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MASSACHUSETTS WATER RESOURCES AUTHORITY

MISCELLANEOUS FIELD STUDIES
MAP MF-2280
SHEET 1 OF 2

INTRODUCTION

This report illustrates, describes, and briefly discusses the acoustic and textural characteristics and the distribution of bottom sedimentary environments in Boston Harbor and Massachusetts Bay. The study is an outgrowth of a larger research program designed to understand the regional processes that distribute sediments and related contaminants in the area. The report highlights the major findings presented in recent papers by Knebel and others (1991), Knebel (1993), and Knebel and Circé (1995). The reader is urged to consult the full text of these earlier papers for a more definitive treatment of the data and for appropriate supporting references.

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

The study area includes Boston Harbor, the inner shelf of Massachusetts Bay, and the northwestern part of Stellwagen Basin (fig. 1). Boston Harbor is an island-studded embayment that generally is less than 5 m deep, except along its two main entrance channels where water depths exceed 10 m (fig. 2). The harbor contains extensive subtidal flats (less than 4 m deep) near the shore and a complex assemblage of discontinuous bottom ridges and depressions elsewhere (Knebel and others, 1991). The inner shelf region of Massachusetts Bay, as used herein, extends offshore from the coastline to water depths of 50 m (fig. 2). Here, the bottom is mostly hummocky and rough and is characterized by ubiquitous highs separated by isolated lows. Farther to the east, Stellwagen Basin forms a large curvilinear depression that has water depths generally greater than 75 m along its central part (fig. 2). As used herein, Stellwagen Basin includes the floor as well as the flanks of the basin, which are formed by the transitional slope from the inner shelf on the west and by Stellwagen Bank on the east.

DATA

The acoustic characteristics and the regional distribution of bottom sedimentary environments in the study area are interpreted primarily from five sidescan-sonar surveys, for which the tracklines are shown composited in figure 3. These surveys include (1) a regional survey conducted by the Raytheon Company for the Massachusetts Department of Natural Resources across the inner shelf (Willett, 1972; Cooks and others, 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 and others, 1991); (3) a nearshore survey by Fitzgerald and others (1990) located just east of Deer Island and Nantasket Beach; (4) a detailed survey (with nearly complete sea-floor coverage) by the U.S. Geological Survey within a 7.0- by 9.3-km area of the inner shelf (see dashed rectangle in figure 3; Bothner and others, 1990, 1992; Butman and others, 1990a, 1992); and (5) a reconnaissance survey by the U.S. Geological Survey located across Stellwagen Basin (Knebel and Circé, 1995). 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 and others, 1990a; Fitzgerald and others, 1990; Knebel and others, 1991; Bothner and others, 1992; Knebel and Circé, 1995).

In addition to the sonographs, this study made use of a large amount of supplemental marine geologic data (fig. 3). These data included (1) grab samples, cores, bottom photographs, and videocamera and photograph transects collected at 470 stations; (2) high-resolution seismic-reflection (boomer) profiles collected concurrently with the sidescan data along all tracklines; (3) previous maps of bottom-sediment types and constituents (cited in Knebel and others, 1991; Knebel, 1993; Knebel and Circé, 1995); and (4) the regional bathymetry, which had been contoured at a 2-m interval (National Ocean Service, 1986a,b).

ACOUSTIC AND TEXTURAL CHARACTERISTICS OF ENVIRONMENTS

Three categories of bottom sedimentary environments have been identified in the study area from characteristic sonograph patterns and the supplemental marine geologic data (Knebel and others, 1991; Knebel, 1993; Knebel and Circé, 1995). These environments reflect the dominant long-term processes of erosion or nondeposition, deposition, and sediment reworking. In discussing these environments, it should be noted that atypical processes (such as storm erosion in depositional areas) can sometimes affect the sea floor within each environment. Such atypical processes 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

Environments of erosion or nondeposition appear on the sonographs either as patterns with isolated reflections or as patterns of strong backscatter. Patterns with isolated reflections (figs. 4A, B) have either a "blotchy" or a "speckled" appearance on the sonographs, and they depict outcrops of bedrock, till, coarse glacial drift, and possibly Coastal Plain rocks (in Massachusetts Bay). Rock masses and boulders that produce such patterns have sharp boundaries, discernible relief, and widths ranging from less than 5 m to more than 30 m. Where present, sediments in areas characterized by isolated reflections range from boulder fields to poorly sorted gravels and sandy gravels (fig. 5). Patterns of strong backscatter, on the other hand, appear as nearly uniform dark records (fig. 4B), which represent winnowed lag deposits of gravel and medium to coarse sands (fig. 5). These lag deposits commonly include boulders, and they contain megaripples (wavelengths 4 m or less) at some locations on the inner shelf.

Environments of Deposition

Environments of deposition are depicted on the sonographs as patterns of weak backscatter (figs. 4C, D). Such patterns are essentially featureless except for broad changes in acoustic return, and they are produced by relatively fine-grained bottom sediments. Bottom-sediment textures in depositional areas range from muds to sandy muds to muddy sands (fig. 5).

Environments of Sediment Reworking

Environments of sediment reworking are characterized by sonograph patterns with patches of strong-to-weak backscatter (figs. 4B, D). Patches within these patterns represent areas on the sea floor that range in size from a few meters to more than 200 m across. They are the result of textural changes in the bottom sediments caused by a combination of erosion and deposition. Patches of strong backscatter (dark in figs. 4B, D) depict erosional features that have been created either by exposing relatively coarse buried deposits at the sea floor 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 deposits. These patchy patterns differ from patterns with isolated reflections (discussed previously) in that the patches lack detectable relief, usually have gradational boundaries, and exhibit subtler changes in backscatter. Sediments in reworked areas range from gravels to sands to muds and include textures that are characteristic of both erosional and depositional environments (fig. 5).

