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Western Gulf of Maine and the southeastern Massachusetts offshore area: sedimentary framework

By R. N. Oldale, Elazar Uchupi, and K. E. Prada

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Western Gulf of Maine and the Southeastern Massachusetts Offshore Area: Sedimentary Framework

By R. N. Oldale[1], Elazar Uchupi[2], and K. E. Prada[2]

Abstract

The sedimentary framework of the western Gulf of Maine and the southeastern Massachusetts offshore area has been interpreted from data obtained with a seismic profiler, supplemented where available, by information from geology on land and from samples offshore. A geologic map, generalized isopach maps, and a generalized contour map of the basement surface provide significant information relative to the framework. Four sedimentary units have been distinguished on the basis of seismic data and are inferred to be 1) coastal plain sediments of Late Cretaceous to early Pleistocene age, 2) moraine deposits of Pleistocene age, 3) glaciomarine and marine deposits of Pleistocene and Holocene age, and 4) glaciolacustrine deposits of late Pleistocene age. The distribution of the inferred coastal plain deposits delineates a drainage system whose streams are believed to have carved, out of the coastal plain and shelf strata, the Gulf of Maine and the cuesta beneath Georges Bank and the islands off southern New England. This erosion is believed to have taken place during late Tertiary or early Pleistocene time. The inferred moraine deposits overlie basement and the unconformity on the coastal plain deposits, and they define stages in the retreat of the last glacier in coastal New England. The acoustic unit assigned to the glaciomarine and marine deposits is believed to represent in part glacial rock flour carried into the marine environment by meltwater streams and in part silt and clay winnowed from the banks and ledges during the post-glacial rise in sea level. The inferred glaciolacustrine deposits are thought to have been deposited in Cape Cod Bay during the retreat of the last ice in that area.

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2. Woods Hole Oceanographic Institution

Contribution No. 2659 of the Woods Hole Oceanographic Institution.

Introduction

Continental shelves of northern latitudes are generally very irregular and characterized by a lowland along the coast, U-shaped troughts extending from shore to the shelf's edge, and a chain of banks along the outer edge of the shelf (Holtedahl, 1958). This type of shelf occurs off New England (fig. 1) and consists of the Gulf of

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Figure 1 near here.

Maine, a broad 90,700 km^2 lowland, and Georges Bank which separates the Gulf from the open ocean. Northeast and Great South Channels provide passageways from the Gulf of Maine to the Atlantic Ocean. Cape Cod Bay, Nantucket Sound, and Buzzards Bay make up smaller lowlands. The floor of the Gulf of Maine is extremely irregular, and is marked by deep basins, low swells, irregular ridges, and flat-topped banks and ledges (Uchupi, 1968). In an early study, Johnson (1925, p. 264-296) suggested that the Gulf of Maine was carved out of continental shelf strata by stream erosion. He further stated that the basins within the Gulf mark positions of former stream valleys, and that Northeast and Great South Channels were the water gaps of the two major drainage systems. The topographic highs within the Gulf were interpreted by him as subordinate cuestas within the lowland. He also believed that Georges Bank was a cuesta cut in Coastal Plain strata. The wide occurrence of glacial deposts in the Gulf of Maine, and the observation that the type of topography found off New England appears to be restricted to formerly glaciated coasts led Shepard and others (1934) to suggest that glacial erosion had played a significant role in the formation of the Gulf. Based on data obtained with a continuous seismic profiler Uchupi (1966) and Oldale and Uchupi (1970) suggested that the Gulf of Maine probably was formed by a combination of pre-glacial fluvial erosion and Pleistocene glacial erosion. Using data from these profiles Oldale and Uchupi (1970) were able to trace the pre-glacial fluvial system that eroded the Gulf of Maine. Interpretation of seismic profiles also suggests that some of the basins are underlain by steeply dipping strata which acoustically resemble known Triassic sedimentary rocks in the Gulf of Maine and the Bay of Fundy (Tagg and Uchupi, 1966; Uchupi, 1966). This interpretation led Oldale and Uchupi (1970) to speculate that the larger basins within the Gulf represent Triassic fault basins modified to their present shape by fluvial and glacial erosion.

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Figure 1.--Bathymetry of the continental margin off northeastern United States and Nova Scotia. The outlined area is the region studied during the present investigation. Bathymetry after Uchupi (1965).

