SIDESCAN SONAR IMAGE, SURFICIAL GEOLOGIC INTERPRETATION, AND BATHYMETRY OF THE LONG ISLAND SOUND SEA FLOOR OFF ROANOKE POINT, NEW YORK

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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 and results published (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 distributions, processes that control these distributions, 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 (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 mosaic presented herein covers approximately 34 km^2 of the sea floor off Roanoke Point, N.Y., in southeastern Long Island Sound (figs. 1 and 2). This site was selected because it contains one of the largest cape-associated shoal complexes along the north shore of Long Island, a feature that is clearly important to an understanding of the sediment transport regime in this part of the sound. The sidescan sonar mosaics enable us to define the geological variability of the sea floor, which is one of the primary controls of benthic habitat diversity. The mosaics also provide a detailed framework for future research, monitoring, and management activities, and they improve 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. The sidescan sonar mosaics additionally serve as base maps for subsequent sedimentological, geochemical, and biological observations, because precise information on environmental setting is important to the selection of sampling sites and to the accurate interpretation of point measurements.

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 west by the East River, on the east by Block Island Sound, and on the south by the sandy bluffs of Long Island, N.Y.

The bedrock beneath Long Island Sound dips southward and is composed of gneissic and schistose metamorphic rocks of pre-Silurian age, similar to the bedrock exposed in southern Connecticut and present at depth in western Long Island (Grim and others, 1970; Rodgers, 1985). Coastal-plain sediments of Cretaceous age overlie the bedrock across most of the southern part of the sound and form a southward- and eastward-thickening wedge beneath Long Island (Fuller, 1914). Wells drilled on Long Island have encountered a coastal-plain section composed of the white micaceous sands and blue, white and red clays of the Raritan Formation and the coarser, yellow and darker gravels, sands, and clays of the overlying Magothy Formation (Fuller, 1914).

At least two tills, one of early Wisconsinan-Illinoian age and one of late Wisconsinan age, overlie pre-Pleistocene strata on Long Island and beneath the sound (Lewis and Needell, 1987; Needell and others, 1987; Stone and others, 1992). The older till is patchy, compact, eroded, and oxidized to a yellowish brown, and includes the Manhasset Formation, Jameco Gravel and Mannetto Gravel of Long Island (Schafer and Hartshorn, 1965) and the till exposed on Falkner Island, Conn. (Gordon, 1980).

The late Wisconsinan Laurentide ice sheet reached southern Long Island, where its terminal position is marked by the Ronkonkoma moraine (Fuller, 1914). The northward retreat of this ice sheet about 19.5 ka produced the Harbor Hill–Roanoke Point–Charlestown moraine across northern Long Island (Sirkin, 1967; Schafer and Hartshorn, 1965) and a succession of minor recessional moraines in Connecticut, including the Hammonasset-Ledyard, Old Saybrook, and Mystic moraines (Flint and Gebert, 1976; Goldsmith, 1982; Poppe and others, 1997a).

The deltaic and varved deposits of glacial Lake Connecticut variously overlie the glacial drift in the Long Island Sound basin (Lewis and Stone, 1991; Stone and others, 1992). This lake, which occupied most of the basin, was formed when the last ice front began to recede from the Harbor Hill–Roanoke Point–Charlestown moraine position 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 coastal plain, glacial drift, and glaciolacustrine deposits all are truncated by an unconformity. This unconformity is a com-

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posite product of the subaerial exposure of these sediments, which occurred after glacial Lake Connecticut drained, and of the marine transgression that took place after 15 ka (Lewis and Stone, 1991). A marine mud facies, which occurs in quiet-water areas throughout the western and central parts of the Long Island Sound basin, records deposition during the postglacial eustatic rise of sea level.

The northern shoreline of Long Island east of Port Jefferson is classified as a glacial deposition coast (Shepard, 1963) because it coincides with the eroded and partly submerged sections of the Harbor Hill–Roanoke Point–Charlestown moraine. This section of the shoreline is characterized by gently curved beaches separated by headlands that project slightly into the sound. The headlands, such as Herod and Roanoke Points, have higher bluffs (up to 40 m total height) and more layers of erosion-resistant clay and boulders than the sand and gravel of the bluffs situated between them (U.S. Army Corps of Engineers, 1969; Koppelman and others, 1976).