DISTRIBUTION OF ENVIRONMENTS

Reconnaissance maps showing the distribution of the three categories of bottom sedimentary environments were constructed from the locations of the characteristic sonograph patterns (figs. 6–9). Within the study area, the locations of the sonograph patterns are strongly correlated with physiographic features, topographic changes, bottom-sediment types, and water depth (Knebel and others, 1991; Knebel, 1993; Knebel and Circé, 1995). These correlations allowed us to infer the distribution of 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 the coarse bottom-sediment types were similar to those found in nearshore areas that were surveyed farther south (Knebel, 1993).

The relative proportions and the local distributions of sedimentary environments differ among Boston Harbor, the inner shelf, and Stellwagen Basin. These differences are outlined in the following sections.

Boston Harbor

Environments of deposition cover 51 percent of the bottom in Boston Harbor, whereas environments of sediment reworking cover 29 percent and environments of erosion or nondeposition cover 20 percent (Knebel and others, 1991) (figs. 7–9). Depositional environments are found primarily over the subtidal flats in the southern part of the harbor and within bathymetric lows located among the islands and away from the main tidal channels (fig. 8). Environments of sediment reworking occupy much of the northern third of the harbor, where they are present over a variety of geomorphic features (fig. 9). Environments of erosion or nondeposition are limited mainly to small areas around the islands, along the southern mainland shore, and within large tidal channels (fig. 7).

Inner Shelf

Environments of erosion or nondeposition occupy 71 percent of the inner shelf area, whereas environments of sediment reworking and deposition occupy just 26 percent and 3 percent of the area, respectively (Knebel, 1993) (figs. 7–9). Environments of erosion or nondeposition are present over extensive areas of the irregular topography near the coast (water depths less than 30 m) and in some large patches farther offshore (water depths 30–50 m) (fig. 7). In these locations, environments of erosion or nondeposition commonly are found either on the crests and upper flanks of bathymetric highs (fig. 4B) or within constricted depressions between highs. Environments of sediment reworking, however, are found primarily (1) in the southeastern part of the area in water depths greater than 30 m, (2) along two irregular bands that extend eastward and northeastward across the shelf from the Boston Harbor entrances, and (3) at small sites located off mainland rivers (fig. 9). At these various locations, reworked sediments usually are found within bathymetric lows or on the lower flanks of ridges and knolls (figs. 4B, D). Depositional environments on the inner shelf are restricted mainly to scattered small lows within the rugged nearshore topography and to narrow patches along the offshore margin of the shelf in water depths of 40–50 m (fig. 8).

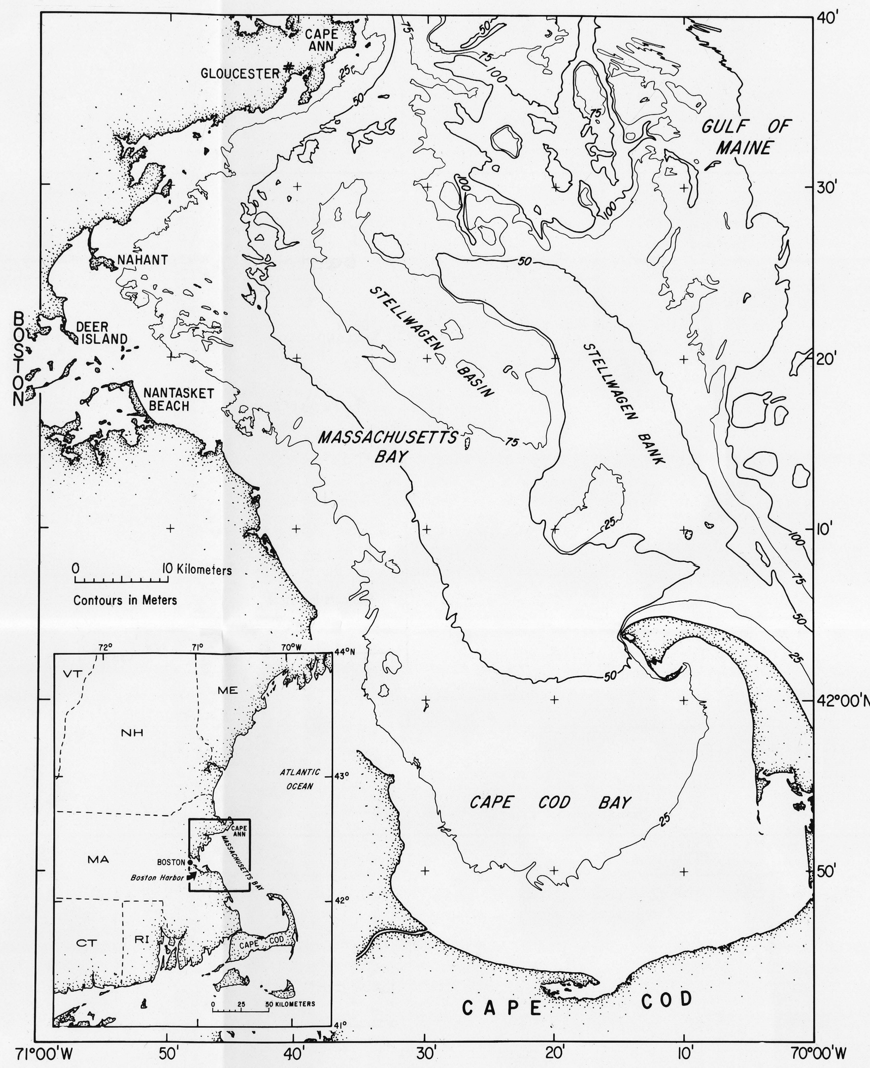

Figure 1.--Index map. Inset shows map area presented in figures 2, 3, 6, 7, 8, and 9.

