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Geomorphology and Sedimentary Framework of Penobscot Bay and Adjacent Inner Continental Shelf

by

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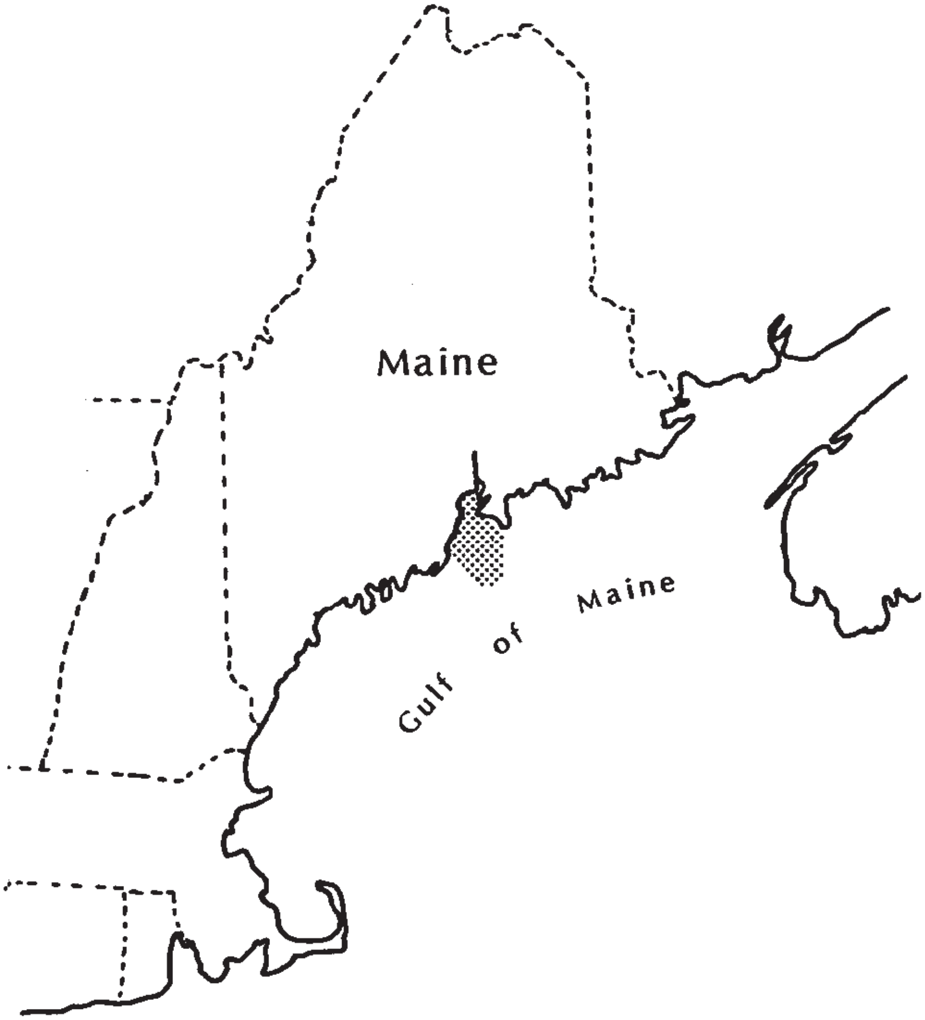

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INTRODUCTION

This report describes the submarine geomorphology, surficial sediments, and Quaternary stratigraphic framework of the western Gulf of Maine within Penobscot Bay and along the adjacent inner continental shelf (Figures 1, 2). Although reference is made to many important terrestrial observations, the research is focused on the nearshore region out to the 100 meter isobath. Within this area complexly-deformed bedrock ranges in age from Precambrian to Devonian, with an unusually large proportion of Precambrian metamorphic outcrops and Devonian granites forming islands in the bay (Osberg et al., 1985). Bedrock is widely exposed along the shoreline and exercises the primary control on the shape of the coast (Kelley, 1987). The Penobscot Bay area is an important element of the Island-Bay Complex coastal compartment of Maine (Kelley, 1987). This area is characterized by broad embayments, of which Penobscot Bay is the largest. The bays are generally carved out of metamorphic rocks, with granitic islands throughout the area. There are no large sand beaches in the bay, despite the presence of the Penobscot River, Maine's 2nd largest river, at the head of the bay. The lack of sandy beaches is puzzling since all the other large river systems in the western Gulf of Maine have sandy beaches at their mouths, and extensive paleodeltas offshore (Kelley, 1988). The intertidal zone of Penobscot Bay is dominated by tidal flat deposits of mixed gravel and mud textures, derived from erosion of glacial sediments.

Like other shelf areas of New England and the Canadian Maritimes, the Penobscot Bay region has probably experienced numerous Quaternary glaciations, and relatively thin glaciogenic sediment only partly mantles submerged bedrock exposures (Needell et al., 1983; Piper et al., 1983). Unlike the outer regions of the Gulf of Maine and beyond, however, local, relative sea level has fluctuated profoundly in central Maine due to isostatic crustal movements as well as eustatic sea-level changes related to growth and disintegration of the Laurentide Ice Sheet (Stuiver and Borns, 1975; Belknap et al., 1987). Within the past 14,000 years, the study area has experienced a deglaciation, two marine transgressions, and a regression of the sea. It is these changes in sea level, which have permitted a variety of terrestrial and marine processes to repeatedly operate over the inner shelf, that have established the regional stratigraphic framework, and most significantly affected the nature of the surficial sediments. The purpose of this paper is to describe the surficial sediments of the area in the context of a stratigraphic framework dictated by Holocene sea-level fluctuations.

PREVIOUS WORK

While many people have studied the Pleistocene geology of the land surrounding Penobscot Bay, no one has synthesized the deglacial history of the area. In the late 19th century Stone (1899) (Table 1) mapped moraines near the western margin of the bay, and described the large washboard moraine complex near Muscongus Bay (Kelley and Belknap, 1988). He also recognized the large number of moraines exposed on the eastern shore of the bay. Leavitt and Perkins (1935) mapped the area during their compilation of the sand and gravel resources of the State. They mapped the widespread occurance of glaciomarine sediment as a "wash plain", and noted its intimate relationship with till. Although Bloom did not work in central Maine, his description (1960, 1963) of Maine's glaciomarine sediment, which he elevated to formation status as the Presumpscot Formation, fits the muddy, late Quaternary deposits of the area very well. More recently, Smith remapped the western shore of the bay while Thompson reexamined the eastern region and compiled the new maps into a State Surficial map (Thompson and Borns, 1985). The current model for deglaciation of this area invokes a floating ice shelf during the early stages of deglaciation. When the ice shelf occassionally became grounded upon topographic high places, small moraines were deposited in close association with glaciomarine mud.

Ostericher (1965) was the first to employ coring and seismic reflection methods to examine submarine stratigraphy in the area. He described acoustic reflectors which correlated with bedrock, till, and the Presumpscot Formation, and described the acoustic properties of the surficial sediments, which he sampled. He recognized the complex transgressive/regressive unconformity on the surface of the Presumpscot Formation and dated wood fragments from cores of its surface at 7,390 years before present (BP). On the basis of this he concluded that the "post-Presumpscot Formation" lowstand of sea level occurred at that time at a depth 15-20 meters. On the basis of data collected for previous reports to the Minerals Management Service (Kelley et al., 1987a,b; Kelley and Belknap, 1988) we have established that the lowstand is marked by shoreline deposits closer to the 60 meter isobath. We have also inferred that the lowstand was reached around 9,500 BP (Belknap et al., 1987).

Knebel and Scanlon (1985) reoccuppied many of Ostericher's earlier seismic profile lines with better geophysical equipment, and have provided maps of the thickness of Quaternary sediment within parts of Penobscot Bay. They also integrated core samples gathered for the construction of a local anchorage with their geophysical data and have summarized the late Quaternary history of the western portion of the study area. Recently, Scanlon and Knebel (1989) recognized "pockmarks" from the seafloor of Penobscot Bay on the basis of side scan sonar data. Previously, these were thought to be channels (Ostericher, 1965). They were not sure of the origin of the pockmarks, but suggested that groundwater or natural gas escape were possible mechanisms. Kelley and others (in press) examined the seismic stratigraphy of Eggemoggin Reach in eastern Penobscot Bay for traces of sediment deformation associated with earthquakes. No convincing evidence was found, although slump deposits and natural gas occurrences were commonplace.

METHODS

Bottom Samples

During the summer of 1988, 169 bottom samples were collected from the Penobscot Bay region by means of a Smith-MacIntyre grab sampler (Figure 3). The device reliably gathers 0.25 cubic meters of sediment with minimal loss of material. Sample stations were located on LORAN-C time delay intersections, and all depths were evaluated by a Raytheon fathometer.

All samples were frozen immediately after collection and field description (Table 2). After sample splitting, gravel was screened out of a subsample which was refrozen for later carbon analysis. Gravel was also screened out of subsamples for carbonate analyses, although the weight of gravel was determined. Carbon and carbonate analyses could not be made on the samples at the present time for lack of sufficient funds, although the samples have been retained for future reference. The textural analyses followed the outline of Folk (1974). This year we departed from previous year's methods by using a Micromeritics Sedigraph to perform the mud fraction size analyses, and a rapid sediment analyzer (a settling tube) for the sand fraction.

Seismic Reflection Profiles

Seismic reflection profiles were made within the study area where no information had previously been gathered (Figure 4). Navigation was by LORAN-C and position fixes were made every 4-5 minutes. Three types of seismic equipment were employed during the study: a 3.5 kHz Raytheon RTT 1000a profiler, an ORE Geopulse "boomer", and an EG&G "boomer" system. The seismic systems were used to deduce the nature of the subbottom geology as well as of the surficial material. In the latter capacity side scan sonar and bottom sampling provided ground truth calibration for interpreting surficial texture as revealed by the relative intensity and overall geometry of the surface acoustic return. The seismic lines were, thus, useful for interpolating between the relatively widely-spaced bottom samples.

Interpretation of the subbottom geology was less direct, and inferences drawn from observations on land, in borings and core holes, and from nearby studies were employed to identify the acoustic reflectors. Bedrock was never penetrated by the seismic systems and its surface usually formed the lower-most reflector on a record. Relief on the surface of the bedrock was extreme, and ranged over tens of meters across short horizontal distances. A seismic unit with chaotic internal reflectors and an irregular surface commonly rested on bedrock. This has been interpreted as till, and prominent moraines exist within the study area (Knebel, 1986). Frequently, a relatively transparent acoustic unit with closely-spaced basal reflectors mantled the till or bedrock. The hard surface return of this unit was usually flat, except in valleys where it was channel-shaped. Where it outcropped near the surface and was cored (Ostericher, 1965), this unit was identified as the glaciomarine Presumpscot Formation. Where it outcrops on land its upper surface is eroding, the regressive unconformity is presently forming, while the offshore surface of the glaciomarine sediment is probably capped by the transgressive unconformity. Overlying the Presumpscot Formation, an acoustically transparent unit of modern mud was recognized in many places. As in nearby areas (Kelley et a;., 1987a,b; Kelley et al., 1988) natural gas occurences were recognized throughout the study area.

Seafloor Observations

Observations of the seafloor were made by side scan sonar profiling. The side scan system used was the EG&G model 260 Seafloor Mapper. This system automatically provides slant-range corrections to the analogue output. It was usually run at a 100 or 200 meter range.

BATHYMETRY

The seafloor of the Penobscot Bay region is more complex than that of any region to the south along the inner shelf of the western Gulf of Maine (Figure 2)(Kelley et al., 1987a,b, 1988). Bathymetric data is also limited compared to southern Maine, making interpretation especially difficult. As in areas to the south, the bathymetry is best understood when simplified to four physiographic compartments (Figure 5).

The *Nearshore Basins* are generally shallow, low relief regions adjacent to the mainland, and separated from other areas by islands and/or shoals. The contact between the basins and the mainland is gradational, and mudflats are the most common intertidal environments bordering the basins. In most Nearshore Basins in Maine, the seafloor is smooth except near bedrock outcrops (Kelley et al., 1987a,b, 1988). In upper Penobscot Bay, however, an extensive area of pockmarks has disturbed the formerly flat seafloor (Scanlon and Knebel, 1989).

Shelf Valleys are long, narrow depressions which usually extend from the Nearshore Basins to gradual terminations in deep water. The Shelf Valleys south of Penobscot Bay typically range in depth from 25-55 meters, although those in Penobscot Bay are deeper. These valleys are usually bordered by bedrock walls, and may possess numerous outcrops of rock along their axes. In Penobscot Bay the large number of islands and the complex nature of the seafloor in general made it difficult to differentiate Nearshore Basins from their bordering Shelf Valleys.

The *Rocky Zones* exhibit extreme relief ranging from 10 meter vertical cliffs to extensive areas of large boulders. In Penobscot Bay, the local rock is granite, and so there are few of the sediment ponds which are often associated with elongate cracks and cleavage in foliated rocks (Kelley and Belknap, 1988). Surrounding most of the large islands of Penobscot Bay are shoals which may be littered with boulders, but rarely contain large sediment pockets.

The seaward portion of the study area is the *Outer Basin*, which generally forms the border of the study area. This is the least known of the physiographic regions because of the lack of bathymetric observations. In Penobscot Bay seafloor appears rocky for a considerable distance seaward of the limits of this study to the Jeffrey's Bank area (U.S. Geological Survey, 1975).

In general, central Penobscot Bay is divided into 3 regions by chains of islands and shoals (Figures 3,5). West Passage (NOS, 1983) is a Nearshore Basin/Shelf Valley complex which separates the mainland from Islesboro Island and associated smaller islands and shoals. It possesses a 60 meter deep depression between Belfast and Camden which extends into the pockmark field to the north. Middle Passage is similar in orientation and depth to West Passage, and is bordered to the east by North Haven and Vinalhaven Islands and the associated shoals which extend toward the north to Cape Rosier. East Passage has a more complex bottom than areas to the west, although it also has a central depression around 60 meters deep. It begins more seaward than the other passages and connects to a Nearshore Basin, Eggemoggin Reach, to the north. It is separated from the Reach by Deer Island, which in turn parallels Eggemoggin reach.

Landward of the Passages, the headward portion of the bay is generally flat and muddy, with relatively few islands. The area seaward of the Passages is more complex, with a deep (140 meters) depression to the east which extends into Muscongus Bay (Kelley et al., 1988). On its outer, western side, the bay is relatively shallow, 60-80 meters, and very complex.

BOTTOM SEDIMENT TEXTURE

Bottom sediment texture on glaciated shelves is notoriously heterogeneous (Trumbull, 1972). Virtually all components of the particle size spectrum were encountered in bottom samples from the Penobscot Bay inner shelf and bay bottom (Figure 6). Although no "pure gravels" were sampled for this study in Penobscot Bay (Figure 7), several "sand and gravel" samples were collected by Ostericher (1965) and reprinted by Knebel (1986) (Figure 8). Most of these are from Rocky Zones near the entrance to the bay and in its central area (Figure 6). Although no size analyses were performed on them, several of our grab samples were composed of only a single cobble, or of several large clasts. Gravel areas on the textural map are probably under-represented, then, and much of what is mapped as bedrock (Figure 6) and which floors the Rocky Zones and borders of the Shelf Valleys (Figure 5) is partly gravel. In addition, many of the small sediment deposits which exist between rock outcrops are probably veneered by gravel, but are too small to map.

