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Geomorphology and Sediments of Western Massachusetts Bay

by

Edward P. Meisburger

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A seismic reflection survey with concurrent bottom sampling was conducted in western Massachusetts Bay to obtain information on bottom topography and sediments, subbottom structure and composition, and the location of sand deposits potentially usable for restoration and nourishment of nearby beaches. Primary data consisted of 242 statute miles of seismic reflection survey and 43 sediment cores.

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Seismic reflection profiles show that most of the area is underlain by a rock mass with a highly irregular surface below which no coherent reflections appear on available records. Highs in this unit outcrop in places while lows are either partly or completely filled with acoustically transparent material having internal reflection patterns which indicate a stratified deposit. Cores and extrapolation from onshore outcrops indicate that the lower unit consists of dissected basement complex rocks overlain in places by glacial drift and the upper (transparent) unit consists mainly of Pleistocene glaciomarine and Holocene sediments.

The predominant sediments of the surface and shallow subsurface (less than 15 feet) deposits in the study area are fine sand, sand and gravel, and clayey silt. Sand suitable for beach restoration and nourishment on the contiguous coast occurs only locally and in generally small quantity relative to other sediments of the study area. Seven potential borrow sites are located and discussed.

PREFACE

This report is one of a continuing series which describes results of the Inner Continental Shelf Sediment and Structure (ICONS) study. One aspect of the ICONS study is locating and delineating offshore sand and gravel deposits suitable for beach nourishment and restoration. The work was carried out under the coastal processes program of the U.S. Army Coastal Engineering Research Center (CERC).

The report was prepared by Edward P. Meisburger, a CERC geologist, under the general supervision of Dr. David B. Duane, former Chief, Geological Engineering Branch, and his successors, Dr. William R. James and Mr. Ralph L. Rector. As part of the research program of the Engineering Development Division, the ICONS study is under the general supervision of Mr. George M. Watts, Chief of the Division. The fieldwork (obtaining cores and seismic reflection records) was carried out by Alpine Geophysical Associates, Inc., under Contract No. DACW33-67-C-0071.

Microfilm copy of the CERC seismic data used in this study is stored at the National Solar and Terrestrial Geophysical Data Center (NSTGDC), Rockville, Maryland 20852. Vibratory cores collected during the field survey program are in a repository at the University of Texas, Arlington, Texas 76010. Requests for information relative to these items should be directed to NSTGDC or the University of Texas.

Comments on this publication are invited.

Approved for publication in accordance with Public Law 166, 76th Congress, approved 31 July 1945, as supplemented by Public Law 172, 88th Congress, approved 7 November 1963.

JAMES L. TRAYERS
Colonel, Corps of Engineers
Commander and Director

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GEOMORPHOLOGY AND SEDIMENTS OF WESTERN MASSACHUSETTS BAY

by

Edward P. Meisburger

I. INTRODUCTION

1. Background.

Ocean beaches and associated dunes provide a necessary and important buffer zone between the sea and fragile coastal areas. At the same time they provide public recreation areas for millions of people. The construction, improvement, and periodic maintenance of beaches and dunes by placement (nourishment) of suitable sand along the shoreline can be an important means of counteracting coastal erosion by providing stability to shoreline positions and permitting recreational facilities (U.S. Army, Corps of Engineers, 1971). Beach nourishment techniques (Hall, 1952) have gained prominence in coastal engineering largely as a result of the successful test program using a hopper dredge at Sea Girt, New Jersey, in 1966 by the U.S. Army, Corps of Engineers (1967), and the successful completion of the nourishment of Redondo Beach, California, in 1969 by a commercial operator under contract to the Corps of Engineers (Fisher, 1970). The Redondo Beach project determined that present technology is advanced enough to make sand and gravel on the shallow parts of the shelves a presently exploitable resource (Duane, 1968) and economically competitive at some locations with previous methods (truck haul and drag scoop) for sand transport and beach construction.

Plans for initial beach restoration and periodic renourishment usually involve large volumes of suitable sandfill. In recent years it has become increasingly difficult to obtain suitable sand from lagoons and wetlands or from inland sources in sufficient volumes and at an economical cost for beach fill purposes. These difficulties are due in part to increased land values, concern over environmental and ecological effects of removing such large volumes of sand, diminution or depletion of previously used land sources, and inflated transportation costs of moving the material from areas increasingly remote from final destinations. Also, sedimentary material comprising the bottoms of lagoons, estuaries, and bays is often fine grained and rich in organics and is unsuitable for long-term effective shoreline protection. While the loss of some fine silt material is to be expected as a newly nourished beach attains a new state of equilibrium with the sea environment, it is possible to minimize the losses through careful selection of the most suitable fill material (Krumbein and James, 1965).

The problems of locating suitable and economical sand deposits led the U.S. Army, Corps of Engineers, Coastal Engineering Research Center (CERC) to initiate a search for exploitable deposits of sand. Exploration efforts were focused offshore with the intent to locate and inventory deposits suitable for future fill requirements, and later refine techniques for specifying most suitable fill characteristics.

The search for sand deposits, referred to initially as the Sand Inventory Program, started in 1964 with a survey off the New Jersey coast (Duane, 1969). Subsequent data collection surveys have included the Inner Continental Shelf areas off New England, Long Island, Delaware, Maryland, Virginia, the Cape Fear area of North Carolina, the east coast of Florida, and southern California. During the past 2 years broader application to the CERC mission of the data collected has been recognized, especially in deciphering the shallow structure of the Continental Shelf, understanding shelf sedimentation and hydraulic processes, unraveling geologic history of the shelves, and evaluating the potential for engineering design of manmade structures on the shelf. This more diversified program is now referred to as the Inner Continental Shelf Sediment and Structure (ICONS) Program.

2. Field and Laboratory Procedures.

The field exploration phase of the ICONS program uses continuous seismic reflection profiling supplemented by cores of the bottom sediment. Both of these sources of data are obtained by contractual agreement with ocean industry firms. These data are analyzed and interpreted by the CERC Geological Engineering Branch. Support data are obtained from the National Ocean Survey (NOS) (formerly U.S. Coast and Geodetic Survey) hydrographic boat sheets, pertinent professional papers, engineering logs from bore holes, and published literature.

a. Data Collection Planning. Geophysical survey tracklines are laid out for the study areas in two basic patterns: grid and reconnaissance lines. A grid pattern, with variable line spacing depending on regional geology, is used to cover areas where a more detailed picture of sea floor and subbottom geologic conditions is desirable, usually those areas suspected of containing sand and gravel. Reconnaissance lines consist of one or more continuous shore oblique zigzag lines which provide minimal coverage for intermediate areas between grids, and a means of correlation of geology between grid areas. Reconnaissance lines provide sufficient information to reveal the general morphologic and geologic aspects of the area and to identify sea floor areas where more detailed additional data collection may be advisable.

Selection of individual core sites is based on a continuous study of the seismic records as they become available from the contractor during the survey. This procedure of picking core locations, based on geologic conditions revealed on the seismic records, allows core-site selection on the best information available and thus maximizes usefulness of both sources of data. It also permits the contractor to complete the required work of obtaining geophysics and cores in one area before moving his base of operations to the next area.

b. Seismic Reflection Profiling. Seismic reflection profiling is a technique widely used for delineating subbottom geologic structures and bedding surfaces in sea floor sediments and rocks. Continuous reflections are obtained by generating repetitive, high-energy, sound pulses near the water surface and recording "echoes" reflected from the sea floor-water interface, and subbottom interfaces between acoustically dissimilar materials. In general, the compositional and physical properties (e.g., porosity, water content, relative density) which commonly differentiate sediments and rocks also serve to produce acoustic contrasts which show as dark lines on the geophysical paper records. Thus, an acoustic profile is roughly comparable to a geologic cross section.

Seismic reflection surveys of marine areas are made by towing variable energy and frequency sound-generating sources and receiving instruments behind a survey vessel which follows the predetermined survey tracklines. The energy source used for this survey was a 50-to 200-joule sparker. For continuous profiling, the sound source is fired at a rapid rate (usually 4 pulses per second) and returning echo signals from sea floor and subbottom interfaces are received by an array of towed hydrophones. Returning signals are amplified and fed to a recorder which graphically plots the two-way signal travel time. Assuming a constant velocity for sound in water at 4,800 feet per second and for typical shelf sediments of 5,440 feet per second, a vertical depth scale was constructed to fit the geophysical record. Geographic position of the survey vessel is obtained by frequent navigational fixes keyed to the record by an event marker.

Detailed discussions of seismic profiling techniques can be found in several technical publications (Ewing, 1963; Hersey, 1963; Miller, Tirey, and Mecarini, 1967; Moore and Palmer, 1968; Barnes, et al., 1972; Ling, 1972).

c. Coring Techniques. The sea floor coring device used in this study is a pneumatic, vibrating piston coring assembly designed to obtain core samples (20-foot maximum length; 4-inch diameter) in Continental Shelf granular-type sediments. The apparatus consists of a standard steel core barrel, plastic inner liner, shoe and core catcher, with a pneumatic driving head attached to the upper end of the barrel. These elements are enclosed in a tripodlike frame with articulated legs, allowing the assembly to rest on the sea floor during the coring operation. The detached state of the core device from the surface vessel has the advantage of allowing limited motion of the vessel during the actual coring process. Power is supplied to the pneumatic vibrator head by a flexible hoseline connected to a large capacity, deck-mounted air compressor. After coring is complete, the assembly is winched on board the vessel; the liner containing the core is removed, capped at both ends, marked, and stored. A review of the historical development of vibratory coring equipment is discussed by Tirey (1972).

d. Processing of Data. Seismic records are visually examined to establish the principal bedding and geologic features in the subbottom strata. After analyses are complete, record data are reduced to detailed geologic cross-sectional profiles showing the primary reflective interfaces within the subbottom. Selected acoustic reflectors are then mapped to provide areal continuity of reflective horizons considered significant because of their extent and relationship to the general structure and geology of the study area. Where possible, the uppermost reflectors are correlated with core data to provide a measure of continuity between cores.

Cores are visually inspected and described aboard the recovery ship. After delivery to CERC, the cores are sampled at close intervals by drilling through the liners and removing parts of representative material. After preliminary analysis, a number of representative cores are split longitudinally to show details of the bedding and changes in stratigraphy. Cores are split using a wooden trough arrangement fabricated at CERC shop facilities. A circular powersaw mounted on a base which is designed to ride along the top of the trough is adjusted to cut through the plastic liner and not disturb the core sediment. By making a second longitudinal cut in the opposite direction, a 120° segment of the liner is cut and can be removed. The sediment above the cut is then scraped away to remove altered and disturbed sediment, and the core is carefully logged, sampled at closer intervals, photographed, and resealed.

Samples from the cores are then examined under a plane light binocular microscope and described in terms of gross lithology, color, mineralogy, and the type and abundance of skeletal fragments of marine organisms. Granulometric parameters (e.g., mean size, sorting) for many of the samples are also obtained by using the CERC Rapid Sand Analyzer (RSA) which is analogous to that described by Zeigler, Whitney, and Hays (1960) and Schlee (1966).

3. Scope.

The primary (main grid) area covered by this report includes the part of Massachusetts Bay lying generally westward of Stellwagen Basin and between lines drawn eastward from Lynn on the north and North Cohasset on the south (Fig. 1). Secondary reconnaissance areas to the north and south are also included to the extent warranted by available data (Fig. 1). These areas encompass a narrow inshore strip extending from the primary survey area north to Cape Ann and south to Duxbury Beach.

Basic ICONS survey data consist of 242 statute miles (186 grid, 56 reconnaissance of seismic reflection profiles and 43 sediment cores. Locations of tracklines and coring sites are shown in Figure 2. Additional data were obtained from large-scale hydrographic smooth sheets, and from pertinent scientific and technical literature, particularly a report by the Massachusetts Coastal Mineral Inventory (MCMI) survey (Willett, 1972).

Although the customary seismic reflection gridline spacing of 1 statute mile and core density used for ICONS studies has proven adequate for fairly detailed analysis of areas off the mid-Atlantic and southeast coasts of the United States, data density to a similar degree in this complex region is not sufficient for detailed treatment. Consequently, this study is more limited in scope and detail than previous ICONS reports covering Atlantic inner shelf areas to the south.

4. Recent Studies.

Several recent studies of surface and shallow subsurface geology off the New England coast contain pertinent information on the study area, e.g., studies of bottom sediments off New England by Schlee and Pratt (1970)

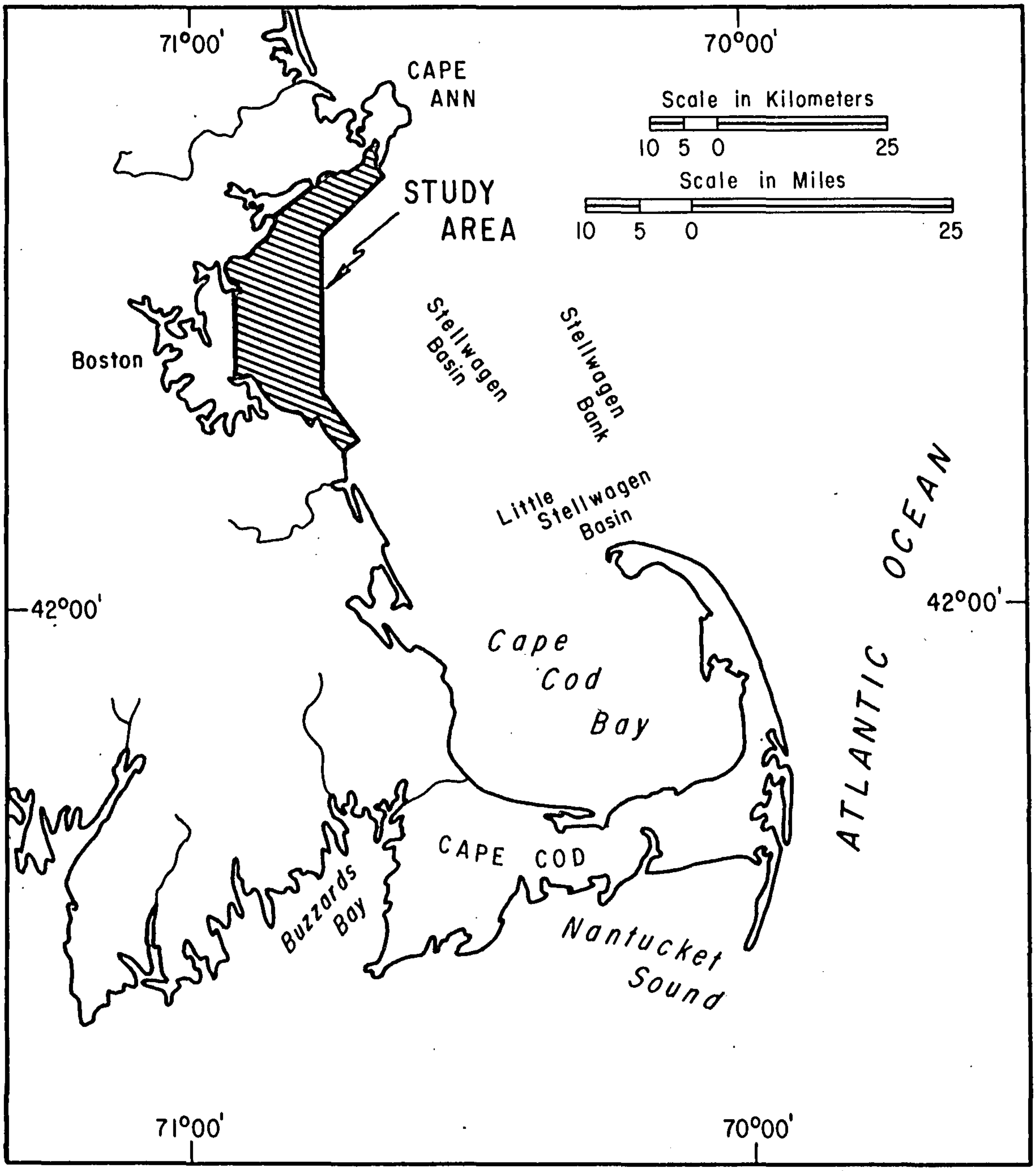


Figure 1. General map of southeastern Massachusetts and Massachusetts Bay showing limits of the study area.

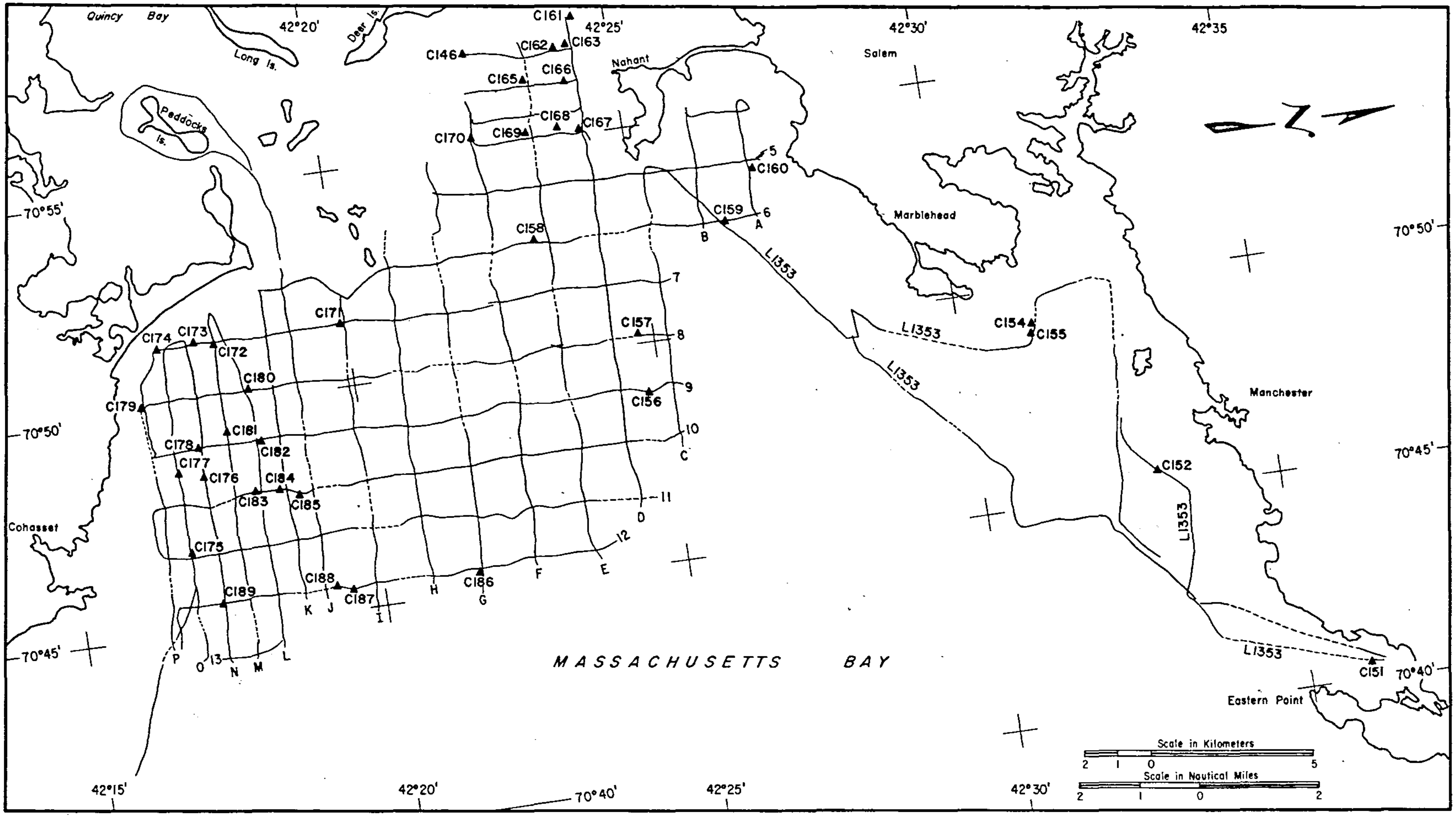


Figure 2. Navigational plot showing survey tracklines and core locations of the ICONS survey.

and Schlee, Folger, and O'Hara (1971). The latter study is based largely on grab samples collected by the U.S. Geological Survey (USGS), Woods Hole Oceanographic Institution, and on subsamples from the tops of cores collected by CERC for this study and made available to USGS; it includes sediment distribution maps and data on sediment textures, composition, organic carbon, and calcium carbonate content.

Surficial sediments of Boston Harbor have been discussed by Mencher, Copeland, and Payson (1968). The study, based largely on 152 grab samples, covers sediment distribution, grain sizes, and organic content.

A seismic reflection study of the sedimentary framework of the western Gulf of Maine and waters off southeastern Massachusetts by Oldale, Uchupi, and Prada (1973) includes maps of surficial geology, bedrock topography, and reduced seismic reflection profiles showing the relationship between reflection units and stratigraphic units.

The Commonwealth of Massachusetts conducted extensive surveys in 1971 of the sea floor along the Massachusetts coast to assess the potential mineral resources of the contiguous inner shelf floor. Basic data collected were seismic reflection profiles, side-scan sonar, bathymetric information, vibratory cores of the bottom sediments up to 40 feet in length, grab samples, and bottom photos. Interpreted results of this survey were compiled in a final report (Willett, et al., 1972) that included text, maps, and data summaries.

An intensive study of a small ocean area situated 11 statute miles east of Boston's Logan Airport (Fig. 1) was made in 1972-73 by Setlow (1973) as part of the New England Offshore Mining Environmental Study (project NOMES). The study delineated and characterized a sand and gravel deposit measuring about 12,000 by 7,000 feet which trended north-northwest across the surveyed area. The field survey collection included 37 seismic reflection profiles, side-scan sonar, and 33 vibatory cores concentrated mostly in the deposit area. The study presents detailed data on physical, chemical, and mechanical properties of sediments recovered in cores; it also included maps showing the configuration of the sand and gravel deposit at the surface and at -5 and -10 feet, selected reduced seismic reflection profiles, and interpretive discussion of the origin of the deposit and its relationship to the regional marine geology.

Soden (1973) used statistical methods to determine a predictive model for the Massachusetts Bay area of probable subbottom sediment character based on the character of the surficial sediment. He found two distinct surface-subsurface relationships based on weight percentage of silt and clay in the surficial sediment. Soden concluded that where silt and clay comprised more than 60 percent of the surface sample, it was highly unlikely that significant deposits of sand and gravel occurred in the subbottom.

5. Hydrography.

Tidal ranges are relatively uniform throughout the study area. At 12 stations within the study limits they vary less than 1 foot--from 8.7 to 9.5 feet mean range and 10.1 to 11 feet spring range (National Ocean Survey, 1974a). Tidal currents in the near approaches to Boston Harbor reach velocities of 1.5 knots. At other inshore stations, tidal current velocities are generally less than 0.5 knot (National Ocean Survey, 1974b).

Schlee, Folger, and O'Hara (1971) reported that bottom flow in the area west of Stellwagen Bank is mostly southerly; however, inshore tide-dominated currents generally set east-west. They also report that bottom drifters released within 15 kilometers of shore often ground at points on shore nearest the release point, indicating a net shoreward bottom drift in the zone encompassing most of the study area.

Generalized ocean wave data for the Gulf of Maine show that waves over 5 feet high occur 12 percent of the time from October through March and from 2 to 10 percent of the time in other months with the minimum frequency occurring from June through August. Waves exceeding 15 feet in height occur less than 1.5 percent of the time in all months; the maximum frequency occurs in December (from unpublished wave data held at CERC).

Surface water temperatures in the study area average 2° to 6° Celsius from January through April, 18° Celsius in August, then decrease to 6° Celsius in December. At a depth of 20 meters, the water temperature averages 2° to 5° Celsius from January through April, rises to 12° Celsius by August, and maintains this temperature through October. The temperature declines after October and reaches 6° Celsius in December (Colton and Stoddard, 1972).