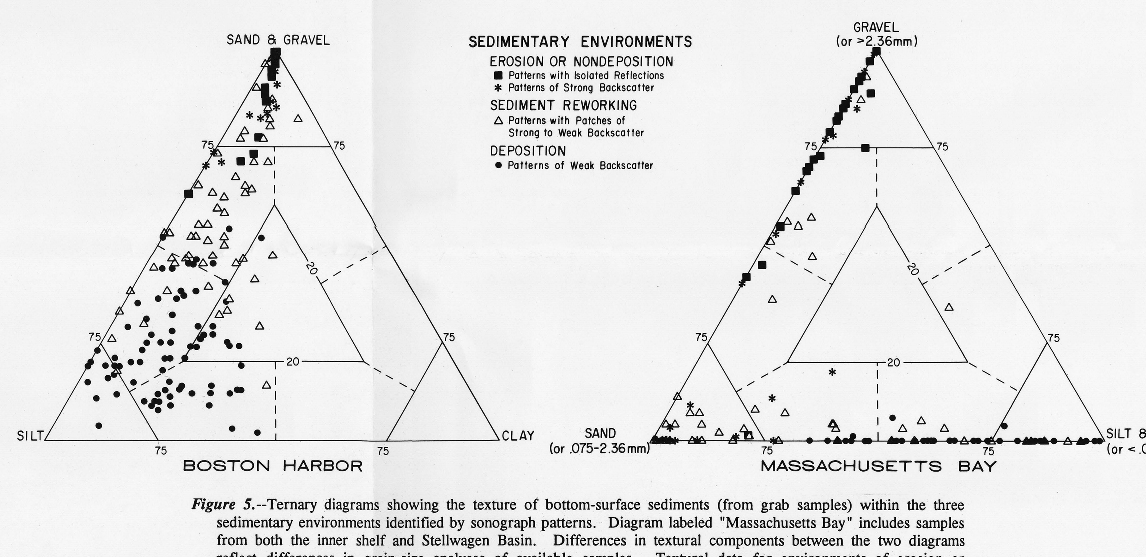

Figure 5.--Ternary diagrams showing the texture of bottom-surface sediments (from grab samples) within the three sedimentary environments identified by sonograph patterns. Diagram labeled "Massachusetts Bay" includes samples from both the inner shelf and Stellwagen Basin. Differences in textural components between the two diagrams reflect differences in grain-size analyses of available samples. Textural data for environments of erosion or nondeposition do not account for boulders observed on the sea floor. Solid triangles shown in the diagram for Massachusetts Bay are points where the textural components of samples from environments of sediment reworking are coincident with those of samples from environments of deposition. Sources of original grain-size data are cited in Knebel and Circé (1995).

Stellwagen Basin

Depositional environments are found across 70 percent of the bottom in Stellwagen Basin, whereas environments of erosion or nondeposition and environments of sediment reworking are limited to 16 percent and 14 percent of the area, respectively (Knebel and Circé, 1995) (figs. 7–9). Environments of deposition are prevalent along the floor and over most of the western transitional slope of the basin, except for an 18-km-long section northeast of Boston Harbor (fig. 8). Environments of erosion or nondeposition are restricted primarily to scattered patches located (1) atop the discontinuous northwestern extension of Stellwagen Bank, (2) over small knolls that protrude above the basin floor, and (3) across prominences on the irregular transitional slope (water depths 50–60 m) northeast of Boston Harbor (fig. 7). Environments of sediment reworking are present (1) across much of the 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 northwestern extension of Stellwagen Bank (water depths 60–80 m) (fig. 9).

DISCUSSION

The distribution of bottom sedimentary environments across the study area is extremely patchy (figs. 6–9). On the reconnaissance maps, the sizes of individual patches that represent single environments range from a few tens of meters to more than 40 km (along the floor of Stellwagen Basin). Much of the small-scale patchiness found within the study area is due to local modifications of bottom-current strength and related sediment transport caused by the irregular topography (Knebel and others, 1991; Knebel, 1993; Knebel and Circé, 1995). Examples of this phenomenon include (1) the existence of environments of erosion or nondeposition within large tidal channels in Boston Harbor, (2) the presence of depositional environments within small lows on the rugged inner shelf, and (3) the occurrence of reworked sediments atop isolated knolls that protrude above the floor of Stellwagen Basin. Some small-scale patchiness on the inner shelf is also the result of local nearshore variations in the supply of fine-grained sediments and of shelf-wide changes in water depth (Knebel, 1993).

In addition to local patchiness, differences in the relative proportions of sedimentary environments among Boston Harbor, the inner shelf, and Stellwagen Basin reflect regional changes in geologic and oceanographic conditions. In Boston Harbor, the prevalence of depositional environments is largely the result of its protection from large waves and its relatively large supply of fine-grained sediments (Knebel and others, 1991; Knebel and Circé, 1995). Concerning its protected nature, the harbor is a nearly enclosed, island-studded embayment. This setting not only limits the fetch for local wave generation but 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 of the bottom by waves is areally limited (Bumpus and others, 1951, 1953; Fitzgerald, 1980; Knebel and others, 1991). In the absence of large waves, deposition of fine-grained sediments inside the harbor is facilitated by generally weak and variable tidal currents (U.S. Coast and Geodetic Survey, 1953; National Ocean Survey, 1977; Butman and others, 1992; Signell and Butman, 1992).