The high bluffs on Long Island's north shore are steep, only partly covered by vegetation, and fronted by narrow beaches. The beaches near Roanoke Point average about 12 m in width (Davies and others, 1973). Both the beaches and bluffs are eroding rapidly; in the vicinity of Roanoke Point the average annual shoreline retreat is about 0.8 m/year (Davies and others, 1973; Bokuniewicz and Tanski, 1983).

DATA COLLECTION AND PROCESSING

Sidescan sonar imagery, bathymetry, subbottom high-resolution seismic-reflection profiles, and navigational data were collected along tracks spaced 150 m apart aboard the research vessel *Asterias* during June 1996 (fig. 2). The bathymetric data (fig. 2) were collected using a 200-kHz echo sounder, logged digitally to a computer, and corrected for the approximately 1.89-m tidal range in the study area by adjusting the measured depth values to the predicted mean sea level for Roanoke Point, N.Y., using commercially available software. Regional bathymetric perspectives were created using digital data (National Oceanic and Atmospheric Administration, 1996; fig. 3). The sidescan sonar data were collected using an SIS-1000 Datasonics 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. Subbottom data were collected in digital form using 2- to 7-kHz swept-frequency CHIRP and 3.5-kHz systems, and, in conjunction with pre-existing Uniboom data (Needell and others, 1987), were used to interpret the stratigraphy (fig. 4). Ship position was determined with a differential Global Positioning System (GPS); navigational data were logged on a computer at 10-second intervals.

The sidescan sonar data were processed according to procedures summarized by Danforth and others (1991) and Paskevich (1992a,b). The sonar data were multiplexed and filtered to convert them into a processing format and to remove speckle noise, and then corrected for slant-range distortions, signal attenuation, and dropped lines that are inherent 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.

These processed data were used to make the composite digital mosaic. 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, unwanted data (where two images overlapped) were digitally eliminated, and images were progressively combined into a composite digital image. Registration of features on adjacent strips of sonar data was generally good throughout the study area. The final digital mosaic, which has a 1-m pixel size (a pixel represents one meter on the sea floor), was output to film, photographically enlarged, and interpreted (figs. 5–8).

Surficial sediments (0–2 cm below the sediment-water interface) and (or) bottom photography were collected at 51 locations during March 1997 aboard the research vessel *John Dempsey*, using a Van Veen grab sampler equipped with a video camera system. The photographic system was used to appraise intra-station bottom variability, faunal communities, and sedimentary structures (indicative of biological and geological processes), and to observe 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 (McCave and Syvitski, 1991); the coarse fraction was analyzed by sieving (gravel) and by rapid sediment analyzer (sand; Schlee, 1966). The data were corrected for the salt content of the samples; 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). The verbal equivalents were calculated using the inclusive graphics statistical method (Folk, 1974) and are based on 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 (1997b).

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

INTERPRETATION

Bathymetry

The tide-corrected bathymetry was contoured at 2-m intervals to facilitate an understanding of the geomorphology of the Roanoke Point Shoal (fig. 2). This perspective is important because the bathymetry is related to the evolution and stability of the shoal and to the physical and biological systems along the north shore of Long Island.

The Roanoke Point Shoal, which extends perpendicular to the shoreline, is asymmetrical about its axis. Minimum water depths are less than 4 m along the shoreward edge of the study area west of both Roanoke and Jacobs Points (fig. 2). The crests of the shoals off these points form "hooked" ridges that extend from bathymetric highs along the western sides of the shoals in seaward convex arcs that continue northeastward around the tips of the shoals. The ridge on the Roanoke Point Shoal, which occurs in less than 6 m of water, accentuates the asymmetry and causes the topography to be steeper on the western and northern flanks and gentler and open on the eastern flank (figs. 2 and 3). The gradient exceeds 9^{o} across the northern flank of the shoal.

Maximum water depths in the study area exceed 34 m and occur in isolated bathymetric lows within a depression off the tip of the Roanoke Point Shoal. Away from the shoal, water depths increase toward the northwest and connect with the elongate axial depression that extends the length of the sound (fig. 3). They shallow to the northeast and toward the west in the area between the Roanoke Point Shoal and the adjacent Herod Point Shoal. Figure 3 also suggests that similar bathymetric features and trends characterize the other shoals along the north shore of Long Island.

Near-Surface Seismic Character

Seismic-reflection profiles provide information on the subsurface geology and its relation to surficial processes and sediment distributions (fig. 4). Coastal-plain strata of Cretaceous age compose the oldest unit that can be recognized on the profiles. This unit is characterized by a strong reflection from its upper surface and by the local presence of nearly continuous, subhorizontal internal reflectors.

