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Processes Controlling the Remobilization of Surficial Sediment and Formation of Sedimentary Furrows in North-Central Long Island Sound

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ABSTRACT

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Sidescan sonar, bathymetric, subbottom, and bottom-photographic surveys and sediment sampling have improved our understanding of the processes that control the complex distribution of bottom sediments and benthic habitats in Long Island Sound. Although the deeper (>20 m) waters of the central Sound are long-term depositional areas characterized by relatively weak bottom-current regimes, our data reveal the localized presence of sedimentary furrows. These erosional bedforms occur in fine-grained cohesive sediments (silts and clayey silts), trend east-northeast, are irregularly spaced, and have indistinct troughs with gently sloping walls. 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 in length from 30 m to over 1,300 m. Longitudinal ripples, bioturbation, and nutclam shell debris are common within the furrows. Although many of the furrows appear to end by gradually narrowing, some furrows show a "tuning fork" joining pattern. Most of these junctions open toward the east, indicating net westward sediment transport. However, a few junctions open toward the west suggesting that oscillating tidal currents are the dominant mechanism controlling furrow formation.

Sedimentary furrows and longitudinal ripples typically form in environments which have recurring, directionally stable, and occasionally strong currents. The elongate geometry and regional bathymetry of Long Island Sound combine to constrain the dominant tidal and storm currents to east-west flow directions and permit the development of these bedforms. Through resuspension due to biological activity and the subsequent development of erosional bedforms, fine-grained cohesive sediment can be remobilized and made available for transport farther westward into the estuary.

ADDITIONAL INDEX WORDS: *Long Island Sound, sedimentary furrows, erosional bedforms, sedimentary structures.*

INTRODUCTION

The U.S. Geological Survey, in cooperation with the State of Connecticut Department of Environmental Protection, 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 (Figure 1). As part of this mapping project, a sidescan sonar mosaic (Figure 2; Poppe *et al.*, 2001) was constructed for the north-central Sound in order to: (1) determine the local sediment distribution and geological variability of the sea floor, which is one of the primary controls of benthic habitat diversity; (2) address environmental concerns related to an active disposal site off New Haven, Connecticut; and (3) explore the relationship of benthic habitats and associated infaunal community structures to the sea-floor geology. The interpretation of features imaged in this mosaic has also improved our understanding of the processes that control the distribution and transport of bottom sediments and associated contaminants.

Anthropogenic wastes, toxic chemicals, and changes in land-use resulting from residential, commercial, and recreational development have stressed the bottom environments of the Sound, causing degradation and potential loss of benthic habitats (Koppleman *et al.*, 1976; Long Island Sound Study, 1994). Geological maps of the sea floor provide a detailed sedimentary framework that can help evaluate the extent of adverse impacts. Because of the affinities between fine-grained sediment and organic and inorganic pollutants in the Sound (Mecray and Buchholtz Ten Brink, 2000), the study of surficial sedimentary processes also elucidates transport and deposition mechanisms affecting contaminant distributions.

This report, which is based on an interpretation of the mosaic shown in Figure 2, outlines mechanisms by which surficial sediment is remobilized within an area of the Long Island Sound sea floor that is characterized by the long-term deposition of fine-grained sediment (Figure 1). This work also

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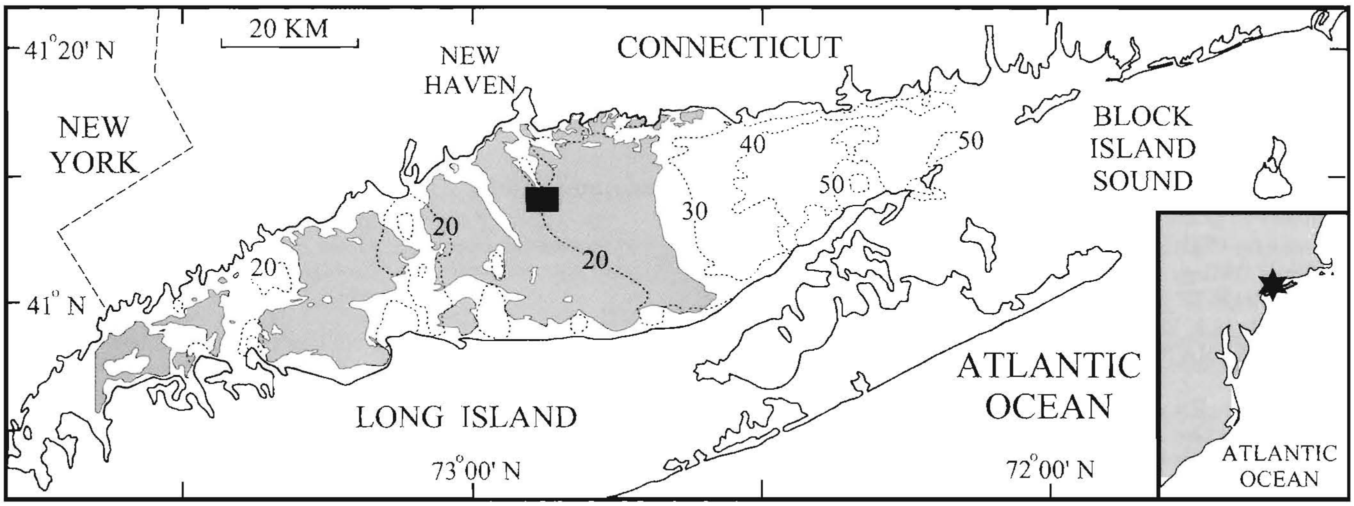

Figure 1. Map showing location of the study area (dark rectangle) in north-central Long Island Sound; inset shows location of Long Island Sound (dark star) along the U.S. east coast. Shaded offshore areas are interpreted to be characterized by the long-term deposition of fine-grained sediment (KNEBEL and POPPE, 2000). Dotted contours show an average of the maximum tidal-current speeds (cm/s) at 1 m above the bottom (SIGNELL *et al.*, 2000). No data are available in some harbors and the westernmost Sound.

complements and expands on recent regional sedimentological analyses of the Sound (KNEBEL and POPPE, 2000; POPPE *et al.*, 2000) .

