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# Seafloor Environments Within the Boston Harbor–Massachusetts Bay Sedimentary System: A Regional Synthesis

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## ABSTRACT

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Modern seafloor sedimentary environments within the glaciated, topographically complex Boston Harbor and Massachusetts Bay area have been interpreted and mapped from an extensive collection of sidescan sonar records and supplemental marine geologic data. Three categories of environments are present that reflect the dominant long-term processes of erosion or nondeposition, deposition, and sediment reworking. (1) Environments of erosion or nondeposition comprise exposures of bedrock, glacial drift, coarse lag deposits, and possibly coastal plain rocks that contain sediments (where present) ranging from boulder fields to gravelly sands and occur in areas of relatively strong currents. (2) Environments of deposition contain fine-grained sediments ranging from muddy sands to muds that have accumulated in areas of predominantly weak bottom currents. (3) Environments of sediment reworking contain patches with textures ranging from sandy gravels to muds that have been produced by a combination of erosion and deposition in areas with variable bottom currents.

The distribution of sedimentary environments across the Boston Harbor–Massachusetts Bay area is extremely patchy. Locally, this patchiness is due either to modifications of bottom-current strength (caused by the irregular topography and differences in water depth) or to small-scale changes in the supply of fine-grained sediments. Regional patchiness, however, reflects differences in geologic and oceanographic conditions among the estuarine, inner shelf, and basinal parts of the sedimentary system. The estuarine part of the system (Boston Harbor) is a depositional trap for fine-grained sediments because it is protected from large waves, has generally weak and variable tidal currents, and receives a large supply of fine-grained detritus from natural and anthropogenic sources. The inner shelf, on the other hand, is largely an area of erosion or nondeposition due to sediment removal and redistribution during past sea-level changes, to sediment resuspension and winnowing by modern waves and currents, and to an inadequate supply of fine-grained sediments. The basinal part of the system (Stellwagen Basin) is mainly a tranquil depositional environment in which fine-grained sediments from several potential sources settle through the water column and accumulate under weak bottom currents.

This study indicates areas within the Boston Harbor–Massachusetts Bay sedimentary system where fine-grained sediments and associated contaminants are likely to be either moved or deposited. It also provides a guide to the locations and variability of benthic habitats.

ADDITIONAL INDEX WORDS: *Sedimentary environments, estuarine and coastal sedimentation, estuarine and coastal processes, seafloor texture.*

## INTRODUCTION

Boston Harbor and Massachusetts Bay form an interconnected sedimentary system that is located on the glaciated continental margin off the northeastern coast of the United Sates (Figure 1). This sedimentary system borders the metropolis of Boston, which has discharged wastes of various kinds into the marine environment since colonial times and which will soon begin (in 1995) the operation of a new ocean outfall that will discharge treated sewage effluent into Massachusetts Bay. Because of concerns about the effects of contaminants from waste disposal, a study was undertaken to outline the characteristics and distribution of the modern sedimentary environments on the seafloor within the Boston Harbor–Massachusetts Bay system. This study was part of a larger research program designed to understand the regional processes that distribute sediments and related contaminants (BOTHNER and BUTMAN, 1990; BOTHNER *et al.*, 1990; BUTMAN *et al.*, 1992).

The study area constitutes approximately 1,700 km$^2$. It is bounded on the north by Cape Ann, Massachusetts, on the west by the Massachusetts coast, on the south by Cape Cod Bay, and on the east by longitude 70°30′W (Figure 1).

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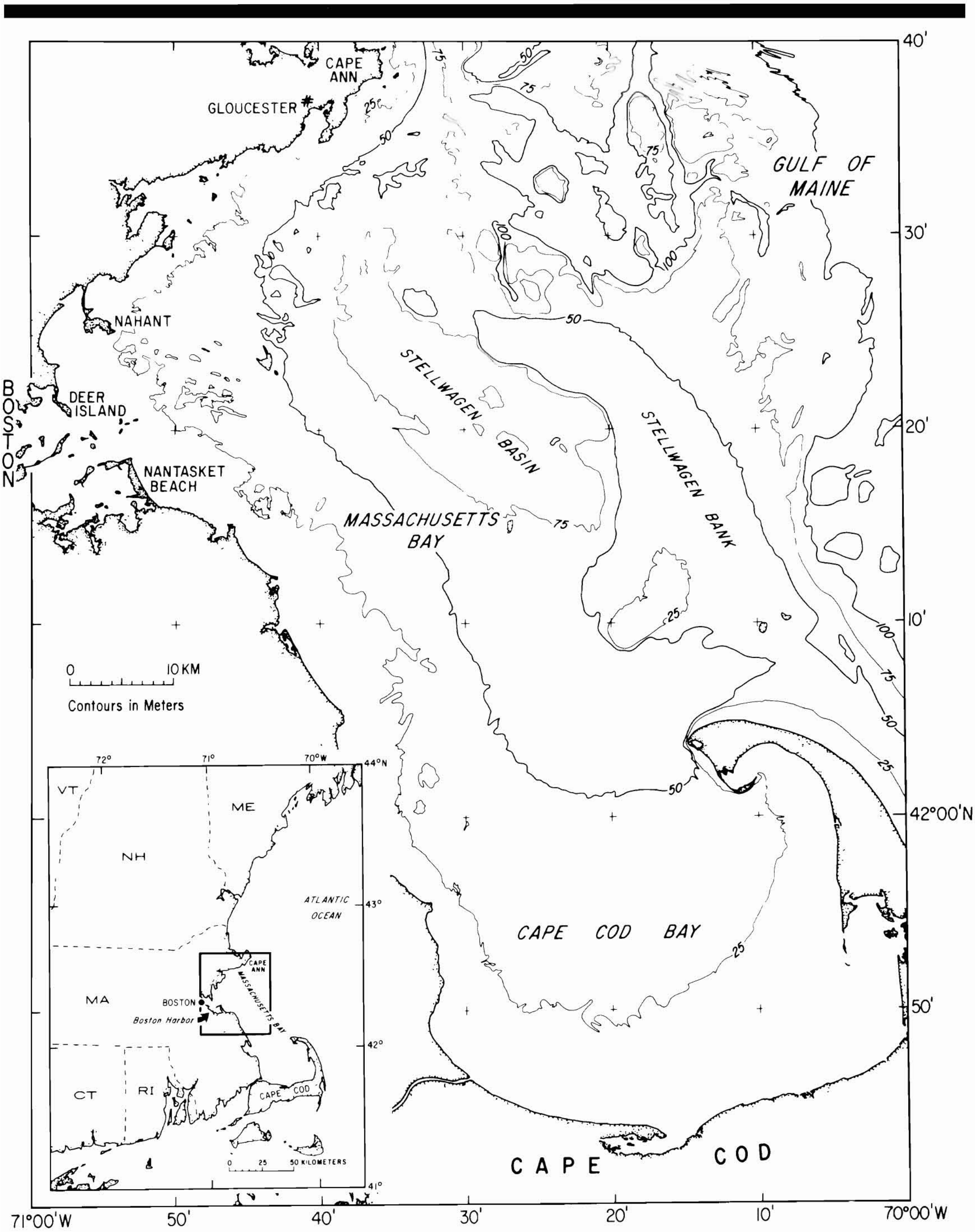


Figure 1. Location map of Boston Harbor and Massachusetts Bay area. Area outlined in inset map is presented in Figures 2–4, 8, 10, and 11.

The sedimentary system within the study area includes an estuary, an inner shelf area, and a deep basin (Figure 1). The estuarine part of the system is comprised of Boston Harbor. It is a shallow embayment that has two main entrances, which are located south of Deer Island and north of Nantasket Beach (Figures 1 and 2). The inner shelf region extends offshore from the coastline to water depths of 50 m. The shelf ranges in width from 4 km off Cape Ann to 20 km off Boston Harbor. Farther to the east, Stellwagen Basin forms a large curvilinear depression that has water depths which are greater than 50 m. As used herein, Stellwagen Basin includes both the floor and the margins of the basin. The margins of the basin are formed by the transitional slope from the inner shelf on the west and by Stellwagen Bank and its discontinuous northern extension on the east (Figures 1 and 2).

Prior to this study, KNEBEL *et al.* (1991) and KNEBEL (1993) outlined the characteristics and distributions of modern sedimentary environments within Boston Harbor and on the inner shelf. Only the major findings from these earlier works have been included here. The reader is urged to consult the full text of these earlier reports for a more definitive treatment of the data, for resulting interpretations, and for appropriate supporting references. In addition to the previous findings, the present paper incorporates new data and interpretations for Stellwagen Basin.

Previous studies of Stellwagen Basin have described the general grain size and composition of the bottom sediments. Regional maps of surficial sediment types and constituents have been presented by TROWBRIDGE and SHEPARD (1932), ROSS (1970), SCHLEE and PRATT (1970), TRUMBULL (1972), SCHLEE *et al.* (1973), and NATIONAL OCEAN SERVICE (1986a,b). Localized studies of sediment texture and composition include those by GILBERT (1975) and SCIENCE APPLICATIONS INTERNATIONAL CORPORATION (1988). TUCHOLKE *et al.* (1972) mapped the acoustic penetrability of the bottom across the basin as an aid in determining the surficial sediment distribution. Generalized maps showing outcrops and subcrops of geologic units within the basin have been completed by OLDALE *et al.* (1973) and OLDALE and BICK (1987). TUCHOLKE and HOLLISTER (1973) described and interpreted the sequence of sediments down to depths of 22 m beneath the basin floor. Studies of the bottom character at waste disposal sites within the basin based on local sidescan-sonar surveys have been presented by LOCKWOOD *et al.* (1982), CURTIS and MARDIS (1984), HUBBARD *et al.* (1988), KEITH *et al.* (1992), and WILEY *et al.* (1992).

In this paper, we present a synthesis of the characteristics and distribution of modern sedimentary environments within the Boston Harbor–Massachusetts Bay sedimentary system. We also discuss the major local and regional factors that have controlled the complex distribution of environments in this area and outline some implications from this work regarding the locations and variability of contaminants and benthic habitats within the system.

