SIDESCAN SONAR IMAGES, SURFICIAL GEOLOGIC INTERPRETATIONS, AND BATHYMETRY OF THE LONG ISLAND SOUND SEA FLOOR IN NEW HAVEN HARBOR AND NEW HAVEN DUMPING GROUND, CONNECTICUT

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INTRODUCTION

The U.S. Geological Survey has produced detailed geologic maps of the sea floor in Long Island Sound, a major East Coast estuary surrounded by the most densely populated region of the United States. These studies have built upon cooperative research with the State of Connecticut that was initiated in 1982. During the beginning phase of this program, geologic framework studies in Long Island Sound were completed (Lewis and Needell, 1987; Needell and others, 1987; Lewis and Stone, 1991). The second and current phase of the program is directed toward studies of sea-floor sediment distribution, processes that control sediment distribution, nearshore environmental concerns, and the relation of benthic community structures to the sea-floor geology.

Anthropogenic wastes, toxic chemicals, and changes in land use patterns resulting from residential, commercial, and recreational development have stressed the environment of the Sound, causing degradation and potential loss of benthic habitats (Koppelman and others, 1976; Long Island Sound Study, 1994). Detailed maps of the sea floor are needed to help evaluate the extent of adverse impacts and to help manage resources wisely in the future. Therefore, in a continuing effort to better understand Long Island Sound, we have constructed sidescan sonar mosaics (complete-coverage acoustic images of the sea floor) within specific areas of special interest (fig. 1). The mosaics presented here cover New Haven Harbor, Connecticut's major port, and the New Haven Dumping Ground, the most active dredge-spoil disposal site in Long Island Sound (Bohlen and others, 1996). The mosaics and their interpretations serve many purposes, including (1) defining the geological variability of the sea floor, which is one of the primary controls of benthic habitat diversity; (2) improving our understanding of the processes that control the distribution and transport of bottom sediments and the distribution of benthic habitats and associated infaunal community structures; and (3) providing a detailed framework for future research, monitoring, and management activities. The sidescan sonar mosaics also serve as base maps for subsequent sedimentological, geochemical, and biological observations, because precise information on environmental setting is important for selection of sampling sites and for accurate interpretation of point measurements.

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GEOLOGICAL SETTING

Long Island Sound is about 182 km long and as much as 32 km wide. It is bordered on the north by the rocky shoreline of Connecticut, on the east by Block Island Sound, on the south by the eroding sandy bluffs of Long Island, and on the west by the East River.

New Haven Harbor Study Area

The New Haven Harbor study area (fig. 1), which covers about 27.4 km^2 along the central Connecticut shoreline, encompasses part of the harbor and extends offshore, covering most of the area between Morgan Point and Oyster River Point (fig. 2). New Haven Harbor not only is Connecticut's largest commercial port facility, but also has a large shellfish industry. Harvested shellfish, primarily farmed eastern oysters (*Crassostrea virginica*) and hard clams or quahogs (*Mercenaria mercenaria*), thrive under conditions that include a stable shallow-water habitat, appropriate nutrients, suitable salinities, and favorable tidal currents (John Volk, Connecticut Department of Agriculture, written commun., 1997).

Much of the northern part of the New Haven Harbor study area lies within a seaward extension of the Central Lowland of Connecticut, and, therefore, presumably is underlain by rocks of Mesozoic age. The principal onshore equivalent of these rocks, the New Haven Arkose (Upper Triassic and Lower Jurassic), is composed of red, pink, and gray, coarse-grained, locally conglomeratic, poorly sorted sandstone interbedded with layers of reddish micaceous siltstone (Flint, 1965; Rodgers, 1985). The Lighthouse Gneiss, a pink or gray-to-red, medium-grained, generally well-foliated granitic gneiss of Proterozoic age, underlies most of the onshore area south of Morris Cove and crops out near Lighthouse and Morgan Points. The Eastern Boundary fault separates the New Haven Arkose from the Lighthouse Gneiss, and it trends west-southwestward across the southern part of Morris Cove and under the central part of this study area. The gray-to-silver, medium- to fine-grained, well-layered to laminated rocks of the Oronoque Schist (Lower Ordovician?) underlie the western part of the study area. These rocks crop out at Bradley and Oyster River Points (Rodgers, 1985). Three bedrock valleys, which are seaward extensions of the West, Mill, and Quinnipiac River valleys, coalesce under New Haven inner harbor north of Sandy Point to form a single linear valley that extends toward the west-southwest (Sanders, 1965).