Sandy gravels and gravelly sands were the most common sediment samples recovered from the Rocky Zones and Shelf Valleys (Figure 7). The distinction between these textures is probably not important, as the samples range continuously through those particle size classes. Frequently the presence or absence of a single, large clast determined the textural category into which the sample was classified. Ostericher's (1965) samples appear to be like those from this study, and were generally from the central and outer portions of the bay. While most of our coarse samples were from relatively shallow (meters) Rocky Zones near islands in the central and outer bay, some were from deeper depressions in Shelf Valleys and Nearshore Basins, or from glacial outcrops in deeper water (Figure 6). As with gravel deposits, the sandy gravels and gravelly sands are more common than could be mapped at the scale presented (Figure 6). Such coarse deposits probably make up small patches of the seafloor along the margins of all Shelf Valleys and Nearshore Basins. It is interesting to note that the grain size distribution of the sand fraction of the sandy gravels and gravelly sands is relatively well-sorted and fine (Figure 9). These analyses do not include the gravel size components, and suggest that the well-sorted sands are not in equilibrium with the coarse gravels. Knebel (1986) has suggested that they have been reworked from formerly-more-extensive deposits during the Holocene Transgression.

Several muddy gravels were collected from the Rocky Zone, Shelf Valley and Outer Basin seaward of Vinalhaven Island (Figures 5,6,7). Ostericher (1965) and Knebel (1986) do not distinguish this textural class, but report poorly sorted "extraneous" sandy,silty, clayey samples from the same area (Figure 8). Size analysis of these samples was difficult as the material often contained a single large clast in a matrix of very fine mud. Most of these samples were from water depths greater than 40 meters.

"Clean" sands were not encounterd in Penobscot Bay. Although many small beaches do exist on islands in the bay (Duffy et al., 1989), most are rich in gravel, and no sandy Nearshore Ramps extend offshore as in southern Maine (Kelley et al., 1987a,b). Sandy muds were also relatively rare, although muddy sands and muds were common (Figures 7,8). These fine grained sediments were almost all from the Outer Basin or Nearshore Basins (Figures 5,6,7,8). In the Nearshore Basins the flat seafloor was uniformly fine grained mud. Many samples were collected from these areas, but not analyzed because their texture was apparent. In the Outer Basins, mud often covered the seafloor even in areas where considerable relief indicated the presence of shallow bedrock.

GEOPHYSICAL OBSERVATIONS

Bottom sediment properties correlate well with environmental settings defined by bathymetry (Figures 5, 6). Considerable variation exists, however, within the various regions. This variation is best depicted by the more detailed examination of surface sediments permitted by side scan sonar and the subbottom information generated by seismic reflection data. The seismic reflection profiles also provide insight into the geological history of the region, which further abets understanding of the overall sedimentary framework.

Nearshore Basins

Nearshore Basins are the major environments of sediment accumulation in the Penobscot Bay region, and for this reason attention is focused on them. These basins are concentrated in the upper reaches of the bay where numerous islands and peninsulas shelter them from the open sea (Figure 5). Southeast of Cape Rosier, Eggemoggin Reach (Figures 2, 10) is a fault-controlled (Osberg et al., 1985) linear embayment which separates Deer Island from the mainland. To the northwest, the central axis of the reach is flat and covered by mud, while the margins are exposed rock, often thinly veneered with gravel (interpreted as reworked till) (Figure 11). The sediment is greater than 30 meters thick along the apparent axis of the fault, although natural gas obscures most of the stratigraphic column. Toward the southeast the seafloor becomes more irregular, suggesting reworking of the Holocene sediments by tidal currents (Figures 12, 13). Wedges of Holocene mud still commonly crop out on the seafloor where protection is provided by islands and shoals, but the margins of the embayment show truncated acoustic reflectors of units interpreted as glaciomarine mud and till (Figures 12, 13). Kelley and others (1989) have inferred that slumping has been common in portions of the Reach south of the study area, and possible slump scars and deposits are recognized in places studied for this report (Figure 13). To the west of Eggemoggin Reach, the Nearshore Basin directly south of Cape Rosier shows either an extreme amount of current scouring, or pockmarks like those described by Scanlon and Knebel (1989) and below (Figure 14). Most of the depressions appear conical (v-shaped in cross section, no side scan sonar was run) and range from less than 5 meters to greater than 10 meters deep, though there is no way to know whether the trackline passes over the centers of the features. Most begin at or slightly above the inferred surface of the Presumpscot Formation, but one clearly extends beneath this surface (Figure 14). Natural gas is interpreted from beneath some of the features, as well as in areas with no depressions.

The major occurrence of pockmarks in the study area is in the Nearshore Basin at the head of Penobscot Bay between Sears Island, Islesboro Island, and the Town of Belfast (Figure 2). The marks are most common at a location midway between the above landmarks (Figure 15), and end abruptly to all sides (Scanlon and Knebel, 1989). Near where the features begin they are relatively small (10-15 meters in diameter) and circular (Figure 16). Where they are very common they were observed to coalesce and form giant pits up to 125 meters in diameter and 25 meters deep (Figures 17, 18). Fishing drag marks commonly cross the marks (Figure 16) and they do not seem to be a problem for commercially-sought organisms (W. Hamilton, Searsport Harbormaster, personal communication, 6/89). They also appear near bedrock or till outcrops in great numbers (Figure 17). Seismic profiles reveal no pockmarks extending deeper than the surface of the Presumpscot Formation in this area (Figure 19) (Scanlon and Knebel, 1989), unlike what was observed to the east (Figure 14). The marks are often associated with natural gas in the sediment (Figure 19), and acoustic windows through the gas frequently, but not always, occur beneath the pockmarks (Scanlon and Knebel, 1989).

To the east of the pockmark field the seafloor is smooth, and bottom samples contained exclusively muddy sediment

(Figure 6). Seismic profiles reveal that the Holocene sediments are thin, however, and overlie what are interpreted as truncated beds of the glaciomarine sediment (Figure 20) (Knebel, 1986). The transgressive unconformity itself appears to overlie a unit with clinoform reflectors interpreted as fluvial/deltaic beds. Beneath them another strong reflector is interpreted as the regressive unconformity, which is cut into the upper few meters of the thick glaciomarine sediment deposit (Figure 20). The lower portion of the glaciomarine sediment very nicely shows the acoustically transparent, massive mud unit of the glaciomarine sediment which was also recognized in Saco bay (Kelley, 1987a). Patchy till deposits partly cover the bedrock surface almost 75 meters beneath sea level.

In the central part of the bay, although mud dominates the seafloor of the Nearshore Basins (Figure 6), the Holocene sediments appear thin, and what is interpreted as Pleistocene sediment crops out on the seafloor (Figures 21, 22). In the Middle Passage "moating" is common aroung outcrops of bedrock, and what are interpreted as truncated reflectors of the glaciomarine sediment are exposed at the seafloor. These are most common the northwestern side of the Passage, and the muddy sands collected from this area (Figure 6) probably represent reworked glaciomarine sediment.

In the East Passage a large outcrop of sand and gravel partly constricts the channel between Islesboro Island and the mainland (Figure 6). Seismic profiles reveal that this deposit is similar in size and shape to the nearby Waldoboro Moraine (Smith, 1982), and it has been interpreted as a seaward extension of that moraine (Figure 22)(Knebel and Scanlon, 1985). In only a few places is the gravel deposit mantled by what appears to be glaciomarine mud.

Shelf Valleys, Rocky Zones and Outer Basins

Because of the large number of protective islands and shoals, features mapped as Shelf Valleys are relatively few (Figure 5). The major Shelf Valley exists along the western side of the embayment and continues into Muscongus Bay (Figure 5) (Kelley and Belknap, 1988). In its deepest area the valley exhibits more than 50 meters of relief, and is very steep sided (Figure 23). Bedrock forms the valley walls and is only very thinly covered by what is interpreted as Holocene sediment at its bottom. The adjacent Rocky Zones are similarly covered by only a few meters of sand and gravel (Figures 5, 6, 23). Although no carbonate analyses were performed, many of the samples from this area contained very carbonate-rich sediment (100% in several samples). In shallower portions of the Rocky Zone (Figures 24, 25) small, and often slumping patches of mud were observed in a few places, but most of the seafloor sediment samples were exposed rock or gravel. No geophysical work has been published from the Outer Basins, but reconnaissance observations suggest that it contains only thin deposits of mud over rock and gravel (Figure 6) (R. Oldale, personal communication). The extremely irregular bathymetry of the area further supports this view.

EVOLUTION AND SEDIMENTARY FRAMEWORK OF THE INNER CONTINENTAL SHELF NEAR PENOBSCOT BAY

The Quaternary sedimentary framework of the Penobscot Bay region has been most-strongly influenced by deglaciation, and the sea-level changes which accompanied it (Stuiver and Borns, 1975; Belknap et al., 1987). Melting ice, possibly in the form of an ice shelf, reached the present Maine coast between 13,800 and 13,200 BP. Many washboard moraines, representing brief grounding-line positions of the ice, were observed in Muscongus Bay (Kelley and Belknap, 1988), although none were recognized from Penobscot Bay. The large, complex moraine in West Passage (Figure 22) represents a more important time of glacial sediment deposition, which probably took longer to form than the smaller washboards. Thrust-like structures within the moraine suggest small readvances of the ice over its own sediment. The size and great depth of occurrence (75 meters) of the moraine imply that by the time ice reached central Penobscot Bay, it was grounded, and no longer an ice shelf.

Accompanying retreat of the ice, glaciomarine sediment, the Presumpscot Formation, was deposited. In some places the lower portions of the of the seismic unit interpreted as glaciomarine sediment appears acoustically transparent (Figure 20), suggesting a muddy deposit. In most other locations the lower portion of this acoustic unit displays closely-spaced seismic reflectors indicative of rapid deposition of beds of coarse and fine grained sediment (Figure 21). It appears that most of the depressions of Penobscot Bay were rapidly filled with this glaciomarine sediment during deglaciation. Fossils from the emergent glaciomarine sediment typically yield radiocarbon dates around 12,500 BP (Stuiver and Borns, 1975; Smith, 1982). By 11,000 BP it is felt that sea level had withdrawn to the elevation of the present coast (Belknap et al., 1987) as a consequence of isostatic uplift due to unloading of the ice. The Presumpscot Formation was then exposed to subaerial erosion sometime between about 11,000 BP and 9,500 BP. By 9,500 BP it is inferred that sea level was at its lowstand around 60 meters below present sea level. No information on the depth of the lowstand has yet been uncovered from Penobscot Bay.

The upper part of the glaciomarine sediment is marked by a strong reflector which has been recognized from cores as an unconformity (Ostericher, 1965; Knebel, 1986). In one location a reflector representing the regressive unconformity was interpreted from Penobscot Bay (Figure 20). It is covered by clinoform reflectors which are interpreted as fluvial beds from the Penobscot River (Knebel, 1986). As sea level rose the river probably began to fill the valley it had cut into the glacial sediment. In the outer bay where the channel of the Penobscot River was restricted by a narrow bedrock gorge, no sediment was deposited. Observations in Muscongus Bay reveal considerable deposition of mud at the terminus of the Penobscot River's paleochannel, but no sandy delta, as was found off the Kennebec River (Kelley et al., 1987b).

The regressive unconformity on the surface of the glaciomarine sediment is only interpreted from one location where a thick deposit of river sediment covered it. In most locations, the strong acoustic reflector at the top of the unit represents the transgressive unconformity. Where this was cored, a sandy, gravel lag deposit was found. A piece of wood dated from this deposit at 20 meters depth produced a 7,390 +/- 500 radiocarbon date, presumably representing the time the surf zone passed that depth (Ostericher, 1965).

Much of the sediment which had existed in the bay was reworked during either the late Pleistocene regression or the Holocene transgression. The extensive, shallow Rocky Zones represent what remains following that reworking. Only in the more-protected Nearshore Basins and Shelf Valleys were important thicknesses of sediment preserved (Knebel, 1986) (Figure 26). Even here, however, currents have apparently begun to remove glaciomarine mud where it is well exposed (Figure 21). Slumping may even be as important in Penobscot Bay as it appears to be in Casco Bay (Kelley et al., 1987a; 1989) (Figure 25). Ostericher (1965) commented often on the number of slump deposits he interpreted from the area.

At some point after a considerable thickness of Holocene sediment had accumulated in upper Penobscot Bay, natural gas was generated and began to accumulate in the fine grained sediment. For reasons that are not yet clear, the gas apparently began to escape from the sediment, possibly in conjunction with pore waters (Scanlon and Knebel, 1989). Once a small pockmark was begun it is simple enough to envision additional gas and water migrating from nearby sediment and enlarging the depression. Scouring of a hole apparently ceased when the bottom reached the surface of the Presumpscot Formation, and the end of the natural gas. What caused the gas to be released in the first place (if indeed this is the cause of the pockmarks), we do not know. When they began to form, and whether they are still forming, we do not yet know either. We have recognized no other features like the Penobscot Bay pockmarks along the coast of Maine, although Fader et al. (1989) have recently described similar features from the U.S.-Canadian boundary. They invoked seismicity as the mechanism for initiation of the pockmarks, and this idea is plausible in Penobscot bay as well. On nearby Sears Island Rand and Gerber (1976) recognized Quaternary faulting during an investigation for siting a power plant. Much more remains to be learned about the pockmarks before all aspects of their occurrence are explained.

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Table 1

Quaternary Geology of Central Maine and Adjacent Inner Continental Shelf Region: Previous Work

Study	Location	Data
Stone, 1899	Central Maine	Terrestrial mapping of moraines
Leavitt and Perkins, 1935	Central Maine	Terrestrial mapping of moraines, marine sediment
Bloom, 1960	Southwestern Maine	Regional terrestrial mapping
Bloom, 1963	Southwestern Maine	Study of sea level changes
Ostericher, 1965	Penobscot Bay	Seismic stratigraphy, coring
Knebel and Scanlon, 1985	Penobscot Bay	Seismic stratigraphy
Knebel, 1986	Penobscot Bay	Seismic stratigraphy
Kelley et al., 1987a	Southwestern Maine inner shelf	Seismic stratigraphy, bottom samples
Kelley et al., 1987b	South central Maine inner shelf	Seismic stratigraphy, bottom samples
Kelley and Belknap, 1988	Muscongus Bay	Seismic stratigraphy, bottom samples
Scanlon and Knebel, 1989	Penobscot Bay	Side-scan sonar
Stuiver and Borns, 1975	Coastal Maine	Study of sea level changes
Smith, 1982	Coastal Maine	Terrestrial mapping of moraines
Thompson and Borns, 1985	Maine	State surficial map
Smith, 1985	Southwestern Maine	Regional terrestrial mapping

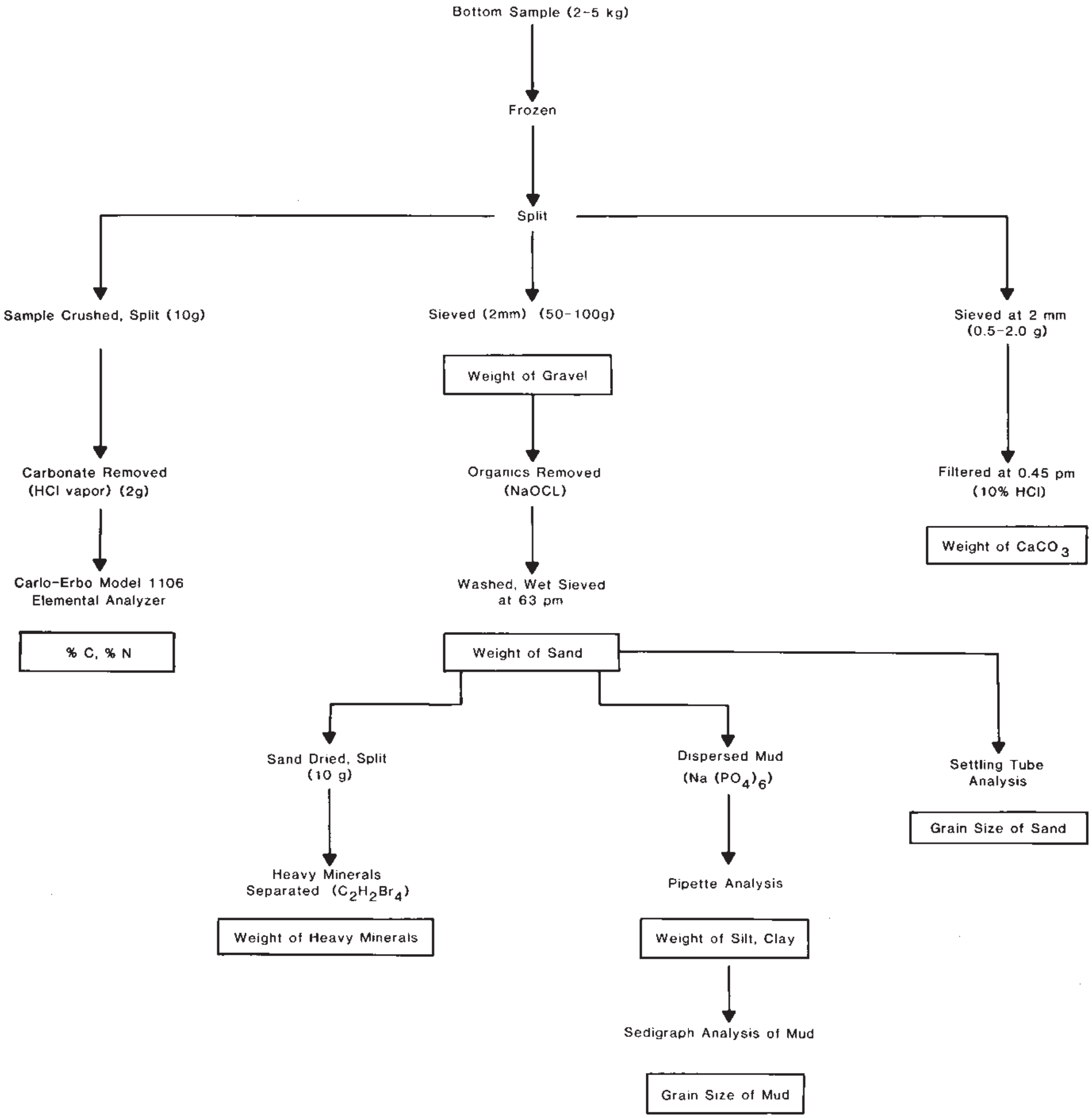


Table 2. Flow diagram for laboratory analyses.