## GEOLOGIC SETTING

### Geologic History

The Boston Harbor–Massachusetts Bay area has had a complex history of glaciation and sea-level change. During Pleistocene time, glaciers scoured the bedrock across the region and covered most of the resulting irregular surface with drift of two different ages. The older drift is pre-Wisconsinan in age (NEWMAN *et al.*, 1990; OLDALE and COLMAN, 1992) and consists primarily of a compact till that contains cobbles and boulders. The younger drift was deposited in late Wisconsinan time during the retreat of the marine-based Laurentide ice sheet (OLDALE, 1986; OLDALE and BICK, 1987; OLDALE *et al.*, 1990) and includes till, subaqueous outwash sand and gravel, and glaciomarine mud (KAYE, 1982; OLDALE and BICK, 1987; RENDIGS and OLDALE, 1990). Stellwagen Bank also was created during late Wisconsinan time by glacial outwash-stream and delta deposits (OLDALE, 1993).

After the retreat of the Laurentide ice sheet, isostatic rebound of the depressed crust caused the shoreline to regress across the present inner shelf area. This produced a sea-level lowstand about 12,000 yr BP that reached about −43 m (compared to present sea level) (OLDALE *et al.*, 1993). The area was then resubmerged in response to the eustatic rise of sea level, and the shoreline reached −3 m or less about 3,000 yr BP (KAYE and BARGHOORN, 1964; OLDALE, 1986; OLDALE *et al.*, 1993). For the past 3,000 yr, the rate of sea-level rise has been slow (less than 1 m per 1,000 yr), and the surface sediments have been subjected to a wave and current regime similar to that at present (KNEBEL *et al.*, 1991).

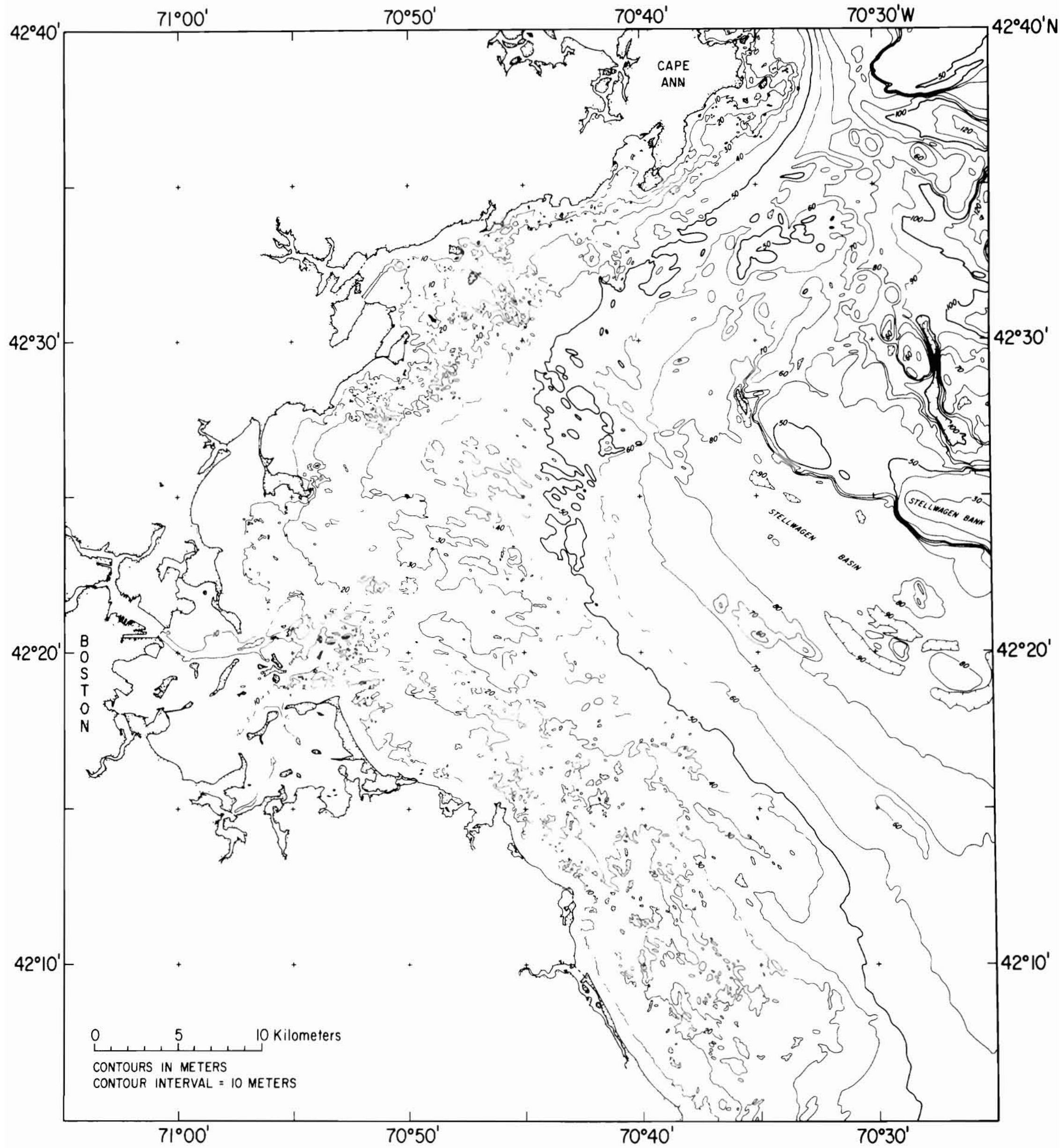


Figure 2. Bathymetric map of Boston Harbor and Massachusetts Bay. Depth contours from NATIONAL OCEAN SERVICE (1986a,b).

## Bathymetry

The bottom topography of Boston Harbor is characterized by extensive subtidal flats (< 4 m deep) near the shore and by a complex assemblage of discontinuous ridges and depressions elsewhere (KNEBEL *et al.*, 1991). Water depths exceed 10 m only within large northeast-trending depressions that underlie the two main harbor entrances (Figure 2).

The seafloor on the inner shelf is hummocky and rough (Figure 2). Near the shore (water depths

< 30 m), the bottom is characterized by ubiquitous knolls and highs separated by isolated depressions. Broad irregular lows interrupt this rugged nearshore topography only near the entrances to Boston Harbor, in the area around Nahant, and southwest of Gloucester (Figures 1 and 2). At greater water depths (30–50 m), the topography is smoother.

The bathymetry of Stellwagen Basin changes from smooth to irregular in going from south to north (Figure 2). In the south, the basin has a broad, flat floor (water depths > 80 m), except where some isolated knolls and depressions interrupt the surface, and its flanks are well defined. In the north, on the other hand, the basin has a narrow, disjointed floor (water depths 60–70 m) and irregular, poorly defined flanks (Figure 2).

## DATA AND METHODS

This report is based on five sidescan-sonar surveys (Figure 3). These include: (1) a regional survey conducted by the Raytheon Company located across the inner shelf (WILLETT, 1972; COOKS *et al.*, 1976); (2) a survey by the U.S. Geological Survey located within Boston Harbor and at local sites on the inner shelf (RENDIGS and OLDALE, 1990; KNEBEL *et al.*, 1991); (3) a nearshore survey by FITZGERALD *et al.* (1990) located just east of Deer Island and Nantasket Beach; (4) a detailed survey (with nearly complete seafloor coverage) by the U.S. Geological Survey located within a 7.4 by 9.3 km area of the inner shelf (see dashed rectangle Figure 3; BOTHNER *et al.*, 1990, 1992; BUTMAN *et al.*, 1990a, 1992); and (5) a reconnaissance survey by the U.S. Geological Survey located across Stellwagen Basin. During these surveys, sonographs were obtained along 1,930 km of tracklines using sidescan-sonar systems that operated at frequencies of 100 or 105 kHz and scanned 75 to 150 m to each side of the ship's track (WILLETT, 1972; BUTMAN *et al.*, 1990a; FITZGERALD *et al.*, 1990; KNEBEL *et al.*, 1991; BOTHNER *et al.*, 1992).

In addition to the sonographs, this study utilized a large amount of supplemental marine geologic data (Figure 3). These data included: (1) grab samples, bottom photographs, cores, and video-camera transects collected at 470 stations; (2) high-resolution seismic-reflection (boomer) profiles collected concurrently with the five sonograph surveys (WILLETT, 1972; FITZGERALD *et al.*, 1990; KNEBEL *et al.*, 1991; BOTHNER *et al.*, 1992); and (3) previous maps of bottom-sediment types and constituents (cited previously), especially textural data that were overprinted on the regional bathymetry (National Ocean Service, 1986a,b).

Four sonograph patterns were used in conjunction with the supplemental marine geologic data to construct a reconnaissance map of sedimentary environments across the study area (Figure 4). These characteristic patterns (which are described in the next section) have been identified and interpreted by KNEBEL *et al.* (1991) and KNEBEL (1993) and found to be strongly correlated throughout the study area with physiographic features, topographic changes, bottom-sediment types, and water depth. Such correlations allowed us to infer the distributions of patterns and environments across similar bottom features and in areas where the trackline and sample coverage were sparse. Extrapolation was especially useful for determining the distribution of environments in the nearshore area between Nahant and Cape Ann. Here, the rugged bathymetry and coarse bottom sediment types were similar to those found in nearshore areas which were surveyed farther south (KNEBEL, 1993).

## CHARACTERISTICS AND LOCATIONS OF SEDIMENTARY ENVIRONMENTS

In the following sections, we outline the characteristics and locations of three categories of sedimentary environments: (1) erosion or nondeposition, (2) deposition, and (3) sediment reworking (Figures 5–11). It should be noted that the characteristics of these environments reflect the effects of dominant long-term processes operating there. At times, atypical processes (such as storm erosion within depositional areas) may affect the seafloor within each environment. Such unusual events, however, could not be recognized from the sidescan-sonar data because they did not leave a permanent imprint on the bottom.

