Open-File No. 97-4

Sedimentary Framework of the Inner Continental Shelf of Maine

with Special Emphasis on Commercial Quality Sand and Gravel Deposits and Potentially Economic Heavy Mineral Placers

by

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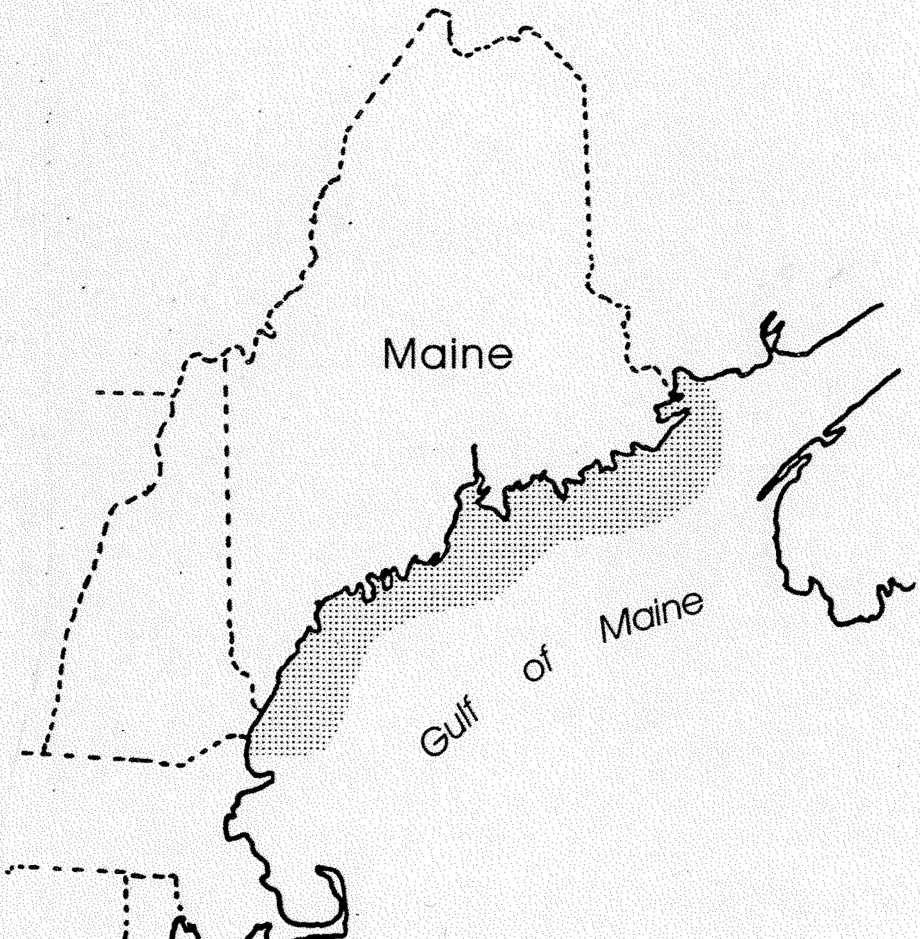

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INTRODUCTION

Sand and gravel aggregate is an increasingly valuable commodity for use as beach replenishment along eroding shorelines, as well as for use in the construction industry. In the future, aggregate from the sea may become important in New England as it has in many other regions of the world. This project was developed to define the surficial sedimentary environments of Maine's inner continental shelf (Figure 1), and to make a preliminary assessment of sand-reservoir volumes and sand composition where existing data permits. This report completes Maine's contribution to the Continental Margins Program sponsored by the American Association of State Geologists and the Minerals Management Service.

PREVIOUS WORK ALONG MAINE'S INNER CONTINENTAL SHELF

Ostericher (1965), in Penobscot Bay, first recognized the thick deposits of glacigenic sediment offshore through seismic reflection methods. He obtained a radiocarbon date from above the unconformity at the top of the glacial-marine sediment, and established that sea level was at about -18 m around 7390 ± 500 yr B.P. Schnitker (1972) found similar glacial-marine sediment in Sheepscot Bay, as did Folger and others (1972) off southwestern Maine and New Hampshire. Borns and Hagar (1965) had focused attention on the role of rivers in delivering sediment from the newly deglaciated landscape to the falling level of the sea, and Schnitker (1974) recognized a large accumulation of sediment at the mouth of the Kennebec River as a deltaic feature. He argued for a -65 m lowstand of sea level off the Kennebec River mouth on the basis of the morphology of the lowstand delta and submerged "berm" on its seaward margin. Belknap and others (1987a) incorporated Schnitker's (1974) sea-level lowstand estimate into a sea-level record for the region, but noted the uncertainty of the offshore data. Shipp and others (1991) provided regional evidence for a lowstand between 55 m and 65 m depth based on seismic reflection data between Wells and Machias, Maine. Through many offshore vibracores, Kelley and others (1992) and Barnhardt and others (1995) established the complex rate of change of early Holocene sea level as an effect of long-term isostatic adjustment coupled with eustatic sea-level rise (Figure 2).

Understanding sea-level change is important in the western Gulf of Maine because of its profound effect on the location of sediment deposition as well as sediment reworking (Belknap and others, 1987a; Kelley and others, 1992). The regression and transgression of the sea generally stripped glacial-marine sediment from bathymetric high points and transferred the material to lower, more seaward regions. Shipp and others (1991) noted that areas shallower than the lowstand of the sea (55 m to 65 m) were rockier and had lost some of their glacial-sediment cover through wave reworking during both the late Pleistocene fall in sea level and the early Holocene rise of the sea. A marked

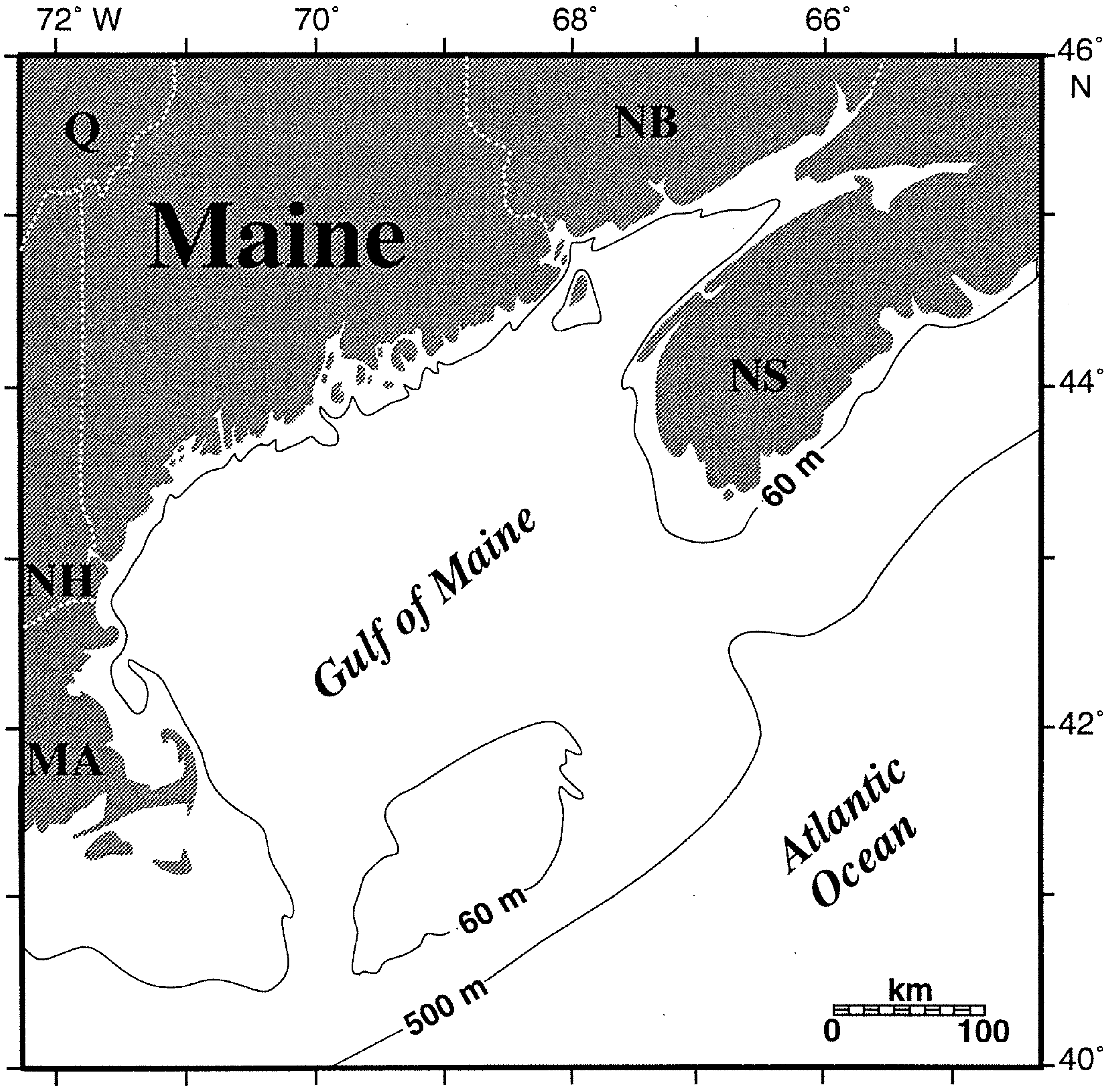

Figure 1. Location of Maine with respect to the 60 and 500 meter isobaths in the Gulf of Maine.

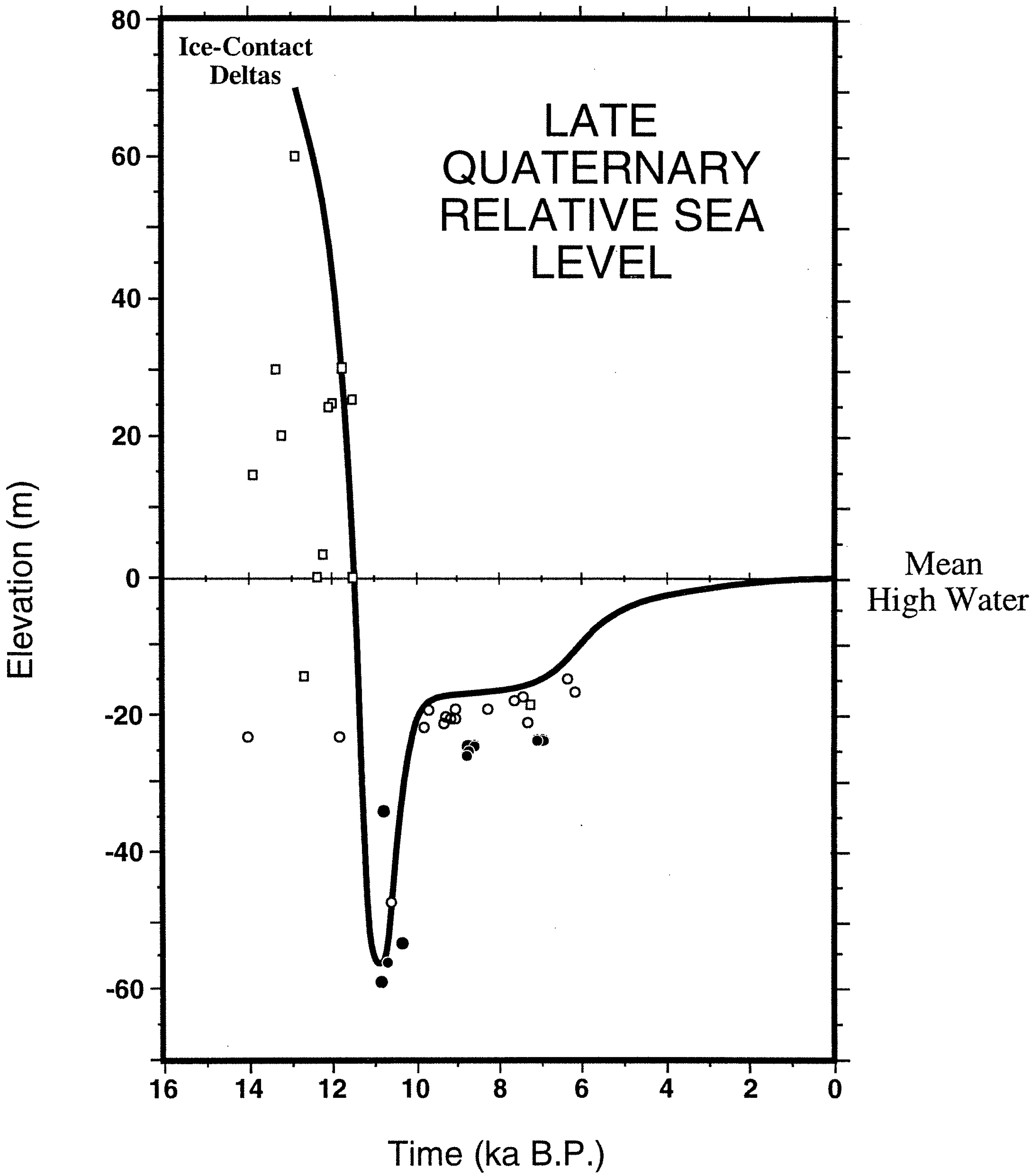

Figure 2. Relative sea-level curve for Maine (from Barnhardt and others, 1995).

unconformity on the surface of the glacial-marine sediment truncates acoustic reflectors in that material at depths shallower than 40 m in Penobscot Bay (Knebel, 1986) and even deeper elsewhere (Kelley and Belknap, 1991). Sea-level changes have been the single most important factor shaping the surficial sediments of the inner continenal shelf since the end of the Ice Age.

Despite reworking during sea-level changes, many of the glacial deposits known from land are recognized offshore. Till has been imaged by seismic reflection methods offshore as a patchy deposit overlying bedrock, as well as in the form of moraines (Belknap and others, 1986, 1987b; Kelley and Belknap, 1991; Knebel and Scanlon, 1985). Till is recognized on acoustic records by its stratigraphic position over bedrock, its general lack of internal stratification and its strong acoustic surface return (Belknap and others, 1989). On side-scan sonar records till is recognized by its strong acoustic return and boulder-littered surface, as well as by its geometry (moraines). In shallow water, morainal deposits can be traced directly from eroding outcrops on land (Belknap and others, 1987b), but in other locations moraines are far removed from land (Kelley and Belknap, 1991).

The dominance of glacial-marine sediment as an offshore deposit was recognized by Belknap and others (1986, 1987b), and Kelley and others (1986). It typically fills depressions in bedrock and is often covered by modern mud or sand. In areas of currents, however, it may crop out on the seafloor. Glacial-marine material has been subdivided into several acoustic facies on the basis of the geometry of the deposit and its internal structure (Belknap and others, 1989; Barnhardt, 1994), but it is often difficult to differentiate from modern mud on side-scan sonar profiles.

