

# Sea-Floor Environments Within Long Island Sound: A Regional Overview

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## ABSTRACT

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Modern sea-floor sedimentary environments within the glaciated, topographically complex Long Island Sound estuary have been interpreted and mapped from an extensive collection of sidescan sonographs, bottom samples, and video-camera observations together with supplemental bathymetric, marine-geologic, and bottom-current data. Four categories of environments are present that reflect the dominant long-term processes of: erosion or nondeposition; coarse-grained bedload transport; sediment sorting and reworking; and fine-grained deposition. (1) Environments of erosion or nondeposition contain exposures of glacial drift, coarse lag deposits, and possibly bedrock and include sediments which range from boulder fields to gravelly coarse-to-medium sands. (2) Environments of coarse-grained bedload transport are mantled by sand ribbons and sand waves and contain mostly coarse-to-fine sands with only small amounts of mud. (3) Environments of sediment sorting and reworking comprise both uniform and heterogeneous sediment types and contain variable amounts of fine sand and mud. (4) Environments of fine-grained deposition are blanketed by muds and sandy muds.

The patchy distribution of sedimentary environments within Long Island Sound reflects both regional and local changes in bottom processes. Regional changes are primarily the result of a strong, east-to-west decreasing gradient of bottom tidal-current speeds, coupled with the net (westward) estuarine bottom drift. The regional current regime has produced a westward succession of environments along the basin floor beginning with erosion or nondeposition at the narrow eastern entrance to the Sound, changing to an extensive area of coarse-grained bedload transport, passing into a contiguous band of sediment sorting, and ending with broad areas of fine-grained deposition in the central and western Sound. However, local changes in processes are superimposed on the regional conditions within the central and western parts of the basin and along the nearshore margins. Within the central and western basin, localized sedimentary environments are produced where the bottom flow is enhanced by, and interacts with, the bottom topography, whereas along the nearshore margins, they variously reflect wave-produced currents, the irregular bathymetry, the indented shoreline, and the proximal supply of sediments.

Results from this study (1) confirm the high trapping efficiency of fine-grained sediments in the Sound, (2) suggest that fine-grained sediments accumulate at an average (regional) rate of 0.08 g/cm<sup>2</sup>/y, and (3) indicate that the post-glacial delta in the eastern Sound was a significant source of fine-grained sediments now buried beneath depositional areas.

**ADDITIONAL INDEX WORDS:** *Long Island Sound, estuaries, sedimentary processes, sedimentary environments, side-scanning methods.*

## INTRODUCTION

Long Island Sound is one of the largest estuaries along the Atlantic coast of the United States (Figure 1). It is a semi-enclosed, northeast-southwest-trending embayment that is 150 km long and 30 km across at its widest point. Its mean water depth is about 24 m. The eastern end of the Sound opens to the Atlantic Ocean through several large passages between islands (see Figure 1), whereas the western end is connected to New York Harbor through a narrow tidal strait. Fluvial input into the Sound is dominated by the Connecticut River.

A study of the modern sedimentary environments on the sea floor within the Long Island Sound estuarine system was

undertaken as part of a larger research program by the U.S. Geological Survey designed to understand the regional processes that distribute sediments and the contaminants associated with them. Knowledge of the bottom sedimentary environments was needed to discern the long-term fate of wastes and contaminants that have been, or will be, introduced into the system.

The study area encompasses 2,900 km<sup>2</sup> or more than 95% of the Sound's sea floor. It is bordered by the Connecticut and Long Island coastlines on the north and south (Figure 1).

Prior to this report, KNEBEL *et al.* (1999) outlined the characteristics and distributions of bottom sedimentary environments for much of the basinal part of the Sound (herein defined as having water depths greater than 10 m). Only the

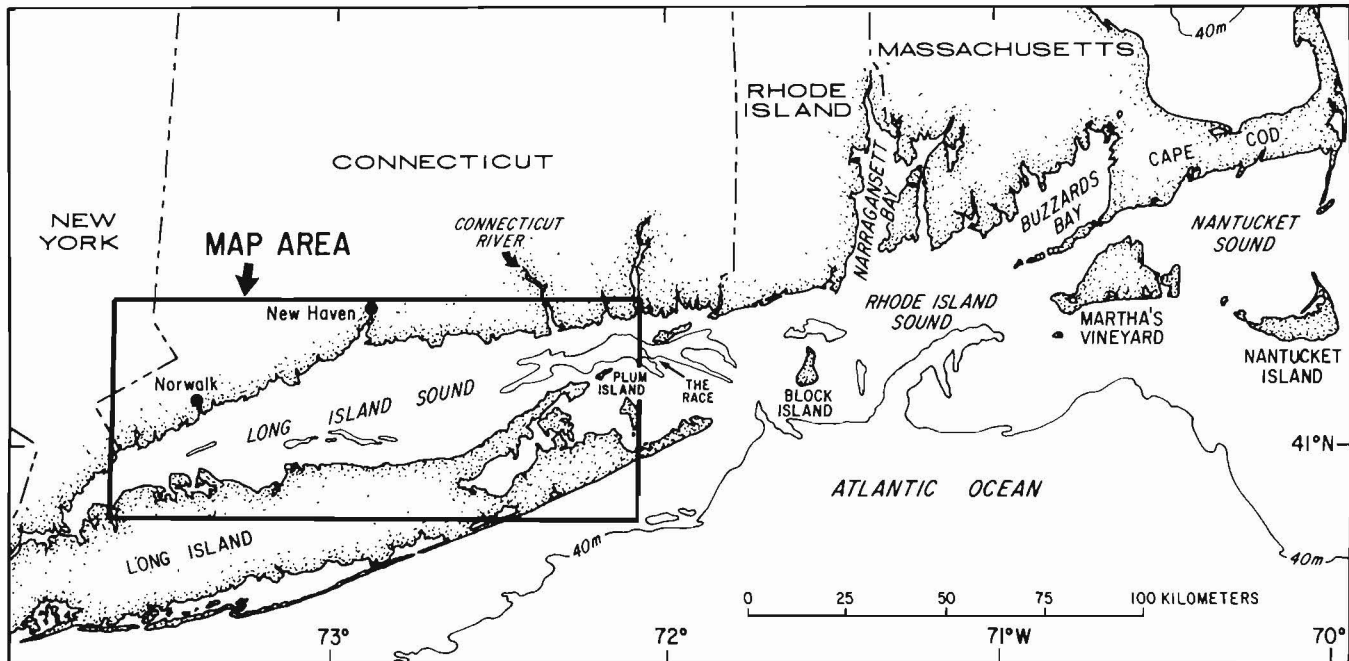


Figure 1. Location of Long Island Sound showing map area presented in Figures 2, 3, 8–12. Bathymetric contours shown are all 40 m. (Reprinted from *Marine Geology*, v. 155, KNEBEL *et al.*, Seafloor environments in the Long Island Sound estuarine system, p. 277–318, Copyright (1999), with permission of Elsevier Science).

major findings from this earlier work have been included here. The reader is urged to consult the full text of that report 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 the easternmost and

westernmost parts of the basin and for the nearshore margins (herein defined as having water depths of 10 m or less). It also includes derivative maps not presented elsewhere.

In this paper, we present a synthesis of the characteristics and distributions of modern sea-floor environments within the Long Island Sound sedimentary system. We also discuss

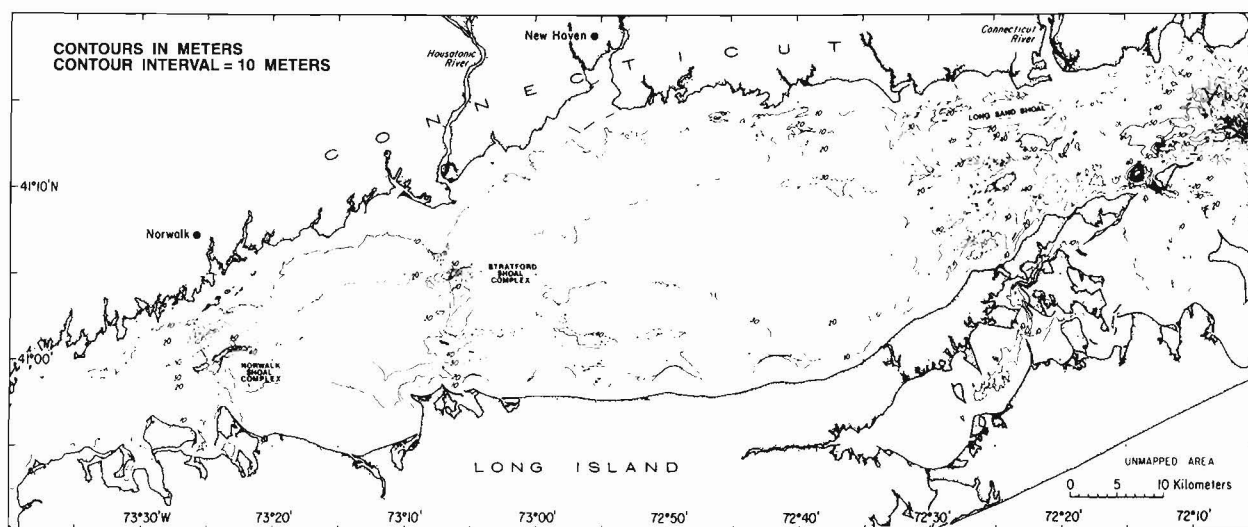


Figure 2. Generalized bathymetric map of Long Island Sound. Depth contours are from U.S. GEOLOGICAL SURVEY (1984, 1986) and NATIONAL OCEAN SERVICE (1989a, b).

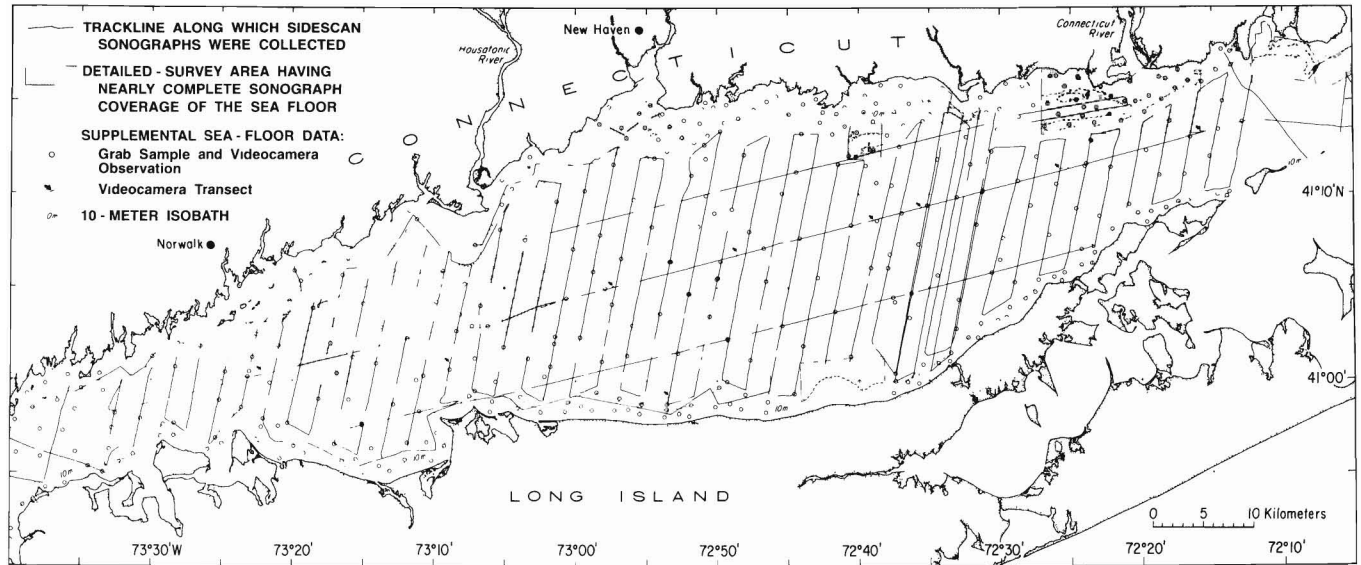


Figure 3. Locations of sidescan sonographs and supplemental data used to infer the modern sea-floor sedimentary environments within the Long Island Sound study area. The 10-m isobath delineates the nearshore margins along the Connecticut and Long Island coasts.

the major regional and local processes that have controlled the complex distribution of environments and outline some implications from this work regarding fine-grained sediment accumulation in the Sound.