### Environments of Erosion or Nondeposition

Areas of erosion or nondeposition appear on the sonographs either as patterns with isolated reflections or as patterns of strong backscatter (KNEBEL *et al.*, 1991; KNEBEL, 1993) (Figures 5 and 6). Patterns with isolated reflections have either a "blotchy" or a "speckled" appearance, and they depict outcrops of bedrock, till, coarse glacial drift, and possibly coastal plain rocks (in Massachusetts Bay). Where sediments are present in these areas, they range from boulder fields to

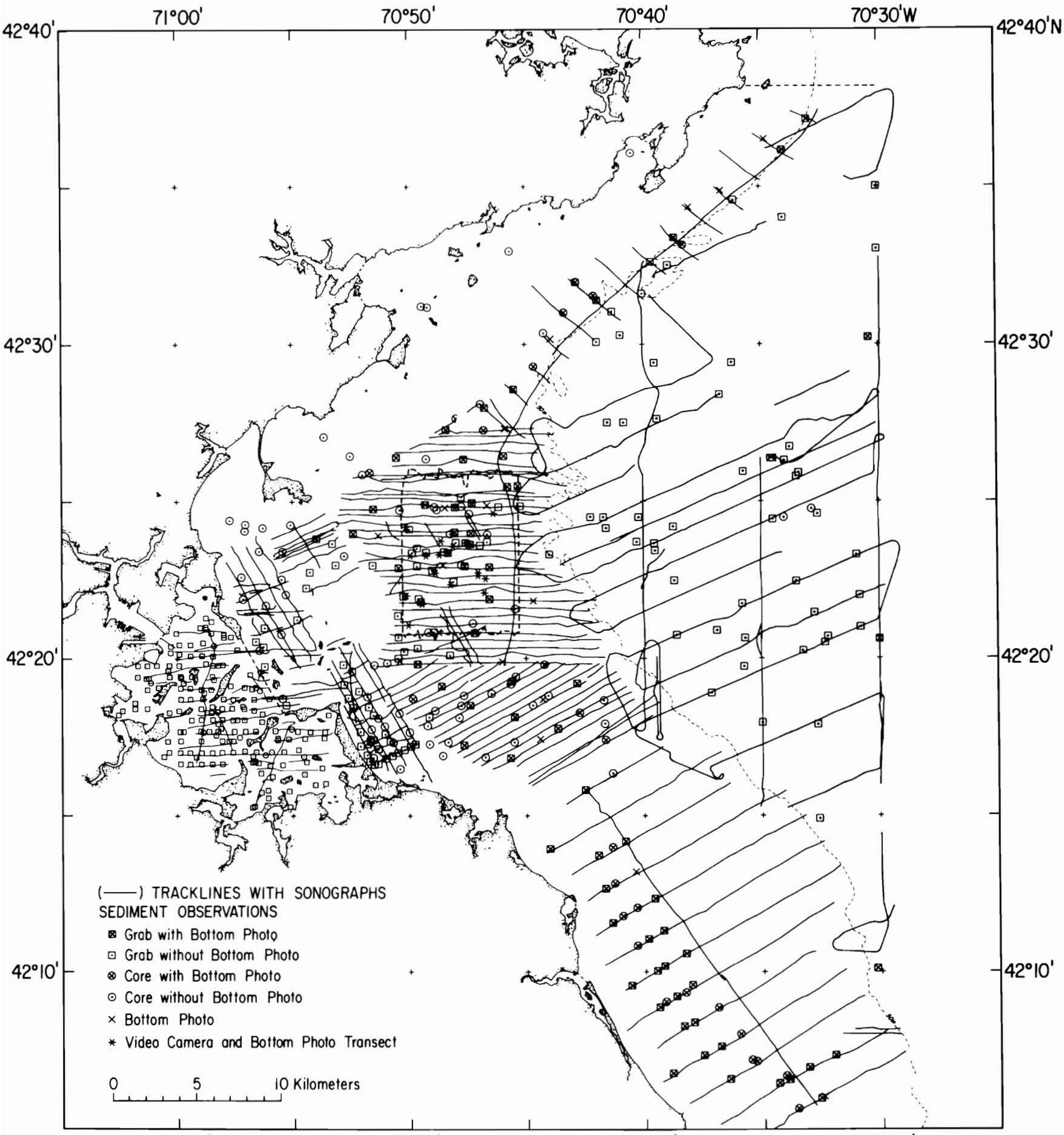


Figure 3. Locations of sidescan sonographs and supplemental sedimentary observations used to infer the characteristics and distributions of modern sedimentary environments within the Boston Harbor–Massachusetts Bay sedimentary system. Sonographs were collected during five surveys that are outlined in the text. Sediment observations from studies or compilations by Mencher *et al.* (1968), Willett (1972), Meisburger (1976), Fitzgerald (1980), Bothner *et al.* (1990, 1992), Fitzgerald *et al.* (1990), and U.S. Geological Survey (1993). Dashed rectangle on the inner shelf defines detailed survey area in which tracklines were spaced 150 m apart (not shown individually), thus providing nearly complete sonograph coverage of the seafloor. Dashed lines define the eastern limit of Boston Harbor and the northern limit of the study area off Cape Ann.

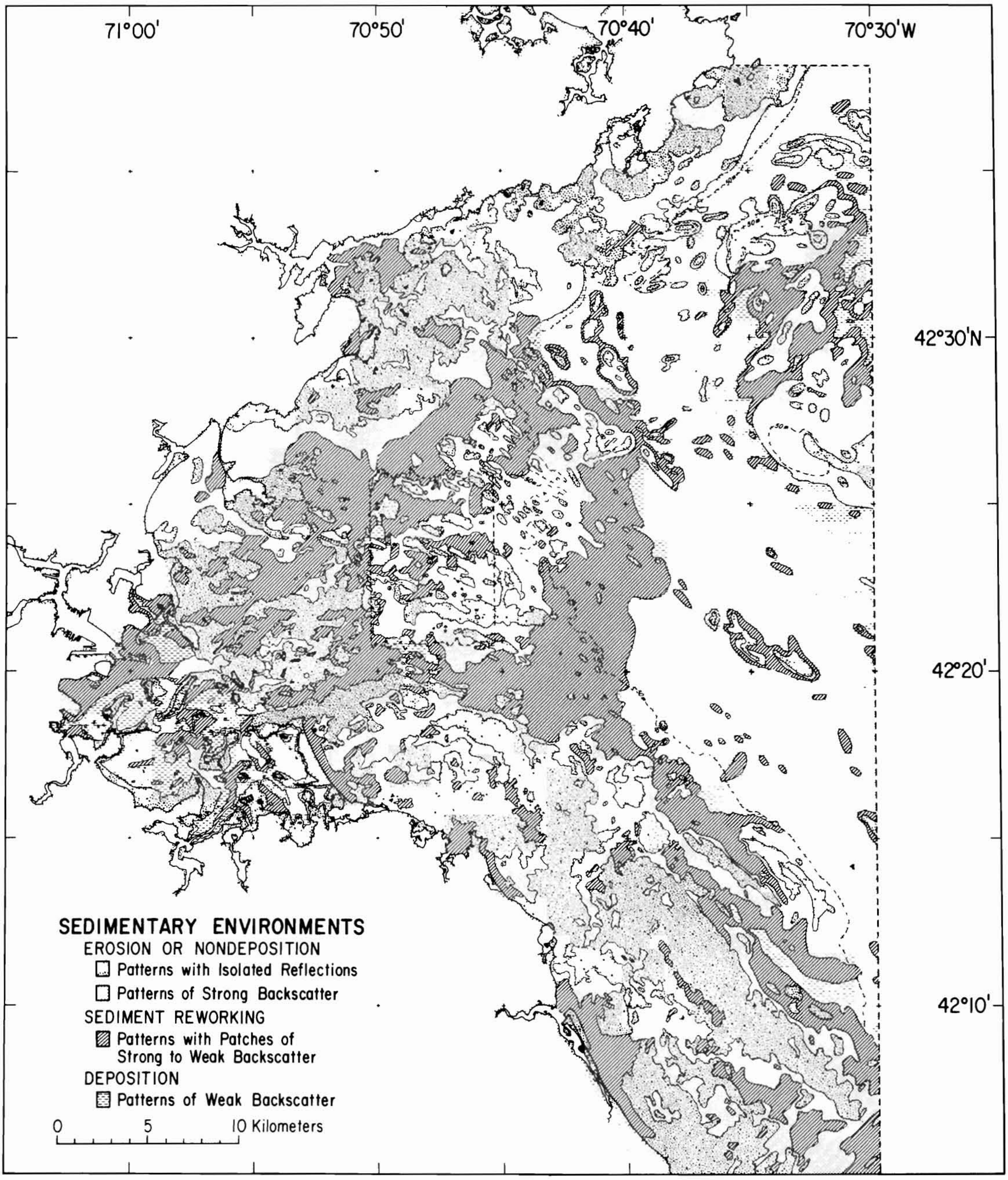


Figure 4. Map showing the distribution of sonograph patterns and sedimentary environments across the Boston Harbor–Massachusetts Bay sedimentary system. Dashed 50-m isobath delineates the offshore limit of the inner shelf in Massachusetts Bay. Dashed rectangle on the inner shelf defines detailed survey area.