Deposition in Boston Harbor also reflects an abundant supply of fine-grained sediments from natural and anthropogenic sources. Fluvial discharge contributes about 12,700 metric tons (t) of suspended solids each year to the harbor area, and, until the end of 1991, the annual amount of suspended solids discharged with municipal wastes (mostly sewage) was about 85,000 t (Menzie-Cura and Associates, Inc., 1991). Other sources that contribute fine-grained sediments to the harbor include (1) the erosion and winnowing of glacial drift and till along insular and mainland shorelines, (2) the possible landward advection of sediments from Massachusetts Bay during times of onshore bottom flow, and (3) the production of biological skeletal debris and fecal particles in the water column (Knebel and others, 1991). Collectively, the annual supply of fine-grained sediments from all sources greatly exceeds the estimated maximum of 46,000 t of fine-grained sediments (Knebel and others, 1991) that accumulate each year on the bottom inside the harbor.

In contrast to Boston Harbor, the dominance of environments of erosion or nondeposition on the inner shelf mainly reflects (1) sediment resuspension and winnowing by waves and currents, and (2) a small supply of fine-grained sediments (Knebel, 1993). Frequent resuspension and winnowing of the bottom sediments on the inner shelf has been documented by long-term bottom-current, transmissometer, and photographic measurements (Butman, 1978; Bothner and Butman, 1988; Bothner and others, 1990; Butman and others, 1990a,b, 1992; Geyer and others, 1992). These measurements show that during winter and spring storms, fine-grained sediments are often resuspended by waves and transported to heights at least 5 m above the bottom. Once resuspended, the sediments are moved laterally by relatively weak bottom currents which are driven by the winds, tides, or changes in water density (Butman and others, 1992).

The preponderance of erosion or nondeposition on the inner shelf is also a consequence of a small supply of fine-grained sediments (Knebel, 1993). Each year, the inner shelf receives only about 2,500 t of suspended solids from small rivers that empty along the coast and a maximum of about 19,300 t of suspended solids from municipal wastes (Menzie-Cura and Associates, Inc., 1991). By comparison, this input is just 22 percent of that contributed by similar sources to Boston Harbor (see previous discussion), even though this influx serves an area that is more than 12 times larger in size. In addition to this direct input, some fine-grained sediments also escape from Boston Harbor and are deposited within the two irregular bands of reworked sediments that extend eastward and northeastward across the shelf from the harbor entrances (Knebel, 1993) (fig. 9). However, the amount of sediments from the harbor that remains on the shelf is probably small because the bands of reworked sediments account for only about 20 percent of the inner shelf surface, and they contain only patches of fine-grained sediments. In general, the supply of fine-grained sediments to the inner shelf from all sources is insufficient to offset the losses due to erosion and transport by waves and currents (Knebel, 1993).

The large areal expanse of depositional environments within Stellwagen Basin reflects a tranquil setting coupled with an adequate supply of fine-grained sediments (Knebel and Circé, 1995). 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, wave-produced currents along the basin floor are less than 4 cm/s (Knebel and Circé, 1995), and the strongest near-bottom steady currents reach speeds of only 20–30 cm/s during large easterly or northeasterly storms (Butman, 1978; Hubbard and others, 1988; Bechtel/Parsons Brinckerhoff, 1991; Geyer and others, 1992). As a result, any resuspension of the surficial muds in the basin is restricted to only short periods of time during the largest storms and is probably caused by a combination of waves and currents (Butman, 1978; Bothner and Butman, 1990; Butman and others, 1990a; Bechtel/Parsons Brinckerhoff, 1991; Bothner and others, 1993).

Modern fine-grained deposits in Stellwagen Basin have been derived from several sources. These sources include (1) sediments winnowed and transported from areas of erosion and reworking on the inner shelf, (2) sediments carried southward in the surface plume of the Merrimack River (which empties just north of Cape Ann) during periods of high spring runoff, (3) sediments resuspended and transported from Stellwagen Bank by storm-driven currents and by internal waves controlled by the density structure of the water column, and (4) sediments advected southward via the regional current in the Gulf of Maine (Knebel and Circé, 1995). Once the sediments from these various sources have been transported over the basin, they can settle through the water column and accumulate on the sea floor under the weak bottom currents. Taken together, these sources produce an accumulation rate on the basin floor of approximately 0.1 cm/yr (Hunt and others, 1992).

SUMMARY

Analyses of sidescan sonographs from five surveys together with supplemental marine geologic data outline the acoustic and textural characteristics and the distribution of three categories of sea-floor sedimentary environments (erosion or nondeposition, deposition, and sediment reworking) within the topographically complex Boston Harbor and Massachusetts Bay area.

(1) Environments of erosion or nondeposition are defined on sonographs by patterns with isolated reflections or by patterns of strong backscatter. These environments comprise exposures of bedrock, glacial drift, coarse lag deposits, and possibly Coastal Plain rocks. Where sediments are present within these environments, they range from boulder fields to gravelly sands. Environments of erosion or nondeposition predominate across the inner shelf, where they occupy 71 percent of the bottom, whereas they occupy 20 percent and 16 percent of the bottom, respectively, in Boston Harbor and Stellwagen Basin.