The bedrock across much of south-central and southeastern Connecticut is unconformably overlain by two tills, one of pre-Wisconsinan age and one of late Wisconsinan age (Schafer and Hartshorn, 1965; Flint and Gebert, 1976; Stone and others, 1992). The younger till forms a thin (2–5 m), discontinuous mantle over nearly all of the higher land around New Haven

Harbor. This till is exposed onshore in the southwestern part of the study area around Oyster River Point, in the southeastern part of the study area around Lighthouse and Morgan Points, and along the northeast shore of Morris Cove (Stone and others, 1992). Although both tills have been identified in the adjoining Branford and Mount Carmel 7.5-minute quadrangles (Flint, 1965), the older till has not been found around New Haven Harbor. The northward retreat of the late Wisconsinan ice sheet is marked in southeastern Connecticut by a succession of minor recessional moraines (including the Hammonasset-Ledyard, Old Saybrook, and Mystic moraines; fig. 1). However, no end moraines have been identified along the shores of New Haven Harbor (Flint, 1965; Goldsmith, 1982).

Stratified drift, deposited by glacial streams as outwash, blankets the till and bedrock over most of West Haven and New Haven as part of the New Haven valley train. Stratified drift also is present around Morris Creek (east of Morris Cove) as part of the Farm River valley train (Flint, 1965; Stone and others, 1992). The drift additionally fills the West, Mill, and Quinnipiac River valleys where they are incised into bedrock (Sanders, 1965). Deltaic sediments deposited in glacial Lake Connecticut overlie both bedrock and glacial drift within New Haven Harbor and extend about 9.5 km south of Morgan Point (Lewis and Stone, 1991; Stone and others, 1992; Stone and others, 1998). This lake, which occupied most of the Long Island Sound basin, was formed when the ice front began to recede from the Harbor Hill–Roanoke Point–Charlestown moraine position (fig. 1) and meltwater was impounded in the expanding, long, narrow basin between the moraine and the retreating ice to the north (Stone and Borns, 1986).

The glaciolacustrine deposits of glacial Lake Connecticut and the underlying glacial drift are truncated by a regional unconformity. This unconformity is a composite product of subaerial exposure, which occurred after glacial Lake Connecticut drained, and marine transgression, which took place after 15 ka (Lewis and Stone, 1991). Marine deposits, which occur in quiet-water areas throughout the Long Island Sound basin, overlie the unconformity and earlier deposits, and they record deposition during the postglacial Holocene eustatic rise of sea level.

Salt-marsh deposits, which consist of seaward-thickening wedges of peaty mud and muddy peat, occur along Morris Creek and the Cove River. Although previously larger, some of the marshes have been filled during city redevelopment. Much of the present shoreline within New Haven Harbor is lined with sediment and manmade materials that have been artificially emplaced (Flint, 1965). Freshwater discharge into New Haven Harbor is minor relative to the total tidal flux of water in and out of the harbor (Bohlen and others, 1996).

New Haven Dumping Ground Study Area

The New Haven Dumping Ground study area, which is located about 10.4 km south-southeast of Morgan Point (fig. 1), encompasses the Central Long Island Sound Disposal Site and covers about 15.9 km^2 in north-central Long Island Sound. This area and three other open-water disposal sites within the Sound (Eatons Neck, Bridgeport, and New London) historically have received the vast majority of the spoils dredged from the borders of the Sound. For example, during 1954 and 1956 more than 4 million cubic meters were dumped at the New Haven site (Schubel and others, 1979). During the period October 1993 through January 1994 the U.S. Army Corps of Engineers dredged approximately 642,000 cubic meters of sediments from the navigational channel in New Haven Harbor, which were then disposed at the New Haven Dumping Ground (Bohlen and others, 1996). The New Haven Dumping Ground continues to be one of the most active disposal sites in New England because its proximity to major commercial and recreational port facilities minimizes disposal costs (Boyd and others, 1972) and because it is thought to be located in a depositional sedimentary environment characterized by relatively weak bottom currents (Morris and others, 1996).