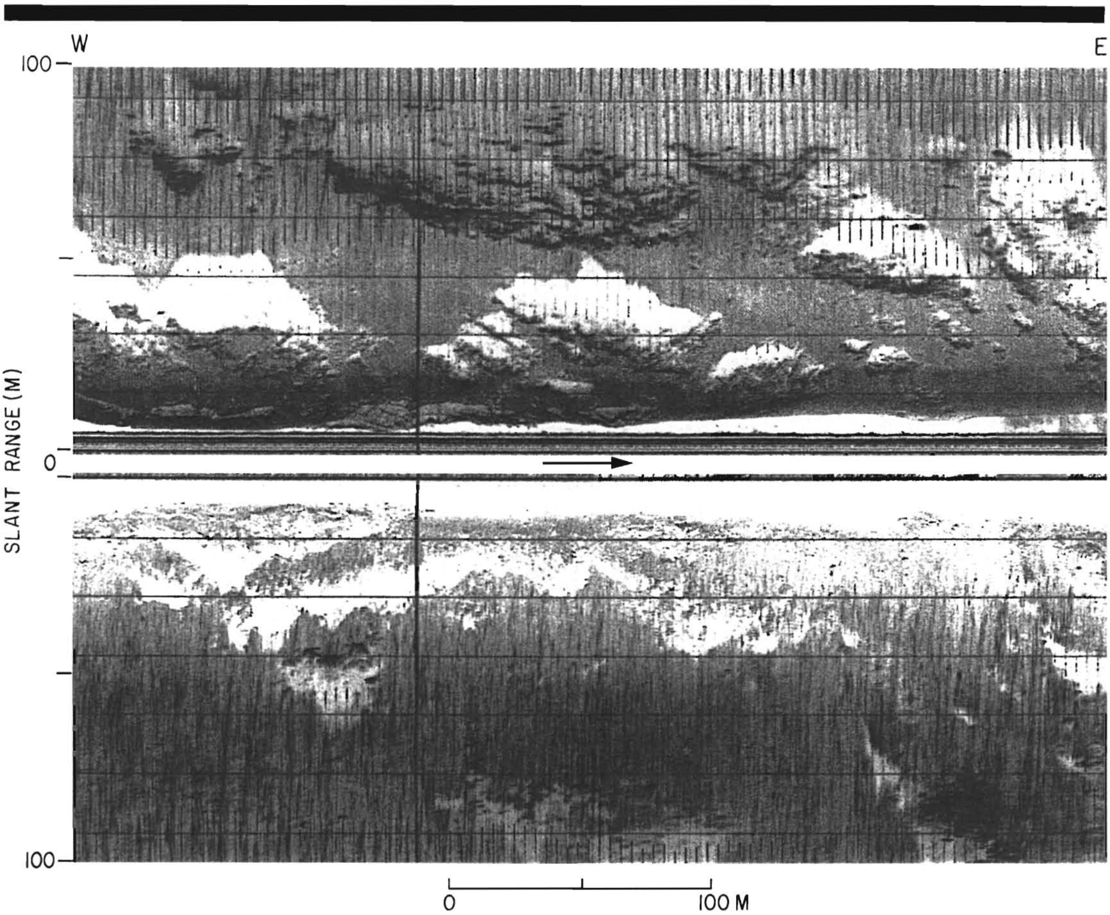


Figure 5. Sonograph showing pattern with isolated reflections produced by bedrock that crops out on the inner shelf of Massachusetts Bay near the southern entrance to Boston Harbor. Blotchy patterns such as this represent environments of erosion or nondeposition and are characterized by relatively large acoustic targets that have discernible topographic relief and produce acoustic shadows (light areas). Arrow shows direction of ship travel. The sonograph is uncorrected for lateral distortion due to the slant range of sound. From KNEBEL *et al.* (1991).

poorly sorted gravels and sandy gravels (Figures 6 and 7). Patterns of strong backscatter, on the other hand, appear as nearly uniform dark records that have been produced by winnowed lag deposits of gravels and medium-to-coarse sands (Figures 6 and 7). These deposits often include boulders, and they contain megaripples (wave lengths 4 m or less) at some locations on the inner shelf.

Environments of erosion or nondeposition are dominant across the inner shelf (KNEBEL, 1993), whereas they are areally restricted both in Boston Harbor (KNEBEL *et al.*, 1991) and in Stellwagen Basin (Figures 4 and 8). On the inner shelf, these environments are present over extensive areas of the irregular topography near the coast (water depths $< 30$ m) and in large patches farther offshore. In these locations, they commonly are found either on the crests and upper flanks of bathymetric highs (Figure 6) or within constricted depressions between highs. In Boston Harbor, these environments are limited primarily to small areas around the islands, along the southern mainland shore, and within large tidal channels. Likewise, in Stellwagen Basin, they are restricted primarily to scattered patches located (1) atop Stellwagen Bank and its northern extension, (2) over small knolls that protrude above the basin floor, and

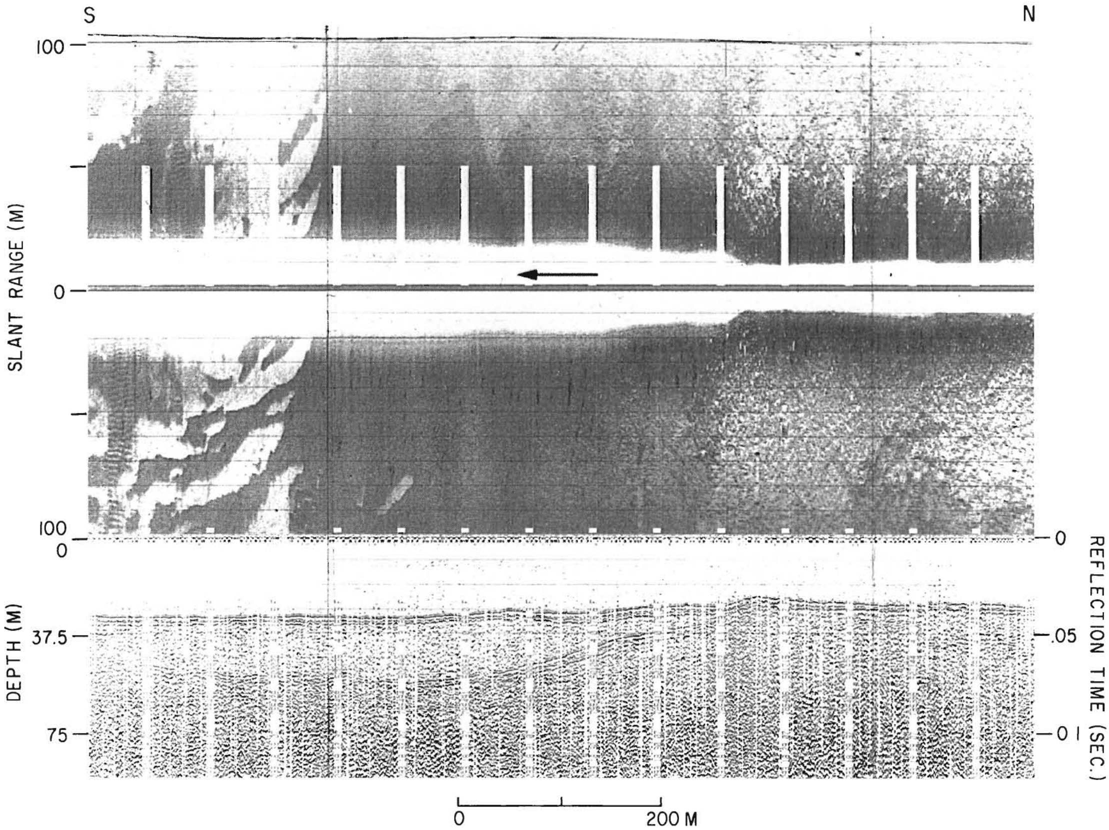


Figure 6. (Top) Sonograph from the inner shelf of Massachusetts Bay which shows the change from pattern with isolated reflections ("speckled") atop a bathymetric high (on the north) to pattern of strong backscatter (uniformly dark) on the flank of the high to pattern of strong to weak backscatter (dark and light) within the adjacent broad low (on the south). Patterns with isolated reflections and patterns of strong backscatter represent environments of erosion or nondeposition, whereas patterns with patches of strong to weak backscatter represent environments of sediment reworking. Megaripples are evident in some patches of strong backscatter within the bathymetric low. Sediments range from bouldery gravels on the crest of the high to winnowed gravelly sands on the flank to a patchy mosaic of gravelly sands and sandy muds in the low. Arrow shows direction of ship travel. The sonograph has not been corrected for lateral distortion due to slant range of sound. (Bottom) High-resolution seismic-reflection (boomer) profile showing outcrop of glacial drift (probably till) atop the bathymetric high where bouldery sonograph pattern with isolated reflections was found. From KNEBEL (1993).

(3) across prominences located along the irregular transitional slope (water depths of 50–60 m) northeast of Boston Harbor.

### Environments of Deposition

Environments of deposition are depicted on the sonographs as patterns of weak backscatter that are featureless except for broad changes in acoustic return (KNEBEL *et al.*, 1991; KNEBEL, 1993) (Figure 9). Such patterns are produced by relatively fine-grained bottom sediments that range in texture from muddy sand to sandy muds to muds (Figure 7).

Environments of deposition predominate in Boston Harbor and in Stellwagen Basin, but they are sparse on the inner shelf (Figure 10). In Boston Harbor, depositional environments are present primarily over the extensive subtidal flats in the southern half of the area and within bathymetric lows situated away from the main tidal channels (KNEBEL *et al.*, 1991). Within Stellwagen Basin, depositional environments are preva-

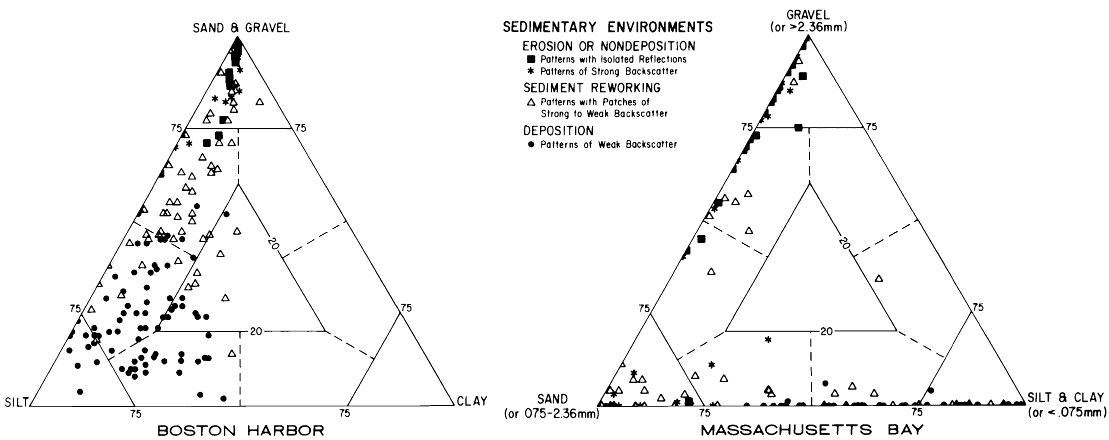


Figure 7. Ternary diagrams showing the texture of surface sediments (from grab samples) within the three sedimentary environments identified by sonograph patterns in the Boston Harbor–Massachusetts Bay sedimentary system. Boston Harbor encompasses the estuarine part of the system, whereas Massachusetts Bay includes both the inner shelf and Stellwagen Basin. The apexes of the diagrams represent 100% of stated textural component. Differences in textural components between the Boston Harbor and Massachusetts Bay diagrams reflect differences in grain-size analyses for available samples. Original grain-size data are from MENCHER *et al.* (1968), WILLETT (1972), FITZGERALD (1980), BOTHNER *et al.* (1990, 1992), FITZGERALD *et al.* (1990), and U.S. GEOLOGICAL SURVEY (1993). The textural data for environments of erosion or nondeposition represent only sediments that were sampled; boulders observed on the seafloor have not been accounted for.

lent along the basin floor and over most of the western transitional slope, except for an 18-km-long section northeast of Boston Harbor (Figure 10). On the inner shelf, however, depositional environments are restricted to scattered small lows located within the rugged nearshore topography and to narrow patches found along the offshore margin of the shelf in water depths of 40–50 m (KNEBEL, 1993).

