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Geomorphology and Late Quaternary Evolution of the Saco Bay Region

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ABSTRACT

Saco Bay is a large coastal reentrant on the southwestern coast of Maine. It has experienced a deglaciation, two marine transgressions, and a withdrawal of the sea to the 65 m isobath within the past 14,000 years. Seismic reflection and side-scan sonar profiles, as well as bottom samples and submersible dives, have permitted mapping of the physiography and surficial geology of the bay. The extensive sandy beaches and muddy salt marshes of the bay are bordered on their seaward side by a gently sloping sandy region called the nearshore ramp. Numerous rippled-scour depressions across this area suggest the transfer of nearshore sand to bedrock-framed shelf valleys which connect the nearshore ramps to the deepest portion of the bay, the outer basin. The muddy outer basin begins with the lowstand shoreline at 65 m depth and continues seaward beyond the 100 m isobath. Throughout the bay bottom, bedrock outcrops are common, but in the rocky zone they are the principal bottom type. In many locations the rocky zone is not exposed rock, but a boulder-capped veneer over a washed till deposit.

As sea level has risen across the bay in the past 9000 years, sands introduced from the Saco River and from eroding till outcrops have probably maintained a barrier beach system. Since the slowing of the rate of sea-level rise began 3,500 years ago, the barrier beaches of Saco Bay have grown seaward. They are presently experiencing a scarcity of sand in some places as a result of a more rapid contemporary rate of sea-level rise and interference from coastal jetties and sea walls. As more and more of the sand within the system moves offshore or is buried beneath residences on the beaches, the future health of the system is endangered.

INTRODUCTION

Saco Bay is a prominent coastal reentrant on the southwestern Maine coast (Fig. 1). On the basis of its geomorphology, the shoreline along this portion of the western Gulf of Maine is classified into the Arcuate Embayments coastal compartment (Kelley, 1987; Kelley et al., 1986). The characteristic features of this compartment, which extends south from Cape Elizabeth into northern Massachusetts, are numerous embayments with conspicuous sandy barrier spits that are separated by rocky headlands of igneous or metamorphic rock (Tuttle, 1960; Osberg et al., 1985). The barrier beaches of the compartment typically protect extensive salt marsh systems, although tombolos which front lagoons or mudflats, such as at Biddeford Pool, also exist (Hulmes, 1981).

While some research has been conducted on the barrier beach and back barrier areas of Saco Bay and other embayments in this compartment (Hussey, 1970; Farrell, 1972; Hulmes, 1981; MacIntyre and Morgan, 1964), only recently has the offshore region of Saco Bay been described (Kelley et al., 1986, 1987), and as yet there has been no integration of the onshore and offshore geology. The purpose of this report is to review the geology of pertinent terrestrial and marine features of the Saco Bay region, and to describe the evolution of these features in the context of late Quaternary sea level fluctuations.

PREVIOUS WORK

Numerous workers in southern Maine have mapped terrestrial deposits resulting from the last glaciation (Thompson and Borns, 1985). Early interest focused on a stratified moraine complex south of Saco Bay which was thought to represent a climatic readvance of glacial ice (Katz and Keith, 1917; Bloom, 1960). Subsequent research has dismissed the concept of a climatic readvance (Smith, 1981) in favor of a deglaciation model of a retreating marine-based ice sheet (Smith, 1982).

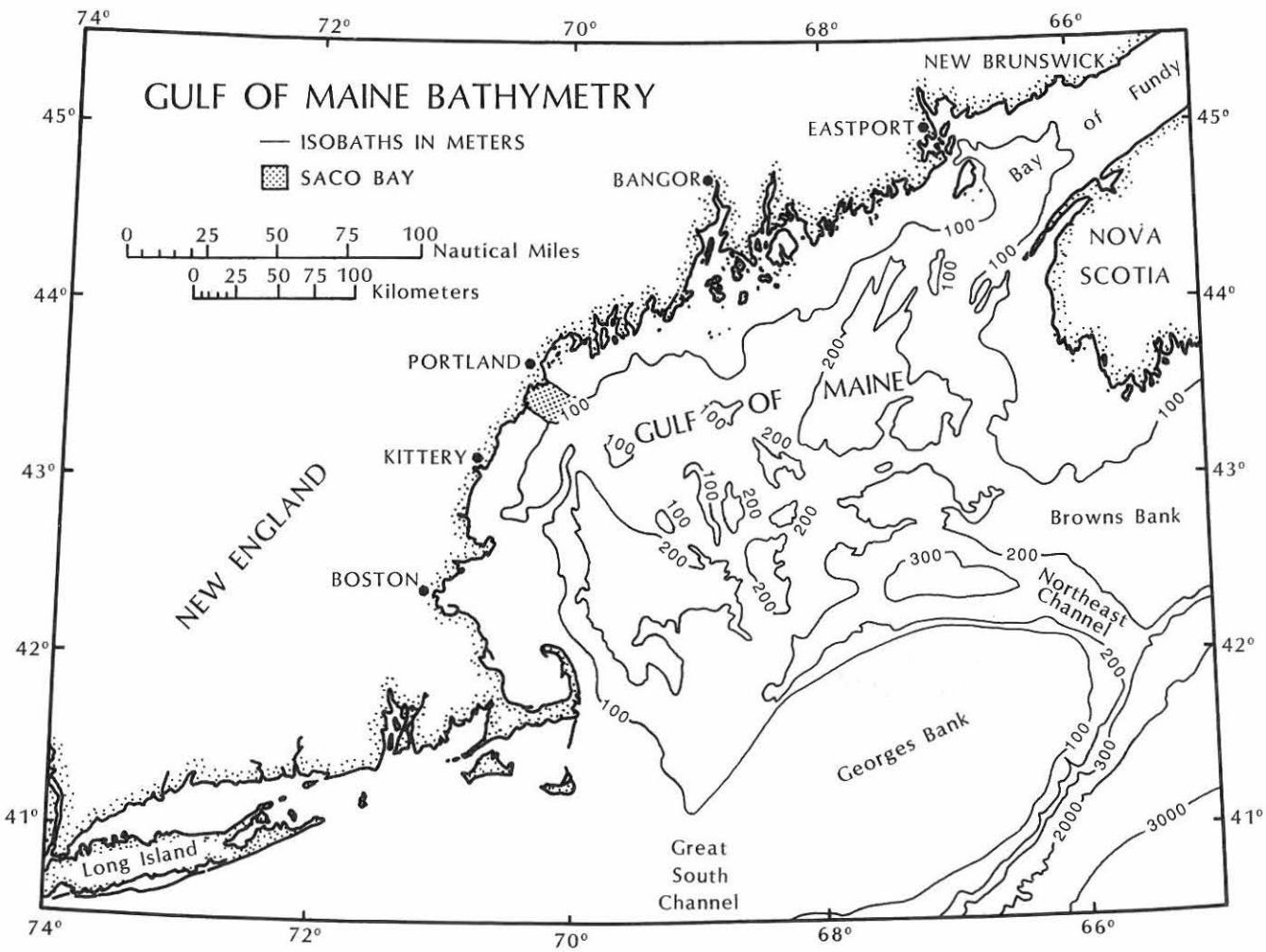


Figure 1. Location of the study area, Saco Bay, in relation to the Gulf of Maine.

Bloom (1960, 1963) first defined the glaciomarine sediments deposited contemporaneously with the retreat of the ice as the Presumpscot Formation. He recognized that the marine inundation leading to deposition of the Presumpscot Formation resulted from isostatic depression of the land by the weight of the ice. He also recognized that sea level fell rapidly due to crustal uplift following removal of the ice (Bloom, 1963). Based on an erosional unconformity on the surface of the Presumpscot Formation that was discernible in borings through the Scarborough River salt marsh, Bloom (1963) felt that relative sea level dropped 10 m beneath present sea level about 7000 years ago. Borns and Hagar (1965) named the regressive fluvial deposits overlying the unconformity on the Presumpscot Formation surface as the Embden Formation in the Kennebec River valley.

