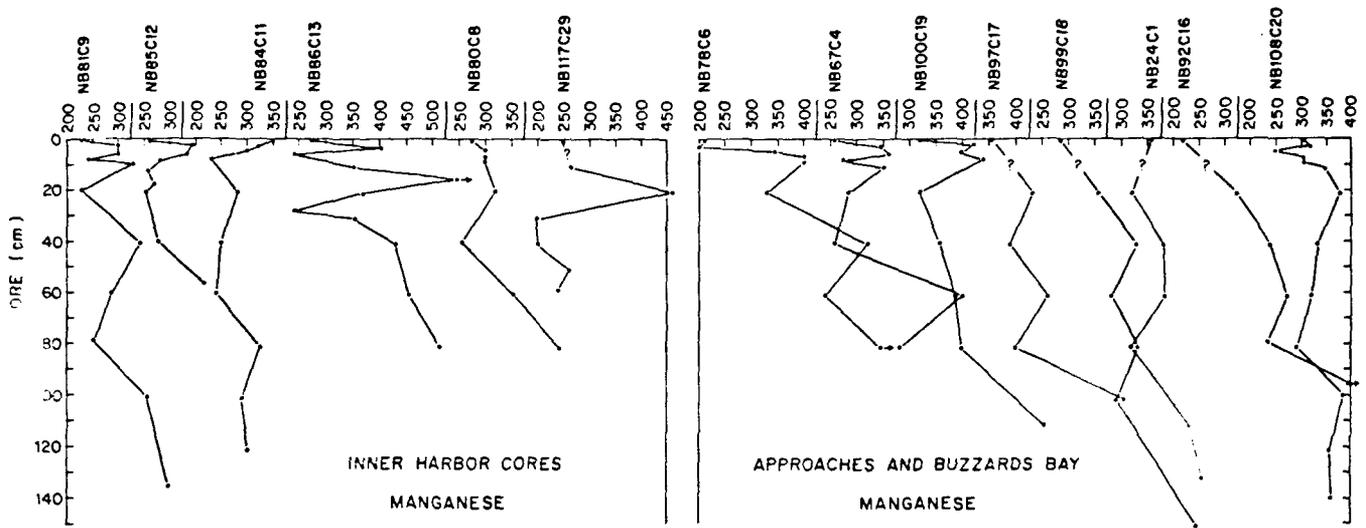


Figure 32. Down-core abundance (ppm) of Mn. Cores transect the study area from north to south, left to right; grouping is with respect to hurricane barrier.

reducing conditions as the sediments become younger. There is much less change in Mn down core 20, from central Buzzards Bay, where redox conditions may have been more constant.

Copper is enriched near the surface, as compared with subsurface samples (Figure 33). In most cores from the approaches, as well as Buzzards Bay, this enrichment becomes negligible at depths of 20 cm or more, below which the Cu content is constant at 24 ± 7 ppm. These background values are reached slightly deeper in cores 4 and 19 outside the harbor and in cores 9 and 14 near the head of the harbor (Figure 33). Because the Mn data seem to indicate that the muds are all reducing, and because in the coring process we probably lost the oxidized top 2 cm of the cores, it seems unlikely that the pattern of near-surface enrichment of Cu is the result of diagenetic remobilization followed by its near-surface precipitation in oxidized sediments. Instead, it seems likely that the enrichment reflects environmental contamination. The Cu rich waste deposit is thickest in the deeper parts of the harbor, and thins both towards the edge of the harbor and, exponentially, towards the ocean. Core 6 from the navigation channel near the hurricane barrier contains anomalously little contaminated sediment because tidal currents interfere with normal sedimentation there.

Careful examination of the relationships between Cu and the other metals in cores (Figures 34, 35, 36, 37 and 38) shows that these metals covary in a consistent manner in highly contaminated surface and subsurface samples that contain more than 100-200 ppm Cu. In samples that are only slightly contaminated, or are not contaminated (i.e., contain less than 100-200 ppm Cu) some of these metals covary in a different way with Cu, or (Cr: Figure 36) do not covary at all with Cu. Thus, it appears that we may be able to differentiate geochemically between sediments that are highly contaminated, and those that are slightly contaminated or uncontaminated. In the highly contaminated sediments of the harbor and navigation channel the order of metal enrichment is $\text{Cu} > \text{Cr} > \text{Pb}$ and Zn. In contrast, a comparison of slightly contaminated surface sediments with uncontaminated subsurface sediments from the approaches shows that the order of metal enrichment at the surface is $\text{Pb} > \text{Cu} > \text{Zn} > \text{Cr}$, the same order of enrichment that is found in central Buzzards Bay (table 10). Since Cu concentrations decrease exponentially away from the harbor, it would appear that the harbor is the source of the Cu in the top of core 20. If this is the case, then while Zn follows Cu, Cr is being removed from the waste, and Pb is being added enroute from the harbor into the bay.

The passage of contaminants from the harbor to the bay takes place by diffusion of continually resuspended particles that spend much of their time in an oxidizing environment, either in the sediment within 1 to 2 cm of the sediment-

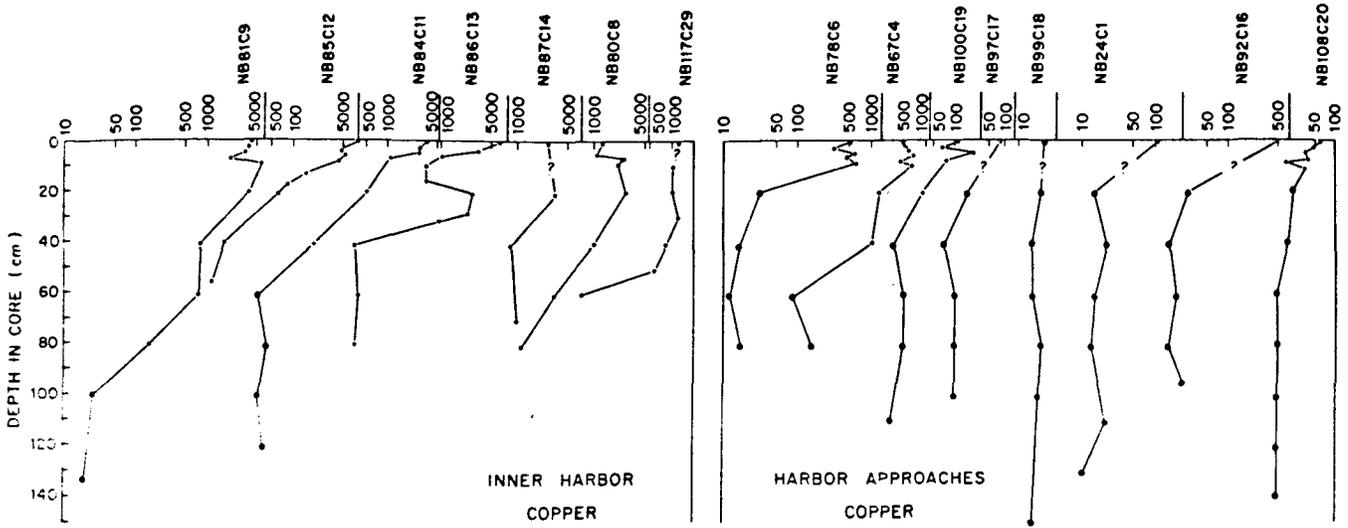


Figure 33. Down-core abundance (ppm) of Cu. Cores transect the study area from north to south, left to right; grouping is with respect to hurricane barrier.

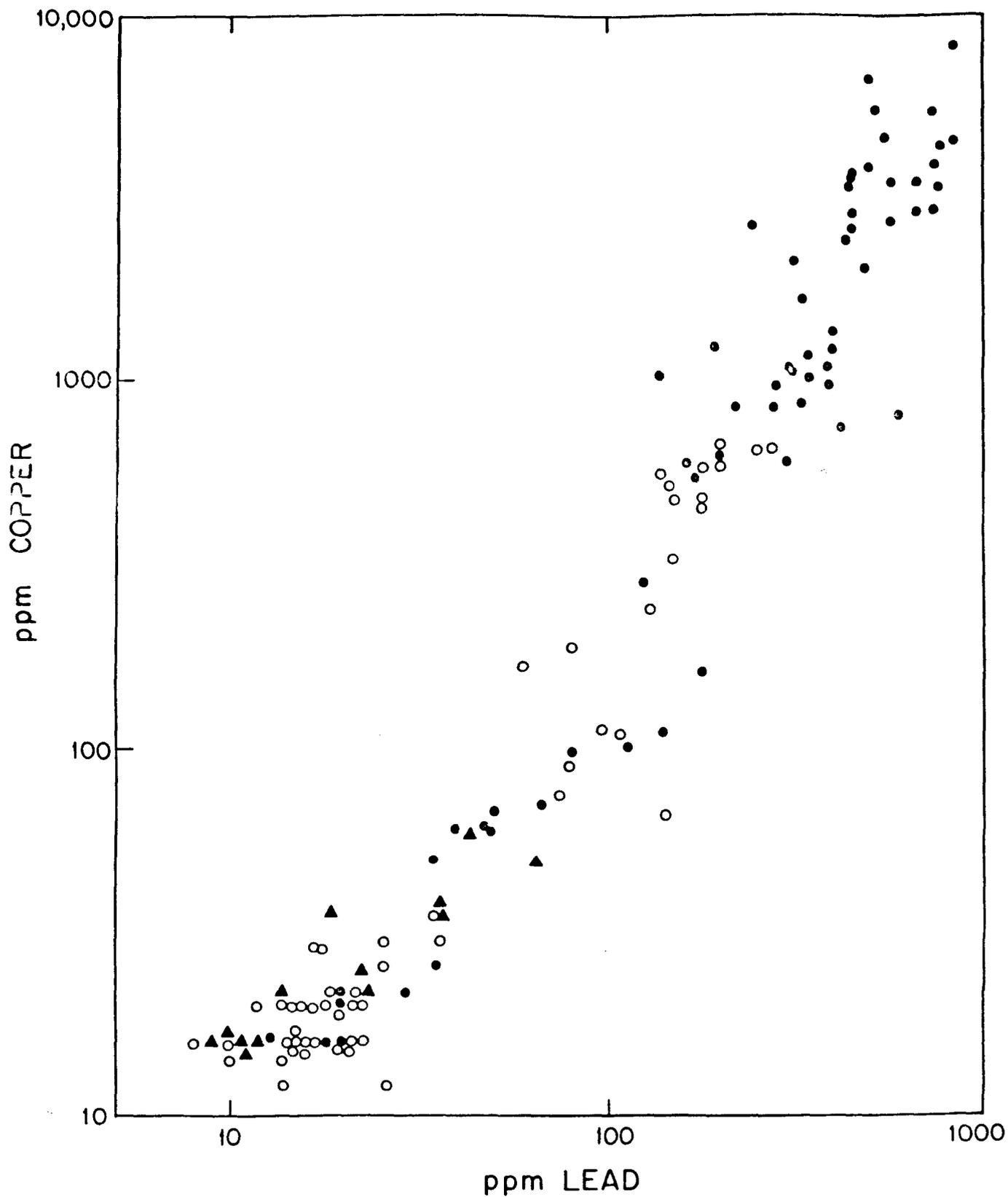


Figure 34. Relationship of Cu to Pb in cores from the harbor (dots), its approaches (open circles) and central Buzzards Bay (c 20, triangles).