(2) Environments of deposition are characterized by sonographs having uniform patterns of weak backscatter. Bottom sediments in these environments are muddy sands, sandy muds, and muds. Environments of deposition cover most of the sea floor in Boston Harbor and in Stellwagen Basin (51 percent and 70 percent, respectively), but they cover only a scant 3 percent of the sea floor on the inner shelf.

(3) Environments of sediment reworking are depicted by sonograph patterns with patches of strong-to-weak backscatter that are the result of textural changes in the bottom sediments caused by a combination of erosion and deposition. These environments contain diverse grain sizes ranging from gravels to sands to muds. Environments of sediment reworking account for 29 percent of the area of Boston Harbor, 26 percent of the area of the inner shelf, and 14 percent of the area of Stellwagen Basin.

(4) The extreme patchiness in the distribution of bottom sedimentary environments and the differences in their relative proportions across the study area reflect both local and regional causes. Local patchiness is mainly the result of (1) modifications in bottom-current strength caused by the irregular topography, (2) changes in water depth, and (3) small-scale variations in the supply of fine-grained sediments. Regional patchiness, however, reflects differences in geologic and oceanographic conditions among Boston Harbor, the inner shelf, and Stellwagen Basin. The prevalence of environments of deposition in Boston Harbor is mainly a result of its protected setting and relatively large supply of fine-grained sediments. The inner shelf, on the other hand, is dominantly an area of sediment erosion or nondeposition due to continued sediment resuspension and winnowing by waves and currents and to a small supply of fine-grained sediments. Stellwagen Basin is primarily a tranquil depositional environment in which fine-grained sediments from several sources settle through the water column and accumulate under weak bottom currents.

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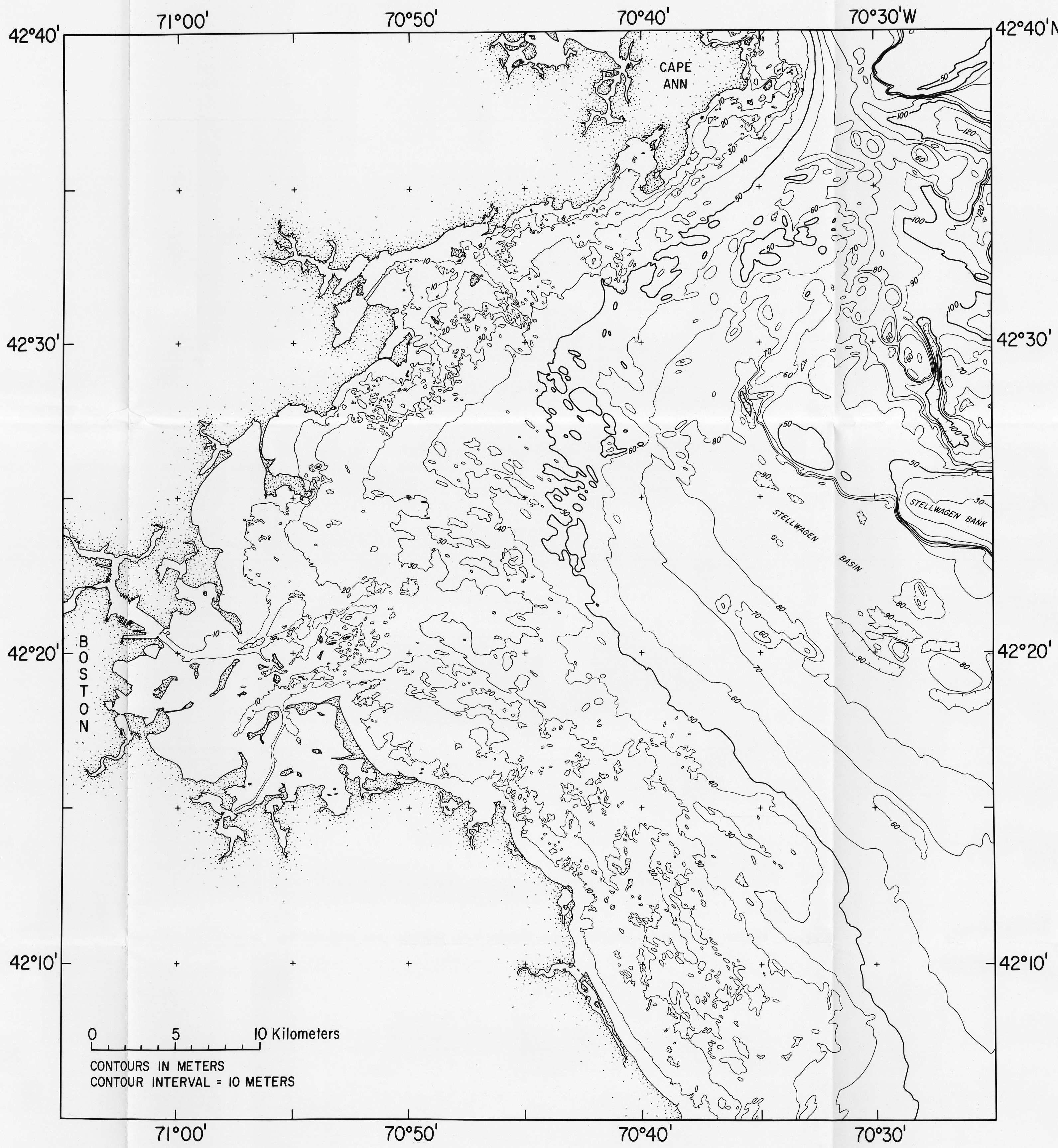


Figure 2.--Bathymetric map. Depth contours are from National Ocean Service (1986a,b). Scale 1:150,000. Transverse Mercator projection. Not to be used for navigational purposes.