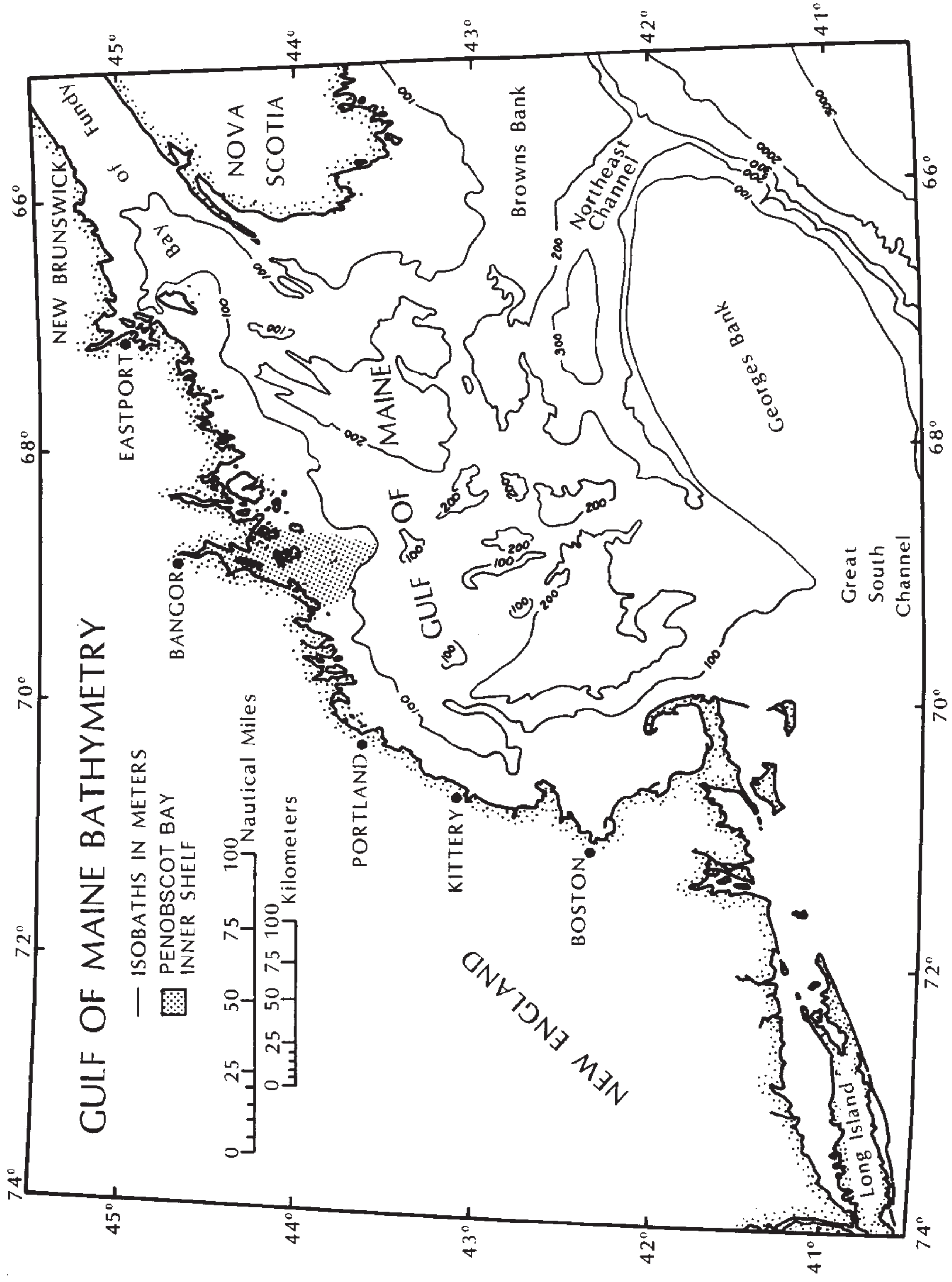


Figure 1. Location of the study area in the western Gulf of Maine.

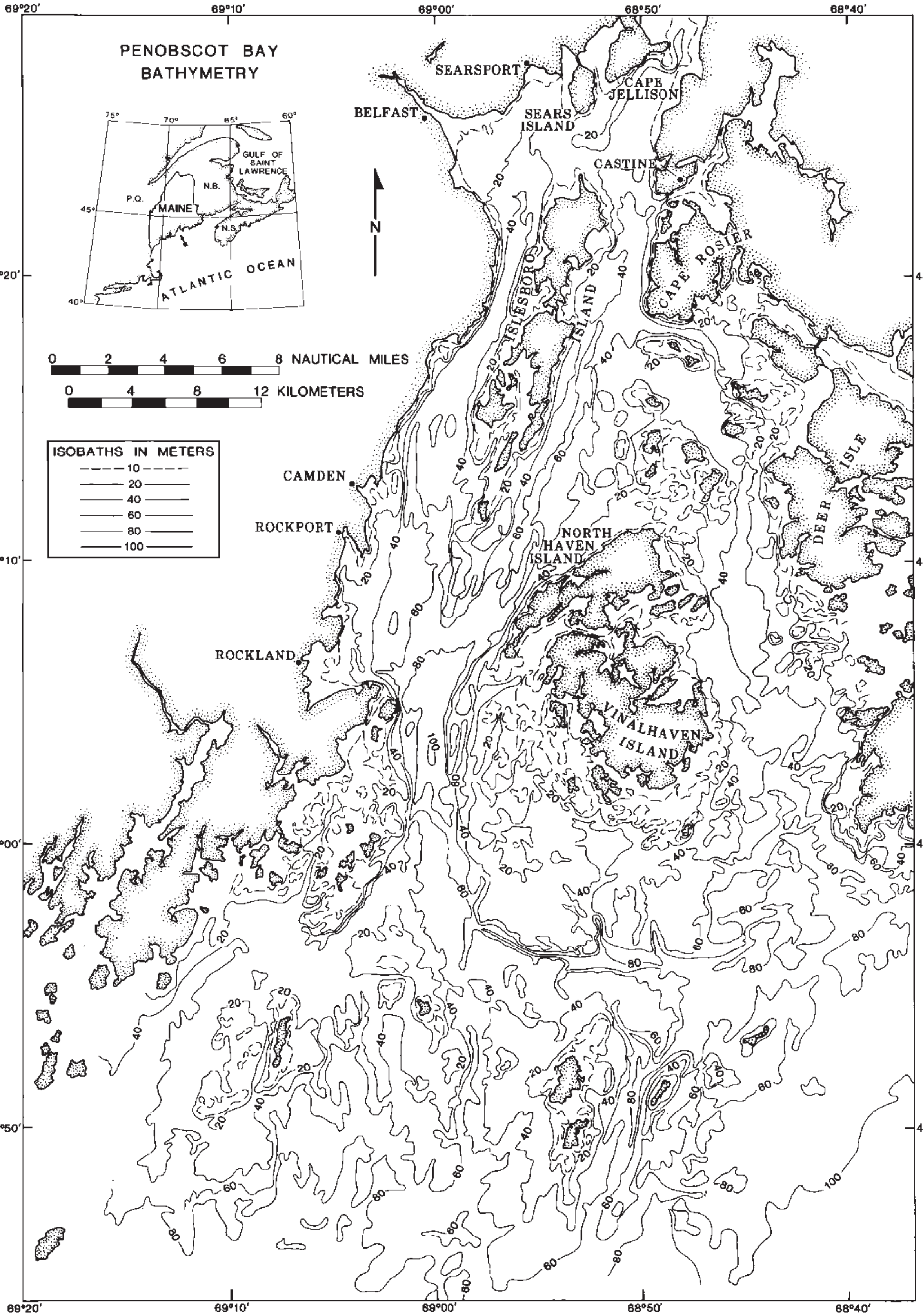


Figure 2. Penobscot Bay bathymetry and locations.

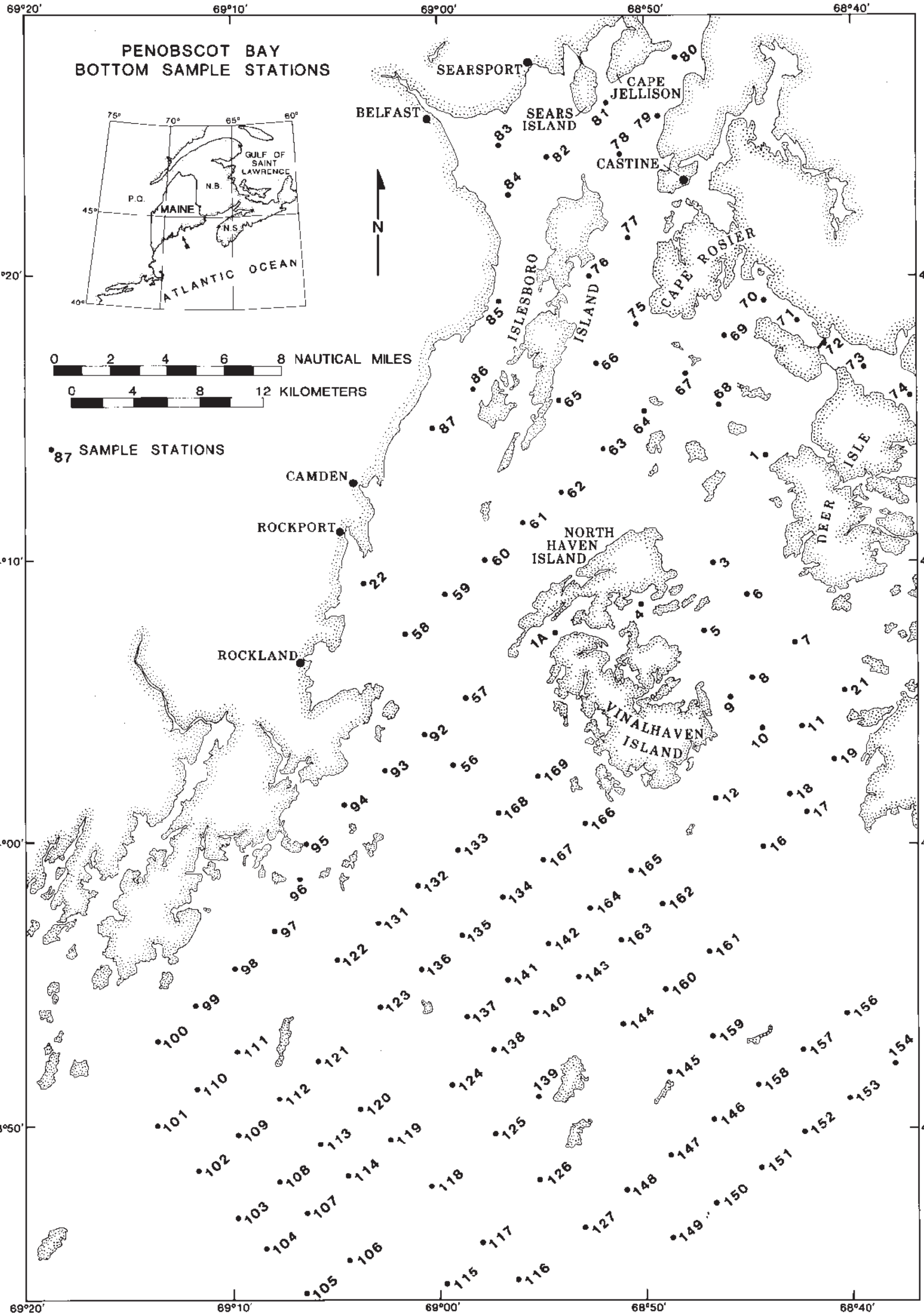


Figure 3. Bottom sample locations.

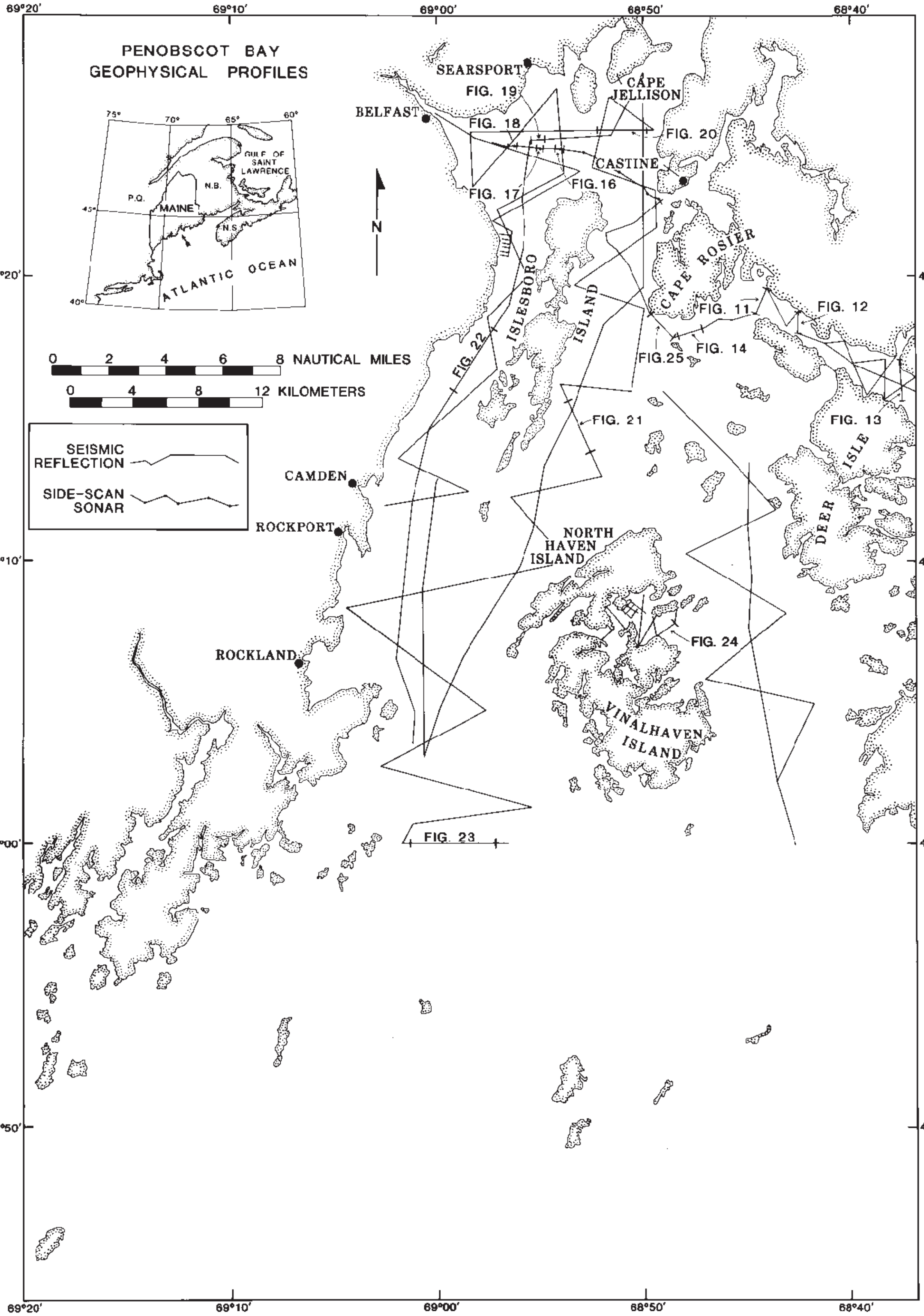


Figure 4. Location of geophysical tracklines in Penobscot Bay. Those used in the text are indicated by figure number.