Glacial drift, composed primarily of till, unconformably overlies the coastal-plain strata. The till, which is characterized by a well-defined upper reflector and highly irregular and discontinuous internal reflectors (Needell and others, 1987), rises shoreward toward Long Island and apparently continues rising landward beneath the shoal. This high may represent an erosional remnant tracing the retreat of the headland and may be evidence for some structural control during the formation of the shoal. Channels and basins in the drift surface are filled with younger sediments (fig. 4A).

Glaciolacustrine strata composed of fan, varved lake, and deltaic sediments deposited in glacial Lake Connecticut (Lewis and Stone, 1991) overlie the glacial drift. These lake deposits are absent beneath the shoal, occurring only in the offshore part of the study area (figs. 4A and B).

Holocene marine sediments, which exhibit persistent, subhorizontal internal reflectors, overlie the marine unconformity. The thickness of the Holocene unit thins to less than 1 m in a band around the base of the shoal and across the seaward (northward)-dipping surface of the underlying glacial drift (fig. 4A). Gas-charged sediments, the result of biogenic methane from decaying organic matter, occur in the thicker Holocene strata northeast of Roanoke Point and obscure the underlying units (figs. 2 and 4B).

Sidescan Sonar Mosaic

The sidescan sonar mosaic portrays an acoustic image of the sea floor that, when combined with the subbottom and bathymetric data, can be used to interpret the surficial geology of the Roanoke Point Shoal (figs. 5, 6, and 8). Distinctive acoustic patterns revealed by this mosaic include (1) higher backscatter (light tones), (2) moderate backscatter, (3) lower backscatter (dark tones), and (4) elongate patches of alternating high and low backscatter. Boundaries between areas characterized by these patterns are commonly gradational, and backscatter is not uniform throughout these areas. Water column phenomena, such as boat wakes and turbulence around obstructions on the bottom, can be observed on the image, as well as anthropogenically produced structures such as an oil platform and associated pipeline off Jacobs Point.

Areas characterized by high backscatter, which primarily coincide with deposits of coarser grained sediments (fig. 7), occur on the Roanoke and Jacobs Point Shoals. For example, the sediments within the high-backscatter areas on the shoals are slightly coarser grained than those sediments within the areas on the shoals characterized by moderate backscatter (fig. 6); means average 1.26 phi and 1.67 phi, respectively. Arcs of high backscatter are present along the western edges of the shoals (associated with the "hooked" ridges discussed above) and occur as somewhat straighter features on the eastern part of the Roanoke Point Shoal. Although the sediments in the arcs and straighter features are coarser than in the areas of moderate backscatter, the locations of these features correspond with areas characterized by topographic change, and much of the backscatter is related to the angle of incidence of the sonar.

High backscatter is also associated with positive-relief isolated targets and fields of targets, and small lobes that extend seaward from the northern base of the Roanoke Point Shoal. The isolated targets are large individual boulders; the fields of targets are bouldery areas. The boulders are primarily scattered in two bands, one along the shoreward edge of the study area off Roanoke Point and another around the northern base of Roanoke Point Shoal. These boulders, probably glacial erratics, rest on the surface of the Pleistocene drift, but, as in the case of the boulders around the northern base of the shoal, protrude up through the thin Holocene marine section. Linear accumulations of sediment, which appear as streaks of high backscatter, extend from some of the boulders, forming obstacle marks (Belderson and others, 1982; fig. 8). The lobes of high backscatter result from slope failure and mass-wasting events (slumps, for example) that cause coarser sediments from the shoal to extend onto the basin floor (fig. 6).

The areas characterized by relatively low backscatter include most of the basin floor surrounding the shoals, except for the area just north-northwest of the Roanoke Point Shoal. These parts of the study area coincide with deposits of finer grained Holocene marine sediments. The average mean grain size of the sediments in the areas of low backscatter is 6.81 phi.

Elongate patches of alternating high and low backscatter, an acoustic pattern produced by sand waves, occur in narrow bands along the western and northeastern upper flanks of the Roanoke Point Shoal (figs. 5 and 6). The alternation in backscatter that creates this pattern is due to a combination of topographic changes (because the angle of incidence of the sonar varies) and differences in sediment texture between crests and troughs. The sand waves are typically less than 1 m high, with average wavelengths of less than 20 m. The asymmetry of the sand waves on the CHIRP subbottom records suggests that the net transport direction in both sand-wave fields is toward the tip of the shoal.