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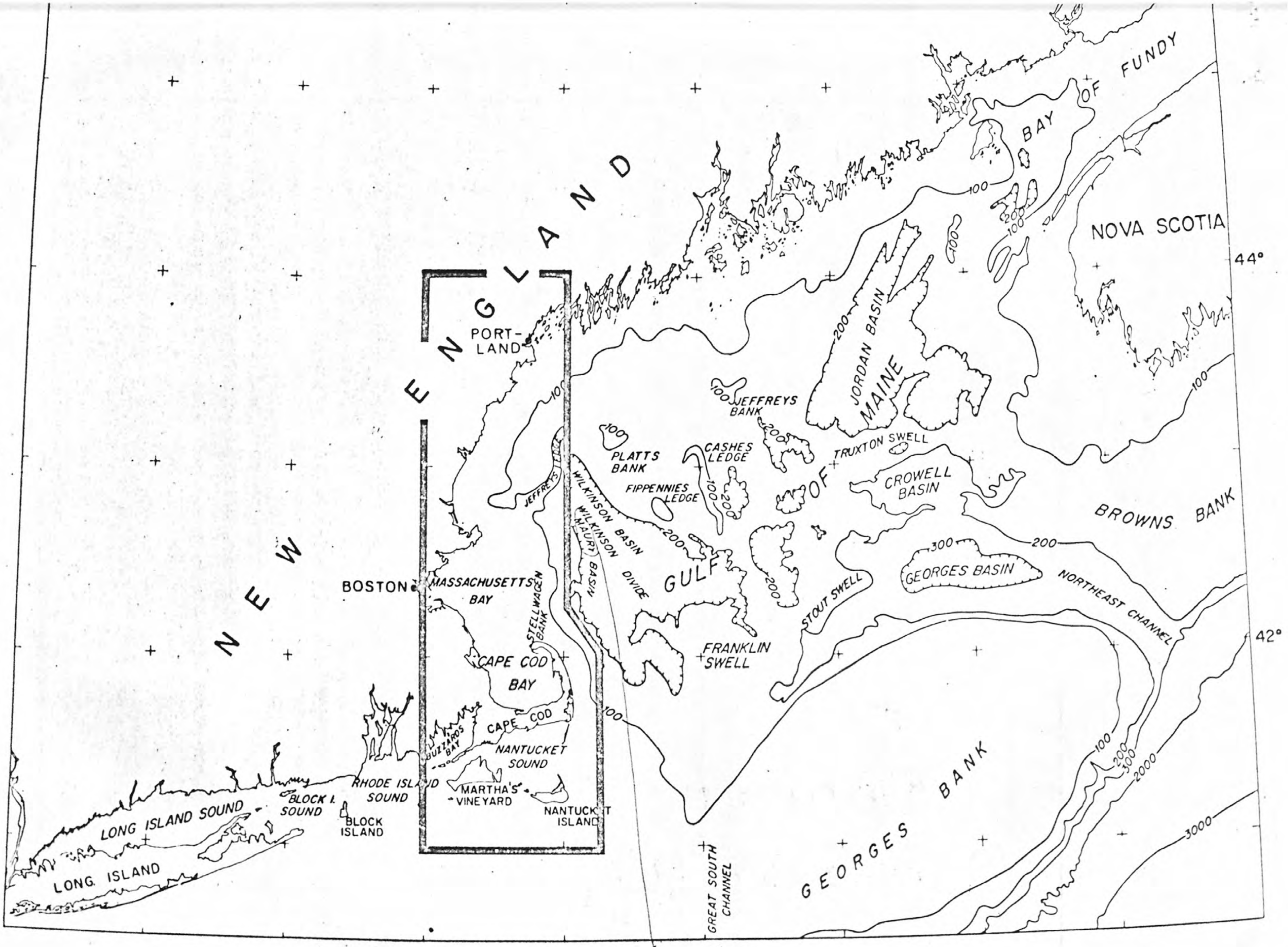
NEW ENGLAND
PORT-LAND
BOSTON
MASSACHUSETTS BAY
CAPE COD BAY
CAPE COD
BUZZARDS BAY
NANTUCKET SOUND
MARTHA'S VINEYARD
NANTUCKET ISLAND
RHODE ISLAND SOUND
BLOCK I. SOUND
BLOCK ISLAND
LONG ISLAND SOUND
LONG ISLAND
STELLWAGEN BANK
JEFFREYS LEDGE
WILKINSON BASIN
MURRAY BASIN
WILKINSON BASIN DIVIDE
PLATTS BANK
FIPPENNIES LEDGE
CASHES LEDGE
JEFFREYS BANK
JORDAN BASIN
GULF OF MAINE
TRUXTON SWELL
CROWELL BASIN
FRANKLIN SWELL
STOUT SWELL
GEORGES BASIN
NORTHEAST CHANNEL
BROWNS BANK
GEORGES BANK
GREAT SOUTH CHANNEL
BAY OF FUNDY
NOVA SCOTIA
44°
42°
100
200
300
2000
3000