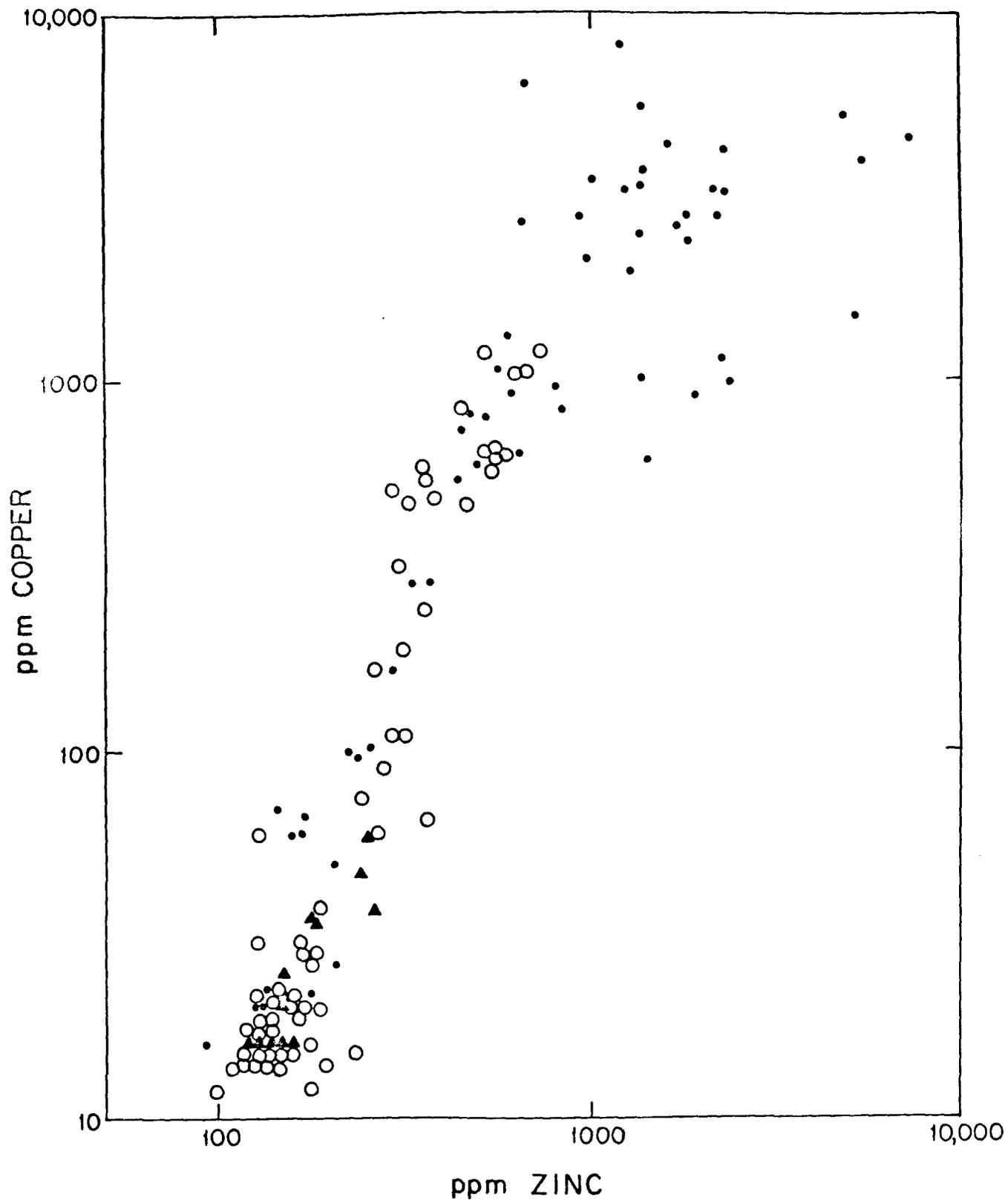
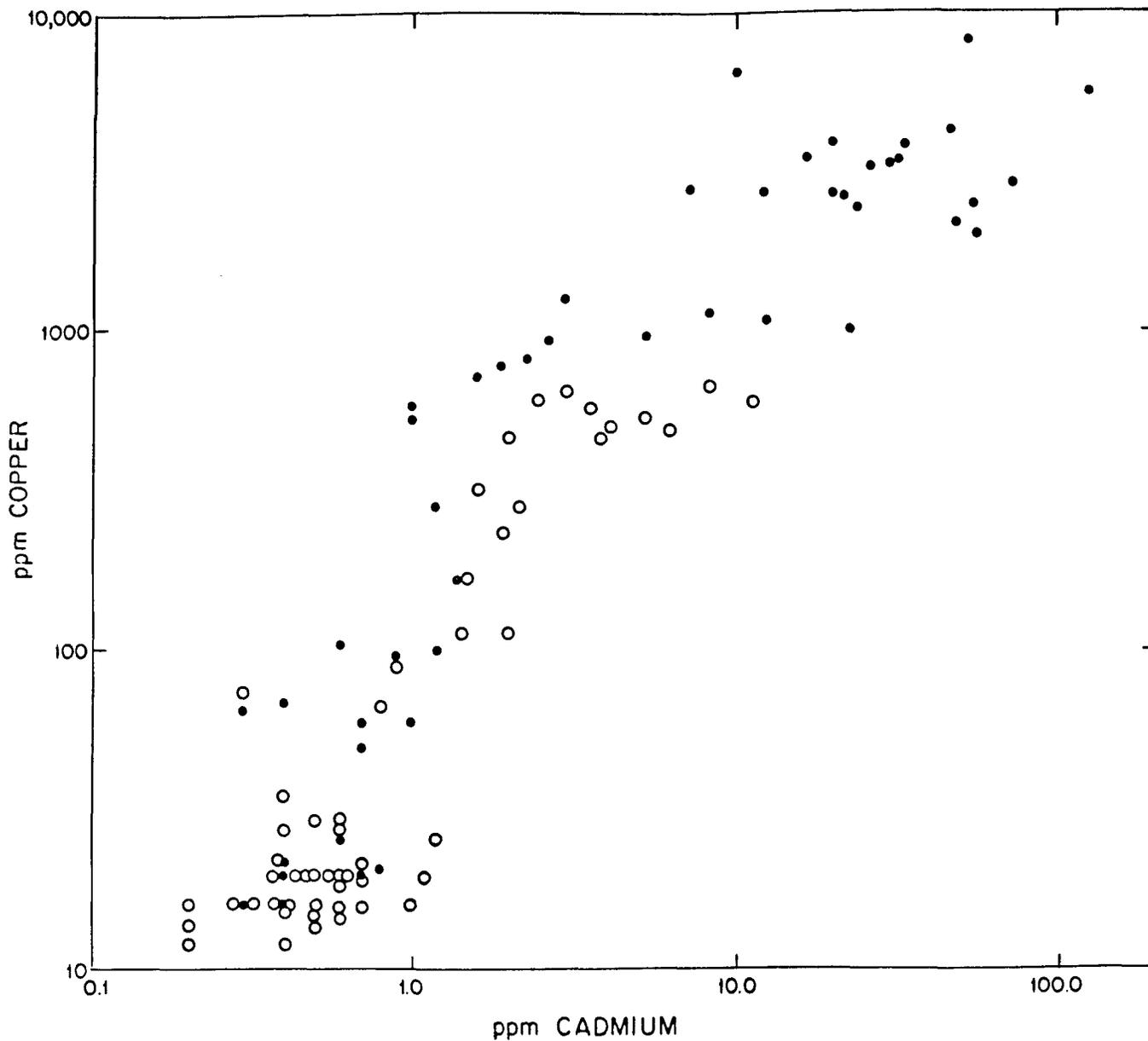


Figure 35. Relationship of Cu to Zn in cores from the harbor (dots), its approaches (open circles) and central Buzzards Bay (c 20, triangles).



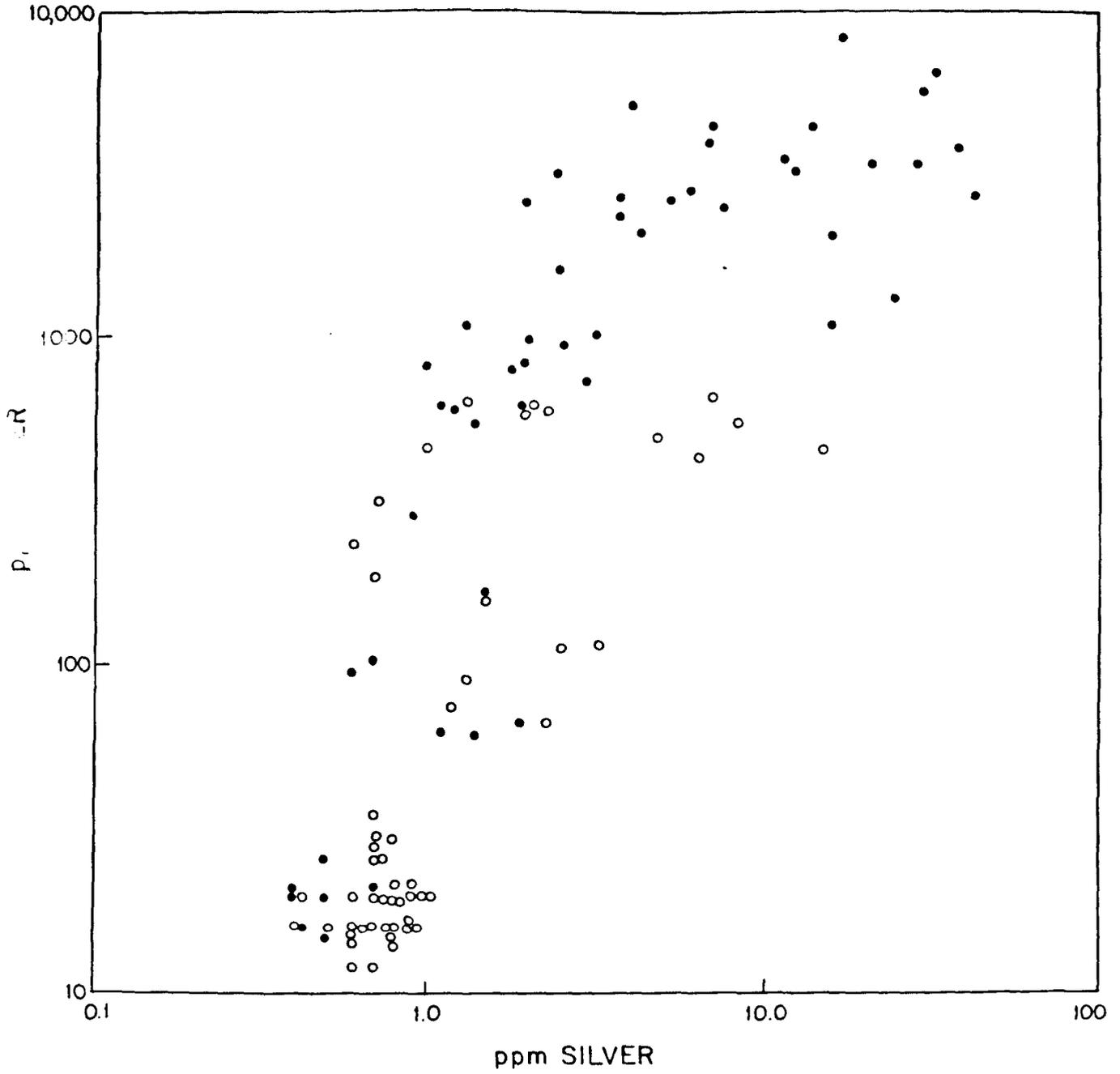


Figure 38. Relationship of Cu to Ag in cores from the harbor (dots) and its approaches (open circles).