Although parts of the image on top of the shoal exhibit a pattern similar to that of sand waves, the direction alternates from line to line, creating a herringbone effect, and the pattern does not continue from line to line. In these instances the pattern is caused by acoustic noise from surface-wave conditions in the shallow water. Turbulence from boat wakes and currents around bottom obstructions also produce patches of alternating high and low backscatter on the image. The faint high-backscatter band, which trends northward from about 1.2 km off the Jacobs Point Shoal, appears to result from the reworking of sediments dredged, presumably, to lay a pipeline or cable.

Surficial Sediment Distribution

The distribution of surficial sediment and the locations of the sediment sampling and bottom photography stations are shown in figure 7. On the basis of lithology, texture, and faunal assemblages, four major sedimentary facies were identified within the study area. Contacts between these environments are gradational and changes in lithology are seldom abrupt.

Facies 1 is located on the crests of the Roanoke Point and Jacobs Point Shoals in water depths of less than 10 m (see also fig. 2). This depositional environment is subjected to the highest energy levels relative to the other facies because of its relief above the wave base and the surrounding basin floor of the sound. For example, numerical models (Signell and others, 1998) show that orbital wave velocities on top of the shoal (the speed necessary to cause resuspension) exceed 15 cm/s over 30 percent of the time and that spring tidal currents exceed 30 cm/s. Facies 1 is characterized by clean, medium-grained, moderately to moderately well sorted siliciclastic sand. The sand, which has means between 1 and 2 phi and unimodal distributions, is typically finely skewed to nearly symmetrical, generally contains little or no gravel, and has less than 1 percent fines (silt plus clay). A few, small bouldery patches are scattered over the central, nearshore part of the Roanoke Point Shoal. Current ripples are ubiquitous. Shells and shell debris and, occasionally, fine-grained organics are concentrated in the ripple troughs. Scattered worm tubes and clam burrows were observed in the bottom video.

Facies 2, which is present in water depths of between 10 and 22 m, occurs on the flanks of the Roanoke Point Shoal and represents the rapid transition from shallow to deeper-water depositional conditions. Sediments in this facies typically are composed of medium- to fine-grained, poorly to very poorly sorted sand. These sediments coarsen westward and become more finely skewed and platykurtic eastward. Worm tubes and hermit crabs are more common in this environment than in the shoal-crest facies. Shells and shell debris, which commonly fill the troughs of current ripples and armor the bottom, were observed in the bottom video cascading downslope.

Facies 3 forms a basal apron around the shoal front and floors the isolated depressions north of the Roanoke Point Shoal. Inorganic sediments in this environment form a seaward progression of poorly sorted, finely skewed, platykurtic, very fine-grained sand, silty sand, and sand-silt-clay. Biogenic debris, including clam (quahog and razor), welk, and snail shells and shell hash, compose most of the bulk sediment in a narrow band at the base of the shoal edge, producing a clast-supported fabric. Current ripples are more conspicuous here than in areas dominated by facies 4; rock crabs are common.

Facies 4, which represents the basin floor environment in this part of Long Island Sound, occurs northwest of the Roanoke Point Shoal and along the edges of the east-trending trough north of the Roanoke Point and Jacobs Point Shoals. The sediments in facies 4 are generally very poorly sorted, bimodal, nearly symmetrical to coarsely skewed, and mesokurtic to very platykurtic clayey silt and sand-silt-clay. Evidence for transport is limited to faint current ripples, shallow scour features around shells, and a variegated appearance caused by current-swept organics. Worm and amphipod tubes as well as shrimp and clam burrows are abundant in the heavily bioturbated bottom; spider crabs and anemones are a common component of the faunal assemblage.

Sedimentary Processes

The main current regimes controlling sedimentary processes around the Roanoke Point Shoal include a wind- and wave-driven regime that predominates nearshore and a tidal regime that predominates offshore around the edges of the shoal. Precipitation, ground-water discharge, freeze-thaw cycles, mass wasting (slumping and gravitational sliding), wind-driven waves associated with storms, and sea-level rise all play important roles in bluff erosion and the evolution of the northeastern coast of Long Island (Davies and others, 1973; U.S. Army Corps of Engineers and U.S. Soil Conservation Service, 1975). As the bluffs recede, the eroded sediments accumulate as talus on the narrow beaches. Wave attack during storms removes the talus and can erode the bluffs. Boulders and coarse gravel remain on the beach as lag deposits; the finer grained sediments are winnowed away. The mean-high-water line migrates landward as the beach deposits are removed, and the cycle of bluff and beach erosion continues. Normal circulation in the sound and prevailing westerly winds combine to set up an eastward longshore littoral drift, as indicated by beach accretion on the west or updrift side of jetties, groins, and other obstructions and by erosion on the sediment-starved east or downdrift side, such as occurs near Friars Head (Omholt, 1974; Schmalz, 1993; fig. 2).