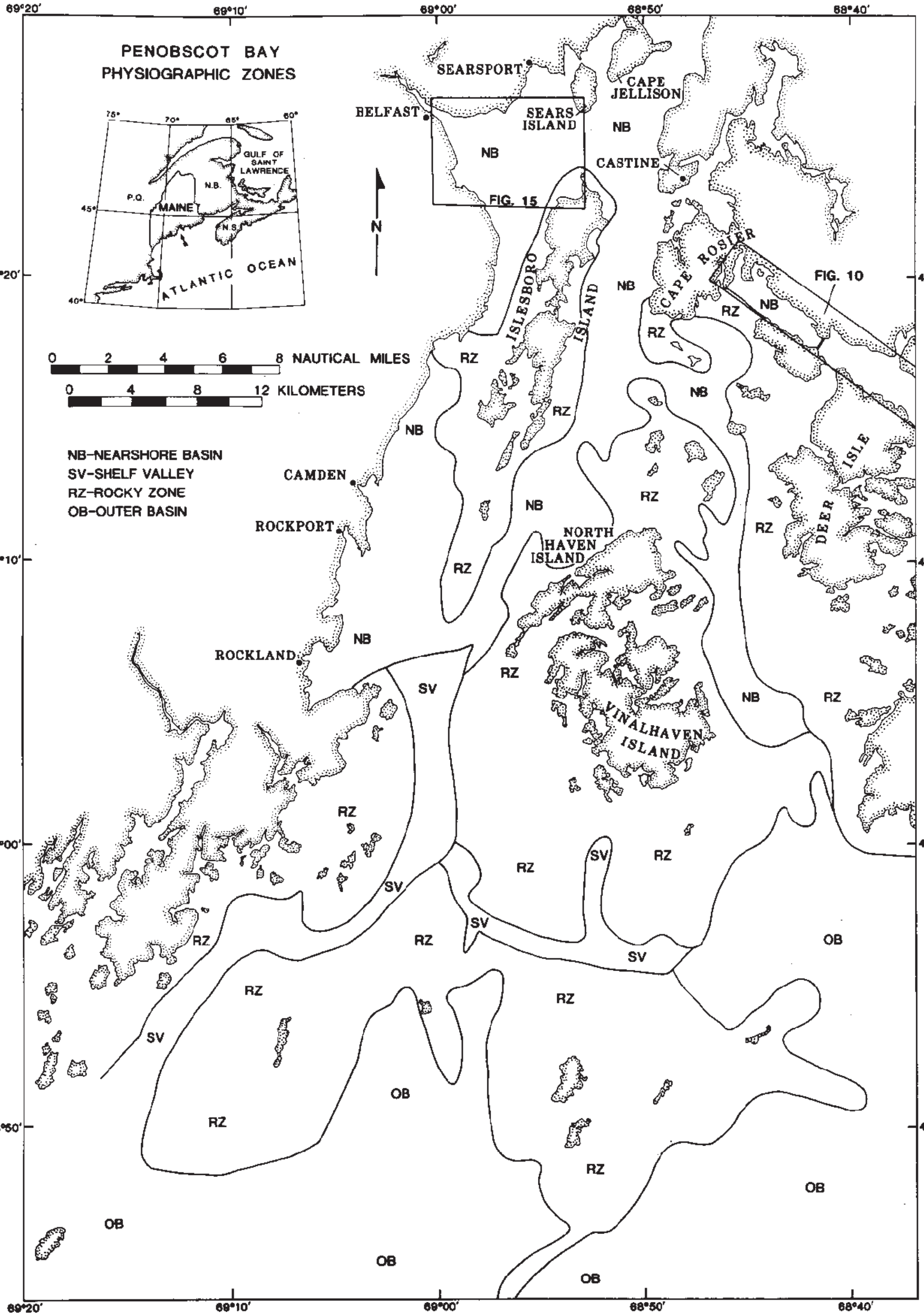


Figure 5. Physiographic regions of Penobscot Bay.

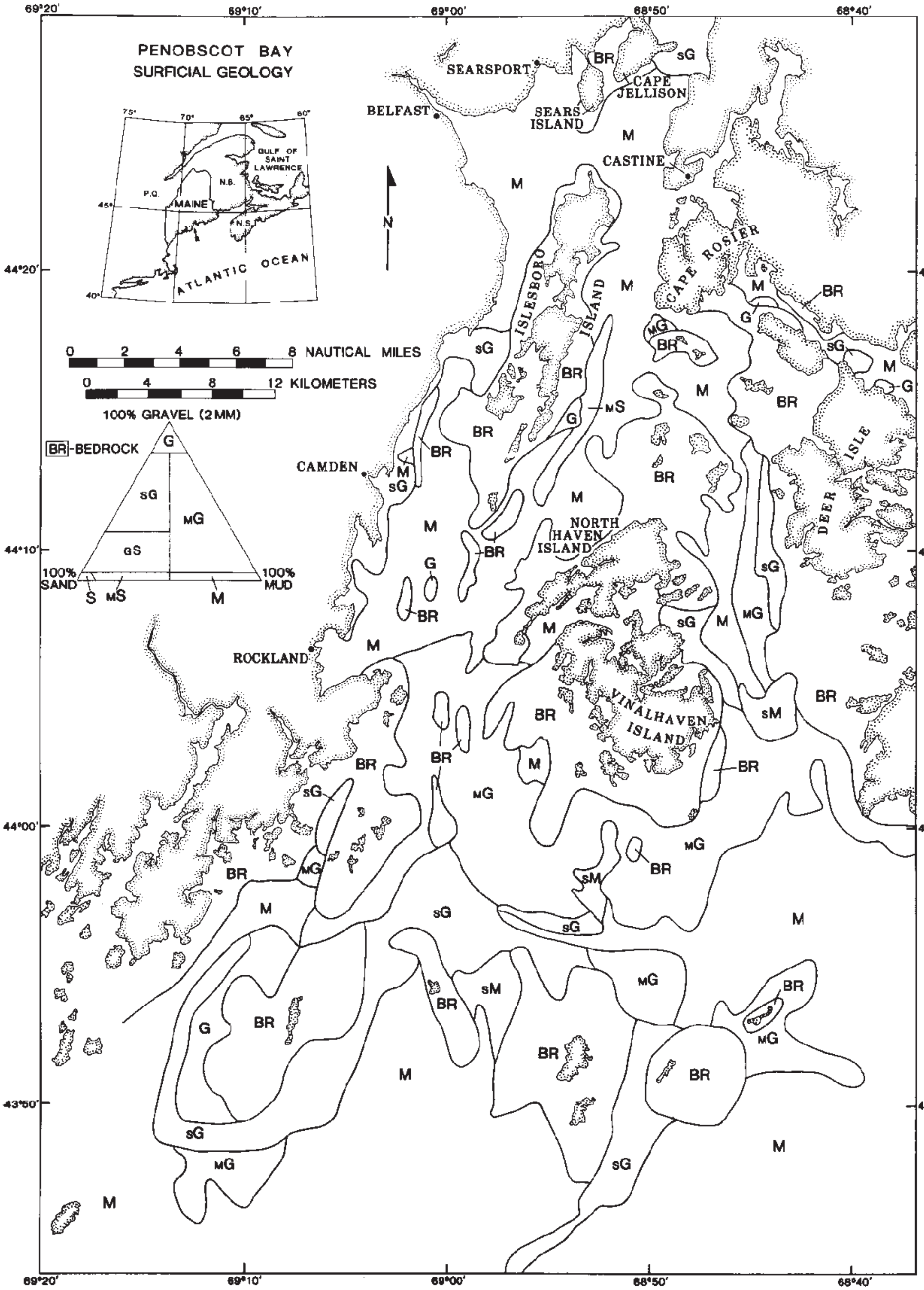


Figure 6. Bottom sediment texture for Penobscot bay. This map was based on, and extrapolated from bottom samples and geophysical observations indicated in figures 3 and 4. It is of note that much more variation of bottom sediment exists than can be shown at this scale.

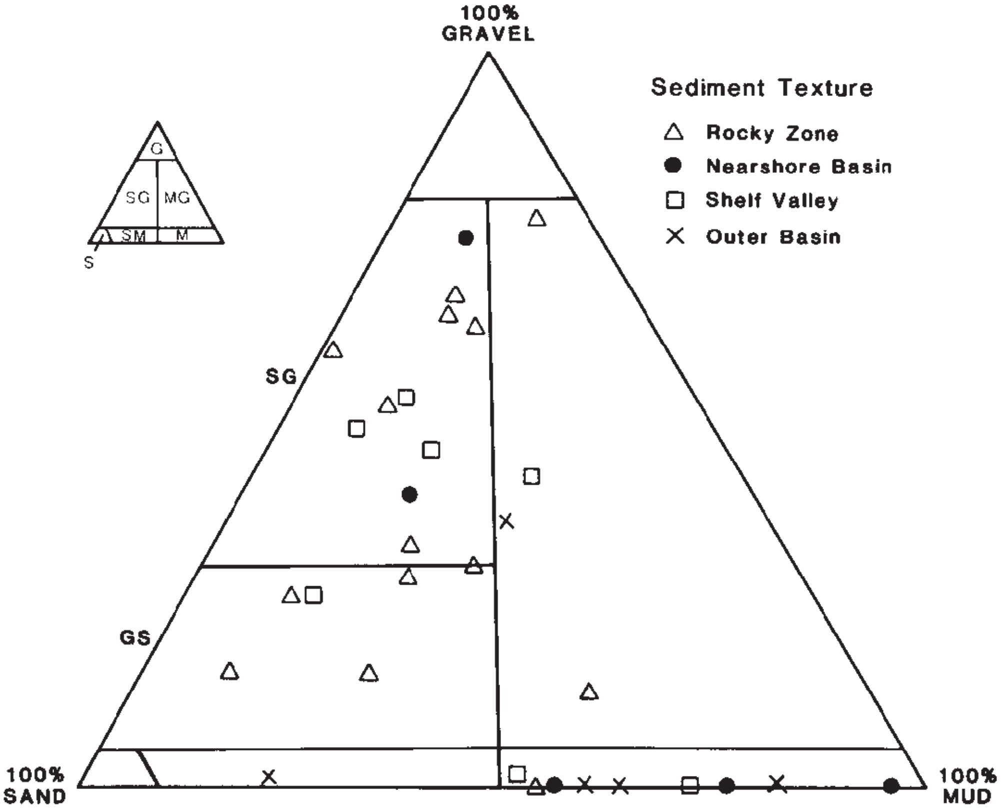
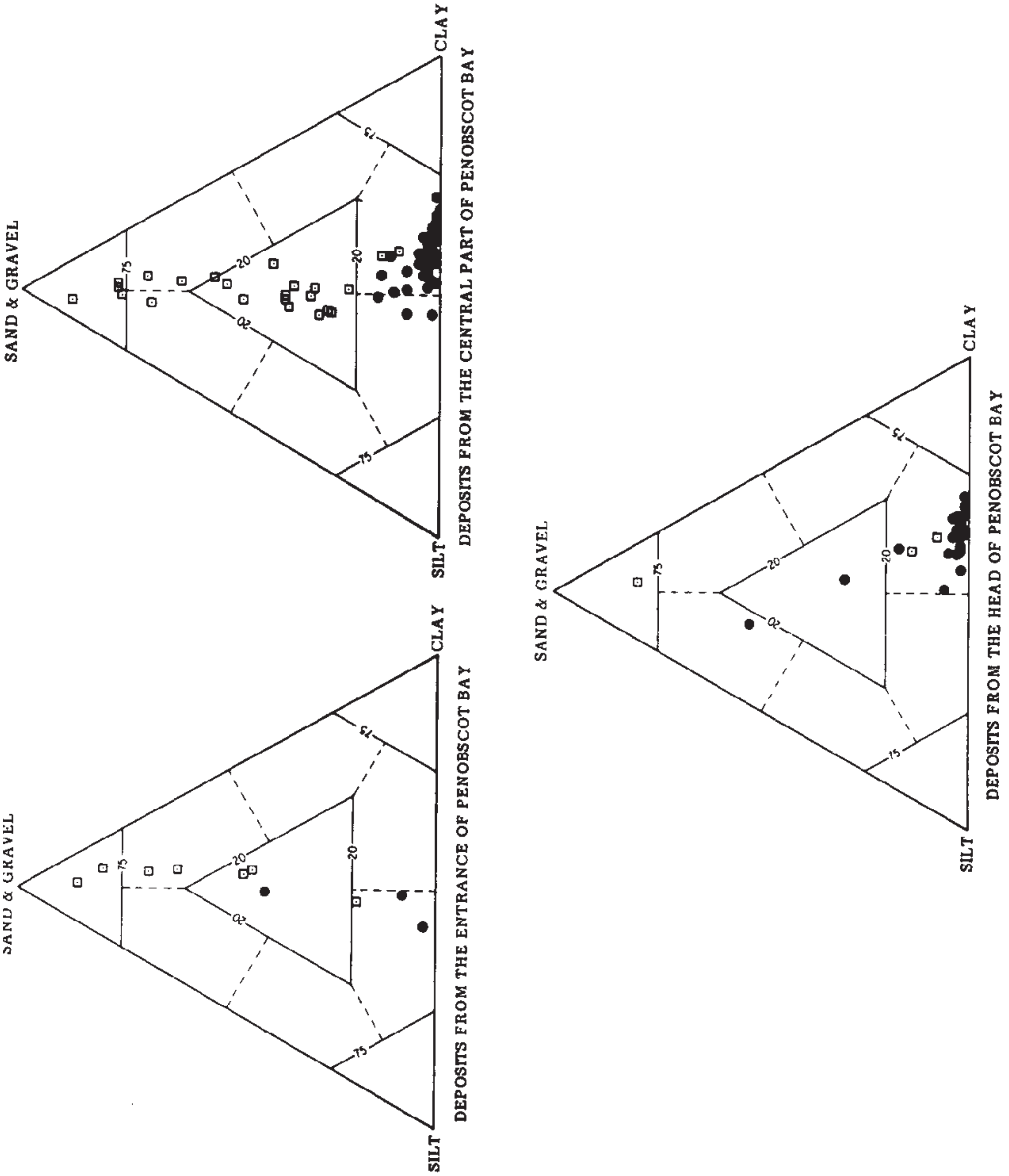


Figure 7. Sediment grain size for select Penobscot Bay samples.



