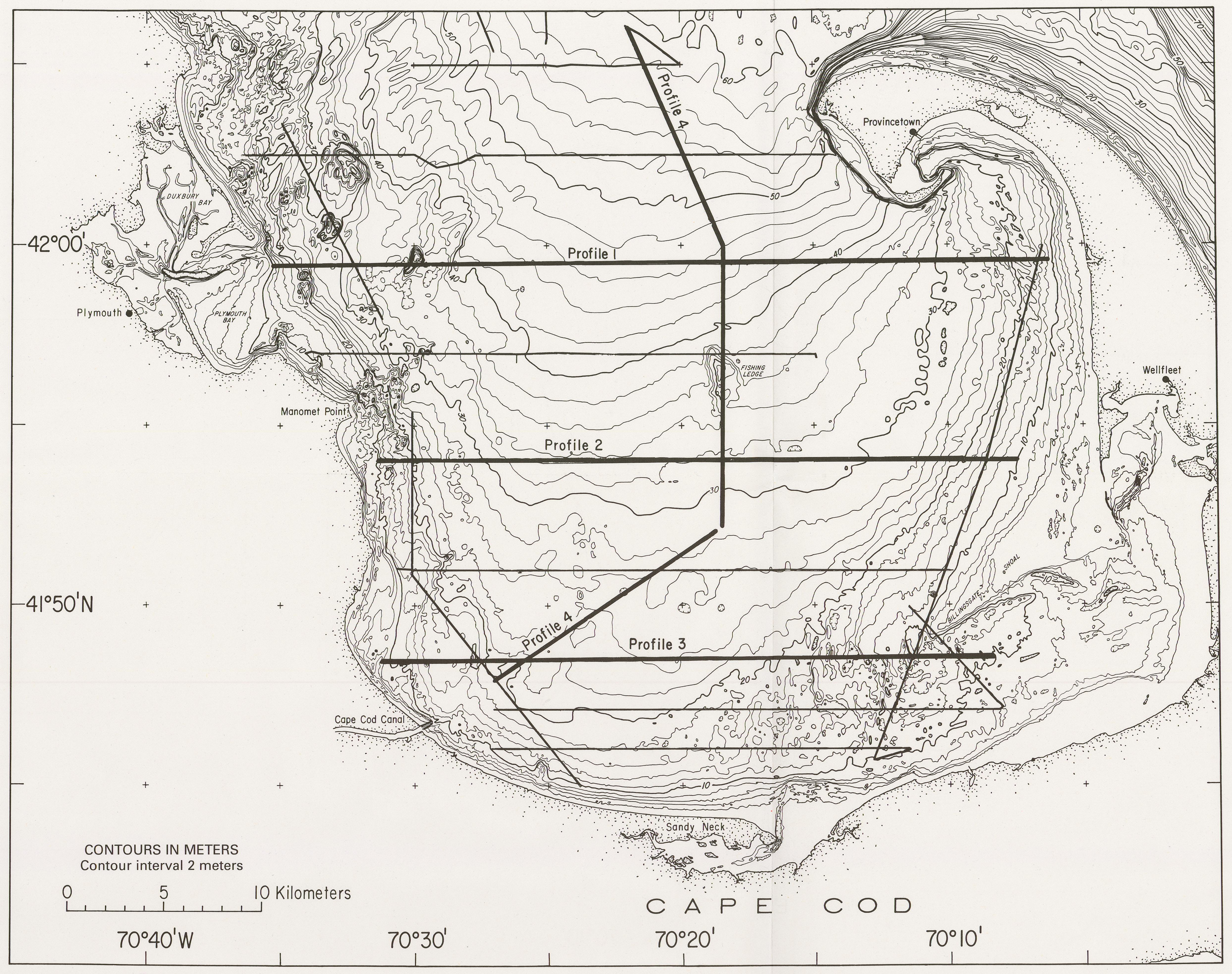

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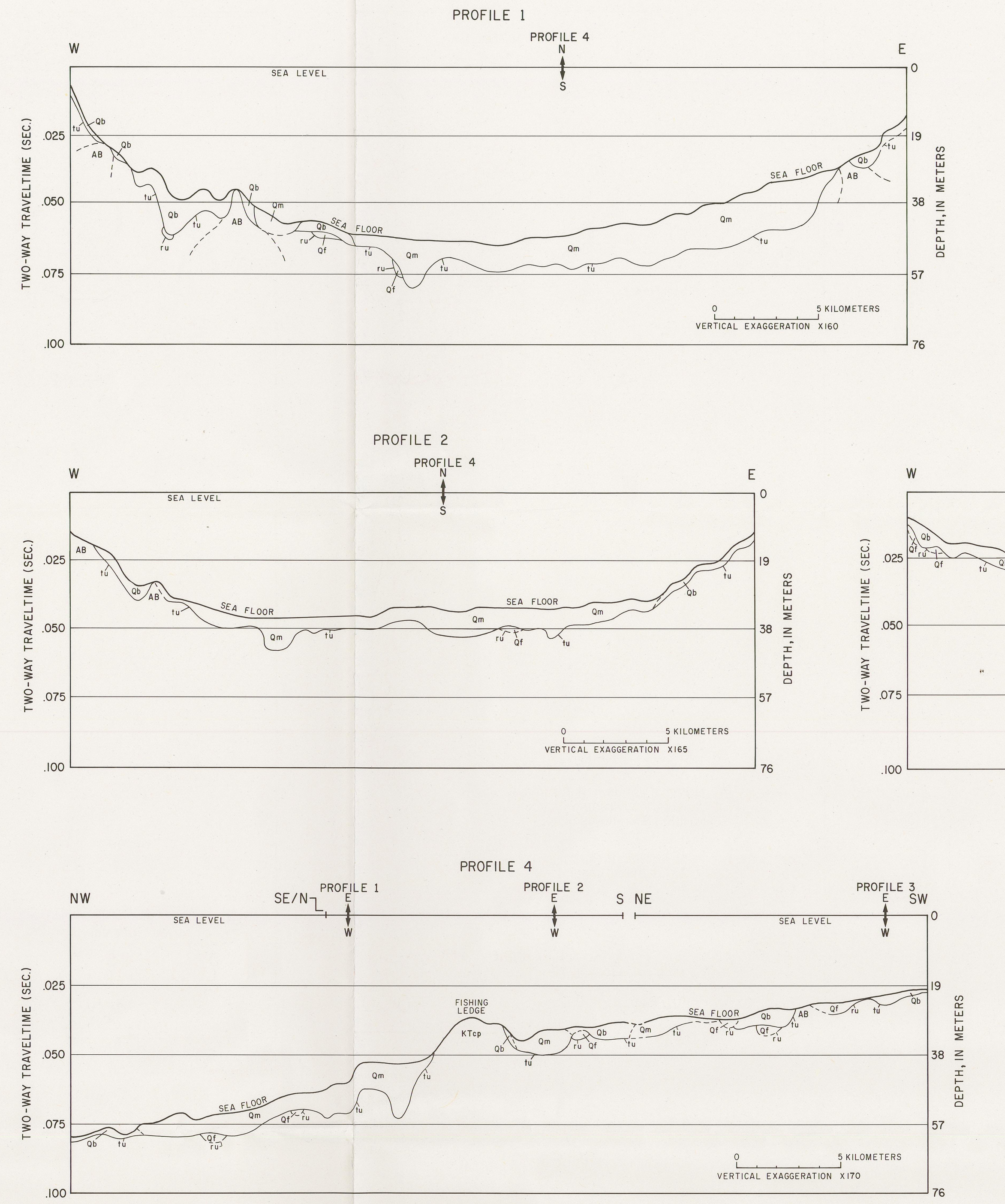
Figure 1.—Bathymetry of Cape Cod Bay and locations of the sidescan sonar and 3.5-kHz high-resolution seismic-reflection survey tracklines. Locations of profiles 1–4 are indicated (see figure 2). Depth contours are from National Geophysical Data Center (1994). Closed, hachured contours indicate depressions. Base map is from National Ocean Service (1998).



EXPLANATION OF SEISMIC UNITS (FIGURE 2)

Qb — **Shallow-water marine deposits (Holocene)**—Undifferentiated sand and silt, with gravel, scattered shells, and shell fragments. Grades offshore into silty sediments (unit Qm). Contains no coherent reflectors; overlies transgressive unconformity

Qm — **Deepwater marine deposits (Holocene)**—Mostly clayey silt and clay with minor concentrations of fine to very fine sand. Generally flat-bedded, homogeneous, and locally massive. Conformably overlies Pleistocene deposits in the deepest parts of the bay; elsewhere overlies the transgressive unconformity. May be overlain by a veneer of sand near the margins of the bay