Deltaic and estuarine materials are recognized from seismic profiles and vibracores off major river mouths (Barber, 1995, Barnhardt, 1994). River-derived sand also occurs at some river mouths and may cover glacial-marine, estuarine, and deltaic sediment. The abundance of sand near rivers has been re-evaluated through coring, and contemporary volume evaluations are reduced from earlier estimates (Barber, 1995; Barnhardt, 1994; Kelley and others, 1995a,b).

Some deposits of offshore mud contain natural gas. Gas-charged sediment is generally found in areas with thick deposits of Holocene mud, although gas may also occur in glacial-marine mud (Shipp, 1989). Gas reduces the sediment shear strength and abets submarine slumping (Kelley and others, 1989a). In some locations, like Belfast Bay, Blue Hill Bay, and Passamaquoddy Bay, gas has erupted from the seabed and excavated large pockmarks on the seafloor (Scanlon and Knebel, 1987; Kelley and others, 1994). The exact origin of the gas and the triggering mechanism(s) are unknown (Kelley and others, 1994).

Bottom sediment mapping in the study area began with the collection of sediment associated with early bathymetric soundings in the late 19th century (see Trumbull, 1972 for summary of early work). The results of systematic bottom sampling were presented in a series of U.S. Geological Survey publications in the early 1970's (Folger and others, 1972; Schlee and Pratt, 1970; Schlee, 1973; Trumbull, 1972). This work was based on a large number of widely spaced samples that were analyzed for both composition and texture. The textural data were presented in the format of ternary diagrams which depict map units in terms of % mud, % gravel and % sand, or % sand, % silt, % clay. Owing to the inherent variability of the seafloor and the wide spacing of the grab samples, the resulting surficial maps were of small scale and lacked detail. Even when more recent compilations were produced, extensive regions (25 km^2) within our study area were represented by only a single bottom sample (Poppe and others, 1989). When bathymetric information and seismic reflection observations were added, a larger scale, more detailed map was produced, but for a restricted region (Folger and others, 1975).

Beginning in the late 1980's, the Maine Geological Survey, University of Maine, and University of New Hampshire began offshore mapping programs supported by the Continental Margins Program of the Minerals Management Service and the American Association of State Geologists. Although early maps used geophysical tools extensively in addition to bottom samples, the resulting maps employed conventional ternary diagrams for textural map units (Kelley and others, 1987a,b). These reports also defined physiographic regions (Kelley and others, 1989b, Kelley and Belknap, 1991), however, by using the provisional bathymetric charts of NOAA. More recent work recognized the mapping advantages of side-scan sonar, as well as its limitations, and defined map units that were recognizable by acoustic imagery alone (Barnhardt and others, 1996).

METHODS

Bottom Samples

Between 1984 and 1991, 1,773 bottom sample stations were occupied (Dickson and others, 1994, Barnhardt and Kelley, 1991; Kelley and Belknap, 1988, 1989; Kelley and others, 1987a,b, 1990, 1995a,b). Two attempts were made at each station where the sampler initially returned empty, after which the site was considered a rock bottom. In all, 1,303 sediment samples were collected.

The bottom sampler used was a Smith-McIntyre stainless steel device that nominally collected up to 0.25 m^3 of sediment. In mud, the sampler did gather 0.25 m^3 of sediment, usually with the surface completely undisturbed. When the sampler was used over a sandy bottom it usually returned an undisturbed sample, unless a large shell blocked its jaws, permitting material to wash out. Over a gravel seafloor it was common for large clasts to prevent closure of the sampler's jaws, resulting in loss of some or all sediment. In those situations, up to two additional attempts were made to obtain a sample before abandoning the station.

Southwest of Cape Small, samples were generally collected from the nodes of a grid with a one nautical mile distance between sample sites. Focus was placed on the large sandy embayments off Wells, Saco and the Kennebec River mouth, as well as in muddy Casco Bay. Relatively few bottom samples were gathered off rocky areas like Kennebunk or Kittery. Geophysical tracklines were later run over the sample stations to permit extrapolation of the bottom-sediment data. North and east of Cape Small, geophysical data were generally gathered before bottom samples. This resulted in a need for fewer samples, and so fewer stations were occupied.

Following collection, samples were frozen in coolers until they could be stored in a freezer in the sedimentology laboratory at the University of Maine. Depending on the level of funding or specific needs of a particular project, samples were analyzed for grain size, organic carbon and nitrogen, carbonate content, and heavy mineral concentration. Standard laboratory techniques were employed for the textural analyses, with pipette methods to evaluate the percent of sand, silt and clay (Folk, 1974), a settling tube to evaluate sand size distribution (settling velocity), and a micromeritics sedigraph to measure the settling velocity of mud-size material (< 62 microns). Carbon and nitrogen were analyzed on a Carlo-Erba Model 1106 Elemental Analyzer, and carbonate content was determined through acid digestion

(Molnia, 1974). Heavy mineral content was measured through heavy liquid analysis (Kelley and others, 1987a) or by means of a Humphrey Spiral (Luepke and Grosz, 1986; Lehmann, 1991).

Side-Scan Sonar Profiles

Analogue side-scan sonar records along 3,358 km of the seafloor were gathered with an EG&G Model 260 slant-range corrected device operating with a Model 272-T towfish at a nominal frequency of 105 kHz. The device was most often run at a 100 m range (200 m wide swath beneath the research vessel), although ranges from 25 m to 300 m were occasionally employed (swaths from 50 m to 600 m beneath the boat).

Interpretation of the side-scan sonar records was aided by ground-truth information from the bottom samples as well as from 63 submersible dives (Belknap and others, 1988). Although objects as small as lobster traps and current ripples were visible at the 100 m range, it was not possible to make detailed textural distinctions using acoustic imagery alone or to directly compare acoustic images with samples that were analyzed for grain-size distribution. Thus, sandy mud and muddy sand, which are textural categories that can readily be distinguished with particle size analyses (Folk, 1974), are essentially identical in acoustic images. Where sand gradually mixes with mud, a contact was drawn in the midpoint between known occurrences of sand and mud. Similarly, where grain-size data were lacking, rippled seabeds were called gravel, even though sand is commonly a minor component of the bedforms.

The heterogeneity of the seabed at all scales precluded mapping all features observed in the side-scan sonar records. To be visible on a map, a feature must be at least 1 mm^2. This means that on a 1:100,000 scale map, the smallest mappable unit on the seafloor must be at least 10,000 m^2. Because outcrops of bedrock and gravel smaller than 10,000 m^2 commonly punctuate generally muddy or sandy areas, it must be understood that the units mapped are not the sole materials present within their polygons, but the dominant materials.

On side-scan sonar images, rock, mud, gravel and sand usually produce distinct acoustic returns and so were mapped as distinct units. Rock yields a strong surface return (dark on side-scan sonar records) often with great bathymetric relief and fractures that result in areas with acoustic shadows. Gravel deposits also produce a relatively strong acoustic return (black to dark gray on side-scan sonar records) and are often closely associated with rock, but lack relief and fractures and are often covered with ripples or boulders. Sand produces a much weaker acoustic return (light to dark gray on side-scan sonar records) than either gravel or rock, and usually lacks local relief. Mud yields a very weak surface return (light gray to white on side-scan sonar records) and, except where it accumulates on steep slopes or near gas-escape pockmarks, it is associated with a smooth seabed.

Seismic Reflection Profiles

Seismic reflection profiles were gathered along 5,011 km of tracklines, often in conjunction with side-scan sonar data. A Raytheon RTT 1000a 3.5/7.0 kHz unit with a 200 kHz fathometer trace was used mainly in relatively shallow water over muddy bottoms, while an ORE Geopulse "boomer" seismic system was most effective in deeper water over thicker deposits of sandy or gravelly sediment.

Nine seismic facies are described from the western Gulf of Maine, seven of which occasionally crop out at the seabed (Belknap and others, 1989). Bedrock (BR) forms the acoustic basement in the area, but commonly crops out on the seafloor. It is recognized by its intense, sharp initial return, and high-relief surface. It is frequently overlain by till (T), which also produces a strong surface return. When it is thick, the mound shape of the till or the chaotic internal reflections distinguish it from bedrock; when it is thin, seismic reflection data alone may not always separate rock and till.

Glacial-marine muddy sediment (GM) may overlie till or bedrock and also commonly crops out at the seafloor. This material provides an intermediate surface return and ranges from well-stratified to acoustically transparent. In depths less than 60 m, it is often unconformably overlain by modern mud (M). Modern mud has a very weak surface return and is typically acoustically transparent.

Deltaic (D) and estuarine (E) sediments from the late Pleistocene to early Holocene occur near some large river mouths. These materials produce strong surface returns, and usually have good internal stratification. They are usually covered by a reworked sand and gravel lag deposit (SG), or modern mud (M).

Thin gravel layers (TGL) and natural gas deposits (NG) are also recognized beneath deposits of sand and mud, respectively. These acoustic units never crop out at the seafloor, although natural gas has erupted from the seabed in some locations (Kelley and others, 1994).

Although seismic reflection profiles are most useful in constructing the geological history of an area, the bathymetry and geological context provided by the seismic reflection profiles, along with the strength of the surface return, also allows identification of the surficial deposit. When used in conjunction with the side-scan sonar, both the age and nature of the surficial sediment are easily interpreted.

Navigation and Compilation

Navigation fixes in the outer estuaries and offshore areas were made every 2-5 minutes with LORAN-C. LORAN coordinates were later converted to latitude/longitude with the computer program, LORCON, and provided an accuracy of ± 100 m (J. Stuart, NOAA, personal communication). In the upper reaches of the estuaries, navigation fixes were established with line-of-sight observations, and radar and visual observations on buoys and landmarks. The accuracy based on these observations varied from less than ± 10 m to around ± 200 m. Some more recent work in Cobscook Bay, Wells Embayment, and in the Kennebec River utilized the global positioning satellite system (GPS) for navigation and was accurate to ± 10 m.

All navigation was converted to the Universal Transverse Mercator projection (UTM) and plotted through the ARC/INFO geographic information system (GIS) (UNIX version 7.03). The shoreline of the region was digitized into the GIS from National Ocena Service Charts (1:100,000). Bathymetry was digitized at a 10 m contour interval from NOAA Bathymetric and Fishing Charts. The charts are only provisional blue-line paper copies for most of the region, but they provide a 2 m contour interval in many locations. Difficulty in interpretation of positive and negative changes in bathymetry on the poorly labeled charts created many possible errors especially in areas where we lacked accompanying geophysical data.

The surficial maps were prepared by overlying the side-scan sonar navigation fixes on the bathymetry in the GIS. A buffer equal to the observational range of the side-scan sonar instrument was drawn parallel to the navigation fixes, and the surficial geology was interpreted from the original side-scan sonar records to a mylar cover sheet that was itself later digitized. Where the spacing of the side-scan sonar lines was less than the width of the range, the surficial geology between the lines was interpolated with the aid of the bathymetry, bottom samples, and seismic reflection profiles (where they existed). Where side-scan sonar data were scarce or absent, reliance was placed on seismic records and bottom samples in conjunction with bathymetry.

Physiographic maps were prepared largely on the basis of the bathymetry with supplementary information provided from the geophysical data (Kelley and others, 1989b; Kelley and Belknap, 1991; Barnhardt and others, 1996).

Heavy Mineral Analyses

Heavy minerals were separated from samples gathered from five rivers and adjacent estuaries/offshore areas along the coast of Maine (Figure 3). Although Saco Bay (Figure 4) had been previously investigated for heavy mineral species (Luepke and Grosz, 1986), no earlier work has occurred at Casco Bay/Kennebec River (Figures 4, 5), Penobscot Bay (Figure 6), Machias Bay (Figure 7), or Oak Bay (Figure 8).

Samples were gathered with a 0.25 m^3 Smith McIntyre grab sampler and located with LORAN-C. Following collection, samples were split into subsamples for analyses of water content, grain size, and mineral analyses (Figure 9). The heavy minerals were separated with a Humphreys 3-turn spiral, and then further concentrated with heavy liquids (Figure 10). The resulting heavy mineral concentrate was then separated with free-fall magnetic techniques (Luepke and Grosz, 1986), with a Frantz Barrier (Magnetic) Separator (Luepke and Grosz, 1986, Lehmann, 1991; Figures 11, 12).

Individual minerals were identified through a combination of X-ray diffraction and optical methods (Luepke and Grosz, 1986, Lehmann, 1991).

RESULTS

Physiography of the Maine Inner Continental Shelf

The inner continental shelf of the western Gulf of Maine is a submerged extension of the northern Appalachian Mountains, and its bathymetry is as complex as the topography on the adjacent upland (Plate 1). The upland consists of a series of "suspect terranes" of varying bedrock lithology and structure that have undergone erosion since at least the Mesozoic Era, and possibly longer (more than 100 million years [Osberg and others, 1985]). Rocks exposed on land and on the seafloor were formed kilometers beneath the earth's surface during continental interactions hundreds of millions of years ago. The overall geomorphology of the region is controlled by the spatial distribution of lithology, faults, folds, and other structural features imparted to the rocks long ago.

Glacial erosion and deposition modified the bedrock skeleton and added to the regional geomorphic complexity. Almost all of the "recent" sedimentary material along the coast and offshore is derived from erosion of glacial deposits. Although bedrock defines the overall shape of the coastal region, glaciation provided the materials for contemporary processes, like waves and currents, to shape into the dynamic habitats of the inner shelf.