GEOLOGICAL SETTING

Long Island Sound is 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 New York metropolitan area. The study area, which is located about 10.4 km south-southeast of the entrance to New Haven harbor (Figure 1), covers about 15.9 km^2 of sea floor in the north-central Sound and includes the New Haven Dumping Ground (also known as the Central Long Island Sound Disposal Site). This dumping ground, along with three other open-water disposal sites (at Eatons Neck, Bridgeport, and New London), has received the vast majority of the spoils dredged from the margins of the Sound. For example, during 1954 to 1956 more than 4 million m^3 of sediment were dumped at the New Haven site (SCHUBEL *et al.*, 1979) and, during the period October 1993 through January 1994, the U.S. Army Corps of Engineers dredged approximately 642,000 m^3 of sediment from the navigational channel in New Haven Harbor, that were then disposed at the New Haven Dumping Ground (BOHLEN *et al.*, 1996). The New Haven Dumping Ground continues to be one of the most active disposal sites in New England because of its proximity to major commercial and recreational port facilities (BOYD *et al.*, 1972) and because it is located in a sedimentary environment characterized by relatively weak bottom currents and the long-term deposition of fine-grained sediment (Figure 1; MORRIS *et al.*, 1996; SIGNELL *et al.*, 2000; KNEBEL *et al.*, 1999; KNEBEL and POPPE, 2000). However, tidal and, to a lesser extent, wind-driven currents can influence the short-term sedimentary processes and surficial sediment distributions here and throughout the Sound (BOKUNIEWICZ and GORDON, 1980; SIGNELL *et al.*, 2000).

Tidal and storm currents in Long Island Sound generally flow in an east-west direction due to the Sound's elongate geometry and regional bathymetric contours. High-energy gravelly environments, which are prevalent in the constricted easternmost part of the Sound, are progressively replaced westward by lower energy sandy and finally muddy environments as the estuary widens and fetch associated with the prevailing westerly winds decreases (POPPE *et al.*, 2000). This progression in sediment grain size along the axis of the Sound reflects a general east-to-west succession of sedimentary environments (characterized by erosion, transport, sorting, and finally deposition) caused by the decreasing gradient of tidal-current speeds coupled with the net westward estuarine bottom drift (Figure 1; KNEBEL and POPPE, 2000). However, the tidal currents alone, which are roughly symmetrical and driven by a 1.89-m tidal range, can still locally exceed 20 cm/s at 1 m above the bottom across the New Haven Dumping Ground (Figure 1; SIGNELL *et al.*, 2000). Furthermore, simulations by SIGNELL *et al.* (2000) show that wind-driven bottom currents flow against the wind at the study area, allowing the prevailing westerly winds to episodically enhance flood tides and providing an explanation for the observed net westward sediment transport (KNEBEL and POPPE, 2000).

Soft fine-grained sediments underlie and surround the coarser dredge spoils that lie within the study area. These naturally occurring muds have been winnowed over the past 13.5 ka from glacial, early postglacial and riverine sediments that lie to the east and have been deposited in the central part of the Sound under the tidally dominated marine regime during the Holocene sea-level rise (Figure 1; NEEDELL *et al.*, 1987; LEWIS and DIGIACOMO-COHEN, 2000).