Tidal and wind-driven currents have extensively reworked both the glacial and postglacial deposits south of the breakwaters at the entrance to New Haven Harbor and continue to influence the sedimentary processes and surficial sediment distributions in both study areas (Lewis and Stone, 1991). Tidal currents alone locally exceed 25 cm/s at the surface across the outer harbor (Caruso and others, 1995), and locally they exceed 20 cm/s at 1 to 2 m above the bottom across the dumping ground (Gordon and others, 1972; Signell and others, 1998; Knebel and others, 1999).

DATA COLLECTION AND PROCESSING

Sidescan-sonar imagery, bathymetric measurements, and high-resolution seismic-reflection subbottom profiles were collected along tracks spaced 150 m apart aboard the research vessel *Asterias* during June 1997 (figs. 2 and 8). The bathymetric data were collected using a 200-kHz echo sounder, were logged digitally, and were corrected for the approximately 1.89-m tidal range in the study areas by adjusting the measured depth values to the predicted mean sea level for the harbor entrance of New Haven, using commercially available software. The sidescan sonar data were collected using an Edgetech sidescan sonar system set to sweep 100 m to either side of the ship's track. These data were logged digitally to 8-mm tape on an ISIS data acquisition system. The subbottom data, which were used to interpret the stratigraphy, were collected in analog form using an Ocean Research Equipment 3.5-kHz profiler transmitting at a 0.25-s repetition rate (figs. 3 and 9). Ship position was determined with a differential Global Positioning System (GPS) and was logged digitally at 10-s intervals.

The sidescan sonar data were processed according to procedures summarized by Danforth and others (1991) and Paskevich (1992a,b). Briefly, the sonar data were multiplexed, filtered to convert them into a processing format and to remove speckle noise, and corrected for slant-range distortions. Additional corrections were applied to compensate for signal attenuation and dropped lines in the sonar data. A contrast enhancement based on the dynamic range of the data was applied, ship navigation was merged with the sonar data, and the data were geographically oriented and displayed on a Mercator grid.

After this preliminary processing the data were used to make composite digital mosaics. Alternating strips of sonar data were placed in their proper geographic location at the appropriate scale and projection (Paskevich, 1992c). Adjacent sonar images were matched for tone, redundant data (where two images overlapped) were digitally trimmed, and images were progressively combined into composite digital images. Registration between the shiptrack navigation and the strips of sidescan sonar data are generally good throughout both of the study areas. The final images were digital mosaics with a 1-m pixel size (a pixel represents one meter on the sea floor). These images were output to film, photographically enlarged, and interpreted (figs. 4, 5, 10, and 11).

Sampling of surficial sediment (0–2 cm below the sediment-water interface) and bottom photography were attempted at 75 locations in the New Haven Harbor study area (fig. 7) and at 25 locations in the New Haven Dumping Ground study area (fig. 8) during March 1996 and March 1998 aboard the RV *John Dempsey*, using a Van Veen grab sampler equipped with a video camera system. The vessel was allowed to drift over the bottom for extended distances (more than 50 m) at seven of the sampling and bottom photography stations in the New Haven Dumping ground study area. These sites are shown as drift stations in figure 8. The photographic system was used to appraise bottom variability around stations, faunal communities, and sedimentary processes. It also documented bedrock outcrops and boulder fields where samples could not be collected.

In the laboratory, the sediment samples were disaggregated and wet sieved to separate the coarse and fine fractions. The fine fraction (less than 62 µm) was analyzed by Coulter Counter (Shideler, 1976); the coarse fraction was analyzed by sieving (gravel) and by rapid sediment analyzer (sand; Schlee, 1966). The data were corrected for salt content of interstitial water in the samples.

Because shells commonly form in situ, they usually are considered not to represent the depositional environment from a textural standpoint. Therefore, bivalve shells and other biogenic carbonate debris were manually removed from the gravel fraction. Size classifications are based on the method proposed by Wentworth (1929); they were calculated by means of the inclusive graphics statistical method (Folk, 1974), using the nomenclature proposed by Shepard (1954). A detailed discussion of the laboratory methods employed is given in Poppe and others (1985). The field methods, station navigation, raw grain-size data, associated statistics, and detailed descriptions of the bottom photography are reported in Poppe and others (1998c).