DEPOSITS FROM THE ENTRANCE OF PENOBSCOT BAY

DEPOSITS FROM THE CENTRAL PART OF PENOBSCOT BAY

DEPOSITS FROM THE HEAD OF PENOBSCOT BAY

Figure 8. Grain size of samples collected by Ostericher as presented by Knebel (1986).

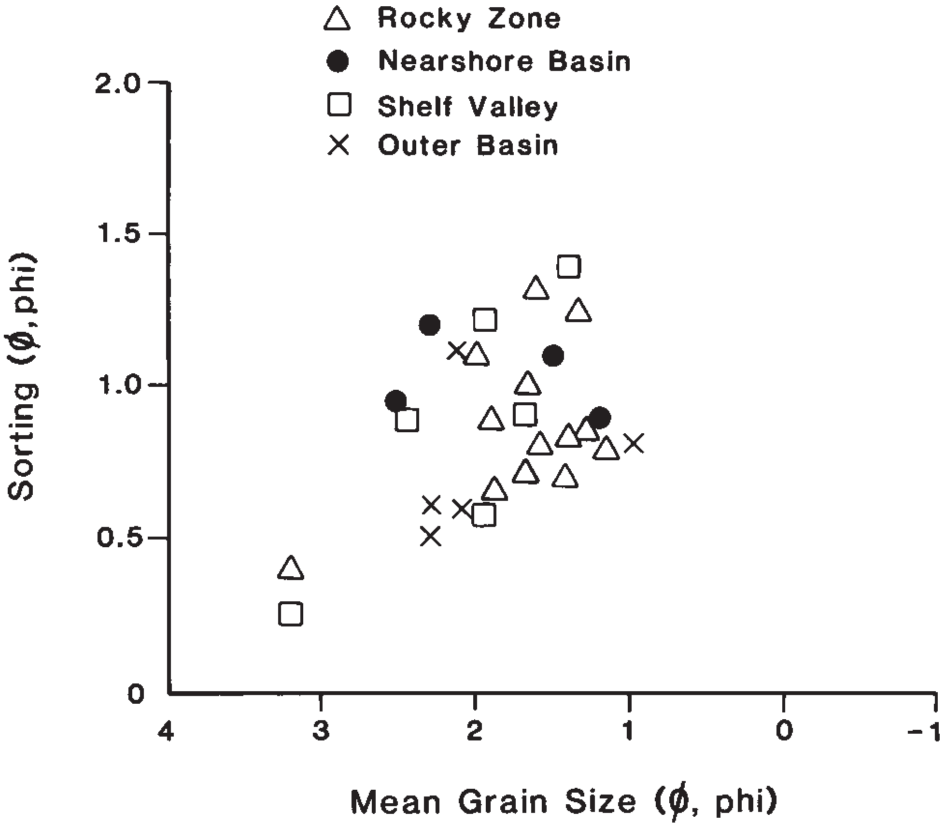


Figure 9. Mean grain size versus sorting for select Penobscot Bay samples. Only the sand fraction of the samples is presented.

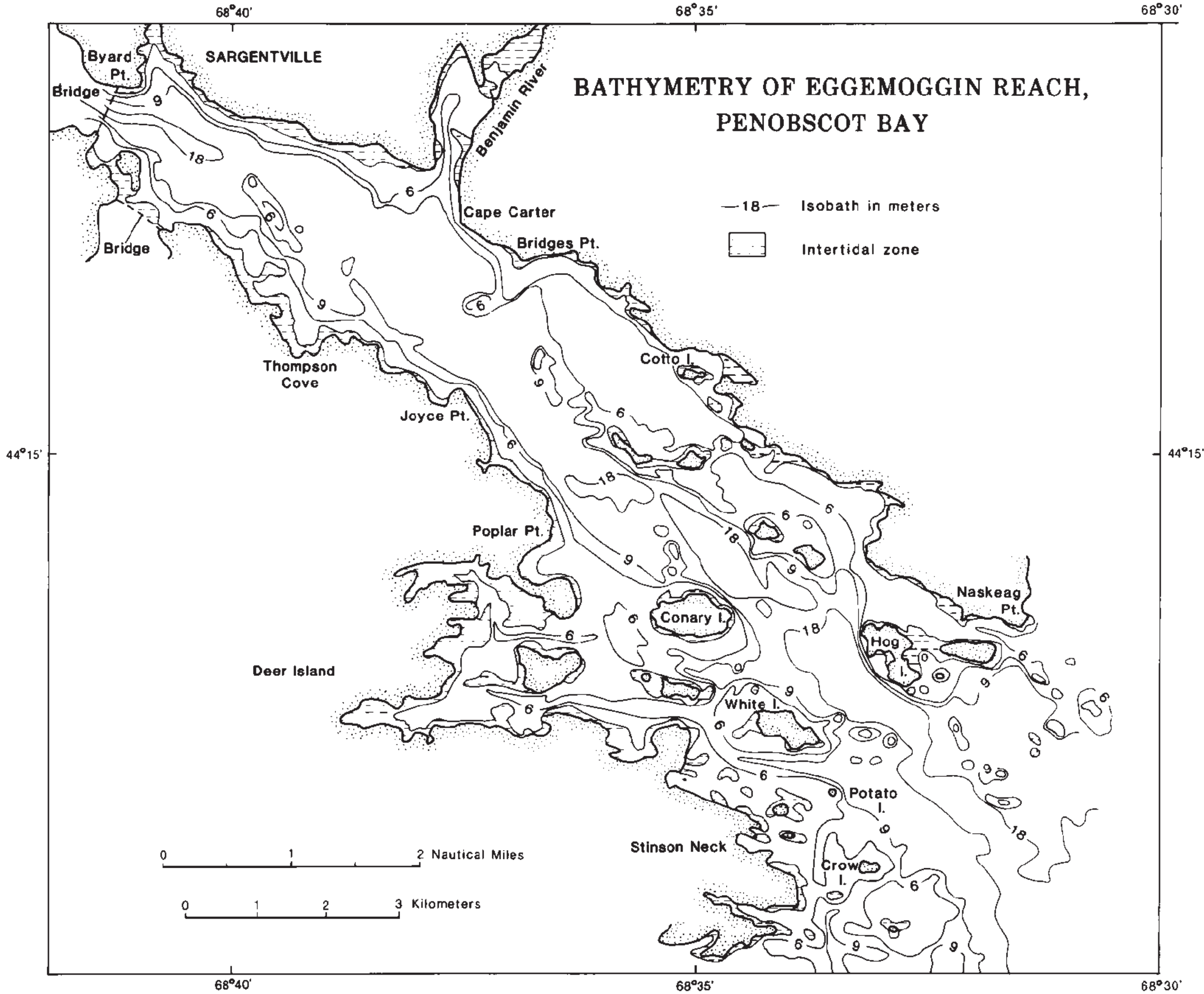


Figure 10. Bathymetry of Eggemoggin Reach. This map is taken from Kelley et al., 1989 (in press). Map location is shown on figure 2.

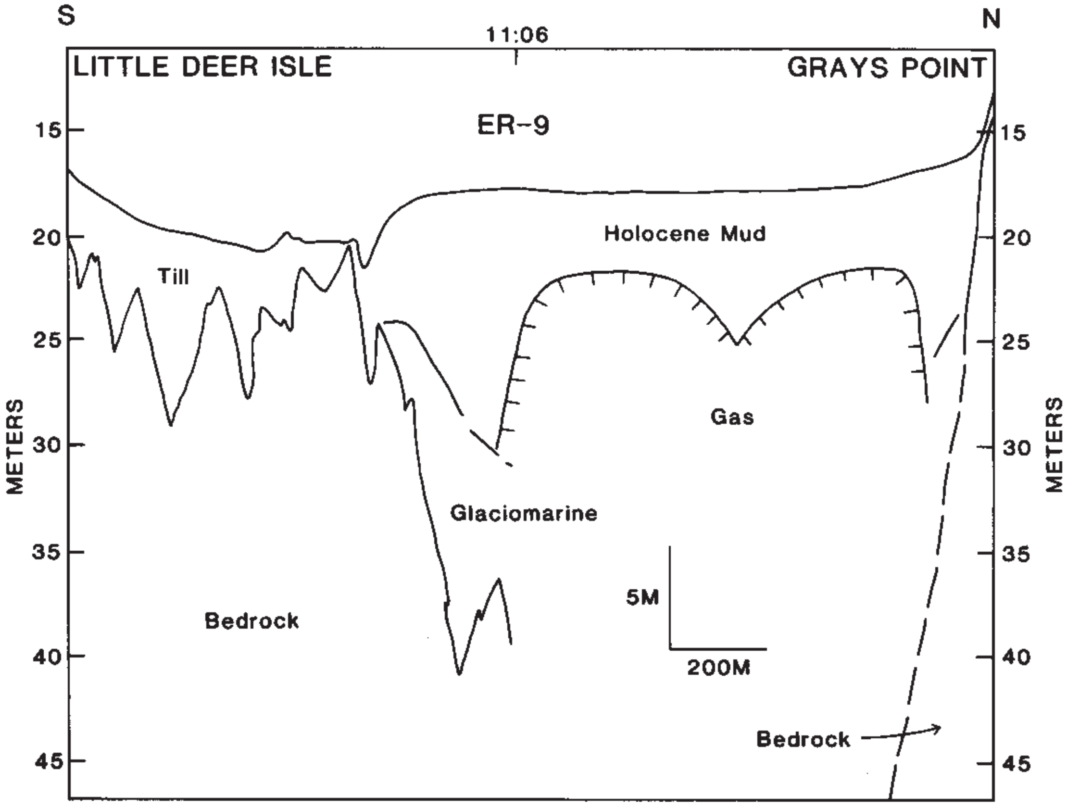


Figure 11. Seismic reflection profile across Eggemoggin Reach, contrasting the central portion of the Reach, with a thick deposit of muddy Quaternary sediment partly obscurred by natural gas, with the margins, which are only thinly veneered by coarser-grained sediment.

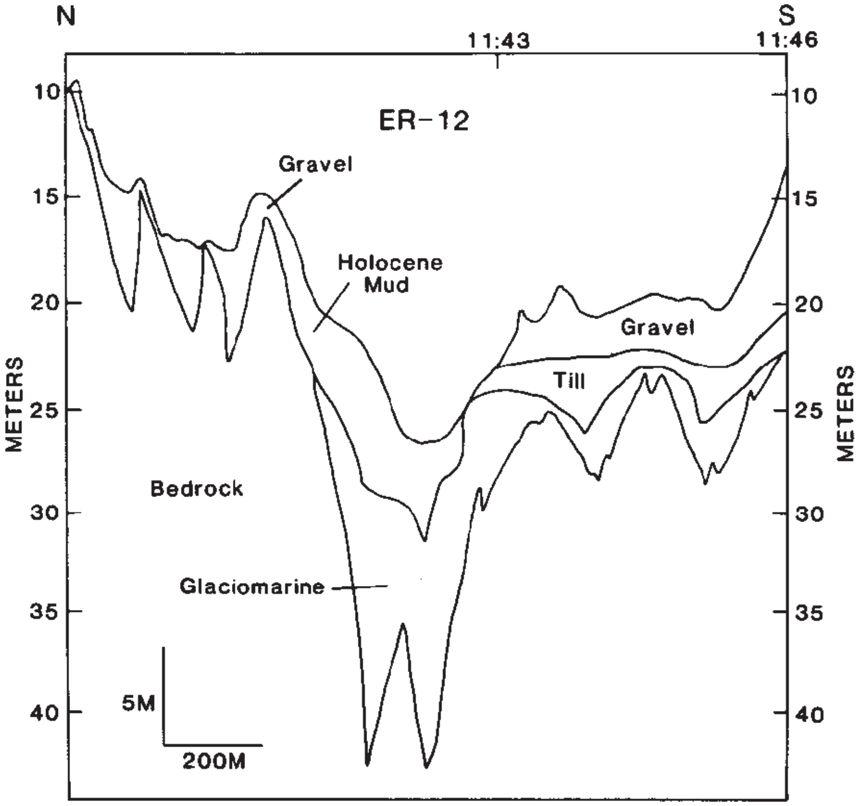


Figure 12. Seismic reflection profile across Eggemoggin Reach. On this cross section bedrock outcrops with overlying till, and modern gravel deposits derived from the till floor the bottom.

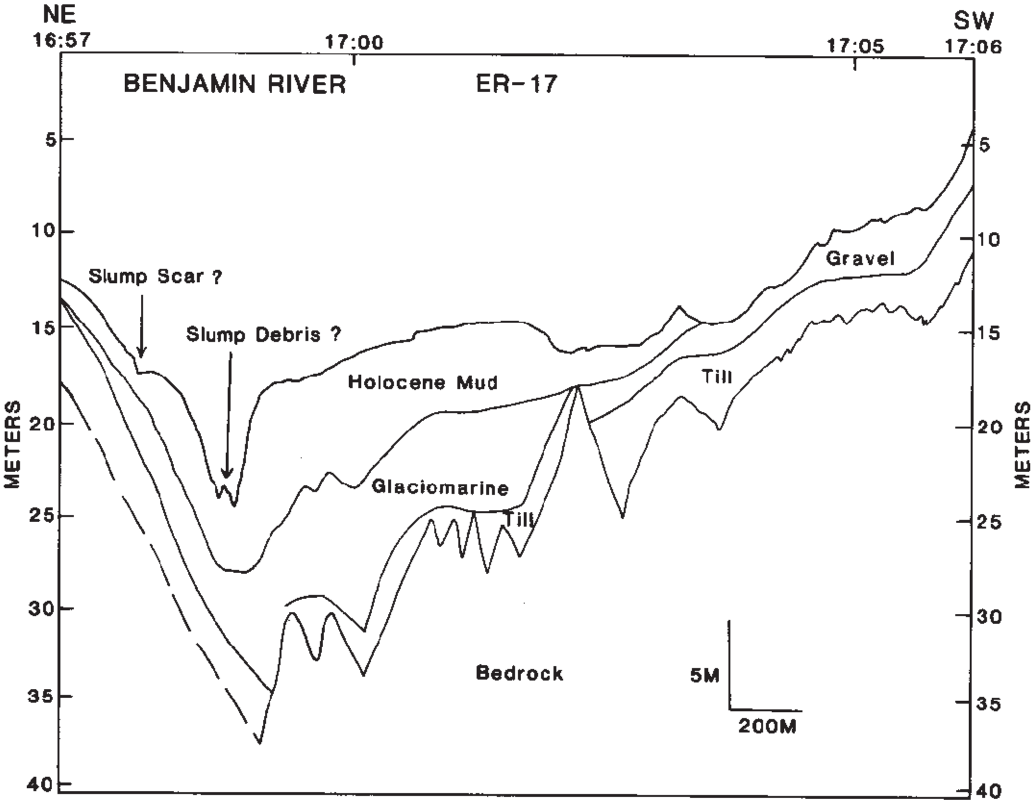


Figure 13: Seismic reflection profile across Egemoggin Reach. A relatively thick wedge of Holocene mud is interpreted from the lee side of a shoal near the Benjamin River. Where the surface of the glaciomarine sediment appears to crop out, gravel appears on the bottom.