## ENVIRONMENTAL SETTING

### Geologic History

In this section, we highlight some salient points about the geologic history of Long Island Sound that pertain to the characteristics and distribution of bottom sedimentary environments. A more extensive account of the geologic history is presented by LEWIS and DIGIACOMO-COHEN (this volume).

Glaciation, ice retreat, and marine submergence characterize the late Quaternary geologic history of the Sound (BLOOM and STUIVER, 1963; LEWIS and NEEDELL, 1987; NEEDELL *et al.*, 1987; LEWIS, 1989; GAYES and BOKUNIEWICZ, 1991; LEWIS and STONE, 1991; STONE and LEWIS, 1991; STONE *et al.*, 1998; LEWIS and DIGIACOMO-COHEN, this volume). During Pleistocene time, glaciers advanced southward across the Long Island Sound basin and deposited drift over the irregular, scoured surface. The Laurentide (last) ice sheet reached Long Island, where its position is marked by a series of end and recessional moraines. The recessional moraine that now forms the north shore of Long Island was the dam for an extensive glacial lake, Lake Connecticut. During its northward retreat from Lake Connecticut, the ice also deposited coarse-grained drift (including lacustrine-fan, morainal, and glaciodeltaic deposits) along the Connecticut coast and nearshore area. The Long Island Sound estuary was created subsequently when the glacially modified basin was submerged by the postglacial eustatic rise of sea level beginning about 15 ka. During the transgression, an extensive marine delta was deposited in the eastern part of the Sound when sea level

was at  $-40$  m; this was caused by the rapid erosion of the lake bed of glacial Lake Hitchcock located within the Connecticut River valley. As marine submergence continued, tidal currents extended their reach throughout the basin and, eventually, controlled the distribution of sea-floor environments.

### Bottom Topography

The sea-floor topography is generally irregular in the funnel-shaped eastern part of the basin (Figure 2). It has especially high relief across the eastern entrance to the Sound, where scour depressions are associated with the narrow passages between islands. Water depths within these depressions typically reach 40 to 50 m and, in places, exceed 100 m. West of the mouth of the Connecticut River (for a distance of 20–25 km), the bottom is characterized by a series of tidal ridges and channels trending east-northeast to west-southwest (FENSTER *et al.*, 1990; FENSTER, 1995). Water depths in this hummocky area are generally less than 50 m, and relief of 20 to 30 m is common.

The topography in the central and western parts of the basin consists of broad areas of relatively flat sea floor separated by the Stratford and Norwalk shoal complexes (Figure 2). In areas of flat sea floor, the bottom slopes toward an east-west axial depression which is about 77 km long and has thalweg depths of 30 to 60 m. The axial depression is narrowest and deepest where it cuts across the shoal complexes. Locally, small knolls and low ridges protrude above the smooth basin floor. The Stratford and Norwalk shoal complexes comprise irregular assemblages of topographic highs and lows that have maximum relief of about 40 m and are oriented generally north-south across the Sound.

The topography of the nearshore margins reflects the char-

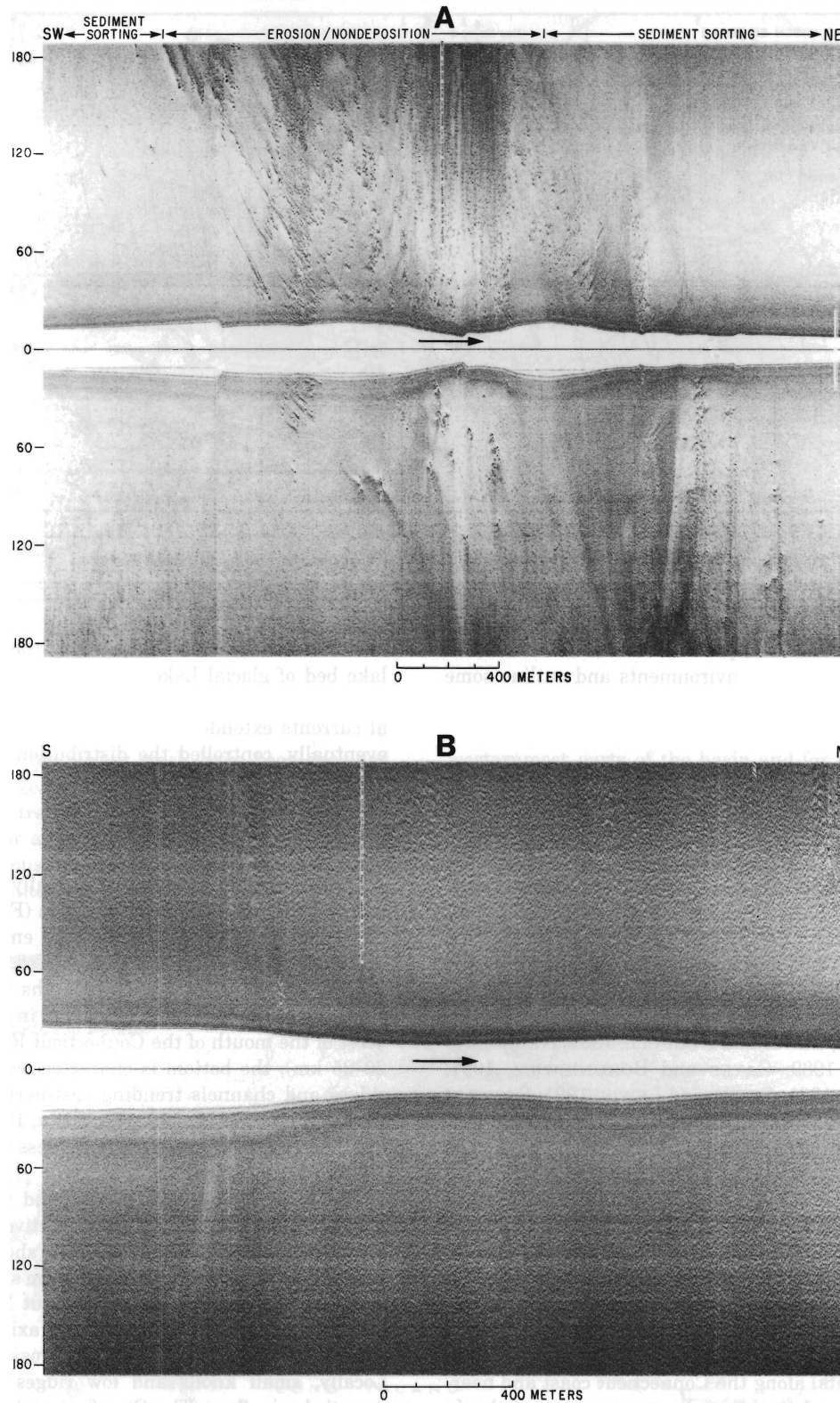


Figure 4. Sidescan sonographs of the bottom within Long Island Sound. Darker tones indicate areas that produced stronger backscatter, whereas lighter tones indicate areas that produced weaker backscatter. Arrows along centerlines indicate direction of ship travel. Sonographs are uncorrected for lateral distortion caused by the slant range of sound. (Reprinted from *Marine Geology*, v. 155, KNEBEL *et al.*, Seafloor environments in the Long Island Sound estuarine system, p. 277–318, Copyright (1999), with permission from Elsevier Science). (A) Sonograph obtained across a small knoll in the north-central part of the Sound that shows a pattern with isolated reflections (center of sonograph) produced by an outcrop of coarse glacial drift. Numerous boulders

acter of the adjacent shoreline. Numerous small bathymetric highs and lows are present over most of the Connecticut margin and the western third of the Long Island margin. In these areas, the topography closely parallels the irregular, indented shoreline formed by rocky headlands and small protected embayments (KOPPELMAN *et al.*, 1976). In contrast, the nearshore topography is relatively smooth along the eastern two-thirds of the Long Island margin. Here, the shoreline is composed of gently curved reaches which are backed by sandy bluffs.

### Hydrodynamic Setting

The bottom circulation in Long Island Sound is dominated by the lunar semidiurnal tide (RILEY, 1956; GORDON and PILBEAM, 1975; BOKUNIEWICZ and GORDON, 1980b; IANNIELLO, 1981; KENEFICK, 1985; SIGNELL *et al.*, 1998, this volume). Within the basin, maximum tidal-current speeds (during a tidal cycle) at one meter above the bottom ( $z = 100$  cm) generally decrease from more than 60 cm/s at the eastern entrance to the Sound to less than 20 cm/s near the western end. However, they are locally variable due to the irregular basin topography, especially across the shoal complexes. Maximum bottom tidal-current speeds over the nearshore margins are typically 20 to 30 cm/s in the eastern Sound and 15 to 20 cm/s in the central and western Sound. The direction of flow of the tide is mainly northeast-southwest, parallel to the trend of the Sound.

Nontidal estuarine circulation exists within the Sound throughout the year (RILEY, 1956; GROSS and BUMPUS, 1972; HOLLMAN and SANDBERG, 1972; GORDON and PILBEAM, 1975; PASKAUSKY and MURPHY, 1976; WILSON, 1976; BOKUNIEWICZ and GORDON, 1980a; KIM and BOKUNIEWICZ, 1991). Residual bottom currents caused by the estuarine circulation flow toward the west and southwest (into the Sound). These currents reach speeds of about 2 to 4 cm/s in the eastern and central parts of the Sound and are locally enhanced to 6 to 8 cm/s along the axial depression in the central and western Sound (SIGNELL *et al.*, this volume).

Wind- and wave-driven bottom currents are locally variable, depending on wind speed, direction, duration, and fetch (BOHLEN, 1975; MCCALL, 1977; BOKUNIEWICZ, 1980; BOKUNIEWICZ and GORDON, 1980a; FREDETTE *et al.*, 1988; SIGNELL *et al.*, 1998; KNEBEL *et al.*, 1999). In general, wind-driven bottom currents are the greatest when strong winds blow along the length of the Sound during storms. At these times, the bottom flow is downwind along the nearshore margins and against the wind along the axial depression in the central and western basin. The effects of wave-produced currents on the bottom flow are mainly limited to water depths of 20 m or less.