Sr. Murray

Most of these earlier studies are based on widely spaced seismic profiler records, and consequently the sedimentary framework of the offshore area could be reconstructed only in the broadest sense. With completion of a reconnaissance survey of the Atlantic Continental Margin of the United States, the U.S. Geological Survey in cooperation with Woods Hole Oceanographic Institution began a more detailed geologic mapping program of the continental shelf. The first area chosen for more detailed study was the westernmost part of the Gulf of Maine (Figure 1). The large amount of seismic profiler data collected within this relatively small area has made possible the refinement of the reconstruction of the sedimentary framework of the central New England offshore area. Because the geologic formations that are segregated on the basis of their acoustical-reflection properties are mostly inaccessible to direct observation, the geologic interpretation of seismic profiles relies heavily on inference. Most of the unit identifications in this report, therefore, are referred to as "inferred". However, seismic surveys are the most expedient means of reconnoitering a marine area for structural and stratigraphic information, and they provide a basis for planning and carrying out more specific geologic investigations whose results may prove or disprove the inferences that were made from the seismic data.

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Methods of investigation

The main tool for defining the sedimentary framework of the western Gulf of Maine, Nantucket Sound, Vineyard Sound, and Buzzards Bay was a seismic profiler. The acoustic energy source was an air gun. A 5 cubic inch chamber was used during the R/V GOSNOLD cruise, and 10 cubic inch chamber during the R/V LULU cruise. During both cruises the gun was towed at a depth of 3 m and fired every 2 seconds. An operating pressure of 1800 psi was derived from a deck-mounted high-volume high-pressure diesel driven compressor system. Signals from the bottom and sub-bottom reflectors were received by a 30 m, 200-element streamer array towed approximately 60 m astern of the vessel at a depth of 4 m. A monolithic preamplifier with a 20 db gain was inserted at the head of the array. The preamplifier output impedence was suitable for driving up to 600 m of tow cable, while the 20 db provided signals greater in amplitude than any tow noise generated by the tow cable. A broad band monolithic amplifier with gain variable to 40 db amplified the received signal. This signal was then fed to suitable line drivers, filtered passively, and recorded on a graphic recorder. During the R/V GOSNOLD cruise the signals were filtered in the band 150 to 250 Hz and recorded on a precision graphic recorder. During the R/V LULU cruise, filter settings were generally 100 to 300 Hz and a graphic recorder designed by E.P. Curley was used. Recorders were set at a 0.5 second scan. The air gun was triggered every fourth scan and the first of the four scans was recorded. Navigation was by Loran A supplemented by radar and visual fixes. During the R/V GOSNOLD cruise, fixes were taken every 60 minutes, and every 20 minutes during the R/V LULU cruise. Ship's speed during both cruises was 11 km per hour.

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Interpretation of seismic profiles

Seismic profiles (Sheet 1) were interpreted visually by placing

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Sheet 1 In pocket; caption on next page.

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an acetate sheet over the records and tracing the individual reflectors with a grease pencil. These interpretations were then reduced visually to line drawings, and at the same time corrected for variations in ship speed. Inferences as to the geologic nature of the acoustic units were made generally on the basis of known geologic history on land, from acoustic signatures of known geologic units, and where possible from rock samples offshore. Generalized isopach maps of the sedimentary units inferred from seismic data, a total sediment thickness map, and a structure contour map of the basement surface were compiled by assuming velocities of 1.5 km/sec for water, 1.5 km/sec for the inferred late Pleistocene lacustrine and marine sediments and Holocene marine sediments, and 1.7 km/sec for the inferred glacial moraine and coastal plain sediments. Although velocity data for these units were not obtained during the present investigations, compressive velocities measured in the Gulf of Maine (Drake and others, 1954) and along the coast (Oldale, 1969) suggest that the assumed velocities are reasonable.

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Sheet 1.--Geologic interpretation of selected seismic profiles.