6. Geologic Setting.

a. Topography. The land area adjacent to the primary study area is comprised of three large geomorphic units (Fig. 3). These units are: (a) the Boston Lowland, occupying a large central segment of the area between study limits; (b) the Fells Upland to the north; and (c) the Sharon Upland to the south. Most of the Boston Lowland consists of marsh and valley flats less than 50 feet above sea level and the remainder contains low hills cresting at less than 150 feet elevation. The original character of this landscape has been considerably altered by urban development. The highlands which flank the Boston Lowland to the north and south consist of rugged hills in places over 300 feet high.

b. Basement Rocks. Most of the Boston Lowland is underlain by a fault-bounded structural low in rocks of pre-Devonian age (Boston Basin) filled with late Paleozoic continental sediments and interbedded igneous rocks known collectively as the Boston Bay Group. Postdepositional erosion carved a highly irregular surface into the Boston Bay Group rocks before the onset of Quaternary glaciation (Upson and Spencer, 1964). This old topography, which now forms the bedrock surface under the Boston

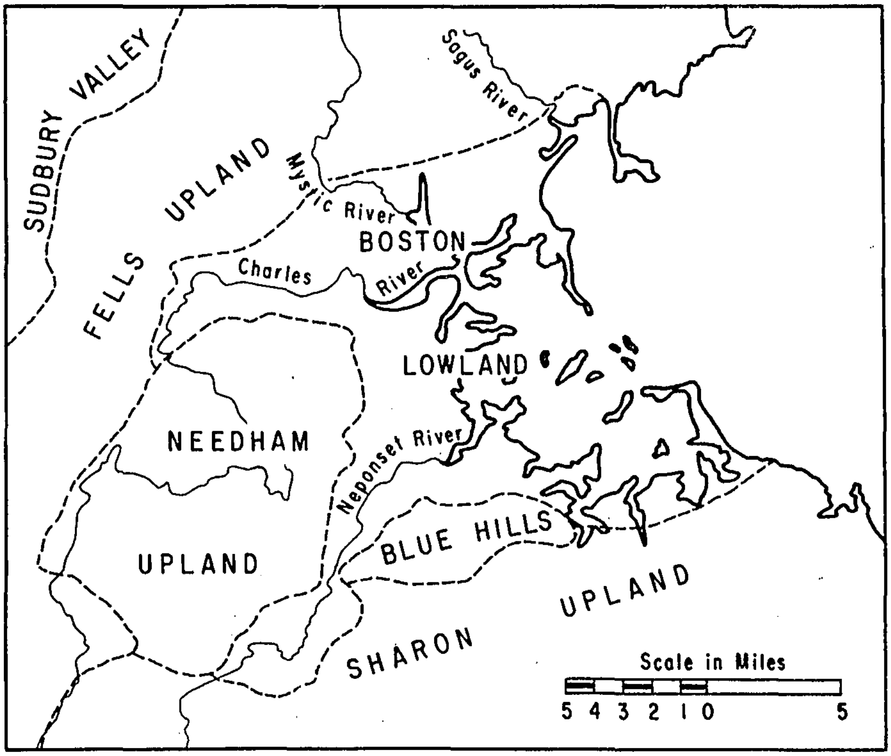


Figure 3. Gross geomorphic subdivisions of the Boston area (LaForge, 1932).

Lowland, was re-eroded in part by glacial ice masses and subsequently buried by glacial drift, alluvium, and coastal deposits.

Since the bedrock surface under the Boston Lowland slopes generally seaward, it probably lies deeper under the study area than on the adjacent landmass. A few highs of the old topography outcrop on the sea floor and form some of the islets in the near approaches to Boston Harbor.

The two upland areas flanking the Boston Lowland to the north and south are comprised chiefly of pre-Devonian igneous and metamorphic rocks with some rocks of the Boston Bay Group. The bedrock surface is generally not as extensively or deeply buried in these areas as in the Boston Lowland. Numerous bedrock exposures occur along the adjacent coast and appear as rocky shoals, pinnacles, and islets in the coastal waters. Presumably the northern and southern parts of the study area are also underlain by the igneous and metamorphic bedrocks comprising the upland areas.

c. Post-Paleozic Deposits. Although bedrock exposures occur throughout the Boston area, most surficial and shallow subsurface deposits consist of Quaternary glacial and glaciomarine sediments. Holocene fluvial and marginal marine deposits are important locally along the coast and major drainage ways.

In general, the glacial and glaciomarine deposits lie directly upon the bedrock surface, although Kaye (1961) believed that patches of coastal plain sediment may occur locally in the Boston area. Oldale, Uchupi, and Prada (1973) inferred the presence of extensive coastal plain sediments ranging from Cretaceous to early Pleistocene age underlying the western Gulf of Maine and waters off southeast Massachusetts. However, they did not find evidence of such deposits within the study limits.

The Quaternary deposits of the Boston area vary in thickness from zero to over 200 feet and are thickest in the ancient bedrock valleys. In the upland areas glacial drift is not thick enough in most places to obscure the relief on the bedrock surface. In the Boston Lowland the bedrock surface is largely buried by overlying Quaternary and Holocene sediments; therefore, existing topographic features are mostly of glacial origin or have formed in response to Holocene fluvial and marine processes (LaForge, 1932; Upson and Spencer, 1964). At the time of LaForge's comprehensive geologic study of the Boston region, no pre-Wisconsin drift had been identified there. He believed that some of the Pleistocene glaciomarine clays probably predated Wisconsin time. Judson (1949) and Kaye (1961) found drift deposits underlying Boston which they identified with pre-Wisconsin glacial stages--the oldest possibly Nebraskan till. Kaye's stratigraphic section based on an excavation under Boston Commons is summarized in Table 1. Tentative correlation with the Pleistocene stratigraphy of Judson (1949) and Upson and Spencer (1964), is also included in the table.

Distribution of the surficial Quaternary glacial deposits in the Boston region is mainly in the form of ground and recessional moraines, outwash plains, eskers, and drumlins. Especially noteworthy are the approximately 180 drumlins which are concentrated mostly in the Boston Lowland. Eroding drumlins situated along the coast are considered to be important sources of beach and nearshore sediment. These drumlins are composed mostly of unstratified till; they range up to 1 mile in length and reach up to 150 feet above the surrounding terrain. Many of the drumlins abut or surround highs in the bedrock surface (LaForge, 1932).

Postglacial deposits in the Boston area consist predominantly of alluvium, swamp and marsh deposits, and shoreline features. Because of intensive urban development in the Boston area, landfill has also become a geologically significant deposit.

d. Pleistocene Geologic History. The record of Pleistocene glacial and interglacial stages in the Boston region is fragmentary; however, there is general agreement that the bulk of glacial deposits in and around Boston is probably of Wisconsin age. Relationships of these deposits to the standard Wisconsin substage chronology are not well known.

At the onset of the Pleistocene there was a well-developed subaerial topography and drainage pattern carved into the preexisting rocks of the Boston Lowland and adjacent uplands (LaForge, 1932; Upson and Spencer, 1964). Presumably pre-Wisconsin continental glaciers overran the region

Table 1. Pleistocene stratigraphy of the Boston Basin.

Epoch	Kaye (1961)[1]	Judson (1949)[2]	Upson and Spencer (1964)[3]
Holocene		Upper peat Marine silt Lower peat	Estuarine deposits
Late Wisconsin (Cary)	Drift IV Mostly outwash (in Boston Basin)	Lexington Outwash Lexington Drift	Outwash
Mid Wisconsin (Tazewell)	Clay III	Boston Clay	Marine clay
Early Wisconsin (Iowan)	Drift III	Boston Till	Till
Illinoian	Drift II	Pre-Boston Till	Bedrock
Illinoian or Yarmouth	Clay I		
Kansan or Nebraskan	Drift I		
	Bedrock		

1. Based on a section under Boston Commons, Massachusetts.
2. Based on excavations at Boston, Massachusetts.
3. Based on borings in fill of ancient valleys in the Boston Basin.

and on retreating left behind drift deposits. Marine sediments were deposited over the drift during interglacial stages when eustatic sea levels were high. However, evidence of such past events has been largely obliterated by subsequent glacial erosion, and only a few remnants have been recognized as probable pre-Wisconsin Pleistocene deposits, e.g., the excavation under Boston Commons where Kaye (1964) found evidence of four, and possibly five, ice advances and three marine transgressions.

The oldest widespread deposit of Pleistocene age in the Boston area is a discontinuous drift layer (Drift III, Table 1) which Kaye (1964) believed was deposited during the early Wisconsin-Iowan substage. This glaciation seems to be the earliest event of Pleistocene time which has left an extensive record in the study area.

After retreat of the glacier associated with Drift III, the Boston area was inundated by the sea and a layer of glaciomarine clay (Clay III, Table 1) was deposited over the drowned irregular topography. Kaye (1964) indicated that a period of subaerial weathering intervened between the deposition of his Drift III and Clay III as evidenced by an oxidation zone in the drift.

It is generally believed that the deposition of Clay III was followed by a period of emergence during which Clay III and exposed part of older deposits were eroded. Whether the offshore study area was exposed to erosion in this period is not known. Kaye (1964) showed relative sea level following deposition of Clay III was lower than -35 feet but did not discuss a minimum. Judson (1949) inferred that sea level probably stood about 90 to 100 feet below present sea level during this period of emergence. Upson and Spencer (1964) believed that sea level associated with what is presumably the same episode was at least -50 feet lower with respect to the land.

Another glacial episode (late Wisconsin) followed the period of erosion leaving deposits consisting primarily of outwash in the Boston Basin. Judson (1949) believed that the ice front did not reach the eastern part of the basin. After this glaciation, relative sea level dropped to -70 feet according to Kaye and Barghoorn (1964) who date the low at around 10,000 years Before Present (B.P.).

Since this time, relative sea level has risen and estuarine and marsh sediments have been deposited in the Boston Basin, especially along the embayed stream valleys. At about 3,000 years B.P. relative sea level reached a near stillstand and essentially modern conditions were established. Development of coastal landforms and marshes, fluvial deposition, and erosion have been the predominant geologic events of the post-transgressive period. In the recent past, engineering activities have also played a significant role in the geological processes.

II. GEOMORPHOLOGY AND SHALLOW SUBBOTTOM STRUCTURE

1. Geomorphology.

a. General. Analysis of submarine bottom topography in ICONS study areas has proven useful in extrapolating core and seismic data between data points where interrelationships exist between bottom topography and other elements of the geological environment. In areas of consistent relationships, it is possible to use available bathymetric data which in most shelf areas are available in more detail than information on any other aspect of the environment.

In the Massachusetts Bay ICONS study area, relationships between bottom morphology and subsurface structure are fairly consistent. Most topographic highs on the sea floor are associated with outcrops of the irregular bedrock surface or glacial till, while topographically flat areas occur where the bedrock and till surfaces are buried. In contrast, relationships between bottom morphology and sediment distribution patterns are ambiguous in most of the area, especially for surficial sediments.

A generalized bathymetric chart of the primary study area, compiled from National Ocean Survey (NOS) smooth sheets at 1:10,000 and 1:20,000 scale, is shown in Figure 4. Since chart control is approximate the figure is intended only to depict bottom morphology and not to provide accurate geographic location of features. A contour interval smaller than the 10-foot interval used in Figure 4 would be required to detail the complex and often subtle bottom topography of the study area.

Although a wide variety of submarine topographic features occur in western Massachusetts Bay, most can be classified under three broad categories: (a) level bottom; (b) submarine hills and ridges; and (c) connecting slopes. Areas in which these terrain elements are predominant are outlined in Figure 5; each area is identified by an alphanumeric to facilitate description. Submarine hills and ridges are divided into two types (Fig. 5) because of differences in form, composition, or genesis.

b. Level Bottom. Areas labeled A in Figure 5 have a gently sloping or level bottom and occur throughout the study area. The most extensive occurrence is in the northern part, generally to the east, southeast, and south of Nahant (A1 in Fig. 5). In the southern part of the study area there is a large area of level bottom extending southeastward from the prominent group of islets and ledges in the near approach to Boston Harbor (A2 in Fig. 5). Smaller areas occur off Nantasket Beach (A3 and A4 in Fig. 5) and minor occurrences, not delineated, exist throughout the area in places where other topographic elements predominate.

Most level bottom areas lie in water deeper than 80 feet but some occur in shallower water. Relief features in the level bottom areas are rare; they consist mostly of a few isolated hills and smooth-surfaced "mounds" of low relief rising generally less than 20 feet above the surrounding sea floor. The smooth surface of these mounds is in contrast

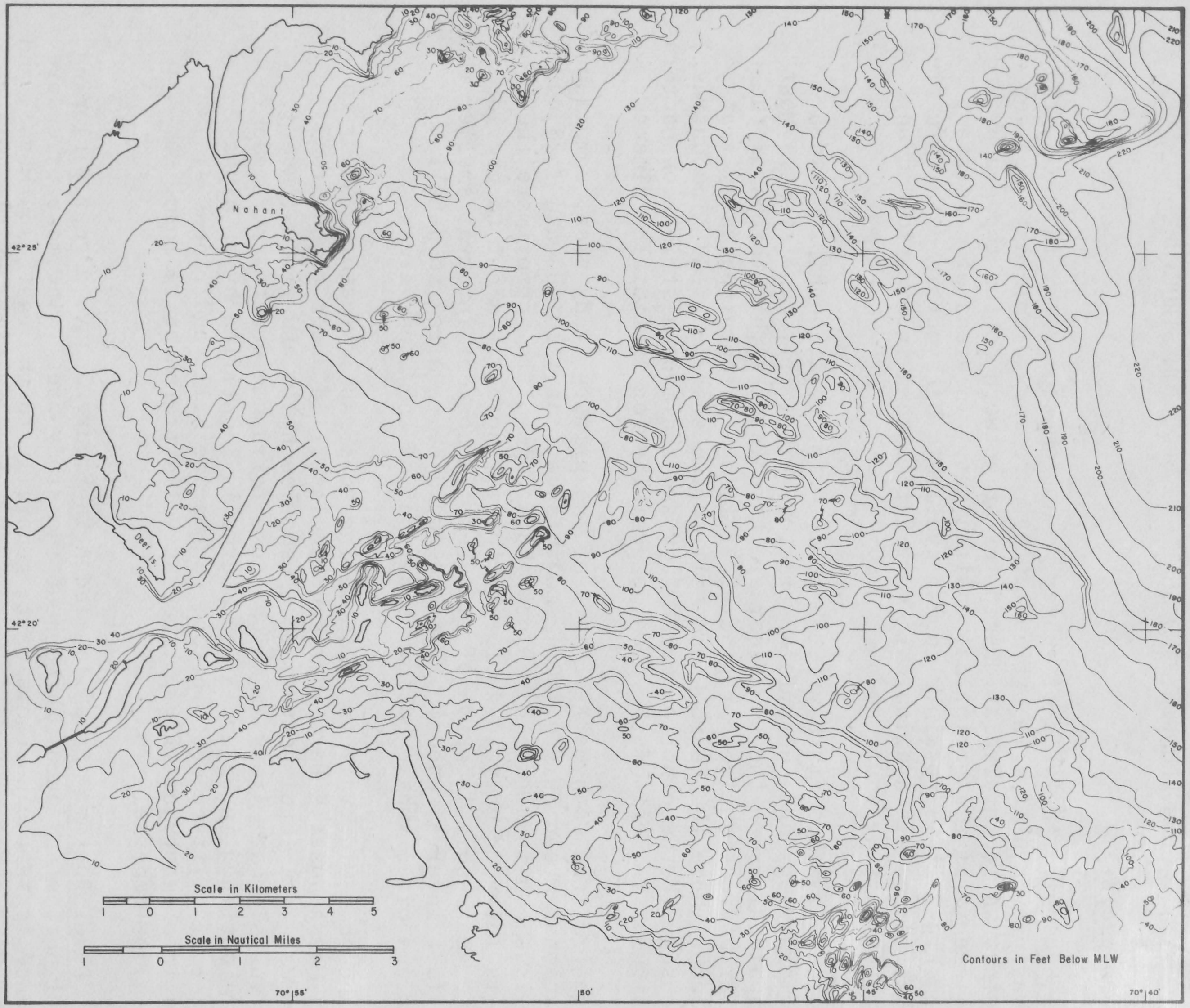


Figure 4. Generalized bathymetry of Massachusetts Bay. Contour interval is 10 feet; depths are below approximate mean low water (MLW). Data and control are approximate; chart not for navigational use.

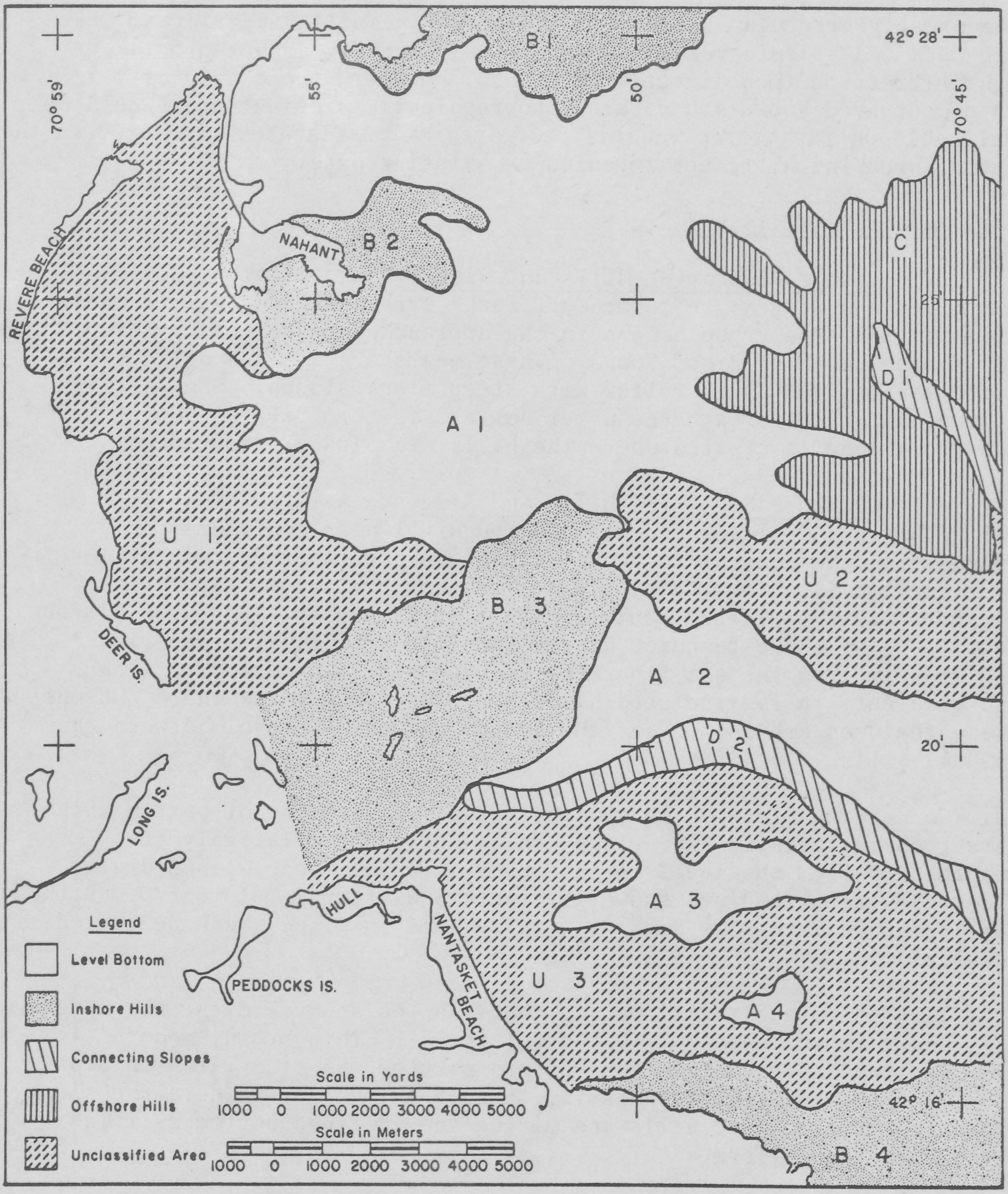


Figure 5. Gross geomorphic subdivisions of the study area. Alpha-numeric designators reference individual subdivisions for ...t discussion.

to the usually irregular surface of the submarine hills and ridges. Bathymetric data and seismic reflection profiles generally do not provide enough information to delineate the mounds; however, the characteristics of surveyed known mounds are topographically distinct and should be identifiable on fathometer records. Other similar features may occur in the the study area which are not revealed by existing data.

c. Submarine Hills and Ridges.

(1) Inshore Submarine Hills and Ridges. Groups of predominantly rugged hills and ridges are common off rocky stretches of coast (B areas in Fig. 5). A large group occurs in the approaches to Boston Harbor, mostly to the south of Broad Sound. These nearshore hills and ridges are characteristically of high relief with steep flank slopes. Some of the more prominent hills breach the water surface to form islets; a rugged bottom topography is created where the hills are closley grouped.

(2) Offshore Submarine Hills and Ridges. A large group of submarine hills and ridges occurs in a roughly linear configuration extending from the central to the northeastern part of the study area (C area in Fig. 5). In general, these features are larger (in plan view), have less relief and gentler side slopes than the inshore hills and ridges. Some of these features have a ramplike profile with one flank rising steeply from the sea floor and the opposite flank sloping at a gentle gradient. A few isolated hills and ridges occur elsewhere but most of these features are in C area; the bottom is usually level between the individual hills.

d. Connecting Slopes. In places, extensive sections of bottom with different characteristic elevations are connected by relatively steep slopes leading from one level to the other. Two of these slopes are of considerable extent and are shown in Figure 5 as terrain element D. Both slopes, although irregular and not well defined in places, can be traced for several miles.

The largest connecting slope lies outside the study limits; the upper part is shown in the bathymetric chart (Fig. 4). This broad, moderately sloping incline descends from the eastern part of the study area to depths of over 200 feet in Stellwagen Basin. Except in the north where the slope is broken up by submarine hills and ridges the inclined bottom is relatively smooth and uniform.

Slope D1 extends northwestward into the mass of offshore submarine hills and ridges of area C (Fig. 5). The slope descends from a section of bottom with characteristic depths of 110 feet or less to a small section of level bottom with characteristic depths of over 140 feet. It continues for 3.5 nautical miles southeastward from the east margin of the study area (Fig. 4).

Slope D2 is a broad, highly irregular incline beginning northeast of Point Allerton at the north end of Nantasket Beach and extending eastward and then southeast to front Nantasket Beach and generally enclose the expanse of low gentle hills and flats off Nantasket Beach (area U3 in Fig. 5).

e. Unclassified Areas. Three areas (U in Fig. 5) do not fit any of the previously described topographic elements, and in many respects, are topographically dissimilar to one another. Areas U1 and U3 are the most alike; both lie adjacent to the coast, are relatively shallow, contain expanses of level bottom, and are characterized elsewhere by an irregular bottom topography, especially inside the 30-foot depth contour. Area U3 is further characterized by many low relief, broadly rounded hills and swales interspersed with low rocky outcrops and areas of level bottom.

Area U2 lies well offshore, and has flat to irregular topography with isolated hills, numerous mounds, and a low extensive platformlike feature which projects as a salient well into the level bottom area A2 (Fig. 5).

2. Shallow Subbottom Structure.

a. General. In a study of the sedimentary framework of the western Gulf of Maine and southeastern Massachusetts waters, Oldale, Uchupi, and Prada (1973) inferred the existence of four discontinuous sedimentary units overlying the basement complex. These units were defined largely on the basis of seismic reflection data and consist of (a) inferred Coastal Plain deposits of Late Cretaceous to early Pleistocene age, (b) Pleistocene glacial drift, (c) glaciomarine and marine deposits of Pleistocene and Holocene age, and (d) Pleistocene glaciolacustrine deposits.

The basement complex rocks were judged to be crystalline and sedimentary rocks of pre-Cretaceous age. Since the sediment units are discontinuous, Oldale, Uchupi and Prada (1973) found the basement exposed in some places and overlain elsewhere by one or more of the sediment bodies.

Oldale, Uchupi, and Prada (1973) found only two of the sediment units within the study area. One, a glacial moraine, occurs in only one place where it forms a large submarine hill lying in the northeast part of the study area and centered at approximately 42° 27.5'N., 70° 41.0'W. (Fig. 4). The other, and the only sediment unit mapped by these authors, comprises marine deposits of Pleistocene and Holocene age. This unit outcrops throughout the area alternating with outcrops of the basement unit. Oldale, Uchupi, and Prada called it the *transparent layer* due to its characteristic acoustic transparency. Typically, they found this unit partly or completely filling topographic lows in the basement unit or in other sediment units. Internal reflectors within the transparent unit were numerous in some places and absent in others. The transparent layer of Oldale, Uchupi, and Prada can be identified on seismic reflection profiles obtained for this study.

b. Acoustic Basement. An acoustic basement containing no internal reflectors is evident on ICONS records. This basement lies under the transparent unit and, in places, may crop out on the sea floor to create topographic highs. By studying cores and comparing them with onshore geology, it appears that the acoustic basement (as defined in this study) is not everywhere coincident with the top of pre-Cretaceous basement complex rocks but includes overlying glacial deposits in places. Willett, et al. (1972) and Setlow (1973) found generally similar reflection patterns in the subbottom of the study area.

The surface of the acoustic basement is highly irregular and complex (Fig. 6). Most of the surface appears to be a combination of two topographic elements: (a) a broad primary system of highs and lows with relief up to 200 feet; and (b) a complex series of secondary relief features with local relief often exceeding 50 feet. The secondary features are profuse and several may appear in the seismic reflection record from a single survey mile. Thus, many secondary relief features may lie undiscovered between survey tracklines, and detailed delineation of surface topography on the acoustic basement is not feasible with available data.

The primary topography on the acoustic basement was deliniated by smoothing the profiles so that slope trends were projected across the base of secondary highs (Fig. 7). The surface contours in Figure 8 are based on the smoothed data; the map is judged to be a reasonable rendition of the primary basement topography because elevations derived from the smoothing process, when plotted and contoured, reveal a coherent pattern of highs and lows with consistent directional trends.

The primary topography consists mostly of elongate lows and elongate to equidimensional or irregular highs. The orientation of primary features is east to east-southeast with some of the linear depressions closed or partly closed. If these depressions are remnants of an ancient drainage system (as seems most likely), then it appears the system has been disrupted. A probable reason for this is that acoustically impenetrable glacial deposits fill parts of the valleys, and that many of the innumerable secondary topographic highs are also glacial features.

c. Transparent Reflection Unit. Commonly the transparent unit is separated into upper and lower subunits by an irregular reflecting surface characteristically producing a strong, well defined signal (Fig. 9). This reflector is called the *blue reflector*, a conventional term used in other ICONS studies to designate the uppermost strong reflector in subbottom strata. The configuration of the blue reflector indicates that it is probably an erosional surface.