### DATA AND METHODS

This report is based primarily on a regional set of sidescan sonographs collected along 1,120 km of tracklines (see regularly spaced lines in Figure 3). This set of sonographs was obtained using a sidescan-sonar system that operated at a frequency of 100 kHz and scanned 187 m to each side of the ship's track. Ancillary sonographs were collected: (1) along the nearshore margins in the central and western Sound; (2) across the basin adjacent to the eastern and western ends of the regional survey lines; (3) along four north-northeast to south-southwest transverse lines located about 20 km southwest of the mouth of the Connecticut River; (4) along two short longitudinal lines located just north of Long Sand Shoal; and (5) within nine detailed-survey areas (having nearly complete sea-floor coverage) located throughout the Sound (POPPE *et al.*, 1992, 1997, 1998a, b, 1999a, b; MICKLE, 1997; TWICHELL *et al.*, 1997, 1998) (Figure 3). Navigational control for all tracklines was provided by a differential Global Positioning System (GPS).

Grab samples and videocamera observations of the bottom were obtained at 413 stations within the study area (Figure 3). Of this total, 147 were occupied at strategic locations along or near the regional survey lines, whereas 266 stations were occupied at locations elsewhere within the basin and along the nearshore margins. Numerous ancillary samples and videocamera observations also had been collected within the nine detailed-survey areas (see foregoing references). Subsamples taken from the upper 2 cm of the sediments in the grab samples were analyzed for texture using sieves (gravel fraction), a rapid sediment analyzer (sand fraction) (SCHLEE, 1966), and a Coulter Counter (silt and clay fractions) (SHIDELER, 1976). Shell fragments greater than 2 mm were removed from the subsamples before analyses. Size classifications were based on the method proposed by WENTWORTH (1929).

In addition to the sonographs and textural observations, this study made use of a large amount of supplemental marine-geologic data. These data included: (1) high-resolution seismic-reflection profiles (2 to 7 kHz or 3.5 kHz) collected concurrently with all sonographs; (2) previous geologic maps based on a regional set of subbottom (boomer) profiles (LEWIS and NEEDELL, 1987; NEEDELL *et al.*, 1987; LEWIS and STONE, 1991); (3) prior regional maps of bottom-sediment types (FELDHAUSEN and ALI, 1976; REID *et al.*, 1979; WILLIAMS, 1981; NEFF *et al.*, 1988; NATIONAL OCEAN SERVICE, 1989a, b); (4) a regional suite of vibracore samples (DONOHUE and TUCKER, 1970; WILLIAMS, 1981; LEWIS and NEEDELL, 1987; NEEDELL *et al.*, 1987; SZAK, 1987); (5) modeled tidal-, wind-, and wave-produced bottom currents (SIGNELL *et al.*, 1998, this volume; KNEBEL *et al.*, 1999); and (6) the detailed

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are present on the sea floor, and bottom sediments (where sampled) are gravelly, coarse sands. Such sonograph patterns depict environments of erosion or nondeposition. The bouldery outcrop is surrounded by sonograph patterns of moderate backscatter that contain uniform fine and very-fine sands and indicate environments of sediment sorting. Abrupt "shifts" in the distance between the centerline and the trace of the bottom in the sonograph are operational artifacts. (B) Sonograph obtained across the rugged sea floor at the eastern entrance to the Sound that shows a pattern of strong backscatter produced by coarse lag deposits. Such patterns are caused by gravelly, coarse-to-medium sands and indicate environments of erosion or nondeposition. Small bedforms (ripples and megaripples) are ubiquitous on the bottom.

bathymetry of the sea floor, having a contour interval of 1 to 2 m (U.S. GEOLOGICAL SURVEY, 1984, 1986; NATIONAL OCEAN SERVICE, 1989a, b).

Seven characteristic sonograph patterns (Figures 4–6) were used in conjunction with the textural, videocamera, and supplemental marine-geologic data to identify and map the sedimentary environments within the study area. These characteristic patterns, which have been interpreted by KNEBEL *et al.* (1999), are strongly correlated with topographic changes, sea-floor morphology, bottom-sediment types, and water depth (see next section). Such correlations allowed us to infer the distributions of sedimentary environments between cruise tracks and across similar bottom features. In the sonographs (Figures 4–6), darker tones indicate areas which produced stronger backscatter (relatively coarse-grained sediments), whereas lighter tones indicate areas which produced weaker backscatter (relatively fine-grained sediments).

### CHARACTERISTICS AND LOCATIONS OF SEDIMENTARY ENVIRONMENTS

In this section, we outline the characteristics and locations of the following four categories of bottom sedimentary environments: (1) erosion or nondeposition; (2) coarse-grained bedload transport; (3) sediment sorting and reworking; and (4) fine-grained deposition. It should be noted that these environments reflect the effects of dominant, long-term processes. Atypical processes, which infrequently affect the sea floor within each environment (such as storm erosion in fine-grained depositional areas), could not be recognized in the sonographs because they either did not leave a permanent imprint on the bottom or were below the detection limit of the sensors.

#### 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.*, 1999) (Figures 4A, B). Patterns with isolated reflections have a “speckled” appearance produced by strong backscatter from numerous boulders or rock masses (up to 3 m in diameter) on the sea floor (Figure 4A). Gravel-size sediments are ubiquitous in these areas and ripples (having wavelengths of 10–20 cm) commonly are present in sediment patches among the boulders and rock masses. Where sediments could be recovered, they were primarily gravels and gravelly coarse sands. The average amounts of gravel-plus-coarse sand, medium sand, fine-plus-very fine sand, and silt-plus-clay are 53, 32, 12, and 3%, respectively (Figure 7). Patterns of strong backscatter, on the other hand, appear as nearly uniform dark sonographs (Figure 4B). These patterns variously exhibit ripples (wavelengths of 10–20 cm), small, low bedforms (wavelengths of 4–10 m; wave heights less than 0.25 m), and scattered boulders. Sediments obtained from areas of strong backscatter were mainly sandy gravels and gravelly coarse-to-medium sands. The average amounts of gravel-plus-coarse sand, medium sand, fine-plus-very fine sand, and silt-plus-clay are 37, 46, 15, and 2%, respectively (Figure 7).

Environments of erosion or nondeposition cover 22% of the study area (Figure 8). Within the basin, these environments were found: (1) across the rugged topography at the eastern entrance to the Sound; (2) within an irregular depression north of Long Sand Shoal; (3) in patches atop the Stratford and Norwalk shoal complexes; (4) within the constricted axial depression where it cuts across the two shoal complexes; and (5) over isolated topographic highs that protrude above the basin floor. Along the nearshore margins, they were found in nearly continuous bands (water depths typically 10 m or less) which border the entire southern shoreline and most of the northern shoreline southwest of New Haven Harbor. East of New Haven Harbor, they comprise nearshore patches which are located primarily atop small knolls and bathymetric highs.

#### Environments of Coarse-Grained Bedload Transport

Coarse-grained bedload transport is indicated by sonograph patterns of sand ribbons and sand waves (KNEBEL *et al.*, 1999) (Figure 5A). Sand ribbons appear on the sonographs as elongate bands (typically 20–250 m wide) of alternate strong and moderate backscatter. They are oriented primarily east-northeast to west-southwest parallel to the trend of the Sound, have boundaries which vary from sharp to indistinct, and, in places, merge toward the west-southwest. Many sand ribbons have small bedforms (wavelengths of 5–10 m; wave heights less than 0.25 m) on their surfaces, and some contain scattered boulders. Samples taken from sand-ribbon areas had textures which ranged from gravelly sands to relatively uniform, medium-to-fine sands, although medium sand was a dominant or major component in all samples. The average amounts of gravel-plus-coarse sand, medium sand, fine-plus-very fine sand, and silt-plus-clay are 33, 37, 26, and 4%, respectively (Figure 7). The sand waves have wavelengths which range from 5 to 300 m, and amplitudes which range from 0.25 to more than 10 m. In the eastern Sound, the sand waves typically are oriented north-northwest to south-southeast, have steeper slip faces toward the west-southwest (into the Sound), and decrease in size and height from northeast to southwest. Locally, however, their orientations are sinuous or oblique on the upper flanks of the larger tidal ridges, and they sometimes become subparallel to the ridge crests. Elsewhere within the Sound, they had variable symmetries and orientations. Ripples (wavelengths of 5–20 cm) are ubiquitous on sand-wave surfaces. Sediments from sand-wave areas are primarily moderately-sorted, medium sands, although coarse and fine sands are dominant at some sites. The sediments also included scattered gravel and shells which typically were concentrated in sand-wave troughs. The average amounts of gravel-plus-coarse sand, medium sand, fine-plus-very fine sand, and silt-plus-clay are 15, 49, 35, and 1%, respectively (Figure 7).

Environments of coarse-grained bedload transport cover 13% of the study area (Figure 9). These environments encompass the extensive area in the east-central Sound that is characterized by the hummocky tidal ridge-and-channel topography (Figure 2). Here, sand ribbons are present within the east-northeast to west-southwest trending tidal channels,

and sand waves are present over the intervening tidal ridges (Figures 5A, 9). A few small patches of sand waves also were found in the central and western Sound atop the Stratford shoal complex and on the tops and flanks of bathymetric highs along the nearshore margins (Figure 9).

### Environments of Sediment Sorting and Reworking

Environments of sediment sorting are characterized by sonograph patterns of moderate backscatter (Figure 5B), whereas environments of sediment reworking are characterized by patterns with patches of moderate-to-weak backscatter (Figure 6A) (KNEBEL *et al.*, 1999). Both patterns reflect a combination of erosion and deposition. Sediments in areas of sediment sorting are mostly fine-to-very fine sands, although they sometimes contain gradational admixtures of coarser and finer sediments near the boundaries with other environments. Areas of sediment sorting also include: (1) scattered boulders and gravel at some sites along the margins; (2) ripples at most nearshore locations; and (3) infaunal burrows at many stations within the basin. The average amounts of gravel-plus-coarse sand, medium sand, fine-plus-very fine sand, and silt-plus-clay are 8, 16, 58, and 18%, respectively (Figure 7). Environments of sediment reworking contain textural patches that range in size from a few meters to more than 200 m. As a result, the sediments are heterogeneous, ranging from shelly and gravelly sands with degraded ripples to uniform muds and sandy muds with infaunal burrows; the transition from one sediment type to another can be abrupt. The average amounts of gravel-plus-coarse sand, medium sand, fine-plus-very fine sand, and silt-plus-clay are 7, 7, 25, and 61%, respectively (Figure 7).

Environments of sediment sorting and reworking cover 24% of the study area (Figure 10). Sediment sorting is dominant in 21% of the area, whereas sediment reworking is dominant in only 3% of the area. On the basin floor, environments of sediment sorting comprise a wide curvilinear band that fringes the western limit of the zone of bedload transport in the eastern Sound. Smaller areas of sediment sorting are present: (1) over low knolls and ridges; (2) on the flanks of the shoal complexes; (3) within short sections of the axial depression near the Stratford shoal complex; and (4) along an irregular strip (water depths of 10–20 m) which borders most of the southern margin. Sediment reworking in the basin is limited to relatively small patches located on the crests and flanks of knolls, along the axial depression, and in areas of low, irregular relief (Figure 10). Over the nearshore margins, small areas of sediment sorting and reworking are present: (1) in coastal embayments; (2) within subtle bathymetric lows; (3) in protected areas amid bathymetric highs; and (4) off the mouths of some streams and rivers.