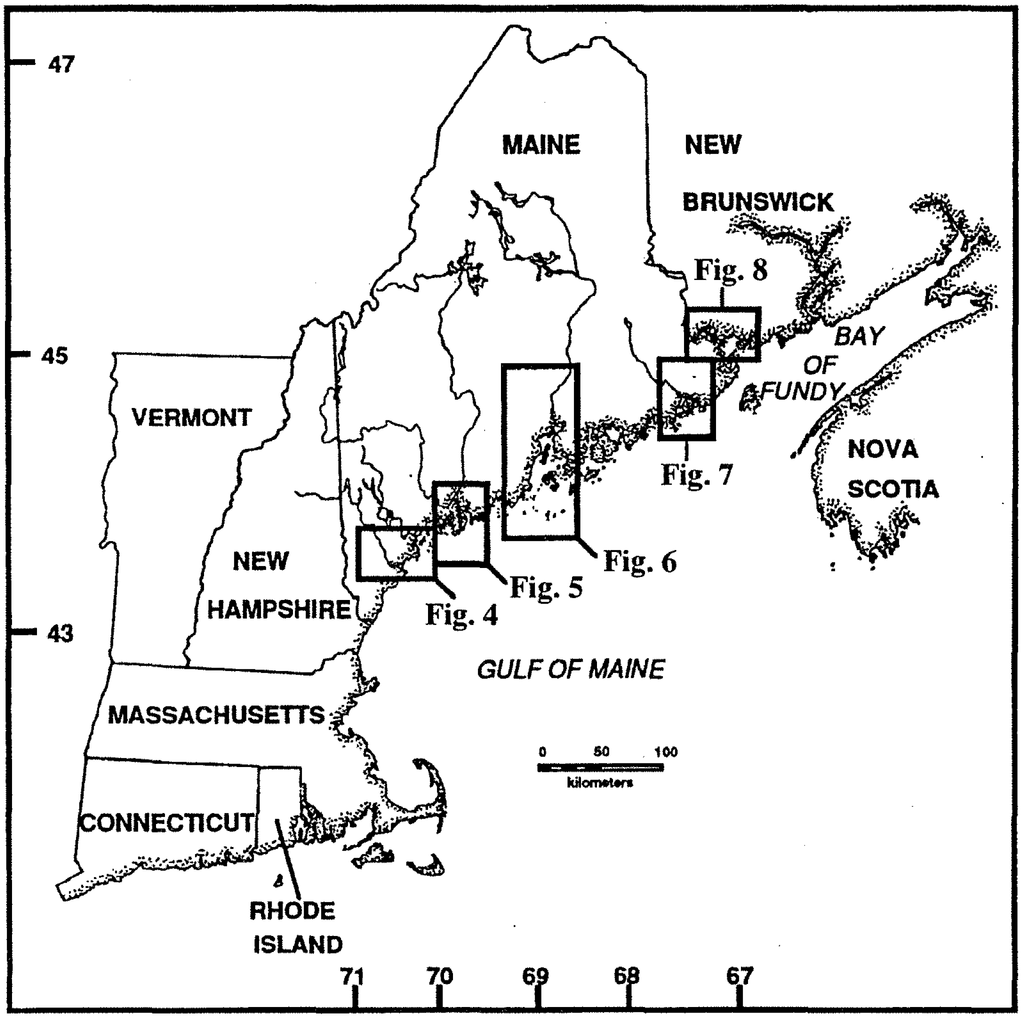

Figure 3. Location of bays and rivers in which heavy minerals were examined (modified from Lehmann, 1991).

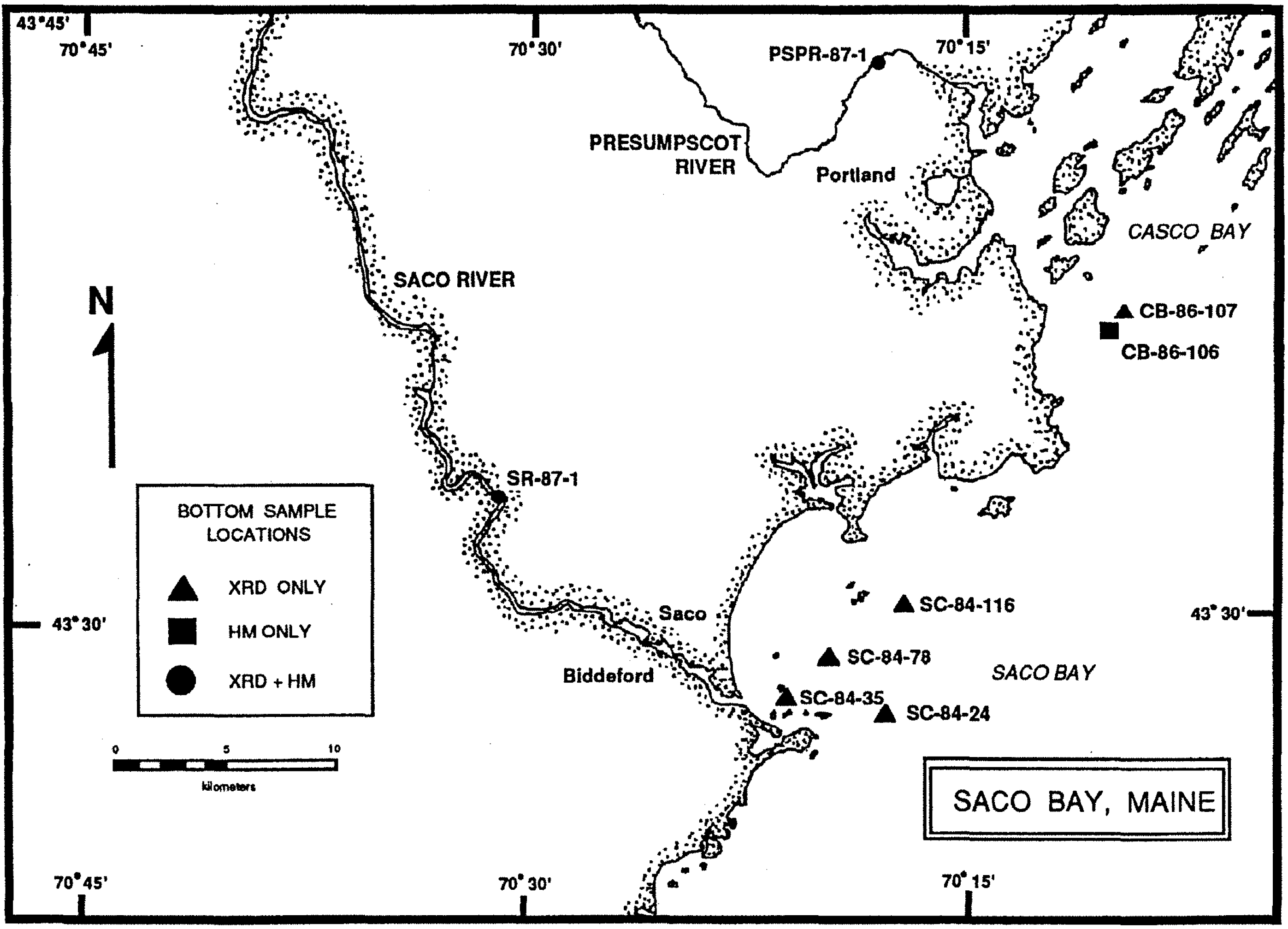

Figure 4. Sample locations for Saco River, Saco Bay and western Casco Bay. Triangles refer to x-ray diffraction analyses only; a square represents heavy mineral analyses only, and circles represent both x-ray and heavy mineral analyses (modified from Lehmann, 1991).

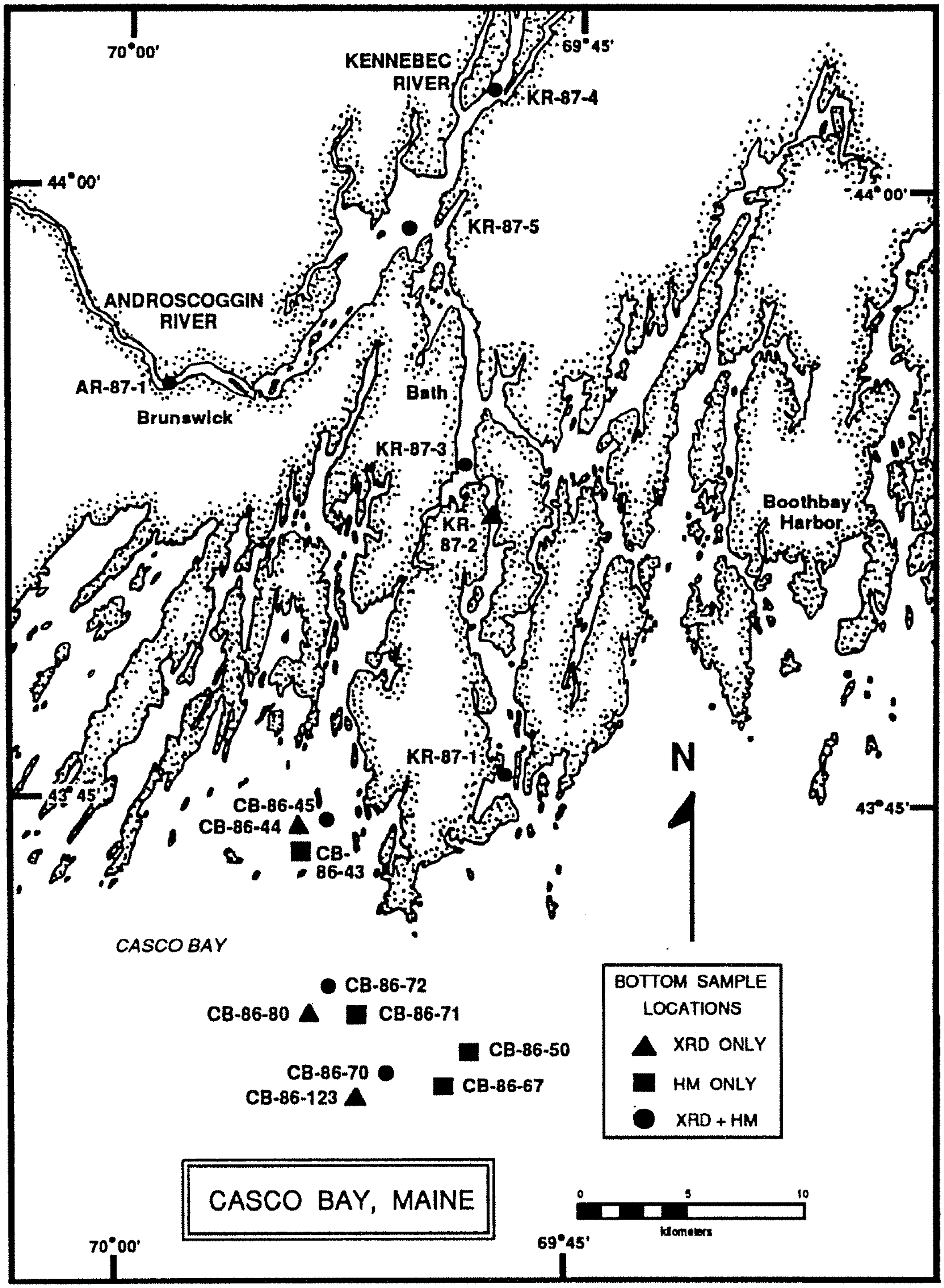

Figure 5. Sample locations for eastern Casco Bay, Androscoggin and Kennebec Rivers. Triangles refer to x-ray diffraction analyses only. Squares represent heavy mineral analyses only, and circles represent both x-ray and heavy mineral analyses (modified from Lehmann, 1991).

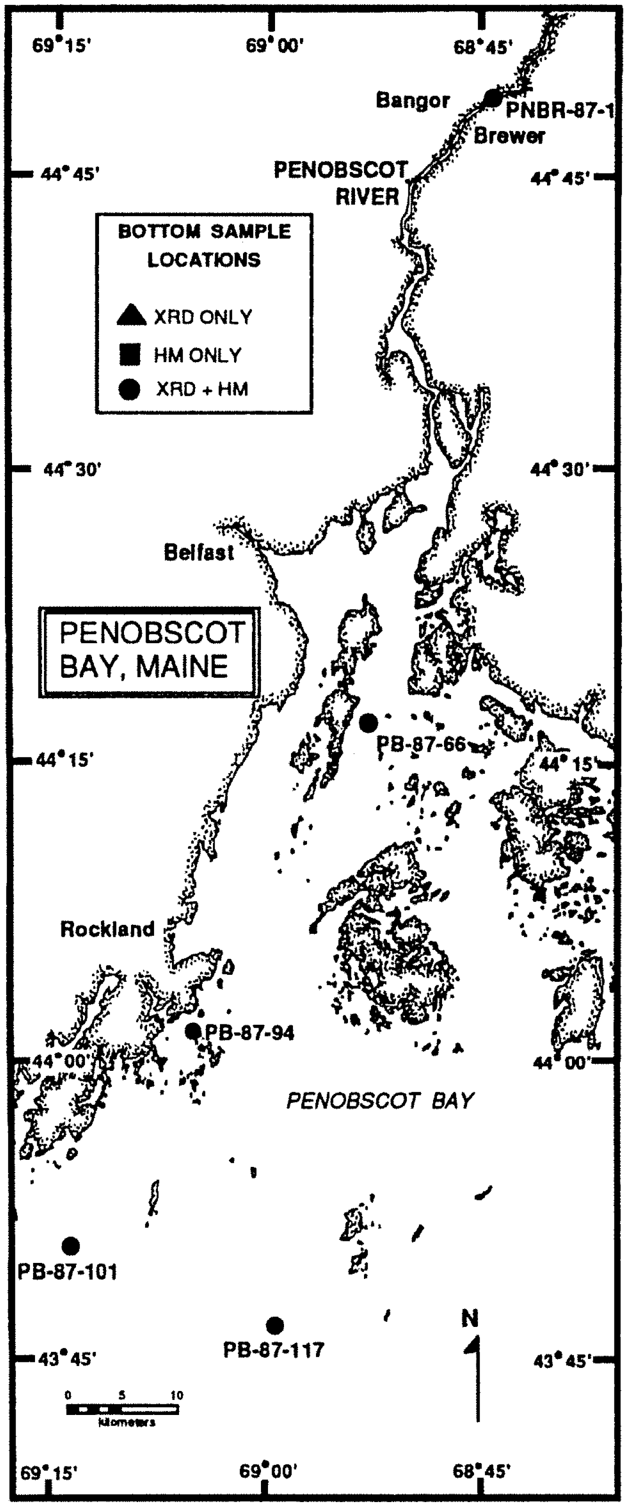

Figure 6. Sample locations for Penobscot River and Penobscot Bay. Triangles refer to x-ray diffraction analyses only. Squares represent heavy mineral analyses only, and circles represent both x-ray and heavy mineral analyses (modified from Lehmann, 1991).