### Environments of Sediment Reworking

Environments of sediment reworking are characterized by sonograph patterns with patches of strong to weak backscatter which range in size from a few meters to more than 200 m (KNEBEL *et al.*, 1991; KNEBEL, 1993) (Figures 6 and 9). These patterns reflect textural changes in the bottom sediments that have been produced by a combination of erosion and deposition. Patches of strong backscatter (dark in Figures 6 and 9) depict erosional features that have been created either by exposing relatively coarse substrata or by winnowing away the finer sediments, whereas patches of weak backscatter (light areas) depict parts of a thin, discontinuous layer of relatively fine-grained sediments that have accumulated over or around the coarser-grained patches. Not surprisingly, sediments in reworked areas range from gravels to sands to muds and include textures that are characteristic of both erosional and depositional environments (Figure 7).

Environments of sediment reworking have variable distributions within each part of the sedimentary system (Figure 11). In Boston Harbor, environments of sediment reworking are present mainly within the northern third of the area, where they generally are uncorrelated with the bottom topography (KNEBEL *et al.*, 1991). On the inner shelf, reworked sediments are found primarily as follows: (1) in the southeastern part of the area in water depths greater than 30 m; (2) along two irregular bands that extend eastward across the shelf from the harbor entrances; and (3) at small sites located off mainland rivers (Figure 11). At these various locations, reworked sediments usually are found within bathymetric lows and on the lower flanks of ridges and knolls (KNEBEL, 1993) (Figures 6 and 9). In Stellwagen Basin, environments of sediment reworking are present as follows: (1) along the irregular transitional slope northeast of Boston Harbor (water depths 50–72 m); (2) on the crests and flanks of scattered small knolls that rise above the basin floor; and (3) within local depressions found atop the rugged northern extension of Stellwagen Bank (water depths 60–80 m).

## DISCUSSION

In the following discussion, we outline the major local and regional conditions that have created the patchy distribution of sedimentary environments within and among the estuarine, inner shelf, and basinal parts of the sedimentary system (Figure 12).

### Boston Harbor

The prevalence of environments of deposition and sediment reworking within Boston Harbor indicates that it is an area where fine-grained sediments are being trapped (Figures 10 and 11). Long-term deposition is evident over 51% of the harbor floor. Another 29% of the bottom is covered by reworked sediments which contain patches of fine-grained sediments.

Deposition of fine-grained sediments in the harbor is largely the result of its protected nature, generally weak and variable tidal currents, and relatively large supply of fine-grained sediments (Figure 12). The harbor is a nearly enclosed embayment that contains numerous islands. This geographic setting not only limits the fetch for local wave generation, but it effectively shelters the harbor from waves and swell coming from Massachusetts Bay. Consequently, the harbor generally has low wave heights throughout the year, and erosion and winnowing of the bottom by waves is limited to small, shallow areas found along mainland and insular shores (BUMPUS *et al.*, 1951, 1953; FITZGERALD, 1980; KNEBEL *et al.*, 1991) (Figure 8).

In the absence of large waves, deposition of fine-grained sediments within the harbor is facilitated by generally weak and variable tidal currents. Deposition over the extensive subtidal flats in the southern half of the harbor (Figure 10), for example, occurs where tidal currents typically do not exceed 15 cm/sec (U.S. COAST AND GEODETIC SURVEY, 1953; NATIONAL OCEAN SURVEY, 1977; BUTMAN *et al.*, 1992). In most other places, depositional environments are restricted to bathymetric lows that either are located away from the main tidal channels or are sheltered from strong tidal currents by islands or points of land (such as the area west of Deer Island; Figure 10) (KNEBEL *et al.*, 1991; SIGNELL and BUTMAN, 1992). In these locations, the near-bottom tidal currents generally do not exceed 20 cm/sec (NATIONAL OCEAN SURVEY, 1977; BUTMAN *et al.*, 1992). In areas of sediment reworking, on the other hand, maximum tidal currents have a wide range of speeds (20–67 cm/sec), are spatially variable, and generally are intermediate in strength between those typical of environments of erosion and deposition (NATIONAL OCEAN SURVEY, 1977; SIGNELL and BUTMAN, 1992). Such variable currents produce an intermediate state of bottom stress which, if perturbed by other forces (such as wind-driven currents), can result in either erosion or deposition (KNEBEL *et al.*, 1991). The accumulation of patches of fine-grained sediments within reworked areas is probably a manifestation of such fluctuations in current strength. In general, the weak and variable currents in areas of deposition and reworking stand in contrast to those found in areas of erosion or nondeposition, which are located primarily within large tidal channels. Here, the near-bottom tidal currents typically exceed 50 cm/sec and, in places, reach 77 cm/sec (U.S. COAST AND GEODETIC SURVEY, 1953; MENCHER *et al.*, 1968; NATIONAL OCEAN SURVEY, 1977; FITZGERALD, 1980; SIGNELL and BUTMAN, 1992). Such currents are strong enough to winnow away the fine-grained sediments, leaving only a lag of gravel and medium-to-coarse sand (KNEBEL *et al.*, 1991).

Deposition in Boston Harbor also reflects an abundant supply of fine-grained sediments from natural and anthropogenic sources. Fluvial discharge into the harbor area contributes about 12,700 metric tons of suspended solids each year and, up until the end of 1991, the annual amount of suspended solids discharged with municipal wastes (mostly sewage) was about 85,000 metric tons (MENZIE-CURA AND ASSOCIATES, INC., 1991). Other sources that contribute sediments to the harbor include: (1) the erosion and winnowing of glacial drift and till along insular and mainland shorelines (CROSBY, 1903; PHIPPS, 1964; MENCHER *et al.*, 1968); (2) the possible movement of sediments into the harbor from Massachusetts Bay during periods of landward bottom flow (see observations by FITZGERALD, 1980; BOTHNER *et al.*, 1988; BUTMAN and FRY, 1991; GEYER *et al.*, 1992); and (3) the production of biological skeletal debris and fecal particles in the water column (FITZGERALD, 1980). Collectively, the supply from all sources could easily account for the estimated range of 4,000 to 46,000 metric tons of fine-grained sediments that accumulate each year inside the harbor (KNEBEL *et al.*, 1991).

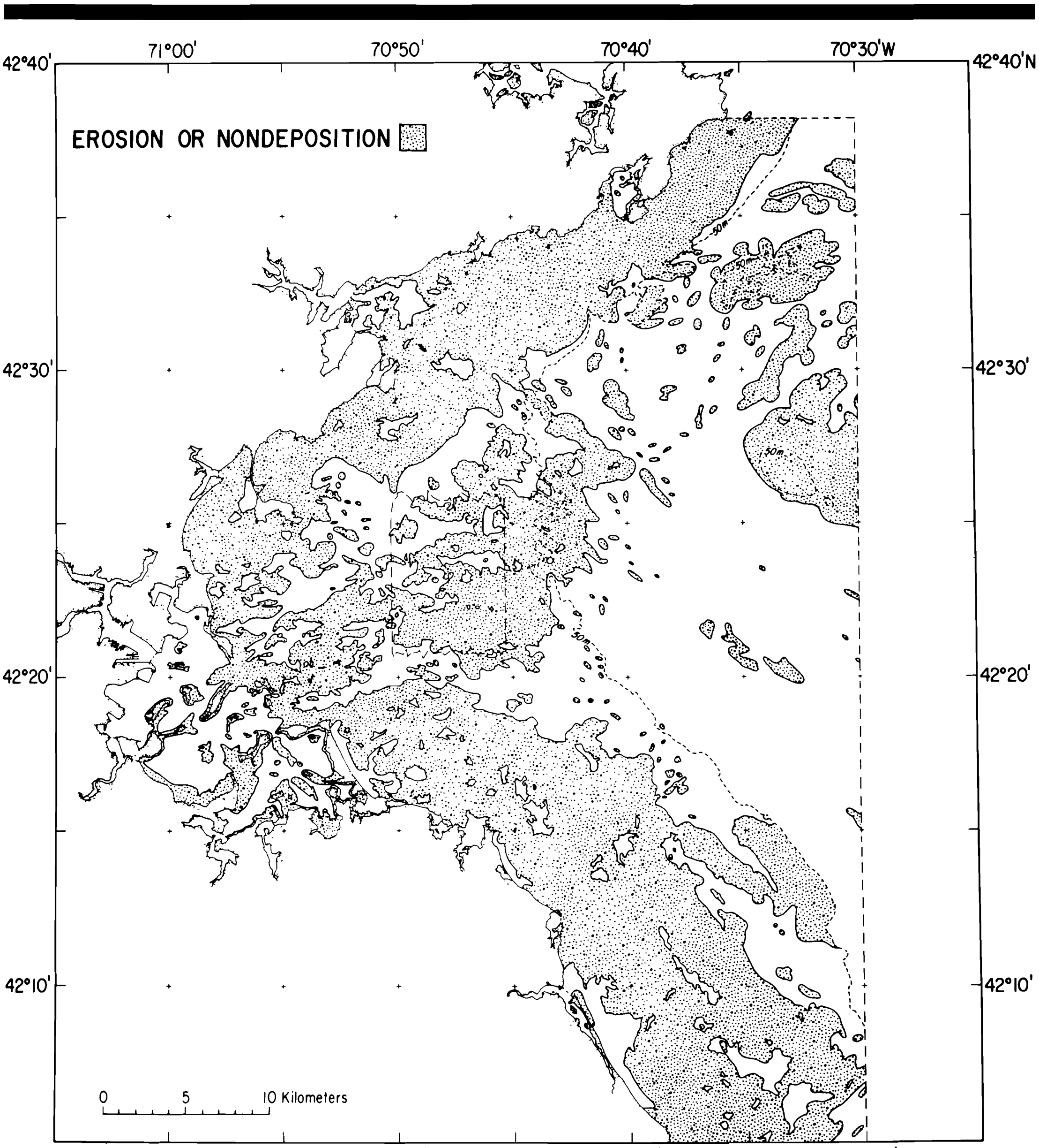


Figure 8. Map showing the distribution of environments of erosion or nondeposition across the Boston Harbor–Massachusetts Bay sedimentary system.

## Inner Shelf

The inner shelf is predominantly an area of long-term sediment erosion or nondeposition where only small amounts of fine-grained sediments accumulate. Environments of erosion or nondeposition occupy 71% of the seafloor in this area, whereas environments of sediment reworking and deposition occupy just 26% and 3% of the bottom, respectively (Figures 8, 10, 11).