The map of surficial sediment distribution shown in figure 7 is based on data from the sediment samples and bottom photography, on tonal changes in backscatter on the sidescan sonar image, and on the correlation of textural and backscatter data with the bathymetry.

INTERPRETATION

Bathymetry

The corrected bathymetry was contoured at a 1-m interval to facilitate an understanding of the surficial geology and general benthic character (figs. 2 and 8). This perspective is important because the sea-floor topography affects the evolution and stability of the physical and biological environments within the study areas.

New Haven Harbor Study Area

The sea floor in the western part of the New Haven Harbor study area has a smooth, gentle gradient that slopes toward the south from Oyster River Point and toward the southwest from a broad bathymetric high which extends southeast from West Haven past the middle breakwater (fig. 2). Steeper gradients are found in the area just north of the gap between the middle and west breakwaters.

The eastern part of the survey area has a more complex morphology. Isolated bathymetric highs, such as Old Head Reef and The Chimneys, are concentrated near the east breakwater and are bedrock outcrops. Isolated bathymetric lows occur northwest of the gap between the east breakwater and Morgan Point and at an abandoned borrow pit (Bohlen and others, 1996) in Morris Cove.

The study area is bisected by the New Haven Harbor navigational channel. This channel, which is periodically dredged to more than 10 m below mean sea level (Bohlen and others, 1996), has steep sides and exceeds 15 m in depth in an isolated depression between the middle and east breakwaters. This is the deepest part of the study area. Broad shallows, notably Shag Bank and Morris Cove, flank the navigation channel over most of its length.

New Haven Dumping Ground Study Area

The sea floor in and around the New Haven Dumping Ground has a relatively smooth gradient that slopes gradually toward the southeast (fig. 8). Water depths range from less than 18 m in the northwestern part of the study area to more than 25 m in the southeast corner. Isolated bathymetric highs are composed of mounded dredge-spoils and the materials used to cap them (Morris and others, 1996). They occur in the central and northwestern parts of the study area. Small-scale linear depressions (sedimentary furrows), which are 0.4 to 0.5 m deep (fig. 9), are concentrated in the eastern and southern parts of the study area. However, because of their shallowness and the 10-s bathymetric sampling rate, and because of their orientation nearly parallel to the ship's track, these features are not resolved in the bathymetry. They are discussed in more detail in the "Sidescan sonar mosaics" section below.

Sidescan Sonar Mosaics

The sidescan sonar mosaics (figs. 4 and 10) portray acoustic images of the sea floor which, when combined with the 3.5-kHz subbottom and bathymetric data, can be used to interpret the surficial geology (figs. 5 and 11). Distinctive acoustic patterns revealed by the mosaics include (1) complex patches of high and low backscatter with individual high-backscatter targets (objects), (2) areas of relatively high backscatter (light tones), (3) areas of moderate backscatter, (4) areas of relatively low backscatter (dark tones), and (5) alternating lines of high and low backscatter (sedimentary furrows). Boundaries between patterns are commonly gradational; backscatter is not uniform throughout these areas. Water column phenomena such as boat wakes and turbulence around obstructions on the bottom, and manmade features such as the New Haven Harbor navigational channel, trawl marks, culch beds (beds of clean shell debris used for setting juvenile oysters), pipelines and (or) cables, anchor scars, and dredge-spoil disposal mounds, are also present on the images.

New Haven Harbor Study Area

Complex patches of high and low backscatter with individual high-backscatter targets coincide with areas characterized by bedrock outcrops (figs. 3A and B; fig. 6A) and concentrations of boulders and gravel. This acoustic pattern occurs in the shallower waters around Oyster River Point, Lighthouse Point, and Morgan Point and within a discontinuous band across the eastern end of the middle breakwater.

Areas characterized by relatively high backscatter, which primarily coincide with exposures of glaciodeltaic deposits, occur adjacent to deposits of boulders and gravel off Oyster River, Lighthouse, and Morgan Points and in a broad band that extends southeast from West Haven across the central part of the study area. The high backscatter tends to be produced by coarser grained sediments, typically gravelly sand and sand. Elongate patches of alternating high and low backscatter, which occur within the southern part of the navigational channel, are interpreted to be sand waves (fig. 6B).