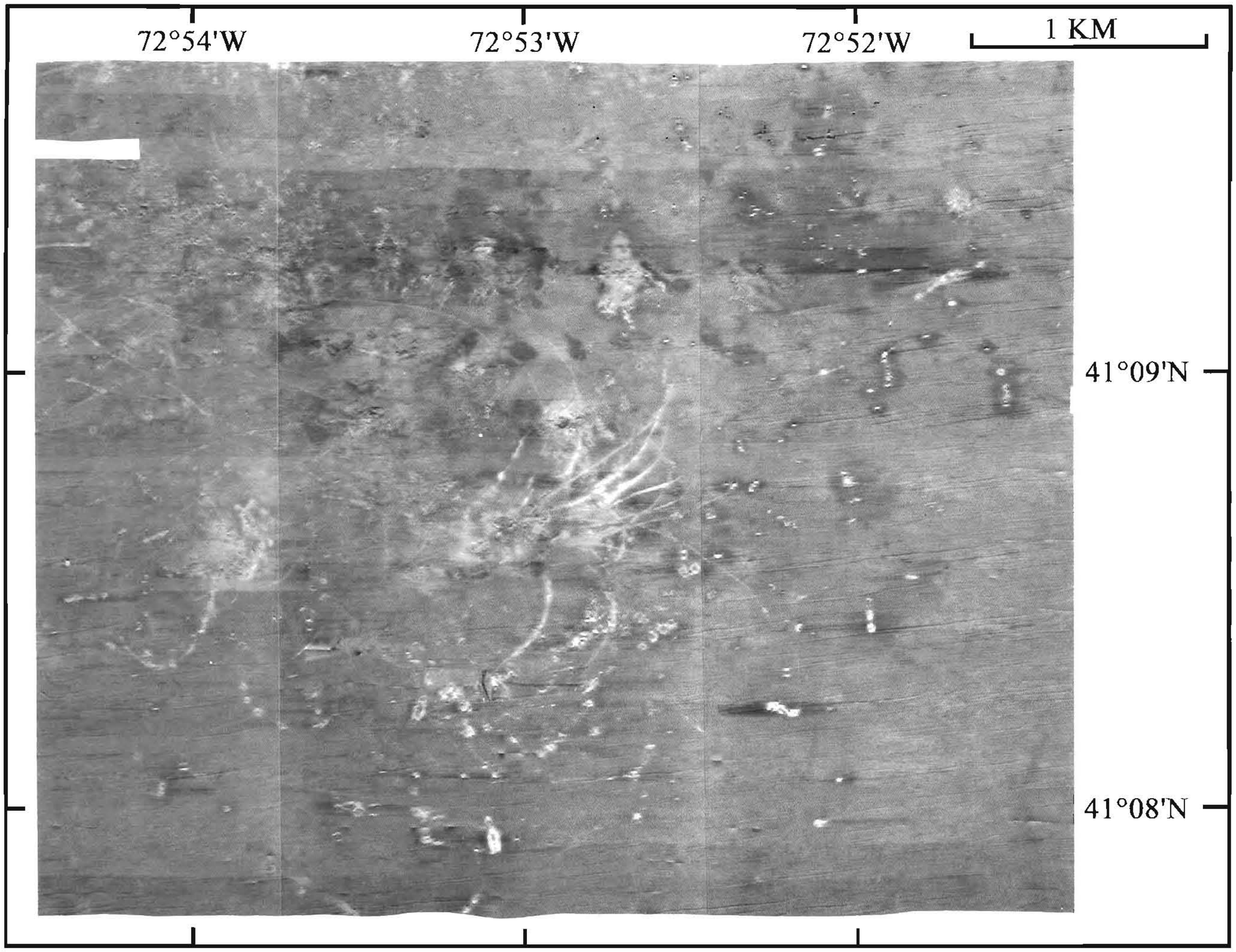

Figure 2. Sidescan sonar mosaic of the sea floor in the vicinity of the New Haven Dumping Ground. Light tones on the image represent areas of high backscatter (generally coarser-grained sediment associated with dredge spoils and areas of the sea floor that sloped toward the seismic source); dark tones represent areas of low backscatter (generally finer-grained sediment and areas of the sea floor that sloped away from the seismic source). East-northeast trending linear features in the southern and eastern parts of the mosaic are sedimentary furrows.

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 RV *Asterias* during June 1997 (Figures 2, 3, and 4). The bathymetric data were collected at a 10-s sampling rate using a 200-kHz echo sounder, were logged digitally, and were adjusted to mean sea level. 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 on an ISIS data acquisition system. High-resolution seismic reflection profiles, which were used to define furrow morphology, were collected in analog form using an Ocean Research Equipment 3.5-kHz profiler transmitting at a 0.25-s repetition rate. 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 *et al.* (1991) and PASKEVICH (1992a). Alternate strips of processed sonar data were placed in their proper geographic location at the appropriate scale and projection (PASKEVICH, 1992b). Adjacent sonar images were matched for tone, were digitally trimmed (where two images overlapped), and were progressively combined into the composite digital image (Figure 2). Registration between the ship's track navigation and the strips of sidescan sonar data are generally good throughout the study area.

Surficial sediment samples and bottom photography were collected at 25 locations within or near the New Haven Dumping Ground (Figure 3) during March 1996 and March 1998 aboard the RV *John Dempsey* using a Van Veen grab sampler equipped with video and still camera systems. The photographic system was used to appraise bottom variability, faunal communities, and sedimentary processes around the