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Geology

Bathymetry:--The area of investigation is located along the western margin of the Gulf of Maine and southeastern Massachusetts enclosing within its boundaries that section of the sea floor between Long. $69^{\circ}40.5'$ and $71^{\circ}00'$ in the southern part and from Long. $70^{\circ}00'$ and $71^{\circ}00'$ in the northern part, and between Lat. $41^{\circ}10'$N to Lat. $43^{\circ}50.2'$ N. The most prominent topographic submarine features in this area are Jeffreys Ledge and Stellwagen Bank (Sheet 2). Both topographic highs

Sheet 2 In pocket; caption on next page.

diverge from Cape Ann and Stellwagen Bank extends almost to the northern tip of Cape Cod. Depths along their flat tops range from less than 40 m on Stellwagen Bank to less than 60 m along most of Jeffreys Ledge. Between the topographic highs on the seaward side is a wide delta-shaped platform that includes Tillies Basin and Tillies Bank. Tillies Basin has a complicated outline consisting of two narrow north trending depressions on the east, and a northwest trending one on the west. The eastern depressions are separated by Tillies Bank. The slope along Long. 70°W that forms the eastern side of this delta-shaped platform is deeply entrenched by gullies (Sheet 2).

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Sheet 2.--Bathymetry ~~and seismic-profile track~~.

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The sea floor between Jeffreys Ledge and the coast is quite irregular, and is marked by numerous highs and narrow depressions. South of Lat. 43°N the sea floor near the coast is much smoother, and most topographic irregularities are restricted to the area inside the 20 m contour. The smoothest area north of Cape Cod occurs within Cape Cod Bay with only the 10-meter-high Fishing Ledge disrupting the continuity of the sea floor. Topographic irregularities within Nantucket and Vineyard Sounds are due to shoals which are believed to be in part modified relict morainal ridges and sand ridges formed by longshore drift during the last rise in sea level (Smith, 1969). On the eastern side of Buzzards Bay and in the narrow tidal inlets in the Elizabeth Islands, much of the sea floor is irregular. (The scale of these irregularities, however, is too small to show on Sheet 2 where the contour interval is 20 m.) In other places the Bay's floor is somewhat smoother. With the exception of Nantucket and Vineyard Sounds the irregularity of the sea floor appears to be controlled in large part by the amount of sediment cover over the basement. In the area along the western side of Buzzards Bay and west of Jeffreys Ledge sediments are very thin or absent and the sea floor morphology reflects that of the basement. A somewhat thicker cover produced the more subdued topography on the sea floor west of Stellwagen Bank and in the area along the eastern side of Jeffreys Ledge and Stellwagen Bank. The relatively smooth topography of Cape Cod Bay, Jeffreys Ledge, and Stellwagen Bank is due to the great amount of sediment present in these areas.

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Basement:--The strong reflector at the base of the seismic profiler sequence has been traced in many places to within short distances of the shore where it crops out as crystalline and sedimentary rocks of pre-Cretaceous age (basement). With but few exceptions this reflector can be traced continuously throughout the area and everywhere it is inferred to represent the upper surface of the basement.

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Subbasement acoustic reflectors were observed east of Tillies Basin and Jeffreys Ledge (Sheet 1, Profiles 309 and 321). Based on their similarity to subbottom reflectors in areas of known Triassic sedimentary rocks in the eastern Gulf of Maine (Tagg and Uchupi, 1966; Uchupi, 1966), the basement in these areas is believed to be the same. This similarity appears to substantiate Oldale's and Uchupi's (1970) suggestion that the major basins in the Gulf of Maine are structural features formed during the Triassic. Another area where subbasement reflectors were observed is the east entrance to Nantucket Sound. These may also represent areas underlain by Triassic sedimentary rock, but the proximity to Carboniferous sedimentary rocks in the Narragansett and Boston Basins suggests that these rocks may be Carboniferous. However, an attempt to trace the Carboniferous sedimentary rock in the Boston Basin failed because subbasement reflectors were absent and the rocks could not be distinguished acoustically from the igneous and metamorphic rocks in the area. The seismic records show that the surface of the basement is generally more irregular where it forms the sea bottom or where overlain solely by glacial or post-glacial deposits than where overlain by sediments inferred to be coastal plain deposits. Thus, in general, the basement surface is more irregular north of Cape Ann, in Buzzards Bay, Cape Cod Bay and parts of Vineyard Sound where it was glaciated than beneath Jeffreys Ledge, Stellwagen Bank, and Nantucket Sound where it was protected from glacial erosion by coastal plain deposits. Differences in the roughness of the basement surface may also be due to differences in the rock units that comprise the basement.