Below the blue reflector, the transparent unit characteristically has one of two aspects on ICONS reflection profiles: (a) a reflectively featureless unit with uniform mottled-gray tone; or (b) an internal reflector pattern consisting of weakly defined, closely spaced reflectors lying in a horizontal or gently warped attitude.

In the subunit lying above the blue reflector, internal reflections are generally much stronger, are often discontinuous, and may lie at relatively steep angles to the horizontal. These reflector patterns

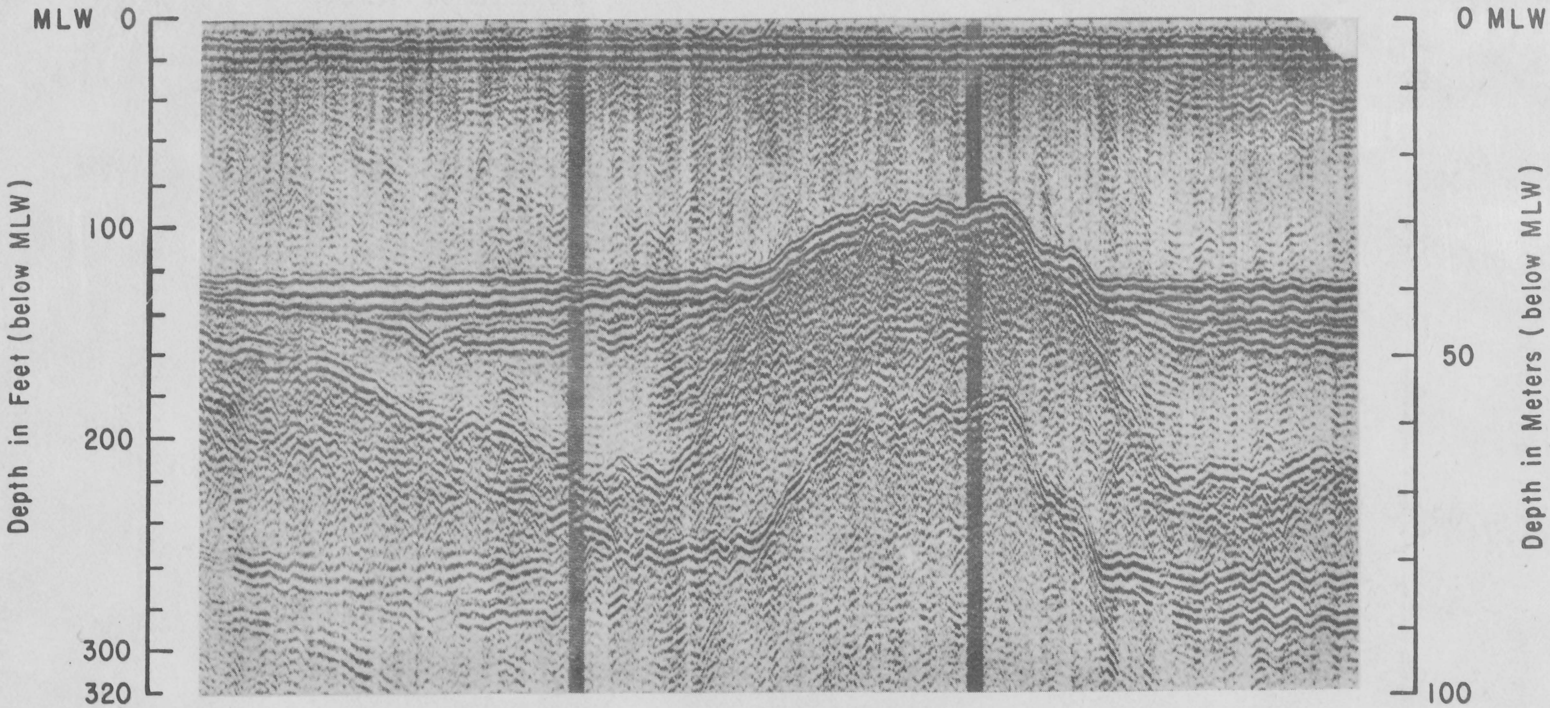


Figure 6. Section of seismic reflection profile showing the acoustic basement overlain in places by the transparent reflection unit. Note topographic highs associated with outcrops of the acoustic basement.

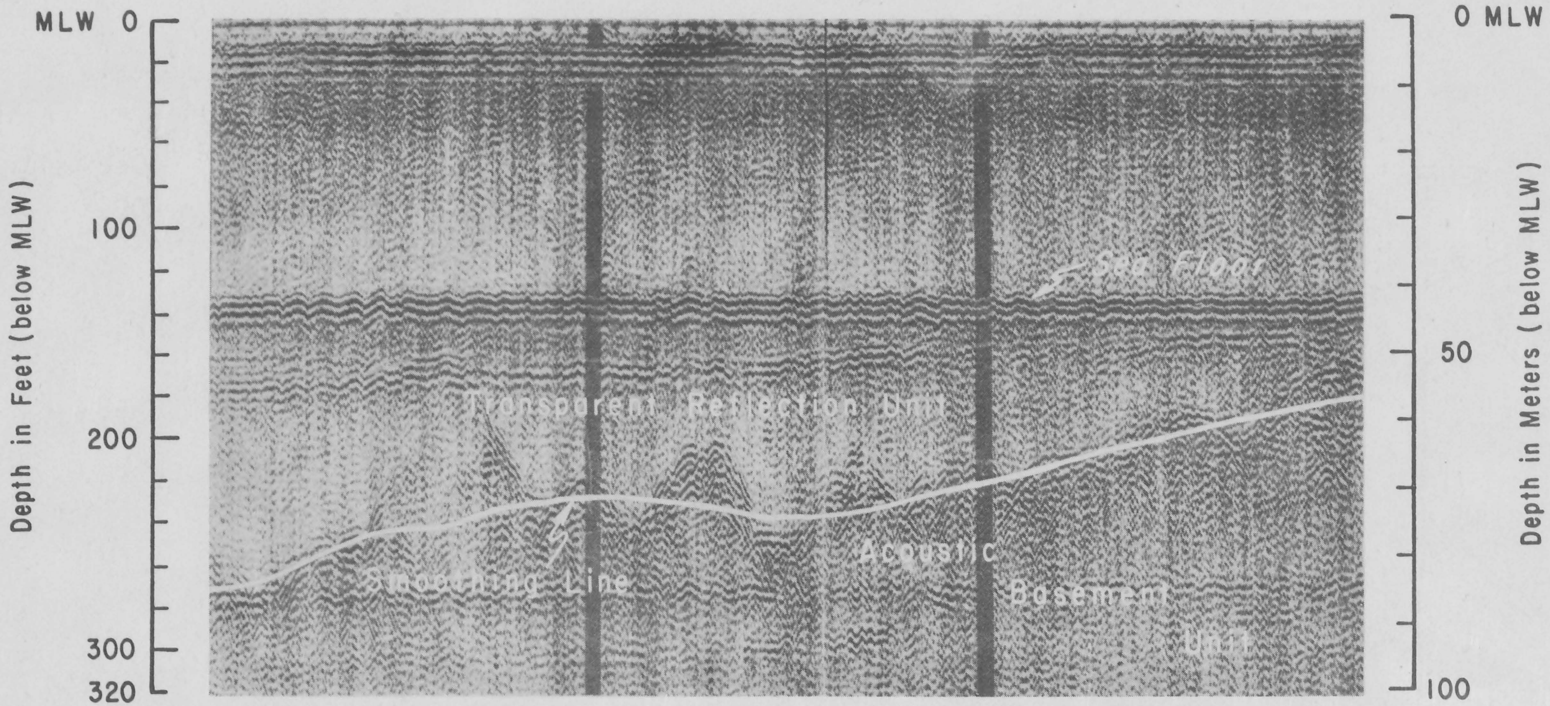


Figure 7. Section of seismic reflection profile showing smoothing procedure used to eliminate secondary highs of the acoustic basement to delineate the primary topography.

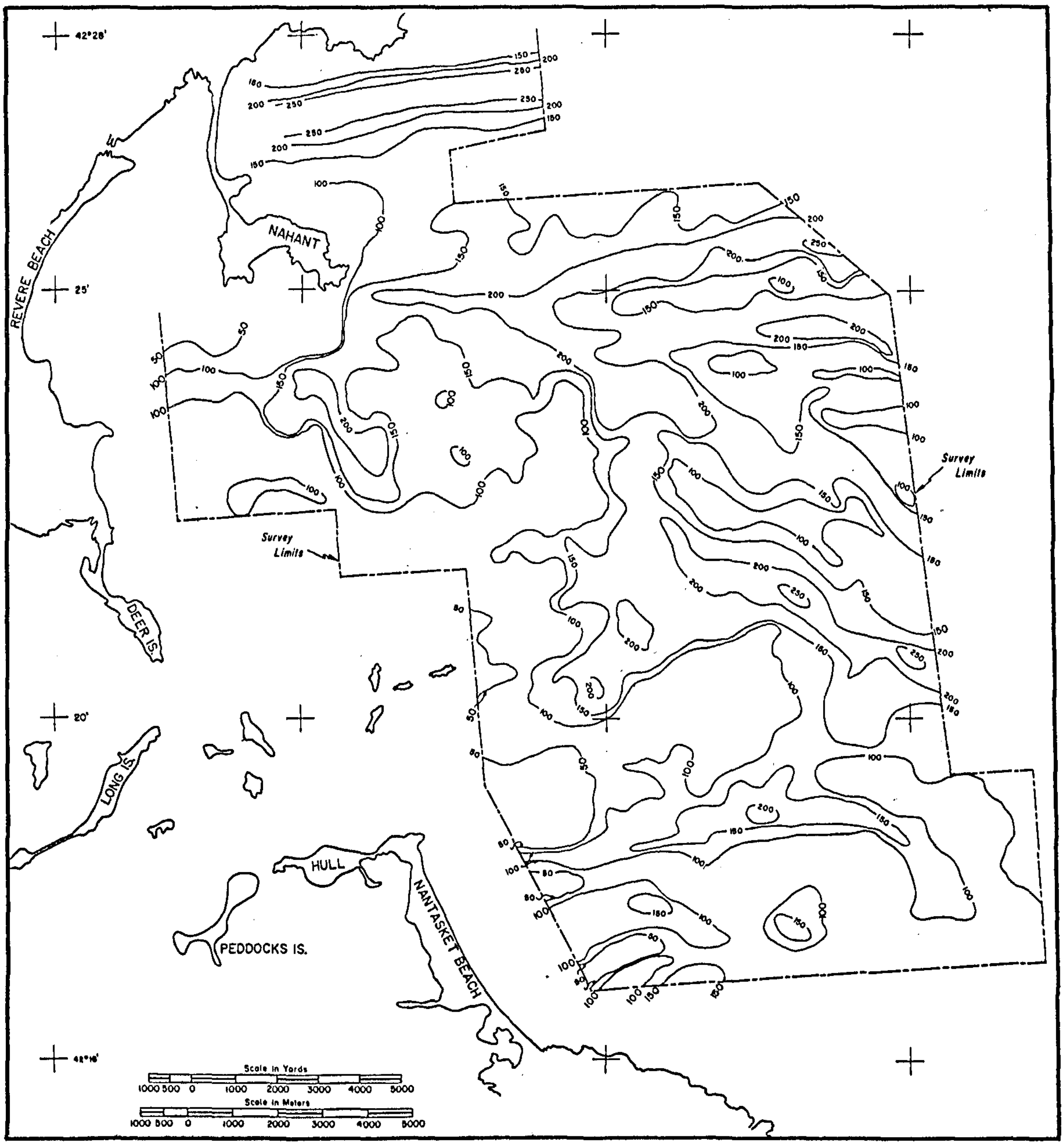


Figure 8. Contours on the primary topography of the acoustic basement. Note general east-west lineation.

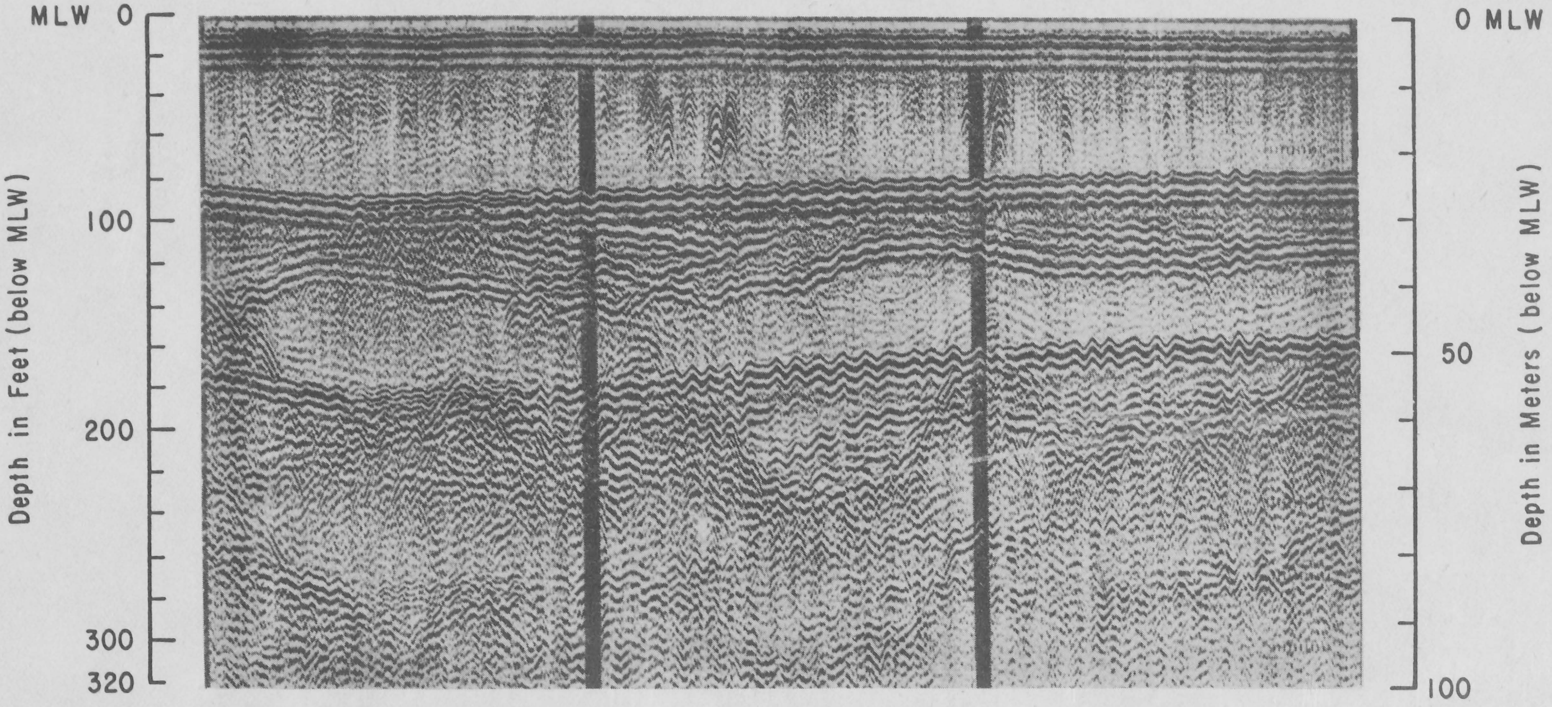


Figure 9. Section of seismic reflection profile showing the transparent reflection unit. Note weak internal reflectors in lower acoustic facies and complex strong internal reflectors in the upper acoustic facies.

indicate that the transparent unit was once eroded and that the irregular erosion surface carved into the unit was subsequently filled by stratified deposits with locally complex bedding patterns.

Both the lower transparent subunit with weak internal reflectors and the upper transparent subunit with strong internal reflectors occur together throughout most of the study area; where only one subunit is present it is usually the lower.

III. SEDIMENT CHARACTERISTICS AND DISTRIBUTION

1. Sediment Characteristics.

a. General. Data from 34 cores collected for this study and from 26 cores collected for the MCMI (Willett, et al., 1972) provided most of the information on surficial and shallow subbottom sediments within the primary study area. In addition, 26 grab samples with most supplemented by bottom photos, were collected within primary limits for the MCMI. Eight ICONS cores from CERC, and 20 cores plus 37 grab samples from MCMI, were in the north and south reconnaissance areas. The ICONS cores were available for direct sampling and analysis. Data from MCMI were obtained from logs, size analysis, and bottom photos contained in Willett, et al., 1972.

Comparison of core top samples, grab samples, and bottom photos shows that gravel occurs in grab samples more than twice as frequently as in core tops. Some of the bottom photos also show cobbles and boulders where grab samples, taken concurrently, do not reveal their presence (Willett, et al., 1972). This bias, previously noted by Schlee and Pratt (1970) and Setlow (1973) from the same region, is a function of sampling techniques. Core dimensions limit recovery to particles of less than 4 inches in diameter and most grab samplers are not large enough to contain large cobbles and boulders. The bottom photos which supplement the samples provide an indication of the location, gross size, and variation of gravelly sediment. Available bottom photos of the study area are limited; since the photos are applicable only to surficial sediments and are qualitative in nature, the sediment-size data should be treated with caution. This is evident where recovered material is poorly sorted and gravelly, indicating possible presence of cobbles and boulders. The sampling problem on the glaciated northeast United States Continental Shelf is discussed by Schlee and Pratt (1970).

The Wentworth Scale for soil classification is used for describing sediment texture in this report. This classification and the Unified Soil Classification are compared in Table 2 (U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1973).

b. Greenish-Gray Mud. The most common subsand-size sediment found in both primary and secondary study areas is greenish-gray silty clay and clayey silt, collectively identified as greenish-gray mud. This mud occurs occasionally in outcrop, mostly under thin overburden. Typical

Table 2. Grain-size scales (soil classification).

Wentworth Scale (Size Description)	Phi Units ϕ^2	Grain Diameter d (mm)	U.S. Standard Sieve Size	Unified Soil Classification (USC)
Boulder				
	−8	256.0		Cobble
Cobble		76.2	3 in.	
	−6	64.0		Gravel: Coarse
Pebble		19.0	¾ in.	
				Gravel: Fine
		4.76	No. 4	
	−2	4.0		Sand: Coarse
Granule				
	−1	2.0	No. 10	
Sand: Very Coarse				
	0	1.0		
Sand: Coarse				Sand: Medium
	1	0.5		
Sand: Medium		0.42	No. 40	
	2	0.25		
Sand: Fine				Sand: Fine
	3	0.125		
Sand: Very Fine		0.074	No. 200	
	4	0.0625		Silt or Clay
Silt				
	8	0.00391		
Clay				
	12	0.00024		
Colloid				

1. From U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1973.

2. $\phi = -\log_2 d(\text{mm})$.

color of the mud ranges from 5G4 5/1 to 5G4 6/1 (Munsell Color Code) and is generally uniform; however, brown and yellow mottling is common.

In most places the mud is massive, and some samples have a fissile structure. Although soft when wet, the massive clays dry to a hard compact mass which breaks readily leaving hackly fracture surfaces. The fissile clays tend to become crumbly when dry and break into small fragments.

Visually discernible characteristics of the greenish-gray mud vary little from place to place. Residue from washing through a 0.062-millimeter mesh sieve shows variation in texture and composition.

The most common constituent of the residue is clastic terrigeneous particles ranging in size from very fine sand to granules and consisting primarily of quartz with lesser amounts of other minerals and rock fragments. Small amounts of plant and wood fragments and mica are also present in most samples. Biogenic grains are generally very rare or nonexistent; where present they consist mostly of small unidentified calcareous fragments, echinoid spines, and foraminifera.

In all but three samples the amount of foraminifera in the residue of a 5-milliliter sample was less than five specimens. Contamination from overlying deposits is possible with such small numbers of specimens. However, the three samples contained enough specimens (more than 20) of foraminifera to rule out contamination; most of the specimens were of a single species (*Elphidium clavatum* Cushman).

c. Sand. Sand recovered in cores from the study area is widely diverse in character. Sizes vary from very fine silty sand to very coarse sand (Figs. 10 and 11); sorting values range from well sorted to poorly sorted (App. A). Granules and pebbles occur in modest quantities, especially with coarser sands.

Typically, sand occurs as the surficial layer; it rarely appears in cores beneath a stratum of dissimilar material. In many places the sand forms only a thin veneer less than 1 foot thick over clay, silt, or gravel. The layer in most of the cores containing sand is less than 5 feet thick. Most cores with a sand layer more than 5 feet thick are from area U3 off Nantasket Beach (Fig. 5) and in the north and south reconnaissance areas. Sand in the study area is chiefly detrital with a minor biogenic content consisting primarily of the hard parts of foraminifera, ostracods, echinoids, and mollusks (Fig. 10). The dominant mineral constituent is quartz. Rock fragments are common in the coarser sands. Mica is generally present, but is usually very sparse, except in the northern reconnaissance area where it is abundant in the finer sand facies.

Foraminifera are generally more abundant in sand than in any of the other sediment types. In most samples the dominant genus is *Elphidium*; *E. clavatum* Cushman, *E. discoidale* (d'Orbigny), and *E. poeyanum* (d'Orbigny) are the common species.

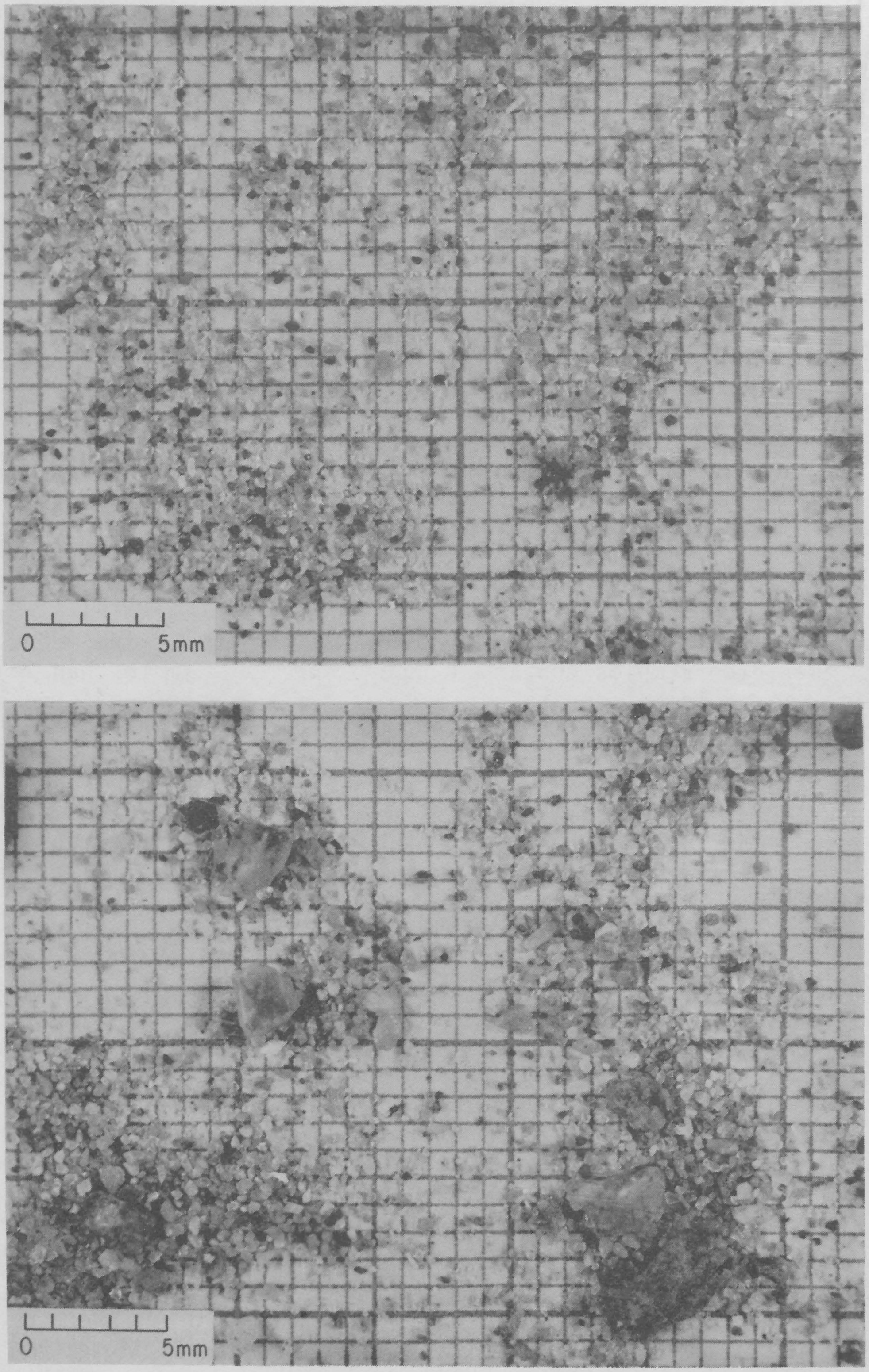


Figure 10. Photos of typical sand samples from the study area. Size distribution curves for these samples are in Table 2.