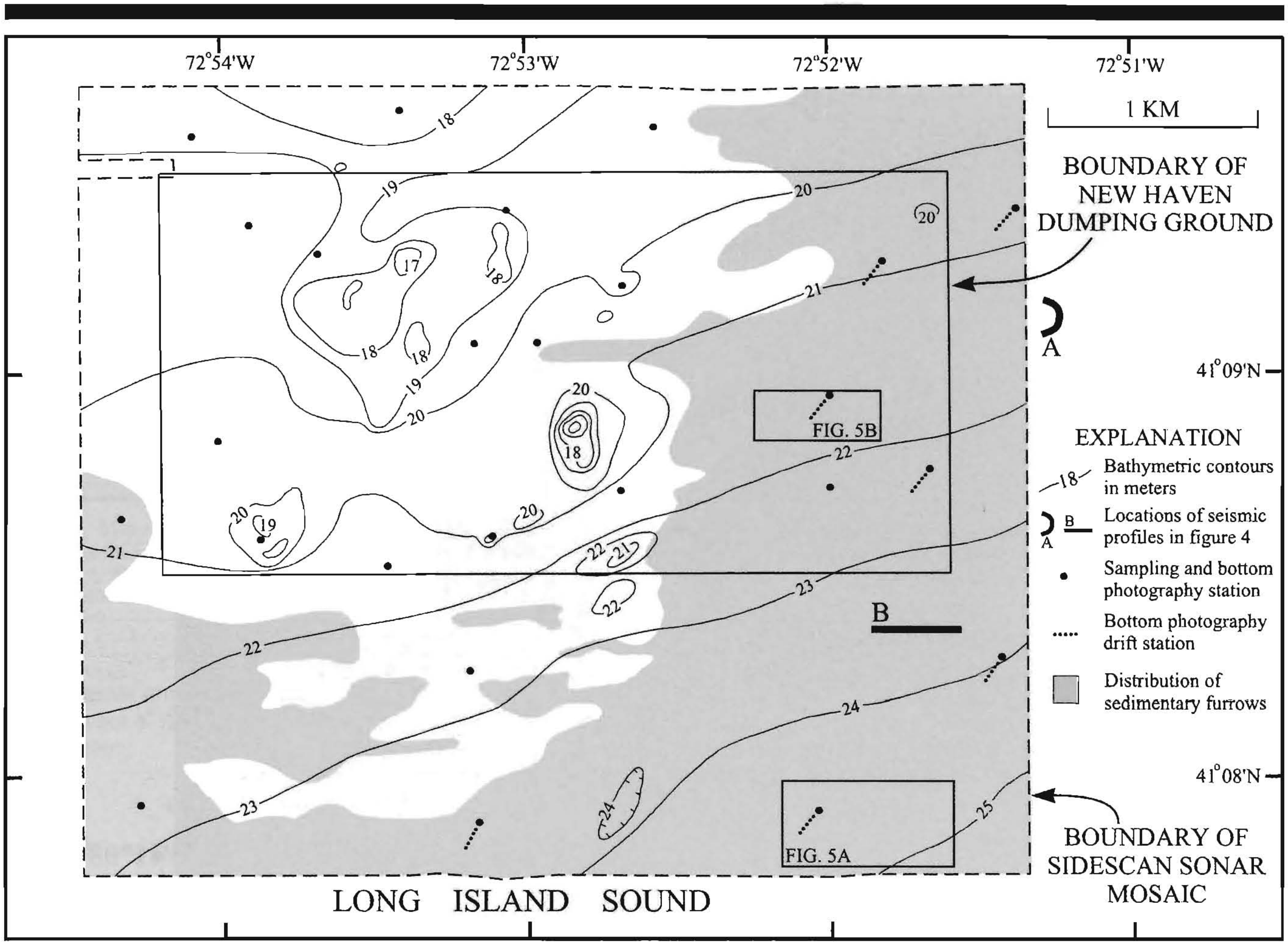

Figure 3. Map showing: the location of the sidescan sonar mosaic presented in Figure 2; boundary of the New Haven Dumping Ground; the subbottom profiles shown in Figure 4; and bottom sampling and photography stations. Also shown are: the distribution of sedimentary furrows (shaded area); the locations of detailed sidescan images presented in Figure 5; and the generalized bathymetry. Depths were contoured to 1 m, corrected for tides, and adjusted to mean sea level.

stations. The ship was allowed to drift over the bottom for extended distances (more than 50 m) at seven stations; these are shown as drift stations in Figure 3. Detailed descriptions of the field methods, navigation, raw grain-size data, bottom photography, and laboratory methods have been reported in POPPE *et al.* (1998); sidescan sonar imagery and its interpretation are available in POPPE *et al.* (2001).

SEDIMENTARY ENVIRONMENTS AND PROCESSES

The corrected bathymetry was contoured at a 1-m interval to facilitate an understanding of the surficial geology and general benthic character (Figure 3). This perspective is important because sea-floor topography affects the evolution and stability of physical and biological environments. The sea floor in and around the New Haven Dumping Ground has a relatively smooth gradient that gradually slopes toward the southeast (Figure 3). Water depths range from slightly less than 18 m in the northwestern part of the study area to slightly more than 25 m in the southeast corner, an average slope of only about 0.1°. Isolated bathymetric highs, which occur in the central and northwestern parts of the study area, are composed of mounded dredge spoils and the materials used to cap them (MORRIS *et al.*, 1996). Except during major storms, such as northeasters and hurricanes, the entire study area lies below the wave base (BOKUNIEWICZ and GORDON, 1980; SIGNELL *et al.*, 2000).

The study area can be divided into two general provinces on the basis of lithology, faunal assemblages, and backscatter intensity on the sidescan sonar image (Figure 2). Contacts between these provinces are gradational; lateral changes in lithology are seldom abrupt. 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 on the sidescan imagery (light and dark tones, respectively) and curvilinear streaks of high backscatter. The high backscatter results from a combination of relatively coarse-grained sediments in dredge spoils or materials used to cap the spoils (MORRIS *et al.*, 1996) and the angle of inci-