Qf — **Fluvial and estuarine deposits (Pleistocene and Holocene)**—Sand, gravel, mud, and freshwater and saltwater peat. Deposits were planed by the last major rise of sea level

KTcp — **Coastal plain deposits (Upper Cretaceous and Tertiary)**—Presence of internal reflectors ranges from discontinuous to absent. Unit is thought to consist of unconsolidated to consolidated deposits of sediment types ranging from gravel to clay

AB — **Acoustic basement (Pleistocene and older)**—Deposits of dense, compact till (Illinoian), which are underlain by Triassic to Precambrian bedrock consisting of igneous, metamorphic, and consolidated sedimentary rocks. Bedrock may crop out locally in nearshore areas

tu — **Transgressive unconformity**

ru — **Regressive unconformity**

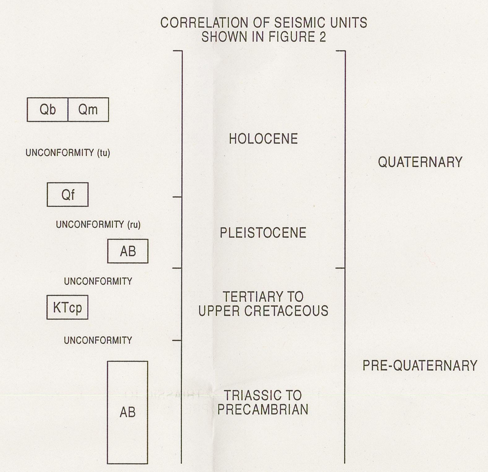


Figure 2.—Interpretations of 3.5-kHz high-resolution subbottom profiles 1–4, and explanation and correlation of seismic units; profile locations are shown in figure 1. Contacts are smoothed for interpretive purposes. Dashed lines represent inferred geologic contacts. Differences in vertical exaggeration are due to the effects of wind and currents on ship speed.