The dominance of environments of erosion or nondeposition on the inner shelf mainly reflect:

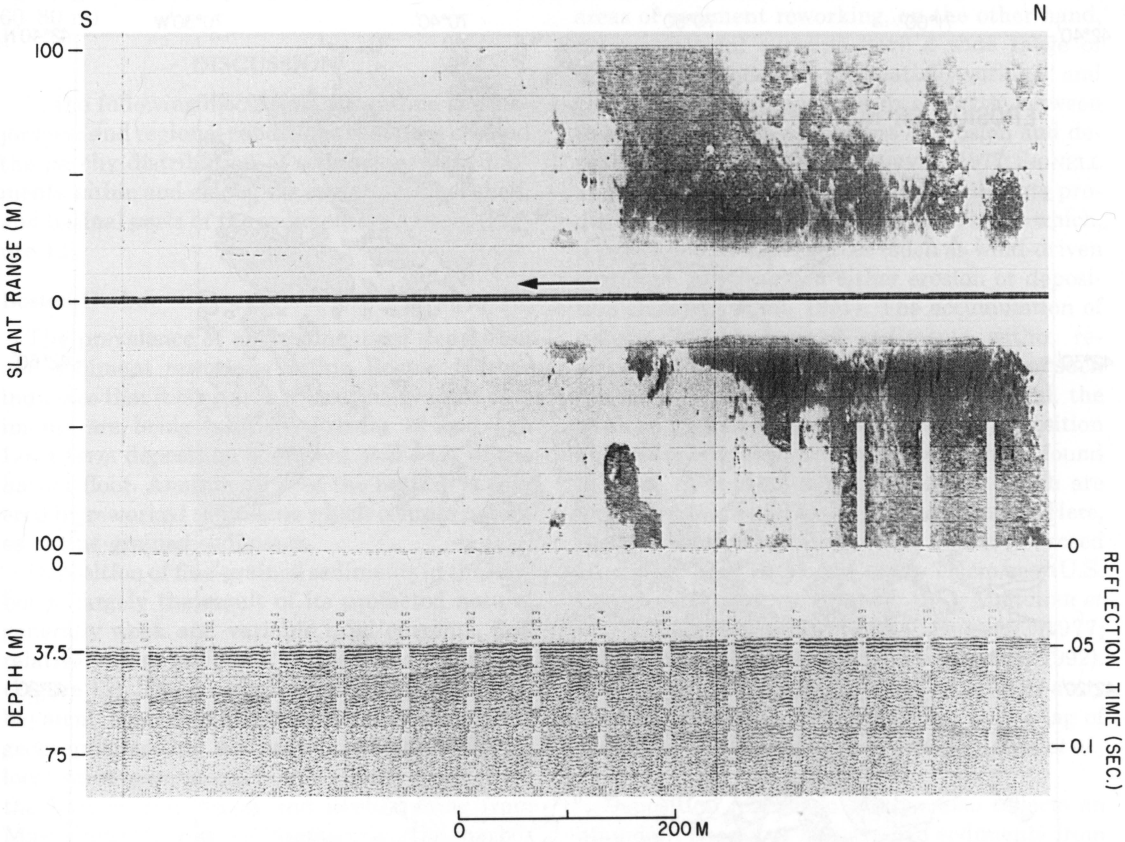


**Figure 9.** (Top) Sonograph from the inner shelf of Massachusetts Bay which shows the change from pattern with patches of strong to weak backscatter (dark and light) on the north to pattern of weak backscatter (uniformly light) on the south. The patchy pattern of strong to weak backscatter, which represents an environment of sediment reworking, is located on the lower flank of a broad knoll and extends onto the floor of the adjacent bathymetric low; it contains sediments ranging from gravelly sands to sandy muds. Boulders are evident within some patches of strong backscatter. The pattern of weak backscatter, which represents an environment of deposition, covers the broad low and contains muds and sandy muds. Arrow shows direction of ship travel. The sonograph has not been corrected for lateral distortion due to slant range of sound. (Bottom) High-resolution seismic-reflection (boomer) profile showing outcrop or subcrop of coarse glacial drift (probably till) in area where sonograph pattern with patches of strong to weak backscatter was found; patches of strong backscatter are sites where the drift is exposed at the seafloor. From KNEBEL (1993).

(1) sediment scour and redistribution during past sea-level fluctuations; (2) sediment resuspension and winnowing by modern waves and currents; and (3) a small supply of fine-grained sediments (Figure 12). During the late Wisconsinan regression of sea level and subsequently during the Holocene transgression, the inner shelf surface was subjected either to two passages of the surf zone or to higher-energy shallow marine processes (depending on the location relative to the sea-level lowstand). As the nearshore zone migrated across the shelf, the tops of highs were eroded, producing either bedrock outcrops or lag deposits derived from coarse glacial drift. Sand and gravel (removed from the highs) were deposited in thin (< 2 m) sheets in peripheral areas, with the sedimentation patterns determined by the bathymetry, the characteristics of the original sediments, and the nature of the bottom currents (WILLETT, 1972; COOKS *et al.,* 1976; MEISBURGER, 1976; KNEBEL, 1993). By the time sea level approached its present position about 3,000 yr BP, bedrock and bouldery lag armored most of the shelf surface.

Modern waves and currents continue to resuspend and winnow the bottom sediments on the

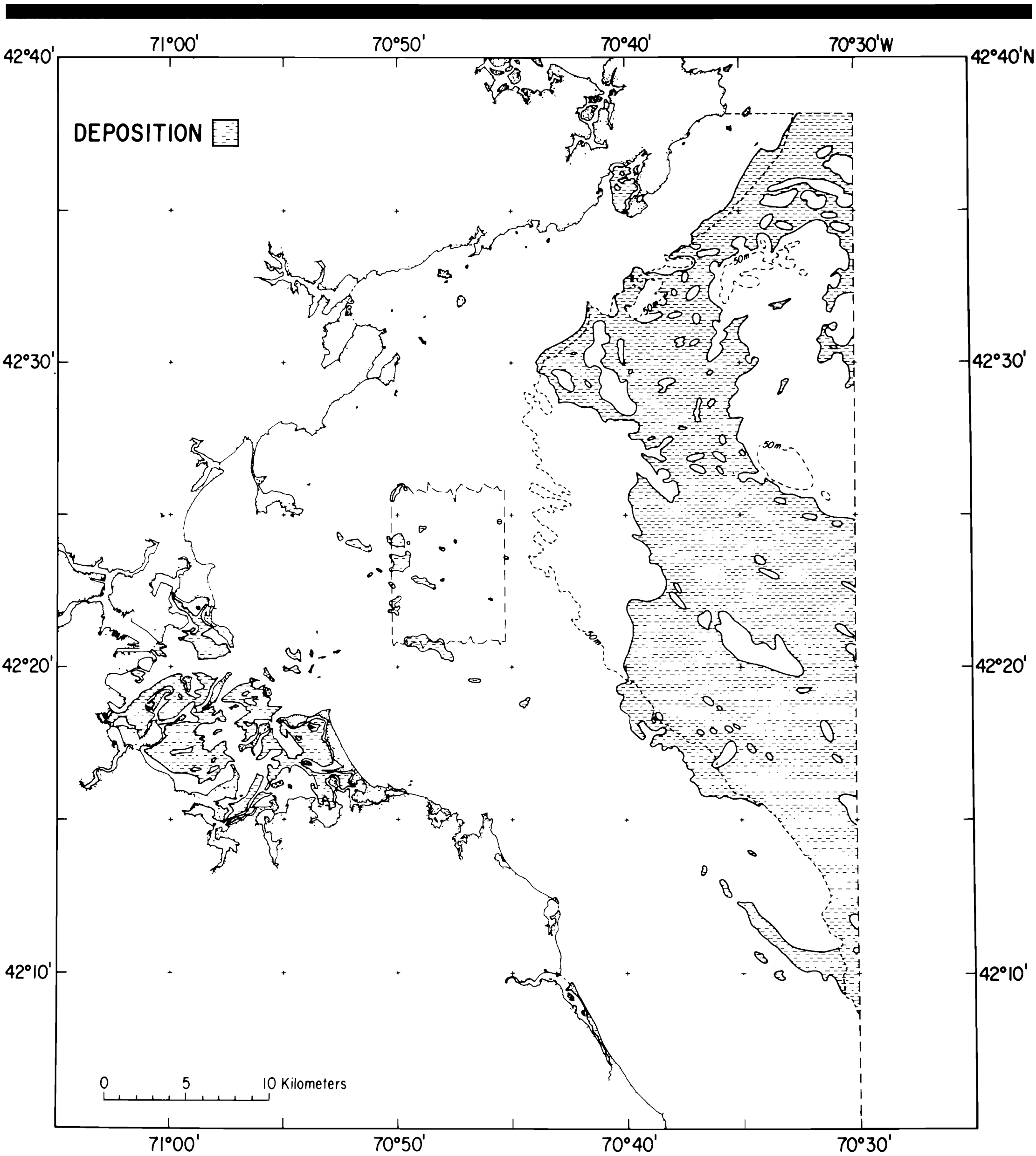


Figure 10. Map showing the distribution of environments of deposition across the Boston Harbor–Massachusetts Bay sedimentary system.

inner shelf. Long-term bottom-current, transmissometer, and photographic measurements made in areas of erosion or nondeposition reveal that during winter and spring storms, fine-grained sediments are resuspended by waves and then moved laterally by wind-driven flow (BUTMAN, 1978; BOTHNER and BUTMAN, 1988; BOTHNER *et al.*, 1990; BUTMAN *et al.*, 1990a,b, 1992; BUTMAN and FRY, 1992; GEYER *et al.*, 1992). Such resuspension and transport winnows the bottom sediments and also removes any fine-grained detritus that accumulates atop bedrock and lag surfaces during calm