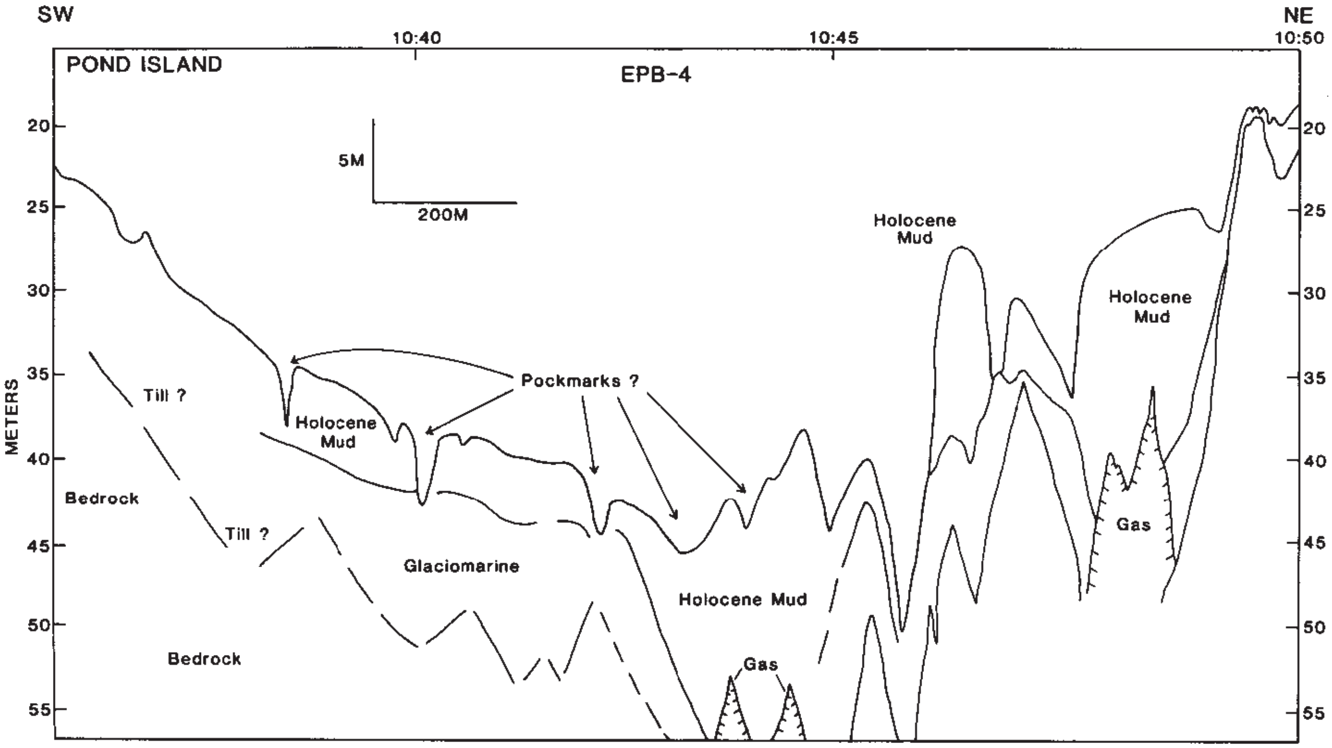


Figure 14. Seismic reflection profile near Eggemoggin Reach. The channel forms appear to be pockmarks in the seafloor.

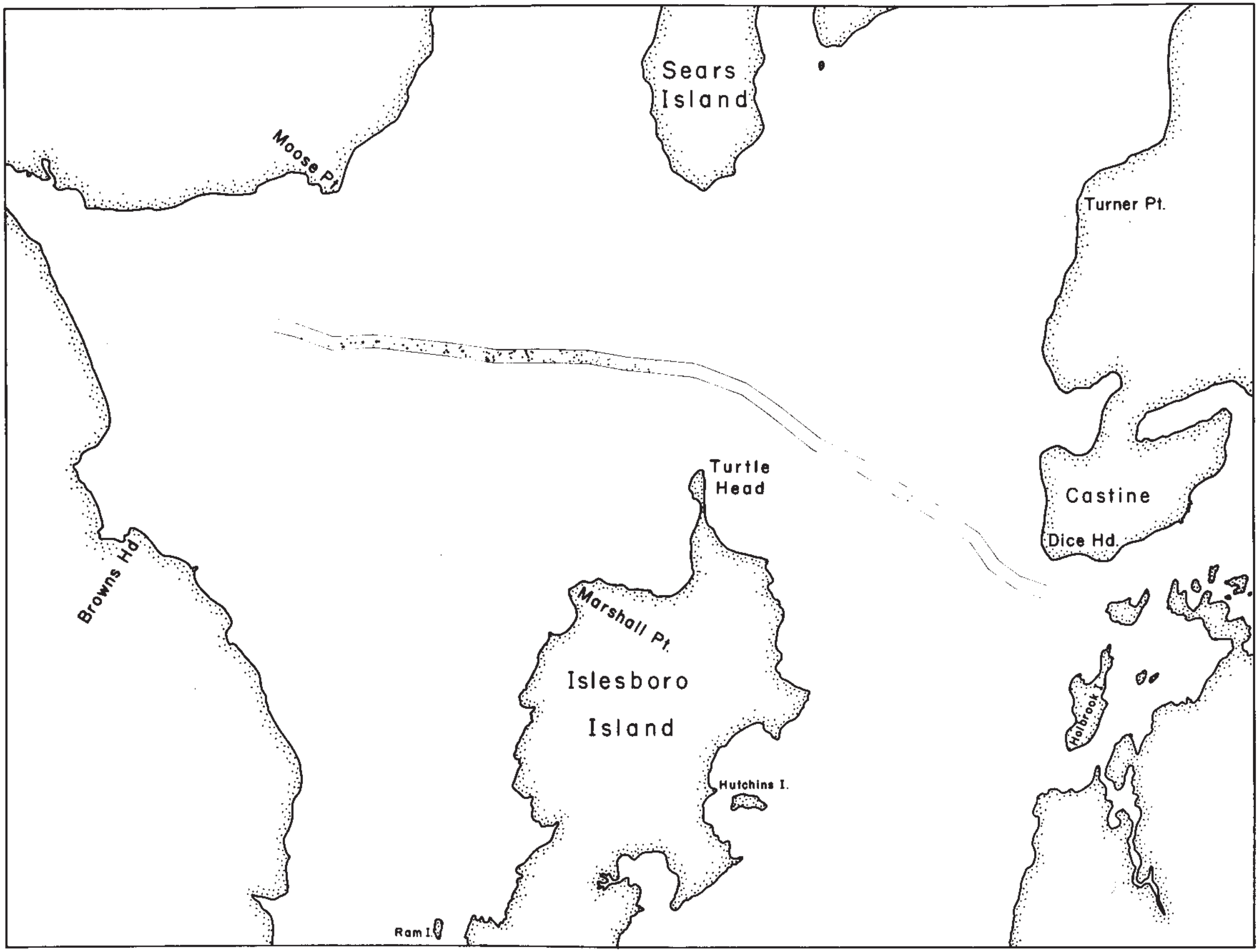


Figure 15. A map of pockmarks in the Belfast Bay area of Penobscot Bay (see Figure 2 for location). The size of the dots reflects the relative size of the pockmarks.

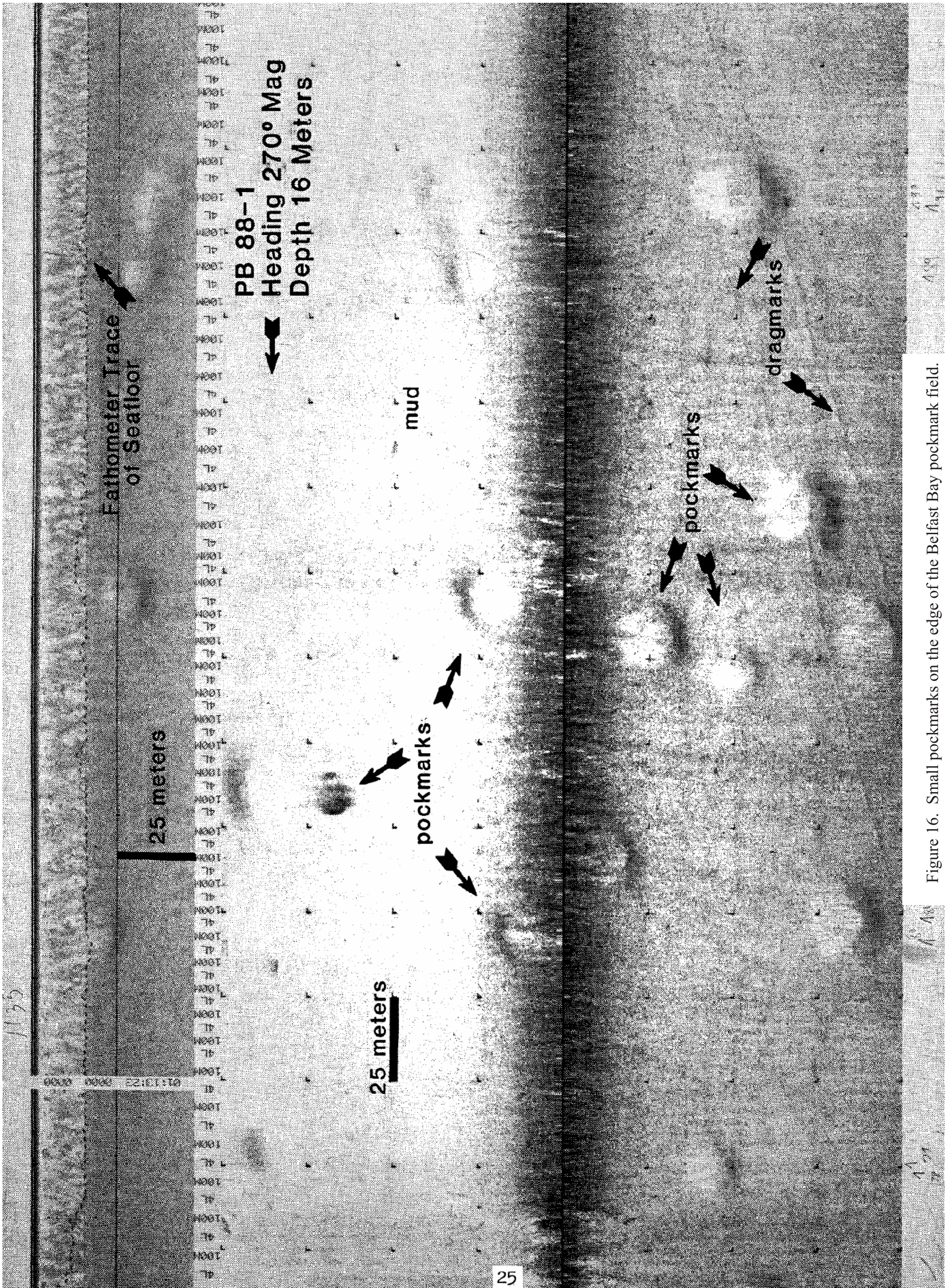


Figure 16. Small pockmarks on the edge of the Belfast Bay pockmark field.

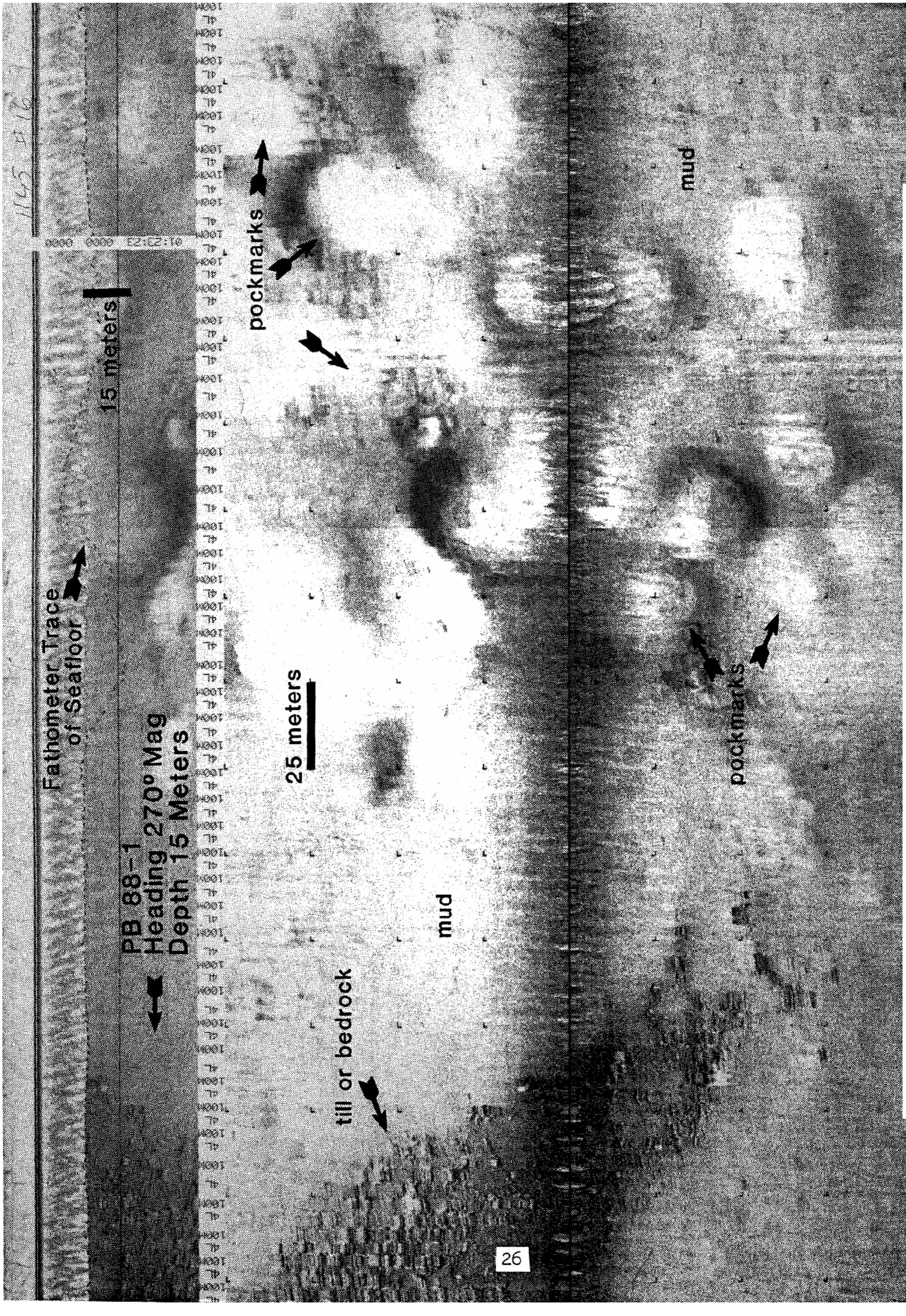


Figure 17. Large pockmarks coalescing near an outcrop of bedrock or till in the Belfast bay pockmark field.