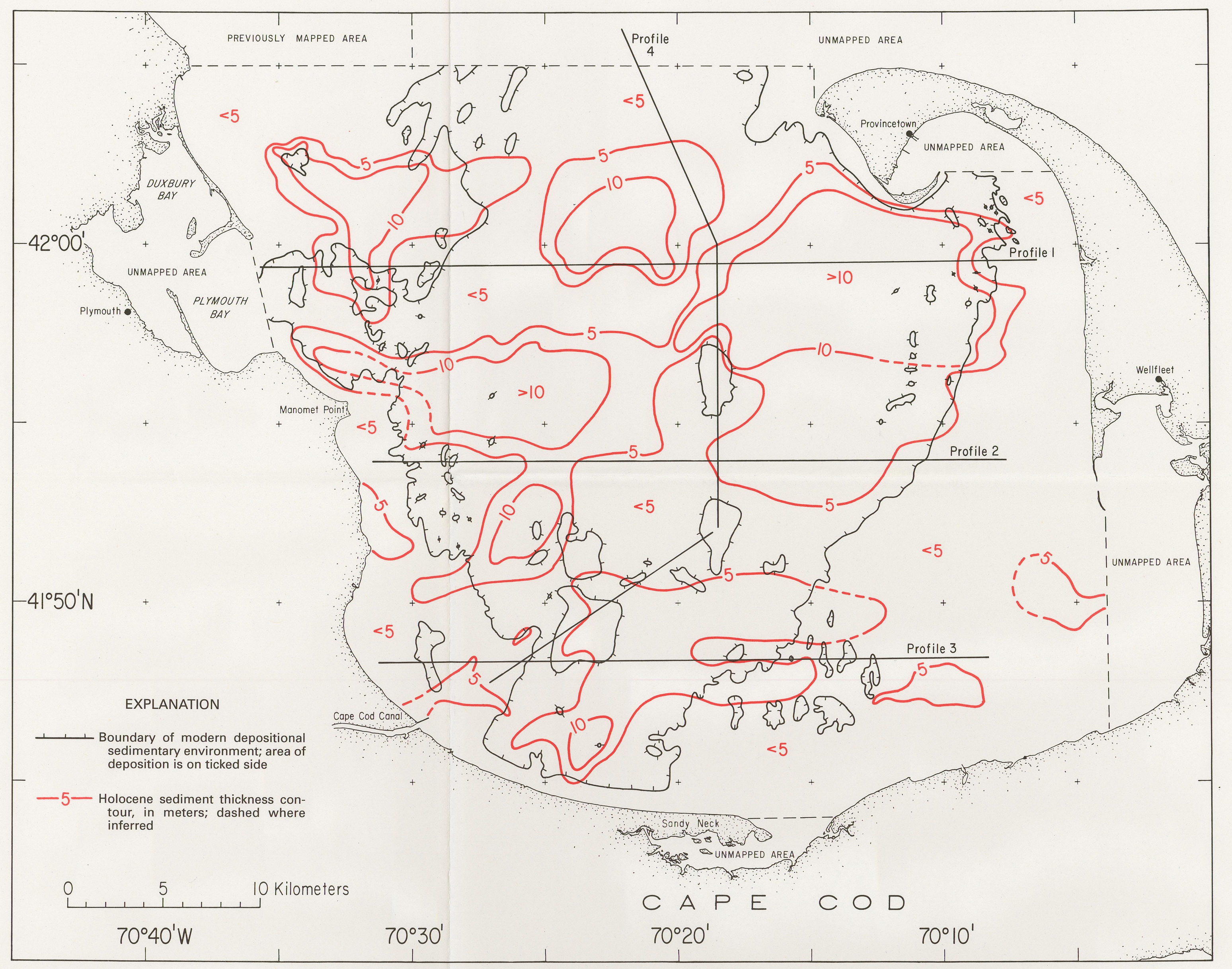


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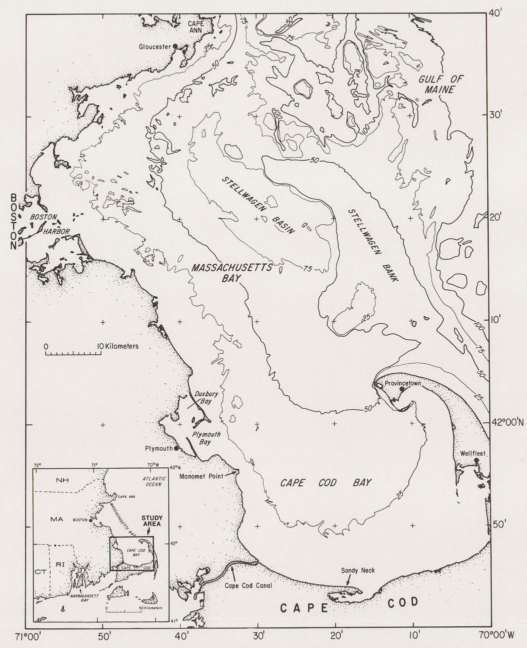
Figure 4.—Isopach map showing the total thickness of Holocene sediments in Cape Cod Bay. Map was constructed from 3.5-kHz seismic data and supplemental information. The thickest accumulations of sediments are primarily fine-grained (silts and clays) and are located within the deeper parts of the modern depositional area. Thickness contours are smoothed to 5-meter intervals. Excluded areas within the modern depositional sedimentary environment are interpreted to be environments of sediment reworking or of erosion or nondeposition. Locations of profiles 1–4 are shown for additional reference.