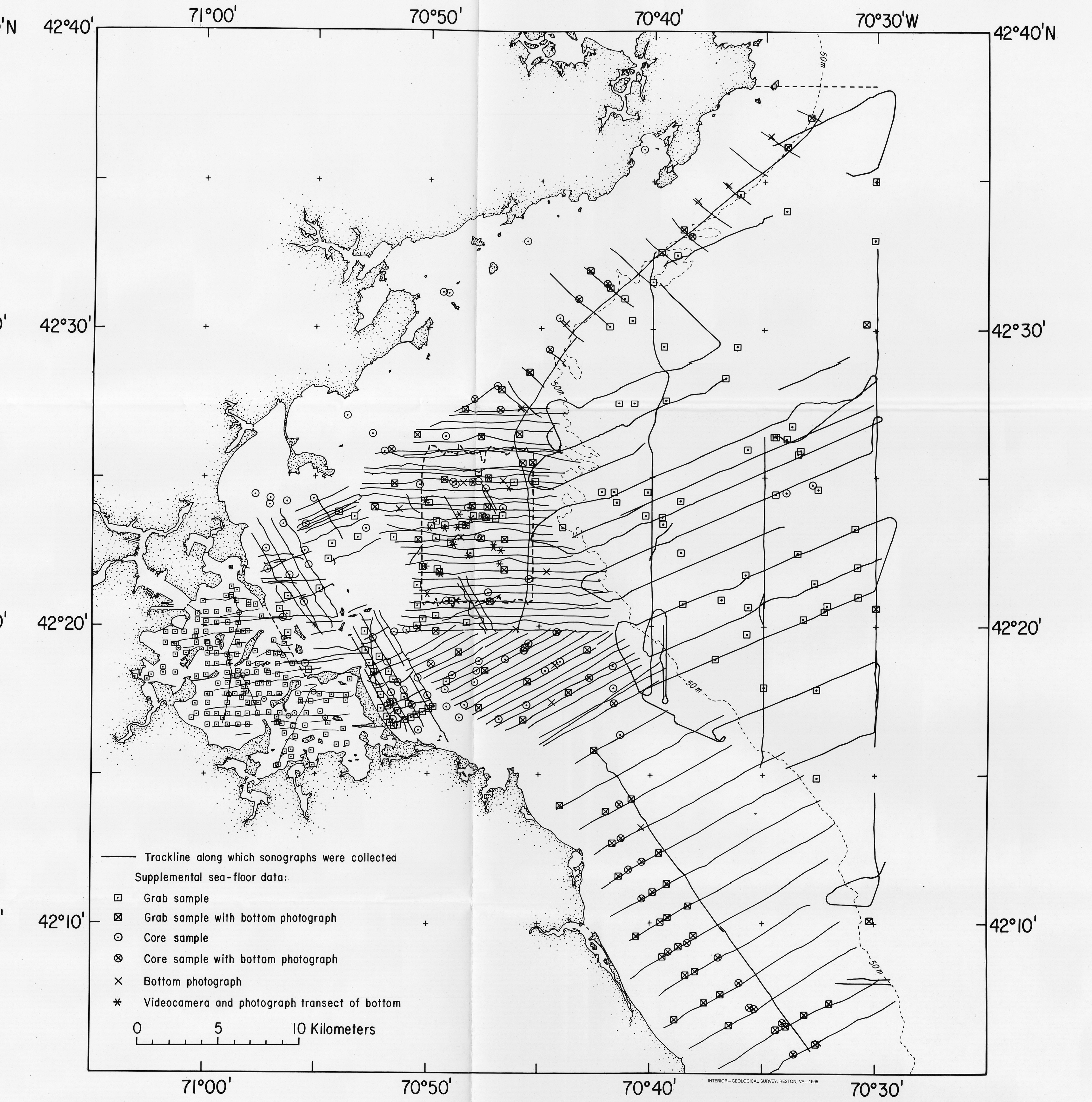
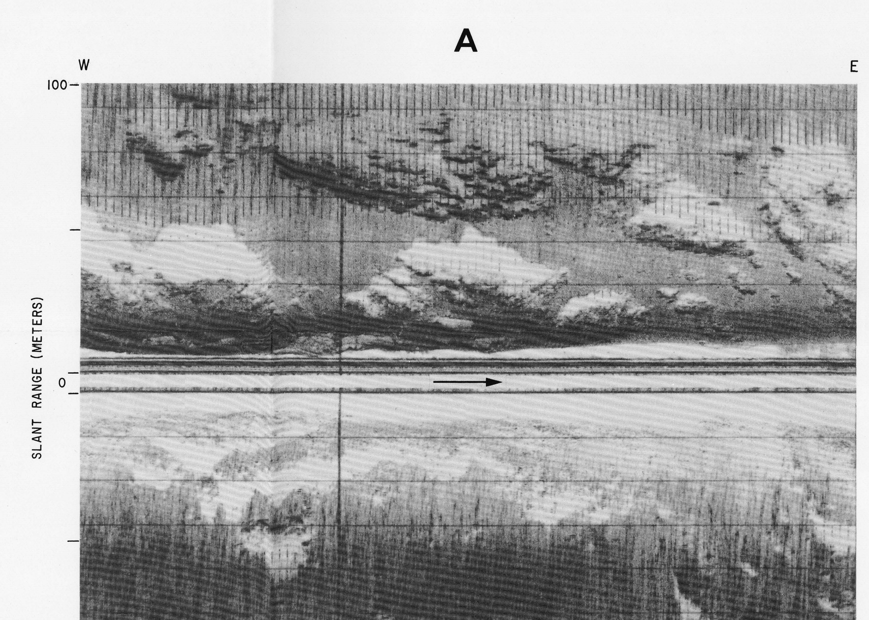
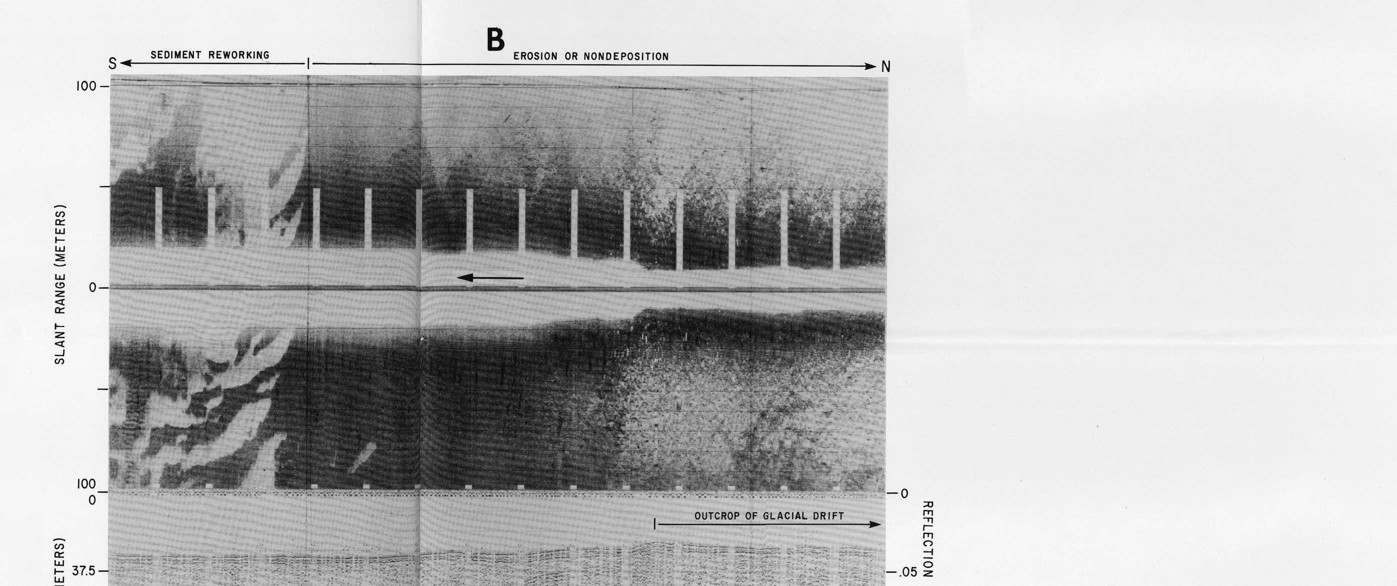