Stuiver and Borns (1975) presented the first detailed chronology of late and early postglacial events based on radiocarbon dates from within the Presumpscot Formation. Their work was recently updated (Smith, 1985; Belknap et al., 1987a) and indicates a receding ice margin at the present coast at 13,200 yr B.P. Most radiocarbon dates from within the Presumpscot Formation range between 11,000 yr B.P. and 13,000 yr B.P., but since many dated objects are shells of intertidal organisms which flourished during the period of falling sea level, the time of maximum marine inundation is often thought to be 13,000 yr B.P. (Thompson and Borns, 1985).

Although early workers recognized that postglacial sea level in Maine fell below the present shoreline (Bloom, 1963; Hussey, 1970), Ostericher (1965) was the first to recognize, using seismic reflection profiling, that the regressive unconformity on the surface of the Presumpscot Formation extended far offshore. He obtained a date of 7,390 yr B.P. from a core sample of the regressive unconformity at 18 m depth in Penobscot Bay. Using seismic reflection profiling methods, Schnitker (1974) later recognized a "berm" or shoreline cut into sediments at 65 m depth, although no age determination could be made of the time of sea level lowstand. In Saco Bay, Kelley et al. (1986, 1987, and below) have also recognized a shoreline around 60 m depth, and that is the generally accepted depth of the lowstand in the region (Shipp, this volume) for a time estimated to be 9,500 yr B.P. - 9,000 yr B.P. (Fig. 2).

Although sandy cores from Saco Bay indicate some river sediment introduction during the most recent transgression (Luepke and Grosz, 1986), Hulmes (1981) concluded that the Biddeford Pool tombolos were formed by the erosion of glacial sediments. Cores from the Pool record no marine sediments cut off from the sea by growing spits, but rather estuarine sediments filling a basin rimmed by (formerly more extensive) glacial deposits (Hulmes, 1981).

Farrell (1972) speculated on the basis of grain size analysis of Saco Bay bottom sediment that glacial deposits were also once more abundant near Prouts Neck. He also recognized relict dunes and lagoons near the Saco River and made cross sections of the Scarborough Marsh from cores. Although he provided no radiocarbon dates, recent dated cores from the Wells Marsh (Belknap et al., 1987a) contain a similar stratigraphy and provide a modern chronology (Fig. 2). Folger et al. (1975) and Oldale et al. (1973) prepared preliminary bottom sediment maps of Saco Bay and vicinity, but Kelley et al. (1987) first integrated a large scale sampling program with side-scan sonar imagery, seismic reflection profiles, and submersible dives.

METHODS

The methods employed for this report are described in detail elsewhere (Kelley et al., 1987) and will only be summarized here. In 1985, 175 bottom stations were occupied in Saco Bay, and 121 samples were analyzed for grain size, % carbon, and % $CaCO_3$. In addition, about 200 km of seismic reflection profile data were gathered with both a Raytheon RTT 1000A 3.5 kHz system and Ocean Research Equipment Geopulse "boomer" equipment. About 50 km of side-scan sonar imagery were also gathered in conjunction with the Geopulse seismic reflection profiles. The side-scan sonar data were collected with an EG&G Model 960 sea floor mapping system which provides slant range corrections on scales of 50 m to 600 m to either side of the vessel. Finally,

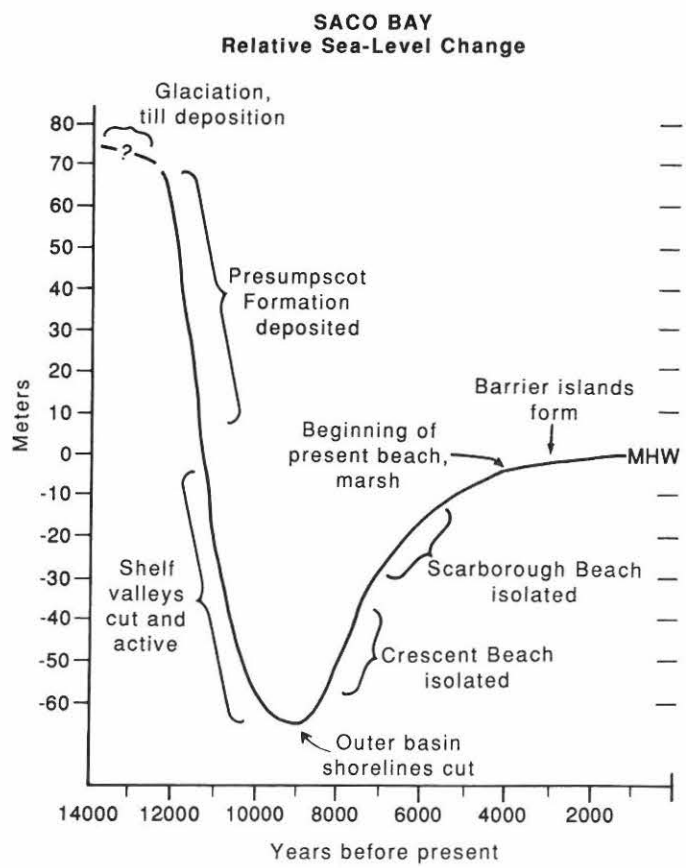


Figure 2. Local relative sea level curve for coastal Maine (modified from Belknap et al., 1987a).

in both 1985 and 1986, submersible dives (*R.V. Johnson Sea Link*; *R.V. Delta*) were made at two locations in the bay. While hundreds of photographs and hours of videotape were collected during the dives, their greatest value was in acquainting the authors with the bottom, which had only been remotely sensed previously.

Interpretation of seismic reflection profile data can be ambiguous, but reflectors observed in Saco Bay were similar to those reported from other locations (Birch, 1984a,b; Belknap et al., 1986, 1987b; King and Fader, 1986). In addition, cores from the bay (Luepke and Grosz, 1986) and borings along Old Orchard Beach (Cimino, pers. commun., 1985) added confidence to the interpretations.

The lowermost reflector observed in most seismic reflection profile lines is interpreted as the surface of bedrock. No reflections are seen beneath the irregular and hard bedrock return which could often be traced directly from outcrops on land. Overlying the bedrock is an acoustic unit with a strong coherent surface return and chaotic internal reflections. This is believed to be till, and side-scan sonar imagery frequently shows boulders on the surface where it is exposed. The most widespread unit in the bay possesses a low-relief and coherent surface reflection with numerous internal reflectors. The internal reflectors typically parallel the underlying topography near the base of the unit and become less prominent in the acoustically transparent upper portion of the record. This unit is interpreted as the glaciomarine Presumpscot Formation (Bloom, 1960) and cores into it indicate a coarse grained surface (Ostericher, 1965; Luepke and Grosz, 1986). This surface is interpreted as the transgressive unconformity created by the most recent rise of the sea. Above this major reflector, a variety of materials form the surface sediment of the bay. Nearshore, a nearly acoustically opaque unit is interpreted as modern sand, while acoustically transparent mud covers the sea floor in the deeper portion of the bay (Kelley et al., 1986, 1987). Thickness of the seismic units is highly variable across the bay, and extensive areas of exposed rock exist. In the axes of paleovalleys sediment is thickest, and as much as 50 m of till and glaciomarine sediment, and 20 m of Holocene material is inferred to exist (Kelley et al., 1986, 1987).

PHYSIOGRAPHY AND SURFICIAL GEOLOGY OF SACO BAY

Supratidal

The supratidal coastal environments of Saco Bay include bedrock outcrops, modern and ancient dunes and spits, lagoons, and a closed tidal inlet. Bedrock outcrops are generally restricted to exposures at prominent headlands such as Biddeford Pool, Prouts Neck, and Cape Elizabeth, or to island shorelines (Fig. 3). Widespread exposures also exist south of Crescent Beach and Higgins Beach, and small outcrops exist or were removed from several locations along Old Orchard Beach (Fig. 3).

Sand dunes comprised of fine, well-sorted sand up to 6 m in elevation front most of the bay's beaches (Farrell, 1972), although dunes are presently absent along those portions of Old Orchard and Higgins Beaches that are developed for residential and commercial structures (Fig. 3; Timson, 1986; Timson and Lerman, 1980). No research has yet been conducted on or in the dunes of Saco Bay.