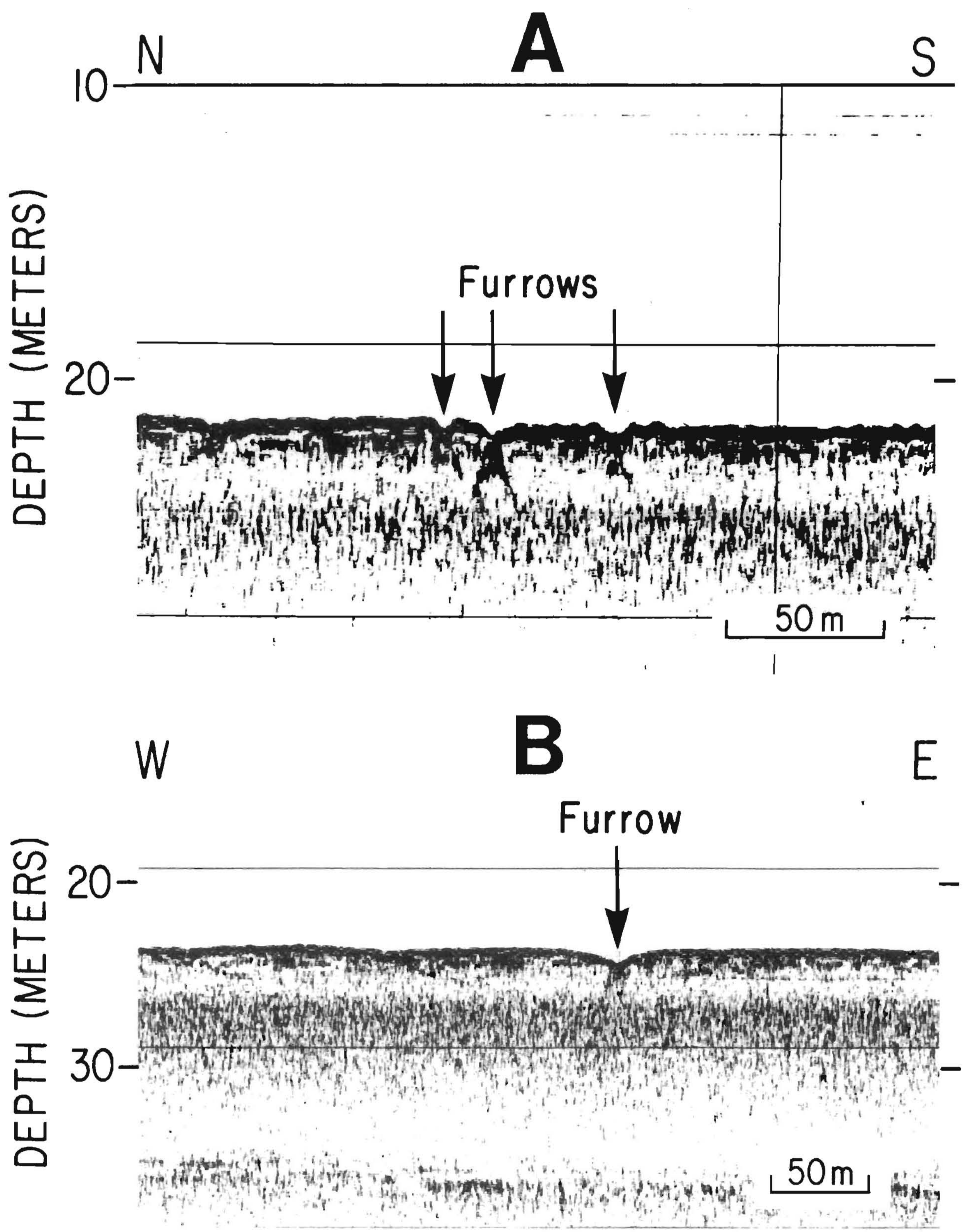

Figure 4. Seismic profiles (3.5 kHz) showing furrow morphology. (A) Cross section across three furrows. Data collected while turning onto a survey line. (B) Oblique cross section of a well developed sedimentary furrow. Note the symmetrical walls. Locations of profiles are shown in Figure 3.

dence of the sonar on the sides of disposal mounds. Sediment samples collected from the vicinity of the New Haven Dumping Ground consist of very poorly sorted fine-grained sands, silty sands, and sandy silts.

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 (Figure 2) may represent either the effect of density surges caused by the impact of dredged materials on the bottom or the subsequent deposition of a diffuse plume of residual finer grained material. Identifiable manmade debris (wires, cables, and pipe) were recognized in the bottom video imagery collected at stations situated on the spoils. Amphipod communities, worm tubes, and shrimp burrows are common in the spoil areas.

The second province, which covers the eastern and southernmost parts of the study area, is characterized by low backscatter on the sidescan image, caused by the predominance of muddy relatively fine-grained sediments. Samples indicate that these sediments are generally poorly sorted siliciclastic silts and clayey silts with unimodal distributions. The second province is also characterized by numerous linear depressions interpreted to be sedimentary furrows (Figures 2, 3, and 5). The furrows, which trend east-northeast, appear as thin slightly sinuous paired lines of high and low backscatter in the sidescan sonar mosaic. The furrows have a patchy irregularly spaced distribution; mean distances between them are about 22 m. The furrows average about 206 m long, but range from 30 m to at least 1,315 m in length. Sedimentary furrows of greater length may be present in this part of the Sound, because many extend out of the mapped area and could not be measured. The average width and relief of the furrows are 9.2 m and 0.4 m, respectively. Because of their shallowness, the 10-s bathymetric sampling rate, and the trend of the features nearly parallel to the ship's track, these features are not resolved in the bathymetry (Figure 3).

Most of the furrows are shallow, broadly V-shaped, and symmetrical in cross section (Figure 4). Where they are asymmetrical, the southern wall (or downslope relative to the regional bathymetry) is commonly steeper. No evidence of control by subsurface structure was evident from the high-resolution seismic-reflection profiles.

Most of the sedimentary furrows appear to gradually taper out at both ends, although the ends of some furrows show a "tuning fork" joining pattern. The junctions open predominantly toward the east (Figure 5A), but some also open toward the west. A few of the sedimentary furrows cross, start at, or end at dredge-spoil mounds (Figure 5B), but most are not associated with the mounds or with any other identifiable bottom features.

Bottom video reveals that the sedimentary furrows in north-central Long Island Sound are rounded linear depressions with gently sloping walls (Figure 6) similar to the Type-2 troughs of FLOOD (1983). A current-swept appearance characterizes the bottom within the furrows. In this regard, scour around coarser grains, sediment accumulations in the current shadows of obstacles, saltating nutclam (*Nucula* spp.) shells, and downstream deflections in the orientation of attached megafauna (hydrozoans and anemones) were observed in the bottom video. Also commonly recorded in the video were the resuspension of sediment and nutclam shells by the burrowing and feeding activities of the benthic megafauna (*e.g.* crabs); and small clouds of sediment generated by the impacts of saltating nutclam shells. These shells are tiny (about 6-mm long), thin walled, light (each valve weighs less than 0.05 g), and once resuspended apparently of a hydraulic equivalence that allows them to be transported by the weak bottom currents. Faint, low (<2 cm high) longitudinal ripples, which trend east-northeast, are common within this part of the study area, but, along with nutclam shells, the ripples appear to be concentrated within the sedimentary furrows. Burrows (constructed by shrimp, clams, mud crabs, and lobsters), animal tracks, burrowing anemones, worm tubes, hydrozoans, and amphipod communities are present in the heavily bioturbated bottom throughout the eastern province.

Other shallow linear depressions, interpreted to be trawl marks (Figures 5A and 5B), are most evident in the eastern part of the study area. Whether this association occurs because trawl marks are more visible or readily preserved in the fine-grained sediments or whether it is because these muddy sediments are a preferred biologic habitat of some commercial species is unknown. The trawl marks can be differentiated from the furrows in that they are much fainter, are usually curvilinear, and show no preferential orientation. Some lineations, especially those located in the western part of the study area, may be anchor drag marks.