### Environments of Fine-Grained Deposition

Environments of fine-grained deposition are depicted on the sonographs as patterns of weak backscatter (KNEBEL *et al.*, 1999) (Figure 6B). These patterns generally are featureless except for broad gradational increases in acoustic return near areas with other environments. Such patterns are produced by bottom sediments that are dominantly muds and

sandy muds. As a group, these sediments had the finest grain sizes of the four sedimentary environments identified in the study area. The average amounts of gravel-plus-coarse sand, medium sand, fine-plus-very fine sand, and silt-plus-clay are 2, 2, 12, and 84%, respectively (Figure 7).

Environments of fine-grained deposition cover 41% of the study area (Figure 11). These environments occupy large areas of the basin floor that have low topographic gradients including: (1) most of the wide central part of the Sound; (2) the region between the two shoal complexes; and (3) sizeable areas west of the Norwalk shoal complex. They also are present in small patches over the nearshore margins, particularly in coastal embayments and where sheltered by topographic highs and points of land. Such patches are most numerous over the margin just east of New Haven Harbor.

## DISCUSSION

### Regional Processes

The basinal part of the Sound exhibits a general east-to-west succession of sedimentary environments that has been produced by the (east-to-west) decreasing gradient of tidal-current speeds coupled with the net (westward) estuarine bottom drift (KNEBEL *et al.*, 1999) (Figures 12, 13). In this regard, a large area of erosion or nondeposition is present across the rugged basin floor at the eastern entrance to the Sound (Figures 8, 12). This is the result of strong bottom ( $z = 100$  cm) tidal currents which typically exceed speeds of about 40 to 50 cm/s (SIGNELL *et al.*, 1998, this volume). These strong currents have produced a sea-floor lag deposit composed of sandy gravel and gravelly sand that is nearly in equilibrium with the modern current regime (BOHLEN, 1982; FENSTER, 1995). The lag deposit has been derived from the erosion and winnowing of the eastern flank of the marine delta which was deposited in this part of the Sound during the postglacial rise of sea level and from the scour and winnowing of glacial lake deposits which once filled the eastern end of the basin (LEWIS and STONE, 1991; FENSTER, 1995; STONE and ASHLEY, 1995).

To the west, a zone of coarse-grained bedload transport has developed on the remaining surface of the postglacial delta (KNEBEL *et al.*, 1999) (Figures 9, 12, 13). Since its formation, the delta not only has supplied a large amount of coarse-grained sediments for subsequent transport, but it has been continually reshaped by strong tidal currents and by the lateral shifting and westward extension of major tidal channels (FENSTER, 1995). These processes have produced the hummocky tidal ridge-and-channel topography which now characterizes this zone. The tidal channels are largely scour features that contain a veneer of sand ribbons over outcrops or subcrops of the marine deltaic facies (FENSTER, 1995; KNEBEL *et al.*, 1999), whereas the tidal ridges are largely accretionary features that are being maintained by sand waves driven obliquely up the ridge flanks (CASTON, 1972; BOKUNIEWICZ *et al.*, 1977; HASKELL, 1977; JOHNSON *et al.*, 1982; MCCAVE and LANGHORNE, 1982; FENSTER, 1995). Maximum near-bottom ( $z = 100$  cm) tidal currents in the zone of bedload transport range from more than 45 cm/s in the east to about 35 cm/s in the west (SIGNELL, 1998, this volume).

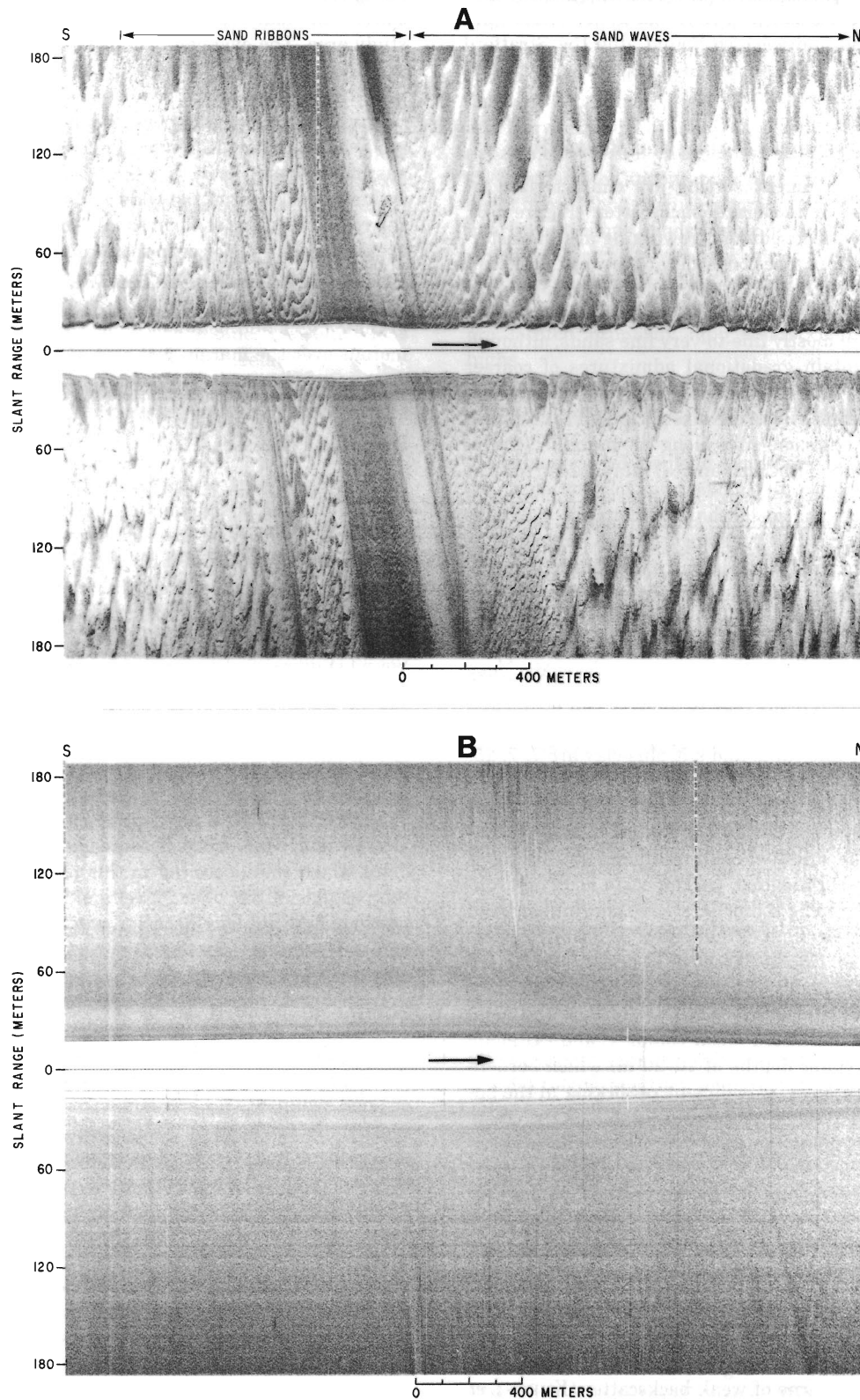


Figure 5. Sidescan sonographs of the bottom within Long Island Sound. Darker tones indicate areas that produced stronger backscatter, whereas lighter tones indicate areas that produced weaker backscatter. Arrows along centerlines indicate direction of ship travel. Sonographs are uncorrected for lateral distortion caused by the slant range of sound. (Reprinted from *Marine Geology*, v. 155, KNEBEL *et al.*, Seafloor environments in the Long Island Sound estuarine system, p. 277-318, Copyright (1999), with permission from Elsevier Science). (A) Sonograph obtained in the east-central part of the Sound that



These speeds generally exceed or are near the threshold of sediment movement for medium sand (MILLER *et al.*, 1977), the dominant component of the sand ribbons and sand waves.

Farther west, a broad curvilinear band of sediment sorting fringes the zone of bedload transport (Figures 10, 12, 13). Gradational sorting across this band is evident from a progressive east-to-west decrease in grain size that is accompanied by a decrease in acoustic backscatter (KNEBEL *et al.*, 1999). Maximum near-bottom ( $z = 100$  cm) tidal-current speeds across the band range from about 25 to 35 cm/s and decrease from east to west in response to the widening of the basin (SIGNELL *et al.*, 1998, this volume). These current speeds generally exceed or are near the threshold of sediment movement for fine and very-fine sands (MILLER *et al.*, 1977), the dominant size fractions within the band. Sandy sediments brought to this area by the net westward bottom transport are sorted according to gradients of current speed and transport frequency (KNEBEL *et al.*, 1999). These sorted sediments have been extended westward in the Sound where they have either covered over or been mixed with older deposits (DONOHUE and TUCKER, 1970; BOKUNIEWICZ, 1980; GORDON, 1980; FENSTER, 1995).

Continuing west, the band of sorted sediments gives way to environments of fine-grained deposition that cover broad areas of the central and western basin (Figures 11–13). Depositional environments here are characterized by relatively weak, near-bottom ( $z = 100$  cm) tidal currents with speeds that typically range from 15 to 25 cm/s (RHOADS *et al.*, 1978; SIGNELL *et al.*, 1998, this volume). In addition to a weak tidal-current regime, the accumulation of muddy sediments in depositional areas occurs via sand-sized particle aggregates which are produced by biological and chemical means and have settling speeds greater than those of constituent grains (KRANCK, 1973, 1975; BIGGS, 1978; RHOADS *et al.*, 1978; YINGST and RHOADS, 1978; KNEBEL *et al.*, 1999). Once on the bottom, particle aggregates either are biologically mixed into the existing sediments or are incorporated into a ubiquitous mantle (about 10 mm thick) of very-fine-sand-sized, organic/mineral fecal pellets, produced by benthic organisms (RHOADS *et al.*, 1978; YINGST and RHOADS, 1978; BOKUNIEWICZ and GORDON, 1980a; GORDON, 1980; TUREKIAN *et al.*, 1980; RHOADS, 1994). Tidal currents regularly resuspend the upper parts of this fecal-pellet layer, causing the rapid dispersal of fine-grained sediments throughout the central and western Sound (YOUNG, 1971; BOKUNIEWICZ, 1980; BOKUNIEWICZ and GORDON, 1980a; GORDON, 1980; RHOADS, 1994). Suspended materials have residence times in such resuspension cycles of 6 months or more. Ultimately, they are buried and isolated from the bottom currents and converted into cohesive sea-floor sediments (BOKUNIEWICZ, 1980; GORDON, 1980; RHOADS, 1994).