Location map showing Cape Cod Bay and Massachusetts Bay and their regional setting. Bathymetric contour interval 25 meters.

INTRODUCTION

Cape Cod Bay is an embayment of the Atlantic Ocean along the southeastern coast of Massachusetts (location map). This glacially formed feature is bounded by Cape Cod on the south and east, by wave-cut glacial deposits along the southeastern Massachusetts coast on the west, and by Massachusetts Bay on the north.

Concerns about pollutants transported into Cape Cod Bay from Boston and other urbanized coastal areas in the region and from the Gulf of Maine have prompted a number of studies detailing the modern sedimentary environments within the regional sedimentary system that includes Cape Cod Bay (Knebel, 1993; Knebel and Circé, 1995; Knebel and others, 1991, 1996). Identifying depositional areas within the regional system is an important aspect of tracing the pathways and ultimate fates of pollutants. This study was undertaken to determine and map the distribution and thickness of the Holocene-age sediments within the area of Cape Cod Bay that is characterized by ongoing deposition, as defined from a previous study of sedimentary environments within the bay (Knebel and others, 1996) and shown here in figure 3.

METHODS

Acoustic profiling data (sidescan sonar and 3.5-kHz high-resolution subbottom profiles) were concurrently collected along regional tracklines (fig. 1) within the bay during June 1994, aboard the Woods Hole Oceanographic Institution research vessel *Asterias*. Geologic interpretations of profiles 1–4 (fig. 2) are based on approximately 370 line-kilometers of digital and analog 3.5-kHz data. The 3.5-kHz signal was triggered every 0.25 s and the returning signals were displayed on an EPC 3-channel recorder with a 0.125-second sweep rate. Subbottom depth and thickness of the Holocene sediments, as well as thickness of the water column, were calculated by means of 3.5-kHz data using an assumed velocity of 1.5 km/s (Oldale, 1969). Figure 4 shows the total thickness of Holocene sediments in Cape Cod Bay.

The sidescan sonar data were obtained from a towfish using a 100-kHz frequency and a 200-meter swath width. The signal penetrated only the top few centimeters of the sea floor. Because figure 5 is a textural interpretation of the sediments at their surface, it does not necessarily correlate with the underlying subbottom stratigraphy as interpreted on profiles 1–4.

In the central basin of the bay (the area deeper than 30 m), the erosional surface produced by the regressive and transgressive unconformities, which mark the onset of the Holocene epoch, could be mapped owing to the acoustic transparency of the overlying fine-grained sediments. However, tracing the erosional surface laterally toward the nearshore margins of the bay, where coarser sediment types and shallow-water conditions exist, was difficult for two reasons. First, these areas produced degraded signal returns because multiple signals were received. Second, the outgoing pulse penetrated the bottom poorly and could not be clearly interpreted. Older deposits of Pleistocene to Precambrian age, which tend to crop out in nearshore areas, similarly were only sporadically identifiable from the seismic records throughout the bay. Because of the gaps in the data, we supplemented our seismic interpretations with land-based and offshore core data, surficial sediment data, and information from previous seismic surveys within the bay (Tucholke and others, 1972; Schlee and others, 1973; Oldale, 1988; Oldale and O'Hara, 1975, 1990; U.S. Geological Survey, unpub. data, 1995; Uchupi and others, 1996). Figure 3 is a map of the modern surficial sedimentary environments within Cape Cod Bay, interpreted from sidescan sonar records and supplemental data by Knebel and others (1996), and it is intended to provide a basis for this investigation.

PREVIOUS INVESTIGATIONS

Hoskins and Knott (1961) conducted one of the first studies using a continuous seismic-reflection profile to determine the stratigraphy within Cape Cod Bay. Additional offshore stratigraphic data from Massachusetts Bay and the Gulf of Maine were obtained from cores and deep seismic profiles and were used to correlate seismic horizons within Cape Cod Bay (Tucholke and Hollister, 1973; Oldale and O'Hara, 1975; Oldale and Bick, 1987; Oldale, 1988).

The glacial history of Cape Cod Bay and Cape Cod has been reported by Oldale and Tuttle (1964), Oldale and O'Hara (1975, 1990), Oldale (1982, 1986, 1988, 1992), and Larson (1982). Sea-level changes during the late Wisconsinan and Holocene were investigated by Redfield and Rubin (1962), Kaye and Barghoorn (1964), Oldale and O'Hara (1980), and Oldale (1988). Uchupi and others (1996) described a regional synthesis of the late Quaternary history of Cape Cod.

A map showing the texture of the surface sediments in the bay was constructed by Schlee and others (1973). A 3.5-kHz echo-sounding survey outlining sediment thickness in the same area was produced by Tucholke and others (1972). Maps displaying modern sedimentary environments of erosion, reworking, and deposition on the sea floor in Cape Cod Bay and Massachusetts Bay as interpretated from sidescan-sonar records have been presented by Knebel (1993), Knebel and Circé (1995), and Knebel and others (1991, 1996).