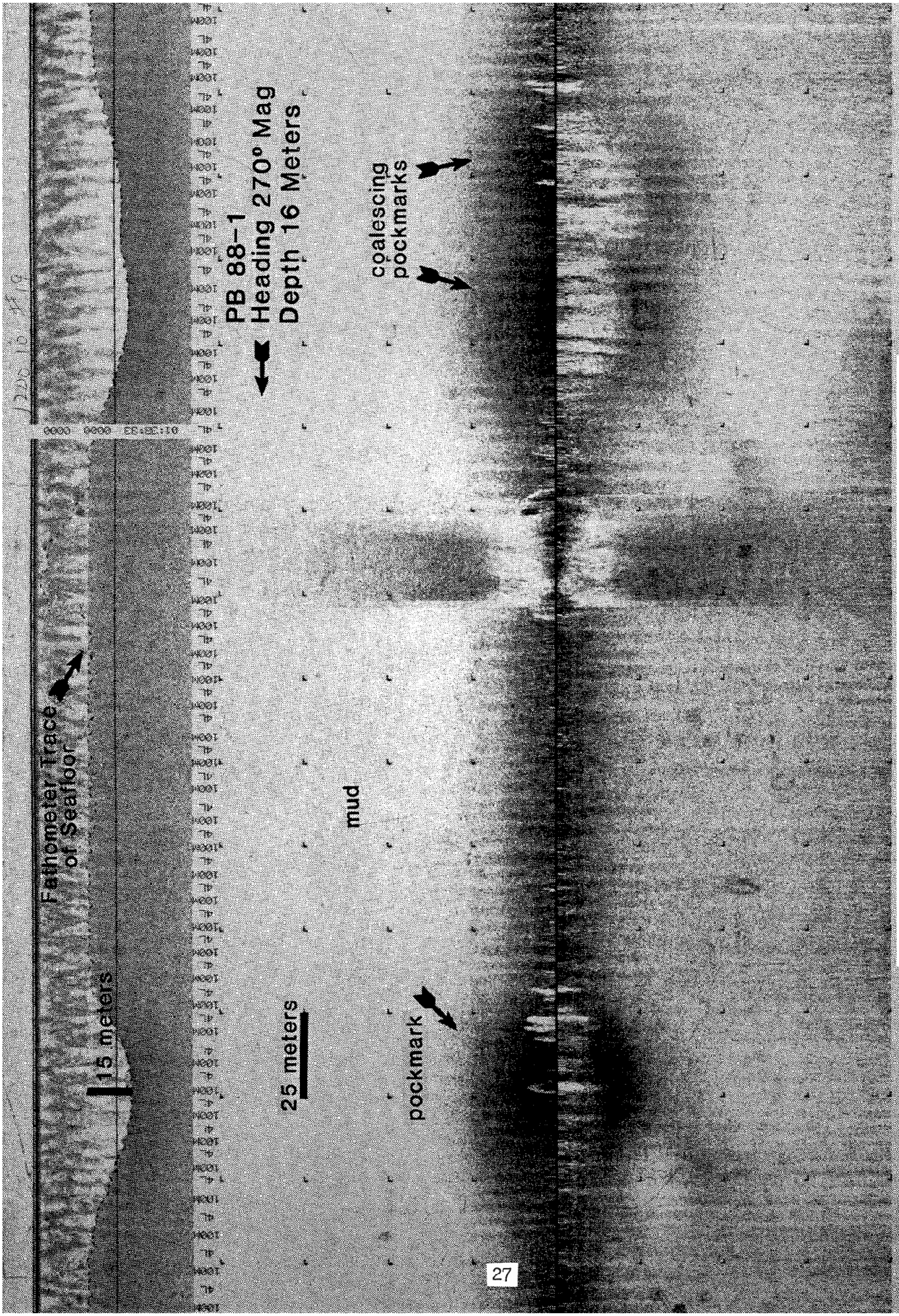


Figure 18. Very large pockmarks in the Belfast Bay pockmark field.

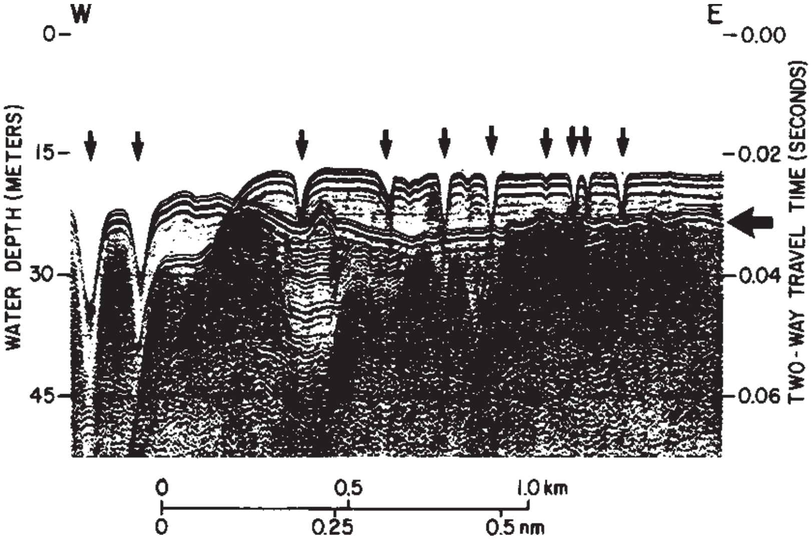


Figure 19. Seismic reflection profile across pockmarks. Note that the bottom of the marks does not penetrate the strong reflector interpreted as the surface of the Presumpscot Formation. Figure from Scanlon and Knebel, 1989.

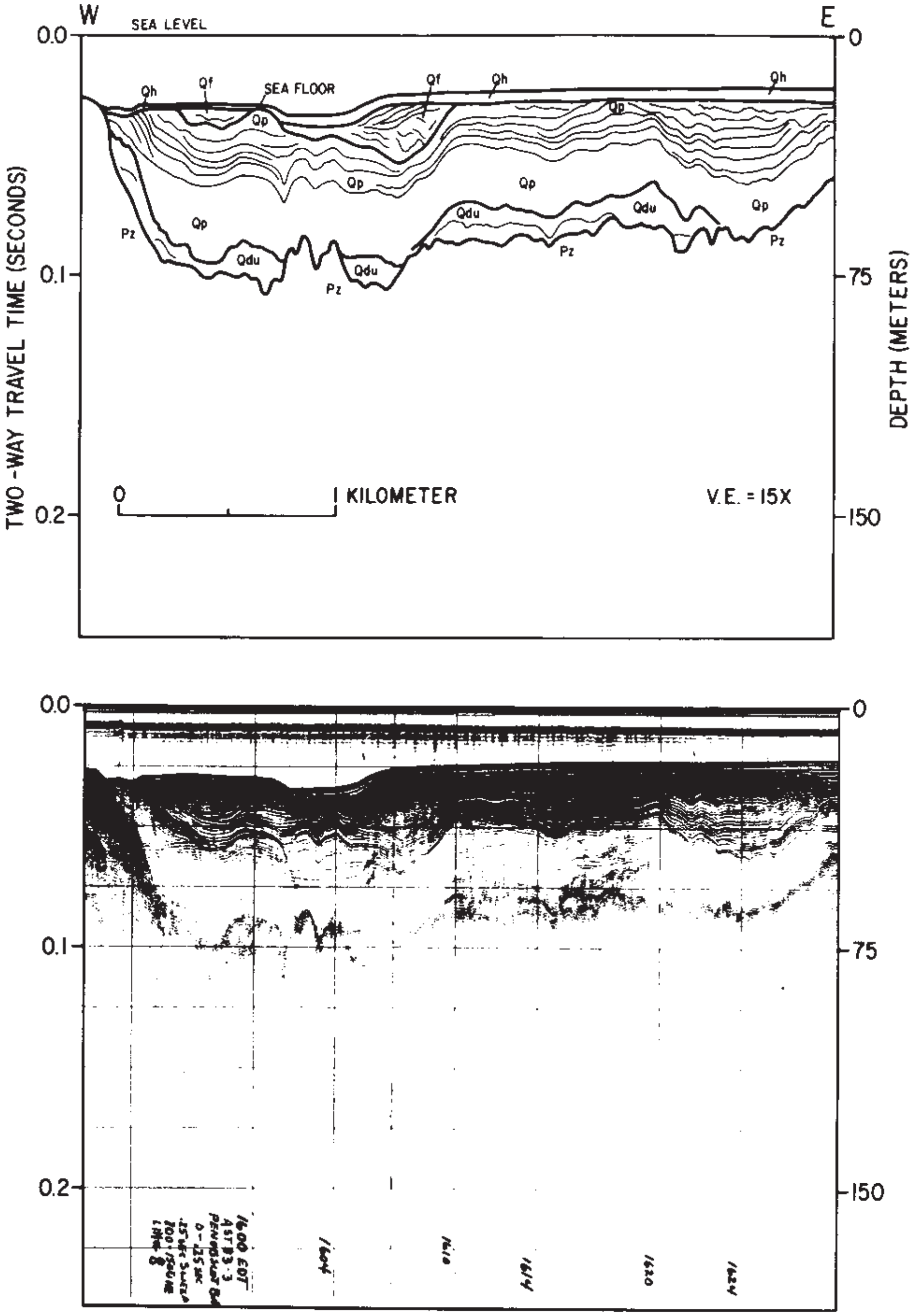


Figure 20. Interpreted seismic reflection profile across the upper portion of Penobscot Bay. Figure from Knebel, 1986.

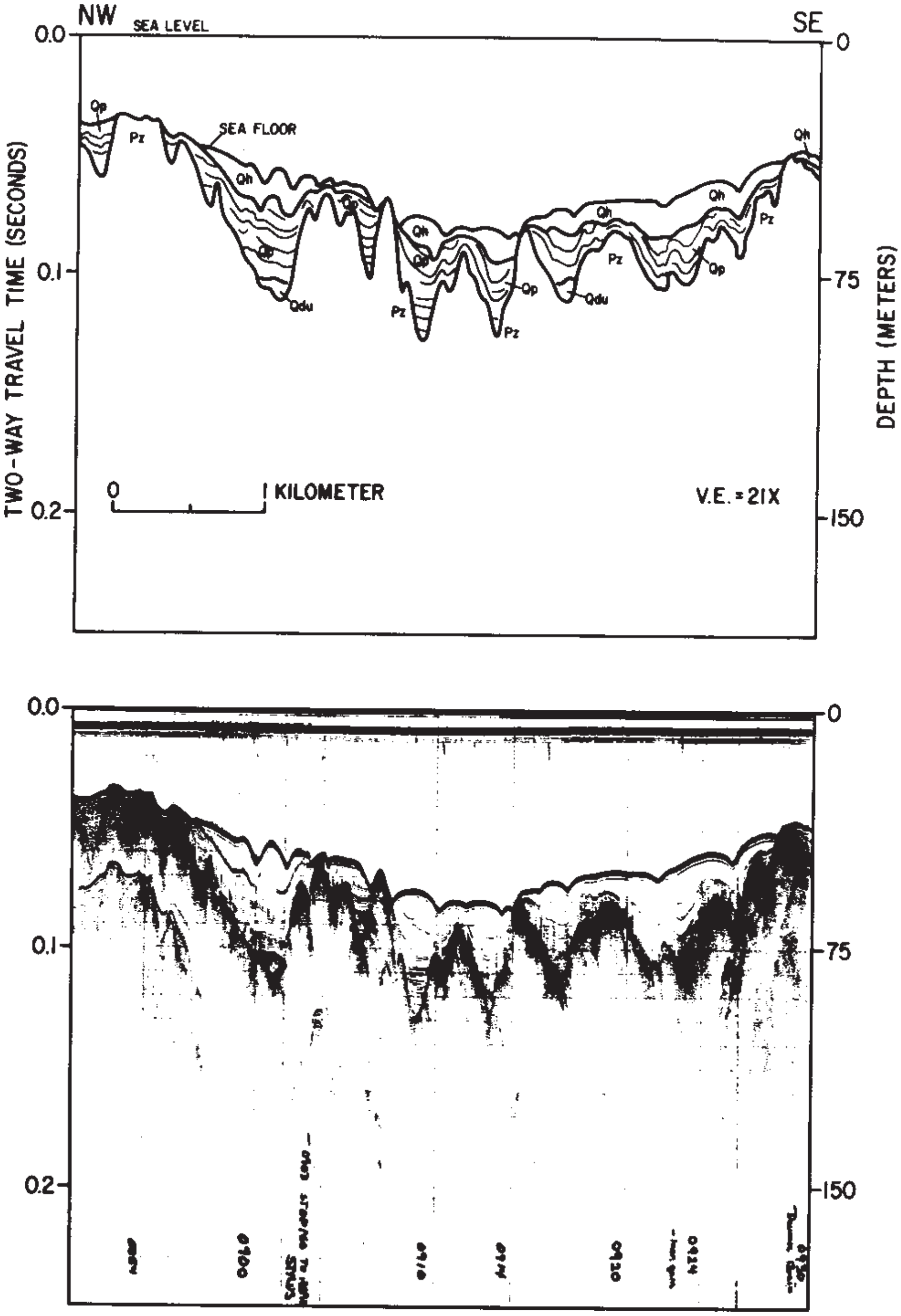


Figure 21. Seismic reflection profile across Middle Passage showing the reworked nature of the seafloor in this exposed area. Figure from Knebel and Scanlon, 1985.

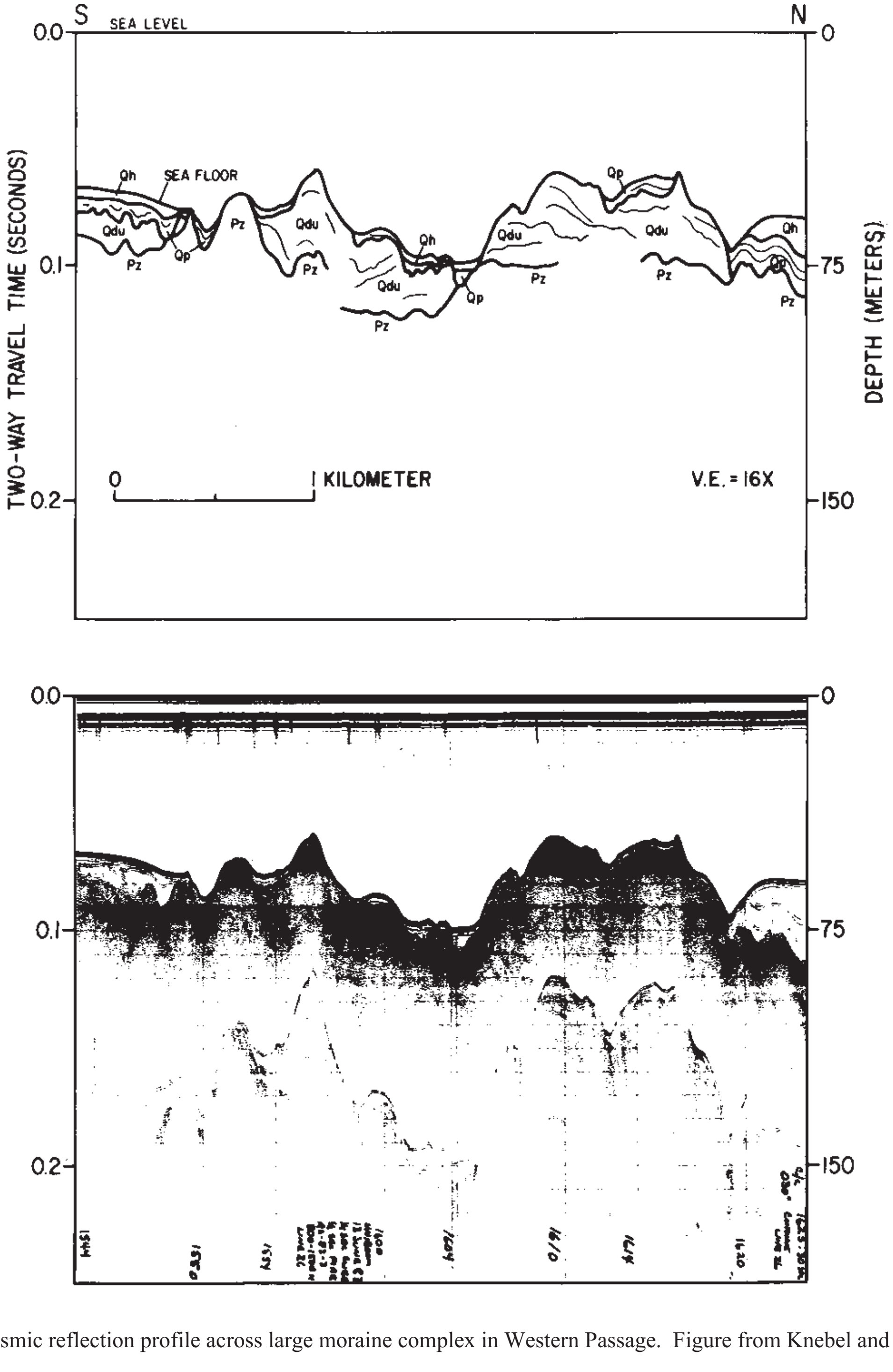


Figure 22. Seismic reflection profile across large moraine complex in Western Passage. Figure from Knebel and Scanlon, 1985.