Table 10. Comparison of background subsurface samples low in metal with metal-enriched surface samples. One comparison is made between the most metal-depleted subsurface sample and most metal-enriched surface sample in core 20 from central Buzzards Bay. The other is between the mean background subsurface value and a mean surface value: the subsurface means were obtained from 10 cores, on 45 samples in which the Cu value fell below 35 ppm at burial depths of 20 cm or more, while the surface means were obtained from 15 metal-depleted surface sediments located in the southern part of the study area at the edge of Buzzards Bay.

| Metal | Mean Back-ground (ppm) (A) | Standard Deviation 1 | Mean Surface (ppm) (B) | Enrichment B/A | Lowest Subsurface Core 20 (C) | Highest Surface Core 20 (D) | Enrichment D/C |
|-------|-------------------------------|-------------------------|---------------------------|-------------------|----------------------------------|--------------------------------|-------------------|
| Ag | 0.7 | + 0.15 | 1.2 | x1.7 | ND | ND | |
| Cd | 0.6 | + 0.25 | 0.7 | x1.1 | ND | ND | |
| Cr | 100.0 | +21.0 | 180.0 | x1.8 | 70 | 107 | x1.5 |
| Cu | 24.0 | + 7.0 | 80.0 | x3.3 | 16 | 60 | x3.7 |
| Pb | 18.0 | + 6.0 | 110.0 | x6 | 9 | 65 | x7 |
| Zn | 147.0 | +24.0 | 280.0 | x1.9 | 120 | 270 | x2.2 |

water interface, or actually in the bottom water. We infer that Cr is stripped from bottom deposits by oxidation processes during transport. As a result, much of the Cr that is found in the outer reaches of the harbor and in Buzzards Bay is natural, and instead of being associated with Cu, is associated with Mn (and Fe) (Figure 39).

In terms of absolute abundance, the four main contaminants of the inner harbor are Cu, Cr, Pb and Zn. It seems likely that we can use the changing relationships between these metals to differentiate between a highly contaminated group of samples controlled by one set of geochemical parameters and a less contaminated or uncontaminated group of samples controlled by other geochemical parameters. In an initial attempt to make this differentiation, we plotted Cu+Cr+Zn against Pb and found a sharp change in their relationship at about 1000 ppm Cu+Cr+Zn, which represents the geochemical boundary between the two groups of samples (Figure 40). This boundary occurs just seaward of Clarks Point and trends more or less NW-SE across the study area (Figure 41). The boundary is well defined by core samples (Figure 40);

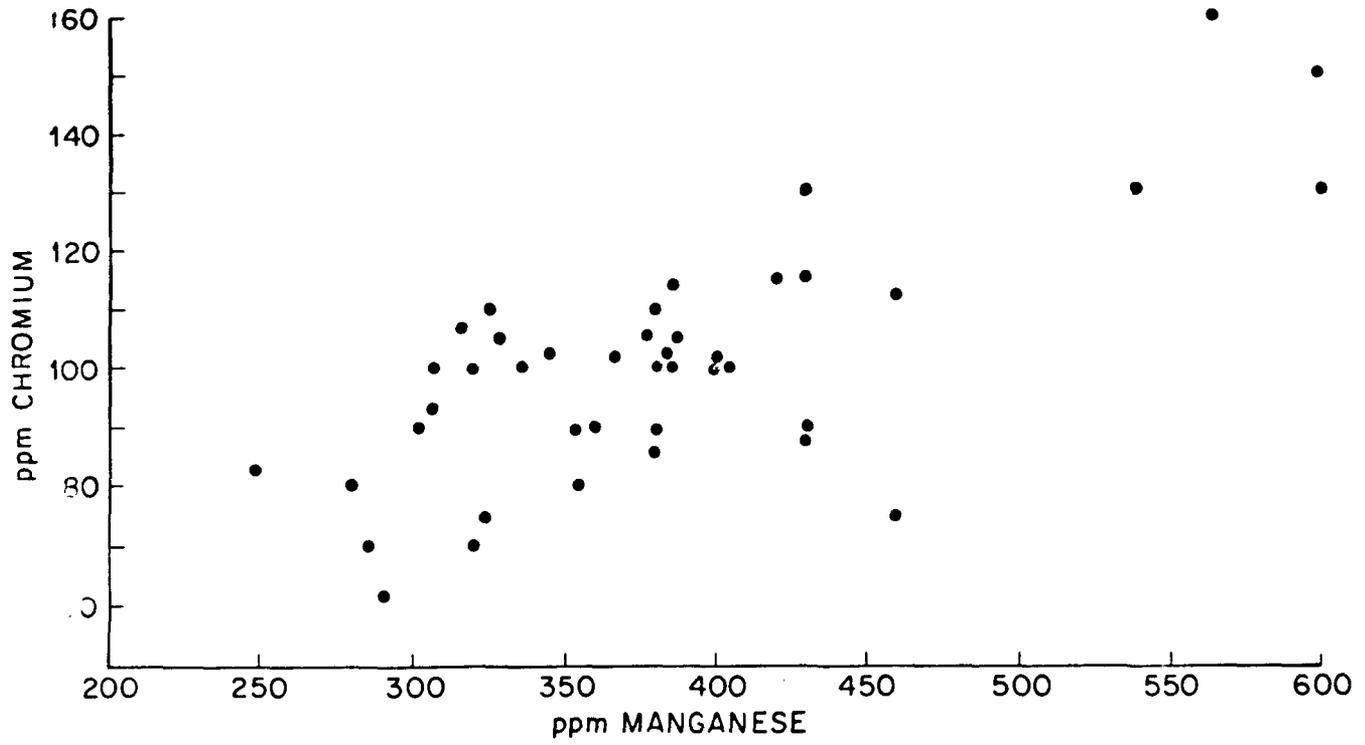


Figure 39. Relationship of Cr to Mn in samples taken from depths of 20 cm and more in cores 1, 16, 17, 18, 19 and 20.

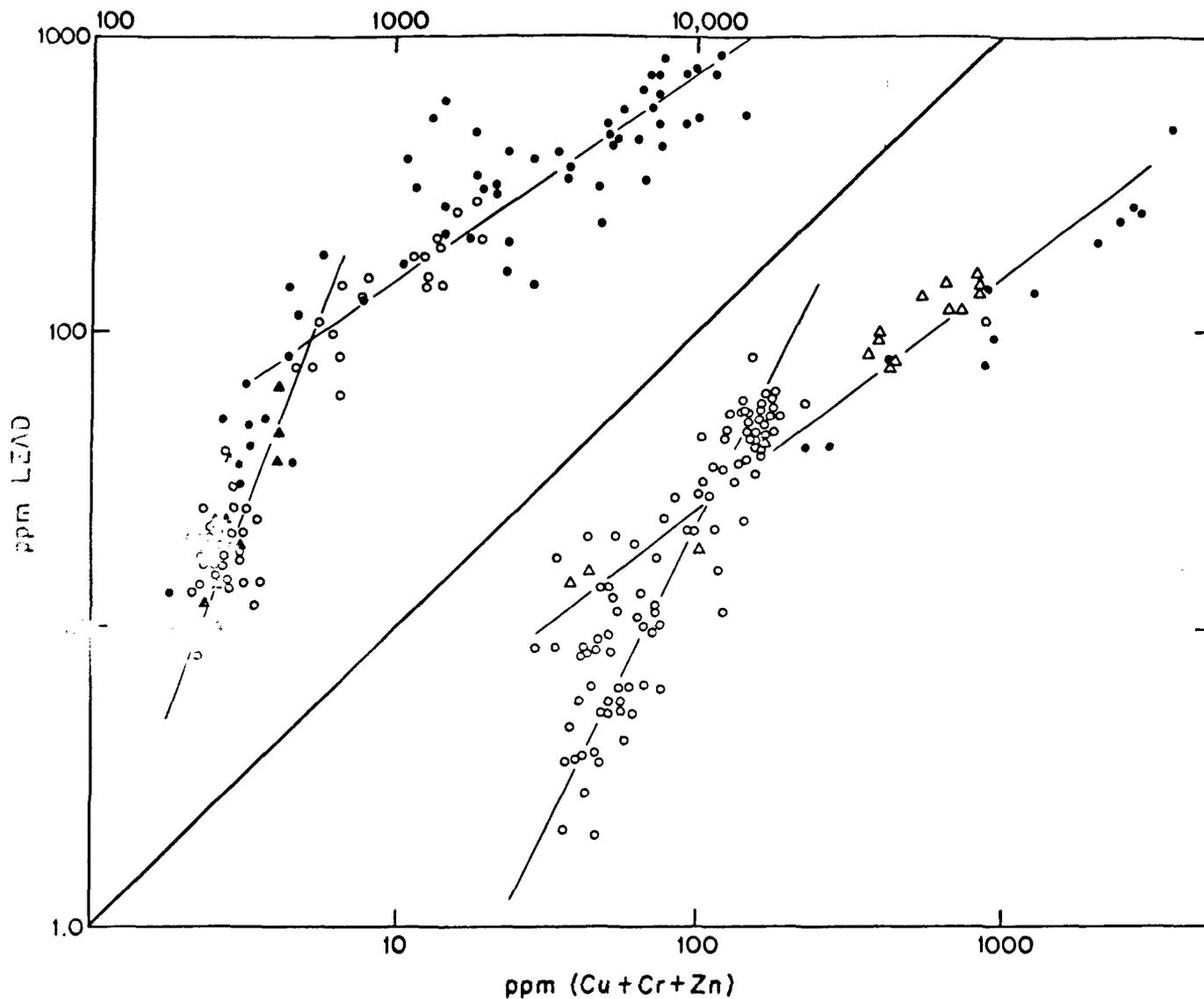


Figure 40. LEFT: Relationship of major contaminant metals to Pb in cores from the harbor (dots), its approaches (open circles) and central Buzzards Bay (c 20, triangles). Straight line shown is an approximate best-fit for two groups of data.

RIGHT: Relationship of major contaminant metals to Pb as seen in surface samples from Buzzards Bay (open circles; Moore, 1963) and in cores from the harbor (dots) and its approaches (triangles; Corps of Engineers, unpublished data). Differences in analytical methods probably cause some data overlap. The similarity of trends in previous and present data should be noted.