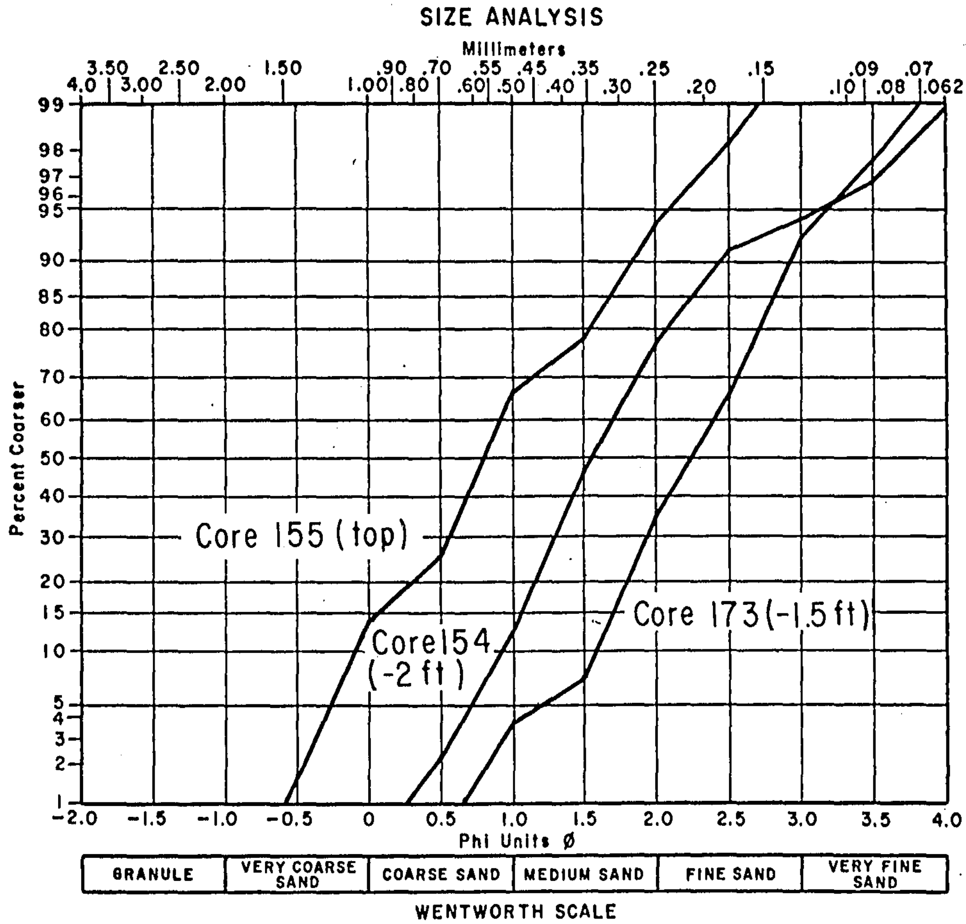


Figure 11. Graphic-size distribution curves for typical examples of sand from the study area. Note strong contrasts in sorting.

Cibicides lobatulus (Walker and Jacob) is dominant in a few samples and is generally present in quantity. Other genera well represented in sandy sediments are *Quinqueloculina*, *Rosalina*, *Ammonia*, *Buccella*, and *Poroeponides*. Mollusk shells, where found, are usually fragmented; the majority are derived from the blue mussel, *Mytilus edulis* Linne´, and the quahog *Mercenaria mercenaria* Linne´.

d. Gravel. Gravel is a common sediment in the study area and often appears in thin layers at or near the bottom surface. Willett, et al. (1972) referred to the surface gravel as a thin widespread "skin" covering large areas of the bottom, and ascribe its distribution to Holocene reworking of glacial till deposits exposed on the sea floor. Thicker deposits of gravel occur in places but are most prominent in the project NOMES site off Nantasket Beach (Setlow, 1973).

Subbottom gravel occurs frequently as thin discontinuous lenses in sand or silt-clay deposits and as a component of glacial till encountered in a few places below the transparent unit. Nearly all surficial gravel occurs in a matrix of either sand or a sand-silt-clay combination. In most places the gravel is poorly sorted and particle sizes range from granules to large boulders. The gravel particles are composed of many rock and mineral types, and are generally well rounded but tend to be irregular in shape (Fig. 12).

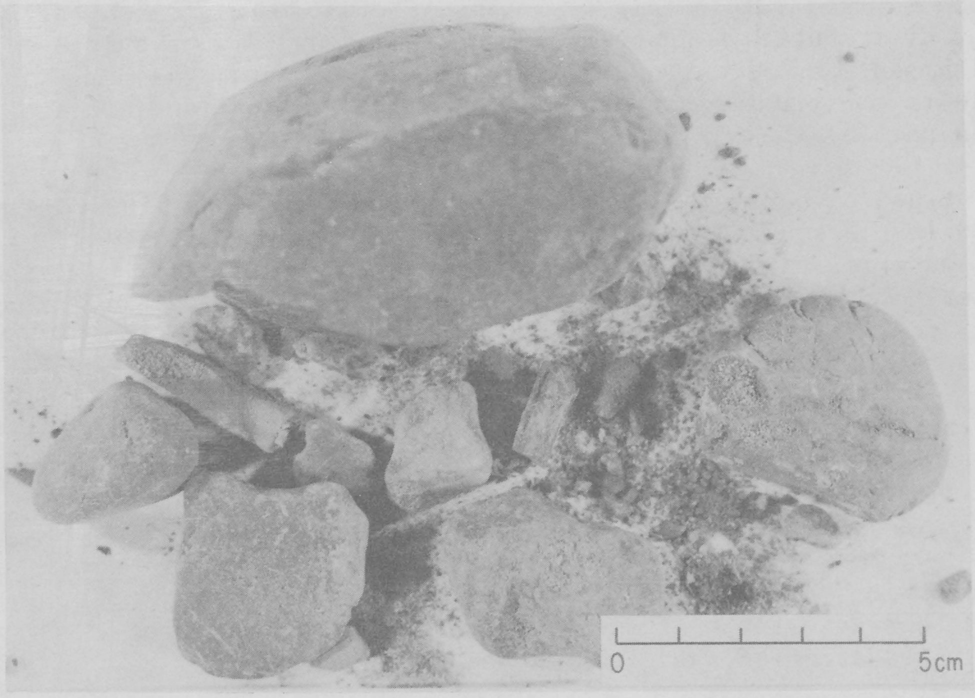
Gravel occurs frequently in the study area as inclusions in other sediment types, either in randomly scattered erratic particles in fine sand, silt, or clay, or in quantity sufficient to class the sediment as gravelly. The latter often occurs in medium or coarse sands. Biogenic particles in gravelly sediments are sparse and consist mostly of the same organisms found in the sand bodies.

e. Silt. Gray to brown silt, sandy silt, and clayey silt, distinct from silty phases of the greenish-gray mud previously described, occurs in local patches throughout the study area. Most of the silt is brown in color and contains various amounts of sand and clay; plant and wood fragments and mica are present in greater abundance than in other sediment types.

These sediments occur primarily as thin surficial deposits, although similar material is present in the subsurface at a few locations. In a few samples from the surficial deposits, the silt contains abundant coal fragments suggesting a source area in Boston Harbor (Mencher, Copeland and Payson, 1968). Some of these deposits may have originated from deposition of current or wave-borne detritus carried out of the harbor area; other deposits are probably the result of dredge spoil disposal. The stratigraphic relationships of the subsurface deposits are unknown.

2. Sediment Distribution.

Surface sediments in the study area are of heterogeneous character and distribution is often complex and seemingly without discernible pattern.



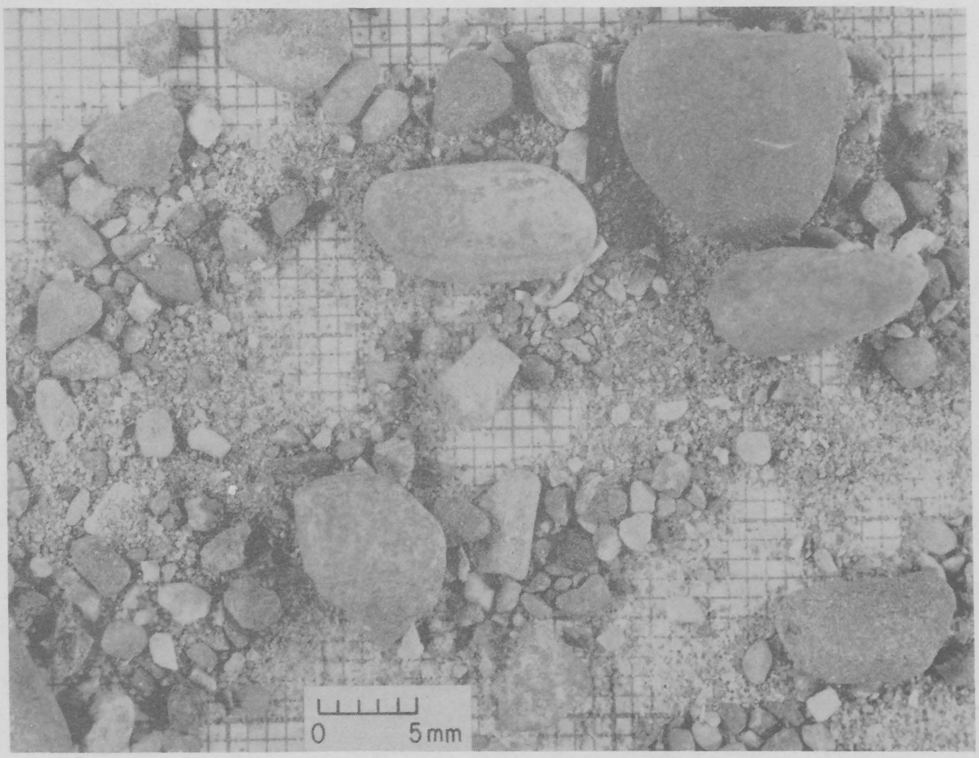


Figure 12. Photos of typical gravelly sediment from the study area. Note rounding and heterogenous size of gravel.

Available surface samples alone are insufficient to establish surface sediment distribution. However, by supplementing surface sample information with side-scan sonar and seismic reflection data, the MCMI study group was able to construct a surface sediment distribution map (Willett, et al., 1972); a part of the map is shown in Figure 13.

All types of surficial sediment deposits tend to be thin. Of the 69 cores in the study area for which data are available, only 12 contain similar material throughout their length. Distinct changes in sediment character occur within 5 feet of the surface in 34 of 60 cores longer than 5 feet. In 25 of these 60 cores the change in sediment character lies within 3 feet of the surface.

Willett, et al. (1972) stated that, in general, cobble and boulder-bearing surface sediments are more characteristic of the study area off Boston and southward while fine surficial sands are dominant to the north. They believe most of the coarse gravelly sediments are part of the thin skin of reworked glacial drift spread across the sea floor by shallow water reworking; locally this layer grades into the parent till body. The fine sand characteristic of the northern reconnaissance area is ascribed to modern progradation of sand from the shore and littoral zone.

Most of the fine sand in the study area seems to be a surface veneer in offshore areas. In places near the coast the fine sand is thicker, as indicated by cores from the relatively shallow inshore areas off Nantasket Beach and in the reconnaissance areas.

All sediment types encountered below the surficial layer are exposed in places within the study area. Thus, there appears to be no sediments within the upper 10 feet of the sea floor that are found only in the subsurface. The most common sediment underlying surficial deposits is greenish-gray silt-clay; also present are sand, gravelly sand, and till-like mixtures of sand, gravel, silt, and clay. All of these sediments are widely distributed throughout the study area. Silt and clay layers tend to be thicker than gravel or sand layers which are often less than 2 feet thick.

Subbottom distribution patterns of the greenish-gray mud and the bedrock-till components of the acoustic basement are more predictable than surficial sediment distribution because of their patterned relationship to the relict disrupted drainage system underlying the study area (Fig. 8).

IV. DISCUSSION

1. Relationship Between Subbottom Strata, Topography, and Sediments.

As previously discussed, the surface of the basement unit is highly irregular throughout the study area. Stratified deposits (transparent unit) completely cover this surface in many places; elsewhere, the stratified material only partially fills the lows and the higher peaks outcrop. At times, the basement surface appears to be planed off at the level of

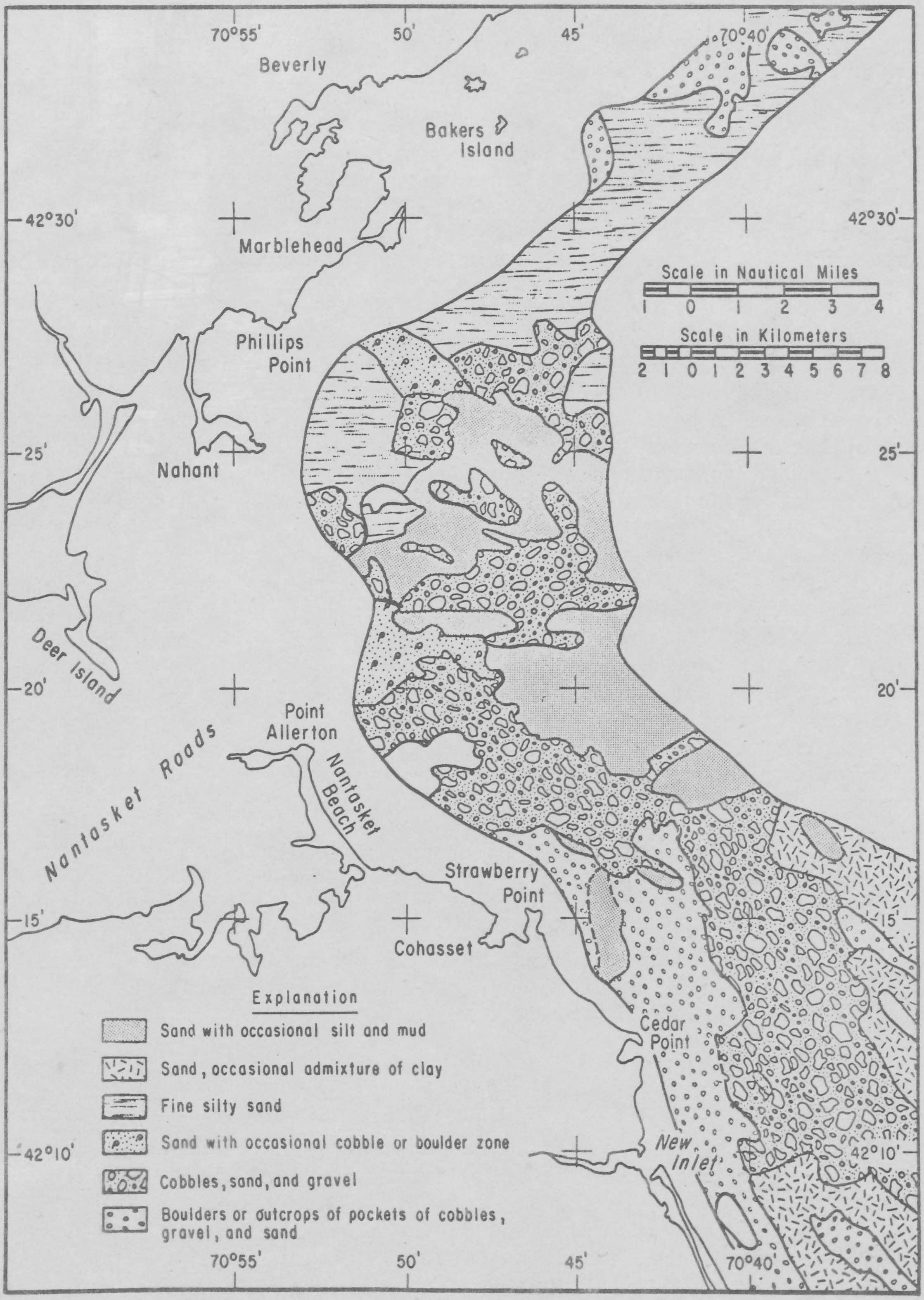


Figure 13. Map showing surface sediment distribution in the study area (after Willett, et al., 1972).

the bottom, and outcrops or very shallow subcrops occur without topographic expression. Therefore, a consistent relationship exists between outcrops of the basement reflection unit and the occurrence of both inshore and offshore submarine hills and ridges.

Since few cores are available from outcrops of the basement reflection unit the rock character of these submarine hills and ridges is unknown. However, it is likely that most of the inshore hills and ridges are essentially complex pre-Cretaceous basement rocks because they lie close off rocky stretches of coast with only thin ground moraine cover, and some inlets in the inshore groups are known to be composed of basement rocks (LaForge, 1932).

The offshore hills and ridges are generally larger and not as steep sided as the inshore features. Scattered surficial samples indicate that these features have a veener of till-like material. Many of the offshore ridges are similar in size and general orientation to the drumlins that form a familiar element of glaciated terrain in the Boston area. However, core data for both inshore and offshore hills and ridges are inadequate for reliable determination of their specific environment of deposition.

A generally consistent relationship also exists between level bottom (area A in Fig. 5) and the occurrence of the transparent reflection unit directly underlying the sea floor. Internal reflections in the transparent unit indicate the level bottom is composed of stratified sediment material. Most cores in level bottom areas entered greenish-gray mud less than 3 feet downhole and several cores indicated that this composition persisted to depths of over 30 feet. The relationship between level bottom, stratified subbottom sediment, and greenish-gray mud, either exposed or under thin fine sand overburden, is especially consistent in area A1 (Fig. 5) which occupies much of the northern half of the study area.

In places, the upper part of the transparent reflection unit contains fine sand rather than the characteristic greenish-gray mud. Where this occurs, the reflection records usually show the transparent unit divided into upper and lower subunits (see Section II, 2c) and the upper part contains strong internal reflectors. However, strong internal reflectors in the upper subunit also occur where cores show the subunit to be composed of mud; therefore, this characteristic reflection is not everywhere indicative of a sand layer.

2. Origin and Distribution of Sediments.

a. Glacial Drift. Most clastic sediments in the study area are of glacial origin, originating as ice-borne detritus subsequently deposited in ice contact and outwash features. In a few places these sediments are distributed in the original deposition patterns left by the retreating glacier and associated braided outwash streams. However, in most places the original character and distribution of these sediments have been altered by postdepositioned reworking and redistribution in a shallow marine environment. This was a result of an emergence (relative uplift of the land) of about 70 feet followed by resubmergence to present depths. According to Kaye and Barghoorn (1964), relative sea level in the Boston area stood at +60 feet or higher at about 14,000 years B.P. During crustal rebound following glacial retreat, relative sea level dropped to -70 feet mean low water (MLW), reaching this level about 10,000 years B.P. At this time sea level gradually rose to -2 feet MLW by 3,000 years B.P. As a consequence of these events, parts of the study area now lying at 0 to -70 feet MLW were subject to a marine regression and transgression while deeper areas were brought within range of high-energy shallow marine processes. Because crustal rebound occurred concurrently with an eustatic rise in sea level, the study area remained under shallow-water marine conditions for some time longer than experienced by stable areas. Thus, the prolonged time of shallow submergence permitted a greater reworking and redistribution of Pleistocene sediments in the Boston area than in more stable shelf areas with a similar wave climate. As a result of shallow marine reworking, glacial till projecting above the glaciomarine clay was eroded and coarse lag deposits were formed on the surface.

The effects of reworking and redistribution of glacial drift in the littoral and nearshore environment can be observed along the existing coast in the study area where glacial drift features, chiefly drumlins, are being eroded and the material transported downdrift to form modern spits and beaches. Where the drumlins have been reduced to near sea level the remaining coarse material has formed a lag pavement. Finer sediment eroded from glacial drift deposits is, according to size, either carried in suspension out of the area or carried downdrift to be deposited on beaches and spits or in adjacent shoreface and offshore bar deposits.

Because of the extensive occurrences of a thin surficial veneer of sand, pebbles, cobbles, and boulders, Willett, et al. (1972) concluded that this surficial skin was the result of widespread redistribution of drift during the Holocene regression-transgression episode occurring around 10,000 years B.P. Another possibility is that the material in the thin widespread deposit is reworked ground moraine essentially *in situ*, related to the late Wisconsin glacial stage. However, there is evidence that the late Wisconsin glacier did not overrun the Boston Basin; Judson (1949), Kaye (1961), and Upson and Spencer (1964) implied that such a ground moraine was never present in the study area.

Outside of the shallow nearshore, littoral and shore zone of the present-day coast, it is unlikely that the gravel can be moved under existing offshore hydrodynamic conditions. Thus, nearly all the gravelly sediments are probably relict.

b. Greenish-Gray Mud. The history and origin of the ubiquitous greenish-gray mud associated with the transparent unit appears to be complex. There are probably two or more superimposed mud units of grossly similar character deposited at various times under different environmental conditions.

Oldale, Uchupi, and Prada (1973) reported that the upper part of the acoustically transparent unit which has been widely sampled, consists of

Holocene silt and clay. They also reported that borehole samples in the transparent unit under Boston Harbor showed the upper part to be composed of Holocene silt and clay and the lower part of glaciomarine silt and clay of late Pleistocene age.

On the basis of core and seismic reflection data, Willett, et al. (1972) also identified two units of silt and clay filling many depressions in bedrock and till deposits. Since the interface between the two units is commonly marked by a veneer of sand and gravel or glacial till, they inferred a glacial advance following deposition of the lower unit and preceding deposition of the upper unit. Willett, et al. believed this advance could be associated with Kaye's (1961) Drift III, and the upper clay unit might correlate with his Clay III (Table 1).

Setlow (1973) distinguished two marine clay units in the project NOMES site. The lower unit averaged 50 feet in thickness and was separated from the upper unit by an erosional unconformity. The upper unit averaged about 25 feet in thickness but thinned rapidly and pinched out against till outcrops. Setlow believed that the lower unit probably correlated with Kaye's (1961) Clay II, and the upper unit with his Clay III (Table 1).

Foraminifera in greenish-gray mud are extremely rare and are absent in most samples. Since remains of other marine animals are comparably rare, little can be gleaned of the origins of this deposit from faunal evidence. However, the almost complete dominance by *Elphidium* spp. of the few foraminifera recovered suggests a marginal marine environment (Phelger, 1960). The barren sections possibly represent time periods with either very rapid deposition or a dominance of environmental conditions precluding or sharply restricting productivity. Alternatively, this scarcity may be due to leaching of tests originally present in the deposit.

Foraminifera in a section of clay and overlying greenish silt corresponding to Judson's (1949) Boston clay and marine silt (Table 1) were studied by Stetson and Parker (1942) and Phleger (1949) from samples obtained in the Boston area. Phleger (1949) found that foraminifera were extremely sparse in the clay section, but that the marine silt contained more foraminiferal fauna dominated by species of *Elphidium*. Few of the other species found in the clay by Phleger (1949) and by Stetson and Parker (1942) occurred in the ICONS samples processed for microfauna.

The general confinement of the greenish-gray mud to valleylike depressions in the acoustic basement suggests that it was deposited at a lower stand of relative sea level in estuaries bounded by interfluves of the acoustic basement material. The paucity, or complete absence of remains of marine organisms in most places also favors such an origin as opposed to "blanket-sedimentation" in deeper water with subsequent erosion of material over the acoustic basement outcrops.

The sediment distribution pattern, fauna or lack of fauna, and lithology of the greenish-gray mud, all indicate it is relict; there is no evidence that such material is being deposited today in any part of the study area.

c. Sand. The widespread sand blanket occurring off the northern part of the study area was considered Holocene by Willett, et al. (1972). One core obtained for the ICONS study (core 152) contained lignite and plant fragments 14 feet downhole under a typical fine sand sequence similar to the fine sand in the northern part. This material yielded a radiocarbon age of 12,000 years (±250 years) B.P. which places deposition of the overlying sand in the Holocene. Foraminifera in the 14-foot section of sand above the dated layer indicate that this layer was deposited in an open marine nearshore setting similar to its present locale.

Information obtained in this study supports the supposition of Willett, et al. (1972), Oldale, Uchupi, and Prada (1973), and Setlow (1973) that in most places, there are at least two distinct sediment subunits of the transparent layer, and that these subunits have recognizable acoustic signatures. Both acoustic facies are sometimes greenish-gray mud, but also, notably off Nantasket Beach, the upper facies with strong internal reflectors may consist of sand. It is not known whether this sand is time-correlative with the upper unit of greenish-gray mud or if the sand was deposited at a later time, possibly after a period of erosion. The latter possibility is most likely since lithology and fauna of the sand suggest an energetic open-marine environment unlike the probably depositional environment of the silt and clay.

Sand or sand and gravel appear to be common where low mounds overlay the transparent reflector. These mounds with their smooth-rounded contours are distinct from the raised bottom created by outcrops of the basement reflector which is characterized by irregular and angular surface topography. Little information is available on the mounds, but some may be relict shoreline or nearshore deposits dating from the late transgressive-regressive sequence of Kaye and Barghoorn (1964). If so, topographic highs in the transparent reflector are promising features for further exploration for suitable beach sand. The extensive sand and gravel deposits of the prime project NOMES area appear to be an example of the relationship between morphology and sediment types.

3. Modern Sedimentation.

Since relative sea level approached its present stand about 3,000 years ago, sedimentation has been most active along the present coastline. Sediments eroding from headlands are being distributed to beaches, spits, and the adjacent sublittoral shoreface zone.

There appears to have been little modern sediment accretion during this time. The widespread skin of gravel and boulders covering much of the area is a relict deposit of the Holocene transgression-regression sequence that remains unburied in most places (Willett, et al., 1972). In addition, the greenish-gray clay is considered a Pleistocene or relict

Holocene deposit which commonly occurs either at or near the surface (less than 2 feet below surface).

Willett, et al. (1972) concluded that silt and clay-size sewage, fly ash from Boston Harbor, and dredge spoils constitute much of the modern sediments contributed to the inner shelf in the Boston area. Most inner shelf ICONS cores with surface deposits of silt contained coal fragments, evidence of origin in the harbor area.