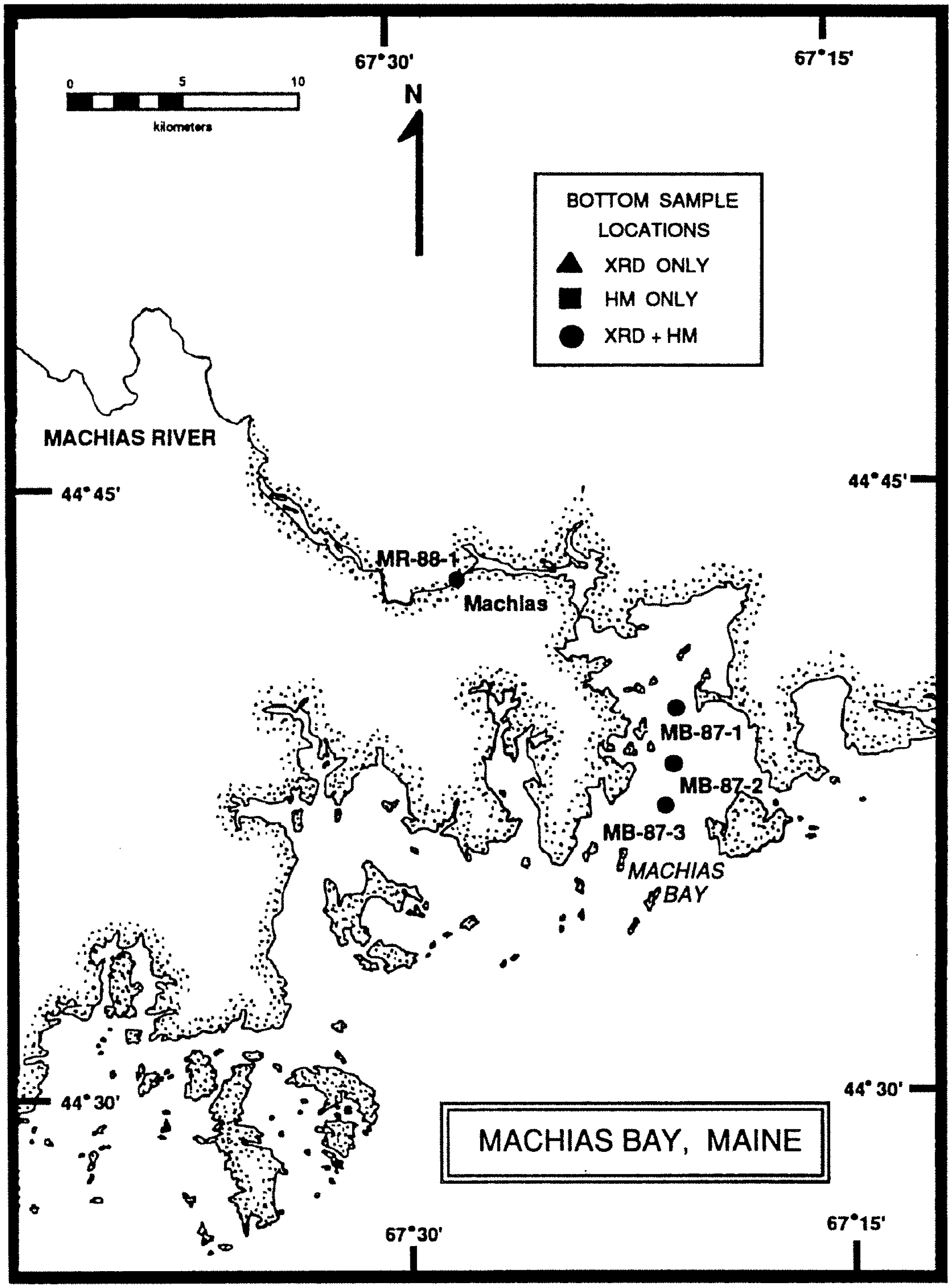

Figure 7. Sample locations for Machias River and Machias Bay. Triangles refer to x-ray diffraction analyses only. Squares represent heavy mineral analyses only, and circles represent both x-ray and heavy mineral analyses (modified from Lehmann, 1991).

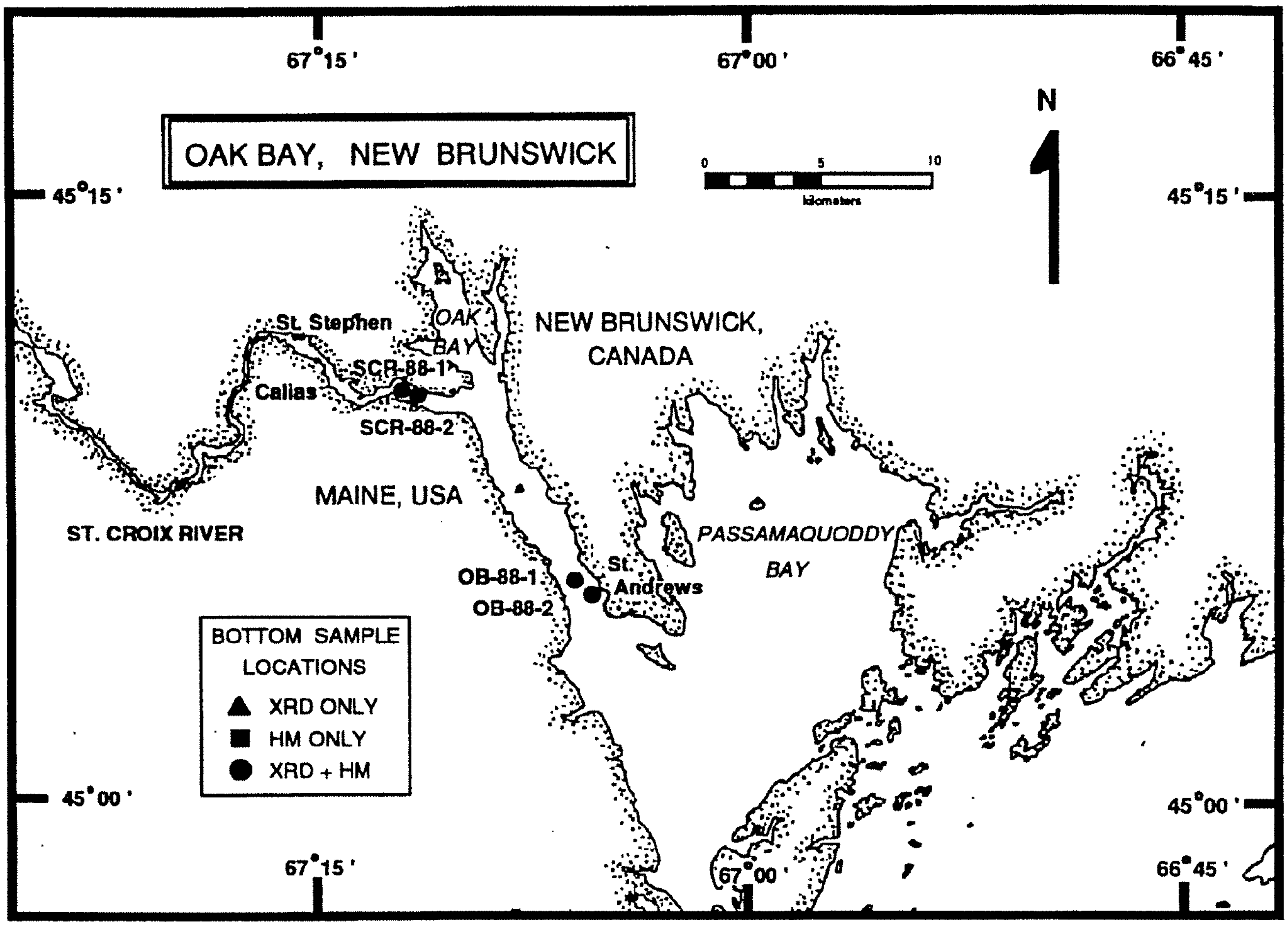

Figure 8. Sample locations for Saint Criox River and Oak Bay. Triangles refer to x-ray diffraction analyses only. Squares represent heavy mineral analyses only, and circles represent both x-ray and heavy mineral analyses (modified from Lehmann, 1991).

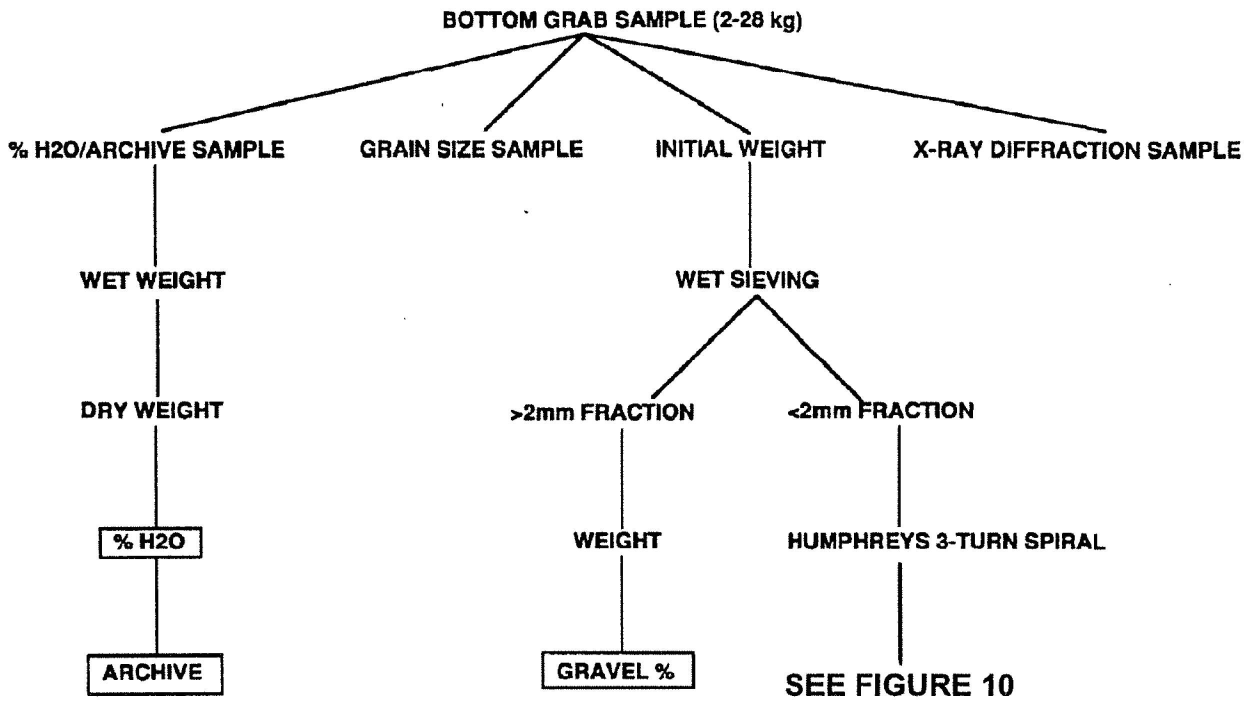

Figure 9. Flow diagram for the processing of sediment samples (modified from Lehmann, 1991).

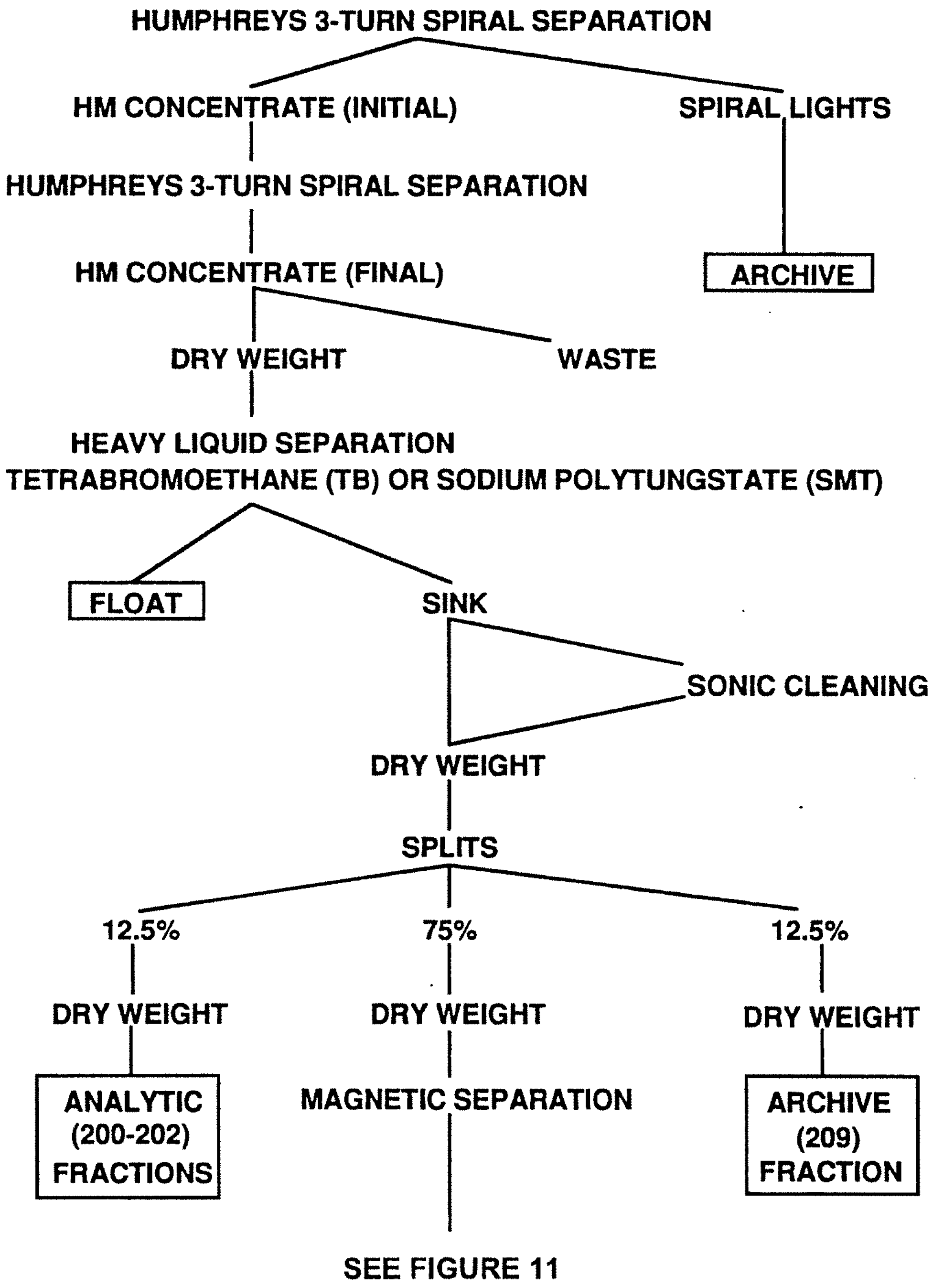

Figure 10. Flow diagram for processing heavy minerals through the Humphreys Spiral (modified from Lehmann, 1991).