GEOLOGIC HISTORY

The morphology of Cape Cod Bay and Cape Cod is the result of glaciation and postglacial sea-level fluctuations during Pleistocene and Holocene time. The bedrock beneath Cape Cod Bay is thought to include crystalline rocks of Precambrian and Paleozoic age as well as sedimentary rocks of Pennsylvanian age. Seismic studies also indicate that Triassic-age sedimentary rocks may underlie part of the bay (Ballard and Uchupi, 1975). The surface of the bedrock is an unconformity capped by isolated erosional remnants thought to represent coastal plain sediments of Late Cretaceous and Tertiary age, similar to those described by Kaye (1983) along the southeastern Massachusetts coast. These deposits may have been submerged and later exposed to subaerial erosion during Early Tertiary time into Oligocene time (Oldale, 1992).

During the Pleistocene, at least two episodes of glaciation scoured the bedrock and overlying deposits in southeastern Massachusetts, including the Cape Cod area. An Illinoian(?)-age drift locally known as the lower New England Till has been described from drumlin exposures in Boston Harbor (Kaye, 1982), and it is interpreted to underlie marine deposits at Sankaty Head, Nantucket (Oldale and Eskenasy, 1983).

The advance of the Laurentide ice sheet into southern New England reached its maximum extent about 21 ka on the present-day islands of Nantucket and Martha's Vineyard. Retreat of the ice slowed north of Cape Cod about 18 ka and was characterized by the formation of a proglacial lake in the general area of present-day Nantucket Sound and Cape Cod Bay (Oldale, 1992). Non-synchronous retreat of the ice sheet produced glaciolacustrine sediment, submarine drift from calving ice fronts, glaciomarine muds, and deltaic-debris flows, which were deposited in the proglacial lake as the ice readvanced and then finally retreated north of Boston about 14 ka. Much of the modern morphology of Cape Cod and the bay was formed during this last glacial activity. It was followed by a late-glacial marine submergence, caused by the weight of the ice depressing the land surface below existing sea level, and then by a rapid regression of the sea during the onset of the Holocene about 11 to 10 ka as the land rebounded in response to removal of the weight of the overlying ice.

The eustatic rise of sea level during early to middle Holocene time produced a rapid transgression of approximately 6 m/ka and was characterized by truncation and erosion of much of the pre-existing glacial sediment. The sea-level rise slowed to 2 m/ka before present sea level was reached about 1 ka. Currently a rise in sea level of 2 to 3 mm/year along the eastern coast of Cape Cod Bay may in part be the result of crustal subsidence as described by Uchupi and others (1996).

BATHYMETRY

Figure 1 is a detailed bathymetric map contoured at a 2-meter interval (National Geophysical Data Center, 1994; Knebel and others, 1996; National Ocean Service, 1998) showing the bottom topography of the semi-enclosed embayment of Cape Cod Bay. The sea floor is generally flat-lying in the central basin, where water depths range from 30 m to almost 60 m. Along the margins of the bay, in water depths of less than 30 m, the sea-floor topography is more irregular and consists of small knolls, ridges, and small depressions. Locally, bedrock crops out in this area along the western margin of the bay near Manomet Point (Oldale and O'Hara, 1980; Uchupi and others, 1996).

Two major topographic features are Fishing Ledge, in the center of the bay, and Billingsgate Shoal, located along the southeastern margin of the bay. Fishing Ledge is a wedge-shaped feature having relief of 6 to 8 m, and is thought to represent the erosional remnant of coastal plain sediments. Billingsgate Shoal extends about 10 km southwestward into the bay from the sandspit dividing the bay from Wellfleet Harbor. It is thought to represent a submerged end moraine formed during a minor readvance of the ice in Cape Cod Bay during the late Wisconsinan glaciation (Oldale, 1992).

In nearshore areas, coarse-grained shallow-water Holocene deposits form the rough sea floor. In contrast, the surface of the deepwater marine deposits, which consist mostly of silt and clay, is generally smooth.

DISCUSSION

Seismic Interpretation

Line drawings of selected subbottom seismic sections within the bay (fig. 2) illustrate the distribution and relations of the near-surface stratigraphic units. The lowest reflector observed from the 3.5-kHz records represents the surface of the acoustic basement (AB) and is shown in profiles 1, 2, and 4. Unit AB represents bedrock, ranging in age from Precambrian to Triassic, and dense, compact Illinoian-age till. It crops out, primarily, in the northwestern part of Cape Cod Bay off Manomet Point, and, possibly, at Fishing Ledge near the center of the bay. An earlier study also shows that this surface represents bedrock (Oldale and O'Hara, 1990). Elsewhere throughout the bay, bedrock lies at least 20 m below the sea floor and dips to the northeast to a depth of approximately 150–200 m at Provincetown (Byron D. Stone, U.S. Geological Survey, written commun., 1997).

A discontinuous seismic unit lacking well-defined internal reflectors unconformably overlies the acoustic basement reflector and is inferred to represent erosional remnants of coastal plain deposits (KTcp) of Late Cretaceous and Tertiary age. The remnants may include Fishing Ledge, a topographic high in the center of the bay (fig.1; fig.2, profile 4).

Other stratigraphic units younger than Mesozoic and older than Holocene are inferred to be of Pleistocene age. They are glaciolacustrine, glaciomarine, and marine sediments which unconformably overlie the acoustic basement and coastal plain deposits. Although not readily identifiable from the seismic records collected for this study, and therefore not shown in profiles 1–4, nevertheless they have been identified from studies utilizing deeper-penetrating seismic equipment (Oldale and O'Hara, 1990).