V. SAND RESOURCES

1. Sandfill Requirements.

Volume requirements for beach restoration and nourishment work estimated for presently authorized Corps of Engineers projects along the coast adjacent to the study area are listed in Table 3. Since initial fill has already been placed on some beaches, only maintenance volumes are listed.

Table 3. Beach sandfill requirements in the study region.

Beach	Initial fill (yd^3)	Annual nourishment (yd^3)	50-year nourishment (yd^3)
Lynn-Nahant	172,000	5,000	250,000
Revere	830,000	20,000	1,000,000
Winthrop	200,000	5,000	250,000
Quincy Shore	(Completed)	10,000	500,000
Nantasket	700,000	20,000	1,000,000
Wessaqusett	(Completed)	5,000	250,000
North Scituate	(Completed)	5,000	250,000
Total	1,902,000	70,000	3,500,000

NOTE: Data from C. Wentworth while at U.S. Army Engineer Division, New England (personal communication, 1975).

It is estimated that as much as 20 percent additional volumes may be required for initial fill on these beaches due to erosion loss since original studies were made (C. Wentworth, personal communication, 1974).

2. Potential Offshore Sand Resources.

a. General. Only a few deposits of sand suitable for beach fill have been identified within the study limits (Fig. 14). Considering the complexity of sediment distribution in the area, it is probable that other suitable deposits, lying between available data points, remain undiscovered.

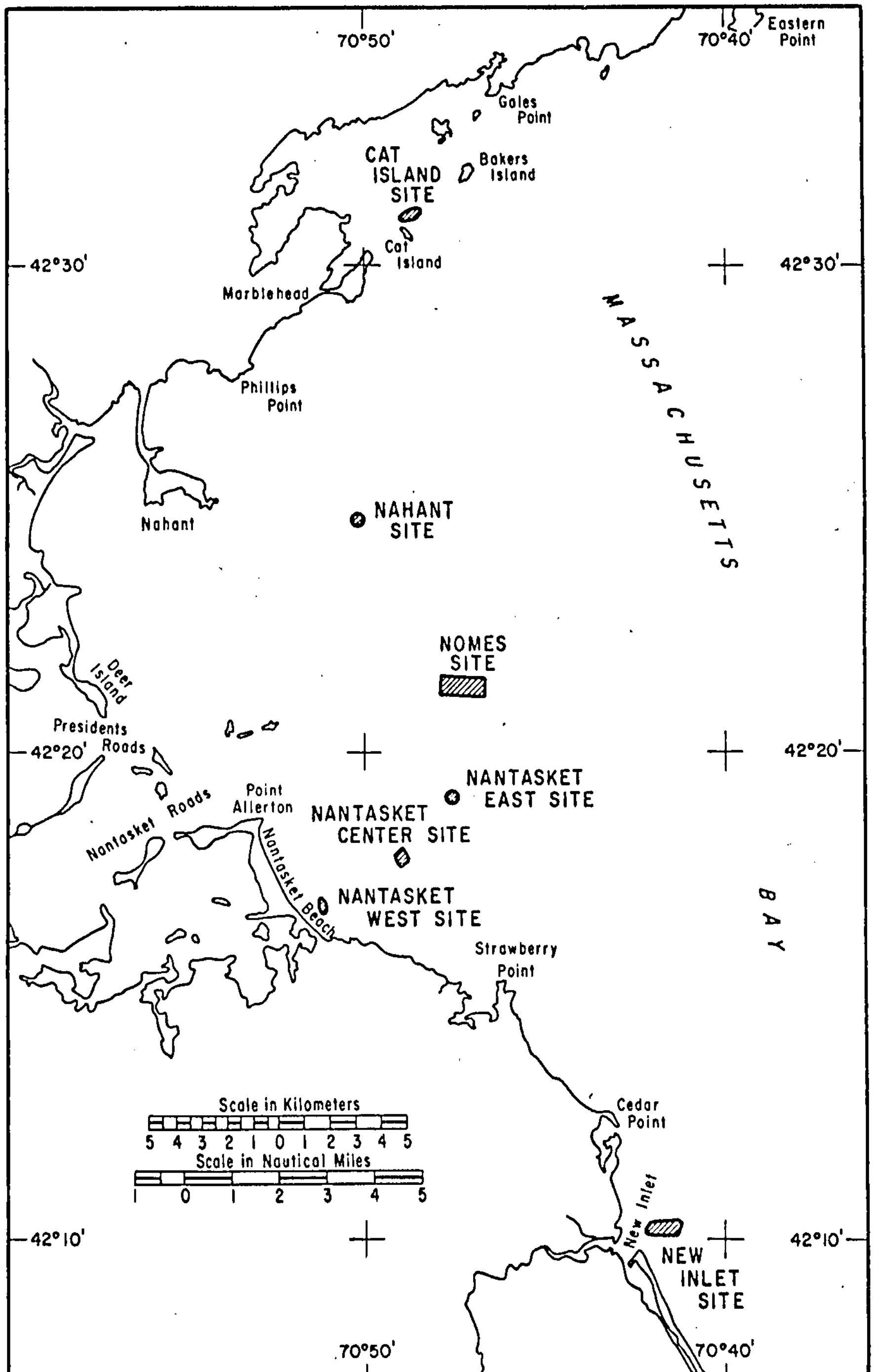


Figure 14. Location of sand deposits selected as potential sources of sand for beach restoration and nourishment. Sand and gravel deposits from the Massachusetts Coastal Mineral Inventory (Willett, et al., 1972) are also plotted.

Based on the assumption that available data are representative, the area as a whole contains relatively small amounts of suitable material.

Potential sand sources are scanty in level bottom areas. Although sand is the common surface deposit in these areas, it is generally fine to very fine grained and unsuitable for beach fill. Furthermore, the thin and discontinuous sand cover is almost everywhere underlain by the ubiquitous green-gray silt and clay. Some of the smooth surface mounds which occur in places in level bottom areas contain thicker deposits of sand. Although little information is presently available on these features, they are judged to be the best prospects in level bottom areas for future exploration.

Sand potential of the submarine hills and ridges is poor in recovery of adequate material from these features because of their bedrock or till composition. Marine reworking and selective sorting of the till composing or mantling submarine hills and ridges during transgressive-regressive phases of the Holocene produced some usable deposits adjacent to the source features (Willett, et al., 1972). Similarily, present-day coastal erosion of drumlins and other till features has provided sand for beaches and spits along the coast of the study area.

In channels between inshore hills and ridges, current and wave action are locally forming modern deposits of sand. A deposit in Cat Island Channel north of the main grid area (see Section V, 2b) is an example of a modern tidal-channel deposit containing suitable bottom material. Since little data have been collected on the inshore hill and ridge areas because of navigation difficulties in such places, their potential as sand sources cannot be assessed. Future exploration of the more accessible channels may prove worthwhile, especially those in which tidal currents are competent to carry sand-size material.

b. Potential Offshore Borrow Sites. Specific sand deposits potentially usable as offshore borrow sites are discussed below and summarized in Table 4. Since information on these ICONS sites is sparse, detailed surveys are considered necessary before a site is selected as a project borrow zone. The prime project NOMES site is also discussed and potentially usable sand and gravel deposits within study limits reported by the MCMI are plotted in Figure 14. Details on the latter sites are given in Willett, et al. (1972) and Setlow (1973).

(1) Cat Island Channel. The Cat Island Channel sand deposit is centered at 42°30.2'N., 70°48.9'W. off Cat Island in the northern reconnaissance area (Fig. 15). The deposit lies in 30 to 55 feet (9.1 to 16.7 meters) of water, is roughly rectangular in shape, measures approximately 330 by 850 yards, and covers an area of about 280,000 square yards. Core data indicate that the deposit is at least 12 feet (3.7 meters) thick. Seismic reflections and topographic data suggest that it may be 20 feet (6.1 meters) thick (Figs. 15 and 16).

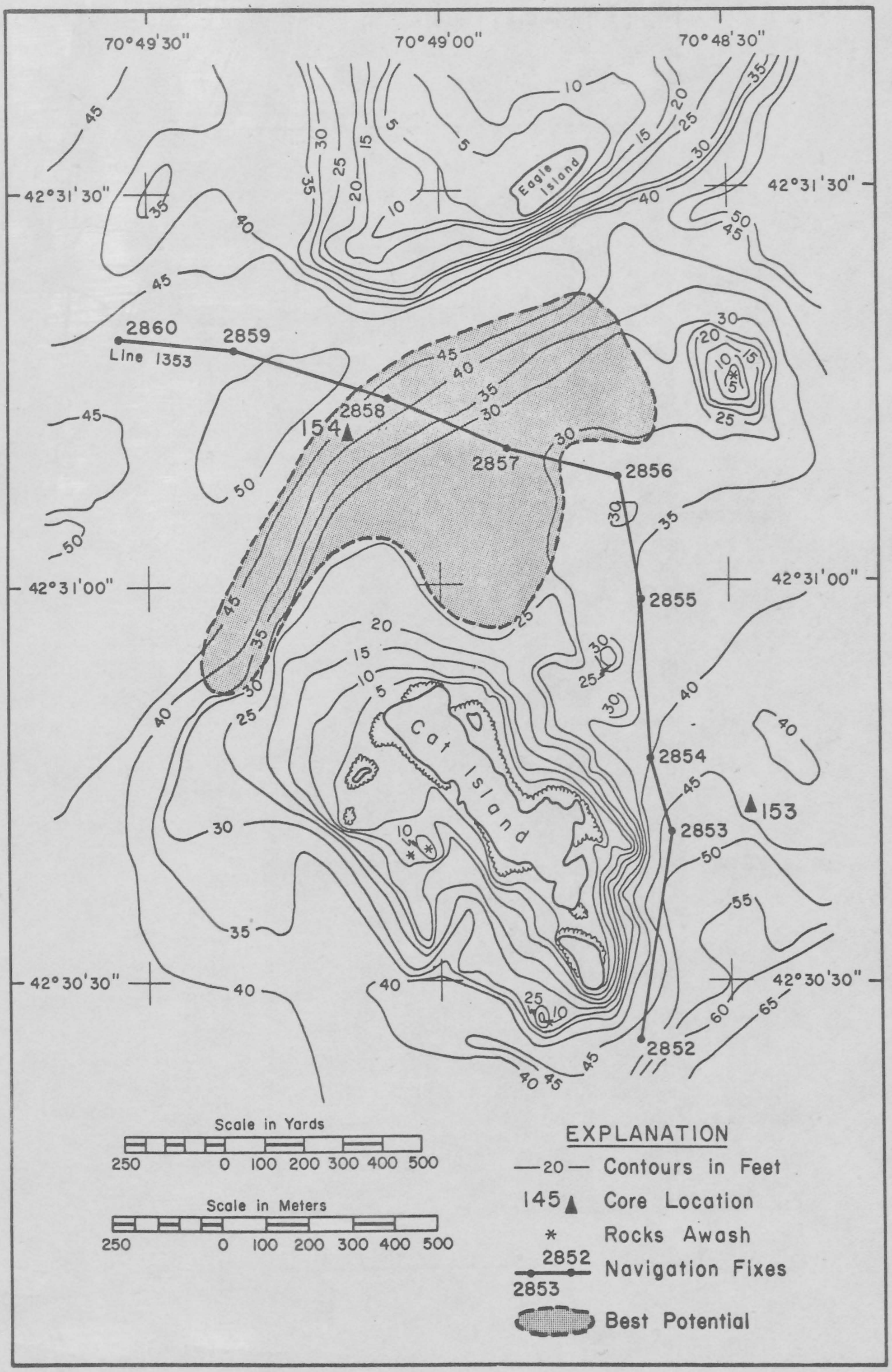


Figure 15. Bottom topography near Cat Island sand deposit. Note topographic expression of the western edge of the deposit.

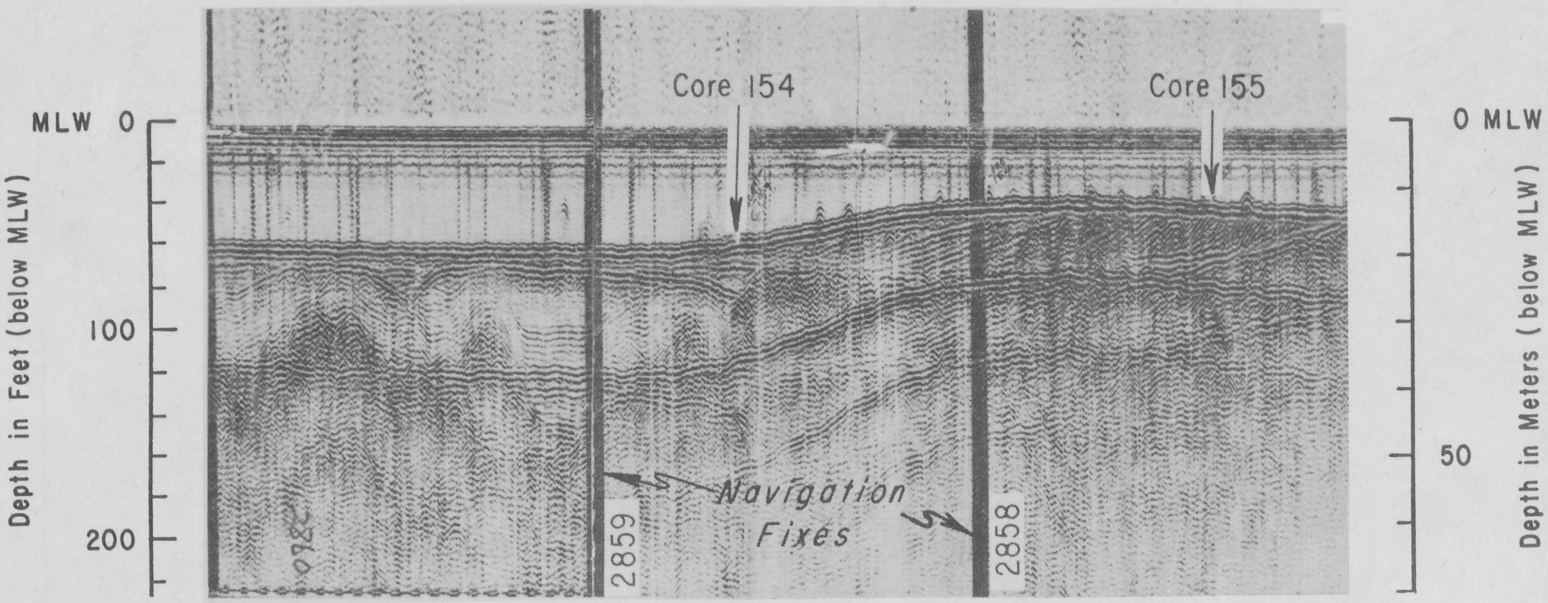


Figure 16. Seismic reflection profile crossing the Cat Island Channel sand deposit. Note the progradation bedding dipping westward. Location of fixes plotted in Figure 14.

Table 4. Characteristics of sand from potential borrow areas[1].

Location	Coordinates	Depth	Sand size					Volume
			Median		Mean		Sorting	Minimum
		(ft)	(phi)	(mm)	(phi)	(mm)	(phi)	(yd^3)
Cat Island	42°30.2'N., 70°48.9'W.	30 to 55	1.64	0.312	1.61	0.328	0.74	1.12×10^6
Nahant	42°24.7'N., 70°50.2'W.	98	medium to coarse sand and pebbles					0.78×10^6
Nantasket East	42°18.8'N., 70°47.6'W.	60 to 70	1.84	0.279	2.12	0.230	0.84	0.68×10^6
Nantasket Center	42°17.8'N., 70°49.0'W.	65	2.46	0.182	2.44	0.184	0.78	0.42×10^6
Nantasket West	42°17.2'N., 70°51.2'W.	25 to 40	medium to coarse sand and pebbles					1.95×10^6
New Inlet	42°10.1'N., 70°41.5'W.	45 to 50	1.88	0.272	1.86	0.275	00.89	2.8×10^6
NOMES Site	42°20.7'N., 70°47.7'W.	70 to 105	sand and gravel					19.5×10^6

1. Preliminary estimates of composite parameters based on available core data; values should not be used for final design purposes.

The Cat Island Channel deposit is expressed topographically as a terracelike feature with the foreslope facing northwestward. Reflection profiles show that this feature was deposited in the lee of a small acoustically opaque ridge which may be a bedrock or till feature (Fig. 16). Internal reflections within the sand deposit indicate presence of relatively high-angle internal bedding planes dipping northwestward and parallel to the topographic foreslope (Fig. 15). This suggests that the deposit grew by progradation from the suspected till or bedrock ridge toward the northwest and may have been formed by overwash deposition of a relict Holocene transgressive shoreline. Alternatively, the deposit may be a modern tidal channel deposit which is probably still actively accreting by northwestward progradation. ICONS cores 154 and 155 were obtained from the sand deposit. Size-analysis data for representative samples from these cores are in Appendix B. Sand from the two cores in the Cat Island deposit is mostly in the medium to coarse-size range. The estimated composite mean diameter of the cored material is 1.61 phi (0.312 millimeter), and the phi sorting is 0.74. The sand is clean and composed largely of quartz grains. The total volume available is estimated to be 1.12×10^6 cubic yards assuming a maximum indicated thickness of 21 feet (6.4 millimeters).

(2) Nahant. This deposit is centered at 42°24.7'N., 70°50.2'W. about 2.9 nautical miles (5.37 kilometers) east of Nahant. The site lies in 98 feet (2.98 meters) of water and has only a slight rise in the bottom (Fig. 17). Only one seismic reflection profile (on east-west line) crosses the site (Fig. 18). The profile shows the deposit is a thin wedge-shaped body abutting a small topographic high in the sea floor and extending to a feather edge 4,100 feet (1,250 meters) to the east. Core 157 from the site contained 5 feet (1.52 meters) of coarse sand and gravel under a 1-foot silt layer (App. B). The silt contained abundant coal fragments characteristic of sediments in Boston Harbor (Mencher, Copeland, and Payson, 1968) and probably originated in that locale.

The seismic reflection profile indicates that the Nahant deposit may be 30 feet (9.1 meters) thick where it abuts the small rise in the sea floor. If the entire deposit is usable sand, and assuming it is half as extensive in the north-south direction as in its east-west extent, a total volume of 4.66×10^6 cubic yards of material is available. Assuming the sand layer is no thicker than 5 feet (1.5 meters) as in core 157, the approximate volume is 0.78×10^6 cubic yards.

(3) Nantasket East. This site is centered at 42°18.8'N., 70°47.6'W. about 3.9 nautical miles (7.2 kilometers) off Nantasket beach in 60 to 70 feet (18.2 to 12.3 meters) of water in a swale between two outcrops of the basement reflector (Figs. 19 and 20).

The north-south seismic reflection line crossing the site (Fig. 18) shows the external form of a low terrace underlain by the transparent unit. There are strong internal reflectors in the upper subbottom, some of which show high-angle internal bedding.

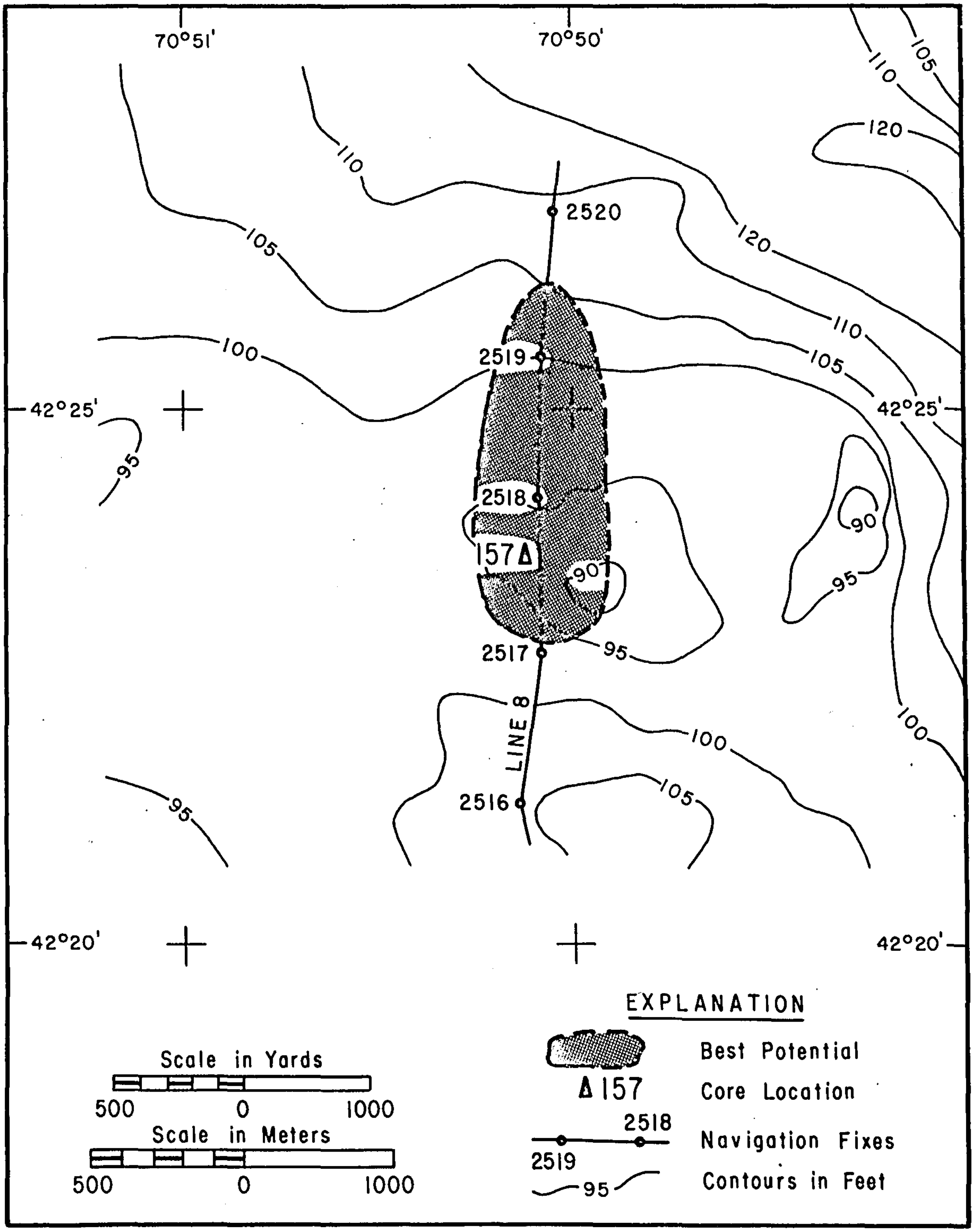


Figure 17. Bottom topography near the sand deposit off Nahant. Note slight topographic expression.

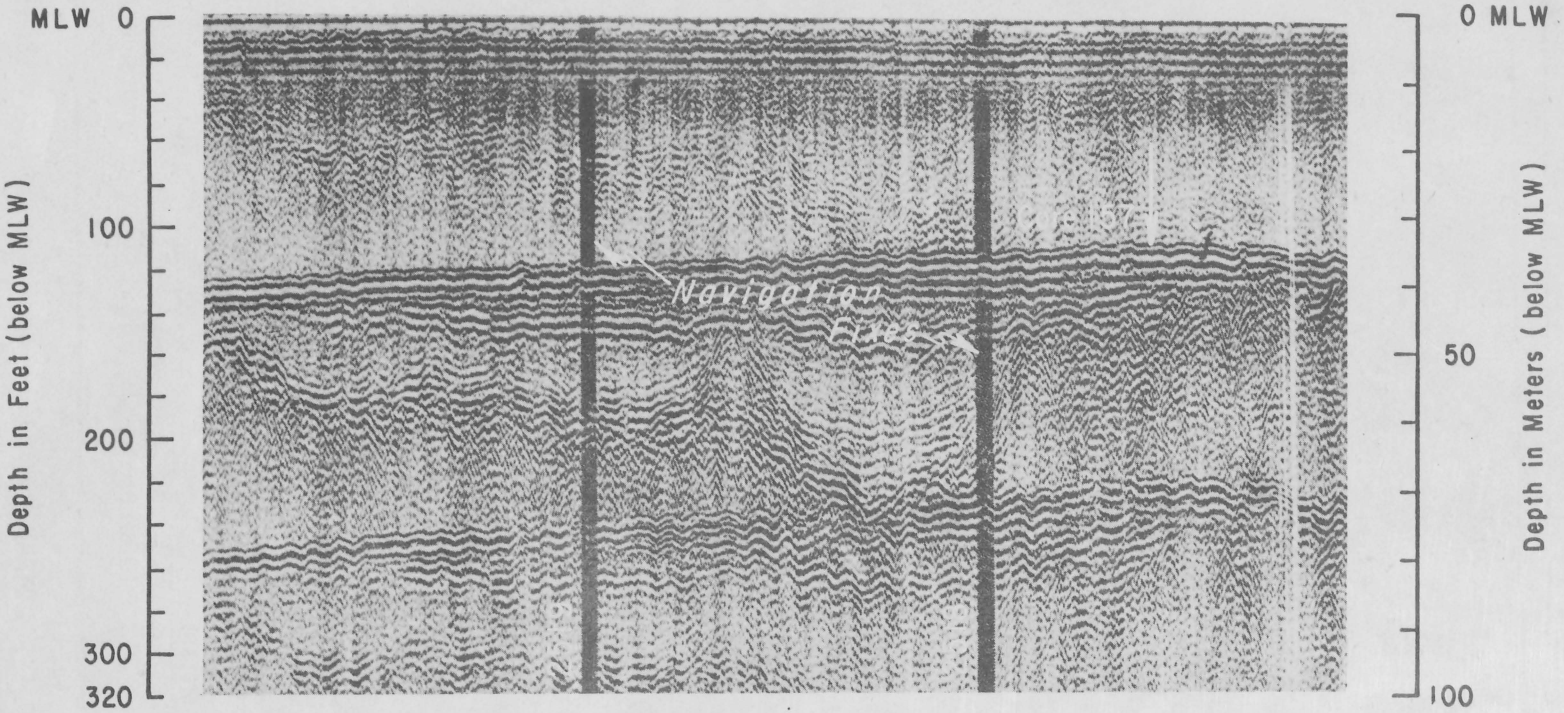


Figure 18. Seismic reflection profile crossing the sand deposit off Nahant. Navigation fixes are plotted in Figure 16.