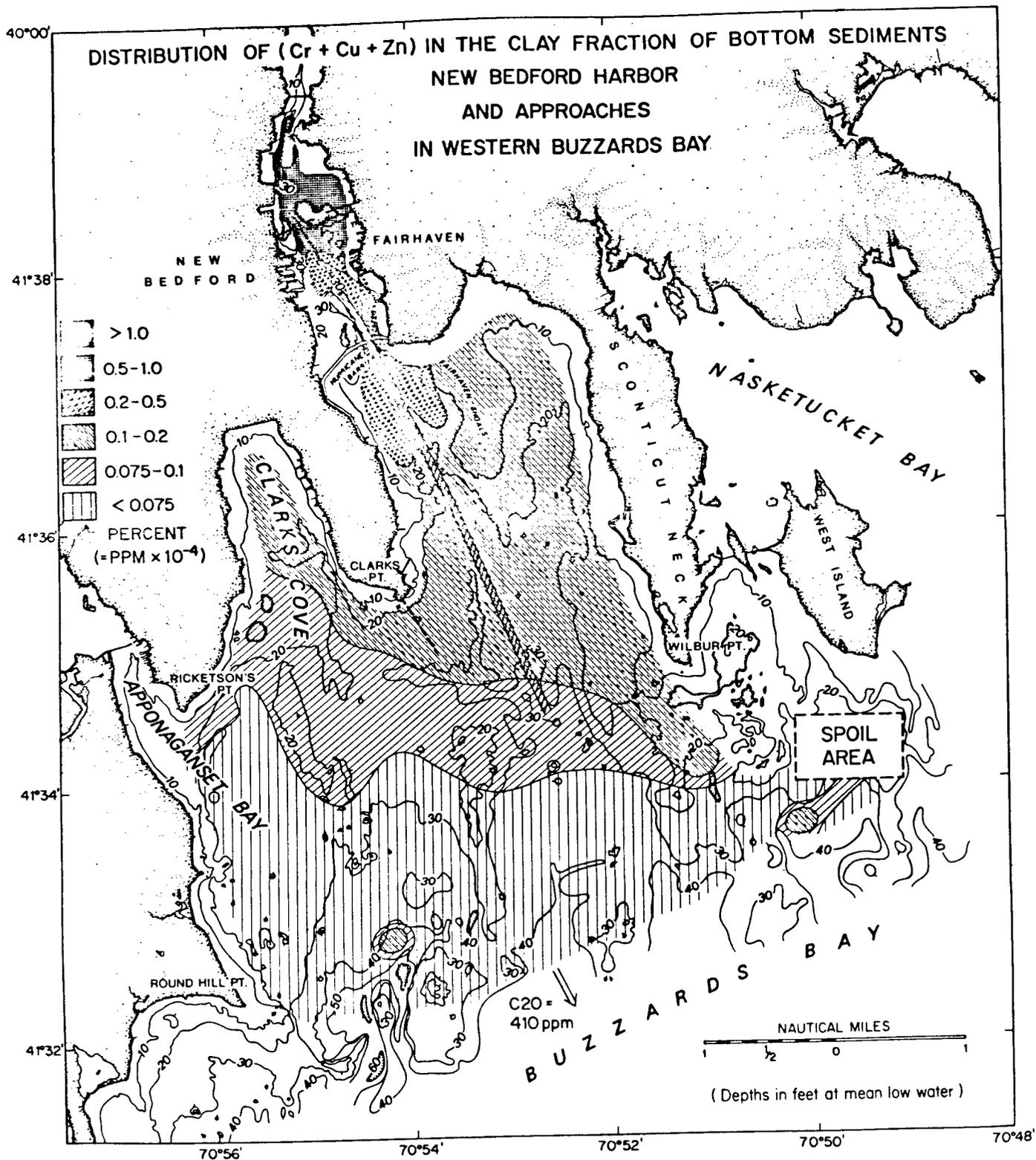


Figure 41. Regional distribution of major contaminant metals in surface sediments. Note high concentrations at the head of the harbor. Also see Figures 24 and 26.

however, many grab samples fall too near the boundary for us to be able to confidently place them into one group or the other on the basis of this plot (Figure 42).

(c) Statistical Relationships Among Metals
As Determined By Factor Analysis

One way in which complex relationships among large numbers of variables can be reduced to a smaller number of simple associations, which explain the variances in the original data, is through the use of factor analysis (Spencer, 1966; Summerhayes, 1972). In factor analysis, the different variables (in this case chemical elements) are grouped on the basis of the degree of their intercorrelation into factors in which specific variables are highly correlated. Mathematically, this process involves determining the eigenstructure of the correlation matrix. The factors, which were derived using a program adapted from Cooley and Lohnes (1971), 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 that have been mapped and plotted down core.

Only two factors are statistically significant (had eigenvalues greater than 1.0). Together they account for 81.9 percent of the total variance in the data (table 11). Both are geochemically meaningful in terms of what we know about regional geochemistry. Factor I is statistically the most dominant, accounting for 60.2 percent of the variance in the data and comprising a strong association among Cu, Cr, Zn and Pb, that is opposite to that for Fe and Mn. Factor II, accounting for 21.7 percent of the variance, comprises a strong association between Fe and Mn and a weak relationship between them and Cr.

Mapping R-scores for factor I, we find that the heavily contaminated samples have high positive scores, while uncontaminated or only slightly contaminated samples have negative scores (Figure 43). When factor I is plotted against factor II, we find that the samples fall into two distinct groups (Figure 44). Highly contaminated, positively scoring samples and the less contaminated or uncontaminated and negatively scoring samples are separated by the zero score for factor I, which may represent the geochemical front between them. Rather than relying solely on the zero score to define this front, we use the zero and -0.2 scores to define a transition zone between the two groups (Figure 43); the -0.2 line almost coincides with the 1000 ppm line for Cu+Cr+Zn, which we were reasonably confident is a geochemical front (compare Figures 41 and 43). The advantage of using factor analysis to define this front is that all of the available data were considered instead of selected variables or small groups of variables. Factor analysis gives us an efficient

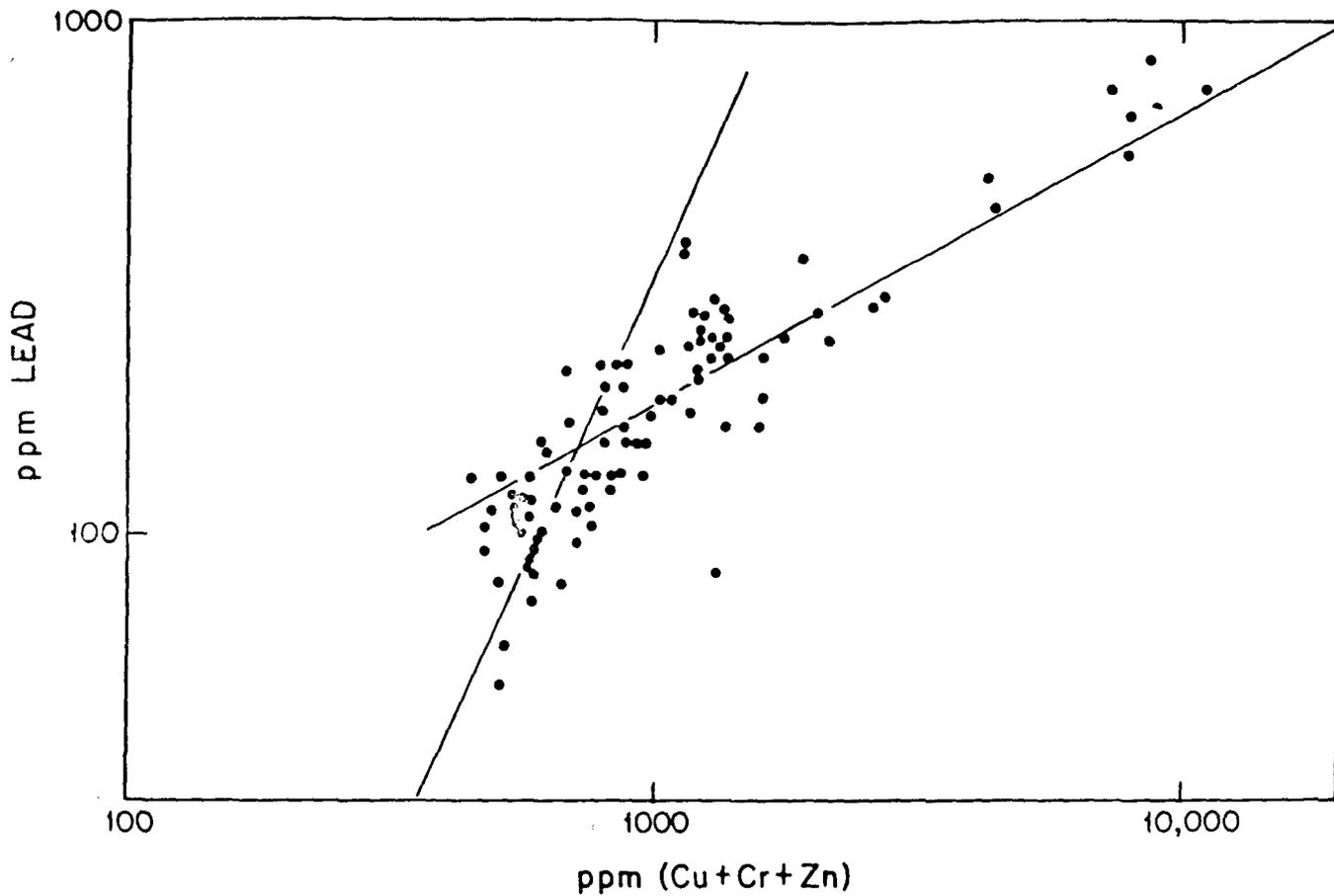


Figure 42. Relationship of major contaminant elements to Pb as shown in grab samples from the harbor and its approaches. Note scatter around straight line relationships taken from Figure 40, LEFT.