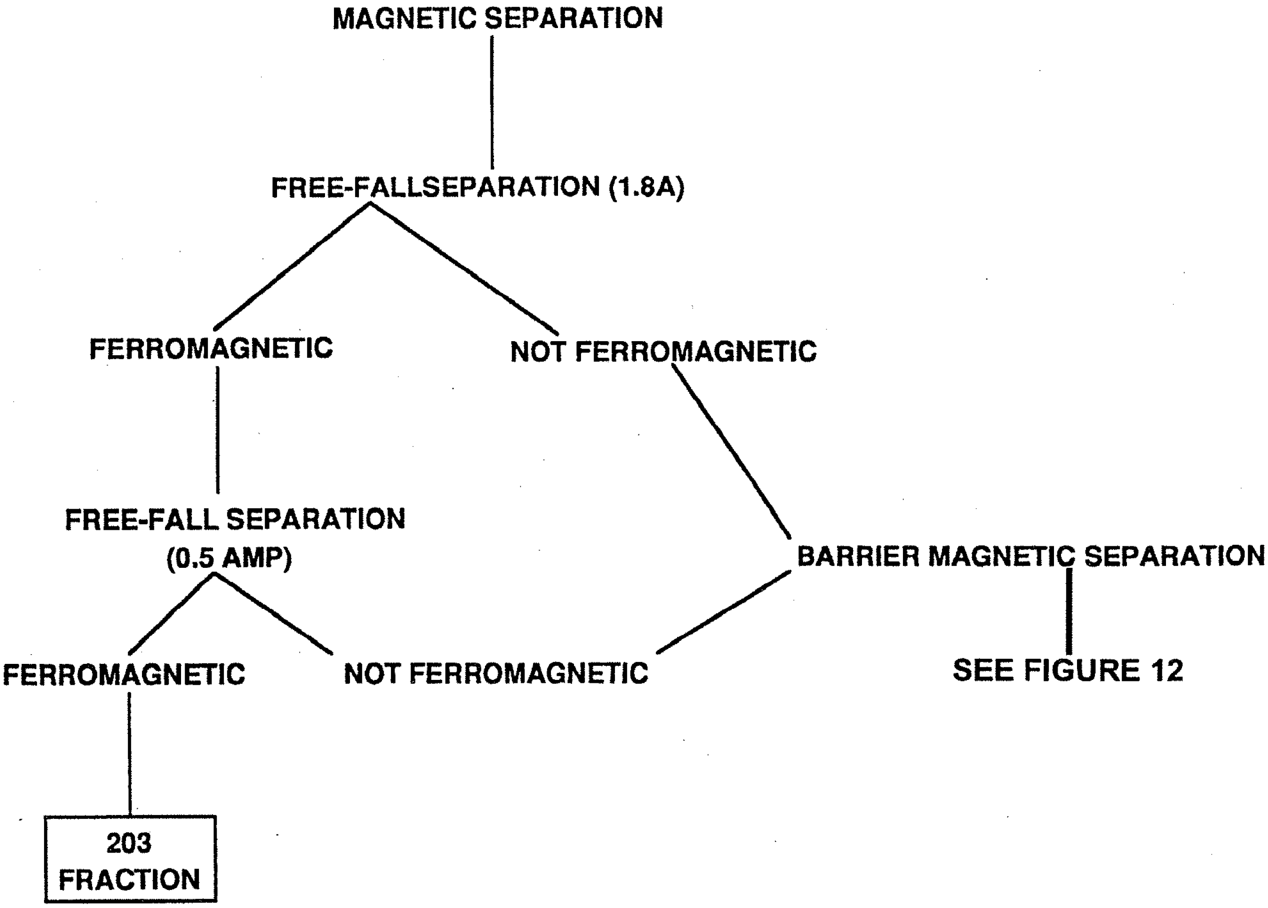

Figure 11. Flow diagram for the beginning of the magnetic separations (modified from Lehmann, 1991).

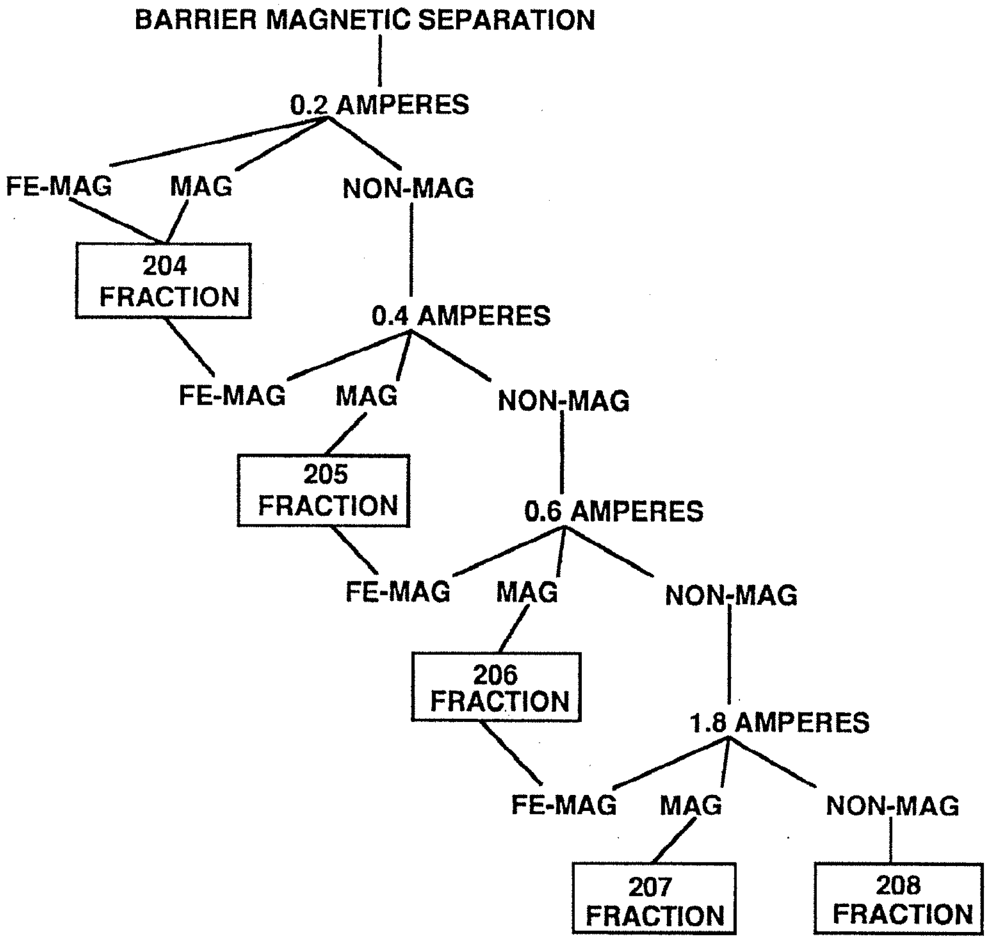

Figure 12. Flow diagram for the magnetic separation of the heavy minerals (modified from Lehmann, 1991).

Nearshore Ramps. Nearshore Ramps are regions that slope gently seaward with widely spaced, shore-parallel bathymetric contours (Plate 1). They are relatively rare features, most common in southwestern Maine where they abut large beaches. Most Nearshore Ramps begin at the shoreline and continue to the 20 m or 30 m isobath. Exceptions to this rule include the large Nearshore Ramp off the Kennebec River mouth, which reaches to depths of 55 m, and those in Narraguagus and Machias Bays, which occur in deeper water. Nearshore Ramps are covered with sand or gravel, with occasional outcrops of bedrock.

Seaward of the Kennebec and Narraguagus Rivers, the Nearshore Ramps are complex, reworked deltaic deposits of late Pleistocene-early Holocene age (Barnhardt, 1994). There is no deltaic feature in Saco Bay, but sand covering the Nearshore Ramp in that bay is derived from the Saco River (Kelley and others, 1989b; 1995a). There is no fluvial input to the Nearshore Ramps in and south of Wells Embayment, but reworking of glacial deposits has provided a sand and gravel veneer for that Nearshore Ramp, as well as for the ramp south of Mt. Desert Island (Barnhardt and Kelley, 1991). Reworked shell deposits cover the Nearshore Ramp off southeast Mt. Desert Island (Barnhardt and Kelley, 1995). The Nearshore Ramp south of Machias Bay is poorly understood, but appears to be a steep bedrock slope covered with a thick deposit of glacial-marine sediment (Shipp, 1989).

Off both the Saco and Kennebec Rivers and Wells Embayment, many vibracores, along with extensive seismic reflection data have suggested that the profiles of the Nearshore Ramps are maintained by waves. The seafloor in these areas is a relatively thin wedge of sandy shoreface material overlying glacigenic sediment (Kelley and others, 1995b).

Nearshore Basins. Nearshore Basins are protected from the open sea by the mainland, peninsulas, islands, or shoals (Plate 1). They are generally bordered by tidal flats on the landward side, and extend seaward with a muddy, smooth seabed. Rock exposures are common along the margins of Nearshore Basins, and outcrops commonly punctuate the smooth seafloor. Nearshore Basins are deeper and contain sediment coarser than mud where bedrock constrictions accelerate tidal currents, as off Eastport. As a rule the seafloor of Nearshore Basins becomes more channelized and coarser grained in the outer reaches of bays. In some Nearshore Basins, unstable muddy material has slumped into channels; in others natural gas eruptions have disturbed the seabed with pockmarks (Kelley and others, 1989a). Nearshore Basins on the western side of Penobscot Bay and northern Blue Hill Bay have highly irregular bathymetry because of gas-escape pockmarks (Kelley and others, 1994; Barnhardt and Kelley, 1995).

Nearshore Basins are concentrated along the central Maine coast (Plate 1) and do not occur near the more wave-exposed Nearshore Ramps, with the exception of those in Narraguagus Bay. The Nearshore Basins occur over local linear depressions in bedrock that are mapped as faults in parts of Casco, Sheepscot, Penobscot, Muscongus, Oak, and Cobscook Bays (Osberg and others, 1985). Many of the Nearshore Basins terminate against thick deposits of glacial sediment on land which cover deep, bedrock, "buried valleys" (Upson and Spencer, 1964; Kelley and others, 1987a).

Rocky Zones. Rocky Zones are the most extensive physiographic region along the inner shelf, except off the Cliffed Shoreline near the Canadian border (Plate 1). These are areas with exposed or shallow bedrock and gravel, accompanied by rapid and extreme changes in bathymetric relief. Cliffs ranging from 3 m to 10 m appear as commonly as on land. The Rocky Zones are generally less than 60 m deep and locally form shoals. Rocky Zones surround many of the large islands in central Maine, and trend parallel to peninsulas to the south.

Although bedrock always occurs in Rocky Zones, "sediment ponds" infill many fractures in the rock, and "gravel aprons" often form "halos" around more isolated bedrock outcrops and islands. Sediment in these "ponds" and "halos" is usually coarse grained and commonly enriched (as much as 100%) with shells from nearby encrusting organisms (Kelley and Belknap, 1991; Barnhardt and Kelley, 1995). Large boulders, up to several meters in diameter, commonly occur on areas of exposed bedrock, and moraines are associated with bedrock knobs in some locations.

During times of lower sea level, most of the areas that are mapped as Rocky Zones were islands or part of the mainland. They may have been once covered with till and glacial-marine sediment, but have lost some or all of their sedimentary cover due to wave and current action at times of lower sea level. Some moraines were not completely removed by these processes, but became armored with boulders and gravel until they could not be eroded any further.

Shelf Valleys. Shelf Valleys are seaward sloping troughs usually floored by sediment of various origins, but with many rocky outcrops. Shelf Valleys are framed by bedrock, and most are seaward extensions of Nearshore Basins (Plate 1). In areas of late Pleistocene/early Holocene sediment deposition, such as off the Kennebec, Narraguagus, and Saco River mouths, Shelf Valleys terminate against Nearshore Ramps. Here, the deeply eroded bedrock valley is buried by sediment. In more exposed locations where tidal currents are strong, Shelf Valleys have no sediment and may be very deep. Because of their exposed location, in most locations Shelf Valleys are not accumulating modern sediment, but may serve as conduits for material escaping nearshore regions. In Penobscot Bay, for example, sediment erupted by gas escape in the upper Nearshore Basin in Belfast Bay may travel down the channel of the basin and into the deep Shelf Valley of the outer bay to the Gulf of Maine.

The origin of the Shelf Valleys, and the deep bedrock troughs beneath Nearshore Basins, is unknown. They were once considered to be ancient products of fluvial erosion (Johnson, 1925), but were later viewed as glacially scoured features (Shepherd, 1931). More recently, deep bedrock valleys nearshore were described as composite features resulting from initial fluvial erosion and later glacial deepening (Uchupi, 1968). The branching nature of some of the Shelf Valleys appears fluvial, but there are more valleys than modern-day rivers and embayments, and many more valleys than present levels of precipitation require. Although possibly some of the Shelf Valleys were deepened by glaciers, they are not consistently lined up with the direction of ice advance (generally northwest to southeast, Thompson and Borns, 1985), and many of them are perpendicular to that direction. It is possible that subglacial meltwater was involved in the formation of these deep troughs as inferred elsewhere (Boyd and others, 1988).

Outer Basins. The Outer Basins occur in water generally deeper than 60 m and are poorly studied, in part, because of their remoteness (Plate 1). They generally border Rocky Zones and extend without interruption into the deeper water of the Gulf of Maine. In most locations Outer Basins have a more subdued bathymetry than Rocky Zones, and are covered by mud with occasional outcrops of rock and gravel. Seaward of Saco, Muscongus, and Narraguagus Bays, where the Outer Basin is a broadened extension of several Shelf Valleys, Outer Basins contain thick deposits of glacial sediment with natural gas. Off Penobscot Bay, Mt. Desert Island, and Machias Bay, Outer Basins have an irregular bathymetry and may, with more investigation, be reclassified as Rocky Zones.

Because they exist in relatively deep water, Outer Basins experience currents and wave activity too weak to erode muddy sediment. For this reason, modern mud accumulates in these deep settings. At times of lower sea level, the Outer Basins below 60 m depth were not exposed subaerially, and accumulated material eroded from Rocky Zones. Thus, one may think of Outer Basins as the deep water correlative of Shelf Valleys and Rocky Zones, where sediment has continuously accumulated since the end of the Ice Age about 14,000 years ago.

Hard-Bottom Plains. Hard-Bottom Plains are extensive areas of low relief that are covered by gravel (Plate 1). A small Hard-Bottom Plain is located off the Wells Embayment and a much larger feature exists off the Cliffed Shoreline near Canada. Bedrock also occurs throughout the Hard-Bottom Plains, but it possesses less relief than found in Rocky Zones. Mud and sand also exist with the gravel, but they are minor components of the sediment.

The Hard-Bottom Plain in southern Maine is associated with a large series of moraines and till deposits. During a time of lower sea level, waves stripped gravel from the moraines and spread it around, creating the Hard-Bottom Plain. The large Hard-Bottom Plain in northeast Maine is also covered by a deposit of till, but it is thin and occurs deeper than 60 m, the depth of the lowstand of the sea. The bedrock in this area is also extremely subdued in relief. It is possible that the rocks here are easily eroded, Mesozoic sandstones like those in the Bay of Fundy. Glaciers may have smoothed them into the low-relief rock presently exposed. Strong tidal currents may be responsible for the reworking of the till and lack of recent sediment accumulation over that material.