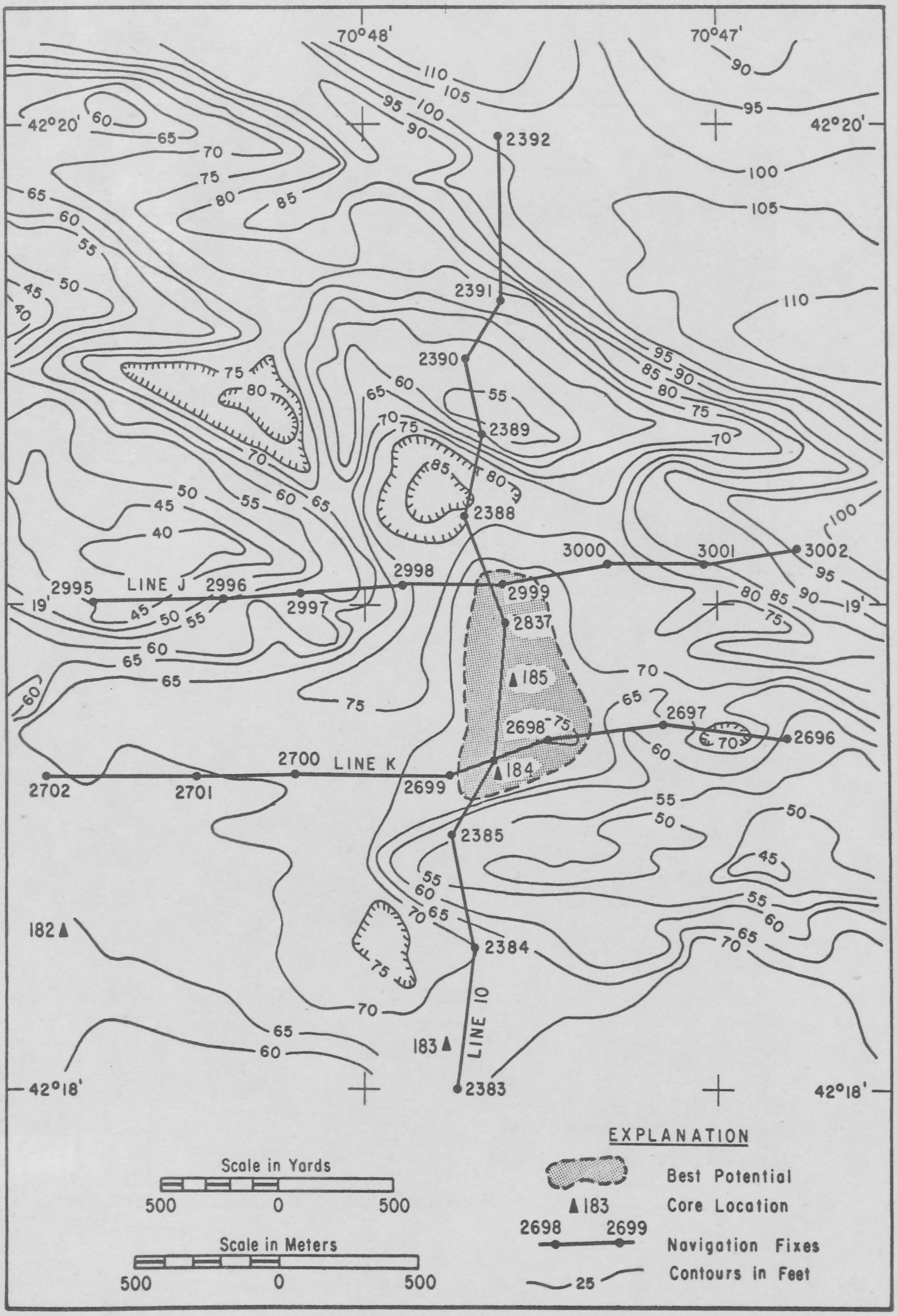


Figure 19. Bottom topography near Nantasket East sand deposit. Note terracelike form of deposit on the north and west sides.

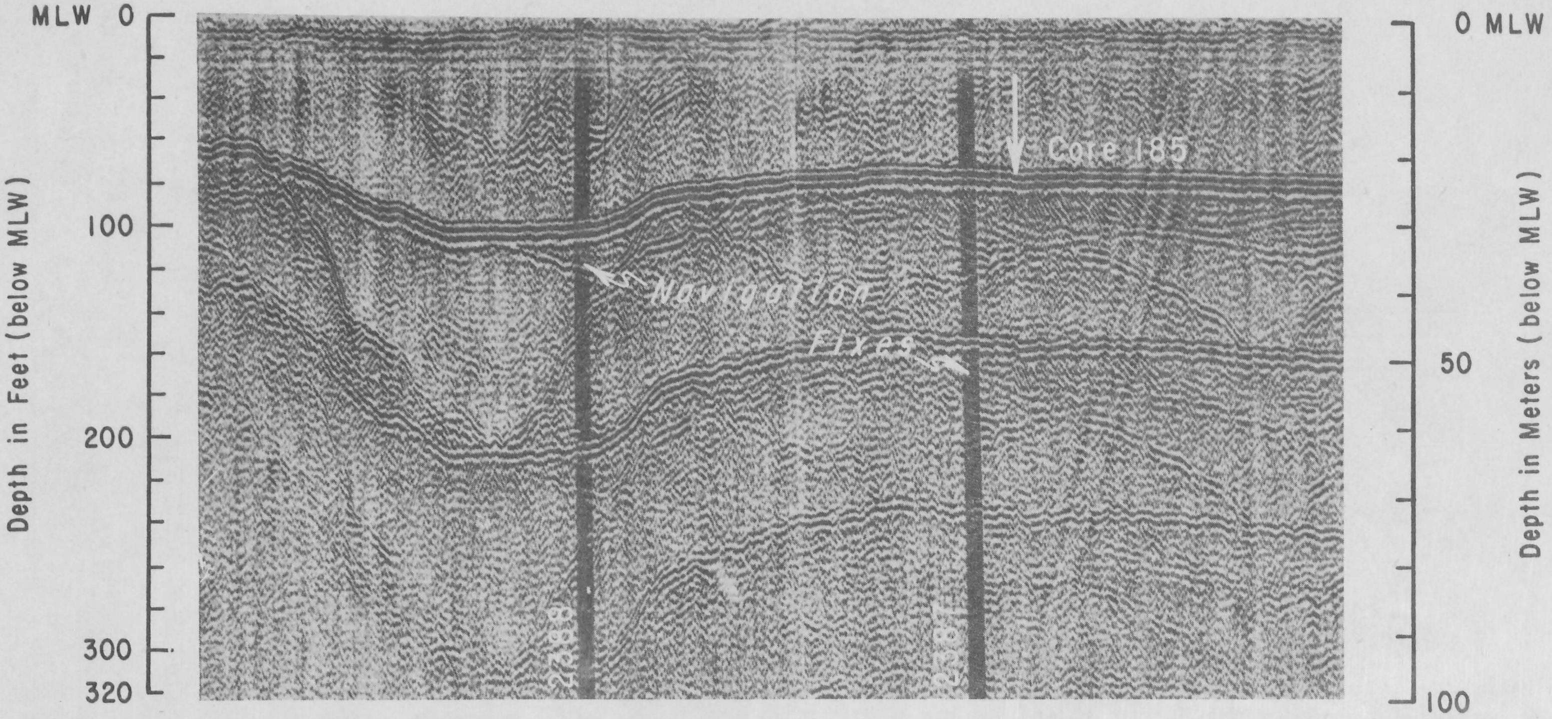


Figure 20. Section of seismic reflection profile crossing the Nantasket East site. Navigation fixes are plotted in Figure 13. Note high-angle internal reflectors near core 185.

Core 185, 6 feet (2 meters) long near the center of the site contained mostly clean, brown quartz sand predominantly in the medium-size range. Grain-size data for samples from this core are in Appendix B. The estimated composite mean diameter of the cored material is 1.84 phi and the phi sorting is 0.84. Core 184 on the border of the deposit contained 2 feet of similar material at the surface underlain by fine sand. The area of the deposit is estimated to be 407 X 10^3 square yards; assuming an average thickness of 5 feet (1.5 meters), the volume available is 0.68 X 10^6 cubic yards.

(4) Nantasket Center. This sand deposit is centered at 42°17.8'N., 70°49'W. about 2.2 nautical miles (4.1 kilometers) off Nantasket Beach. The site lies in 65 feet (19.8 meters) of water and occupies a slight topographic swale immediately north of a low steep-faced outcrop of the acoustic basement (Figs. 21 and 22). Only one seismic reflection profile (line M; Fig. 21) crosses this deposit. On this profile (Fig. 22) the deposit appears situated in the transparent acoustic unit which fills a small depression in the acoustic basement.

The transparent unit is divided into the typical upper and lower acoustic subunits with the upper unit filling a depression in the lower unit. Strong internal reflectors in the upper unit indicated northward-dipping bedding planes in the deposit.

Core 181, 7 feet (2.1 meters) long, was taken from the central part of the deposit area and contained clean, gray quartz sand in the fine to medium sand range. The estimated composite mean diameter of the cored material is 2.46 phi (0.182 millimeter); the estimated phi sorting is 0.78. All of the upper unit is probably composed of similar sand; therefore, the deposit may be a maximum of 25 feet (7.6 meters) thick at its thickest point. The one areal dimension determined from the available profile showed the deposit to extend 600 yards (548 meters) in a north-south direction. Assuming that the other surface dimension is at least one-half and that the sand is 25 feet (7.6 meters) thick, a volume of 1.50 X 10^6 cubic yards of suitable material is estimated in this deposit; a thickness of only 7 feet would give an available volume of about 0.42 X 10^6 cubic yards.

(5) Nantasket West. This site, centered at 42°17.2'N., 70°51.2'W. approximately 0.7 nautical mile (1.30 kilometers) off Nantasket Beach (Fig. 14), lies in an area of nearly level bottom which slopes northward from about -25 to -40 feet (-7.6 to -12.2 meters) MLW (Fig. 23).

A north-south seismic reflection profile crossing the site shows the deposit in the upper reflection facies of the transparent unit (Fig. 24). The facies contain strong internal reflectors and near the south end of the deposit the internal reflectors indicate probable high-angle bedding dipping southward.

Two cores penetrated the upper part of the Nantasket West deposit. The northernmost core (173) recovered 11 feet (3.4 meters) of medium sand. To

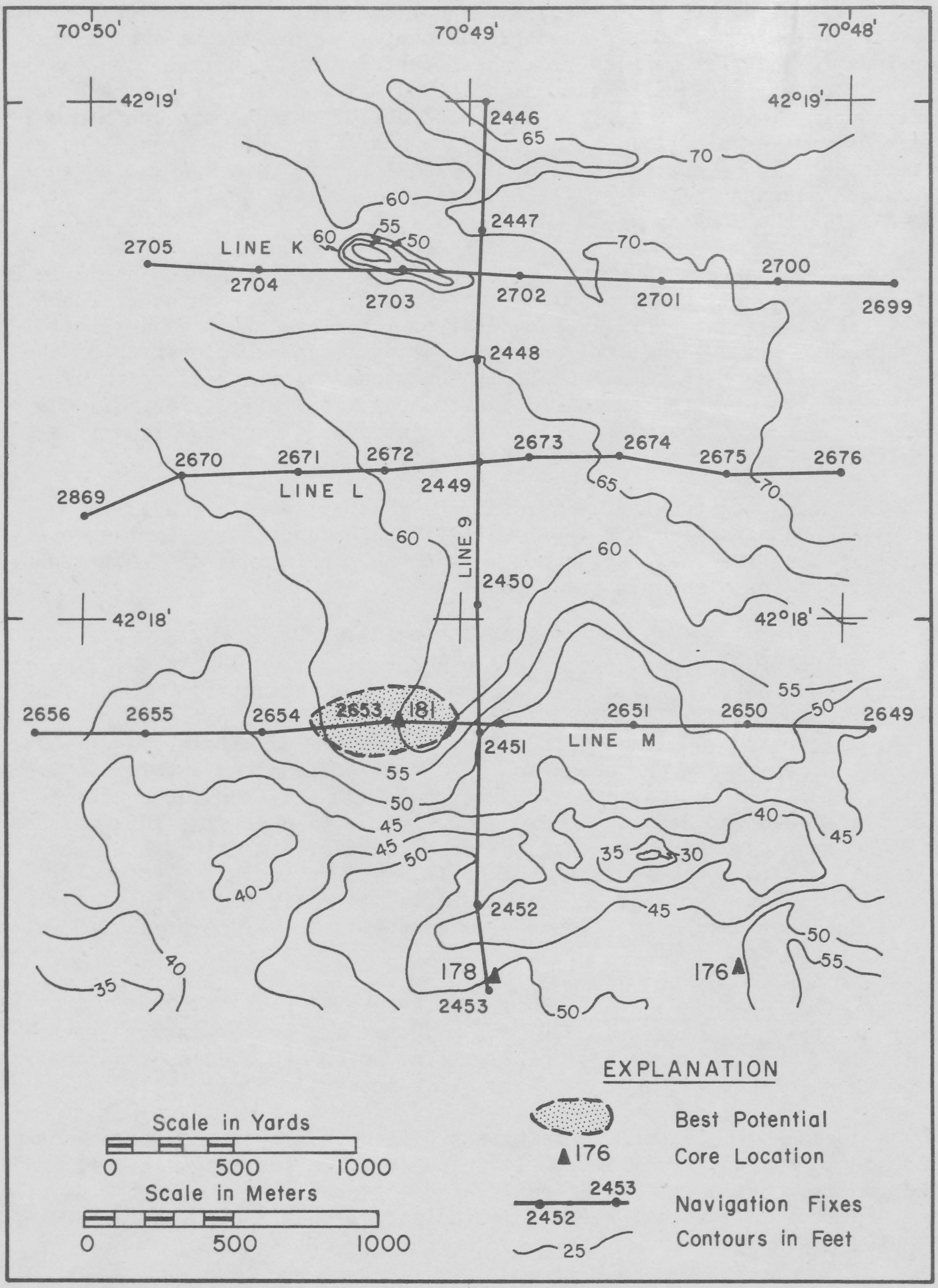


Figure 21. Bottom topography near Nantasket Center sand deposit. Note general lack of topographic expression in the site area.

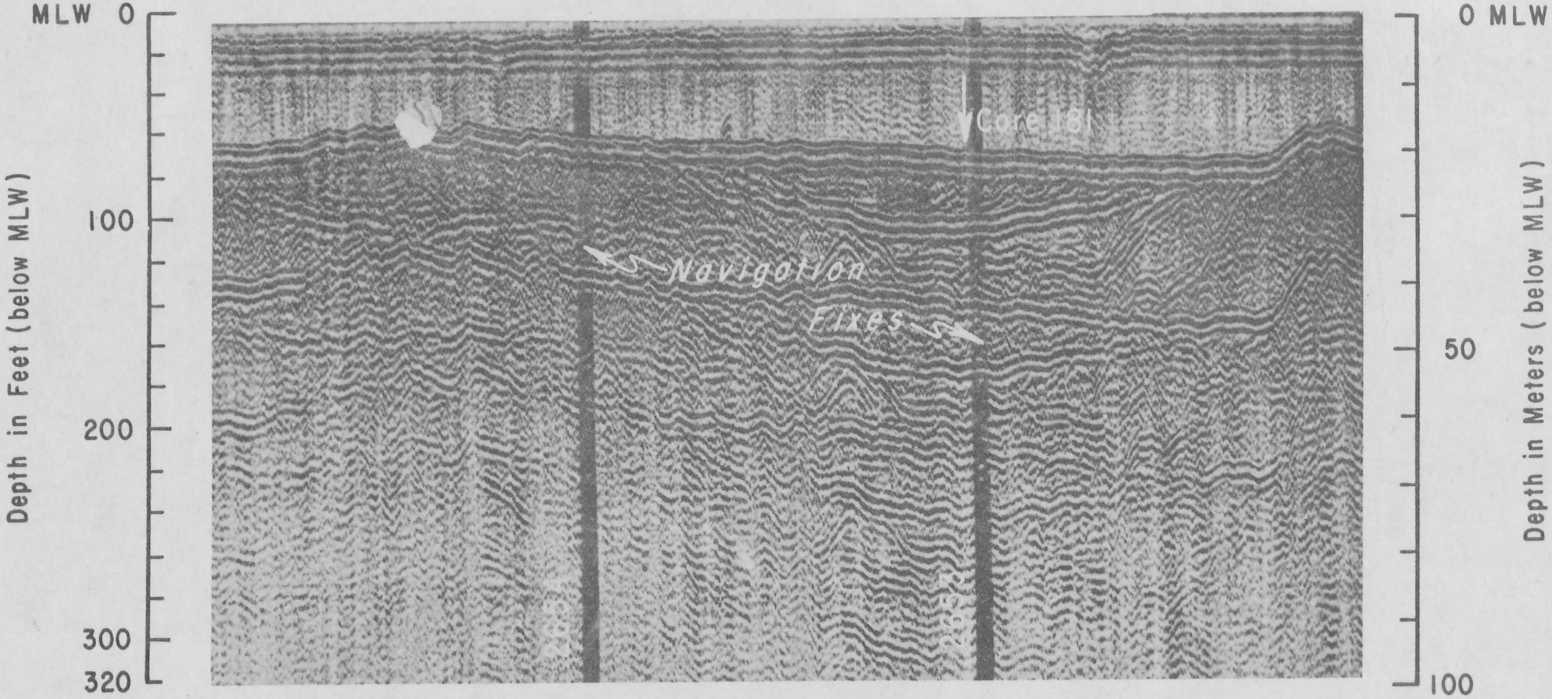


Figure 22. Section of seismic reflection profile crossing the Nantasket Center sand deposit. Navigation fixes are plotted in Figure 20. Note outcrop of acoustic basement east of site.

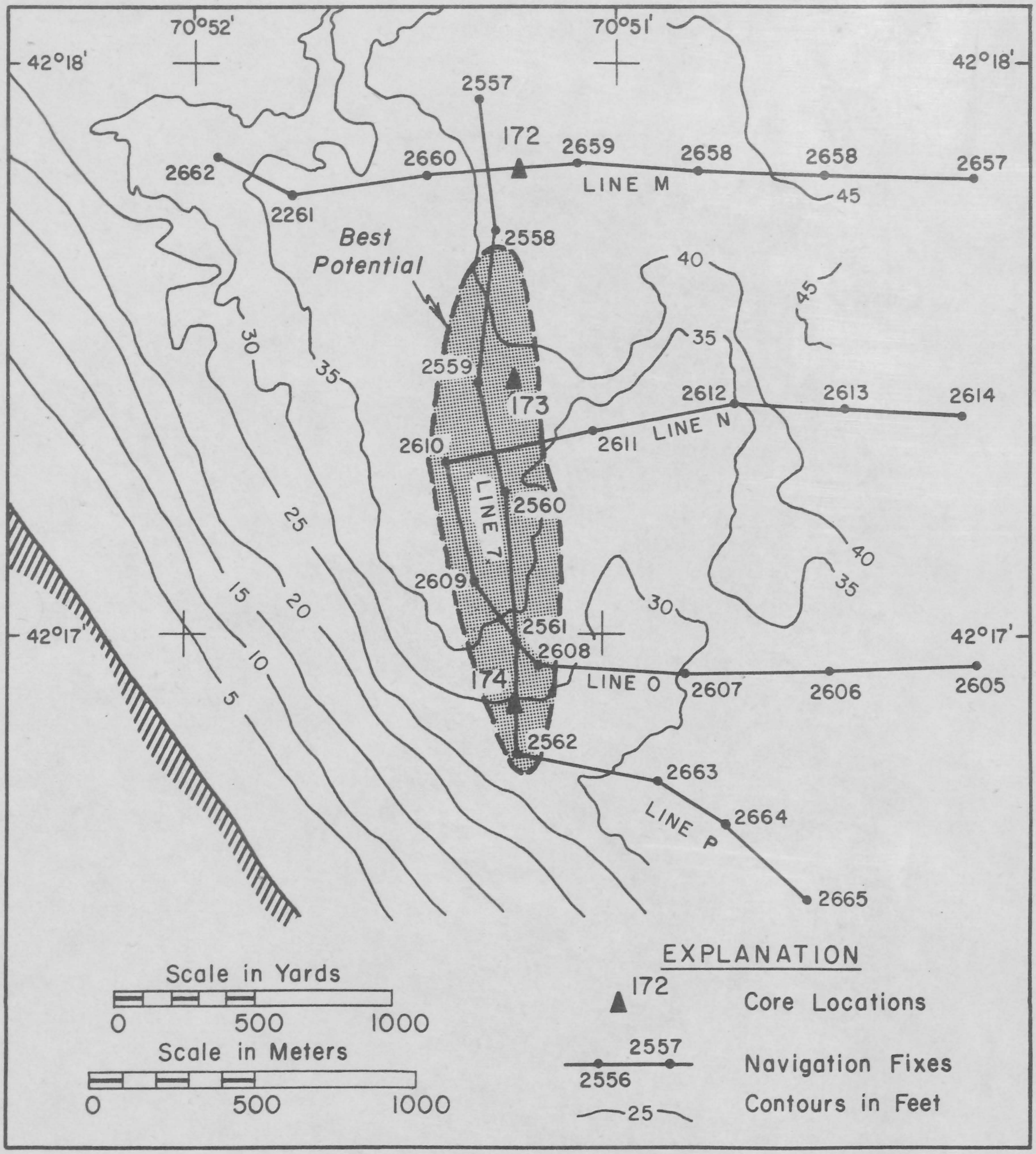


Figure 23. Bottom topography near Nantasket West and deposit. Note shoreface area to west and south.

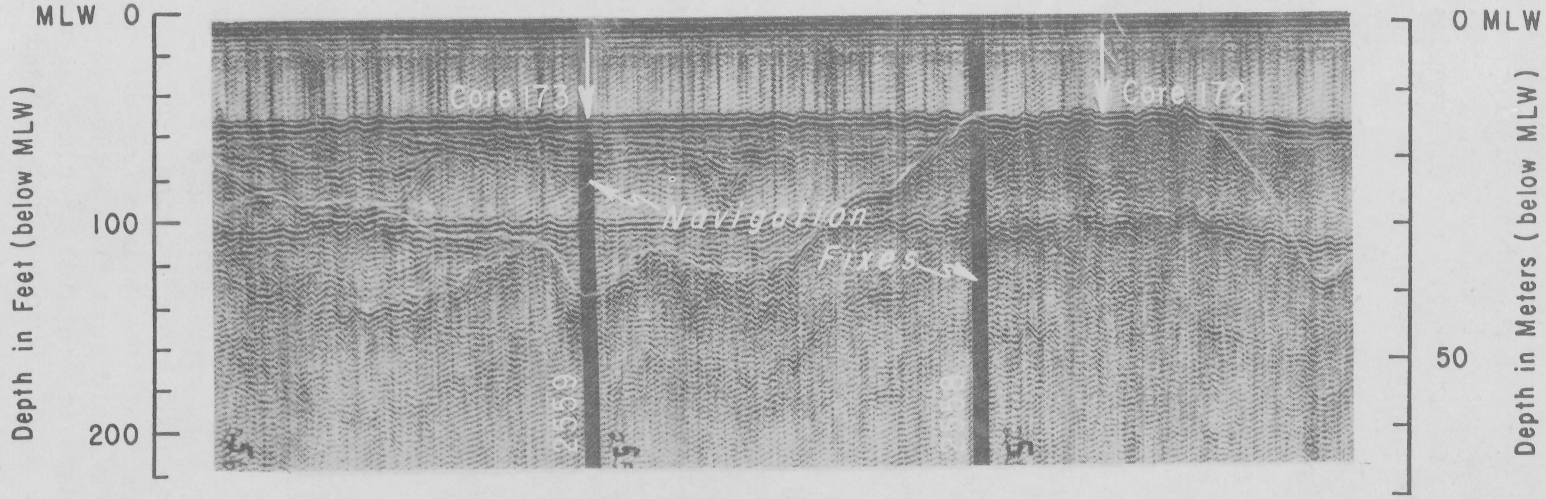


Figure 24. Section of seismic reflection profile crossing the Nantasket West sand deposit. Navigation fixes are plotted in Figure 22.

the south, core 174 from the area of the presumed high-angle bedding penetrated 9 feet (2.7 meters) into clean, coarse, gravelly sand containing some pebble and cobble-size material. The differences in sand texture of the two cores indicate that this deposit may be highly variable in sand grain size.