Areas characterized by relatively low backscatter coincide with accumulations of fine-grained Holocene marine sediment. These areas include (1) the main navigational channel north of Lighthouse Point, (2) Morris Cove, (3) patches north and south of the east breakwater, and (4) the area that extends northwest from the middle breakwater, around the northern end of the west breakwater and along most of the western boundary of the study area. Subbottom profiles (figs. 3A and B) show that the deposits of fine-grained sediment near the breakwaters occur in lenses that overlie the high-backscatter glaciodeltaic sediments. Maximum thicknesses of the lenses south of the east breakwater (fig. 3A) and northwest of the middle breakwater (fig. 3B) are about 1.5 and 2.0 m, respectively. The small patches of higher backscatter that occur within the low-backscatter areas in and adjacent to the channel north of Lighthouse Point and around the abandoned borrow pit in Morris Cove are largely artifacts of small-scale bathymetric changes that affect the angle of incidence of the sidescan sonar.

Shallow curvilinear and looping depressions, interpreted to represent trawl marks associated with shellfishing, occur throughout much of the study area, but are most conspicuous along the western edge of the study area (fig. 6C), in scattered patches inside of the breakwaters, and near Oyster River Point and Lighthouse Point (fig. 6D). The trawl marks, which coincide with active shellfishing lease areas, owe their curvature to (1) the side-mounted deployment of trawl gear that requires the fishing vessel to turn toward that side to minimize abrasion against the hull, and (2) the practice of trying to stay near an area once a concentration of hard clams has been discovered. Broader, high-backscatter looping features along the southern edge of the study area may represent relatively recently constructed culch beds. The navigational channel and dredge marks from two pipelines or cables are also visible in the central part of the image.

New Haven Dumping Ground Study Area

The sidescan sonar image of the New Haven Dumping Ground study area can be divided into two general provinces (figs. 10 and 11). The first province, which extends over the central and northwestern parts of the study area, is characterized by complex patches of high and low backscatter and curvilinear streaks of high backscatter. The high backscatter results from a combination of relatively coarse-grained sediments in dredge spoils or in materials used to cap the spoils, and the angle of incidence of the sonar against the sides of disposal mounds (Morris and others, 1996). The curvilinear streaks of high backscatter are best developed in the central part of the study area and represent material dumped from hopper dredges or scows that discharged the dredged materials while under way, leaving a swath across the seabed. Halos of low backscatter around some of the disposal piles may represent the effect of density surges caused by the impact of dredged materials on the bottom, or they may represent the subsequent slower sedimentation of the diffuse plume of residual finer grained material (Schubel and others, 1979).

The second province, which covers the eastern and southernmost parts of the study area, is characterized by low backscatter, caused by relatively fine-grained sediments, and by numerous linear depressions, interpreted to be sedimentary furrows. The furrows appear as thin paired lines of high and low backscatter (fig. 12A). They trend east-northeast, are irregularly spaced, and have indistinct troughs with gently sloping walls (figs. 9 and 13). Most of the furrows are symmetrical in cross section; but where asymmetrical, the southern (or downslope relative to the regional bathymetry) wall is commonly steeper. The average width and relief of the furrows is 9.2 m and 0.4 m, respectively. The furrows average about 206 m long, but range from 30 m to 1,315 m in length.

Although most of the sedimentary furrows appear to gradually taper out, some furrows show a "tuning fork" joining pattern. The junctions open predominantly toward the east (fig. 12A), but some open toward the west. A few of the sedimentary furrows cross, start at, or end at dredge-spoil mounds (fig. 12B), but most are not associated with the mounds or with any other features.

Shallow linear depressions, interpreted to be trawl marks, are most evident in the eastern part of the study area. Whether this association is because trawl marks are more visible in the fine-grained sediments or whether it is because these muddy sediments are a preferred biologic habitat is unknown. The trawl marks can be differentiated from the furrows in that they are much fainter, are usually curved, and show no preferential orientation. Some of the lineations, especially those toward the west, may represent anchor scars.

Sedimentary Environments

Sedimentary environments are mapped within the study areas on the basis of lithology and faunal assemblage. Contacts between these environments are inferred because the transitions between the various environments are gradational, and lateral changes in lithology are seldom abrupt.