The sediments are transported eastward along the coast to headlands where they are deflected offshore. The sands accumulate in a series of shore-connected, cape-associated arcuate shoals, such as the shoals present off Roanoke and Jacobs Points; the silts and clays are moved farther offshore to lower-energy environments. This mechanism continuously supplies sand to sustain the shoal and also supplies finer grained sediment to the basin floor and to the protected areas between adjacent shoals (fig. 3). In addition to acting as sediment sinks in the longshore regime, the shoals also shield the headlands from wave action (Swift and others, 1972; McNinch and Wells, 1999). Because the onshore transport of offshore sediments from the deeper, lower-energy benthic environments of the sound is minimal (U.S. Army Corps of Engineers, 1969), bluff erosion and longshore transport are the major processes affecting the delivery of sediments to these shoals.

Earlier work on cape-associated shoals (Swift and others, 1972; Duane and others, 1972) and shoreface-attached sand ridges that are not perpendicular to the shoreline (Swift and others, 1984; McBride and Moslow, 1991) shows that the areas shoreward of the crests on most shoreface-attached shoals, unlike the Roanoke Point Shoal, are bathymetrically open to their updrift sides and have gentler slopes on their updrift sides than on their downdrift sides. We attribute these differences in topography to a greater sediment supply and to a narrower foreshore area along the north shore of Long Island. On Cape Cod near Truro, Mass., for example, a series of shoreface-attached hooked bars have morphologies similar to that of the Roanoke Point Shoal (Uchupi and others, 1996). Their association with narrow beaches and rapidly eroding sea cliffs suggests that an ample sediment supply is important to the development of hooked shoreface-attached shoals that are bathymetrically closed to their updrift sides and that have steeper slopes on the updrift sides.

Constriction of the gross tidal flow around cape-associated shoals leads to increased tidal speeds off the tips of the shoals and weaker tidal velocities in adjacent bays or indentations between the shoals (Pingree, 1978). Tidal currents, through their strength and oscillatory nature, help to control the overall shape and extent of the Roanoke Point Shoal and are responsible for the steep gradients on the flanks, the cuspate shape of the slump deposits at the base of the northern flank, the accumulations of sediment in the current shadows of boulders, and the ubiquitous presence of current ripples on the shoal. The strong tidal currents deflected around the shoal are also responsible, through sediment bypassing or decreased deposition, for the thinness of the Holocene section and the curved depression in the Long Island Sound basin floor north of the shoal (figs. 2 and 4).

Although relatively equal volumes of water move during ebb and flood tides, residual tidal-stress convergence occurs when one tide is stronger, causing net circulation and bedload transport. A stronger flood tide off Roanoke Point (Eldridge Tide and Pilot Book, 1996) results in a residual westward transport, as evidenced by asymmetrical obstacle marks, which are accumulations of sediment in the current shadows around boulders (Belderson and others, 1982; fig. 8). This residual flow is also apparently strong enough to sweep fine sands off the northern flank of the shoal, which are subsequently deposited on the basin floor northwest of the shoal (fig. 5), and possibly to permit transport by eddy patterns characteristically associated with headlands (Pingree, 1978; Pattiaratchi and Collins, 1987). Applying Pingree's mechanism, the counterclockwise flood-tide eddy west of Roanoke Point Shoal would involve interaction of several factors, as follows: (1) Coriolis and centrifugal force act together opposing the pressure gradient, (2) bottom water moves down the pressure gradient toward central upwelling, and (3) the convergent residual flow allows sandier material to accumulate. Conversely, in the clockwise ebb-tide eddy east of the shoal: (1) Coriolis and centrifugal force are opposed, (2) bottom water moves away from central downwelling, and (3) divergent residual flow of bottom water favors nondeposition. These processes are consistent with the occurrence of coarser grained sediments and a high-backscatter area west of the shoal, and finer grained sediments and low backscatter east of the shoal.

Wind-generated waves and strong tidal currents continue to extensively erode and rework both the glacial and postglacial deposits and to influence the sedimentary processes around the Roanoke Point Shoal. The irregular bottom topography and textural distributions reflect these processes.

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