Landward of the active frontal and back dune environments, extensive paleodunes and occasional relict spits, lagoons, and shorelines are preserved (Figs. 3, 4). Undeveloped paleodunes and spits are covered by a mature Pitch Pine forest and possess 2-3 m of rounded relief. Freshwater-brackish lagoons lie landward of the paleodunes. These environments have not yet been cored, and paleoenvironmental interpretations are based only on morphology (Nelson, 1979; Farrell, 1972). Paleoshorelines are also inferred to exist along the landward margin of Biddeford Pool (Hulmes, 1981), as well as in the Prouts Neck area (Nelson, 1979). Emerged beach deposits are mapped on Prouts Neck (Thompson and Borns, 1985) although no research has been conducted on the internal stratigraphy of these features. The shorelines appear as linear ridges or sloping surfaces cut into till, but are of low local relief (<2 m). One closed inlet is positively known from the present Old Orchard-Scarborough town border (Fig. 3; Farrell, 1972). This inlet was similar in size to the Goosefare Brook inlet and was closed when the railroad line was built in the late 19th century. During construction on the site of this former inlet, Farrell (1972) observed trough cross-bedding in trenches along its former axis. Prior to the closing of the inlet, Pine Point was a barrier island and much smaller in size than at present. Farrell (1972) inferred that inlet closure led to the rapid growth of Pine Point by sand derived from the south.

Intertidal

Sand beaches, sand flats, and salt marshes are the principal intertidal components of Saco Bay (Fig. 3). Farrell (1972) made numerous topographic surveys at five equally-spaced stations along Saco Bay and evaluated the grain size of 120 samples from Pine Point to the Saco River. He noted differences in topography and sediment texture between the two ends of the beach. While the Pine Point end of the beach exhibited a wide (225 m), flat, largely intertidal profile with a primary grain size mode at 2 phi (fine sand), the Saco River end of the beach was narrow (60 m) and steep with a primary grain size mode at 1 phi (medium sand). An abrupt contact between the two extremes was located at the central portion of the beach. He associated both the narrowing and coarsening of the beach to the south with the loss of a fine grained sub-population of sediment from that area. Although Farrell noted few significant changes in the width of Old Orchard Beach, Nelson (1979) determined that the shoreline was retreating rapidly at Camp Ellis, Western Beach, and Higgins Beach, and spits were actively growing into the Scarborough and Spurwink Rivers.

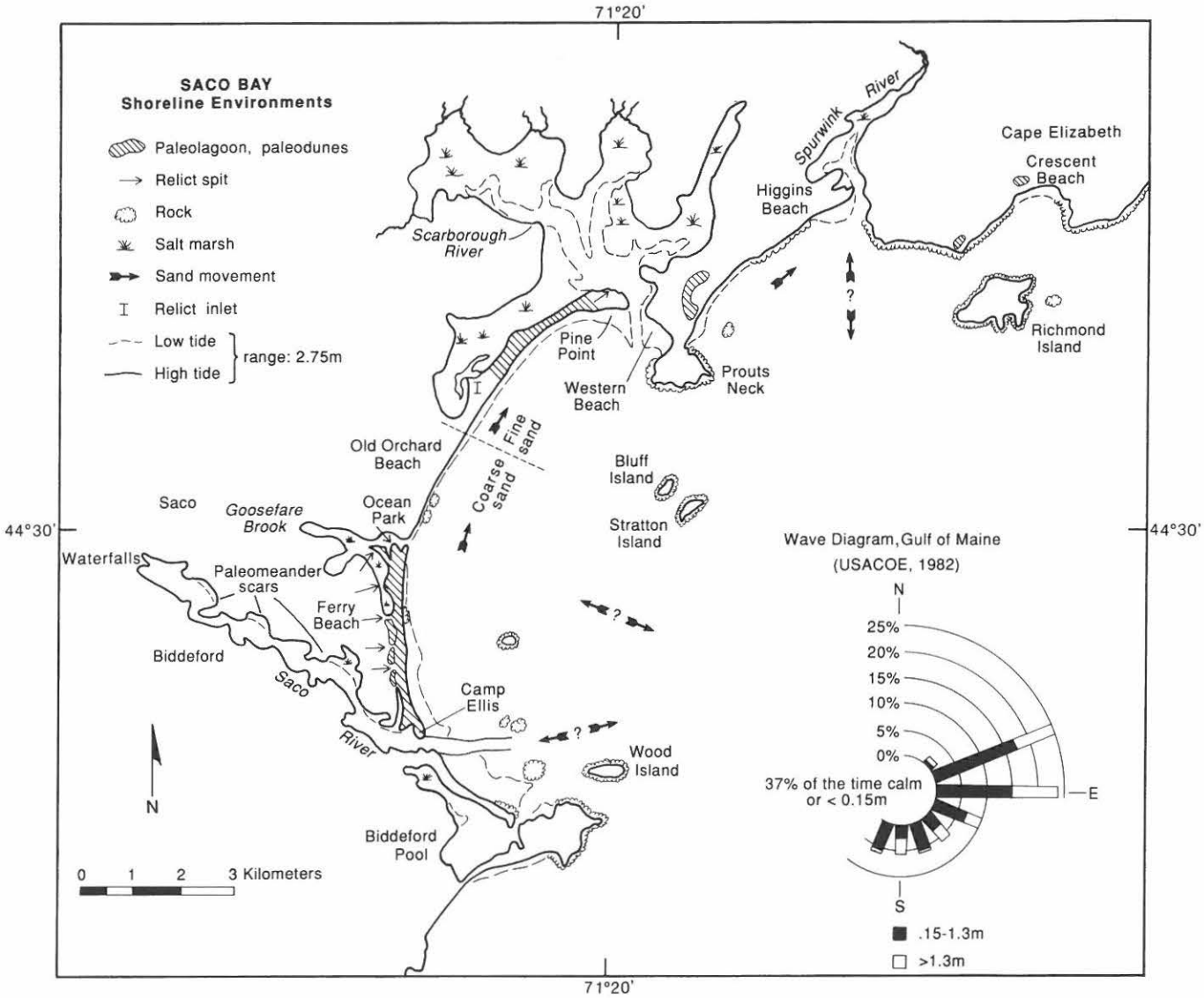
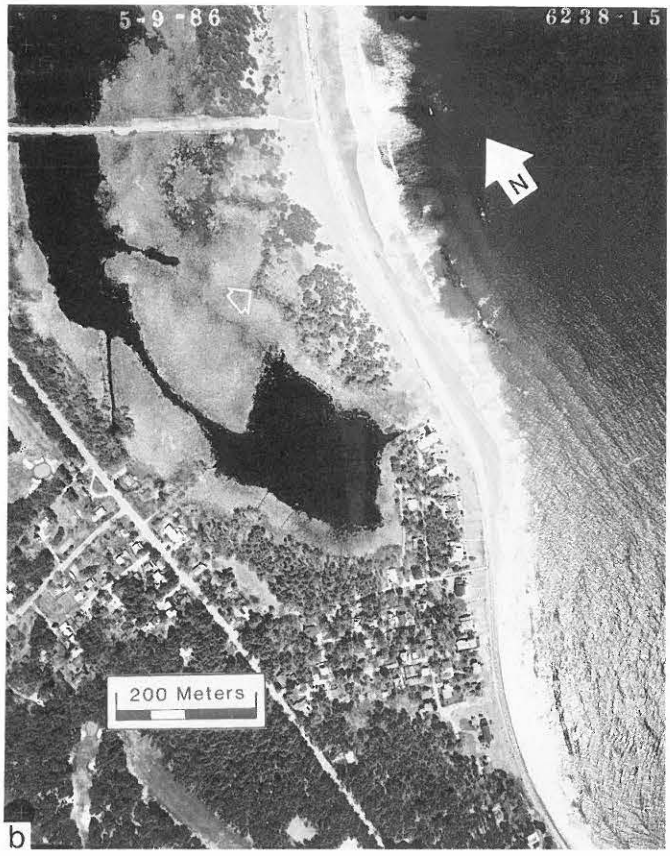


Figure 3. Supratidal and intertidal environments and landforms in Saco Bay. Wave diagram modified from U.S. Army Corps of Engineers (1982) represents hindcast height and direction data from Latitude 43°50'N, Longitude 68°00'W, 1948-1950.