## Local Processes

Local processes are superimposed on the regional east-to-west succession of sedimentary environments (Figures 8–13). Topographic highs in the central and western parts of the basin cause local increases in bottom tidal-, wind-, and wave-produced currents (FELDHUSEN and ALI, 1976; KOPPELMAN *et al.*, 1976; BOKUNIEWICZ and GORDON, 1980a; BOWMAN and ESAIAS, 1981; KIM and BOKUNIEWICZ, 1991; SIGNELL *et al.*, 1998). These increases, in turn, produce patchy areas of sediment erosion, transport, sorting, and reworking that interrupt the prevailing fine-grained deposits (KNEBEL *et al.*, 1999). For example, localized areas of erosion or nondeposition and bedload transport are present on the tops of the Stratford and Norwalk shoal complexes and over prominent highs that protrude above the basin floor. At these locations, coarse glacial drift crops out or forms subcrops at the sea floor (MCCRONE *et al.*, 1961; WILLIAMS, 1981; LEWIS and STONE, 1991; TWICHELL *et al.*, 1997). In addition, localized environments of sediment sorting and reworking are present on the lower flanks of the shoal complexes, over subtle basinal highs, and in areas of low, irregular relief. Here, the degree of current enhancement is less than that for areas of erosion and transport, and the sorted and reworked sediments reflect either selective winnowing or variable bottom flow (KNEBEL *et al.*, 1999).

Topographic enhancement of the bottom currents also causes localized areas of sediment erosion, sorting, and reworking along the axial depression in the central and western basin (Figures 8, 10, 12). Areas of erosion or nondeposition are present in the most constricted parts of the depression (where it cuts across the shoal complexes), whereas areas of sediment sorting and reworking are present along short sections of the depression near the Stratford shoal complex. Hydrodynamic modeling indicates that scour or winnowing in these areas can occur during storms generating winds toward the east, when the westward-directed bottom flow along the axial depression reinforces both the ambient flood-tidal currents and the near-bottom estuarine flow (SIGNELL *et al.*, 1998, this volume).

Bottom topography is also a factor in the localized area of sediment erosion or nondeposition found within the irregular depression north of Long Sand Shoal in the eastern Sound (Figures 8, 12). Here, near-bottom ( $z = 100$  cm) tidal currents reach speeds of 40 to 50 cm/s, and the ebb currents are stronger than the flood currents (SIGNELL *et al.*, 1998). This residual flow causes ebb-oriented, easterly migrating bedforms along the northern flank of Long Sand Shoal (COFFIN, 1988; HORNE and PATTON, 1991) and a net eastward transport of sediments out of the depression (HASKELL, 1977; SIGNELL *et al.*, 1998). The dominance of ebb currents is likely related to

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shows an environment of coarse-grained bedload transport depicted by patterns of sand ribbons and sand waves. The sand ribbons are present within a large tidal channel and are composed of coarse-to-fine sands. Some sand ribbons have small bedforms on their surfaces. The sand waves are present over broad tidal ridges. They have heights of 1 to 4 m and spacings of 30 to 80 m and are composed primarily of medium sands. Seismic-reflection profiles obtained across this area show that most sand waves are asymmetrical toward the west-southwest. (B) Sonograph which shows a pattern of moderate backscatter produced by uniform fine-to-very fine sands and indicative of an environment of sediment sorting. Sonograph was obtained within the broad curvilinear band of sorted sediments located across the east-central basin floor (see Figure 10).

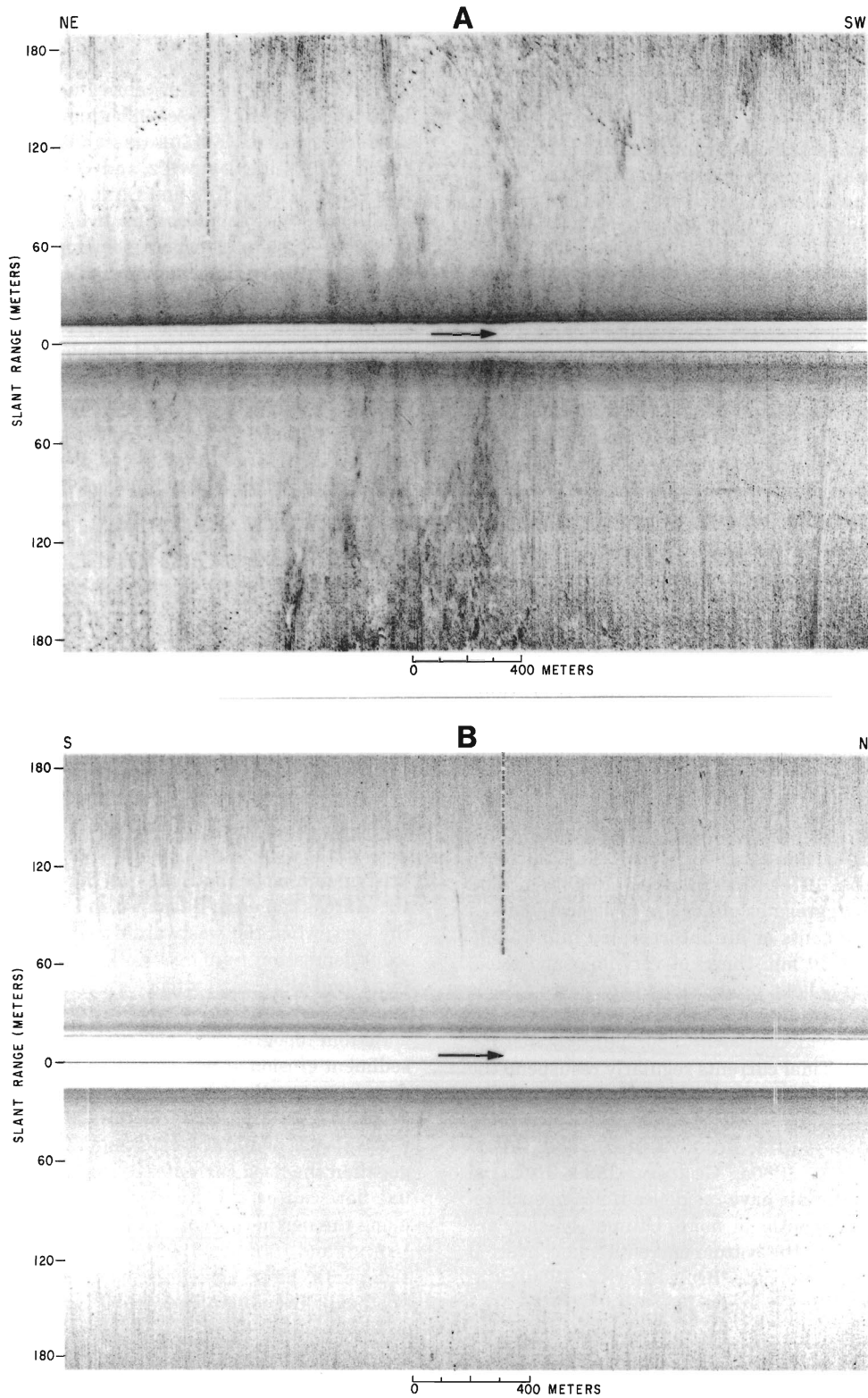


Figure 6. Sonographs of the bottom within Long Island Sound. Darker tones indicate areas that produced stronger backscatter, whereas lighter tones indicate areas that produced weaker backscatter. Arrows along centerlines indicate direction of ship travel. Sonographs are uncorrected for lateral distortion caused by the slant range of sound. (Reprinted from *Marine Geology*, v. 155, KNEBEL *et al.*, Seafloor environments in the Long Island Sound estuarine system, p. 277–318, Copyright (1999), with permission from Elsevier Science). (A) Sonograph obtained over a small bathymetric knoll in the west-central part of the Sound that shows a pattern with patches of moderate-to-weak backscatter (center of sonograph) indicative of an environment of

the eastward convergence of the depression between Long Sand Shoal and the Connecticut coast (Figure 2).

Other localized processes operate along the nearshore margins. The nearly continuous bands of sediment erosion and sorting along most of the southern margin (Figures 8, 10, 12) largely reflect wave-produced bottom currents (KNEBEL *et al.*, 1999). Here, a band of sediment erosion or nondeposition borders the shoreline and extends offshore to water depths of about 10 m. Farther offshore, a band of sediment sorting (water depths 10–20 m) separates nearshore areas of erosion or nondeposition from areas of fine-grained deposition in the basin. Together, the two bands form a zone nearly coincident with that in which wave-generated speeds regularly exceed 15 cm/s (SIGNELL *et al.*, 1998). In particular, the band of sediment erosion or nondeposition experiences wave-generated currents which are greater than 15 cm/s more than 10% of the time, whereas the band of sediment sorting experiences similar speeds between 1% and 10% of the time (SIGNELL *et al.*, 1998). Orbital speeds of 15 cm/s generally are sufficient to resuspend silts and clays from the bottom sediments (KOMAR and MILLER, 1975). Our samples show that these size fractions have been largely winnowed from the margin sediments which originate from morainal deposits along the Long Island shore (KOPPELMAN *et al.*, 1976; WILLIAMS, 1981). The prevalence of sediment erosion and sorting along the southern margin also confirms previous empirical studies which indicate that the effects of waves on the bottom are generally limited to water depths of 20 m or less (MCCALL, 1977; BOKUNIEWICZ and GORDON, 1980a; GORDON, 1980; FREDETTE *et al.*, 1988).

The distribution of sedimentary environments over the northern nearshore margin is more complex (Figure 12). The distribution is especially patchy east of New Haven Harbor, where environments of erosion or nondeposition are largely restricted to the tops of small bathymetric highs. These small areas of erosion or nondeposition are interspersed with patches of sediment sorting, reworking, and deposition that are variously located in coastal embayments, near points of land, amid bathymetric highs, and offshore of streams and rivers. Southwest of New Haven Harbor, environments of erosion or nondeposition are more continuous, forming an irregular band along most of the shoreline. However, a diverse assemblage of other environments is present at greater water depths along this stretch of the margin.

The differences in distributions between the southern and northern margins of Long Island Sound exist despite the fact that both margins are subjected to similar wave speeds and gradients (SIGNELL *et al.*, 1998). One plausible explanation for the poor correlation between the distribution of bottom environments and the wave regime over the northern margin is that rivers and streams entering along this part of the coast not only contribute relatively large amounts of sediments (compared to the southern margin) (BOKUNIEWICZ *et*

*al.*, 1974; GARVINE, 1974; GORDON, 1980; FARROW *et al.*, 1986; KIM and BOKUNIEWICZ, 1991; RHOADS, 1994), but they also promote a northerly nearshore bottom drift (RILEY, 1956; GROSS and BUMPUS, 1972; HOLLMAN and SANDBERG, 1972; GORDON and PILBEAM, 1975; PASKAUSKY and MURPHY, 1976) which can transport sediments toward the coast. The irregular bottom topography and the indented shoreline (controlled by bedrock) also help to shelter finer-grained deposits from bottom currents. As a result, the supply of sediments at many locations along the northern nearshore margin could be sufficient to offset or mask the degradational effects of waves.