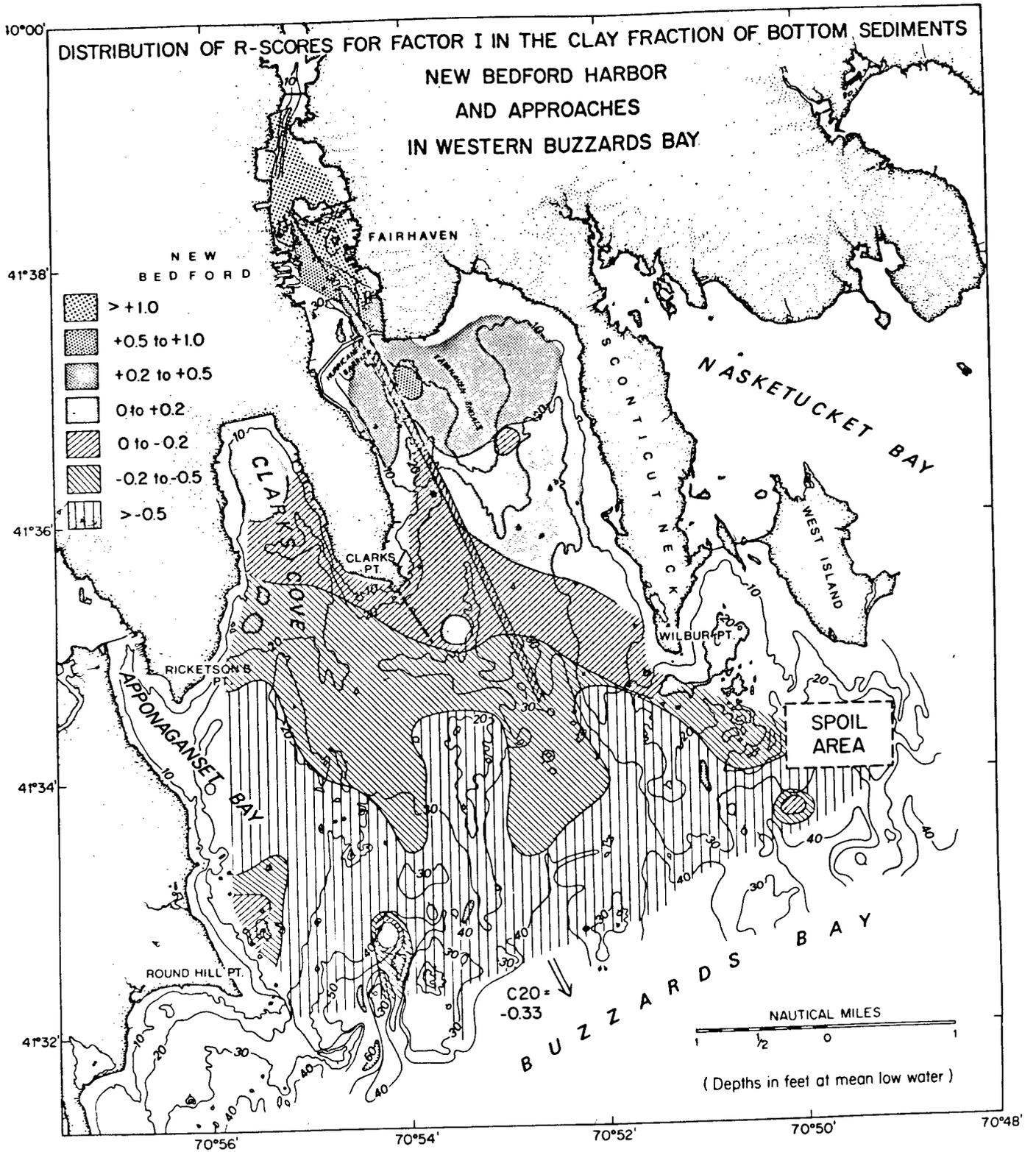


Figure 43. Regional distribution of Factor I R - scores for surface sediments. Note transition zone (0 to -0.2) separating positive from negative scores.

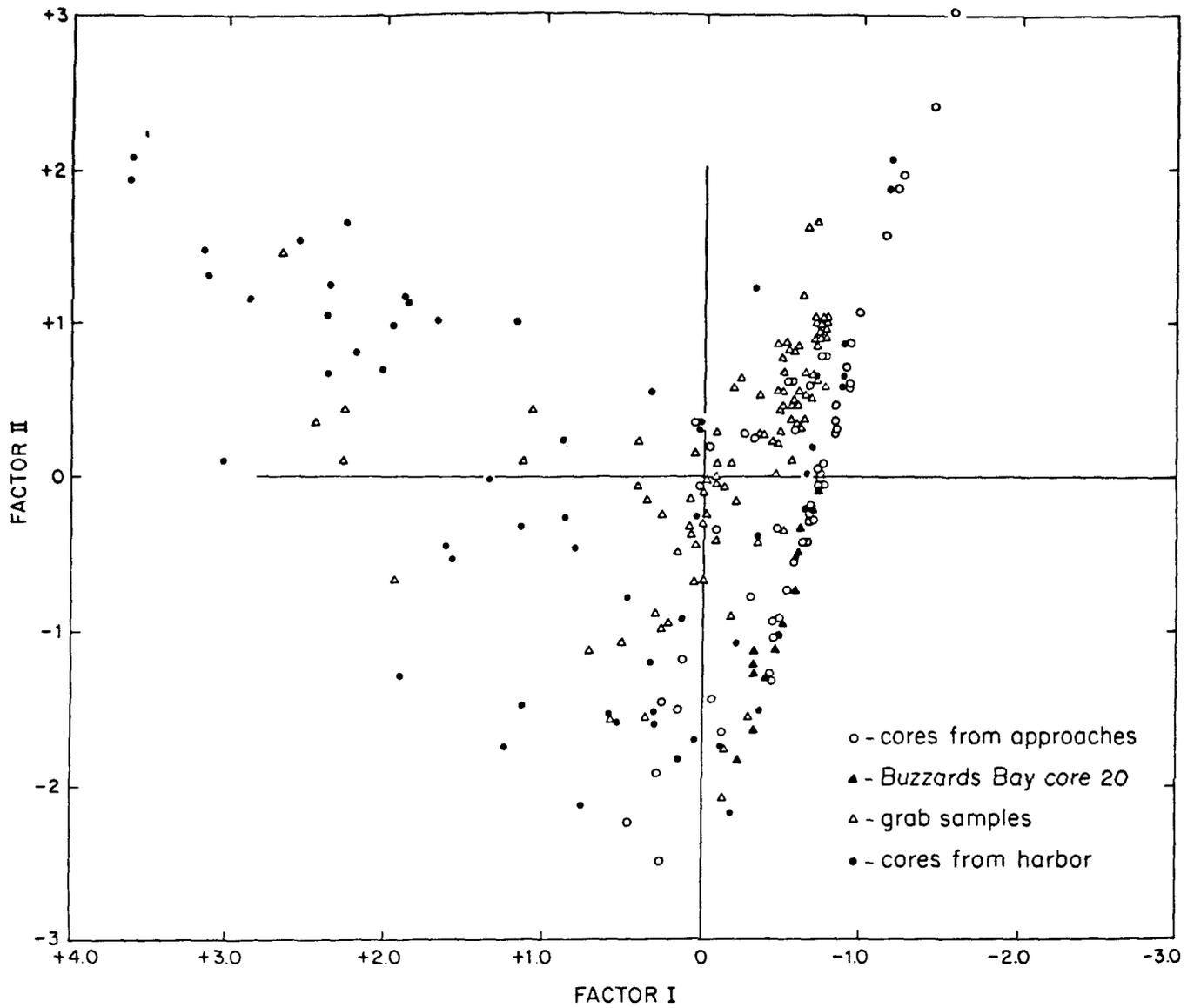


Figure 44. R - scores for Factor I plotted against those for Factor II. Samples from various parts of the study area are divided into two groups by a Factor I R - score of zero. Factor I R - scores of 0 to -0.2 have been taken to represent a transition zone between the two groups. Uncontaminated samples (those having strongly negative scores) group along a straight line, contaminated samples falling to the left of that line.

Table 11. Results of factor analysis of geochemical data, showing:

- (1) the main factors that control the data variance
- (2) the percentage of the variance explained by each factor
- (3) the eigen values of each factor, and
- (4) the factor loadings within each factor of variables with loadings greater than 0.3 (the loadings are given in brackets). The other factors generated by this analysis had eigenvalues of less than 1.0, so were not statistically significant.

| Factor I | Factor II |
|-----------|-----------|
| 60.2% | 21.7% |
| 3.61E | 1.31E |
| Cu (.93) | Fe (.77) |
| Pb (.92) | Mn (.70) |
| Cr (.88) | Cr (.31) |
| Zn (.74) | |
| Mn (-.58) | |
| Fe (-.51) | |

statistical, as well as an objective, basis for differentiation.

Within the negatively scoring group there are two separate subgroups, sharing a common trend (Figure 44). One, consisting entirely of subsurface samples from cores, falls along a straight line, suggesting control by uniform geochemical processes. The other group consists almost entirely of grab samples and core top samples. There is strong evidence to suggest that the displacement between the two subgroups is a function of surface contamination by chemical wastes. Four samples seaward of the transition zone have transition zone scores; two of these samples are known to be related possibly to spoil dumping, discussed earlier; the remainder have scores so close to -0.2 that they cannot be taken as contaminated (Figure 43).

Factor II seems, in part, to be related to diagenesis. In the approaches to the harbor, seaward of the transition

zone shown in Figure 45, factor II generally scores most positively in samples from topographic highs where oxidizing conditions are likely to be best developed and is least positive, or negative, in muddy samples from depressions. In the highly reducing sediments of the harbor and navigation channel, this factor shows local variations which may be related to localized redox conditions.

Down-core we find that positive scores for factor I always occur in the youngest sediments (Figure 46). In the harbor, negative scores at the bottoms of cores occur in sandy sediment containing substantial amounts of manganese (compare Figures 32 and 46). These down-core changes represent a fundamental geochemical change from surface reducing to buried oxidizing environments, confirming the value of the zero score as a geochemical front. These changes represent a change in sedimentary regime, and not diagenesis.

In several cores, the profile of factor I scores is quite variable, probably because of changes in sedimentation associated with major events such as maintenance dredging and hurricanes. Only core 11, from protected shallow water, can be considered with confidence to have a complete record of the history of contamination. The profile from this core shows a gradual increase in the amount of contamination in recent years. There are up to 40 cm of contaminated sediment in this core. If we assume an average sedimentation rate of 4 mm/yr, then this indicates that contamination has been present for up to 100 years.

Summary of Metal Dispersal

There are very large amounts of metal in the sediments of New Bedford Harbor. Most abundant of these is Cu, with substantial amounts of Cr, Zn and Pb. Elements like Ag, As, Cd and Hg are also enriched with respect to background levels, although together these elements total less than about 100 ppm. Metal is most abundant on the west bank, near the head of the harbor, where industrial plants have been discharging substantial amounts of Cu in particular, for at least 80 years. Here Cu+Cr+Zn combined form more than 1 percent of the dry sediment's weight. The metal is most concentrated in the silt and clay fractions of the sediment. Forty percent of the Cu and Zn and 8 percent of the Cr are non-extractable and must occur in resistant mineral phases. Most of the Cr and about 20 percent of the Cu and Zn occur as authigenic minerals, probably sulphides. The remaining Cu and Zn are either complexed with fulvic acids or in cation exchange positions in the sediment. We deduce, therefore, that about 60 percent of the Cu and Zn, and about 90 percent of the Cr, enter the harbor in solution. The Massachusetts Division of Water Pollution Control (1975)