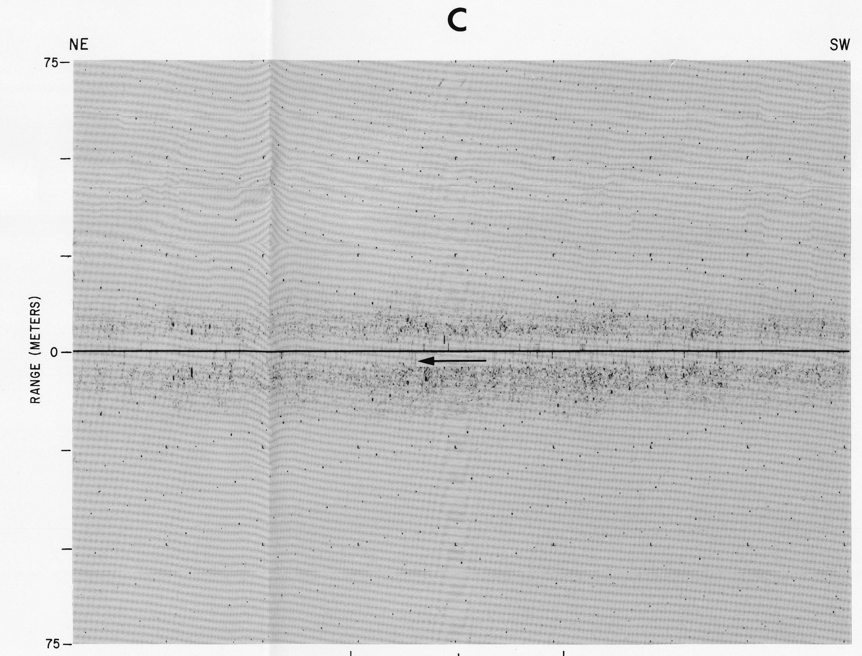
Figure 3.--Locations of sidescan sonographs and supplemental sedimentary observations. Dashed lines define the eastern limit of Boston Harbor and the northern limit of the study area off Cape Ann. Dashed 50-m isobath delineates the offshore limit of the inner shelf of Massachusetts Bay. Dashed rectangle on the inner shelf defines detailed-survey area having nearly complete sonograph coverage of the sea floor. Data symbols are shown smaller in Boston Harbor because of space constraints. Scale 1:150,000. Transverse Mercator projection.