Surficial Geology of the Maine Inner Continental Shelf

The surficial materials of the inner continental shelf of the western Gulf of Maine are the most complex of any place along the United State's Atlantic Margin. Igneous, metamorphic and sedimentary rocks spanning more than a billion years of earth history form the regional basement. Glacial deposits containing all clast sizes from boulders to mud partly mantle the rocks. These materials, in turn, have been reworked by coastal processes during extreme excursions of sea level over the past few thousand years to create locally, better texturally sorted deposits of modern sediment. Biological processes, including shell formation and gas eruption, have added to and disturbed the sediments, respectively. As discussed above, the selection of map units to describe this complexity involves a compromise between providing detailed information where it exists and generalizing where data are scarce or absent.

Rocky Areas. Rocky seabeds occupy 42% of the inner continental shelf bottom and are the most abundant surface material in the study area (Plate 2). Where little data exist and the seafloor is very irregular, a rocky bottom was inferred. Thus, large areas of rocky bottom are mapped off extreme southern Maine, Penobscot Bay, and off Petit Manan Point. Large areas of rock also occur surrounding the many granitic islands in Blue Hill and Frenchmen Bays, and elongate bodies of rock follow the linear trend of the peninsulas north of Cape Elizabeth. Although common as shoals less than 10 m deep, large outcrops of rock were relatively rare in deeper water.

No effort was expended to identify the nature of the bedrock, but side-scan sonar images clearly depict parallel fractures and elongate outcrop patterns common in layered rocks, as well as more rounded bodies of rock often associated with plutonic (granitic) rocks. The surfaces of rock outcrops are usually covered with algae (seaweed) and encrusting organisms in shallow water, and with only encrusting organisms at greater depths. Fractures in rock and regions surrounding rock outcrops are commonly covered with shells of dead organisms formerly attached to the rock surface, as well as with angular fragments of rock. Fractures filled with gravel are often called "sediment ponds" or "Neptunian dikes," and are generally thin deposits (Kelley and others, 1989a).

Gravelly Areas. Gravel sediment occupies 12% of the inner shelf, but it does not occur in many large bodies. Only off the Kennebec River mouth, where palimpsest deltaic sediments crop out near reworked glacial moraines off Wells, Penobscot, and Saco Bays, and in the deeper waters near the Canadian border are there large regions where gravel dominates the seafloor (Plate 2). In many instances the gravel has a rippled surface, and may contain minor amounts of coarse sand. In areas where scouring of the seabed has occurred, a gravel lag deposit armors the seafloor, at least temporarily. Gravel also occurs in broadly linear bands where moraines exist on the seabed. Gravel, in association with minor rock and sand, is a major feature of the seafloor from the Canadian border to Englishman

Bay. Here, low-relief bedrock is mantled by till, which fills in rock depressions but lacks much relief itself.

Sandy Areas. Well-sorted sand is relatively rare along the inner shelf of the western Gulf of Maine and only accounts for 7% of the seafloor sediment (Plate 2). The sandiest region is in southern Maine, where sand is concentrated in Nearshore Ramps. A single, large sandy region occurs off the Kennebec River mouth and many smaller bodies of sand are scattered throughout the study area. This material is acoustically uniform and strongly contrasts with bordering areas of gravel and rock. Although many samples from shallow water contain "clean", well-sorted sand, areas mapped "sand" or sand with other materials frequently contain sediment in which the sand is mixed with minor quantities of mud or gravel.

Muddy Areas. After rocky areas, muddy regions are the most abundant on the inner shelf and occupy 39% of the seafloor (Plate 2). Mud covers vast areas of the Nearshore and Outer Basins. It is the dominant seabed material in all nearshore areas except for southern Maine and near Canada. It is also the major deep-water surficial material in all locations except off southern Maine.

Mud accumulates where there is an available supply of fine-grained sediment and quiet conditions that favor the slow settling of small particles, or their entrapment by sessile organisms. In the nearshore regions, mud probably comes from eroding glacial bluffs and seasonally from rivers. Deep water mud must be derived from erosion of deposits in shallow water.

Muddy seafloors are featureless on acoustic records unless they have been disturbed or contain anomalous, "hard" objects. Drag marks left by fishing boats are very common in all sedimentary environments along the inner shelf, but are most noticeable over muddy seabeds. Gas-escape pockmarks are more localized disturbances, but, where they occur in abundance, they profoundly alter the seabed. In Belfast, Blue Hill and Passamaquoddy Bays thousands of hemispherical depressions, hundreds of meters in diameter and tens of meters deep, mark the muddy bottom (Fader, 1991; Kelley and others, 1994; Barnhardt and Kelley, 1995).

Sediment Volumes

Glacial erosion stripped pre-Pleistocene sediment from the Maine inner shelf and left a thin and patchy distribution of generally glacigenic sediments (Plate 3). Because of the highly irregular bedrock relief, there are few deposits with more than 10 m of sediment that are areally extensive enough to depict at a scale of 1:500,000.

Regions with < 10 m of sediment are most abundant (Plate 3). They include all areas of bedrock outcrop, along with surrounding gravel deposits (Rocky Zones, Plate 1). Rock-dominated areas follow the trend of bedrock peninsulas on land, and possess generally circular outcrop patterns surrounding granitic bodies near Penobscot Bay. Near the Canadian border the areally extensive Hard-Bottom Plain (Plate 1) seldom contains more than a few meters of sediment cover.

Regions with between 10 m and 30 m of sediment are found in depressions between bedrock islands and peninsulas (Nearshore Basins, Plate 1), such as in Casco and Penobscot Bays, and in some deep-water locations (Outer Basins, Plate 1). Most of the sediment in these deposits is glacial-marine mud, although Holocene mud is locally quite thick. There are many more locations with small areas of sediment >10 m thick, but they cannot be confidently plotted on a 1:500,000 scale because they are too small, or because geophysical coverage does not adequately define the deposits. Even within those areas mapped with between 10 m and 30 m of sediment, it is possible there are thinner deposits not recorded on the seismic reflection profiles.

Areas with sedimentary deposits greater than 30 m are even more rare than deposits between 10 m and 30 m in thickness. Areas with more than 30 m of sediment are too small to appear on a 1:500,000 scale map. Detailed maps exist for some areas, however, where thick deposits can be outlined (Figures 13-17). In Wells, the thickest deposits are located in relatively deep water near the lowstand shoreline. No cores exist for this area, but surficial material is sandy and a large quantity of sand may exist near the 60 m isobath (Shipp, 1989). In 20 m to 40 m depth seaward and north of Bald Head Cliff, till and gravel deposits are commonly greater than 10 m thick (Figure 13).

Off large rivers like the Saco and Kennebec, substantial deposits of sand were introduced to the inner shelf during times of lower sea level (Kelley and others, 1992). Sand in Saco Bay does not exceed 7 m in thickness (Figure 14), but at least that much glacial-marine sediment also exists beneath the modern sand. Off the Kennebec River, sediment deposits greater than 40 m are common between the bedrock ledges (Figure 15). Much of this is sand and gravel related to delta construction in the late Pleistocene and early Holocene (Barnhardt, 1994). This area contains the thickest deposits of coarse-grained sediment along the Maine inner shelf (Kelley and others, 1995a).

In Penobscot Bay, despite the presence of Maine's largest river, there are no thick deposits of sand or gravel yet recognized (Figure 16). There are three troughs filled with more than 10 m of sediment in many locations, but most of this sediment is glacial-marine mud, and the remainder is modern mud (Kelley and others, 1995b). The lack of a large sandy delta dating from the time of the sea-level lowstand remains unknown.

Data is more scattered to the east of Penobscot Bay, but a detailed study off Gouldsboro Bay probably obtained results typical of the region. Rock ridges continue seaward of the bedrock peninsulas on land, with sediment deposits greater than 30 m in thickness recognized in several locations (Figure 17). As in other areas, however, the thickest sediment deposits are largely comprised of muddy glacial-marine sediment (Shipp, 1989).

Some of the thickest sedimentary deposits off the Maine coast are recognized off Machias Bay (Figure 18). Off Sprague Neck, one of the largest moraines in the region (Shipp, 1989),

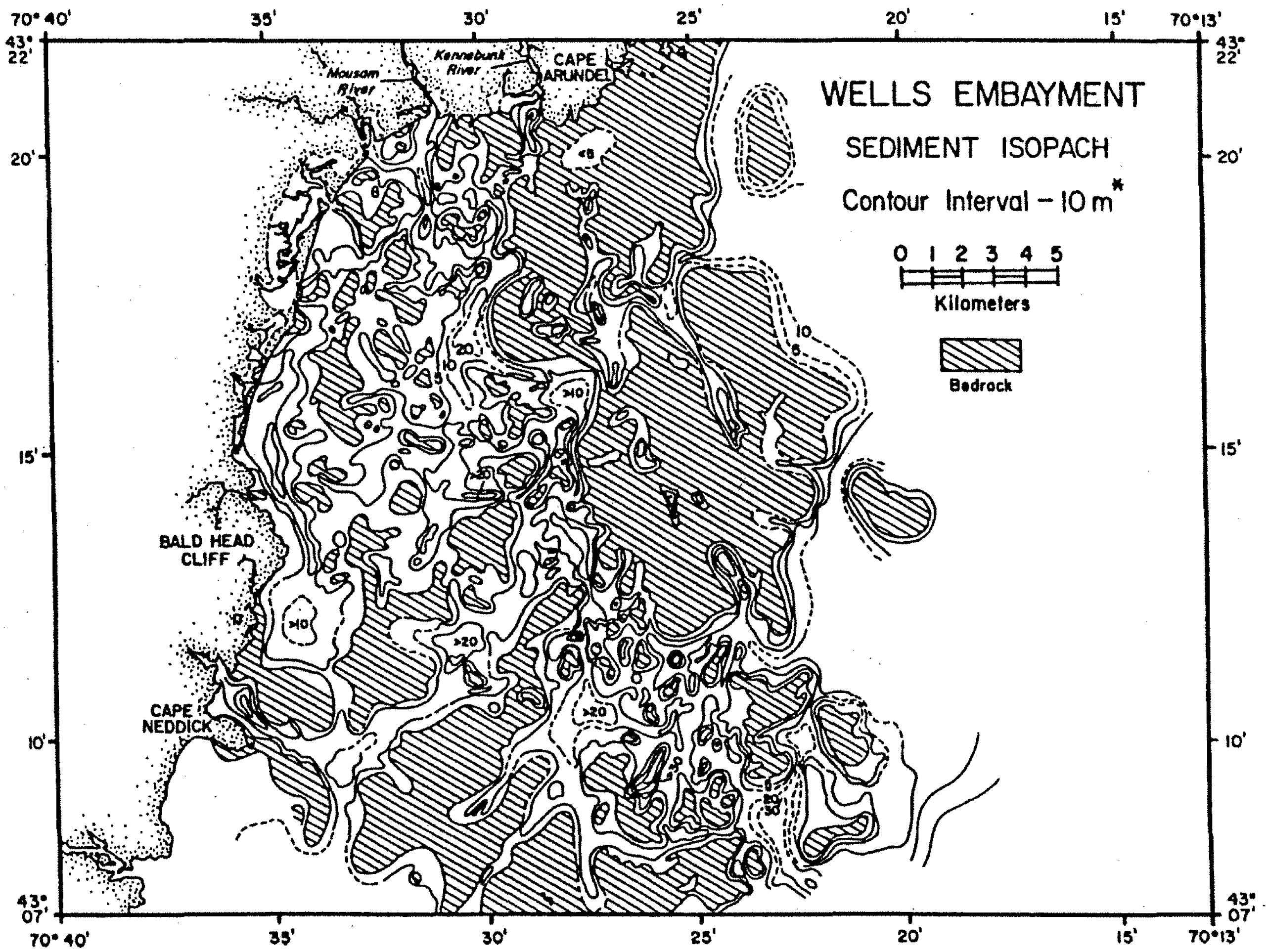

Figure 13. Sediment isopach map for Wells embayment, Maine. As discussed in an earlier report (Kelley and others, 1987a), sand is concentrated in a wedged-shaped deposit near shore (modified from Shipp, 1989).

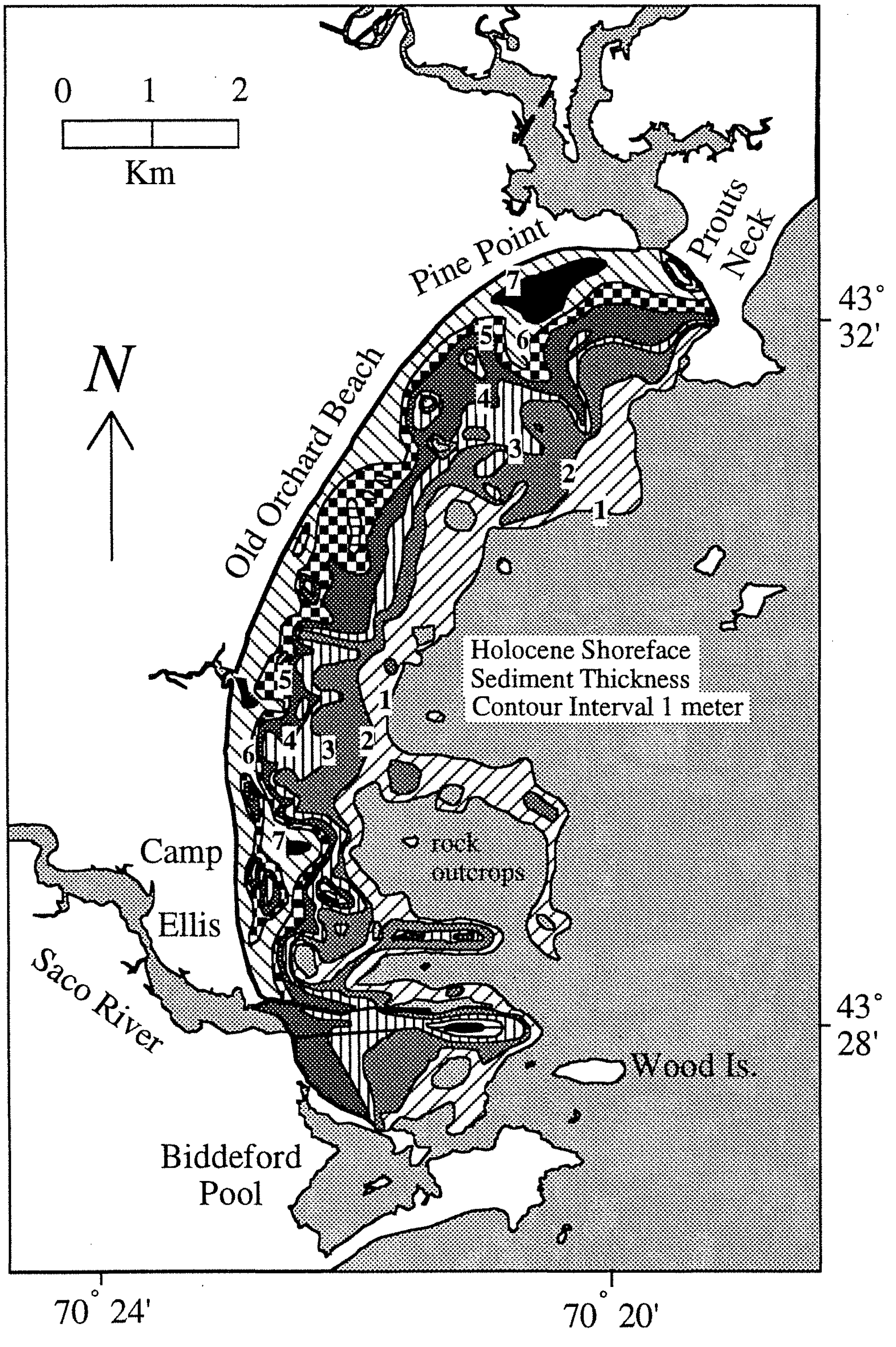

Figure 14. Volume of sand in the nearshore region of Saco Bay. Volume estimates are based on interpretation of seismic reflection data in conjunction with vibracores. Contour interval is 1 m. (After Barber, 1995 and Kelley and others, 1995a.)