It is estimated that this elongate deposit covers an area of 650,000 square yards. The erosion surface separating the lower and upper reflection subunits is very irregular; the upper subunit averages about 15 feet (4.6 meters) in thickness. Assuming the entire upper reflection facies is composed of sand, the volume available is 1.95 X 10^6 cubic yards..

(6) New Inlet. The New Inlet site is centered at 42°10.1'N., 70°41.5'W. about 1 nautical mile (1.85 kilometers) off New Inlet (Fig. 25), and lies in a section of relatively level bottom in 45 to 50 feet (13.7 to 15.2 meters) of water. The single seismic reflection profile crossing the site shows that the sand is part of the fill from what appears to be an ancestral stream channel (Fig. 26). Cores 192 and 193 recovered clean, medium quartz sand from this site. The composite mean diameter of cored material is 1.88 phi (0.272 millimeter); the estimated phi sorting is 0.89.

If the drowned channel is an ancient extension of North River and the deposit is continuous between the line and New Inlet, the area of deposit would be approximately 840 X 10^3 square yards. Using a minimum thickness verified by cores of 10 feet (3 meters), the volume of sand available would be 2.80 X 10^6 cubic yards. If the entire channel is filled with similar sand, the volume would be 14 X 10^6 cubic yards.

Since the deposit (if it is an ancient stream channel) extends for some indeterminate distance seaward, the potential reserve of sand may be much larger than estimated.

(7) Project NOMES Site. The site selected for project NOMES is centered at approximately 42°20.7'N., 70°47.7'W. about 12 nautical miles (22 kilometers) east of Deer Island (Fig. 14) in water depths of 70 to 105 feet (21.3 to 32 meters). The detailed geology of this site was reported by Setlow (1973). The locale studied is a square area 14,000 feet (4,267 meters) on a side. The deposit, which was to be the site of a dredging experiment, measures about 12,000 by 7,000 feet (3,658 by 2,134 meters) at the surface and trends north-northwest (Setlow, 1973).

The deposit is expressed topographically as a flat-topped platform, and contains mostly poorly sorted, gravelly sand, and sandy gravel (Fig. 27). Maps of the deposit at the surface (-5 and -10 feet) are shown in Figures 28, 29, and 30. Measurements from Setlow (1973) show that in the 10-foot thickness, the deposit contains a volume of approximately 19.5 X 10^6 cubic yards (14.9 X 10^6 cubic meters) of sand and gravel.

VI. SUMMARY

Survey data consisting of 242 statute miles of seismic reflection profiles and 43 sediment cores were collected under the ICONS program

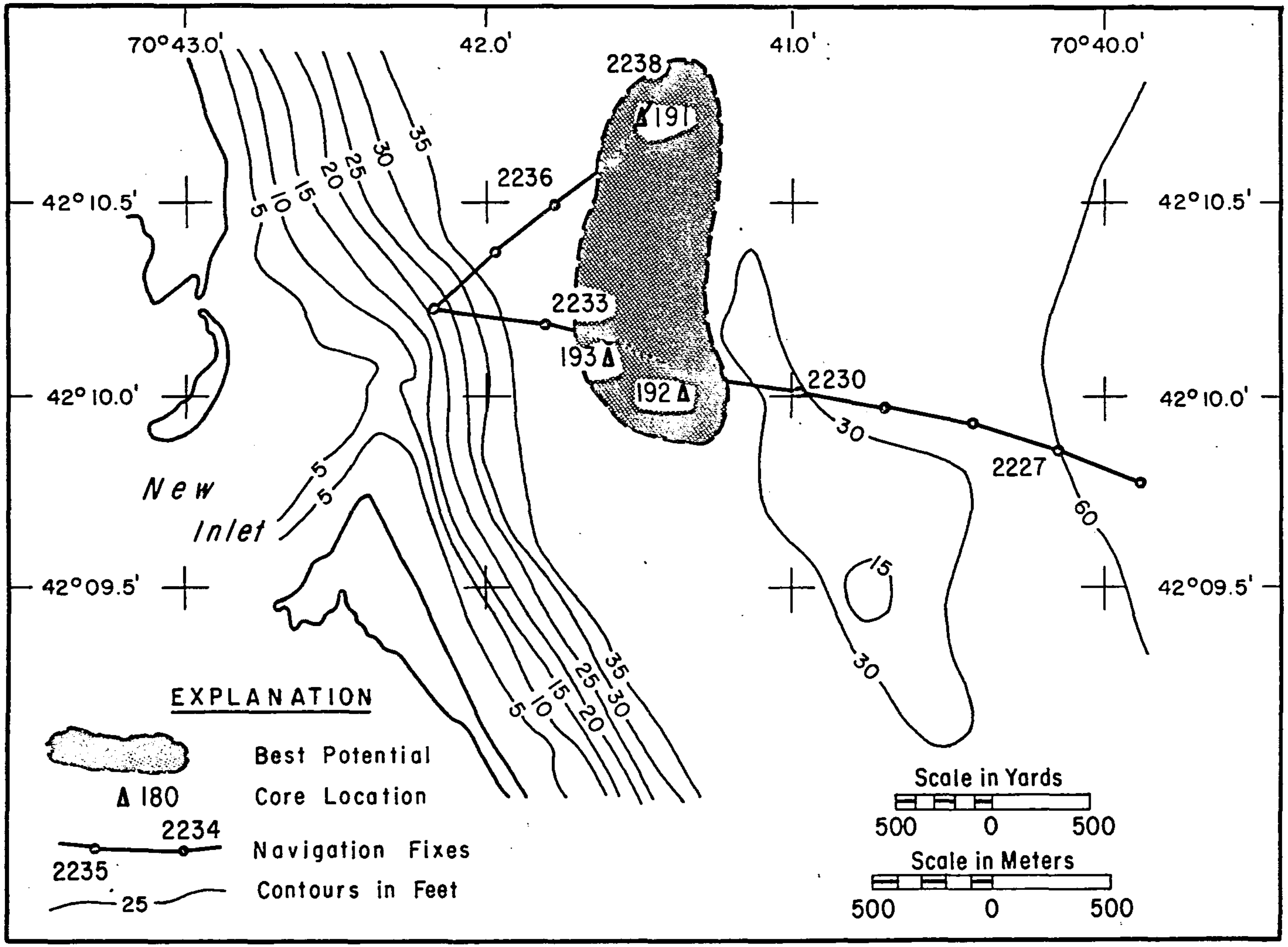


Figure 25. Section of seismic reflection profile crossing the Nantasket West sand deposit. Navigation fixes are plotted in Figure 23. Note high-angle interval reflectors near core 174.

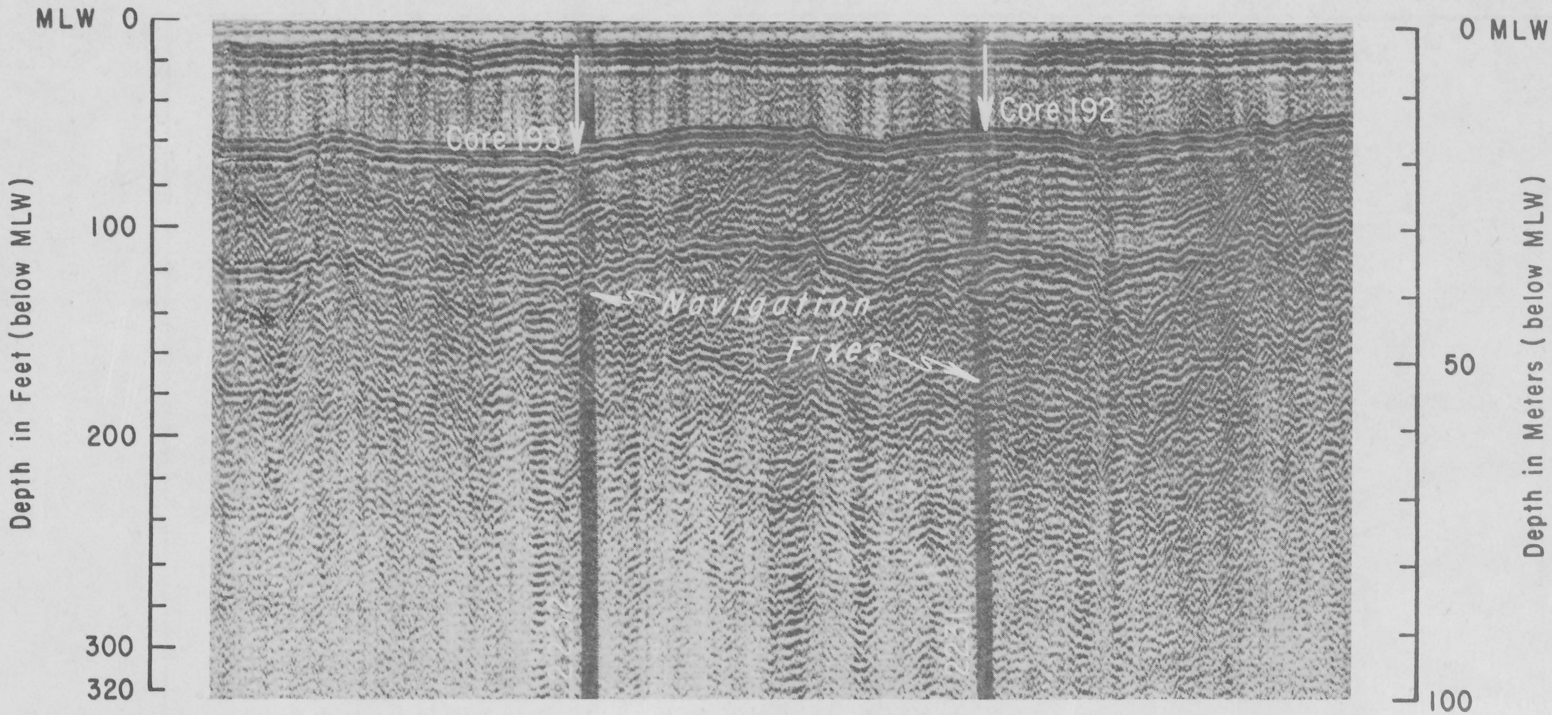


Figure 26. Section of seismic reflection (record) crossing the New Inlet sand deposit. Navigation fixes are plotted on Figure 25. Note channellike depression which holds the deposit.

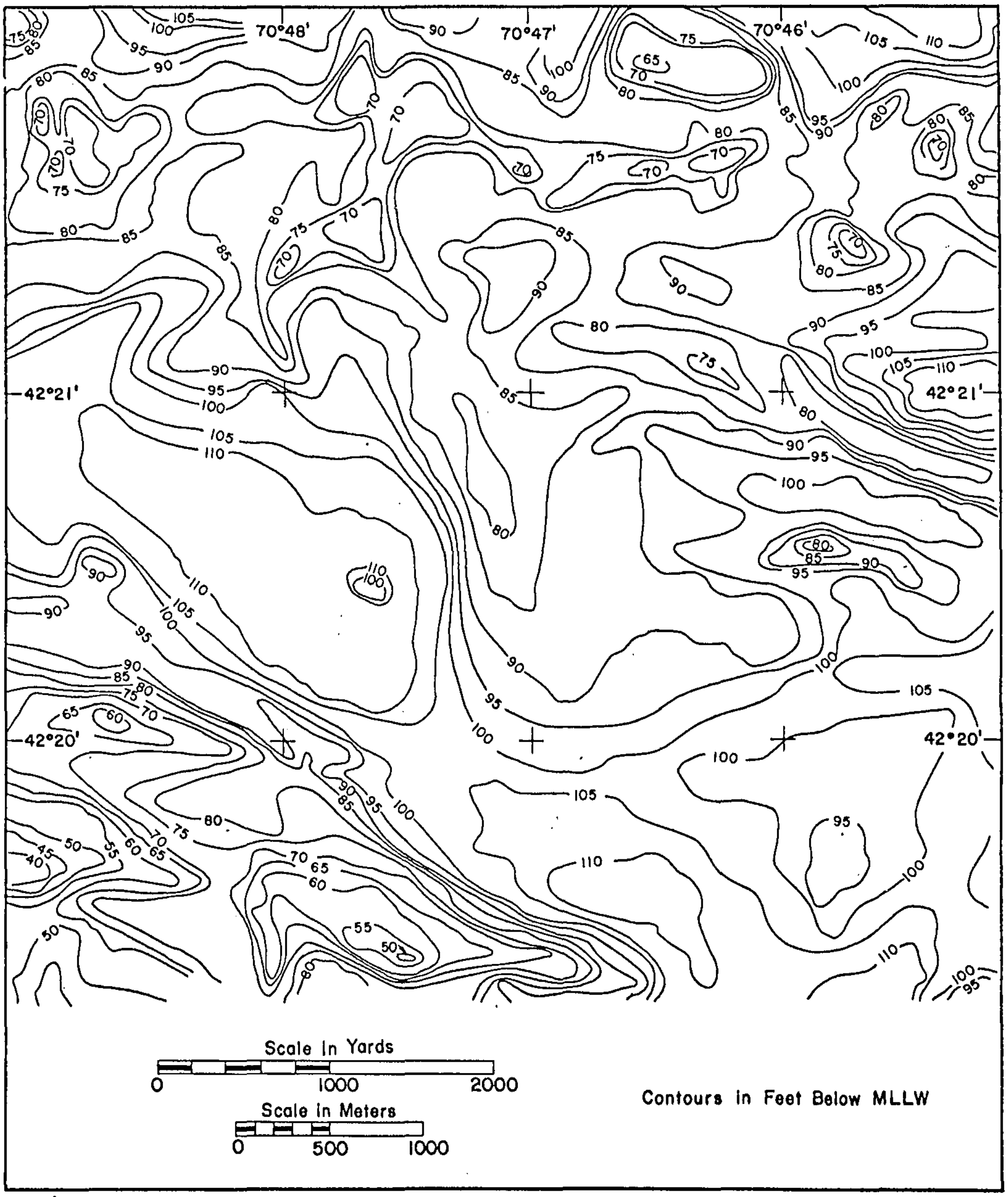


Figure 27. Bottom topography in the project NOMES site.

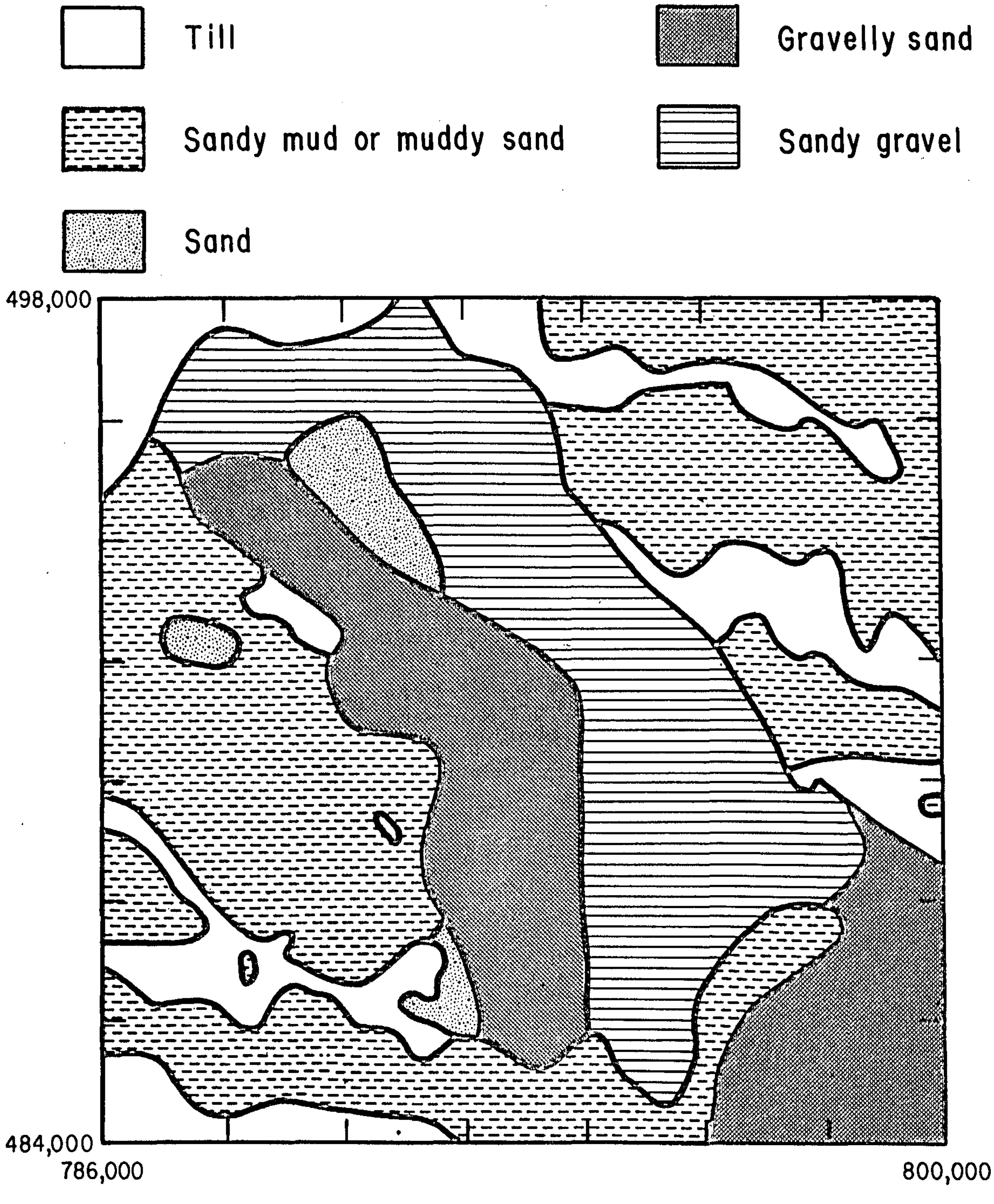


Figure 28. Sediment distribution at the bottom-water interface, project NOMES site (Setlow, 1973). Note small amount of sand compared to gravelly sediments.

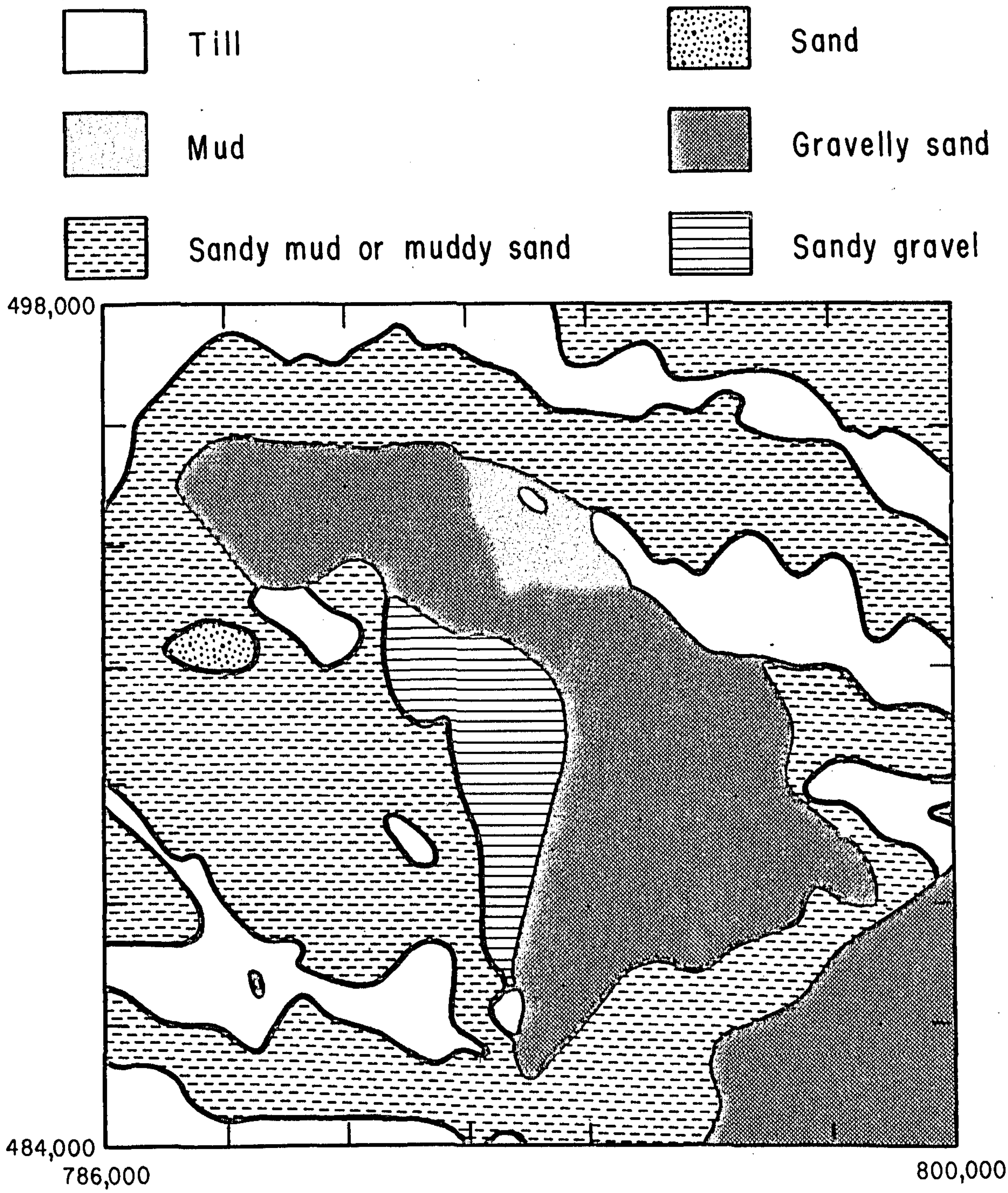


Figure 29. Sediment distribution in the prime NOMES site at a depth of 5 feet below the sea floor.

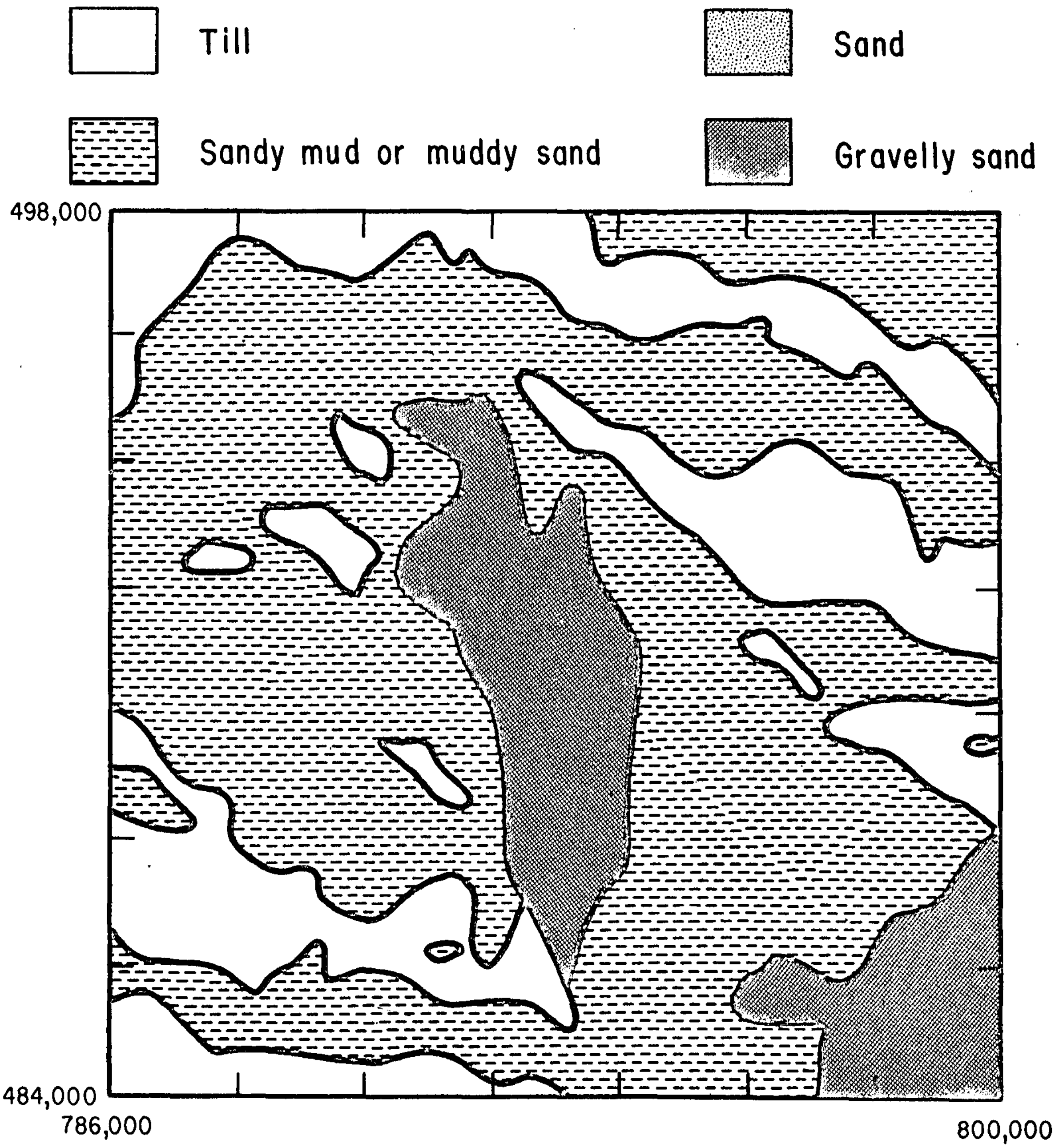


Figure 30. Sediment distribution in the prime NOMES site at a depth of 10 feet below the sea floor.

for study of the bottom morphology, sediments, and shallow structure of western Massachusetts Bay. These data were supplemented by NOS hydrographic smooth sheets and published scientific and technical literature.