#### IMPLICATIONS FOR FINE-GRAINED SEDIMENT ACCUMULATION

Long Island Sound retains nearly all of the fine-grained sediments which are delivered to it from various sources (BOKUNIEWICZ and GORDON, 1980a; GORDON, 1980; BOKUNIEWICZ, 1988). The primary factors that control this high (nearly 100%) trapping efficiency are: (1) the large volumetric capacity of the Sound; (2) the rapid biological processing of constituent particles into aggregates and pellets; (3) the relatively low tidal-current speeds over the central and western parts of the basin; and (4) the low rate of sediment infilling compared to the rate of sea-level rise. In addition, the regional east-to-west succession of sedimentary environments outlined in this report indicates that the entrapment of fine-grained particles in the Sound is a consequence of the net westward-directed bottom drift caused by the superposition of the estuarine circulation on the tidal-current gradient. In particular, fine-grained sediments from major coastal rivers, which empty into the eastern Sound (especially the Connecticut River), are mixed into the bottom waters and, then, transported westward into the Sound (BOKUNIEWICZ *et al.*, 1974; BENNINGER, 1978; GORDON, 1980; KNEBEL *et al.*, 1999). These sediments become trapped in the central and western parts of the basin and ultimately form part of the extensive fine-grained deposits there (BOKUNIEWICZ and GORDON, 1980a; GORDON, 1980; KIM and BOKUNIEWICZ, 1991; RHOADS, 1994).

In addition to the input from large rivers, other major sources of fine-grained sediments in the Sound include: shoreline and bluff erosion (especially along the southern shoreline); coastal streams; urban and cropland runoff; and sewage treatment plants (GORDON, 1979, 1980; BOKUNIEWICZ and GORDON, 1980a; BOKUNIEWICZ and TANSKI, 1983; BOKUNIEWICZ, 1988; FARROW *et al.*, 1986; RHOADS, 1994). The total estimated mass of fine-grained sediments supplied to the Sound from all major sources is about  $9.3 \times 10^8$  kg/y (FARROW *et al.*, 1986; RHOADS, 1994). Of this total, about  $4.7 \times 10^8$  kg/y (or 51%) is supplied by large rivers (BOKUNIEWICZ and GORDON, 1980a; GORDON, 1980). Secondary sources of

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sediment reworking. The patches contain variable amounts of fine sand (dark) and mud (light), and have been produced by a combination of sediment winnowing and deposition over a subcrop of coarse sediments. (B) Sonograph obtained across the flat floor of the central basin that shows a pattern of weak backscatter produced by uniform muds and indicative of an environment of fine-grained deposition.

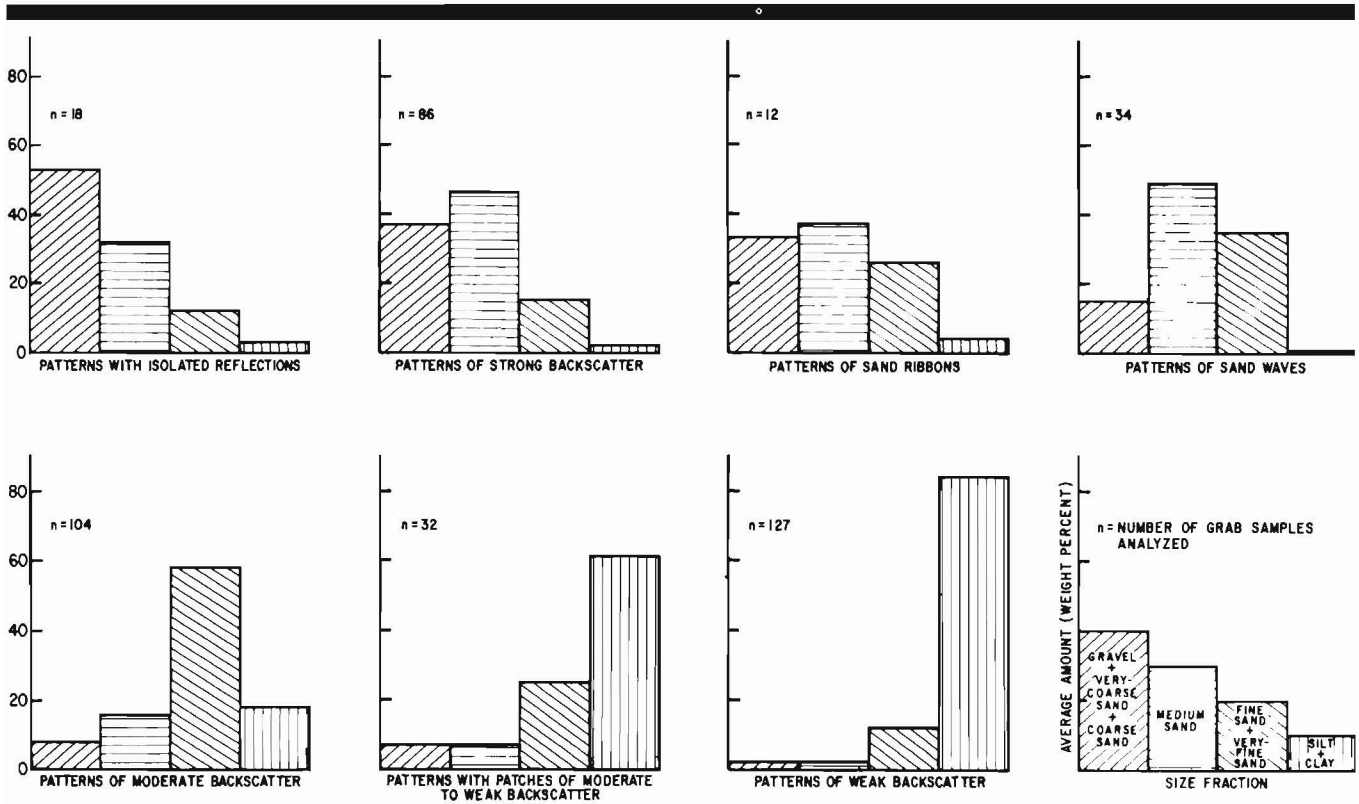


Figure 7. Histograms showing the average amounts of characteristic size fractions in bottom sediments for each of the sonograph patterns identified in the study area. Histograms are based on analyses of grab samples obtained at 413 locations (see Figure 3). Textural data for patterns with isolated reflections and for patterns of strong backscatter do not account for boulders observed on the sea floor.

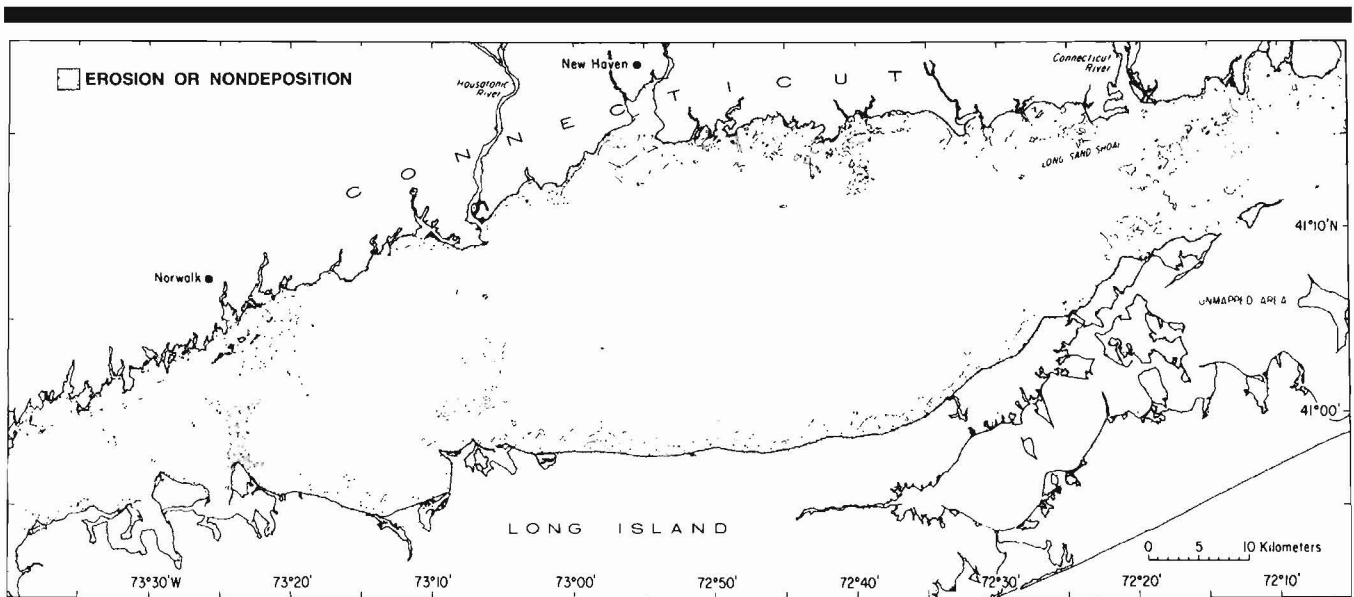


Figure 8. Distribution of environments of erosion or nondeposition, which cover 22% of the study area.

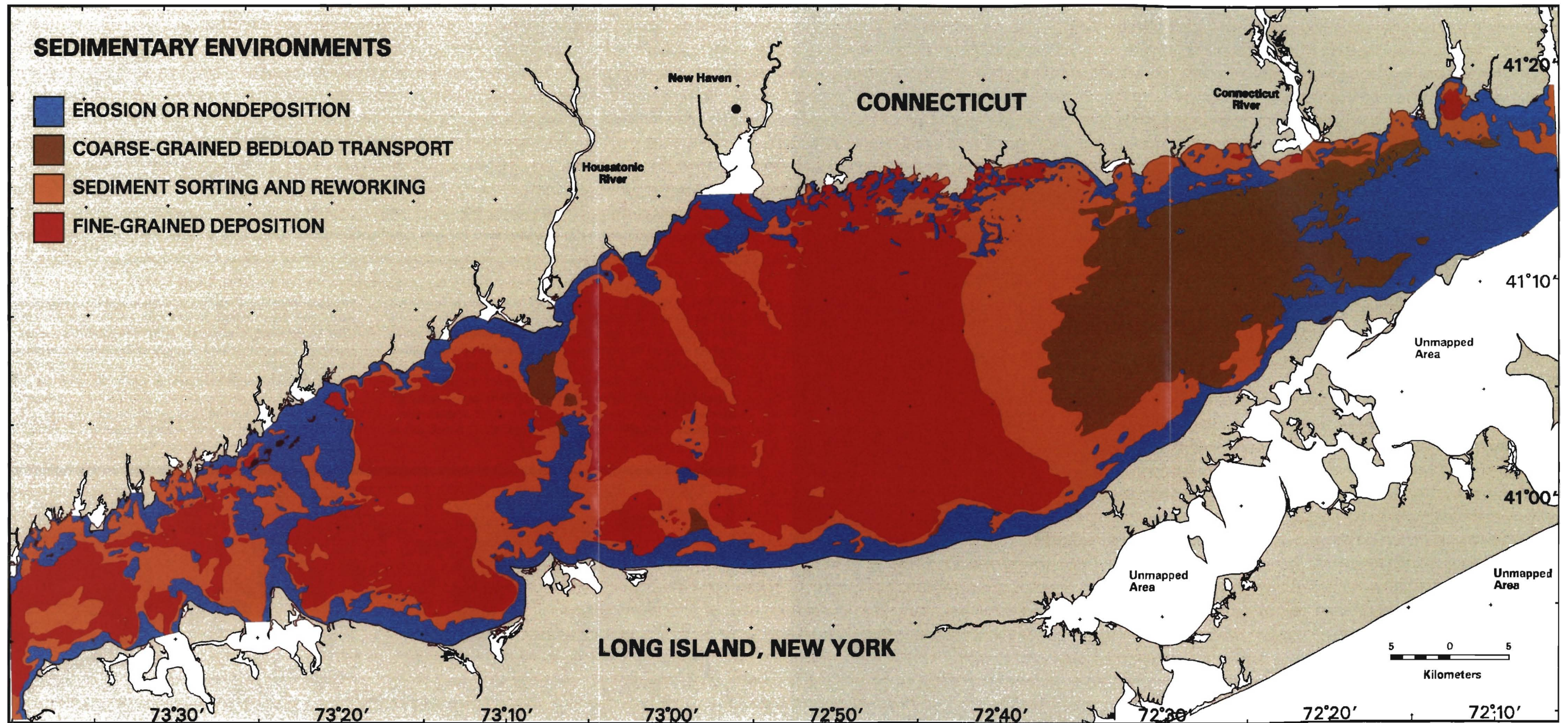


Figure 12. Composite regional map which shows the distributions of the four categories of sea-floor environments identified within the Long Island Sound study area.