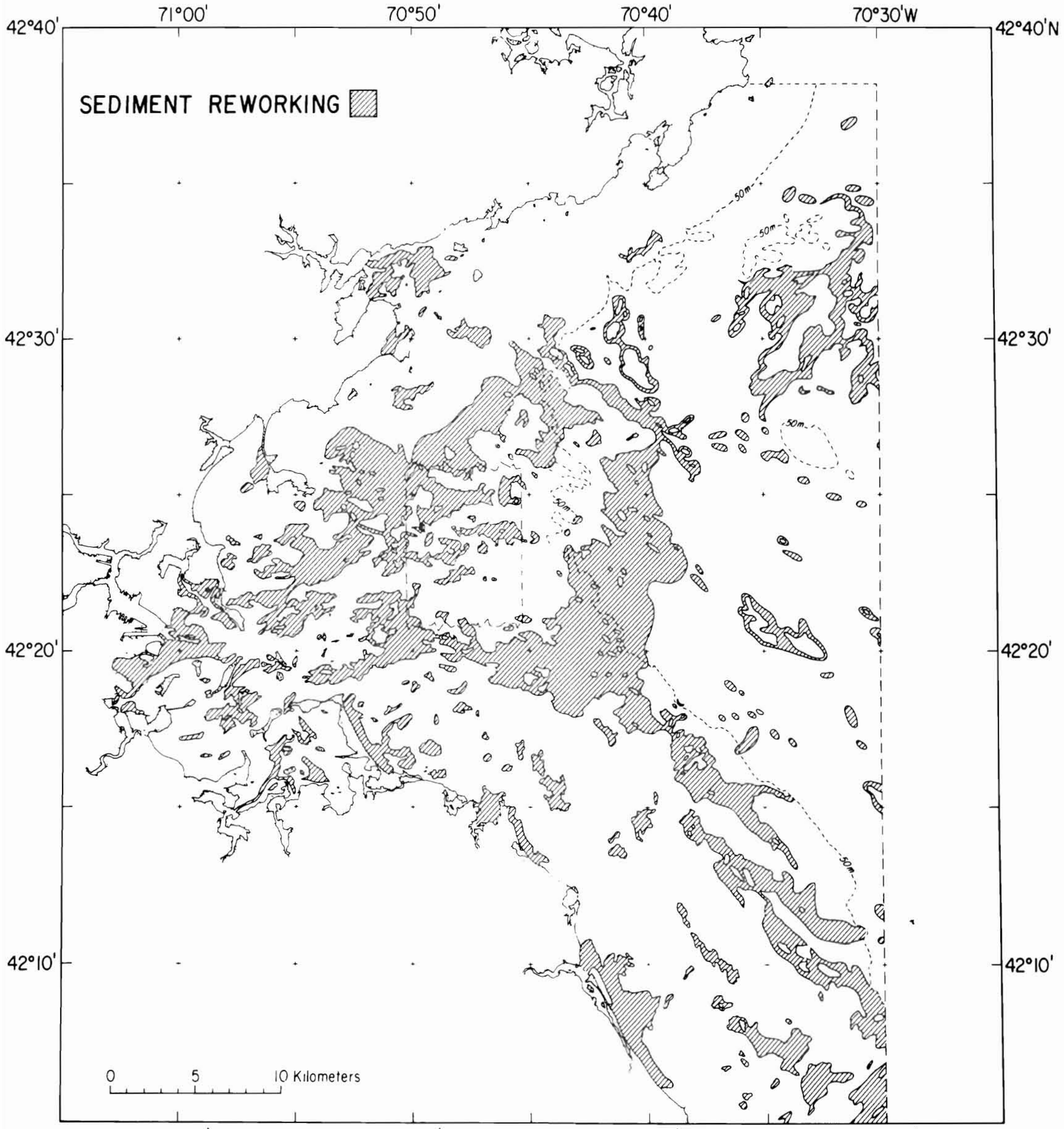


**Figure 11. Map showing the distribution of environments of sediment reworking across the Boston Harbor–Massachusetts Bay sedimentary system.**

periods (especially during the summer) (SEBENS and WHITMAN, 1990; SHEA *et al.*, 1991; BOTHNER *et al.*, 1992).

The preponderance of erosion or nondeposition on the inner shelf is also a consequence of the generally small supply of fine-grained sediments. Each year, the inner shelf receives only about 2,500 metric tons of suspended solids from small rivers that discharge along the coast and a maximum of about 19,300 metric tons of suspended solids from municipal wastes (MENZIE-CURA AND ASSOCIATES, INC., 1991). This input is just 22% of that con-

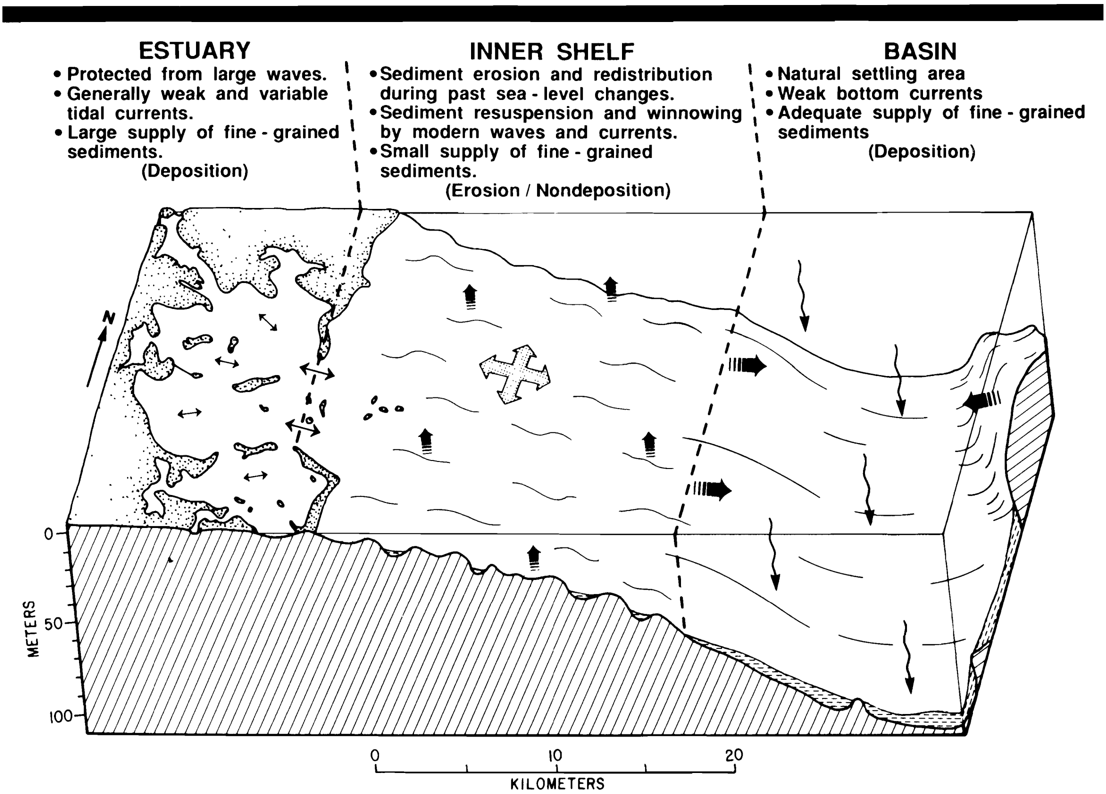


Figure 12. Perspective diagram which summarizes the major factors that have controlled the complex spatial distribution of sedimentary environments within and among the estuarine, inner shelf, and basinal parts of the Boston Harbor–Massachusetts Bay sedimentary system. The dominant sedimentary environment within each part of the system is also indicated.

tributed by similar sources to Boston Harbor (see previous discussion), although it serves an area that is more than 12 times larger in size. As a result, the supply of fine-grained sediments to most of the inner shelf is insufficient to offset losses due to erosion and transport by modern waves and currents (KNEBEL, 1993).

Despite the fact that erosion and winnowing are widespread, storm-generated waves and currents are unable to completely remove all fine-grained sediments that are present within the 29% of the inner-shelf area which is occupied by environments of sediment reworking and deposition. This is the result both of the decreased frequency of sediment resuspension by waves at greater water depths and of local decreases in bottom-current strengths caused by the irregular shelf topography (KNEBEL, 1993). Accordingly, environments of reworking and deposition are found in patches on the deeper parts of the inner shelf (> 30 m) and at local sites of relatively low energy, such as within broad lows and on the lower flanks of highs (Figures 6 and 9). In contrast, areas of erosion or nondeposition are found mostly in shallower water (< 30 m) and at sites of relatively high energy such as on the crests and upper flanks of highs (Figure 6) and within constricted depressions between highs.

The accumulation of fine-grained detritus in some areas of sediment reworking is also due to a local net supply of sediments from nearby sources. This situation exists, for example, within the two irregular bands of reworked sediments that extend eastward across the shelf off Boston Harbor (Figure 11). Here, the accumulation of fine-grained material reflects a net supply of sediments coming out of the harbor and onto the inner shelf. Such a source is indicated by the following: (1) the elevated levels of organic carbon, *Clostridium perfringens* spores (a bacterium spore characteristic of sewage), and other contaminants in the sediments (SHEA *et al.*, 1991; BUTMAN *et al.*, 1992; HUNT *et al.*, 1992); (2) the connections of the bands with the two harbor entrances suggesting a flux of sediments out of the harbor; and (3) the presence of ebb tidal plumes of harbor water (with entrained fine-grained sediments) that extend over the bands of reworked sediments (FITZGERALD, 1980; EG&G WASC OCEANOGRAPHIC SERVICES, 1984; SHEA *et al.*, 1991; BUTMAN *et al.*, 1992; SIGNELL, 1992). Accumulation within these bands is facilitated not only by the hydraulic drop that takes place during plume expansion (SHEA *et al.*, 1991) but by the weak and variable bottom flow during non-storm conditions that tends to restrict the transport of fine-grained sediments away from the area (BUTMAN and FRY, 1990, 1992; BUTMAN *et al.*, 1992). On a smaller scale, a net supply of sediment also accounts for fine-grained deposits within local areas of sediment reworking located near the shore (Figure 11). In these limited areas, the sediments probably have been contributed either by the small mainland rivers or by the erosion of adjacent headlands (STETSON and SCHALK, 1935; MEISBURGER, 1976).

### Stellwagen Basin

Stellwagen Basin is dominated by environments of deposition (Figure 10). Depositional environments are found across approximately 70% of the bottom, whereas environments of erosion and sediment reworking are limited to 16% and 14% of the area, respectively.