A reflector representing a regressive unconformity (ru) is characteristically preserved in valley-like depressions on the Pleistocene surface (fig. 2, profiles 1–4). It outlines stream channels that were filled with fluvial and estuarine deposits of sand, gravel, mud, and peat (unit Qf) during late Wisconsinan and early Holocene time when the surface was subaerially exposed by a lowstand of sea level (Oldale and O'Hara, 1990; Van Heteren and van de Plassche, 1997).

A gently undulating reflector (tu) truncates the surface of the Pleistocene and valley-fill (Qf) deposits. It represents an unconformity created as the sea transgressed the area and planed the older Pleistocene and fluvial deposits. This unconformity is well defined in the deeper central basin of the bay (fig. 2, profiles 1 and 4). It is generally flat lying or gently dipping and can be traced laterally toward the margins of the bay (fig. 2, profiles 1–4), where it becomes indistinguishable from the present sea floor.

Two seismic units of Holocene age are present atop the transgressive unconformity. One (unit Qm) is acoustically transparent and homogeneous and has occasional parallel to subparallel internal reflectors. Occurring primarily in the central and deeper parts of the bay (fig. 2, profiles 1, 2, and 4), it consists mostly of clayey silt and clay with minor amounts of fine to very fine sand. The other seismic unit (Qb) grades into and replaces the fine-grained sediments along the margins of the bay. This unit contains internal reflectors that range from parabolic to gently dipping, and it consists of sandier nearshore deposits.

Thickness of Holocene-Age Sediments

Figure 4 is an isopach map that outlines the total thickness of the undifferentiated Holocene-age sediments, consisting of fluvial and estuarine deposits (Qf), deepwater marine deposits (Qm), and shallow-water marine deposits (Qb). It was constructed by using the 3.5-kHz seismic records and supplemental information to measure the difference in depth between the approximate sea floor and the transgressive unconformity (tu). Areas containing 10 to 15 m of Holocene sediment are found in the deeper parts of the bay south and west of Provincetown, near the tip of Cape Cod. The thickness of Holocene sediments tends to decrease to 10 m or less in the southern part of the bay. The sediments are also relatively thin near the topographic high in the center of the bay (Fishing Ledge) and along the bay's margins. The thickest areas of sediment accumulation generally are found within the boundaries of modern depositional environments as mapped by Knebel and others (1996).

Variations in the thickness of Holocene sediments are a result of infilling of topographic lows in the underlying Pleistocene surface in conjunction with a modern current regime that allows for long-term deposition of fine-grained sediments in deeper parts of the bay (Knebel and others, 1996). Along the margins, the Holocene sediments are generally thinner and coarser because the silt and clay are winnowed away by the nearshore currents and deposited in the deeper parts of the bay (Knebel and others, 1996).

The rate of Holocene sediment accumulation in the deeper areas of Cape Cod Bay is estimated to be 0.1 cm/year, similar to the rate within nearby Stellwagen Basin (Tucholke and Hollister, 1973; Hunt and others, 1992; Knebel and others, 1996). Based on this rate, the thickest accumulations of sediment in the deeper parts of Cape Cod Bay correlate with an age of 10 to 15 ka, similar to the approximate age of the late Wisconsinan/Holocene boundary.

Surficial Geology

The nature and distribution of surficial sediments located within the modern depositional area of Cape Cod Bay, as determined from sidescan sonar data and supplemental information, are presented in figure 5. The contact between very coarse to very fine sand and sandy to clayey silt was constructed using grain size analyses of grab samples and core data (Schlee and others, 1973; Oldale and Bick, 1987; U.S. Geological Survey, unpub. data, 1995). Coarser grain sizes and higher concentrations of sand and gravel generally are located shoreward of this contact and in shallower waters in the bay.

The finer grained sediments are sandy to clayey silts in the central part of the bay, where the water is deeper and resuspension caused by storms and tidally induced currents is minimal (Knebel and others, 1996). The sediments become finer as the water deepens, with the finest clayey sediments concentrated north-northeast of Fishing Ledge. Modern fine-grained sediments possibly are derived from both local and regional sources, which include (1) wave erosion of nearshore areas; (2) input from local streams, groundwater discharge, and runoff; (3) Boston Harbor; (4) Massachusetts Bay (see location map); and (5) rivers that discharge into the Gulf of Maine (Knebel and others, 1996).

Along the eastern and western margins of the depositional area, around local topographic highs (such as Fishing Ledge), and in areas identified as being environments of erosion, nondeposition, or sediment reworking (compare figs. 3 and 5), the sediments are gravel and coarse sand, and may be covered by a thin layer of medium to very fine sand. Southward from the depositional area the sediments also tend to coarsen, grading from silty sand to fine and very fine sand toward the nearshore area, similar to trends observed by Schlee and others (1973). An enclosed area mapped in the southern part of the bay contains more than 70 percent fine to very fine sand within the surficial sediments (fig. 5).

Two large areas of relatively coarse, sandy Holocene sediment deposition extend across the shallow margins of Cape Cod Bay, one located off Plymouth Bay and the other located just northwest of Sandy Neck (fig. 5). Deposition within the area off Plymouth Bay is attributed to a large supply of sediments provided by a combination of longshore drift and offshore transport from Plymouth and Duxbury Bays (Knebel and others, 1996). Here, the supply of sediments is sufficient to offset losses caused by erosion and transport out of the area by waves and currents. Just northwest of Sandy Neck, on the other hand, the depositional environment can be attributed to other factors. There, relatively coarse sediments are deposited in a zone influenced both by storm-driven currents and by a lower frequency of wave-produced resuspension (Knebel and others, 1996). This zone possibly is a pathway for sediment transport into the central basin.