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Inferred coastal plain deposits:--Basement is overlain in places by an acoustic unit characterized by well defined, flat, continuous internal reflectors and an irregularly undulating uppermost acoustic surface that in places truncates the internal reflectors (Sheet 1). The uppermost surface is inferred to be an unconformity underlain by coastal plain sediments of late Cretaceous to early Pleistocene age. The acoustic nature of this unit is similar to those on records from Fippennies Ledge (Uchupi, 1966), which is underlain by coastal plain deposits of Tertiary age (Schlee and Cheetham, 1967), and to those on seismic records on erosional remnants of Cretaceous age on the Scotian Shelf (King and others, 1970). Additional reasons for inferring that the acoustic unit represents coastal plain deposits include the fossiliferous boulders of Eocene age (Crosby, 1879), the silicified and carbonaceous wood of Tertiary age and glauconite in the drift of Cape Cod (Oldale, 1968); the erosional remnants of Miocene and Eocene sediments in Marshfield and Scituate, and on Nonomesset Island (Bowman, 1906; Emerson, 1917; Woodworth and Wiggleworth, 1934); and the coastal plain deposits of Miocene and late Cretaceous age beneath Martha's Vineyard and Georges Bank (Woodworth and Wigglesworth, 1934; Stetson, 1949; Gibson and others, 1968). It is possible that the acoustic unit inferred to be coastal plain may in part represent older glacial drifts. If so it is separated from the drift of the last ice by an unconformity eroded during an interglacial stage or substage. However, this seems unlikely as interglacial times are generally characterized by deposition on the coastal plain and shelf during high sea-level stands. The deposits of Aftonian age on Martha's Vineyard (Kaye, 1964) and fossil shells in the drift of Farmdalian age on outer Cape Cod (Oldale, 1968) indicate high stands of sea level during those interglacial times. The distribution of the coastal plain deposits (Sheet 3), as inferred from seismic data, indicates that they form the

Sheet 3 In pocket; caption next page.

core of the major bathymetric highs north of Cape Cod and underlie Nantucket Sound and the islands to the south. The isopach map (Sheet 3) delineates a drainage system that can be traced to the western edge of Murray Basin, the eastern and southern margins of Nantucket Sound, the mouth of Vineyard Sound, and the entrance of Buzzards Bay. The system draining from the vicinity of Cape Ann may represent seaward extensions of the rivers north of this Cape. The narrow depressions forming Tillies Basin appear to be remnants of this drainage system as are the gullies east of Stellwagen Bank. Other channels appear to have been formed of the drainage system out of Massachusetts Bay, and Cape Cod Bay. Several of these channels extend across Stellwagen Bank to connect with the gullies east of this bank. The drainage system appears to have been little affected by subsequent glaciation of the region. These channels are probably seaward extensions of the buried ones described from land by Upson and Spencer (1964). The valleys represent streams that probably carved the lowlands forming the Gulf of Maine, Nantucket and Vineyard Sounds, Buzzards Bay, the cuesta beneath Georges Bank, and the islands south of Massachusetts.

Sheet 3.--Reconnaissance isopach map of the inferred coastal plain deposits.

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Inferred moraine deposits:--A thick acoustically-defined unit occurs in many places above the erosion surface of late Tertiary or early Pleistocene age beneath and seaward of Jeffreys Ledge and Stellwagen Bank and in the areas east and south of Cape Cod. It locally overlies the basement surface (plate 4) nearer shore. The upper surface of

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Sheet 4 In pocket; caption next page.

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this unit is characterized by a non-systematic pattern of topographic highs and lows. Reflecting horizons within the unit are generally discontinuous and irregular in profile, and individual and grouped parabolic-shaped reflectors are common. The unit is generally thickest in channels cut in the deposits assigned to the Coastal Plain. This acoustic unit is inferred to be equivalent to the thick accumulations of glacial drift exposed above sea level on Cape Cod and the island south of Cape Cod. Although the term moraine is most often associated with deposits composed mostly of till (Flint, 1947, p. 126), it is used here to identify deposits generally associated with the close proximity of glacial ice including fluvial ice-contact and outwash deposits, proglacial deltaic deposits, and basal and superglacial till. The discontinuous and irregular reflectors; irregular upper surface; and parabolic reflectors, believed to be boulders or gravel, are thought to represent sediments deposited in the chaotic depositional environments associated with the close proximity of glacial ice. The unit probably represents deposits of more than one glaciation in a manner similar to the Pleistocene section on Martha's Vineyard, where deposits of all the major glacial stages are inferred to be present (Kaye, 1964).

Sheet 4.--Generalized surficial geologic map.