Subsurface data from the beaches of Saco Bay are very scanty, and very little is known of the tidal inlets of the bay. Engineer's logs for high rise construction near the former site of a tidal inlet revealed 15 m of sand beneath the dunes of that area with scattered horizons of peat and gravel (Cimino, pers. commun., 1985). Most of the borings met refusal in very stiff clay, interpreted as the Presumpscot Formation, around 20 m depth. Beyond the bedform migration studies of Trefethen and Dow (1960) and Farrell (1970) on the tidal deltas of the Scarborough River, there have been no published reports from these environments.

The Scarborough Marsh has been extensively cored by Farrell (1972). A typical cross section (Fig. 5) grades upward from a sand or mud flat overlying the Presumpscot Formation possibly as deep as 7 m. Silty sand or a thin brackish water peat underlies a much thicker *Spartina* peat which forms the present marsh surface. Although Farrell provides no radiocarbon dates for the Scarborough Marsh, an identical stratigraphic section was cored and dated from the Webhannet River Marsh in Wells, Maine (Belknap, et al., 1987a, Kelley et al., 1988). The transition from freshwater to salt marsh occurred at 3,500-4,000 yr B.P. and marks a time when the rate of sea level rise throughout the region slowed significantly (Oldale, 1985a; Scott and Greenburg, 1983).

Spit progradation, beach retreat, and salt marsh accretion are measurable, on-going processes in Saco Bay today as the supratidal landforms indicate they were in the past. Tidal deltas



and inlets remain as important, unstudied components of the intertidal system.

Nearshore Ramp

The nearshore ramp is defined as that portion of Maine's inner continental shelf possessing coast-parallel contours and extending seaward from sand beach regions like Saco Bay (Kelley et al., 1987; Fig. 7). The slope of the nearshore ramp is very gentle (0.6^{o} is the average of 6 shore-normal traverses) except near local bedrock outcrops (Fig. 6). Very fine sand with a mean grain size varying from 3.2 phi to 3.6 phi floors much of the central and outer nearshore ramp (Farrell, 1972; Kelley et al., 1987) except near rock outcrops and in the vicinity of Prouts Neck. Adjacent to bedrock exposures, gravel, shells, and mud deposits crop out on the sea floor, and inferences based on seismic records indicate these are reworked Pleistocene sediments (Table 1; Fig. 8).

At the 10 m isobath, an abrupt contact between the fine sands of the central bay and coarser sand of the beach face appears to mark the location of wave base under non-storm, summer conditions (Fig. 9). The material landward of wave base is shaped into megaripples with a spacing of 1-2 m and orientation of 050° mag (parallel to the beach trend). The height of the bedforms cannot be calculated since the shadow of one ripple terminates against the adjacent ripple. Occasionally, 1-2 m deep channels, normal to the coast and lined with megaripples, extend from the inner to the outer nearshore ramp. These appear similar to the storm-generated, rippled-scour depressions described by many others (Cacchione et al., 1984; Morang and McMaster, 1980), although their origin remains uncertain.

Cores from the nearshore ramp indicate that the upper sandy substrate does not extend very far beneath the surface (Fig. 10; Luepke and Grosz, 1986). Five out of twelve vibracores collected by the Army Corps of Engineers to evaluate the inner bay as a source of sand for beach nourishment encountered what is interpreted as the Presumpscot Formation within 2 m of the surface (Kelley et al., 1987). While the contact with the Presumpscot Formation appears deeper except near bedrock on most seismic profiles, it may be lost in the bubble pulse which obscures the upper 5-7 meters of most records.

Figure 4. Aerial photographs of Saco Bay shoreline features: (a) Goosefare Brook (background) is fronted by extensive paleodunes (forested) and embayed by several relict spits (arrows with white outline). Residential development is wisely located in the paleodunes on the south side, but extends with seawalls onto the frontal dune to the north; (b) Massacre Pond is fronted by paleodunes (arrow) at Scarborough Beach State Park. Much of the former lagoon is a freshwater marsh today. Bulge in beach is caused by wave shadow from an offshore outcrop. Photographs taken May 9, 1986.

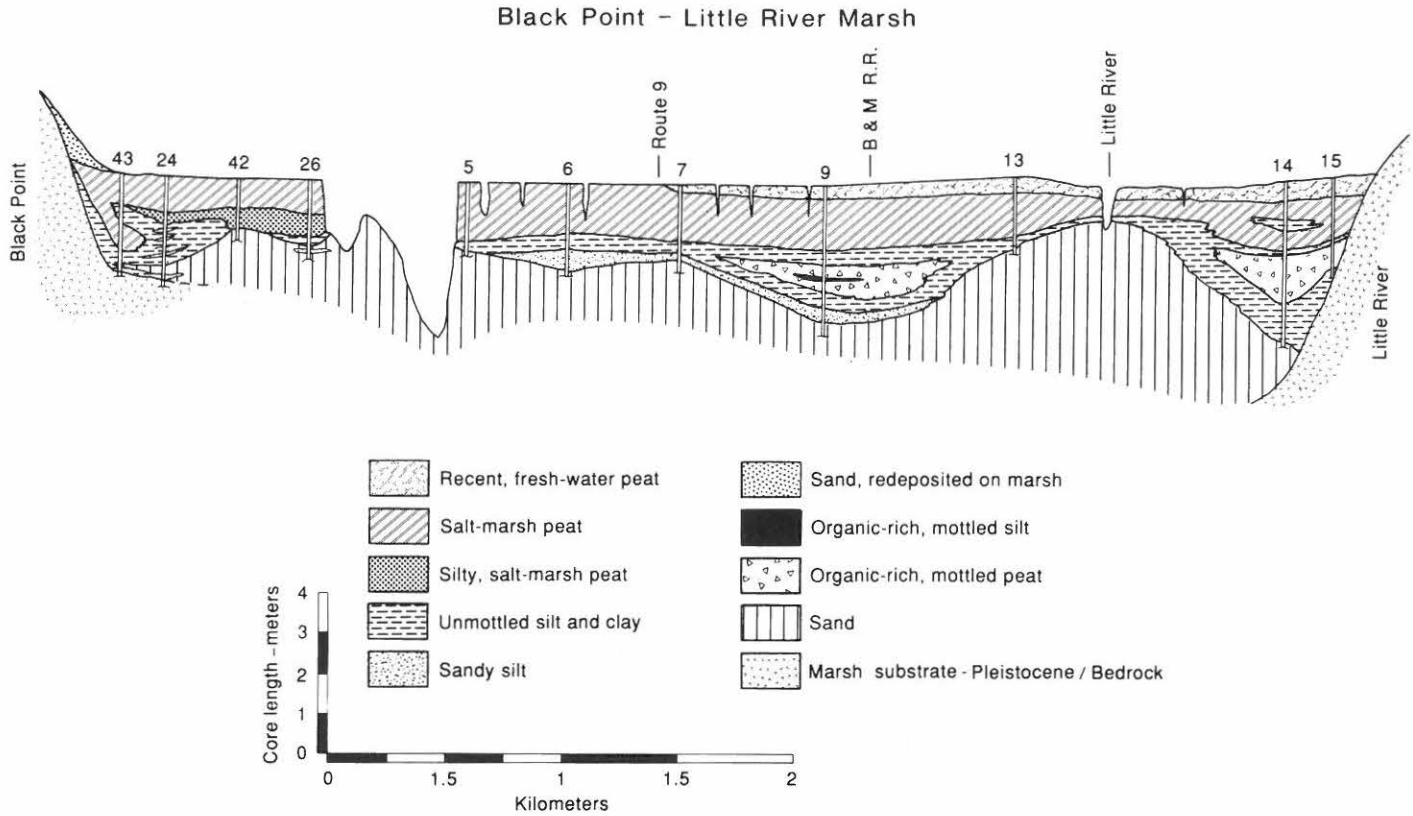


Figure 5. Cross section of Scarborough Marsh behind Pine Point (after Farrell, 1972). Borings from the Maine Department of Transportation (Bloom, 1963) indicate that the bedrock is greater than 30 meters beneath the marsh surface.