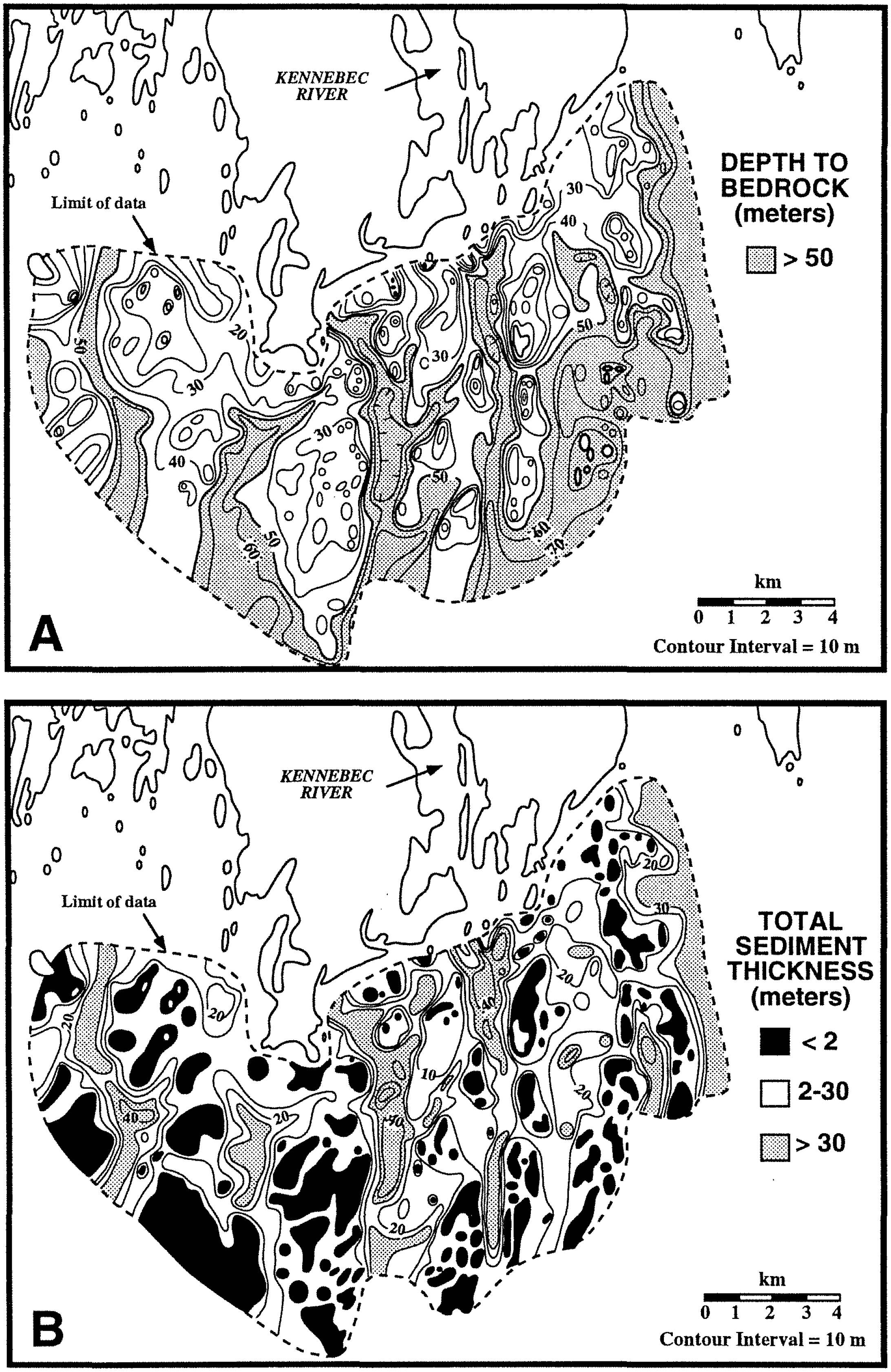

Figure 15. Structure contour map of bedrock surface off the Kennebec River mouth (A). Isopach map (B) of total sediment thickness (from Barnhardt, 1994).

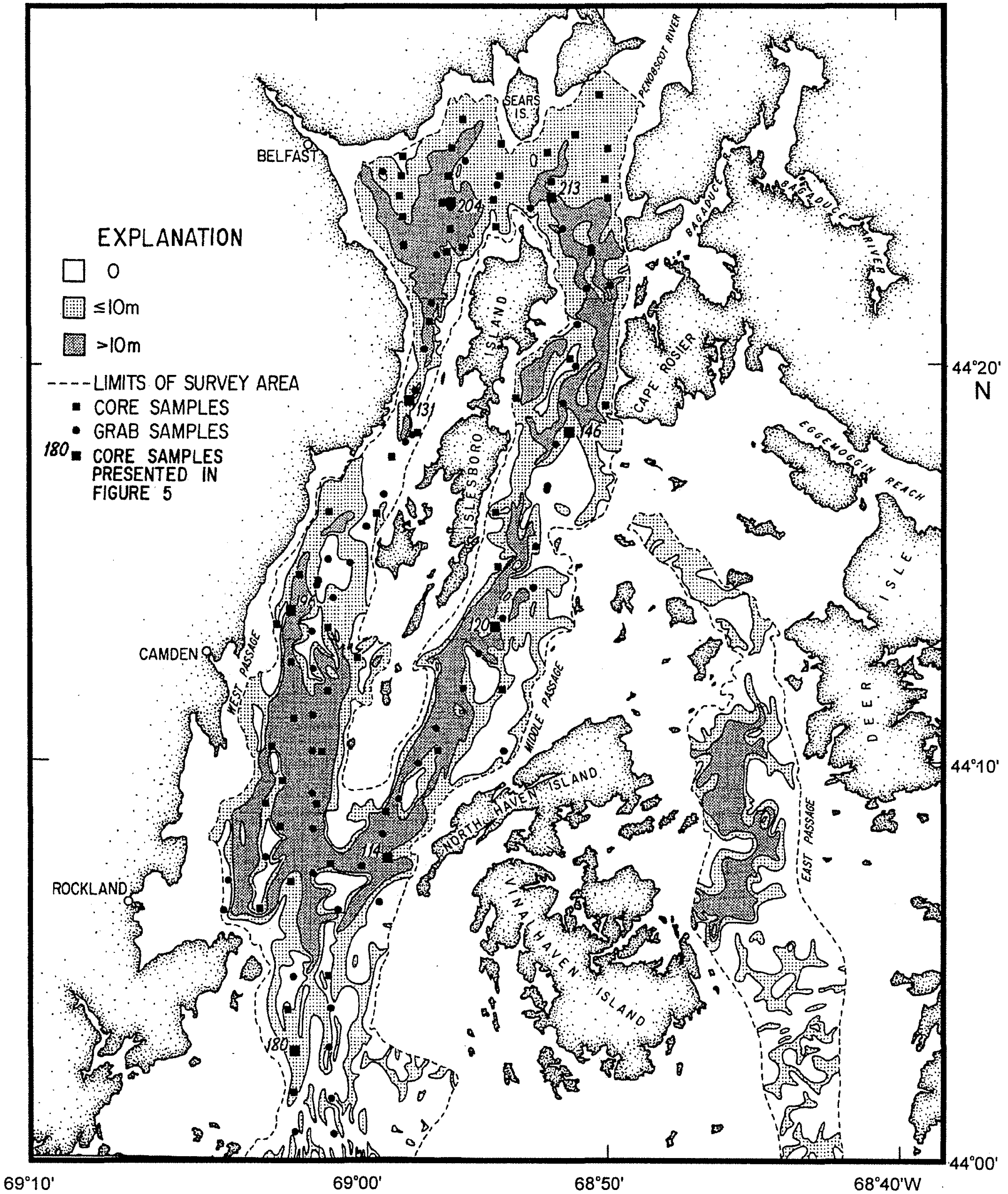

Figure 16. Sediment thickness in Penobscot Bay (modified from Knebel, 1987).

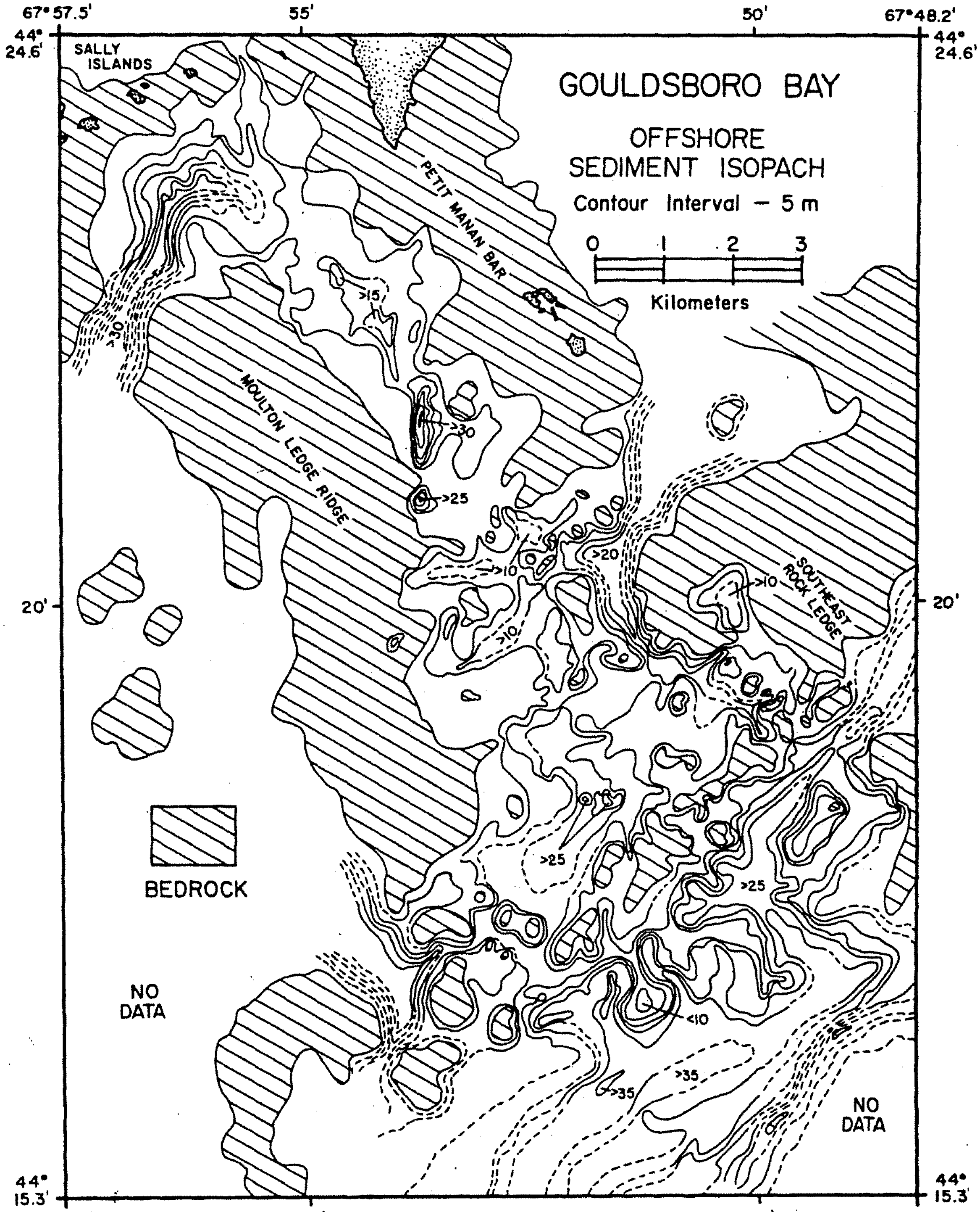

Figure 17. Isopach map of Gouldsboro Bay (modified from Shipp, 1989).