Deposition within Stellwagen Basin reflects a tranquil setting coupled with an adequate supply of fine-grained sediments (Figure 12). Stellwagen Basin is a natural settling area that was isolated from the rest of the Gulf of Maine when Stellwagen Bank was formed during late Wisconsinan time (OLDALE and EDWARDS, 1990; OLDALE, 1993). Since its formation, the basin has been a locus of deposition for fine-grained marine detritus (TUCHOLKE and HOLLISTER, 1973). At present, bottom currents along the floor of the basin are quite low, averaging less than 7 cm/sec (BUTMAN, 1978; HUBBARD *et al.,*, 1988; BECHTEL/PARSONS BRINCKERHOFF, 1991; GEYER *et al.,*, 1992). Maximum near-bottom tidal currents here are typically less than 8 cm/sec (BUTMAN, 1978; BUTMAN *et al.*, 1992; IRISH and SIGNELL, 1992), and calculations for waves measured at the long-term data buoy in Massachusetts Bay (NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION, 1990) show that the maximum wave-produced orbital speeds along the basin floor are less than 4 cm/sec. The strongest near-bottom steady currents in the basin reach speeds of 20–30 cm/sec during large easterly or northeasterly storms, although these currents alone are probably not strong enough to erode the bottom (BUTMAN, 1978; HUBBARD *et al.*, 1988; BECHTEL/PARSONS BRINCKERHOFF, 1991; GEYER *et al.*, 1992). Any resuspension of the surficial muds in the basin is probably caused by a combination of waves and currents that are generated only during the largest storms (BUTMAN, 1978; BOTHNER and BUTMAN, 1990; BUTMAN *et al.*, 1990a; BECHTEL/PARSONS BRINCKERHOFF, 1991; BOTHNER *et al.,*, 1993). In addition to weak bottom currents, the general tranquility of the basin is indicated by the ubiquitous microtopography on the basin floor produced by biologic activity (SCIENCE APPLICATIONS INTERNATIONAL CORPORATION, 1988) and by the accumulation of fine-grained sediments over anthropogenic objects dumped on the seafloor in this area (WILEY *et al.*, 1992).

The modern rate of sediment accumulation in Stellwagen Basin is approximately 0.1 cm/yr. This rate is based on accelerator mass-spectrometer $^{14}C$ data from a core collected along the axial part of the basin (water depth = 88 m) (HUNT *et al.*, 1992), and it is similar to rates estimated from conventional $^{14}C$ dates obtained from other cores collected in Stellwagen Basin and in nearby Tillies Basin (TUCHOLKE and HOLLISTER, 1973). If this modern accumulation rate remained uniform during late Holocene time, then about 3 m of fine-grained sediments were deposited along the basin floor since sea level approached its present position about 3,000 yr BP.

Modern fine-grained deposits in Stellwagen Basin probably have been derived from several sources. Some sediments undoubtedly have been winnowed and transported from areas of sediment erosion and reworking on the inner shelf. This is indicated not only by the frequent resuspension of bottom sediments by waves during large storms but by downwelling and off-shelf bottom transport that occurs across the deeper parts of the shelf area in response to northerly and easterly storm winds (HUBBARD *et al.*, 1988; GEYER *et al.*, 1992; BUTMAN *et al.*, 1993). Long-term bottom-current measurements made at 30 m water depth off Boston Harbor reveal that, even on the middle part of the shelf, the mean bottom current and transport of resuspended sediments during storms is southeastward and slightly offshore toward Stellwagen Basin (GEYER *et al.*, 1992; BOTHNER *et al.*, 1993).

Another potential source of fine-grained sediments for Stellwagen Basin is the Merrimack River. Water-property measurements, satellite images, and current models show that the surface plume of the Merrimack River (which debouches just north of Cape Ann) often moves southward into Massachusetts Bay and over the northern part of the basin during periods of high spring runoff (BUTMAN, 1978; BOTHNER and BUTMAN, 1990; BUTMAN and BEARDSLEY, 1992; GEYER *et al.*, 1992; BLUMBERG *et al.*, 1993). Fine-grained sediments, which are entrained in this surface plume, can settle through the water column and onto the basin floor during these episodic events.

Some fine-grained sediments in the basin could also come from Stellwagen Bank. Stellwagen Bank lies in the path of large winter and spring storms which generate waves capable of resuspending and winnowing fine-grained sediments on the bank's shallow crest (20–50 m water depth). In addition, the surface sediments atop the bank can be resuspended and winnowed during the summer by strong currents (sometimes > 50 cm/sec) that are produced in part by internal tides (IRISH and SIGNELL, 1992). Once resuspended, the fine-grained sediments can be transported off the bank and over Stellwagen Basin. This is indicated by the following: (1) westward bottom currents produced by easterly storm winds (BUTMAN, 1978); (2) bottom tidal currents across the bank that are oriented on flood into the basin (BUTMAN, 1978; GEYER *et al.*, 1992; IRISH and SIGNELL, 1992); (3) the near-bottom mean flow on the northern part of the bank that is directed toward the southwest (BUTMAN *et al.*, 1992; GEYER *et al.*, 1992); and (4) storm-produced bedforms that extend down the western flank of the bank to depths of 55 m (VALENTINE and SCHMUCK, 1993).

Finally, some fine-grained sediments can be advected over the basin via the regional current pattern in the Gulf of Maine. Long-term current measurements, drifter observations, and the distribution of nutrients indicate that the regional circulation pattern includes a semipermanent southerly surface flow south of Cape Ann that extends across much of the northern half of Stellwagen Basin (HUBBARD *et al.*, 1988; BUTMAN *et al.*, 1992; GEYER *et al.*, 1992). Because this regional current can incorporate water and entrained sediments from a number of rivers that empty into the Gulf of Maine (GEYER *et al.*, 1992), it potentially carries fine-grained detritus that can settle onto the basin floor.

The remaining areas of Stellwagen Basin (30%) that are occupied by environments of erosion or sediment reworking generally are sites of relatively high energy. These areas are found: (1) atop Stellwagen Bank and its discontinuous northern extension; (2) on the crests and flanks of prominent knolls that protrude above the basin floor; and (3) over prominences located along the irregular transitional slope northeast of Boston Harbor (Figures 8 and 11). Compared to environments of deposition, which are found along the basin floor and over uniform marginal slopes, these areas are present either where large waves and strong currents affect the bottom on Stellwagen Bank throughout the year or where bottom-current strengths are locally enhanced by seafloor relief. The local enhancement of bottom currents by seafloor relief is a phenomenon that has been observed not only on the inner shelf in this area, but in several other coastal and estuarine areas as well (KNEBEL *et al.*, 1982; KNEBEL, 1986, 1989). Such relative increases in current strength can either eliminate or greatly restrict the accumulation of sediments over topographic highs. Indeed, the juxtaposition of environments of erosion to those of sediment reworking around some sites of local topographic relief in Stellwagen Basin are likely manifestations of such relative changes in current strength and related sediment transport.

## SUMMARY AND IMPLICATIONS

Analyses of an extensive set of sidescan sonographs and supplemental bathymetric, sedimentary, subbottom, and bottom-current data outline three categories of modern seafloor sedimentary environments across the glaciated, topographically complex Boston Harbor and Massachusetts Bay area. (1) Environments of erosion or nondeposition comprise exposures of bedrock, glacial drift, coarse lag deposits, and possibly coastal plain rocks that contain sediments (where present) ranging from boulder fields to sandy gravels to gravelly sands with megaripples and that occur in areas of relatively high energy. (2) Environments of deposition are blanketed by muddy sands, sandy muds, and muds that have accumulated under dominantly weak bottom currents. (3) Environments of sediment reworking contain sediment patches with diverse grain sizes (ranging from sandy gravels to sands to muds) that have been produced by a combination of erosion and deposition and occur in areas with variable bottom currents.

The relative proportions of the three categories of sedimentary environments vary among the estuarine (Boston Harbor), inner shelf, and basinal (Stellwagen Basin) parts of the sedimentary system. Environments of erosion or nondeposition predominate across the inner shelf where they occupy 71% of the bottom, whereas in Boston Harbor and Stellwagen Basin they occupy only 20% and 16% of the bottom, respectively. Depositional environments, on the other hand, cover most of the seafloor in Boston Harbor and in Stellwagen Basin (51% and 70%, respectively), whereas they cover only a scant 3% of the area of the inner shelf. Environment of sediment reworking are subordinate within all parts of the sedimentary system, accounting for 29% of the area of Boston Harbor, 26% of the area of the inner shelf, and 14% of the area of Stellwagen Basin.

The differences in the relative proportions of the sedimentary environments across the margin reflect regional changes in the geologic and oceanographic conditions among the different parts of the sedimentary system. The prevalence of environments of deposition in Boston Harbor indicates that it is an effective trap for fine-grained detritus. Deposition of fine-grained sediments in the harbor is a result of its protected setting, generally weak and variable tidal currents, and relatively large supply of fine-grained sediments. In contrast, the inner shelf is dominantly an area of sediment erosion or nondeposition where only small amounts of fine-grained sediments have accumulated. This is due to sediment erosion and redistribution during past sea-level changes, to continued sediment resuspension and winnowing by modern waves and currents, and to the small supply of fine-grained sediments. Finally, Stellwagen Basin is a locus of deposition for fine-grained sediments. This is because it is a natural settling area, has only weak bottom currents, and receives an ample supply of fine-grained sediments from the inner shelf, Stellwagen Bank, or the Gulf of Maine.

The distribution of sedimentary environments across the study area is extremely patchy. This patchiness reflects not only the regional changes in geologic and oceanographic conditions across the margin but local changes within each part of the sedimentary system as well. Local changes are the result of: (1) modifications in the bottom-current strength caused by the irregular seafloor topography and by changes in water depth; and (2) local variations in the supply of fine-grained sediment.

The distribution of bottom sedimentary environments across the Boston Harbor–Massachusetts Bay system indicates areas where fine-grained sediments and related contaminants are likely to be either removed or deposited. The distribution, therefore, can be used as a guide to select sites at which to measure the inventories of contaminants in the sediments or to monitor the changes in contaminant levels with time. Moreover, knowledge of the causes and patchiness of the sediment distribution help to explain any observed spatial variations in contaminant concentrations.

An understanding of the spatial variability of sedimentary environments also provides clues concerning the locations of habitats for benthic organisms. This is because benthic habitats are largely controlled by the kinds of bottom substrate and by the strengths of bottom currents. Both of these environmental factors are implicit in the definitions of our three categories of sedimentary environments. Data from this study, therefore, can be used not only to outline the distribution of benthic habitats across the margin, but also to indicate areas where benthic habitats are locally diverse (such as in areas of sediment reworking) or where they can be affected by contaminants deposited with fine-grained sediments.

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