DISCUSSION AND CONCLUSIONS

Although the deeper (>20 m) waters of north-central Long Island Sound are long-term depositional areas characterized by fine-grained, cohesive sediments and relatively weak bottom currents (Figure 1; GORDON, 1980; SIGNELL *et al.,* 2000; KNEBEL *et al.,* 1999; KNEBEL and POPPE, 2000), our data reveal the localized presence of sedimentary furrows and longitudinal ripples (Figure 6). These features indicate sediment erosion or transport, and they typically form in environments that have recurring, directionally stable, and occasionally strong currents (DYER, 1970; LONSDALE *et al.,* 1973; HOLLISTER *et al.,* 1974; FLOOD, 1983). The lack of abrupt lithologic transitions, the faint appearance of the associated longitudinal ripples, and the abundance of tracks made by bottom-dwelling animals suggest that the processes that created these furrows are slow or only intermittently active. In any case, the furrows are not relict. Relict features would have been either obliterated by bioturbation or by the relatively high postglacial sedimentation rates within the study area (LEWIS and DIGIACOMO-COHEN, 2000).

Previous work near the New Haven Dumping Ground (GORDON *et al.,* 1972; SIGNELL *et al.,* 2000) indicates that (1) resuspension is the major mechanism of bottom sediment transport; (2) the principal factors controlling resuspension are the speed of the tidal currents, episodically enhanced (over a period of several days) by wind and wave-driven currents; and (3) once suspended, sediment does not entirely settle out between tidal cycles. Therefore, resuspension, or at

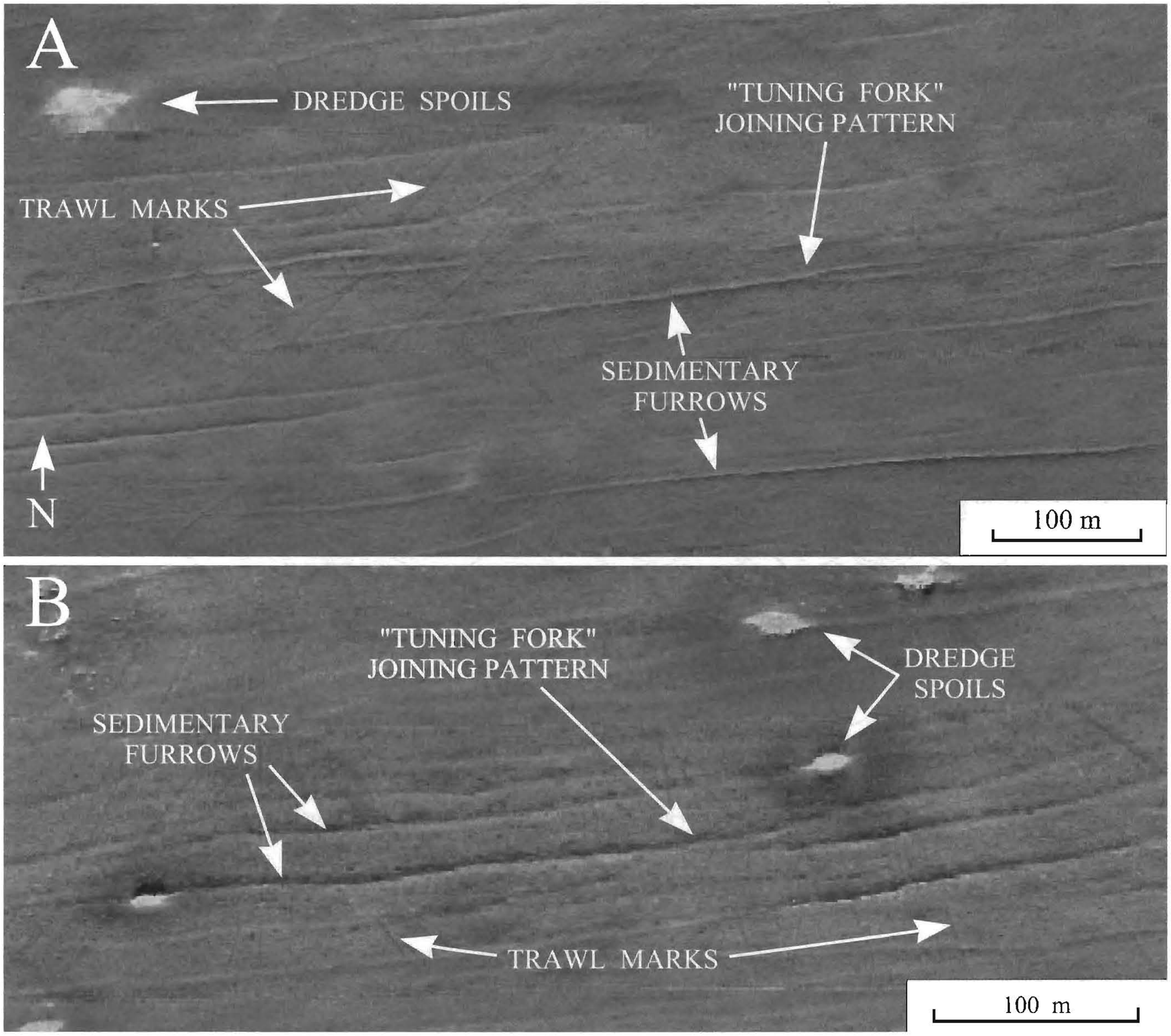

Figure 5. Detailed sidescan sonar images from north-central Long Island Sound. Conspicuous east-northeast trending linear features are sedimentary furrows. Faint curvilinear features are trawl marks and anchor scars. Patches of high backscatter (light areas) are dredge-spoil mounds. (A) Image shows the "tuning fork" joining pattern exhibited by some furrows. Most forks open to the east suggesting net westward transport. (B) Image shows the association of some furrows with dredge spoils. The extension of furrows from both the east and west sides of spoil mounds and transport of spoil material into the furrows (as shown by the cuspate high-backscatter lobes pointing into the furrows) is further evidence for the strong oscillatory nature of the tidal currents. Locations of images are shown in Figure 3; a perspective view of these furrows is shown in Figure 6.

least transport, at the dumping ground should be greater during spring tides and weaker during neap tides. Although the amount of suspended sediment at any one site in the Sound is highly variable, data from GORDON *et al.* (1972) indicate average amounts of suspended sediment at 13 mg per square cm of bottom. Now, however, our new bottom video data suggest that benthic biological activity, rather than currents, is responsible for most of the sediment resuspension.