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Glaciomarine and marine deposits:--The uppermost seismic unit in the basins landward of Jeffreys Ledge and Stellwagen Bank, in topographic lows in the basement along the coast, and locally in lows in the inferred moraine and coastal plain deposits offshore (Sheet 4) is characterized by a relative acoustic transparency. As this characteristic best defines the unit it is here called the transparent layer. The unit can be penetrated by high frequency (3.5 to 12.0 kHz) as well as low frequency (105 to 300 Hz) subbottom profiling. Numerous internal reflectors can be seen in the transparent layer, and locally reflectors defining cut and fill and slump structures are present. In some places continuous internal reflectors are absent and the unit has a mottled appearance in the records. Generally the layer has a flat upper surface, but the thickness of the unit varies greatly because it is controlled in large part by the surface configuration of the material below it. Maximum thickness encountered during the survey was 100 m in Tillies Basin. Elsewhere, its thickness exceeds 30 to 40 meters in many places (Sheet 5). The uppermost part of the

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Sheet 5 In pocket; caption next page.

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sediments represented by this transparent layer have been extensively sampled and are known to consist of silt and clay of Holocene age. In Boston Harbor boreholes near 3.5 kHz subbottom profiles showed the upper part of the layer to be silt and clay of Holocene age and the lower part to be glaciomarine silt and clay of late Pleistocene age (R.H. Burroughs, oral comm. 1970). A similar correlation is inferred for the transparent layer offshore. The mottling in the records is inferred to represent local deposits of coarser grained material, perhaps sand and gravel, within the silt and clay. The silt and clay represented by the transparent layer thus has a complex origin. Initially most of the material consisted of glacial rock flour carried to the sea by meltwater streams and deposited in the basins. Later, as the rising Holocene ~~rise in~~ sea ~~level~~ submerged the banks and ledges, silt and clay were winnowed from glacial drift by wave action and carried into the basins by currents. Finally the upper part of the silt and clay deposit probably contains some material carried to the sea by modern streams.

Sheet 5.--Reconnaissance isopach map showing the combined thickness of the inferred moraine and late Pleistocene-Holocene deposits.

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No internal reflector within the transparent layer could clearly be inferred to be an unconformity between the glaciomarine and Holocene marine deposits. This suggests that in most places offshore deposition has been continuous since late-Pleistocene time.

Contact relationships between the late-Pleistocene to Holocene marine deposits and moraine deposits are complex. The moraine deposits represent in part subaerial facies of the glaciomarine deposits. Near the contacts between these units the sediments may grade from one to the other. Similarly the marine deposits of Holocene age, although stratigraphically younger, grade laterally into reworked glacial drift on the topographic high. Thus in many places a reflector representing the contact between these units was not present in the seismic records.

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Glaciolacustine deposits:--The upper acoustic unit that occurs in Cape Cod Bay and slightly north of the bay rests on basement in most places and locally on the acoustic units inferred to be remnants of coastal plain deposits or moraine deposits. A survey of Cape Cod Bay using a high resolution seismic profiler (Hoskins and Knott, 1961) showed the unit to be composed of two parts. The lower part has numerous horizontal internal reflectors and becomes thicker to the north. The upper part has fewer continuous internal reflectors and locally is characterized by internal parabolic reflectors. This upper part thickens toward the south. Hoskins and Knott (1961) inferred that the lower part represented coastal plain deposits of Tertiary age. The upper part was believed to be glacial drift of Pleistocene age and the parabolic reflectors boulders or gravel within the deposit. As no reflectors that might represent an unconformity were observed between the upper and lower part we have inferred that the acoustic unit represents, wholly, deposits of Pleistocene age, perhaps glaciolacustine sediments deposited in Cape Cod Bay during the retreat of the last ice.

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Total sediment thickness and basement structure:--Maps showing total sediment thickness and depth to basement, as determined from seismic data, are shown in sheets 6 and 7. Much of the area adjacent to the coast as far south as Plymouth consists of closely-spaced basement outcrops with a sediment thickness of less than 20 m in the lows between the outcrops. Seaward of this coastal zone and south of

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Sheets 6 and 7 in pocket; captions on next two pages

Plymouth the sediments gradually thicken and outcrops of the basement are absent. Maximum thickness occurs beneath Jeffreys Ledge, Stellwagen Bank, Cape Cod, Nantucket Sound and the islands farther south. Within these areas the greatest thickness occurs in narrow troughs. A well developed drainage system is defined by both maps, particularly south of Cape Ann. Many of these valleys appear to be offshore extensions of present day onland drainage systems such as the streams that drain Boston Harbor and the Merrimack River. Other submarine valleys like the ones off Plymouth and in Nantucket and Vineyard Sounds may be offshore extensions of onland preglacial river valleys now buried by glacial drift. As many of the valleys are wholly or in part filled with sediment inferred to be moraine, the drainage is thought to be pre-glacial. The streams carved the lowlands and cuestas out of the continental shelf strata. North of Cape Ann the seismic lines are far apart and only one major drainage system could be delineated.