SUMMARY

The stratigraphic relations and distribution of Holocene-age sediments in Cape Cod Bay have been described from a set of sidescan sonar and 3.5-kHz high-resolution seismic-reflection records, supplemented with sediment-core data, surficial grab-sample data, and information from previous seismic studies of the bay and adjacent areas.

(1) The stratigraphically lowest Holocene seismic unit identified from the seismic records, Qf, represents deposits of fluvial and estuarine gravel, sand, mud, and freshwater and saltwater peat, which have been preserved in channel-like depressions. The upper surface of these deposits is truncated by an erosional unconformity that was formed during the last major transgression of sea level.

(2) The thickest accumulations of Holocene sediments are found within a previously defined area of modern sediment deposition in the bay (Knebel and others, 1996). Ten to 15 m of fine-grained clayey silt (seismic unit Qm) occurs within the central basin of the bay in water depths of 30 to 50 m. These sediments thin laterally and coarsen along the bay margins.

Relatively coarse (sandy) Holocene sediments (seismic unit Qb) have been deposited along the margins of the bay and locally over bathymetric highs in water depths typically less than 30 m along the southern and eastern margins of the bay, and typically less than 45 m along the western edge of the bay. In the northwestern part of the bay these sediments are in water as deep as 50 m. The thickness of these deposits is highly variable, ranging from less than 5 m to more than 10 m. Their distribution and textural characteristics have been affected by modern nearshore processes within the semi-enclosed bay.

(3) Surficial sediment distribution within the modern depositional area of the bay indicates that fine-grained sediments are concentrated primarily in the deeper areas of the bay. These sediments grade laterally to silty clay and clay in the deepest part of the bay west of Provincetown. Toward the shoreline of the semi-enclosed bay, the sediments coarsen because the fines are winnowed by nearshore currents and storm-induced waves and are transported to deeper areas within the bay.

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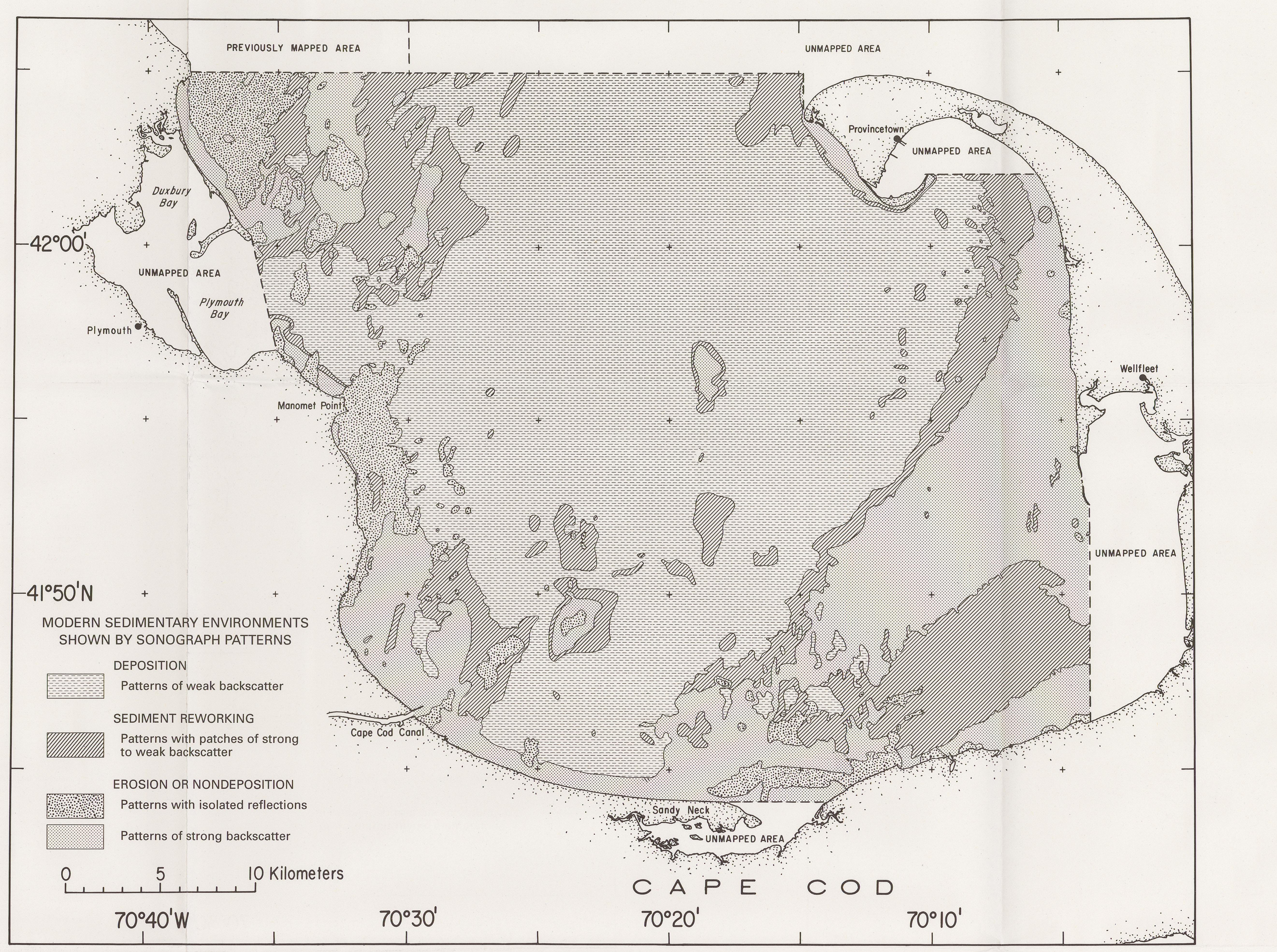

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Figure 3.—Distribution of modern sedimentary environments in Cape Cod Bay, interpreted from sidescan sonar records and supplemental marine geologic data (Knebel and others, 1996).