While it is true that the currents in the north-central Sound are usually not strong enough to initiate erosion, once sediments are resuspended by biological activity, the currents can transport them. The "tuning fork" joining patterns of the furrows, which usually open toward the east, indicate net westward sediment transport (Figures 5A and 5B; DYER, 1970; 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

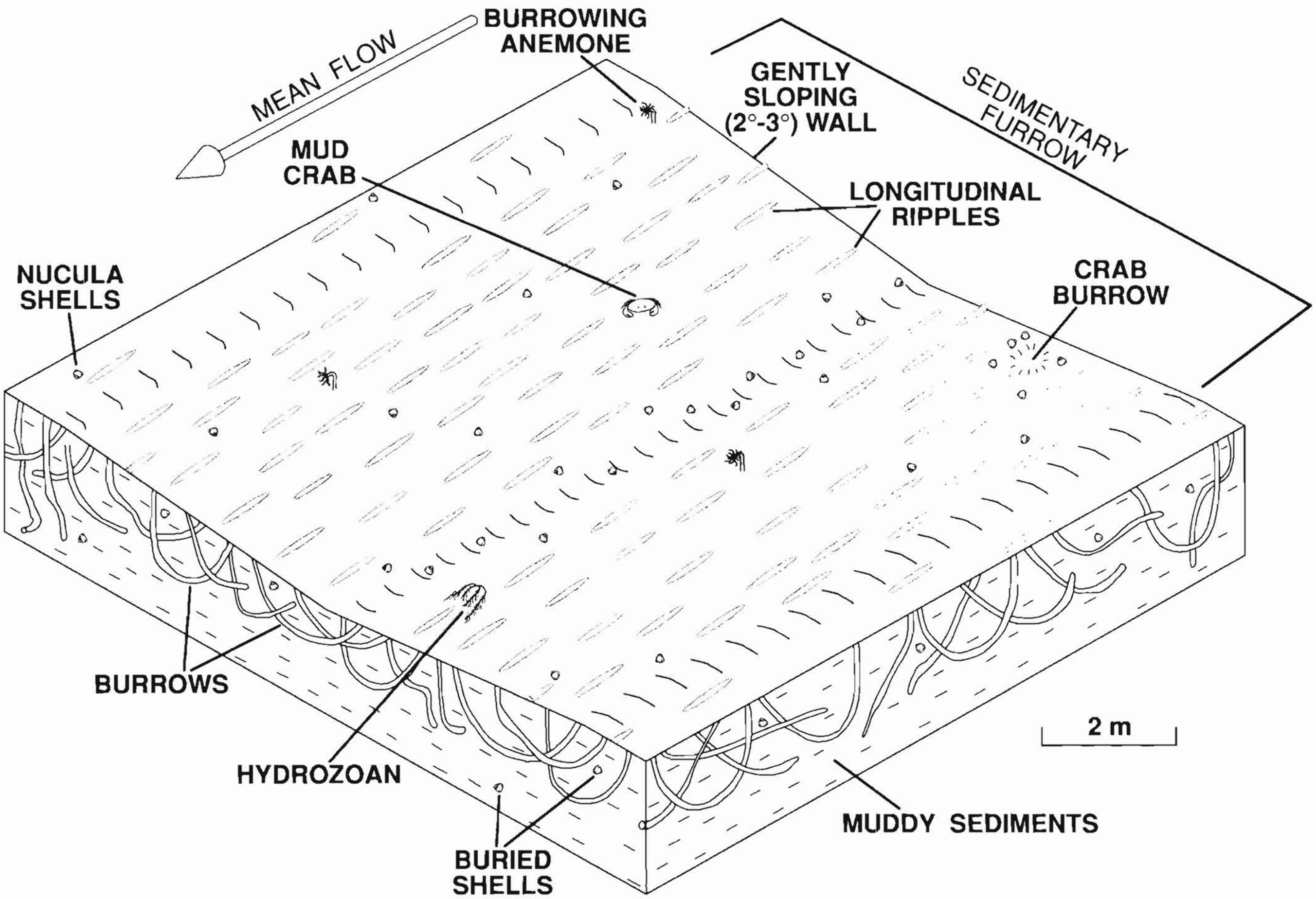

Figure 6. Perspective view of an idealized sedimentary furrow in the muddy cohesive sediments of north-central Long Island Sound. Figure highlights a shallow v-shaped linear depression with gently sloping walls, longitudinal ripples, current-deflected hydrozoans and anemones, bioturbation, and nutclam (*Nucula spp.*) shells.

flows in either direction. Studies by FLOOD (1981, 1983) also show that coarse-grained sediments are also important for the initiation and development of furrows in muddy sediments. Coarse sediments that are available within the study area include nutclam shells and sand associated with the dredge spoils.