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Sheet 6.--Reconnaissance isopach map of the total thickness of sedimentary material above basement.

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Sheet 7.--Reconnaissance contour map of the basement surface, showing inferred drainage.

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Geologic history

Based on seismic data obtained during the present study, supplemented by information available on land, the geologic history of the western Gulf of Maine, Cape Cod, Nantucket and Vineyard Sounds, Buzzards Bay, Nantucket and Martha's Vineyard can be summarized as follows. Up to Cretaceous time the history of the area may have been similar to that displayed by the onland geology. The sedimentary, tectonic, and erosion cycles that left their imprint on land should have also played a part in the formation of the basement presently offshore. During most of the Paleozoic and Early Mesozoic time New England was characterized by granitic intrusions and volcanic activity. During the Carboniferous Period narrow fault troughs that filled with continental deposits developed in some places. Boston Basin represents one such trough that extends offshore. A more extensive series of fault troughs that filled with continental sediments developed during the Triassic, and many of the larger basins in the Gulf of Maine are thought to be offshore equivalents of the Triassic basins on land.

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Late Cretaceous continental deposits on Martha's Vineyard (Woodworth and Wigglesworth, 1934) suggest that much of the area may have been above sea level during Late Cretaceous time. Meanwhile, marine deposition was taking place along the shelf's edge as attested by the presence of Late Cretaceous marine sediments in the submarine canyons south of Georges Bank (Stetson, 1949). In early Tertiary time the Gulf of Maine and the shelf to the west was submerged with the transgression reaching its peak during the Miocene as indicated by the Miocene glauconitic sediments along the coast south of Cape Ann (Bowman, 1906; Emerson, 1917). In late Tertiary or early Pleistocene time sea level dropped or the region was uplifted. Streams extended their courses across the shelf and carved a series of lowlands beneath Buzzards Bay, Vineyard and Nantucket Sounds, and the Gulf of Maine and they carved cuestas beneath the Elizabeth Islands, Marthas Vineyard, Nantucket, Stellwagen Bank, Jeffreys Ledge, and Georges Bank. Erosional remnants were left beneath the smaller banks within the Gulf of Maine. Great South and Northeast Channels were the water gaps of much of this drainage system.

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The glacial chronology of New England is not completely understood. Most workers recognize evidence for two glacial advances separated by an interglacial stage or substage (Schafer and Hartshorn, 1965). Others have suggested that all glacial stages are present in the region (Kaye, 1961 and 1964). Glacial stages within the deposits offshore cannot be recognized in the seismic data. It is possible that older drifts and interglacial deposits may make up a part of the sediments inferred to be coastal plain deposits. More probably they may occur as part of the sediment labeled as moraine deposits, in a manner similar to that described by Kaye (1964) for the Pleistocene section on Martha's Vineyard. Since such distinctions within the acoustic unit inferred to be moraine are not possible, the glacial history presented here describes events associated with the last glaciation of the area that occurred in Woodfordian time. Radiocarbon dates on material in the drift on outer Cape Cod (Zeigler, 1960, and Oldale, 1968) suggest that the last ice advanced into southeastern New England between 20,000 and 26,000 years ago. Fossil material, glauconite, and the paucity of feldspars in the drift (Oldale, 1968) also suggests that the ice overrode shelf sediments of Farmdalian Age as well as older glacial drifts and coastal plain sediments. The maximum advance of the ice was to Martha's Vineyard and Nantucket (Schafer and Hartshorn, 1965; Pratt and Schlee, 1969) where large terminal moraines were built by the Buzzards Bay, Cape Cod Bay and possibly the South Channel lobes. Retreat of the ice from this maximum position began sometime after 15,300±800 B.P. as shown by a radiocarbon