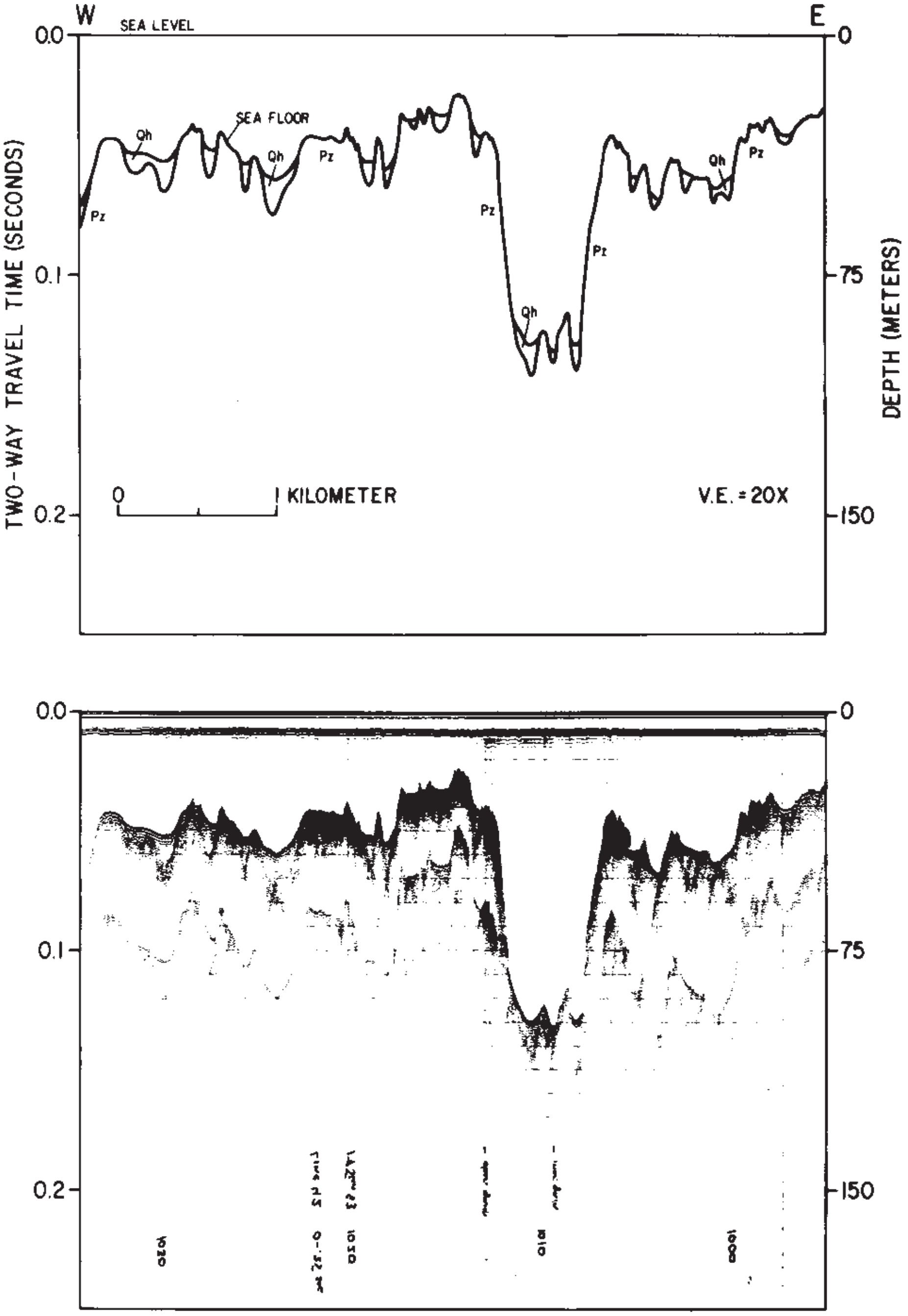


Figure 23. Seismic reflection profile across Shelf Valley of the Penobscot River in outer Penobscot Bay. Figure from Knebel, 1986.

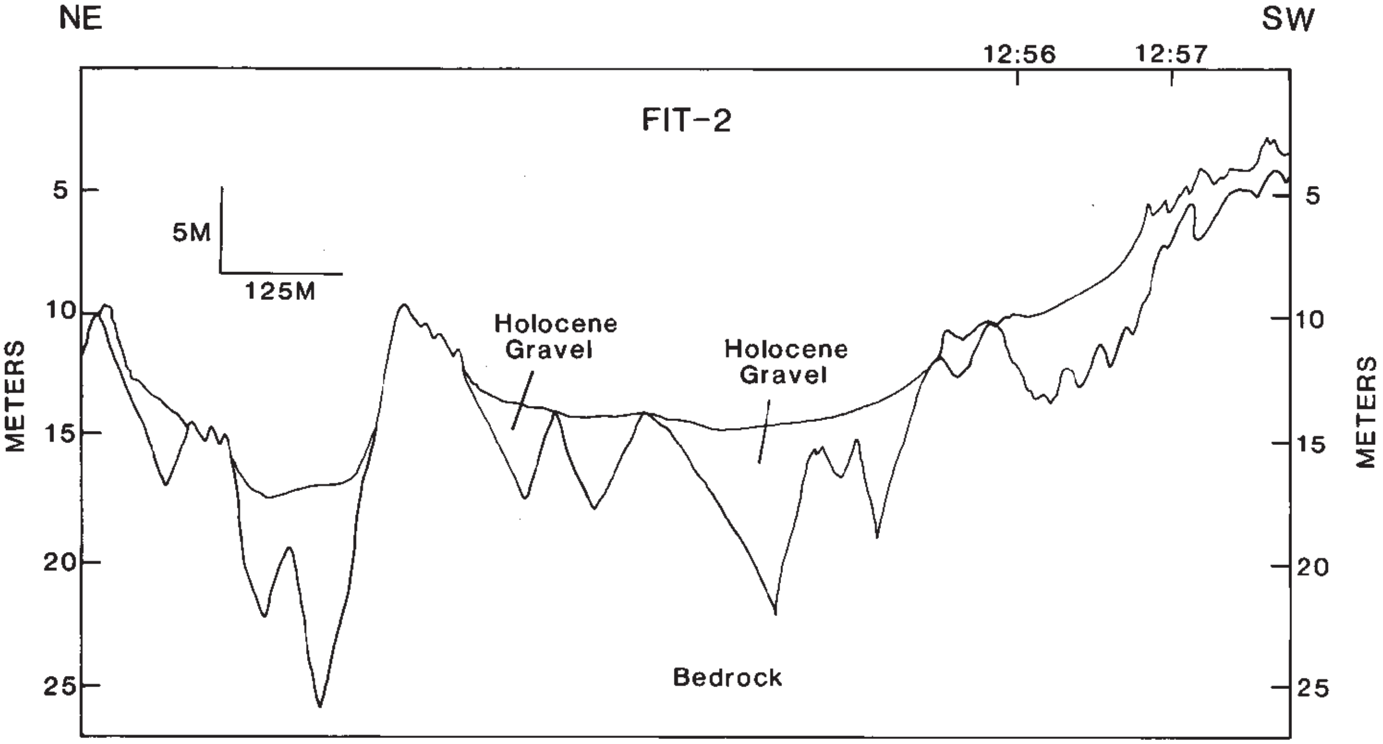


Figure 24. Seismic reflection profile across Fox Island Thoro showing abundant bedrock exposures common in the Rocky Zones.

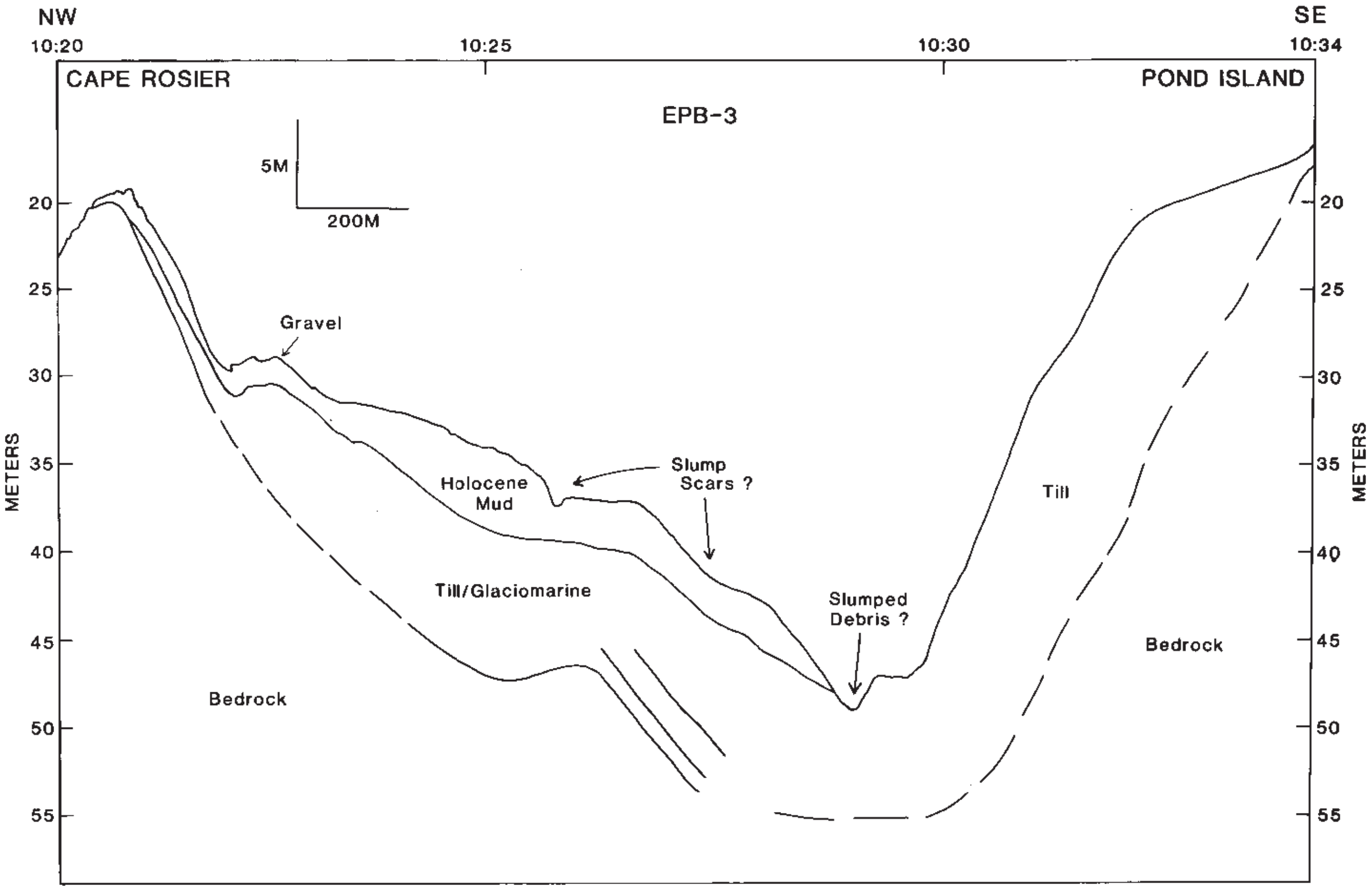


Figure 25. Seismic reflection profile across channel south of Cape Rosier. Slump scars and coarse-grained sediments floor the bottom in this generally rocky area.

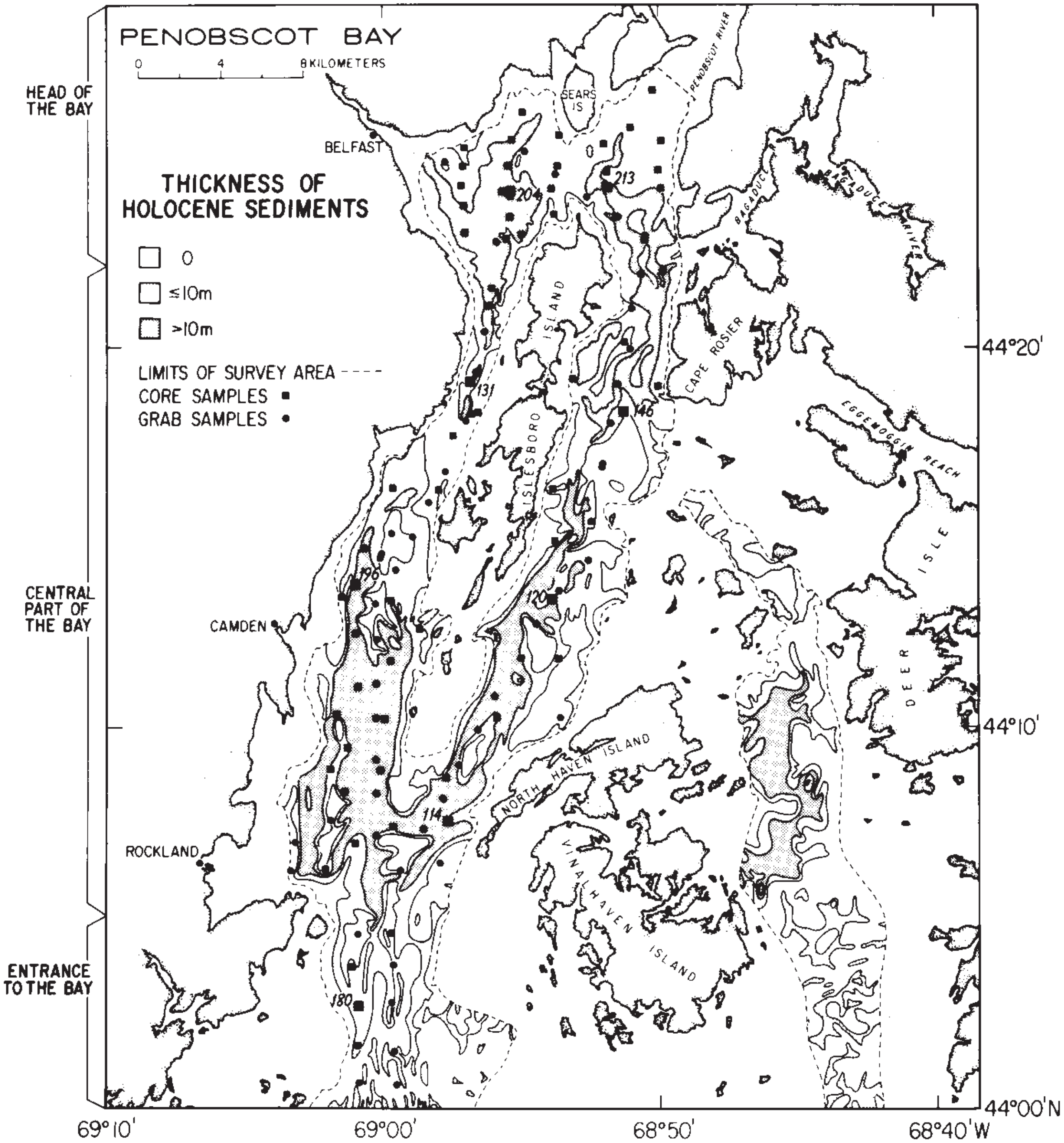


Figure 26. Very generalized Holocene sediment thickness map for Penobscot Bay. Figure from Knebel, 1986, and partly based on cores and samples by Ostericher, 1965.