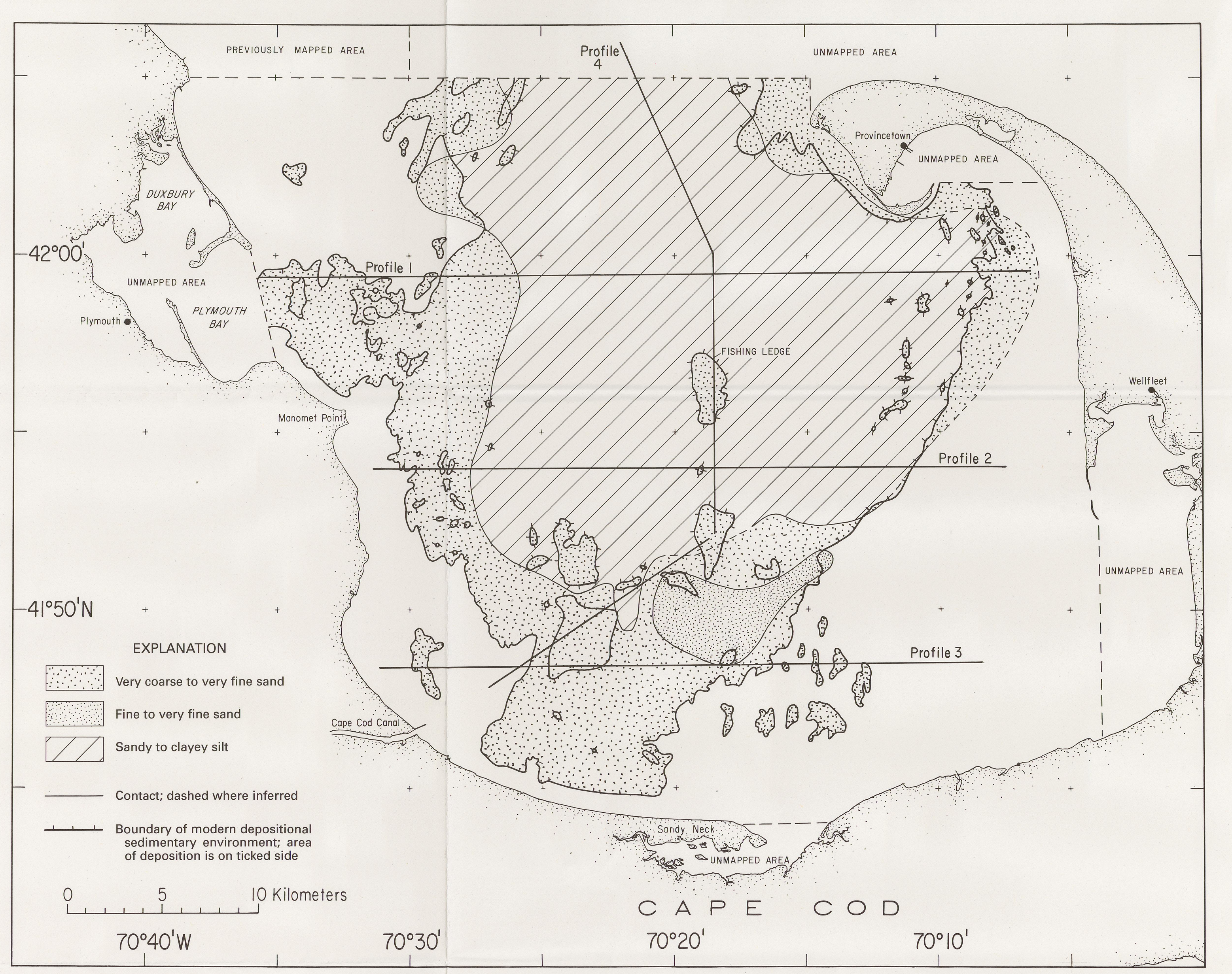

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Figure 5.—Surficial sediment map of the sea floor within the modern depositional area of Cape Cod Bay, as interpreted from sidescan sonar data and correlated with textural analyses of cores and grab samples from supplemental data. Because the sonar pulses penetrated only the top few centimeters of the sea floor, this map gives a textural interpretation of the sediments only at their surface. It does not necessarily correlate with the underlying subbottom stratigraphy as interpreted on profiles 1–4.

INTERIOR—GEOLOGICAL SURVEY, RESTON, VA—2002

DISTRIBUTION AND STRUCTURE OF HOLOCENE SEDIMENTS IN CAPE COD BAY, MASSACHUSETTS

By
Richard R. Rendigs and Harley J. Knebel
2002

ISBN 0-607-99171-2

Printed on recycled paper