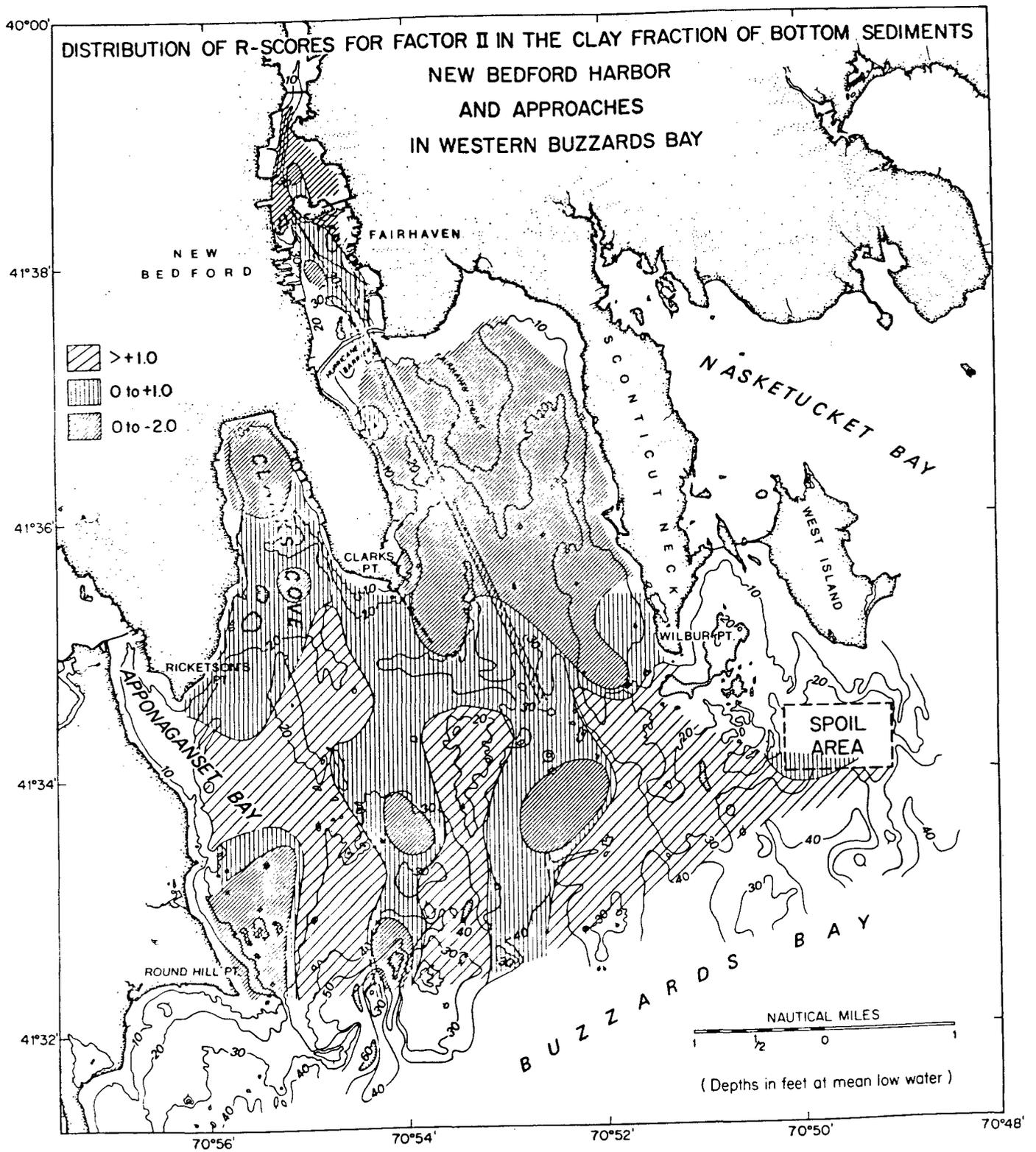


Figure 45. Regional distribution of surface sediment, Factor II R - scores.

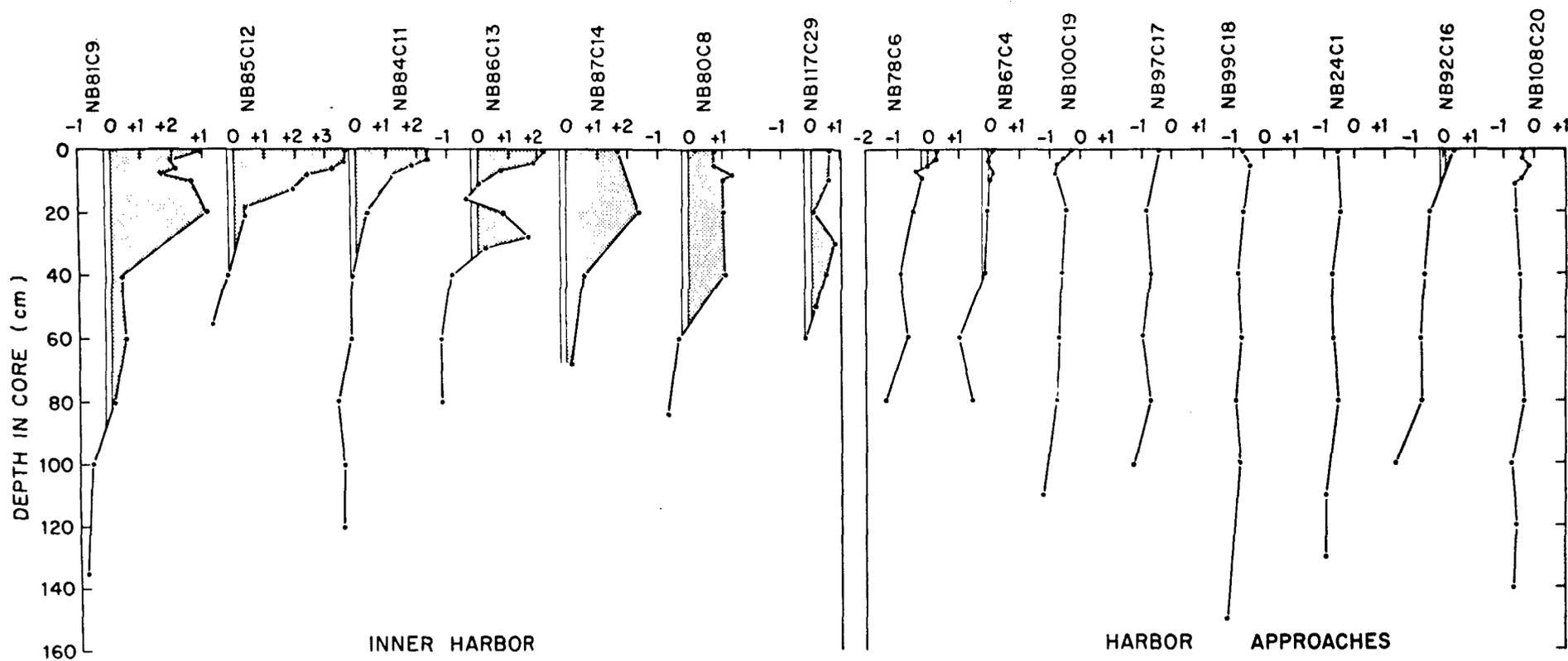


Figure 46. Down-core, Factor I R - scores. Stippled area represents the region of positive scoring. The 0 to -0.2 transitional zone has been outlined. Cores have been ordered, from left to right, along a north-south transect.

found 0.5 ppm metal in solution in the harbor waters suggesting that most of the industrial effluent is rapidly removed from the water column. Whatever the form of the dissolved species, it appears that they are rapidly fixed, probably by the organically enriched agglomerates in suspension throughout the water column, and are transported to the bottom to be incorporated into the sediment column. Chemical changes may occur in the suite of metals as they move through the relatively oxidizing milieu of seawater and into highly reducing bottom sediments.

In some places these metalliferous muds were penetrated and 'pre-industrial' sediments that contained very low levels of metal, typical of the regional background, were recovered. Metalliferous sediments are about 0.5 m thick, on average. They contain about 40 percent actual solids, according to Corps of Engineers reports; therefore, it would be possible to recover these sediments by suction dredge. This raises the intriguing question of whether the metals in them could be recycled.

If we assume that the area covered by metalliferous mud is 4 km²; that these muds are 0.5 m thick; that 40 percent of the mud consists of solid material with a density of 2.65 gm/cc; that 13 percent of these solids consist of clay, and that 0.5 percent (or 5000 ppm) of clay consists of metal (Cu+Cr+Zn), then the harbor contains about 1.4 x 10³ metric tons of metal. These metals are in the clay fraction in the approximate proportion 45:30:25, which gives us approximately 6.4 x 10⁵ kg of Cu, 4.5 x 10⁵ kg of Cr and 2.3 x 10⁵kg of Zn. At current prices of about \$1.54/kg for Cu, \$1.63/kg for Cr and \$.82/kg for Zn, the deposit would be worth about \$2 million. This is a conservative estimate, since the average thickness of metalliferous sediment may be greater than 0.5 m, the water content of subsurface sediments may be less than 60 percent, and the metals are also found in the silt fraction, as well as the clay fraction. We do not know, however, if the metals are in forms that make them readily extractable, nor do we know what the cost of mining a deposit like this would be.

According to available EPA records, the average discharge of Cu into the harbor in recent years has been about 90 kg/day. If we assume that the discharge rate for the past 80 years has averaged 45 kg/day, then the harbor should contain about 1.4 x 10⁶kg of Cu, or about twice as much as we have calculated. Considering the assumptions that were made, this agreement is surprisingly good. In fact, if the harbor had not been dredged in the 1930's and 1950's the carpet of metalliferous sediment would be about twice as thick as it is now, and would have contained twice as much metal.

We think that the exponential decrease in the abundance of Cu away from the main source of Cu in the harbor is due to lateral mixing through horizontal eddy diffusion caused by near-bottom turbulence. Because Cu is found mainly in the clay fraction, we can point to this mechanism as being the probable means of fractionation of clay from silt.

In Buzzards Bay, only the top 20 cm of the sediment is enriched in Cu that is probably anthropogenic, as is the case in other areas where such enrichment occurs (cf. Bruland and others, 1974; Edgington and Robbing, 1976; Thomson and others, 1975; Young and others, 1973). If the rate of sedimentation is 3 mm/yr, and Cu has been reaching the bay for 80 years, we might expect to see at least 25 cm of metalliferous sediment since, as in the case of plutonium, metal would have been mixed downwards in the sediment column by bioturbation (cf. Bowen and others, 1976; Livingston and Bowen, 1976). If the rate is as low as 1 mm/yr as suggested by Bowen and others (1976), we would expect to see at least 8 to 10 cm of metalliferous sediment above a mixed layer smeared with metal by bioturbation. Both assumptions ignore the fact that diagenetic processes may cause the Cu (like plutonium) to be redistributed upwards within the sediment column. We conclude that without a more detailed examination of the chemistry of sediments in the bay, we cannot pin down more accurately the history of waste accumulation there.

We can, however, make some estimate of the amount of material that escapes the harbor. We previously calculated that the harbor muds now contain some 1.4×10^3 metric tons of metal, and that probably the same amount had been removed by dredging, giving us a total of 2.8×10^3 metric tons. If we now assume that waste-contaminated mud covers 150 km² in central Buzzards Bay (the area of mud mapped by Moore, 1963), is 10 cm thick, contains 30 percent clay, of which 150 ppm is waste metal (the difference between surface and background amounts of Cu+Zn+Pb in core 20), and contains 50 percent of solids with a density of 2.65 gms/cc, then the amount of waste metal in the bay is 0.9×10^3 metric tons, approximately 32% of the estimated input to the harbor.

Seaward movement of metals, most of which are found in the clay-sized fraction, occurs against the predominantly landward flow of near bottom suspensates, probably by eddy diffusion. We surmise that the amount of turbulence near the bottom increases landward, keeping clay in suspension longer and fractionating it from silt. Within this resuspended material, the lateral diffusion of wastes that originate in the harbor takes place. We know that there is almost no contamination at station AR6, 0.8 km north of the major source of metal (Figure 26), therefore, landward transport of metals must be less effective than seaward transport. This is because

north of AR6 the net flow is seaward at all depths, while south of AR6 it is landward at the bottom and seaward at the surface.

Seaward of Clarks Point the Cu distribution can be taken as representative of all metals except Cr. It appears that waste Cr does not move seaward of a well defined geochemical front at Clarks Point. Seaward of this front Cr tends to follow Fe and Mn, its abundance becoming dependent on the chemistry of the environment. Mn and Fe are highest in sandy sediments both down core and on topographic highs, where they are associated with iron-stained sand grains. These metals are least abundant in depressions and are especially low in the harbor, where reducing conditions are prevalent.

We infer that Cr exists in the form of sulphides that are oxidized during seaward diffusion. Other metals may also be affected by this process, though to a much lesser degree. Aside from the obvious difference between Cr and the other waste metals, we have no data which would indicate how other metal wastes are chemically changed during their migration towards Buzzards Bay. We do know that the concentration of Pb relative to Cu increased toward the Bay, probably as the result of atmospheric fallout.