TABLE 1. GEOLOGICAL ENVIRONMENTS OF SACO BAY

Environment	Depth(m)/ Elevation(+)	#Samples	%C	%N	%$CaCO_3$	%Mud	%Sand	%Gravel	Morphology
Paleodunes, spits	+3 - +6	(a)					100		Hummocky dunes, recurved spits
Modern dunes	+3 - +6	(a)					100		Linear ridges, low hummocks
Beaches	0 - 3	120(b)					100		Sigmoidal profile curvilinear trend,
Nearshore ramp	0 - 30	49(c)	1.5	0.2	2.2	6	92	2	Smooth seaward slope with rock outcrops
Shelf valley	30 - 65	26(c)	5.4	0.65	3.0	23	67	10	U-shaped channel with rocky margins
Rocky zone	0 - 100	26(c)	2.6	0.3	8.4	12	51	37	Variable, from high relief rock to flat, boulder-littered plains
Outer basin	55 - 100	20(c)	3.1	1.7	4.3	61	38	1.0	Smooth with gentle seaward dip and rock outcrops

a: personal observation (Kelley)
b: Farrell, 1972
c: Kelley et al., 1987

Shelf Valleys

At several locations in Saco Bay (Fig. 7) the nearshore ramp grades without interruption into channels we term shelf valleys (Kelley et al., 1987; Swift et al., 1980). The shelf valleys are framed by bedrock and only partly filled with sediment today (Fig. 11). Most of the floors of the shelf valleys are covered with muddy sand which grades into sandy mud in a seaward direction (Kelley et al., 1987). Till and glaciomarine sediment are interpreted to partly fill the valleys, and a strong seismic reflector marks what is interpreted as the channeled surface of the Presumpscot Formation (Fig. 11). Toward the margins of the

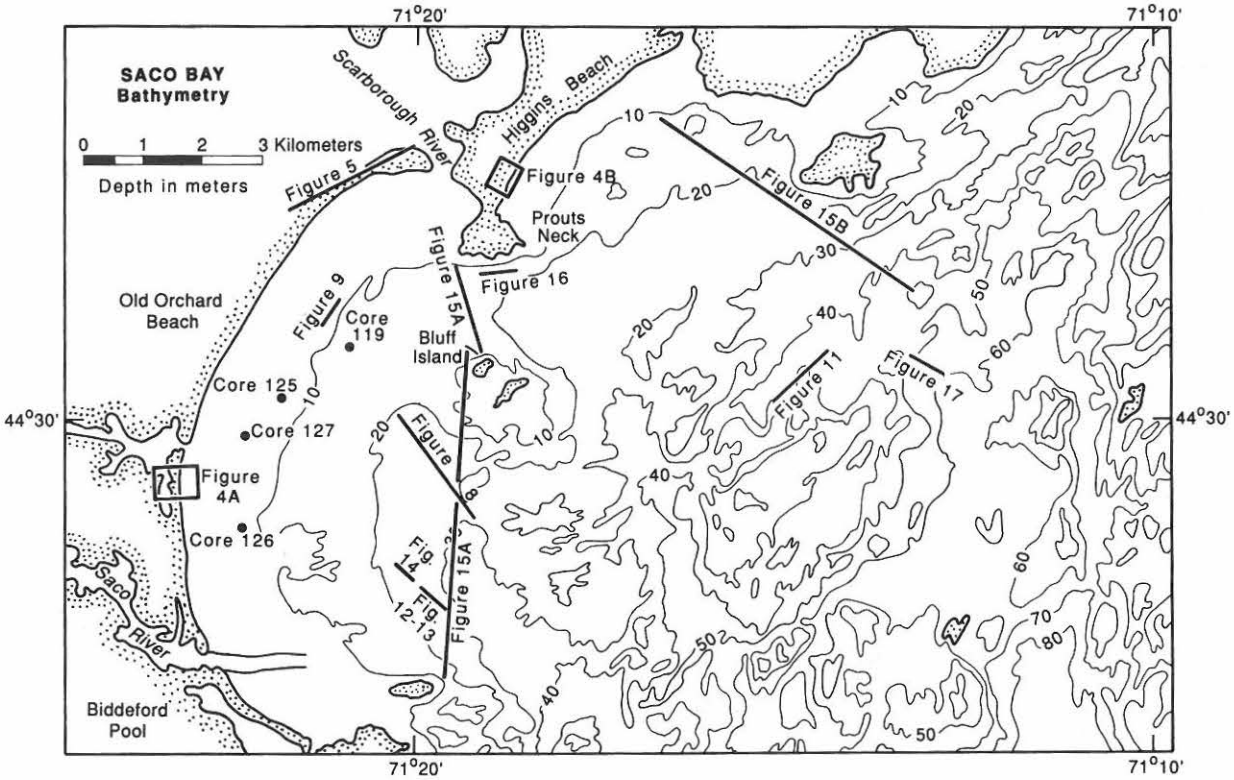


Figure 6. Bathymetric map of Saco Bay with location of figures cited in the text (simplified from National Ocean Survey, 1970).

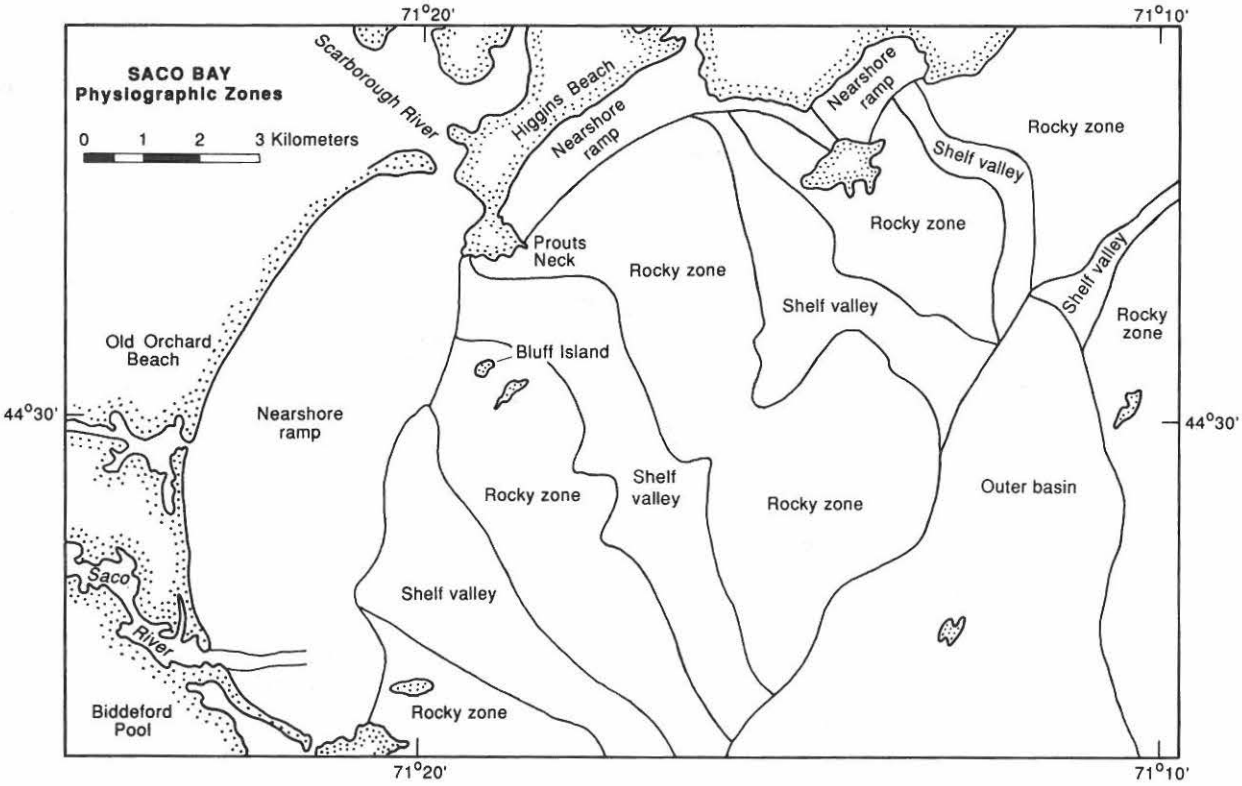


Figure 7. Physiographic zones of Saco Bay. Details about local bottom sediment conditions are described in Kelley et al. (1987).