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date (Kaye, 1964) on leaves stratigraphically below till and outwash. Retreat of the lobes was not entirely synchronous. The Buzzards Bay lobe retreated somewhat faster than the Cape Cod Bay lobe (Schafer and Hartshorn, 1965), and the Cape Cod Bay lobe in turn retreated rather more rapidly than the South Channel lobe. The differential retreat of the lobes may have been caused by differences in the depth and size of the basins, the smallest of which is Buzzards Bay and by far the largest and deepest of which are Great South Channel and the basins to the north. The first major stand in the retreat is marked by the outwash and moraines on inner Cape Cod that were deposited by the Buzzards Bay and Cape Cod Bay lobes. During this time the extremities of the lobes were in positions approximated by the west and north shore of Cape Cod. The South Channel lobe occupied a more southerly position so that its western edge was east of Nantucket. Possibly a lake formed between the ice lobes and the islands to the south as is suggested by the thick clay layer in the subsurface of southeastern Cape Cod (Koteff and Cotton, 1962). The lake, if it existed, was probably dammed to the east by the South Channel lobe and to the south and west by drift. Progradation of outwash and deltaic sediments in a southerly direction appears to have filled the lake. Retreat of the ice northward from Cape Cod resulted in a proglacial lake in Cape Cod Bay, dammed to the south and west by drift and to the east by the South Channel lobe. Initially the lake was narrow, and a minor stand of the ice resulted in deltaic and lacustine deposits along the north shore of Cape Cod. Smaller moraines south of Plymouth (Schafer and

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Hartshorn, 1965) and a part of the drift on outer Cape Cod, deposited into the lake by meltwater of the South Channel lobe, may correlate with this stand. Continued retreat of the ice from Cape Cod Bay to a position north of Duxbury allowed the lake to expand. Probably at this time meltwater of the South Channel lobe built most of the outer Cape and to the west meltwater deposited the deltas at Duxbury (Chute, 1965). Fine grained sediments from the Cape Cod Bay and South Channel lobes were deposited in the lake, while the Cape Cod Bay lobe contributed coarse material to the lake sediments from ice or by rafting. As the western side of the South Channel lobe retreated away from the outer cape the lake drained by way of Little Stellwagen Basin. The glacial sediments of Cape Cod and in Cape Cod Bay were deposited sometime before 14,000 years ago since by then the ice front had retreated to a position north of Boston (Kaye and Barghoorn, 1964) and marine submergence had occurred. From the point when the drift was deposited on the outer cape, stages in the retreat of the South Channel lobe are not well known. However, it seems probable that the glacial deposits in Stellwagen Bank are deltas deposited in a marine environment. The finer grained glaciomarine sediments (rock flour) were deposited in Stellwagen Basin, possibly from meltwater of the South Channel lobe, as the seismic recordings from the bank suggest an eastern source for these deposits. Although not as well displayed, structure in Jeffreys Ledge suggest a similar origin for the glacial deposits atop the ledge and the fine grained sediments in the basins to the west of the ledge. Continued shrinkage of the South Channel lobe resulted in the deposition of moraine sediments over the Coastal Plain sediments northeast of Stellwagen Bank and east of Jeffreys Ledge. By about 12,000 years ago the western part of the Gulf of Maine was free of glacial ice. As the region was submerged the glacial deposits atop the banks were reworked. The fines were winnowed out of these deposits came to rest in the deeper and quieter water of the basins east and west of the topographic highs. The late Pleistocene high stand of sea level along much of coastal New England was due to the depression of the crust by ice loading. Sea level may have been as high as 37 meters above the present level (Bloom, 1960; Kaye and Barghorn, 1964). During this submergence a gray silt-clay containing a cold water marine fauna was deposited along the coast (Sheet 4). In response to ice unloading the crust rebounded and sea level dropped again. In Boston this emergence occurred 11,000 years ago when sea level dropped 21 m below its present level (Kaye and Barghoorn, 1964). Farther north in Maine the emergence occurred 4200 years ago and sea level dropped 2 m below its present level (Bloom, 1960). From this emergence sea level rose again reaching to nearly its present level several thousand years ago. During this last rise in sea level deposition by littoral drift resulted in the formation of the northern tip of Cape Cod (Zeigler and others, 1965), as well as the barrier islands and spits along the New England coast, while modern streams have contributed silt and clay to the bathymetric lows.

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Economic deposits

The relatively thin sediment cover indicated by the seismic profiles in the western Gulf of Maine, Nantucket and Vineyard Sounds, and Buzzards Bay demonstrates that the petroleum potential within the coastal plain sediments appears to be non-existant. The mineral resources of the region are probably restricted to sand and gravel. The geologic map compiled from the seismic profiles indicates that the best sites for these deposits are the top of the banks and ledges. Smaller concentrations of sand and gravel occur locally along the coast and in Cape Cod Bay. In many places these smaller concentrations are covered by a variable thickness of marine mud of Holocene age. The large basins appear to contain little gravel as in most places the transparent layer rests directly on basement.

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