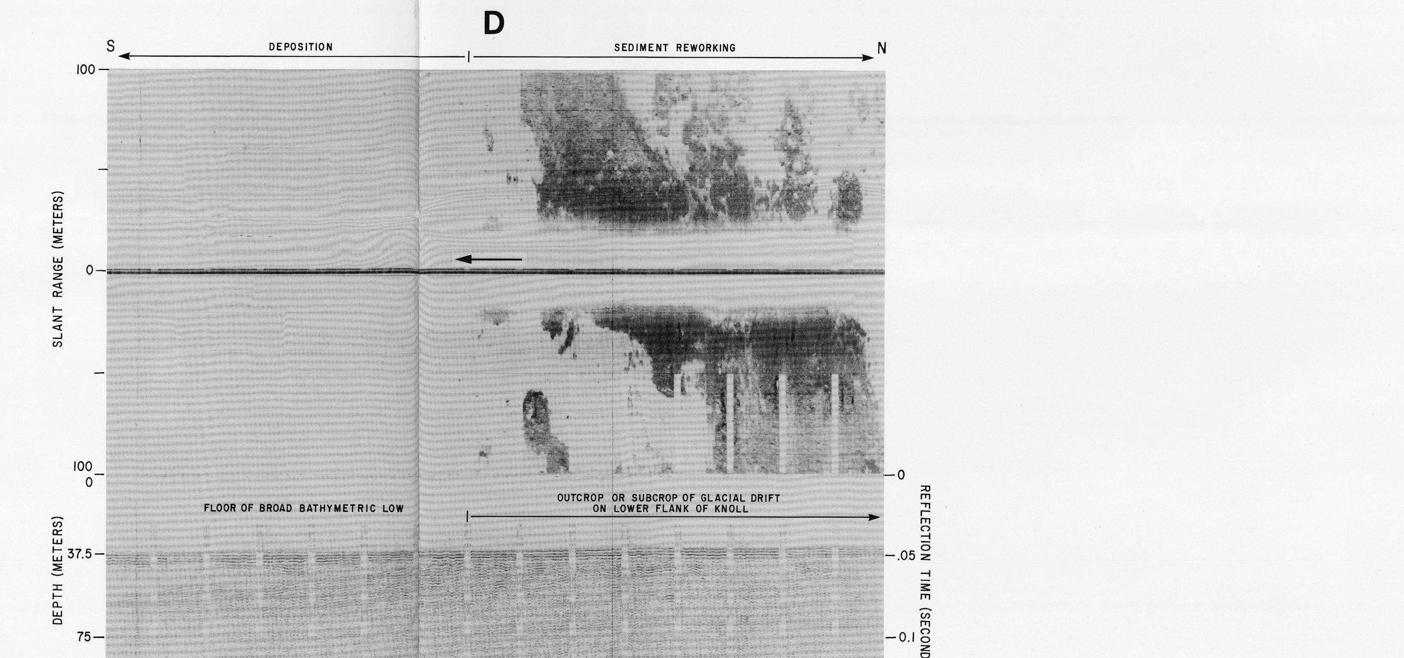
Sonograph A shows a pattern with isolated reflections produced by an outcrop of bedrock near the southern entrance to Boston Harbor. Patterns produced by bedrock outcrops generally have a "blotchy" appearance on the sonographs, whereas patterns produced by outcrops of coarse glacial drift have a "speckled" appearance (see sonograph B). Both of the patterns with isolated reflections (blotchy and speckled) depict environments of erosion or nondeposition.



Sonograph B shows the change (north to south) from a pattern with isolated reflections ("speckled") located atop a bathymetric high, to a pattern of strong backscatter (uniformly dark) on the southern flank of the high, to a pattern of strong-to-weak backscatter (patchy dark and light) within the adjacent broad low farther south. Patterns with isolated reflections and patterns of strong backscatter depict environments of erosion or nondeposition, whereas patterns with patches of strong-to-weak backscatter depict environments of sediment reworking. Below sonograph B, the high-resolution seismic-reflection (boomer) profile shows an outcrop of glacial drift (probably till) atop the bathymetric high where the sonograph pattern with isolated reflections was found.



Sonograph C shows a pattern of weak backscatter produced by muds in an environment of deposition along the floor of Stellwagen Basin. Lines of dots on the record are operational artifacts.



Sonograph D shows the change (north to south) from a pattern of strong-to-weak backscatter (patchy dark and light), which depicts an environment of sediment reworking on the lower flank of a broad knoll, to a pattern of weak backscatter (uniformly light), which depicts an environment of deposition on the floor of the adjacent bathymetric low. Below sonograph D, the high-resolution seismic-reflection (boomer) profile shows an outcrop or subcrop of coarse glacial drift (probably till) where the environment of sediment reworking was observed; patches of strong backscatter on the sonograph are sites where the drift is exposed at the sea floor.

Figure 4.--Sidescan sonographs showing characteristic acoustic patterns. Arrows along centerlines indicate direction of ship travel. Sonographs A, B, and D are uncorrected for lateral distortion caused by the slant range of sound.

MAPS AND DIAGRAMS SHOWING ACOUSTIC AND TEXTURAL CHARACTERISTICS AND DISTRIBUTION OF BOTTOM SEDIMENTARY ENVIRONMENTS, BOSTON HARBOR AND MASSACHUSETTS BAY

By

Harley J. Knebel and Ronald C. Circé

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