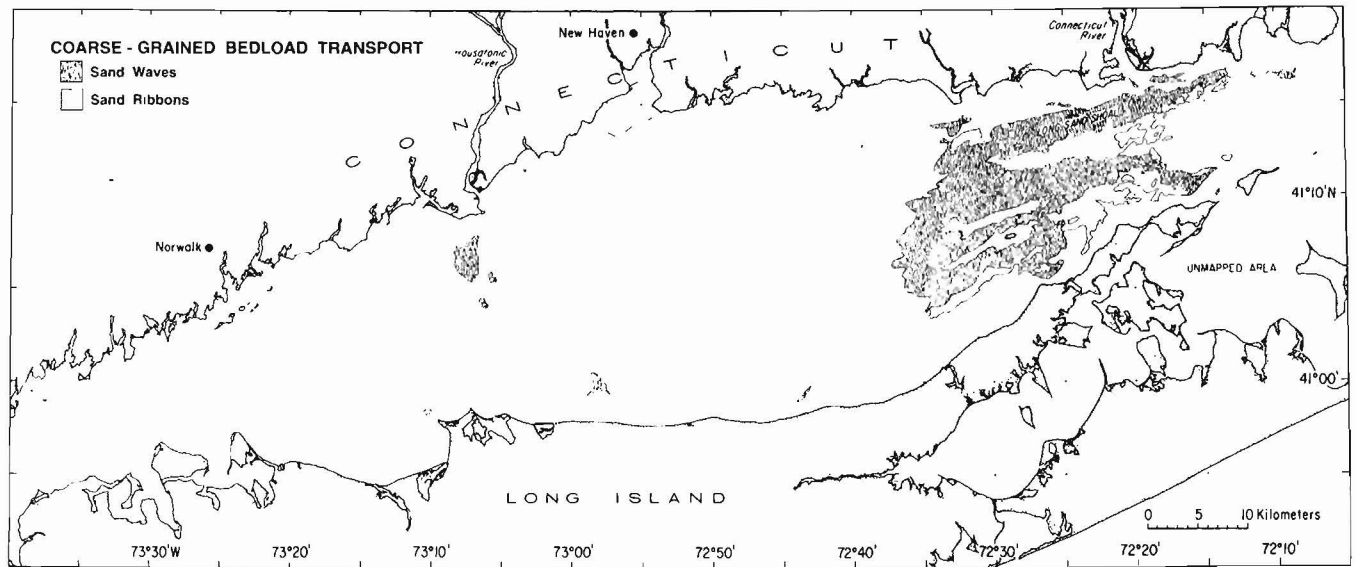


Figure 9. Distribution of environments of coarse-grained bedload transport, which cover 13% of the study area. Subareas of sand ribbons and sand waves are indicated.

fine-grained sediments include biologic production, airborne transport, and off-site dispersal of dredged material. These sources contribute only small amounts of fine-grained sediments to the Sound (BENNINGER, 1976; GORDON, 1980; BOKUNIEWICZ and GORDON, 1980a; RHOADS, 1994), although they can be qualitatively important in terms of sediment geochemistry.

We can use the yearly input of fine-grained sediments to estimate an average (regional) rate of accumulation for de-

positional areas in the Sound. Such an estimate is possible because of the high trapping efficiency of the system and because newly introduced fine-grained detritus is rapidly and widely dispersed throughout the central and western parts of the basin (BOKUNIEWICZ, 1980; BOKUNIEWICZ and GORDON, 1980a; GORDON, 1980; RHOADS, 1994; KNEBEL *et al.*, 1999). By using the mass of fine-grained sediments supplied by the major sources ( $9.3 \times 10^8$  kg/y) and the total depositional area in the Sound ( $1,226 \text{ km}^2 = 1,197 \text{ km}^2$  within the study area

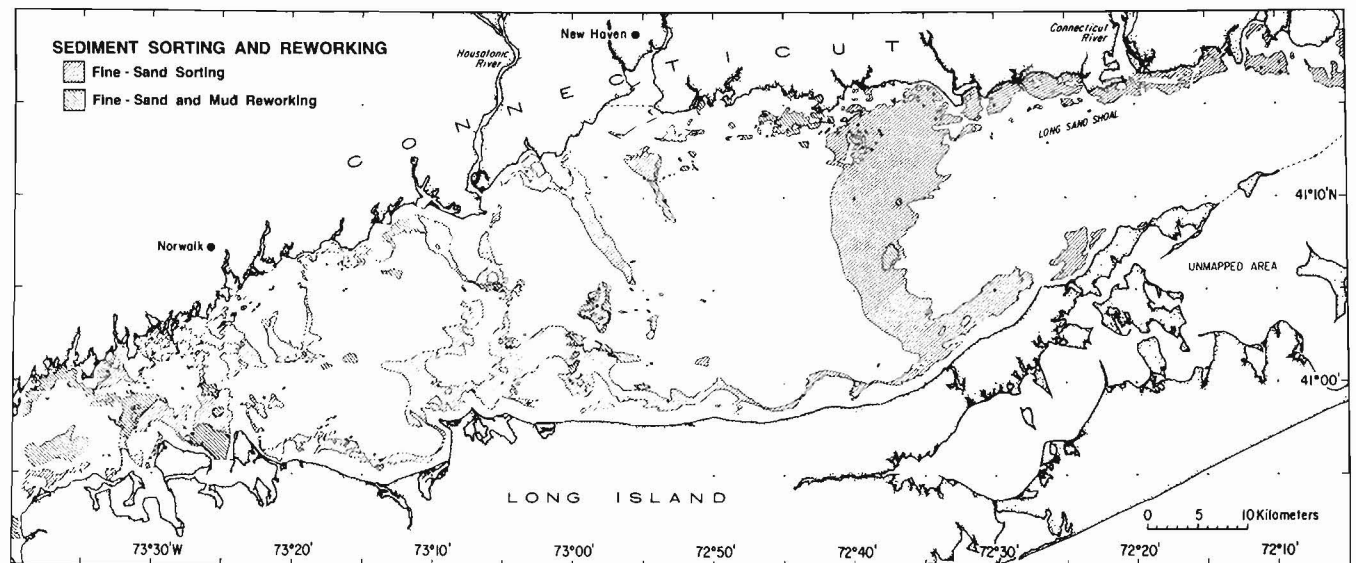


Figure 10. Distribution of environments of sediment sorting and reworking, which cover 24% of the study area. Subareas of sediment sorting and sediment reworking are indicated.

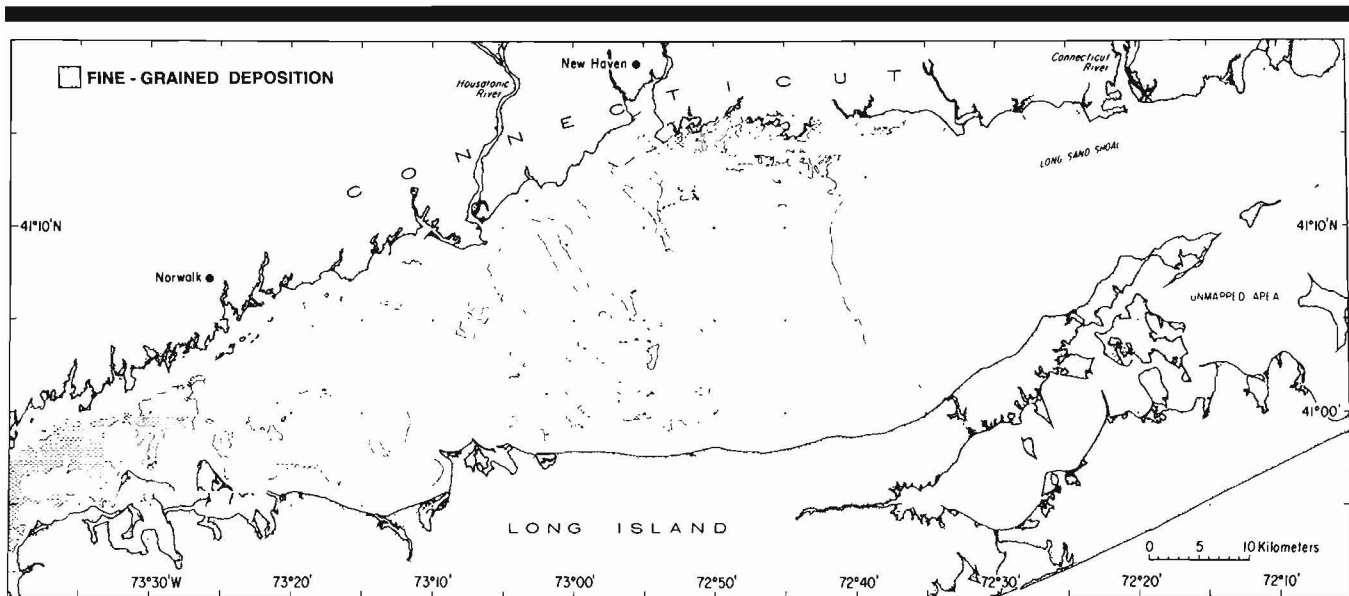


Figure 11. Distribution of environments of fine-grained deposition, which cover 41% of the study area.

plus 29 km<sup>2</sup> external in the westernmost Sound), we estimate an average accumulation rate of  $7.6 \times 10^5$  kg/km<sup>2</sup>/y or about 0.08 g/cm<sup>2</sup>/y. It should be noted, however, that some fine-grained sediments also are present in areas of sediment reworking (Figure 6A). These were not used in our calculation because reworked environments comprise just 3% of the total area (Figure 10) and contain only thin, steady-state mud deposits which are maintained by a combination of erosion and deposition (KNEBEL *et al.*, 1999). Our average rate of accumulation is only slightly higher than that (0.05 g/cm<sup>2</sup>/y) previously estimated by RHOADS (1994) who used the same total sediment input but a larger assumed depositional area (1,792 km<sup>2</sup>). Moreover, it agrees with the regional accumulation rate (0.09 g/cm<sup>2</sup>/y) estimated by KIM and BOKUNIEWICZ (1991) based on near-bottom suspended-sediment concentrations.