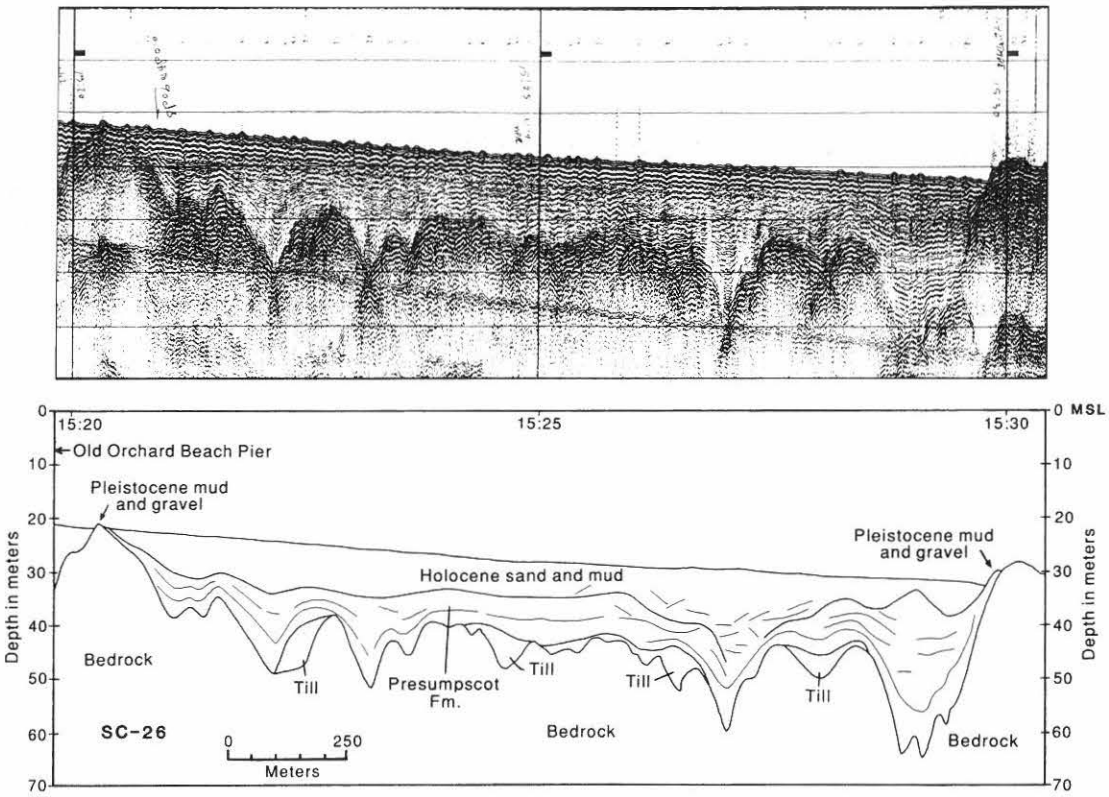


Figure 8. Seismic reflection profile normal to Old Orchard Beach. Location shown in Figure 6.

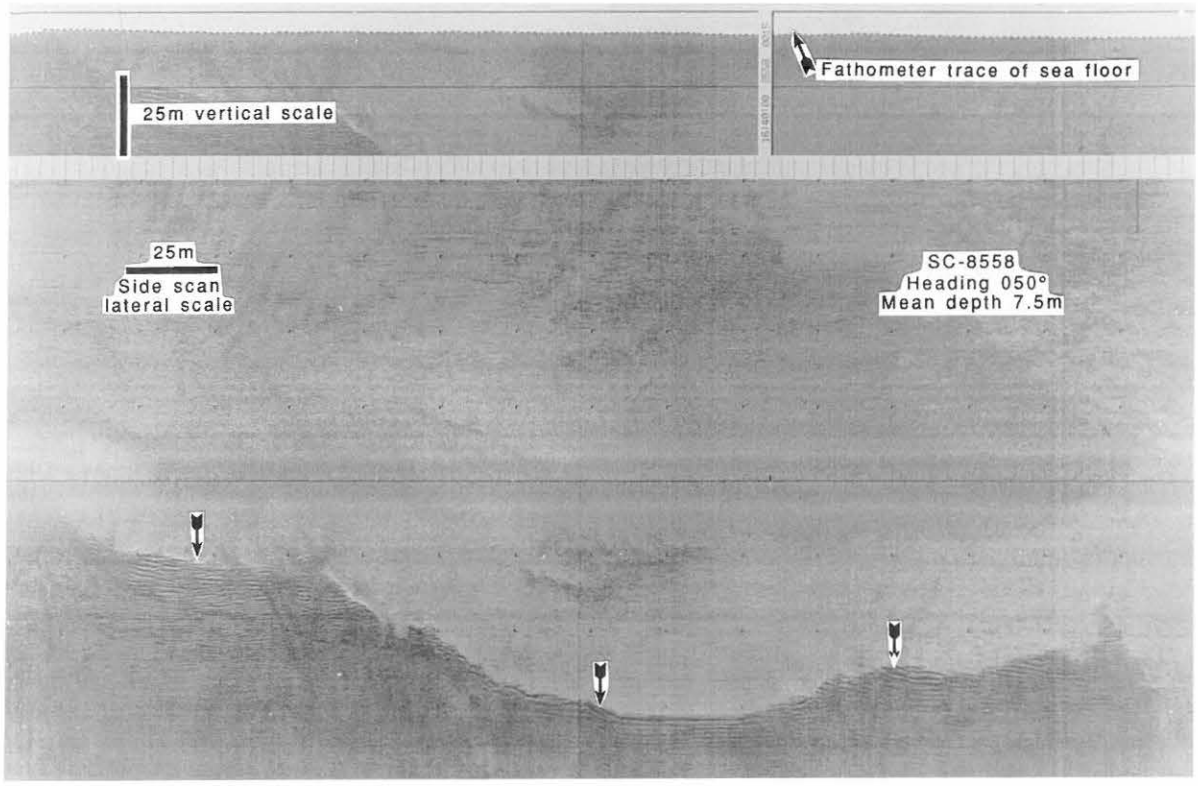


Figure 9. Side-scan sonar image of inferred wave base in inner Saco Bay (arrows). Bedforms have a spacing of 1-2 meters. Location shown in Figure 6.