SYNTHESIS

General Discussion

It has long been known that estuaries are gradually being filled by fine-grained sediments (Schubel, 1971; Drake, 1976), and New Bedford Harbor is no exception. Until recently, it was thought that rivers supplied most of this fill. We now know that rivers tend to deposit much of their suspended load near the heads of their estuaries. Downstream there is a net landward transport of fine-grained sediment from the continental shelf into the estuary (Meade, 1969; Schubel, 1971; Hathaway, 1972; Swift, 1976; Rutherford and Church, 1976).

The fine-grained sediments that accumulate in estuaries have large surface areas, so tend to adsorb and transport significant quantities of pollutants. In addition, industrial and human wastes that are not in dissolved form usually occur as fine particles which travel with the fine-grained sediment. As a result, many estuaries are thought to act as sinks, effectively preventing the transfer of pollutants to the open ocean.

In spite of this general knowledge, we still do not have the adequate understanding of the physics, chemistry,

geology and biology of estuaries that is needed for the many environmental decisions that must be made about their use (Officer, 1976). It follows that we cannot predict with certainty the effects of environmental change in estuaries. Our study was designed to remedy this deficiency by providing some basic scientific information about the movement of fine-grained sediments in New Bedford Harbor and the role they play in waste dispersal; in effect this is a test of the estuarine sink model.

The weakly stratified Acushnet River estuary is typical of the many small embayments along the New England Coast. In this region, erosion of exposed crystalline and metamorphic rocks is generally slow, and there is not much glacial debris, so that rivers carry little suspended sediment (Folger, 1972). Differences between New Bedford Harbor and similar environments along this coast may be ones of degree, rather than kind, reflecting local variations in river discharge, tidal range and exposure. Given this basic similarity, our findings about sediment and waste dispersal in the New Bedford Harbor area may apply in many respects to other New England inlets, as well as to similar estuaries in other parts of the world.

Sediment Dynamics

The major topographic feature of the study area is the drowned valley of the Acushnet River. This valley has been partially filled by up to 60 ft. (18 m) of post glacial sands and silts, which overlie some 10 ft. (3 m) of tills and gravels that cover the local bedrock. The present sedimentary regime, represented by deposits of a mixture of silt and clay, appears to have been in effect for at least 200 years.

The fine-grained sediments presently being deposited in this region must come from a combination of coastal erosion, river discharge, and the landward movement of sediment from the continental shelf. Under normal conditions, the Acushnet River carries little suspended sediment, and erosion of the locally rocky shore line is minimal. We assume, therefore, that most of the recent fine-grained sediment in New Bedford Harbor comes from the continental shelf, via Buzzards Bay. This landward movement of fines has been well documented elsewhere (e.g. in Long Island Sound - Bokuniewicz and others, 1976) and probably occurs as a function of residual bottom drift caused by waves "feeling the bottom" (Bumpus and others, 1974; Drake, 1976). Our work shows that the sediments being deposited in New Bedford Harbor and its approaches must have come from Buzzards Bay. En route, they are partially fractionated by flood tide bottom currents that transport more silt than clay landward. The clay is

less able than silt to settle in the shallows and becomes preferentially concentrated in deeps in the study area and in central Buzzards Bay. The fractionation process probably works by causing small clay-rich agglomerates to remain in suspension longer than large silt-rich agglomerates. The clayey suspensions seem to be organically enriched, and their deposition appears to have led to the development of a thin mobile layer of sediment or "fluff" like that found, for example, in Delaware Bay (Weil, 1976). Our observations suggest that "fluff" is widespread in the study area. We also know that bioturbation makes Buzzards Bay muds easily resuspendable (Rhoads and Young, 1970). Thus, it seems likely that the sediment-water interface is poorly developed for much of the year and may form a soupy transition zone between subsurface silts and turbid bottom waters.

Construction of the New Bedford hurricane barrier has caused a notable increase in the sedimentation rate within the harbor. If our data are correct, the present rate of sedimentation in the deeper portions of the harbor is 4 cm/yr. It would, therefore, require at least 20 years to produce a 1 meter shoaling of the harbor. We can only assume that the increase in the rate of sediment accumulation is a direct product of a reduction in tidal flushing produced by the construction of the hurricane barrier.

Waste Dispersal

Large quantities of potentially toxic metals have been discharged into the harbor and its approaches. These include Cu, Cr, Pb and Zn, with lesser amounts of As, Ag, Cd and Hg. These metals rapidly become part of the bottom sediment, particularly the clay fraction and, for the most part, remain within the confines of the harbor. Metalliferous sediment is found only at or near the surface and is, therefore, clearly of recent input, dating back a maximum of 100 years. The major source of metal discharge was found to be located on the harbor's west bank, between the Coggeshall and New Bedford-Fairhaven bridges. Metal concentrations in the harbor are sufficiently high to warrant consideration of their recycling potential.

Recent work has shown that organo-metallic complexes play an important role in the fixing of metals in sediments (Presley and others, 1972; Neissenbaum and Swaine, 1976). Work on New Bedford Harbor sediments indicates that substantial amounts of Cu and Zn are complexed with fulvic and humic acids; but this work has also shown that an equally significant portion of these metals are resistant to acid leaching techniques. During seaward migration, the chemistry of the metals appears to change, probably as the result of oxidation, which removes Cr but not other metals. This

difference in the behavior of Cr is consistent with studies in Long Island Sound (Thomson and others, 1975). The most significant compositional change takes place across a well defined geochemical front located near Clarks Point. Further work is needed to define the precise significance of this front.

There is an exponential decrease in the abundance of metal away from the harbor, which is consistent with similar studies elsewhere (Goldberg, 1976). Contaminated muds have been found in the center of Buzzards Bay. We conclude that up to 32 percent of the metals discharged into the harbor have been spread out over Buzzards Bay, most probably by eddy diffusion of particulates. Actual fluxes of metals to the bay floor are composed of at least two separate parts: harbor input and atmospheric fallout (Bruland and others, 1974; Goldberg, 1976). We have calculated that the flux of clay to the bottom of Buzzards Bay is $0.12 \text{ gms/cm}^2/\text{yr}$ and we know that these clays contain 24 ppm natural Cu and up to 36 ppm waste Cu. The natural flux of Cu must then be $2.9 \text{ } \mu\text{g/cm}^2/\text{yr}$ and the industrial flux must reach $4.2 \text{ } \mu\text{g/cm}^2/\text{yr}$. If we assume that the industrial flux is the product of fallout and local input, and that fallout contributes $0.5 \text{ } \mu\text{g/cm}^2/\text{yr}$ (Bruland and others, 1974), then the Cu input from local sources is $3.7 \text{ } \mu\text{g/cm}^2/\text{yr}$. The industrial flux of the other major contaminants, Zn and Pb, can be similarly reduced; when this is done, we find that some 25 percent of the excess metal found in the surface sediments of Buzzards Bay are the products of atmospheric fallout. When input by atmospheric fallout is taken into account, we discover that transport of metal out of the harbor amounts to 24 percent of the total discharged into it.

Elderfield and Hepworth (1975) have shown that in some estuaries there is a tendency for the diagenetic enrichment of surface sediments, which may be confused with surface sediment contamination. Diagenetic remobilization, hence surface enrichment, has been shown to affect plutonium in the sediments of Buzzards Bay (Bowen and others, 1976) and uranium in Long Island Sound (Thomson and others, 1976). Thomson and others (1976) found no evidence, however, for the remobilization of Cu, Pb or Zn through diagenetic processes. If diagenesis was a significant contributor to the surface enrichment of metals, then it would be expected that there would also be elevated concentrations of Fe and Mn in the surface sediments of the New Bedford area. Our data indicates, however, that Fe and Mn surface enrichment does not take place. We, therefore, must conclude that the elevated levels of Cu, Pb and Zn found in surface and near surface sediments of Buzzards Bay do not result from natural processes.

Our study of the patterns of sediment distribution

and metal dispersion in the New Bedford Harbor region allow us to make some deductions about the dispersal of materials introduced by sewage outfalls. The solids contained in sewage effluent are agglomerates in the clay to silt size range and tend to settle to the bottom near the point of discharge. These solids are easily resuspended and move about the study area with other clay to silt size particles. A large proportion of the material in suspension, especially in surface waters, is organic. The movement of these fine-grained solids may partially account for the fact that bottom waters are depleted in dissolved oxygen and that the mobile carpet of fine-grained sediment, which has been found here is richer in organic matter than are the underlying silts. Based on our other data, it seems reasonable to suggest that a portion of the solids injected into the harbor approaches at the Clarks Point outfall eventually find their way into the harbor and that at least 10 percent of the solids introduced into the harbor by outfalls behind the hurricane barrier escape to Buzzards Bay.

The major findings of this study are:

1. The construction of a hurricane barrier has caused a significant increase in the sedimentation rate in New Bedford Harbor;
2. The harbor acts as an imperfect trap for materials that are introduced into it, thereby allowing the transfer of industrial contamination to Buzzards Bay;
3. The surface and near surface sediments of New Bedford Harbor are highly enriched in metals, these metals having been derived locally.

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REFERENCES

- Bokuniewicz, H.J., Gebert, J., and Gordon, R.B., 1976: Sediment mass balance of a large estuary, Long Island Sound. *Est. Coast. Mar. Sci.* 4:523-536.
- Bowen, V.T., Livingston, H.D., and Burke, J.C., 1976: Distribution of transuranium nuclides in sediment and biota of the North Atlantic Ocean. IN 'Transuranium Nuclides in the Environment', Int. Atom. En. Agency, Vienna: 107-120.
- Broecker, W.S., 1974: *Chemical Oceanography*. Harcourt Brace Jovanovich, Inc., New York, 214pp.
- Bruland, K.W., Bertine, K., Koide, M., and Goldberg, E.D., 1974: History of metal pollution in southern California coastal zone. *Env. Sci. Tech.* 8(5): 425-432.
- Bumpus, D.F., Lynde, R.E., and Shaw, D.M., 1974: Physical oceanography of the Middle Atlantic Bight. IN 'Coastal and Offshore Inventory, Cape Hatteras to Nantucket Shoals'. Mar. Pub. Ser. 2, Univ. Rhode Island: 1-72.
- Calvert, S.E. and Price, N.B., 1970: Minor metal contents of recent organic-rich sediments off South-West Africa. *Nature* 227:593-595.
- Camp, Dresser, and McKee, 1974: Waste-water collection system and treatment facilities. City of New Bedford Report: 227 pp.
- Chester, R. and Hughes, M.J., 1967: A chemical technique for the separation of ferro-manganese minerals, carbonate minerals, and absorbed trace elements from pelagic sediments. *Chem. Geol.* 2:249-262.
- Collins, B.P., 1976: Suspended material transport: Narragansett Bay area, Rhode Island. *Est. Coast. Mar. Sci.* 4:33-44.
- Cooley, W.S. and Lohnes, P.R., 1971: *Multivariate Data Analysis*. John Wiley, New York, 364 pp.