We do not completely understand the processes which produce or maintain the sedimentary furrows in north-central Long Island Sound. However, given the geometry of the basin and conditions in the study area, we can offer two possible mechanisms. In the first mechanism, adapted from FLOOD (1983), benthic biologic activity resuspends nutclam shells. Then, secondary helical-flow patterns produced by the tidal currents, which develop just above the sea floor, align the nutclam shell debris mobilized by biological activity into convergent flow zones (Figure 7A; HOLLISTER *et al.,* 1974; MCLEAN, 1981). Furrow development is initiated due to enhanced erosion within the elongate shell beds caused by abrasion (related primarily to sediment resuspension from the impacts of saltating shells) and from current scour around individual shells. The furrows lengthen as the concentrated shells move downstream in the bottom currents.

Alternately, in a mechanism adapted from MCLEAN (1981), depressions form in the turbulent wakes of current flow around dredge-spoil disposal mounds. Easily transported non-cohesive grains (coarse silt and very fine sand) eroded from the disposal mounds subsequently are made available to abrade and lengthen such depressions into furrows in the muddy seabed (Figure 7B). While no seismic evidence exists for the furrows cutting into disposal mounds, cuspate high-backscatter lobes do extend off both the eastern and western sides of disposal mounds associated with furrows (Figure 5B). These lobes are evidence for the reworking of high-backscatter materials from the disposal mounds by near-bottom currents and for the transport of these materials into the adjacent furrows. However, it is important to note that most of the sedimentary furrows in the north-central Sound are not associated with disposal mounds or any other identifiable obstacles.

In summary, the elongate geometry and regional bathy-

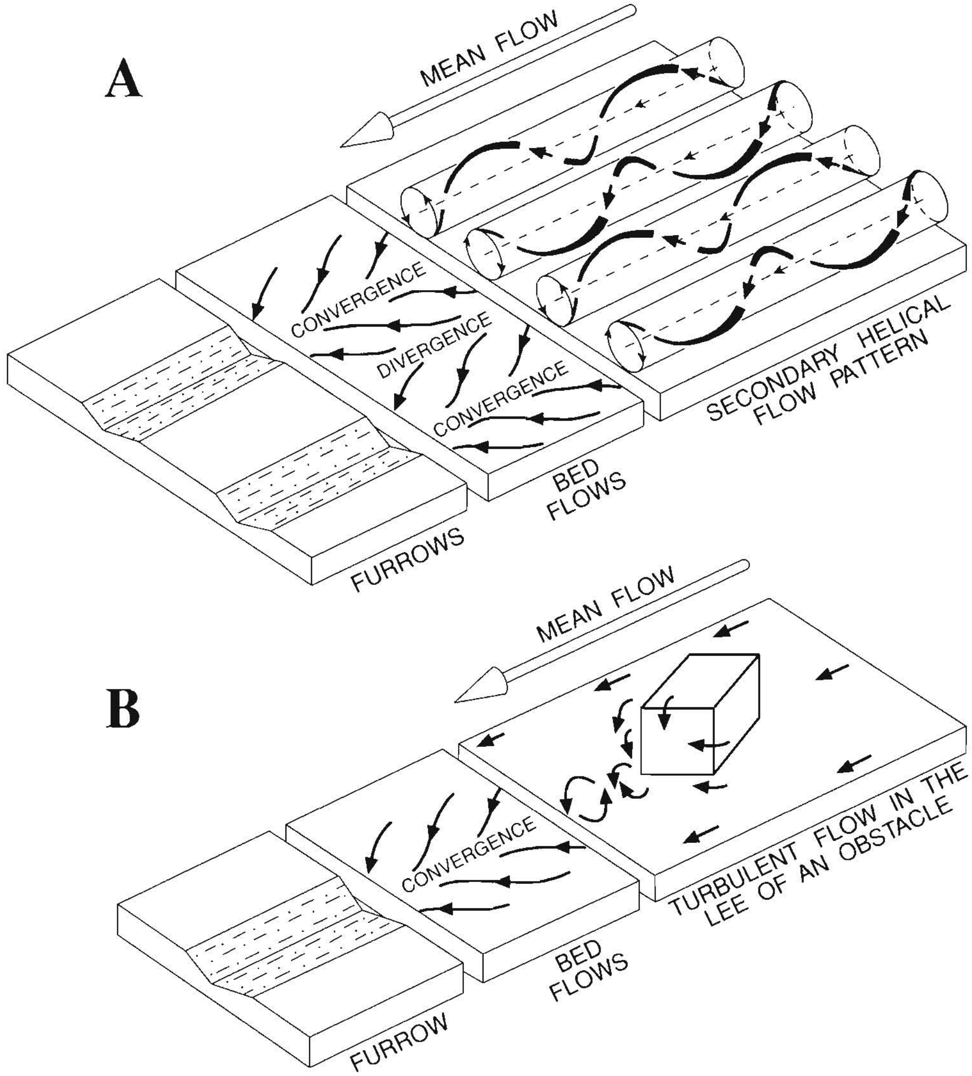

Figure 7. Schematic representations showing two possible mechanisms for the formation of the sedimentary furrows in north-central Long Island Sound. (A) Secondary helical flow patterns produced by tidal currents (HOLLISTER *et al.*, 1974; MCLEAN, 1981) sweep biologically resuspended coarse material, such as nucula shells or very fine sand, into linear zones of convergence. These coarse particles are driven downstream by strong tidal currents and cut the linear furrows into the soft cohesive sediments. From FLOOD (1983). (B) Turbulent wakes produced by obstacles on the seafloor (*i.e.* dredge spoil disposal mounds) may also initiate furrow development. From MCLEAN (1981). Coarse silt and very fine sand from the disposal mounds are the abrading agent in this mechanism.

metric contours of Long Island Sound combine to constrain the tidal and storm currents and cause dominantly east-west flow directions. These conditions, in turn, produce the helical and turbulent flow patterns that are conducive to the development of erosional furrows. Through resuspension due to biological activity and the subsequent development of sedimentary furrows and longitudinal ripples, fine-grained cohesive sediment can be remobilized, and, at least episodically, be made available for transport farther westward into the estuary.

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