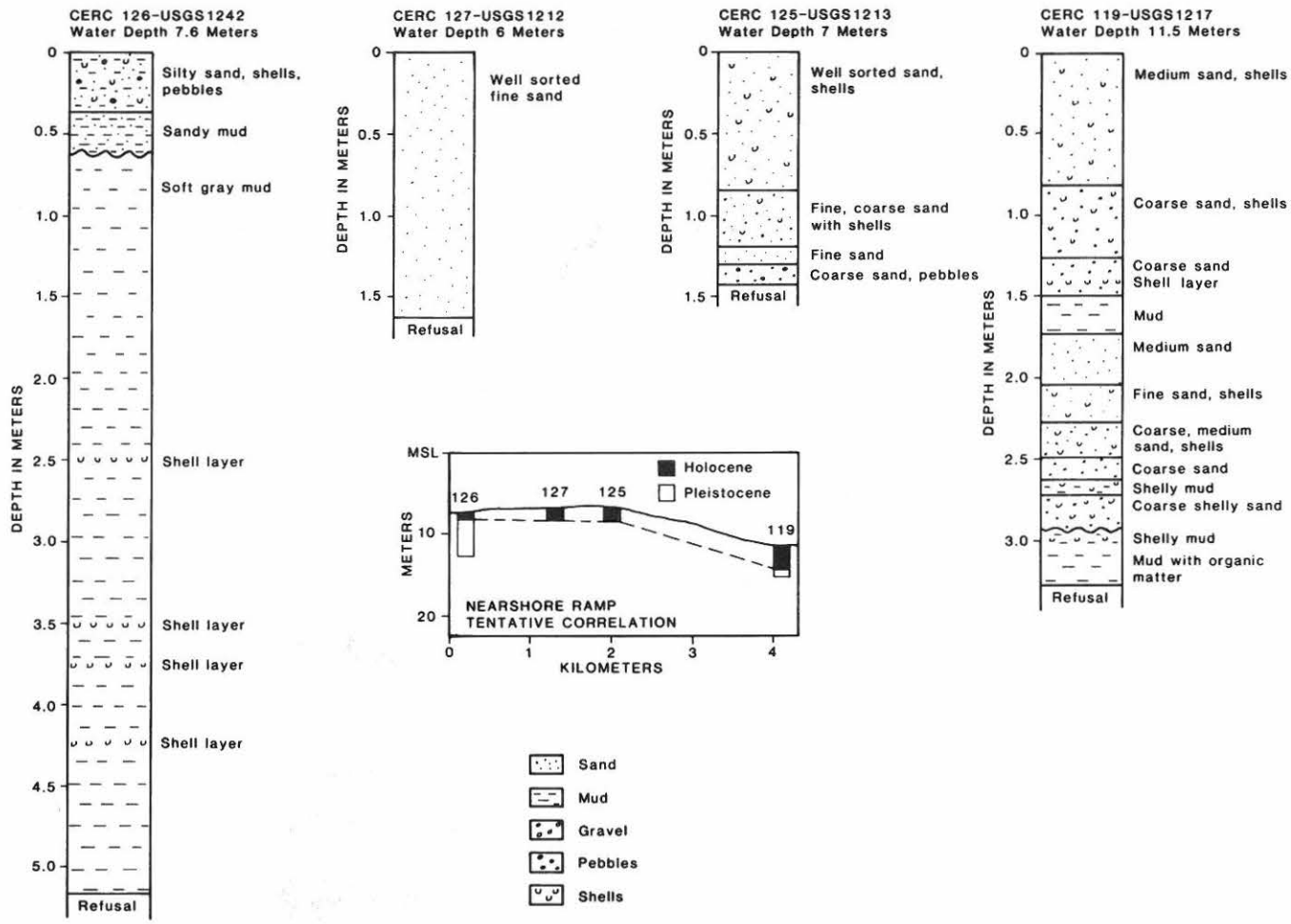


Figure 10. Vibracores from the nearshore ramp collected by the U.S. Army and described by Luepke and Grosz (1986). The unconformity over the muddy deposits is inferred on the basis of local stratigraphy. Cores are located in Figure 6.

shelf valleys and near bedrock "islands" in the channels, Pleistocene sediment appears to crop out on the sea floor (Figs. 12, 13). On side-scan sonar records this material is very dark (strong acoustic reflector) compared to the muddy, very light channel axis deposits (weak acoustic reflectors). Bottom samples returned from the margins of channels are usually a muddy, sandy gravel with a large concentration of shell debris (Kelley et al., 1987). Submersible observations reveal that the carbonate debris and possibly cobbles, which are common in the channel margin deposits, originate from the bedrock outcrops. In other locations extensive fields of megaripples exist near rock outcrops. The crests of the bedforms are often parallel to those of waves associated with "northeasters", or major winter storms, rather than normal to the valley trend (Figs. 3, 14). During a summer submersible dive to the megaripples of one shelf valley (Fig. 14), the edge of the field of bedforms was observed by one of us (Kelley) to be covered with mud, and up to several centimeters of mud filled many of the troughs of the sandy gravel megaripples. Generally speaking, the shelf valleys are finer grained, and richer in organic and carbonate carbon than the nearshore ramps (Table 1).

Rocky Zone

Rocky interfluves separate the shelf valleys, and the rocky zone is the most extensive physiographic region of the southwestern Maine inner continental shelf (Fig. 7; Kelley et al., 1987). Although exposed bedrock is the major component of the rocky zone, flat, coarse-grained substrates described as "gravel plains" are locally common (Kelley et al., 1987). They appear as boulder-littered, low-relief surfaces with a complex mosaic of sediment textures. Between Prouts Neck and Bluff/Stratton Island (Fig. 6, 15), bands of gravel with boulders up to 6 m in diameter alternate with sandy mud patches (Fig. 16). Farrell (1972) recognized the unusual sediment texture here and postulated that the shallow area was held up by a large till deposit.

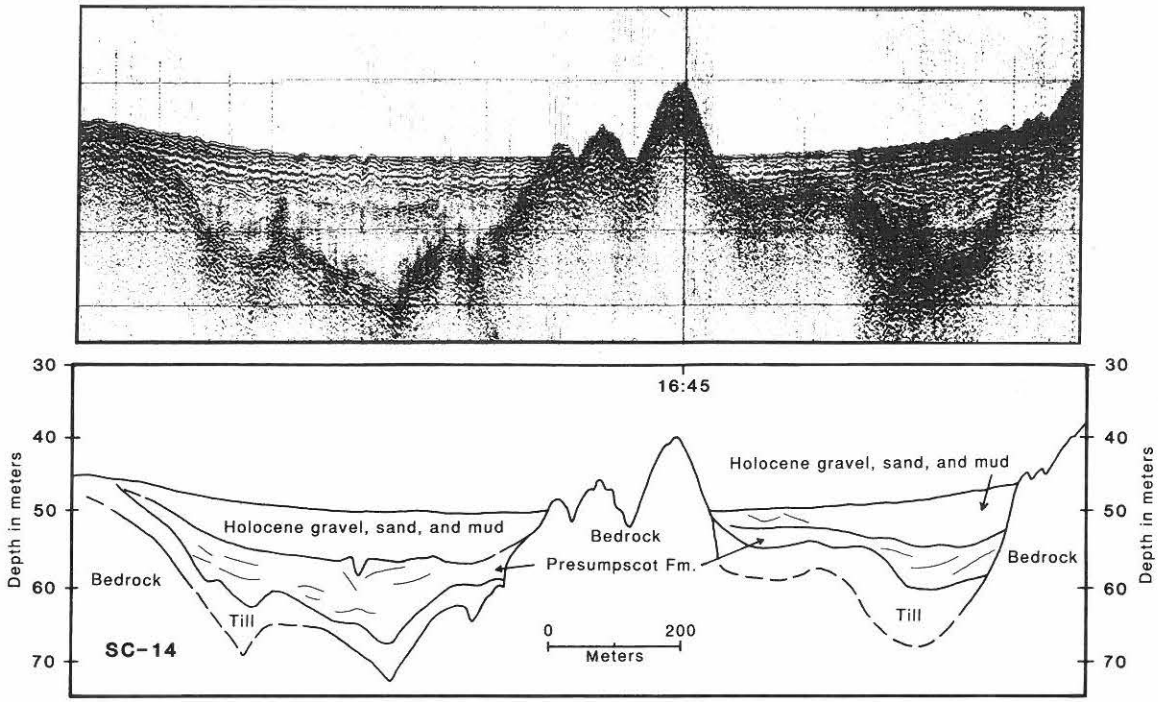


Figure 11. Seismic reflection profile normal to a shelf valley which is partly filled with Quaternary sediment. The surficial sediment is muddy sand in the axis of the channel and muddy gravel where Pleistocene units crop out on the sea floor. Location shown in Figure 6.