Our regional rate of accumulation is also consistent with the known range of local accumulation rates. Local accumulation rates in the Sound are undoubtedly quite variable because, as this study shows, they can be affected by changes in the bottom and subbottom topography as well as by the hydrodynamic regime. Indeed, the available sidescan and subbottom data indicate that the thickness of fine-grained deposits and, hence, local accumulation rates typically approach zero near the boundaries with other environments (KNEBEL *et al.*, 1999). On the other hand, accumulation rates ranging from 0.05 to 0.08 g/cm<sup>2</sup>/y have been measured at one depositional site in the central part of the basin located away from any boundaries (BENNINGER *et al.*, 1979; BENOIT *et al.*, 1979). An even higher rate (about 0.1 g/cm<sup>2</sup>/y) has been measured in an area of deposition on the northern margin (KRISHNASWAMI *et al.*, 1984), where the proximity of sediment supply has likely affected the amount of accumulation (see previous discussion). Thus, our average regional accumulation rate is considered to be a reasonable standard against which local rates can be compared and evaluated.

Information from this study suggests that the erosion of the postglacial marine delta in the eastern Sound was an important source for the cumulative mass of fine-grained sediments now buried beneath depositional areas in the central and western Sound. When formed, the marine delta likely capped the entire eastern part of the Sound (LEWIS and STONE, 1991; FENSTER, 1995). However, since about 8 to 9 ka, tidal currents have eroded away the eastern flank of the delta and transported the resulting fine-grained sediments westward into the Sound (FENSTER, 1995). The large area of erosion or nondeposition now present across the eastern entrance to the Sound outlines where deltaic deposits (and underlying glacial lake clays) have been removed; it encompasses about 195 km<sup>2</sup>. Based on the thickness of analogous deposits beneath the western flank of the delta (LEWIS and NEEDELL, 1987), we estimate that about 15 m (average thickness) of deltaic sediments have been eroded away on the eastern flank. In order to determine the potential mass of fine-grained sediments produced from this area of erosion, we assumed the following: (1) a particle density of 2.65 g/cm<sup>3</sup>; (2) an average silt-plus-clay size fraction of 55% (by weight) (based on vibrocore samples of deltaic strata presented in DONOHUE and TUCKER, 1970; LEWIS and NEEDELL, 1987; NEEDELL *et al.*, 1987; SZAK, 1987); and (3) a porosity of 50% (HAMILTON, 1974). Using these parameters, we calculate that the mass of fine-grained sediments available from the erosion of the eastern flank of the delta totaled about  $2.1 \times 10^{12}$  kg.

Fine-grained sediments also were supplied from the scour of tidal channels that developed on the top of the old delta. These tidal channels, which now contain a veneer of sand ribbons (Figures 5A, 9), constitute an area of about 103 km<sup>2</sup>. Based on subbottom profiles across the channels (LEWIS and NEEDELL, 1987) and on the average topographic relief of the channels (NATIONAL OCEAN SURVEY, 1989b), we estimate

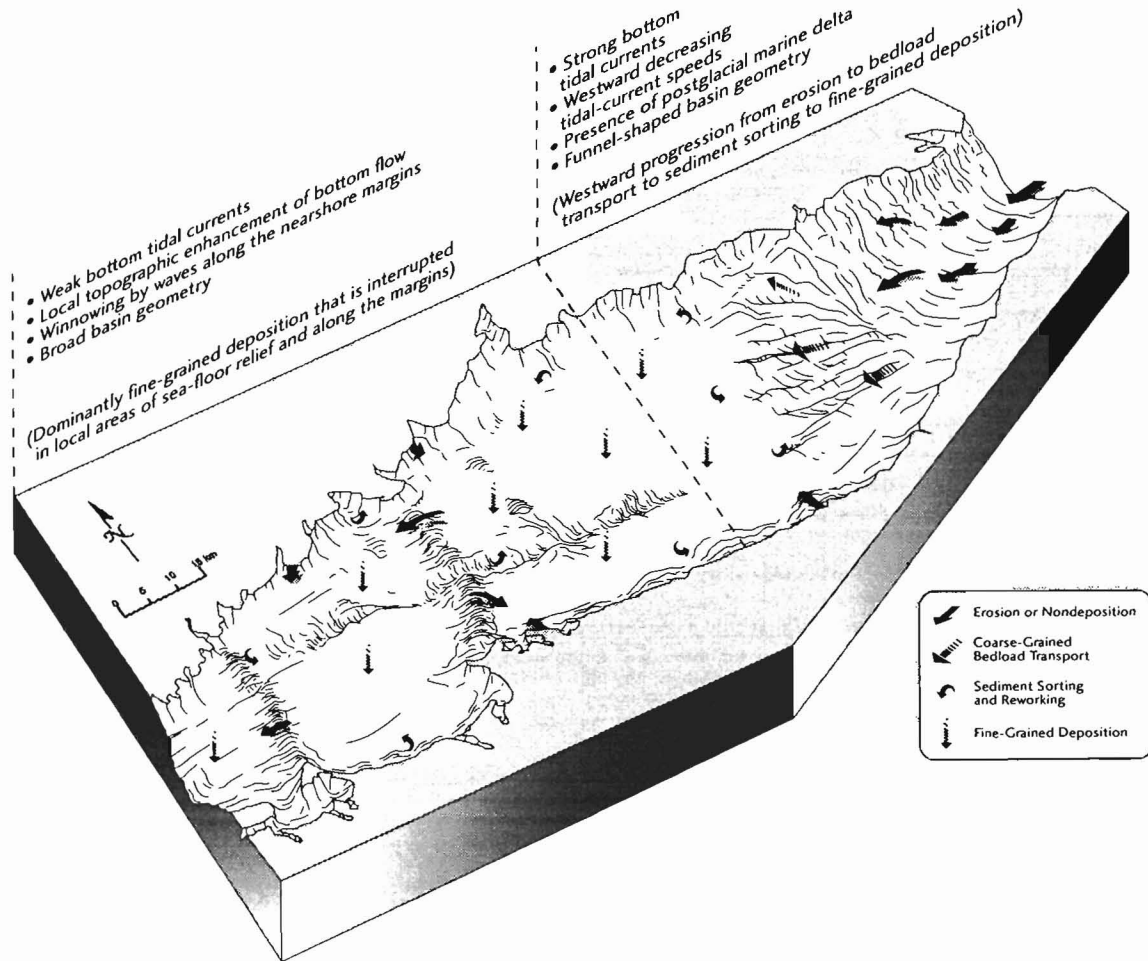


Figure 13. Perspective diagram which summarizes the major factors that have controlled the complex distribution of sedimentary environments in Long Island Sound. The dominant sedimentary environments within each part of the system are also indicated.

that about 5 m (average thickness) of deltaic sediments have been removed from them. By using this inferred amount of erosion and the area of the tidal channels, along with the foregoing figures for particle density, average texture, and porosity, we estimate that the supply of fine-grained from tidal-channel erosion was about  $0.4 \times 10^{12}$  kg. Thus, the total mass of fine-grained sediments that was derived from the erosion of the postglacial delta (eastern flank plus the tidal channels) and made available for deposition in the central and western Sound, was about  $2.5 \times 10^{12}$  kg. By comparison, this amount is  $2.7 \times 10^3$  times the present annual supply of fine-grained sediments from all major sources.

### SUMMARY

Analysis of an extensive set of sidescan sonographs, bottom samples, and videocamera observations, together with supplemental bathymetric and marine-geologic data, outlines the sedimentary characteristics and the distribution of four categories of modern, long-term sea-floor environments within the glaciated, topographically complex Long Island Sound es-

tuary. (1) Environments of erosion or nondeposition comprise exposures of glacial drift, coarse lag deposits, and possibly bedrock that contain sediments (where present) ranging from boulder fields to gravelly coarse-to-medium sands. These environments, which cover 22% of the area, were found: across the rugged sea floor at the eastern entrance to the Sound; atop bathymetric highs and within constricted depressions in the central and western basin; and in irregular nearshore bands which border much of the shoreline. (2) Environments of coarse-grained bedload transport comprise sand ribbons and sand waves that are composed of sediments ranging from gravelly sands to relatively uniform medium-to-fine sands. These environments, which cover 13% of the area, are restricted primarily to the hummocky tidal ridge-and-channel topography on the surface of the postglacial marine delta in the eastern Sound. (3) Environments of sediment sorting and reworking contain textures ranging from uniform fine-to-very fine sands (sorting) to variable patches of sand and mud (reworking) that reflect a combination of erosion and deposition. They encompass 24% of the area and are located mainly:



within a wide curvilinear band across the east-central Sound; along parts of the axial depression in the central and western basin; over the tops and flanks of low knolls and ridges; and in strips and patches along the nearshore margins. (4) Environments of fine-grained deposition comprise areas of featureless sea floor that are blanketed by muds and sandy muds. They cover 41% of the area, including broad areas of generally flat sea floor in the central and western basin and small areas over the nearshore margins.

The distribution of sedimentary environments within Long Island Sound is extremely patchy. This patchiness reflects both regional and local changes in geologic and oceanographic conditions (Figure 13). The basic distribution of sedimentary environments in the Sound is controlled by the regional east-to-west decreasing gradient of bottom tidal-current speeds coupled with the net (westward) estuarine bottom drift. This regional flow regime has produced a westward succession of environments ranging from erosion or nondeposition at the narrow eastern entrance to the Sound, to an extensive zone of coarse-grained bedload transport over the postglacial delta in the east-central Sound, to a peripheral band of sediment sorting located where the estuary noticeably widens, to broad areas of fine-grained deposition on the flat basin floor in the central and western Sound (Figure 13). However, the fine-grained deposits in the central and western basin become discontinuous in local areas where the bottom flow is enhanced by and interacts with the sea-floor topography. In these areas, increased sediment transport has produced a patchy complex of other environments. Local patchiness is particularly evident over and along the nearshore margins. Here, the diverse assemblage of environments reflects the effects of wave-produced bottom currents, the indented shoreline, the irregular bottom topography, and the proximal supply of sediments.

The distribution of bottom sedimentary environments has several implications regarding the present and past accumulation of fine-grained sediments in the Sound. First, the regional east-to-west succession of environments indicates that fine-grained bottom sediments delivered to the eastern Sound (especially from the Connecticut River) are transported westward into the Sound and sequestered in the central and western parts of the basin. This finding supports the contention that the trapping efficiency of the Sound is nearly 100%. Second, this study shows that fine-grained depocenters in the Sound constitute an area of 1,226 km<sup>2</sup>. Using this accurately determined area together with the supply of fine-grained sediments from all major sources ( $9.3 \times 10^8$  kg/y), we estimate that the average modern regional accumulation rate is 0.08 g/cm<sup>2</sup>/y. Finally, the distribution of environments in the eastern Sound indicates that partial removal and scour of the postglacial marine delta was an important source of fine-grained sediments which now are buried in depositional areas to the west. The estimated cumulative mass of fine-grained sediments derived from the marine delta is  $2.5 \times 10^{12}$  kg or about  $2.7 \times 10^3$  times the modern annual supply of fine-grained sediments.

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