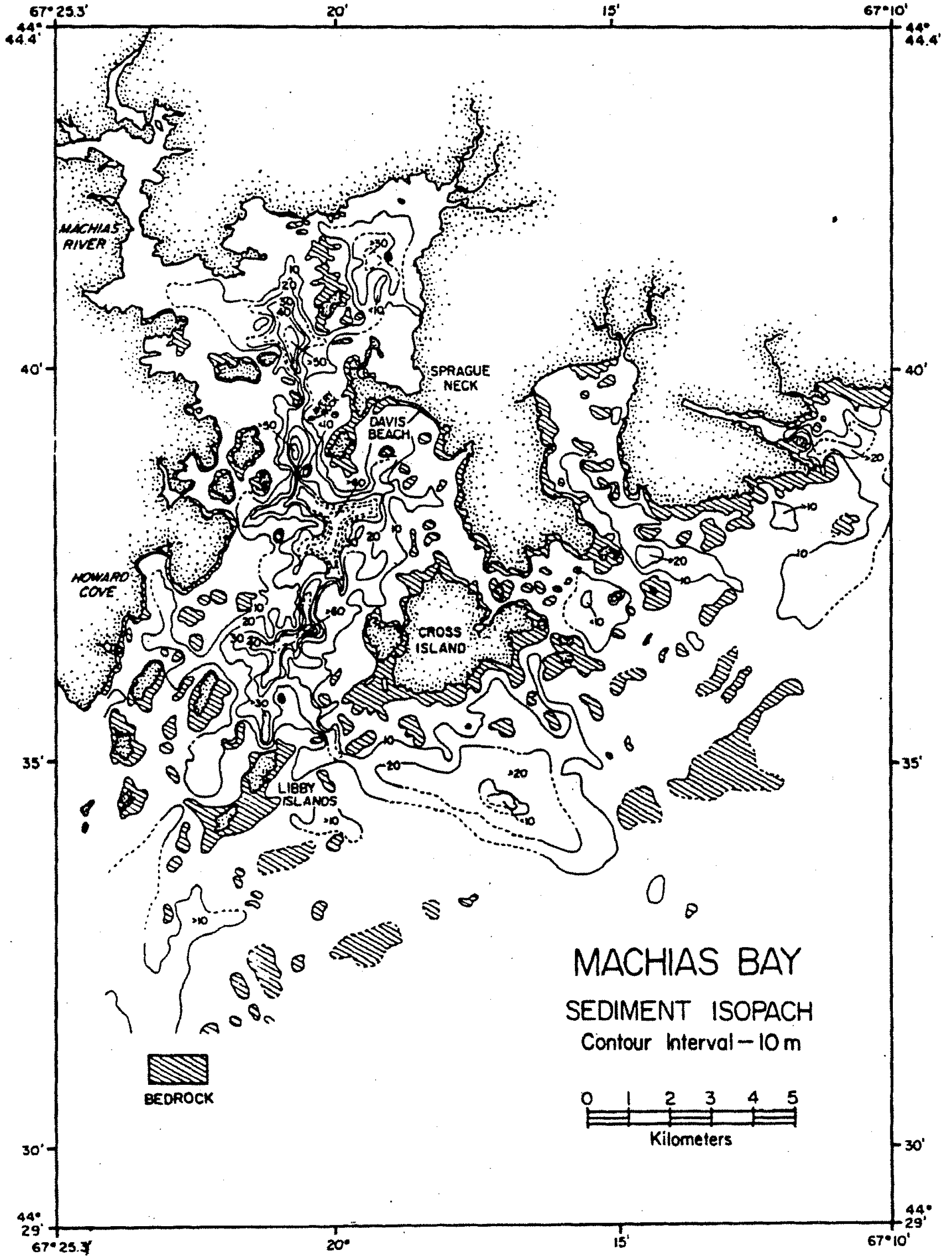

Figure 18. Isopach map of Machias Bay (modified from Shipp, 1989).

has a sediment thickness exceeding 50 m, with an area of great sediment thickness extending to the south. Off Sprague neck the sediment is probably till, but to the south the thick sedimentary deposits are stratified. They may be sand and gravel or mud, but no cores have been collected in this area.

Heavy Mineralogy of Sediment Samples

The abundance of heavy minerals was generally low, but quite variable in the sediment samples (Table 1). The highest concentration in a single sample, 6% of the dry sample weight, was found in Casco Bay, where the bay-wide average was higher than elsewhere, 2.6%. Although each of the areas studied was variable, Oak Bay contained the lowest concentrations with a mean value of 0.21% (Table 1).

Although the areas selected for sediment samples were presumed to be sandy, material from gravel to mud were found in many samples (Table 2). The gravel was largely composed of rock fragments or shells, but wood and railroad cinders were also observed. Fine-grained sediment was not observed to contain heavy minerals. The silt-size fraction was dominated by quartz and feldspar, and the clay-size fraction was dominated by illite and chlorite as observed elsewhere in Maine (Kelley, 1989).

Heavy minerals in the rivers and bays were variable, but generally similar (Tables 3, 4). Garnet, epidote, and pyriboles dominated most locations. Garnet was most abundant in rivers and associated bays that drain western Maine's high-rank metamorphic terrane. Garnet was not so common in eastern Maine where volcanic and intrusive mafic rocks are common (Tables 3, 4). Less abundant, but important minerals include sillimanite and kyanite in abundance from Saco Bay, in the southwest, and magnetite and ilmenite in abundance in the St. Croix and Machias Rivers, respectively. Oak Bay and the associated St. Croix River contained the highest concentrations of magnetite (Tables 3, 4).

ACKNOWLEDGMENTS

We wish to acknowledge the Maine Geological Survey and the Minerals Management Service-American Association of State Geologists Continental Margins Program. Funding for this project came from the U.S. Department of Interior Minerals Management Service's Continental Margins Program through cooperative agreement 14-35-0001-30534.

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SAMPLE #	BULK WT(g)	H2O %	NET WT(g)	HM WT(g)	HM WT %
CB-86-43	27310.00	20.80	21630.00	1297.30	6.00%
CB-86-45	26080.00	18.35	21290.00	203.34	0.96%
CB-86-50	11520.00	16.90	9570.00	54.80	0.57%
CB-86-67	22720.00	22.00	17720.00	511.30	2.89%
CB-86-70	15880.00	17.70	13070.00	419.50	3.21%
CB-86-71	13650.00	18.40	11140.00	332.40	2.98%
CB-86-72	16960.00	20.70	13450.00	422.70	3.14%
CB-86-106	8300.00	15.90	6980.00	53.50	0.77%
PSPR-87-01	17327.20	40.12	5719.71	101.83	1.78%
SR-87-01	21182.80	22.21	15132.99	192.80	1.27%
AR-87-01	25673.30	22.14	18371.81	679.80	3.70%
KR-87-01	21409.09	17.51	17660.36	313.20	1.77%
KR-87-03	18914.80	18.84	14524.68	315.30	2.17%
KR-87-04	7892.50	13.74	6636.01	134.97	2.03%
KR-87-05	14605.70	13.10	12404.62	86.32	0.70%
PB-87-66	19640.60	11.75	17024.47	54.30	0.32%
PB-87-94	19323.00	16.97	15373.38	146.43	0.95%
PB-87-101	10296.50	10.20	9126.82	261.40	2.86%
PB-87-117	14560.30	17.06	11566.70	190.99	1.65%
PNBR-87-01	23632.20	15.81	19196.44	79.18	0.41%
MB-87-1A	8148.95	24.23	5542.92	178.47	3.22%
MB-87-1B	4120.50	22.72	2909.49	4.80	0.16%
MB-87-2A	3180.20	26.70	2021.65	24.15	1.19%
MB-87-2B	2134.70	24.70	1434.52	14.60	1.02%
MB-87-3A	3550.15	25.52	2333.51	77.44	3.32%
MB-87-3B+C	9775.25	23.04	6849.52	239.80	3.50%
MR-88-01	21810.00	4.50	20730.00	12.37	0.06%
OB-88-01	22890.00	17.72	17730.00	26.40	0.15%
OB-88-02	12670.00	23.54	8930.00	24.43	0.27%
SCR-88-01	12400.00	50.96	3870.00	29.14	0.75%
SCR-88-02		43.99		55.33	

Table 1. Bulk sample properties. BULK WT is the initial sample weight, the NET WT is the BULK WT minus the percent water (H2O%) in the sample. HM is the weight of heavy minerals, and HM% is the weight percent of heavy minerals in the sample (from Lehmann, 1991).

SAMPLE #	GRAIN SIZE	PHI	SORTING	SKEWNESS	GRAVEL TYPE
SR-87-01	f.s	2.5	p	c-near sym	rock frags & mica
PSPR-87-01	vf-c.s	4.0 - 3.0	v.p-p	str.f	fine roots
AR-87-01	med-c.s	1.3 - 0.8	p-mod.	str.c	RR cinders
KR-87-01	med.s	1.1	w	str.f	shell hash
KR-87-02	c.s	0.6 - 0.3	p	str.c	wood
KR-87-03	f-c.s	2.5 - 0.6	mod.w	c-f	wood* & rock frags
KR-87-04	c.s	0.4	p	near sym	rock frags
KR-87-05	c.s	0.7	p	near sym	rock frags & wood*
CB-86-43	med-c.s	1.1 - 0.8	p-w	near sym-f	NR
CB-86-50	vc.s	-0.1	mod.w	f	NR
CB-86-67	med.s	1.8	w-v.w	near sym	NR
CB-86-71	med.s	1.1	mod.w	c-near sym	NR
CB-86-72	f.s	2.1	w	near sym-f	NR
CB-86-106	m.s	1.8	mod.	str.c-near sym	NR
PNBR-87-01	vc.s	-0.6	mod.	str.f	rock frags
PB-87-66	vc.s	-0.1	p	near sym	rock frags
PB-87-94	vc.s	-0.3	p	str.f	rock frags
PB-87-101	c.s	0.6	p	c	rock frags
PB-87-117	c.s	0.8	v.p	near sym-f	rock frags
MR-88-01	vc.s	-0.5	mod.	near sym-f	rock frags
MB-87-1A	f.s	2.9	w	f-str.f	roots-wood*-shells
MB-87-1B	granules	-1.2	mod.w	str.f	shells & rock frags
MB-87-2A	c.z-f.s	4.3 - 3.8	v.p-p	str.f	shells
MB-87-2B	c.z-f.s	4.3 - 3.4	v.p-mod.	str.f	shells
MB-87-3A	vf.s	3.1	p	near sym	shells
MB-87-3B+C	vf.s-f.s	3.1 - 2.5	p	c-near sym	rock frags
SCR-88-01	c.s	0.2	v.p	str.f	rock frags
SCR-88-02	N/A	N/A	N/A	N/A	rock frags
OB-88-01	vc.s	-0.3	p	str.f	rock frags
OB-88-02	vc.s	-0.2	p	str.f	rock frags

Table 2. Grain size results. Abbreviations mean: **vf** = very fine; **f** = fine; **med** = medium; **c** = coarse; **vc** = very coarse; **s** = sand; **z** = silt; **vp** = very poorly; **p** = poorly; **mod** = moderately; **w** = well; **vw** = very well; **sym** = symmetrical; **str** = strongly; **frags** = fragments; **RR** = railroad cinders; **wood** = sawdust, and **NR** = not recorded (from Lehmann, 1991).

	SACO BAY *	CASCO BAY	PENOBSCOT BAY	MACHIAS BAY	OAK BAY
MAG	tr-3.53	0.30-3.29	0.65-8.82	1.64-3.02	3.29-5.01
	0.76	1.73	3.19	2.26	4.15
ILM	2.33-6.10	0.49-7.74	0.70-2.47	0.91-2.55	5.15-7.22
	3.66	3.89	1.40	1.91	6.19
GAR	21.80-50.50	15.78-38.31	21.16-59.97	1.54-3.88	10.86-16.84
	32.94	25.33	40.70	2.55	13.85
STA	3.60-7.52	0.97-8.73	0.91-1.32	0.00-0.13	2.32-2.65
	4.98	2.84	1.08	0.02	2.49
PYR	16.80-28.85	10.42-23.27	4.25-19.38	20.44-45.01	14.04-16.48
	24.16	17.04	12.86	31.94	15.26
AND	**	0.00-3.11	5.69-6.19	0.82-1.65	0.93-1.02
		2.06	5.94	1.28	0.97
SIL	4.20-12.30	0.06-2.38	0.04-0.19	present	present
	8.32	0.59	0.09	(tr)	(tr)
KYN	***	0.00-1.38	0.04-0.22	NP	NP
		0.40	0.13	0.00	0.00
ZIR	0.90-2.90	0.02-1.10	0.22-0.91	0.66-2.34	0.65-0.71
	1.70	0.67	0.52	1.15	0.68
TRM	5.30-10.75	0.01-1.30	0.08-0.31	0.09-0.58	0.91-1.10
	7.12	0.50	0.22	0.25	1.00
RUT	tr-0.50	0.07-0.11	0.09-0.26	0.02-0.04	0.01-0.05
	0.12	0.09	0.16	0.03	0.03
EPI	5.50-13.20	27.09-37.48	10.61-25.34	21.52-46.44	28.01-31.15
	9.60	31.38	19.20	37.20	29.58
SPH	0.90-3.40	0.02-1.13	0.03-0.20	0.017-0.96	0.21-0.36
	2.21	0.23	0.10	0.57	0.29

Table 3. Observed percentage of heavy minerals from bay samples. Abbreviations as follows: **mag** = magnetite; **ilm** = ilmenite; **gar** = garnet; **sta** = staurolite; **pyr** = pyriboles; **and** = andalusite; **sil** = sillimanite; **kyn** = kyanite; **zir** = zircon; **trm** = tourmaline; **rut** = rutile; **epi** = epidote + apatite; **sph** = sphene; **NP** = not present; **tr** = trace; **present** = > trace. For each mineral the range of values of samples is given, with the mean concentration shown below (from Lehmann, 1991).

	SACO	PRESUMP	ANDRO	KENNEBEC	PENOB	MACHIAS	SAINT CROIX
MAG	1.46	3.67	0.31	0.01-0.41 0.13	2.01	1.24	8.24-14.37 11.31
ILM	4.36	5.64	2.87	0.68-11.91 5.71	3.54	5.97	0.39-1.34 0.87
GAR	31.52	26.98	40.23	11.29-29.66 19.23	21.74	4.77	1.11-2.43 1.77
STA	0.91	4.93	0.98	0.97-12.67 5.70	0.92	1.41	NP 0.00
PYR	20.30	8.81	17.36	12.58-27.38 19.92	9.95	32.12	21.03-36.24 28.64
AND	1.58	0.78	1.56	0.77-3.89 2.47	2.49	0.93	0.68-0.88 0.78
SIL	1.24	0.53	0.67	0.25-1.75 1.18	NP	NP	present (tr)
KYN	0.80	0.78	0.09	0.06-0.20 0.13	NP	NP	NP 0.00
ZIR	0.98	1.83	0.51	0.17-0.99 0.59	1.01	1.70	1.65-1.68 1.67
TRM	4.04	1.59	0.06	0.06-0.35 0.16	0.31	0.92	0.14-0.14 0.14
RUT	1.14	0.50	0.08	0.03-0.23 0.10	0.04	0.04	0.06-0.18 0.12
EPI	25.57	33.28	29.90	21.17-26.29 23.10	28.84	24.36	31.97-34.50 33.24
SPH	0.09	0.07	0.02	present (tr)	NP	1.28	0.12-0.35 0.24

Table 4. Observed percentage of heavy minerals from river samples. Abbreviations as follows: **mag** = magnetite; **ilm** = ilmenite; **gar** = garnet; **sta** = staurolite; **pyr** = pyriboles; **and** = andalusite; **sil** = sillimanite; **kyn** = kyanite; **zir** = zircon; **trm** = tourmaline; **rut** = rutile; **epi** = epidote + apatite; **sph** = sphene; **NP** = not present; **tr** = trace; **present** = > trace. The rivers from left to right are: Saco, Presumpscot, Androscoggin, Kennebec, Penobscot, Machias, and St. Croix . The range of values, with the mean concentration shown below, is provided for the Kennebec and St. Croix Rivers (from Lehmann, 1991).

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