New Haven Harbor Study Area

The surficial sediment distribution in the New Haven Harbor study area is shown in figure 7, along with the locations of the sediment sampling and bottom photography stations. The finest grained sediments in this study area are organic-rich (Duxbury, 1963; Turekian and others, 1972), poorly sorted silts and clayey silts that dominate in and adjacent to the main shipping channel north of Lighthouse Point, within the abandoned borrow pit in Morris Cove, northwest of the middle breakwater, and in patches just north and south of the east breakwater. Slightly coarser, very poorly sorted sandy silts occur in the shallower areas within Morris Cove and west and north of the west breakwater. These muddy areas are extensively bioturbated; most bottom features in them originate from biologic activity. Amphipod communities, worm tubes, shrimp burrows, snails, and mud crabs are common.

The muddy sediments grade into bands of poorly sorted silty sand and coarser grained sediment as water depth decreases. Although faint current ripples occur in the silty sands, the effects of bioturbation are still evident. Scattered shells and shell debris are present; crabs, worm tubes, hydrozoans, bivalves, and gastropods are common components of the faunal assemblage.

Sands occur off Oyster River Point and are the dominant lithology in a broad band across the central part of the study area. This band extends south-southeast from West Haven along the seaward-trending bathymetric high, in and adjacent to the navigational channel south of Lighthouse Point, in the vicinity of the gap between the middle and east breakwaters, and across most of the study area outside the breakwaters. The sands shoreward of the breakwaters are typically fine to medium grained and poorly sorted. The sands near the gap between the middle and east breakwaters are typically medium grained and moderately well sorted. Sorting decreases and the distributions become finely skewed and very leptokurtic in the sand outside the breakwaters. There, current ripples are ubiquitous; decreased visibility caused by resuspension of sediment during a passing storm was observed in bottom video. Locally, shells (oyster, razor, and quahog) and shell debris litter the bottom and concentrate in ripple troughs. Starfish, hermit crabs, welk, clam burrows, and hydrozoans are common.

Gravelly sediments, which tend to be very poorly sorted and bimodal, are concentrated in shallow environments around Lighthouse Point, Morgan Point, and Oyster River Point and in a narrow band just southeast of the middle breakwater. Starfish and shell and shell debris from oysters, razor clams, and quahogs are common; hydrozoans grow on the shell material.

Sidescan sonar and bottom photography revealed the presence of boulders and bedrock adjacent to Morgan Point and Oyster River Point, on Old Head Reef, and at scattered locations southeast of the east breakwater (for example, Big Boil and The Chimneys). Sponges, algae, and seaweed are attached to the rocks; patches of rippled sand with scattered shells occur between the boulders. A thin (less than 2 cm), possibly seasonal, layer of fine-grained detritus covers the rocks. The limited thickness of this layer suggests that it is episodically removed by storm-generated currents.

New Haven Dumping Ground Study Area

Muddy sediments dominate in the vicinity of the New Haven Dumping Ground. These sediments are generally poorly sorted siliciclastic silts and clayey silts with unimodal distributions. A current-swept appearance characterizes the bottom; scour around coarser grains, sediment accumulations in the current shadows of obstacles, and saltating shells were observed in bottom video. Faint longitudinal ripples, which trend east-northeast, are common, but, along with nutclam (nucula) shells, appear to be concentrated within the sedimentary furrows. Burrows (shrimp, clam, mud crab, and lobster), anemones, worm tubes, hydrozoans, and amphipod communities are present in the heavily bioturbated bottom.

Very poorly sorted fine-grained sands, silty sands, and sandy silts are common within the New Haven Dumping Ground part of the study area. These coarser grained sediments reflect the presence of dredge spoils or materials used to cap the spoils (Morris and others, 1996). Identifiable manmade debris (wires, cables, and pipe) are occasionally present in bottom video at these stations. Amphipod communities, worm tubes, and shrimp and crab burrows are common in the spoil areas.

SEDIMENTARY PROCESSES

New Haven Harbor Study Area

High-energy environments prevail in the shallow waters around Oyster River Point, Lighthouse Point, and Morgan Point. Strong tidal currents and wind-driven waves prevent the deposition of Holocene marine sediments and erode the finer fraction from the sea-floor sediments, leaving exposed bedrock and lag deposits of boulders and gravel (fig. 7).