Massachusetts Bay is a drowned glacial terrain characterized by large areas of near-level bottom interspersed with sharply irregular hills and ridges. It is bordered to the west by a bold rocky coast with sections of sandy beach and spits.

Two distinctive acoustic units appear in seismic reflection profiles of the study area. One is characterized by its acoustic impenetrability and is believed to represent basement rock and till. The second acoustic unit is characterized by relative acoustic transparency and internal reflections suggesting a stratified material. In most places the transparent unit is comprised of greenish-gray silt-clay or sand deposits.

The general contour of the acoustically impenetrable reflection unit suggests a surface topography initially formed by stream erosion and later disrupted by glacial erosion and till deposits. The greenish-gray silt-clay deposits are confined to lows in this topography.

Rocks and sediments underlying Massachusetts Bay range from early Paleozoic to Holocene age and include extensive deposits of glacial, glaciofluvial, and glaciomarine sediment. Sediment character and distribution in the study area are complex. The chief sediment types are: (a) sand ranging in size from very fine to coarse but generally in the fine to medium category; (b) clean, gravelly sand and sandy gravel; (c) mixtures of silt, sand, and gravel; (d) compact greenish-gray silt-clay; and (e) brown, sandy clayey silt.

Most sediments in the offshore area are judged to be relict. Active deposition of modern sediments is taking place in the nearshore area and fine silty sediments are accreting at a slow rate in some offshore areas. However, in most places the sediments have not yet buried the relict deposits.

Six sites, scattered throughout the study area, contain sand potentially suitable for beach restoration. An estimated total of 7.75×10^6 cubic yards of sand is distributed at the following sites:

(a) Cat Island (1.12×10^6 cubic yards)

(b) Nahant (0.78×10^6 cubic yards)

(c) Nantasket East (0.68×10^6 cubic yards)

(d) Nantasket Center (0.42×10^6 cubic yards)

(e) Nantasket West (1.95×10^6 cubic yards)

(f) New Inlet (2.8×10^6 cubic yards)

In addition, 19.5 X 10^6 cubic yards of sand and gravel have been delineated in the project NOMES site.

The complex geology and sediment distribution in this area indicate that any specific engineering use, e.g., sand resources, channel dredging, laying of pipelines, or foundations for offshore structures, will require a more detailed exploration of the specific project site than made in this study.

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APPENDIX A

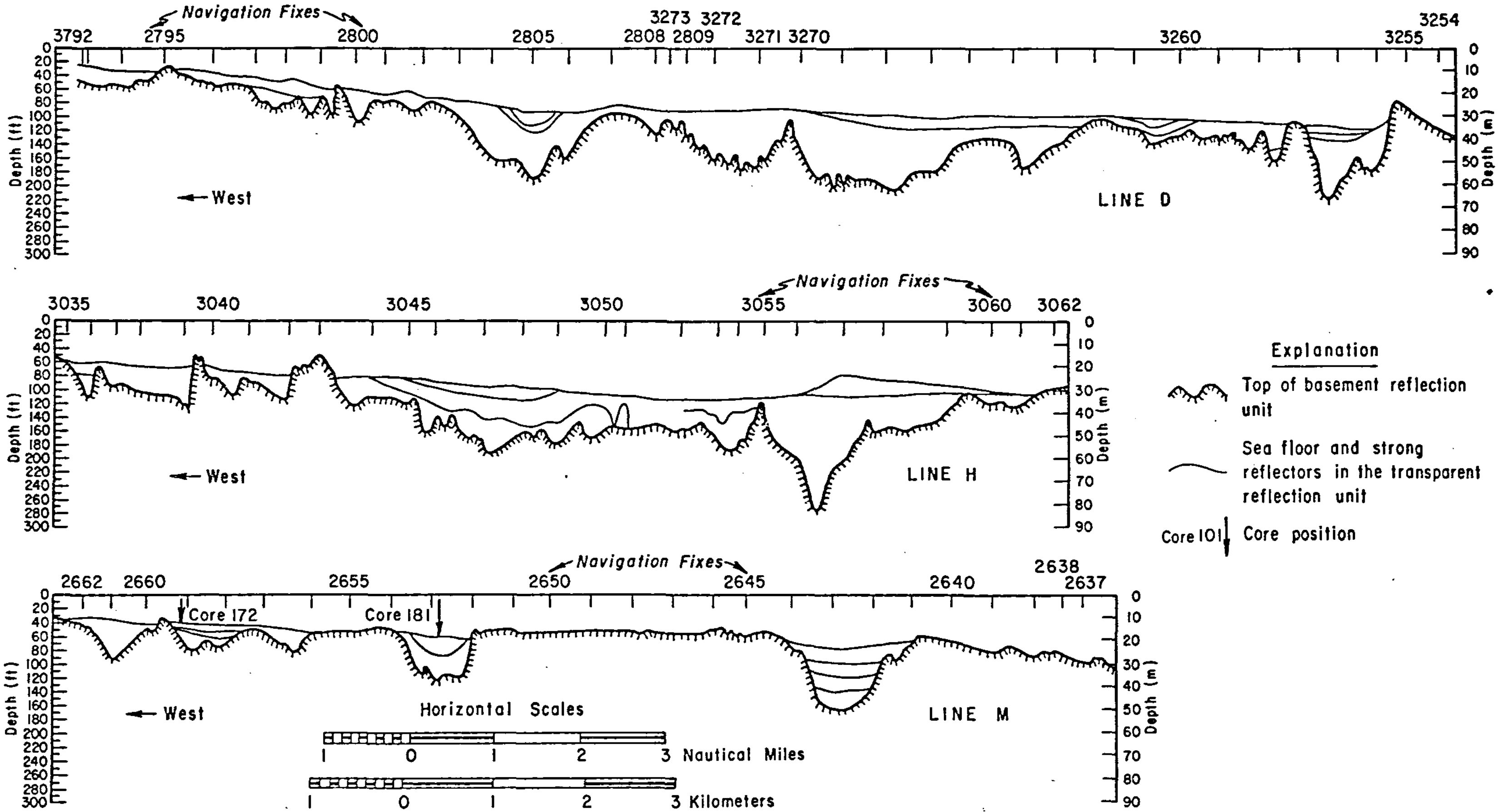
SELECTED GEOPHYSICAL PROFILES

Appendix A contains line profile drawings of selected seismic reflection records from the study area.

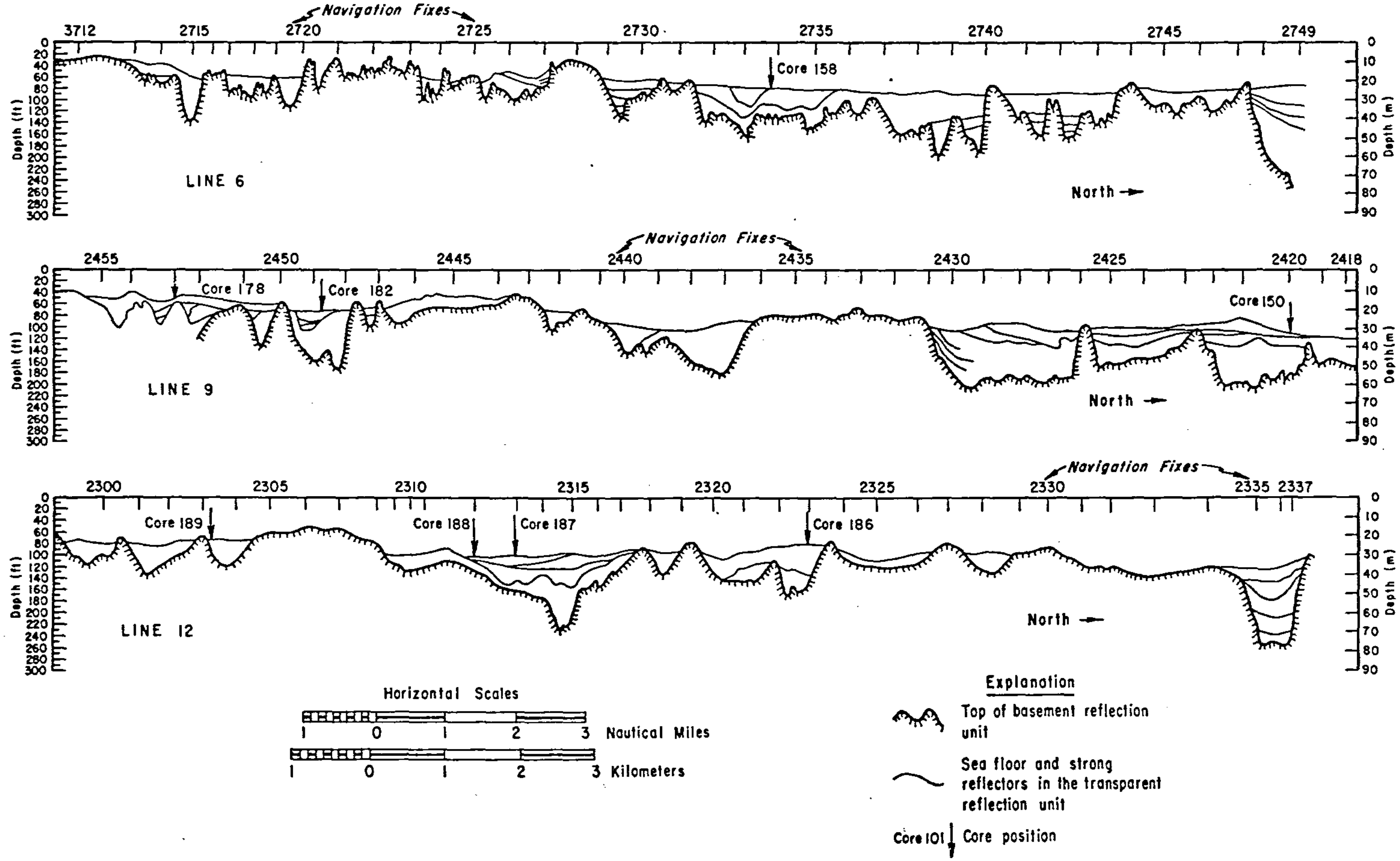
Fix numbers are plotted along the upper margin of the profile.

All depths are in feet below mean sea level (MSL), and based on an assumed sound velocity of 4,800 feet per second in water and 5,440 feet per second in the subbottom.

Position of lines and fixes are plotted on Figure 2.



Navigation Fixes
3792 2795 2800 2805 2808 2809 3273 3272 3271 3270 3260 3255 3254
Depth (ft)
Depth (m)
West
LINE D
Navigation Fixes
3035 3040 3045 3050 3055 3060 3062
West
LINE H
Explanation
Top of basement reflection unit
Sea floor and strong reflectors in the transparent reflection unit
Core 101
Core position
Navigation Fixes
2662 2660 2655 2650 2645 2640 2638 2637
Core 172
Core 181
West
LINE M
Horizontal Scales
1 0 1 2 3 Nautical Miles
1 0 1 2 3 Kilometers



Navigation Fixes
3712
2715
2720
2725
2730
2735
2740
2745
2749
Core 158
Depth (ft)
Depth (m)
LINE 6
North
2455
2450
2445
2440
2435
2430
2425
2420
2418
Core 178
Core 182
Core 150
LINE 9
2300
2305
2310
2315
2320
2325
2330
2335
2337
Core 189
Core 188
Core 187
Core 186
LINE 12
Horizontal Scales
1 0 1 2 3 Nautical Miles
1 0 1 2 3 Kilometers
Explanation
Top of basement reflection unit
Sea floor and strong reflectors in the transparent reflection unit
Core 101
Core position

APPENDIX B

GRANULOMETRIC DATA

SEDIMENT SAMPLE DATA

Core no.	Interval (ft)	Description	Median (mm)	Median (phi)	Mean (mm)	Mean (phi)	Standard Deviation (mm)	Standard Deviation (phi)
151	Top	fine sand						
	-1.5	fine sand						
	-5.0	fine sand						
	-9.0	fine sand						
	-11.5	fine sand						
	-14.0	fine sand						
152	Top	fine sand						
	-1.5	fine sand						
	-4.5	fine sand						
	-6.0	fine sand						
	-7.0	fine sand and shells	0.173	2.53	0.183	2.45	1.59	0.67
	-9.0	fine sand and shells	0.142	2.82	0.157	2.67	1.55	0.63
	-12.0	sandy silt						
	-13.5	medium sand	0.420	1.25	0.387	1.37	1.72	0.78
	-14.0	peat						
	-14.6	medium sand	0.361	1.47	0.366	1.45	1.07	2.10
	-15.0	fine sand	0.129	2.95	0.158	2.66	1.73	0.79
153	Top	fine sand	0.163	2.62	0.168	2.57	1.40	0.48
	-1.5	fine sand	0.159	2.65	0.159	2.65	1.35	0.43
	-2.0	fine sand						
	-4.0	fine sand						
	-5.0	fine sand	0.135	2.89	0.133	2.91	1.34	0.42
	-6.0	silty fine sand						
	-8.0	sandy silt						
	-9.0	sandy silt						
	-11.0	silty clay						
	-15.0	silty clay						
154	Top	medium sand	0.323	1.63	0.310	1.69	1.40	0.49
	-1.0	medium sand	0.310	1.69	0.299	1.74	1.53	0.61
	-2.0	medium sand	0.344	1.54	0.323	1.63	1.64	0.71
	-4.0	medium sand	0.275	1.86	0.274	1.87	1.40	0.48
	-7.0	medium sand						
	-9.0	fine sand						
	-12.0	silty fine sand						
	-13.5	silty clay						
155	Top	coarse sand and gravel						
	-3.0	coarse sand and gravel	0.599	0.74	0.551	0.86	1.66	0.73
	-4.0	coarse sand and gravel	0.578	0.79	0.599	0.74	1.93	0.95
	-6.0	medium sand	0.295	1.76	0.293	1.77	1.44	0.53
	-7.0	medium sand	0.312	1.68	0.301	1.73	1.40	0.48
	-8.0	coarse sand and gravel						
	-12.0	coarse sand and gravel	0.796	0.33	0.732	0.45	1.61	0.69
	-13.0	coarse sand and gravel	0.697	0.52	0.629	0.67	1.76	0.81
	-14.0	coarse sand and gravel	0.441	1.18	0.390	1.36	1.64	0.72
156	Top	silt						
	-1.0	silt						
	-5.0	silty clay						
	-8.0	silty clay						
157	Top	silt						
	-1.0	coarse sand and gravel						
	-2.0	coarse sand and gravel						
	-2.5	coarse sand and gravel						
	-3.0	medium sand	0.387	1.37	0.321	1.64	1.50	0.58
	-4.0	medium sand	0.366	1.45	0.344	1.54	1.42	0.51
	-5.5	medium sand	0.349	1.56	0.328	1.61	1.43	0.52
158	Top	silt						
	-1.0	clayey silt						
	-4.0	clayey silt						
	-5.0	clayey silt						
	-7.0	clayey silt						
	-9.0	clayey silt						
	-13.0	clayey silt						
159	Top	fine sand and shells	0.154	2.70	0.170	2.56	1.82	0.86
	-1.0	fine sand and shells						
	-5.0	silty clay						
	-6.0	silty clay						
	-7.0	silty clay						
	-8.0	silty clay						
	-15.0	silty clay						
160	Top	fine sand						
	-1.0	fine silty sand						
	-2.0	fine sand						
	-4.0	silt						
	-6.0	silt						
	-7.0	silty clay						
	-11.0	silty clay						
	-12.9	silty clay						

SEDIMENT SAMPLE DATA—Continued

Core no.	Interval	Description	Median		Mean		Standard deviation	
	(ft)		(mm)	(phi)	(mm)	(phi)	(mm)	(phi)
161	Top	fine sand and gravel	0.129	2.95	0.168	2.57	2.10	1.06
	-1.0	fine sand and gravel						
	-2.0	very fine sand						
	-4.0	very fine sand	0.101	3.31	0.130	2.94	1.72	0.78
	-6.0	very fine sand	0.115	3.12	0.141	2.83	1.85	0.89
	-9.0	very fine sand						
	-11.0	clay						
	-14.7	clay						
162	Top	fine sand and shells	0.176	2.51	0.179	2.48	1.78	0.83
	-1.5	silty clay						
	-7.0	silty clay						
	-10.5	silty clay						
	-13.0	silty clay						
163	Top	coarse sand and gravel	0.807	0.31	0.774	0.37	2.11	1.08
	-1.0	coarse sand and gravel						
	-2.0	silty clay						
	-3.0	silty clay						
	-6.0	silty clay						
164	Top	coarse sand and gravel						
	-1.0	coarse sand and gravel						
	-3.0	silt and gravel						
	-4.0	silt and gravel						
165	Top	silty clay						
	-6.0	silty clay						
	-8.0	silty clay						
	-11.0	silty clay						
	-16.0	silty clay						
166	Top	sand, shells, and gravel						
	-3.2	silty gravel						
167	Top	silty fine sand						
	-1.0	silty fine sand						
	-3.0	silty fine sand						
	-5.0	silty fine sand						
	-7.0	fine sand and gravel						
168								
169	Top	medium sand	0.435	1.20	0.382	1.39	1.58	0.67
	-1.0	silt, sand and gravel						
	-2.0	medium sand	0.257	1.96	0.250	2.00	1.46	0.55
	-4.0	medium sand						
	-6.0	silt						
	-8.0	silt						
	-14.0	silty clay						
170	Top	fine sand	0.165	2.60	0.192	2.38	1.74	0.80
	-1.0	fine sand	0.156	2.68	0.160	2.64	1.43	0.52
	-1.5	fine sand	0.142	2.80	0.145	2.79	1.47	0.56
	-2.0	sand, shells, and gravel						
	-2.1	silt						
	-4.0	silt						
	-7.0	silt						
	-11.0	silt						
171	Top	fine sand	0.227	2.14	0.252	1.99	1.79	0.84
	-1.0	fine sand	0.210	2.25	0.207	2.27	1.39	0.47
	-3.0	fine sand						
	-6.0	fine sand	0.166	3.11	0.133	2.91	1.59	0.64
	-7.0	fine sand	0.135	2.89	0.137	2.87	1.47	0.56
	-7.8	clayey silt	0.152	2.72	0.179	2.48	1.79	0.84
172	Top	fine sand	0.207	2.27	0.222	2.17	1.60	0.68
	-1.0	fine sand	0.213	2.23	0.230	2.12	1.56	0.64
	-1.5	sand, shells, and gravel						
	-2.0	fine sand	0.179	2.48	0.188	2.41	1.42	0.51
	-3.0	fine sand	0.176	2.51	0.189	2.40	1.50	0.58
	-5.0	fine sand	0.160	2.64	0.167	2.58	1.38	0.46
	-7.0	fine sand	0.200	2.32	0.225	2.15	1.61	0.69
	-8.0	sand, shells, and gravel						
	-9.0	silt						
	-13.0	silt						
	-15.0	silt						
173	Top	fine sand	0.193	2.37	0.198	2.34	1.38	0.46
	-1.0	fine sand	0.210	2.25	0.216	2.21	1.59	0.63
	-1.5	fine sand						
	-4.0	fine sand						
	-8.0	fine sand						
	-9.0	fine sand	0.222	2.17	0.252	1.99	1.69	0.76
	-11.3	fine sand	0.227	2.14	0.259	1.95	1.68	0.75

Core no.	Interval (ft)	Description	Median (mm)	Median (phi)	Mean (mm)	Mean (phi)	Standard deviation (mm)	Standard deviation (phi)
174	Top	coarse sand and gravel						
	-1.0	coarse sand and gravel						
	-5.0	coarse sand and gravel						
	-8.0	coarse sand and gravel						
	-9.0	coarse sand and gravel						
175	Top	silty fine coarse sand						
	-1.5	silty clay						
	-3.0	silty clay						
	-9.0	silty clay						
	-15.9	silty clay						
176	Top	silt, shells, and gravel						
	-1.0	silt, shells, and gravel						
	-3.0	silt, shells, and gravel						
	-6.0	silt, shells, and gravel						
	-7.0	silt, shells, and gravel						
	-11.5	silty clay						
177	Top	medium sand						
	-1.0	silt						
	-4.0	silt						
	-7.0	silt						
	-10.0	silt						
	-13.0	silt						
	-15.0	silt						
178	Top	fine sand and gravel	0.274	1.87	0.261	1.97	1.33	0.41
	-3.0	fine sand	0.237	2.08	0.255	1.97	1.52	0.60
179	Top	silt, sand, and gravel						
	-1.0	silt						
	-2.0	silt						
	-3.0	silt						
180	Top	sand, shells, and gravel						
	-2.0	silt and gravel						
181	Top	medium sand	0.277	1.85	0.319	1.65	1.79	0.83
	-1.0	fine sand	0.221	2.18	0.245	2.03	1.78	0.83
	-2.0	fine sand						
	-3.0	fine sand						
	-4.0	fine sand						
	-7.0	fine sand						
182	Top	fine sand	0.192	2.38	0.200	2.32	1.44	0.53
	-1.0	fine sand	0.204	2.29	0.215	2.22	1.64	0.37
	-2.0	fine sand						
	-5.0	fine sand						
	-8.0	fine sand	0.206	2.28	0.218	2.20	1.46	0.55
	-9.0	medium sand	0.358	1.48	0.358	1.48	1.69	0.76
	-11.0	medium sand	0.283	1.82	0.272	1.88	1.66	0.73
	-14.0	medium sand						
183	Top	medium sand						
	-1.0	very fine sand						
	-2.5	very fine sand						
	-3.0	very fine sand						
	-4.0	very fine sand						
	-5.0	very fine sand						
184	Top	fine coarse sand						
	-1.0	fine coarse sand	0.578	0.79	0.503	0.99	2.10	1.07
	-1.5	fine sand						
	-2.0	fine sand	0.230	2.12	0.230	2.12	1.36	0.44
	-4.0	fine sand	0.199	2.33	0.200	2.32	1.45	0.54
	-5.0	fine sand						
	-6.0	fine sand						
	-7.0	silt						
	-8.0	silt						
	-9.0	fine sand						
	-11.0	fine sand						
	-13.0	fine sand						
185	Top	medium sand and gravel	0.342	1.55	0.310	1.69	1.43	0.52
	-1.0	medium sand and gravel	0.398	1.33	0.349	1.52	1.46	0.55
	-2.0	medium sand	0.409	1.29	0.379	1.40	1.37	0.45
	-4.0	fine sand	0.159	2.65	0.187	2.42	1.88	0.91
	-6.0	fine sand						
186	Top	silty medium sand						
	-2.0	silty sand and gravel						
	-3.0	silty sand and gravel						

Core no.	Interval (ft)	Description	Median (mm)	Median (phi)	Mean (mm)	Mean (phi)	Standard deviation (mm)	Standard deviation (phi)
187	Top	silt						
	-2.0	silt, sand, and gravel						
	-3.0	silt, sand, and gravel						
	-6.0	silt, sand, and gravel						
	-7.0	clayey silt						
	-9.0	clayey silt						
	-11.0	clayey silt						
188	Top	silty sand and gravel						
	-3.0	silty sand and gravel						
	-6.8	silty clay						
189	Top	silty clay						
	-7.0	silty clay						
	-14.0	silty clay						
190	Top	silty clay						
	-1.0	silty clay						
	-5.0	silty clay						
	-10.0	silty clay						
	-16.0	silty clay						
191	Top	sand and gravel						
	-2.0	sandy gravel						
	-3.5	silty clay						
192	Top	medium sand	0.301	1.73	0.299	1.74	1.32	0.40
	-1.0	medium sand	0.301	1.73	0.289	1.79	1.40	0.49
	-3.0	medium sand						
	-5.0	medium sand	0.285	1.81	0.283	1.82	1.34	0.42
	-10.0	medium sand	0.304	1.72	0.287	1.80	1.35	0.43
193	Top	medium sand	0.259	1.95	0.266	1.91	1.82	0.86
	-1.0	medium sand	0.423	1.24	0.460	1.12	2.60	1.38
	-2.0	medium sand	0.467	1.10	0.490	1.03	2.09	1.06
	-3.0	medium sand	0.312	1.68	0.287	1.80	1.40	0.48
	-4.0	medium sand	0.308	1.70	0.297	1.75	1.31	0.39
	-6.0	medium sand						
	-8.0	medium sand	0.555	0.85	0.551	0.86	1.71	0.77
	-9.0	medium sand	0.279	1.84	0.274	1.87	1.38	0.46
	-10.0	medium sand	0.473	1.08	0.460	1.12	1.49	0.57
	-11.0	medium sand	0.488	1.16	0.473	1.08	1.65	0.72
	-13.5	medium sand	0.441	1.18	0.454	1.14	1.50	0.58

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A seismic reflection survey and bottom sampling were conducted in western Massachusetts Bay to obtain data on bottom topography and sediments, subbottom structure and composition, and sand deposits suitable for beach restoration and nourishment. Primary data consisted of 242 miles of seismic reflection survey and 43 sediment cores.

1. Beach nourishment. 2. Geomorphology. 3. Marine sediments. 4. Seismic reflection. 5. Massachusetts Bay. I. Title.

TC203 .U581tp no. 76-3 627 .U581tp

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