- Drake, D.E., 1976: Suspended sediment transport and mud deposition on continental shelves. IN 'Marine Sediment Transport and Environmental Management' (eds. D.J. Stanley and D.J.P. Swift). Wiley Intersci., New York: 127-158.
- Edgington, D.N. and Robbins, J.A., 1976: Records of lead deposition in Lake Michigan since 1800. *Env. Sci. Tech.* 10(3):266-274.
- Elderfield, H., Thornton, I., and Webb, J.S., 1971: Heavy metals and oyster culture in Wales. *Mar. Poll. Bull.* 2(3):44-47.
- Elderfield, H. and Hepworth, A., 1975: Diagenesis, metals and pollution in estuaries. *Mar. Poll. Bull.* 6(6): 85-87.
- Ellis, J.P., Summerhayes, C.P., Stoffers, P., and Kelly, B., 1977: Data File: New Bedford Harbor and approaches. *Tech. Rpt. Woods Hole Ocean. Inst.* (in preparation).
- Emery, K.O. and Uchupi, E.A., 1972: Western North Atlantic. *Mem. Am. Assoc. Petrol. Geol.* 17:532pp.
- Farrington, J.W., Henrichs, S.M., and Anderson, R., 1976: Fatty acids and Pb210 geochronology of a sediment core from Buzzards Bay, Massachusetts. *Geochim. Cosmochim. Acta* (in press).
- Farrington, J.W., Frew, N., Gschwend, P.M., and Tripp, B.W., 1977: Hydrocarbons in cores of northwestern Atlantic Ocean and continental margin sediments. *Est. Coast. Mar. Sci.* (in press).
- Folger, D.W., 1972: Characteristics of estuarine sediments of the United States. *U.S.G.S. Prof. Paper 742*: 94pp.
- Goldberg, E.D., 1976: Pollution history of estuarine sediments. *Oceanus* 19(5):18-26.
- Gordon, C.M., 1975: Sediment entrainment and suspension in a turbulent tidal flow. *Mar. Geol.* 18:M57-M64.
- Gross, M.G., 1967: Concentrations of minor elements in diatomaceous sediments of a stagnant fjord. IN 'Estuaries', *Am. Assoc. for the Adv. of Sci.* 273-282.

- Gross, M.G., 1972: Geologic aspects of waste solids and marine waste deposits, New York metropolitan region. Bull. Geol. Soc. Am., 83:3163-3176.
- Hathaway, J., 1971: Data File: Continental margin program, Atlantic coast of the United States, Vol. 2, Sample collection and analytical data. Tech. Rpt. Woods Hole Ocean. Inst. (unpubl. ms.): 496pp.
- Hayes, M.O., 1975: Morphology of sand accumulation in estuaries. IN 'Estuarine Research', Vol. 2 (ed. L.E. Cronin): 3-22.
- Hoff, J.G., 1971: Water pollution--a case history. Science Teacher 38(1):3pp.
- Hough, J.L., 1940: Sediments of Buzzards Bay, Massachusetts. J. Sed. Pet. 10(1):19-32.
- Johnson, R.G., 1974: Particulate matter at the sediment-water interface in coastal environments. J. Mar. Res. 32(2):313-330.
- Kelly, B., 1976: Biology of New Bedford Harbor sediments: a progress report. Unpub. ms., 11pp.
- Kranck, K., 1973: The nature and deposition of suspended marine sediment. Bedford Inst. Oceanogr. Rpt. Ser. BI-R-73-12:19pp.
- Krauskopf, K.B., 1967: Introduction to Geochemistry. McGraw-Hill, New York, 721pp.
- Livingston, H.D., and Bowen, V.T., 1976: Plutonium and Cesium-137 distribution patterns in coastal sediments of the northwest Atlantic Ocean. Sympos. Environmental Chemistry and Cycling Processes. Augusta, Georgia, April 1976.
- Manheim, F.T., Meade, R.H., and Bond, G.C., 1970: Suspended matter in surface waters of the Atlantic continental margin from Cape Cod to the Florida Keys. Science 167:371-376.
- Massachusetts Division of Water Pollution Control, 1971: New Bedford Harbor and Acushnet River: Water Quality Study. Mass. Water Res. Comm.

- Massachusetts Division of Water Pollution Control, 1975: Buzzards Bay: Water Quality Data. Mass. Water Res. Comm.:136pp.
- Meade, R.H., 1969: Landward transport of bottom sediments in estuaries of the Atlantic coastal plain. J. Sed. Pet. 39(1):222-234.
- Meade, R.H., 1972: Transport and deposition of sediment in estuaries. IN 'Environmental Framework of Coastal Plain Estuaries' (ed. B.W. Nelson). Mem. Geol. Soc. Am. 133:91-120.
- Meade, R.H., Sachs, P.L., Manheim, F.T., Hathaway, J.C., and Spencer, D.W., 1975: Sources of suspended matter in waters of the Middle Atlantic Bight. J. Sed. Pet. 45(1):171-188.
- Milliman, J.D. and Barretto, H.T., 1975: Background. IN 'Upper Continental Margin Sedimentation off Brazil' (eds. J. Milliman and C.P. Summerhayes). Contr. Sedimentol., Schweizerbart'sche, Stuttgart: 1-10.
- Moore, J.R., 1963: Bottom sediment studies, Buzzards Bay, Massachusetts. J. Sed. Pet. 33:511-538.
- New England Aquarium, 1973: Site selection and study of ecological effects of disposal of dredged materials in Buzzards Bay, Massachusetts. Unpublished Rpt, DACW33-77-C-0024:70pp.
- Nissenbaum, A. and Swaine, D.J., 1976: Organic matter--metal interactions in recent sediments: the role of humic substances. Geochim Cosmochim. Acta.
- Officer, C.B., 1976: Physical oceanography of estuaries. Oceanus 19(5):3-9.
- O'Hara, C.J., Oldale, R.N., and Robb, J.M., 1976: Late Tertiary, Pleistocene, and Holocene development of the inner continental shelf off southeastern Massachusetts. Geol. Soc. Am. Abstr. 8(6), November 1976, Denver, Colorado: 1033.
- Oostdam, B.L. and Jordan, R.R., 1972: Suspended sediment transport in Delaware Bay. IN 'Environmental Framework of Coastal Plain Estuaries' (ed. B. W. Nelson), Geol. Soc. Am. Mem. 133:143-150.

- Presley, B.J., Kolodny, J., Nissenbaum, A., and Kaplan, I.R., 1972: Early diagenesis in a reducing fjord, Saanich Inlet, British Columbia-trace element distribution in interstitial water and sediment. *Geochim. Cosmochim. Acta* 36:1073-1090.
- Pritchard, D.W., 1955: Estuarine circulation patterns. *Proc. Am. Soc. Civil Eng.*, 81:717.
- Rhoads, D.C., 1963. Rates of sediment reworking by Yoldia limatulina in Buzzards Bay, Massachusetts and Long Island Sound. *J. Sed. Pet.* 33:723-727.
- Rhoads, D.C., 1973: The influence of deposit-feeding benthos on the water turbidity and nutrient recycling. *Am. J. Sci.* 273:1-22.
- Rhoads, D.C. and Young, D.K., 1970: The influence of deposit-feeding organisms on sediment stability and community trophic structure. *J. Mar. Res.* 28:15-176.
- Roman, M.R., 1977: Tidal resuspension in Buzzards Bay, Massachusetts. II: Seasonal changes in the size distribution of chlorophyll, particle concentration, carbon, and nitrogen in resuspended particulate matter. *Est. Coast. Mar. Sci.*, (in press).
- Roman, M.R. and Tenore, K.R., 1977: Tidal resuspension of organic carbon and chlorophyll-a. *Est. Coast. Mar. Sci.*, (in press).
- Rutherford, F. and Church, T.M., 1976: Use of silver and zinc to trace sewage sludge dispersal in coastal waters. A.C.S. Symposium Series 18, 'Marine Chemistry in the Coastal Environment' (ed. T.M. Church): 440-452.
- Sanders, H.L., 1958: Benthic studies in Buzzards Bay. I. Animal-sediment relationships. *Lim. Oceanog.* 3:245-258.
- Schafer, J.P. and Hartshorn, J.H., 1965: The Quaternary of New England. IN 'The Quaternary of the United States' (ed. H.E. Wright and D.G. Frey). VII Contr. Int. Assoc. Quat. Res., Princeton Univ. Press: 113-128.
- Schnitker, D., 1974: Supply and exchange of sediments in rivers, estuaries, and the Gulf of Maine. *Mem. Inst. Geol. Bassin d'Aquitaine, No. 7, 'Relations Sedimentaires Entre Estuaires et Plateaux Continentaux'*: 81-86.

- Schubel, J.R., 1968: Suspended sediments of the northern Chesapeake Bay. Ches. Bay Inst. Tech. Rpt. 35: Ref. 68-2, The Johns Hopkins University: 264 pp.
- Schubel, J.R., 1971: The estuarine environment: estuaries and estuarine sedimentation. Short Course Lecture Notes, Am. Geol. Inst.: 340 pp.
- Skei, J.M., Price, N.B., Calvert, S.E., and Høltedahl, H., 1972: The distribution of heavy metals in sediments of Sorsfjord, West Norway. Water, Air and Soil Pollution 1:452-461.
- Spencer, D.W., 1966: Factor Analysis. Woods Hole Oceano. Inst. Ref. 66-39: 80 pp.
- Strahler, A.N., 1966: A geologist's view of Cape Cod. Am. Mus. Nat. Hist., Nat. Hist. Press, New York, 115 pp.
- Summerhayes, C.P., 1972: Geochemistry of continental margin sediments from northwest Africa. Chem. Geol., 10:137-156.
- Summerhayes, C.P., Melo, U., and Barretto, H.T., 1976: The influence of upwelling on suspended matter and shelf sediments off southeastern Brazil. J. Sed. Pet. (in press).
- Swift, D.J.P., 1976: Continental shelf sedimentation. IN 'Marine Sediment Transport and Environmental Management' (eds. D.J. Stanley and D.J.P. Swift). Wiley Intersci., New York: 311-350.
- Thomson, J., Turekian, K.K., and McCaffrey, R.J., 1975: The accumulation of metals in and release from sediments of Long Island Sound. IN 'Estuarine Research', Vol. I. (ed. L.E. Cronin): 28-44.
- Thornton, I., Watling, H., and Darracott, A., 1975: Geochemical studies in several rivers and estuaries used for oyster rearing. Sci. Tech. Environment, 4, Elsevier, Amsterdam: 325-345.
- Tourtelot, H.A., 1964: Minor-element composition and organic carbon content of marine and non-marine shales of Late Cretaceous age in the western interior of the United States. Geochim. Cosmochim. Acta 28:1579-1604.

Turekian, K.K. and Wedepohl, K.H., 1961: Distribution of the elements in some major units of the earth's crust. Bull. Geol. Soc. Am., 72:175-192.

U.S. Army Corps of Engineers, 1962: Clark Point, New Bedford, Massachusetts, Beach Erosion Control Study. House Doc. 584; 87th Congr., 2nd Session: 63 pp.

U.S. Army Corps of Engineers, 1970: Small navigation project--New Bedford and Fairhaven Harbor, Massachusetts--detailed project report: 48 pp.

U.S. Army Corps of Engineers, 1972: Final Environmental Impact Statement--Operation and Maintenance of New Bedford Hurricane Barrier: 14 pp.

Weil, C.B., 1976: A model for the distribution, dynamics, and the evolution of Holocene sediments and morphologic features of Delaware Bay. Ph.D. thesis, Univ. Delaware (unpublished): 408 pp.

Young, D.R., Johnson, J.N., Soutar, A., and Isaacs, J.D., 1973: Mercury concentrations in dated varved marine sediments collected off southern California. Nature 244:273-275.