As water depth increases, the strength of storm and tidal currents at the sea floor decreases. Conditions favoring erosion are replaced by environments characterized by sediment sorting and winnowing. Current ripples in the sandy areas and sediment resuspension observed in bottom video reflect this constant sorting by tidal and storm currents.

Fine-grained sediments accumulate in lower energy environments protected from strong tidal and storm conditions, such as in the navigational channel north of Lighthouse Point, in Morris Cove, and in lenses adjacent to the breakwaters. The locations of the lenses and the presence of surrounding coarser grained sediments suggest that the lenses of fine-grained sediments are associated with the breakwaters. If so, average sedimentation rates for the lenses can be estimated by measuring their thickness and calculating the age of the breakwaters. Construction of the first breakwater was authorized in 1879, and construction of all three breakwaters was completed by 1915 (Sargent and Bottin, 1989). Thus, average sedimentation rates during the 82-year period between completion of construction and collection of the subbottom data were 1.8 and 2.4 cm/yr, respectively, for areas south of the east breakwater and northwest of the middle breakwater. These estimates are somewhat high if deposition of the fine-grained sediments began soon after construction was initiated.

New Haven Dumping Ground Study Area

Although the deeper (greater than 15 m) waters of north-central Long Island Sound are long-term depositional areas characterized by fine-grained cohesive sediments and relatively weak bottom currents (Gordon, 1980; Signell and others, 1998; Knebel and others, 1999), our data reveal the localized presence of sedimentary furrows and longitudinal ripples (figs. 12 and 13). These features are erosional and typically form in environments that have recurring, directionally stable, and occasionally strong currents (Dyer, 1970; Hollister and others, 1974; Reineck and Singh, 1980; Flood, 1983). However, the lack of abrupt lithologic transitions, the faint appearance of associated longitudinal ripples, and the abundance of tracks made by bottom-dwelling animals suggest that the processes that created the furrows in north-central Long Island Sound are only intermittently active. Previous work near the New Haven Dumping Ground (Gordon and others, 1972) has shown that (1) resuspension is the major mechanism of bottom sediment transport, (2) suspended sediment does not entirely settle out between tidal cycles, and (3) the principal factors controlling resuspension are the speed of the tidal currents and the intensity of wave action over a period of several days. Therefore, resuspension at the dumping ground should be larger during spring tides and weaker during neap tides. Although the amount of suspended sediment at any one site is highly variable, data from Gordon and others (1972) also show that the average concentration of suspended sediment in the water column at the dumping ground exceeded 13 mg/cm^2.

The "tuning fork" joining patterns of the furrows, which usually open toward the east, indicate net westward sediment transport (figs. 12A and B; Flood, 1983). However, because adjacent furrow junctions do occasionally open in opposite directions, these joining patterns also suggest that the tidal regime is important to furrow formation and that the furrows can form when water flows in either direction. Studies by Flood (1981, 1983) show that coarse-grained sediments are also important for the initiation and development of furrows in muddy sediments. Coarse sediments available within the study area include nucula shells and sand associated with the dredge spoils.

Given the conditions in the study area, at least two possible mechanisms could produce the sedimentary furrows observed in north-central Long Island Sound. In the first mechanism (adapted from Flood, 1983), secondary helical-flow patterns, which develop just above the sea floor, align mobile nucula shell debris in convergent flow zones (fig. 14A). Furrow development is initiated due to enhanced erosion within the elongate shell beds caused by scour around individual shells and by impacts from saltating shells. The furrows lengthen as the shells move downstream in the bottom currents. Alternatively, in a mechanism adapted from McLean (1981), furrows form in the turbulent wakes produced by flow around dredge-spoil disposal mounds. Easily transported sand grains eroded from the disposal mounds subsequently abrade the lengthening furrows into the muddy seabed (figs. 12B and 14B). Although cuspate high-backscatter lobes extend off both the eastern and western sides of some of the disposal mounds, suggesting this kind of reworking by tidal currents (fig. 12B), most of the sedimentary furrows in north-central Long Island Sound are not associated with disposal mounds or identifiable obstacles.

The elongate geometry and regional bathymetric contours of Long Island Sound combine to constrain the dominant tidal and storm currents to east-west flow directions and permit the development of erosional bedforms. Through the development of sedimentary furrows and longitudinal ripples, fine-grained cohesive sediment can be remobilized, and, at least episodically, be made available for transport farther west into the estuary.

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