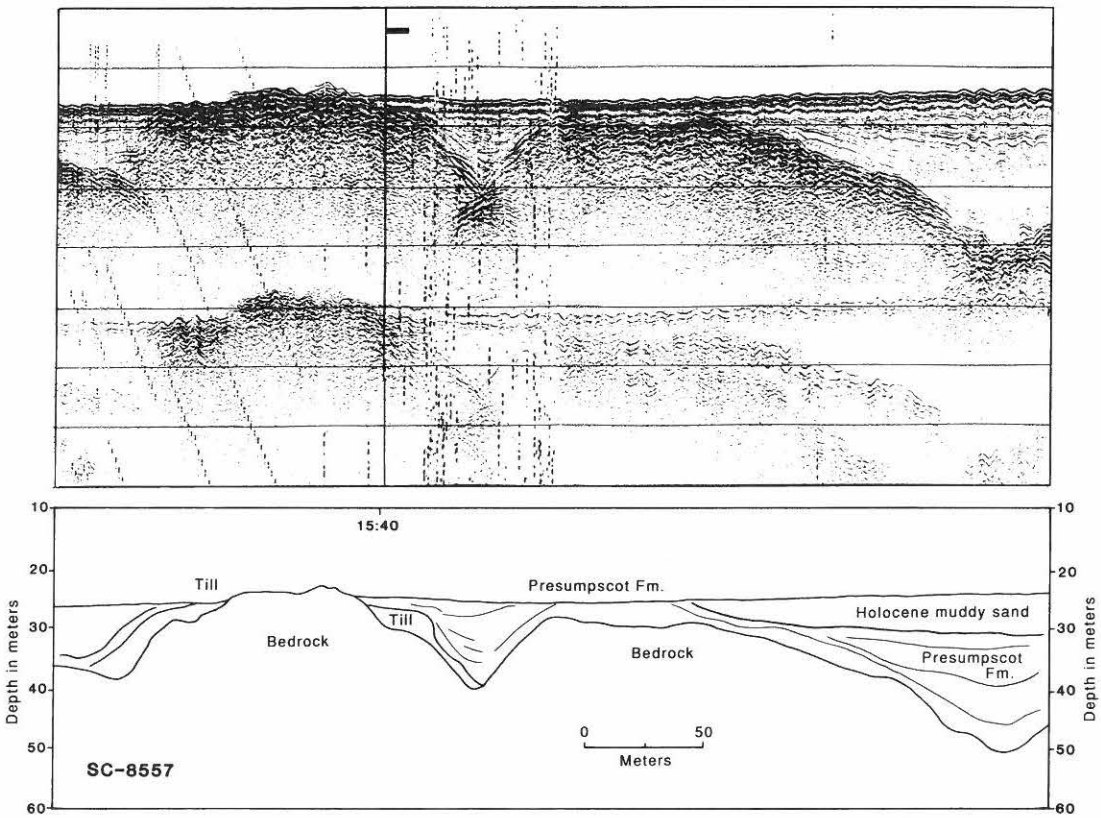


Figure 12. Seismic reflection profile across small rock "island" in a shelf valley. Where Pleistocene units are inferred to crop out on the sea floor, muddy gravel exists. See Figure 13 for side-scan sonar image collected simultaneously. Note the 15:40 time mark represents the same place in each figure. Location shown in Figure 6.

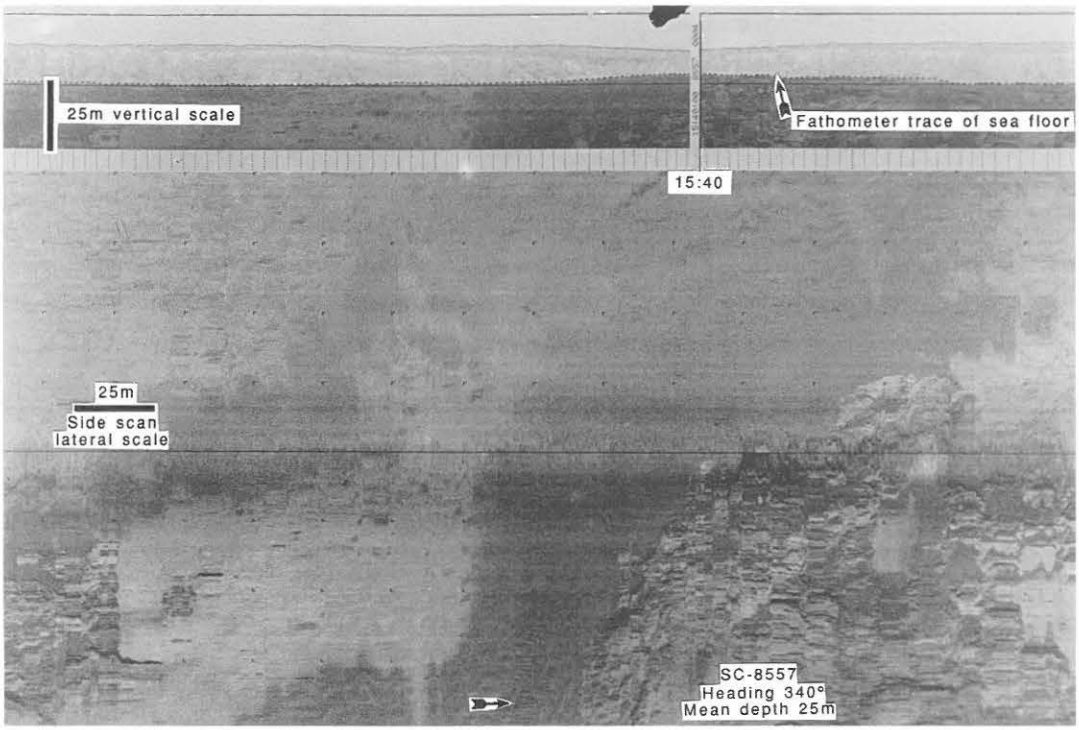


Figure 13. Side-scan sonar image of bedrock island in shelf valley seen in Figure 12. The dark portion of the image is muddy gravel derived from eroding Pleistocene sediments at the sea floor. Megaripples (arrow) in gravel are indicative of the winnowing of the Pleistocene sediment. Light tones represent muddy bottom. Location shown in Figure 6.

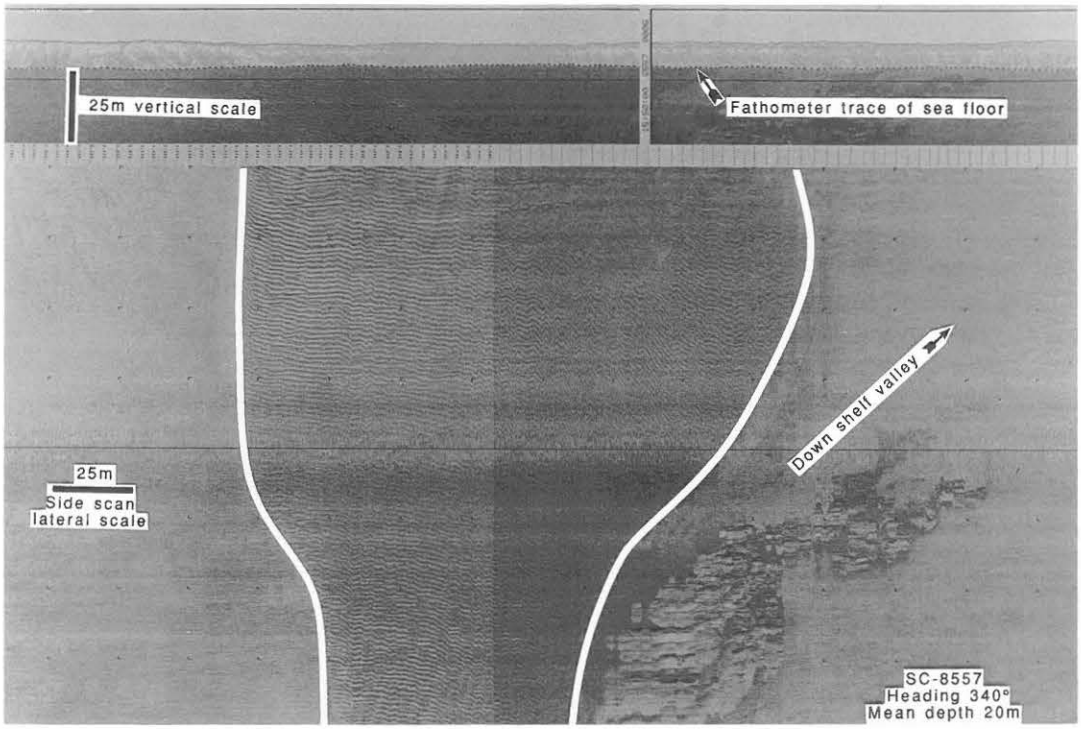


Figure 14. Side-scan sonar image of megaripple field in shelf valley. The field is oriented with bedform crests parallel to that of northeast storm waves (NW-SE) and is adjacent to a bedrock outcrop. While muddy sand dominates the floor of the shelf valley thalweg, the gravelly sand of the megaripples originates from eroding Pleistocene sediments near the outcrop. Location shown in Figure 6.

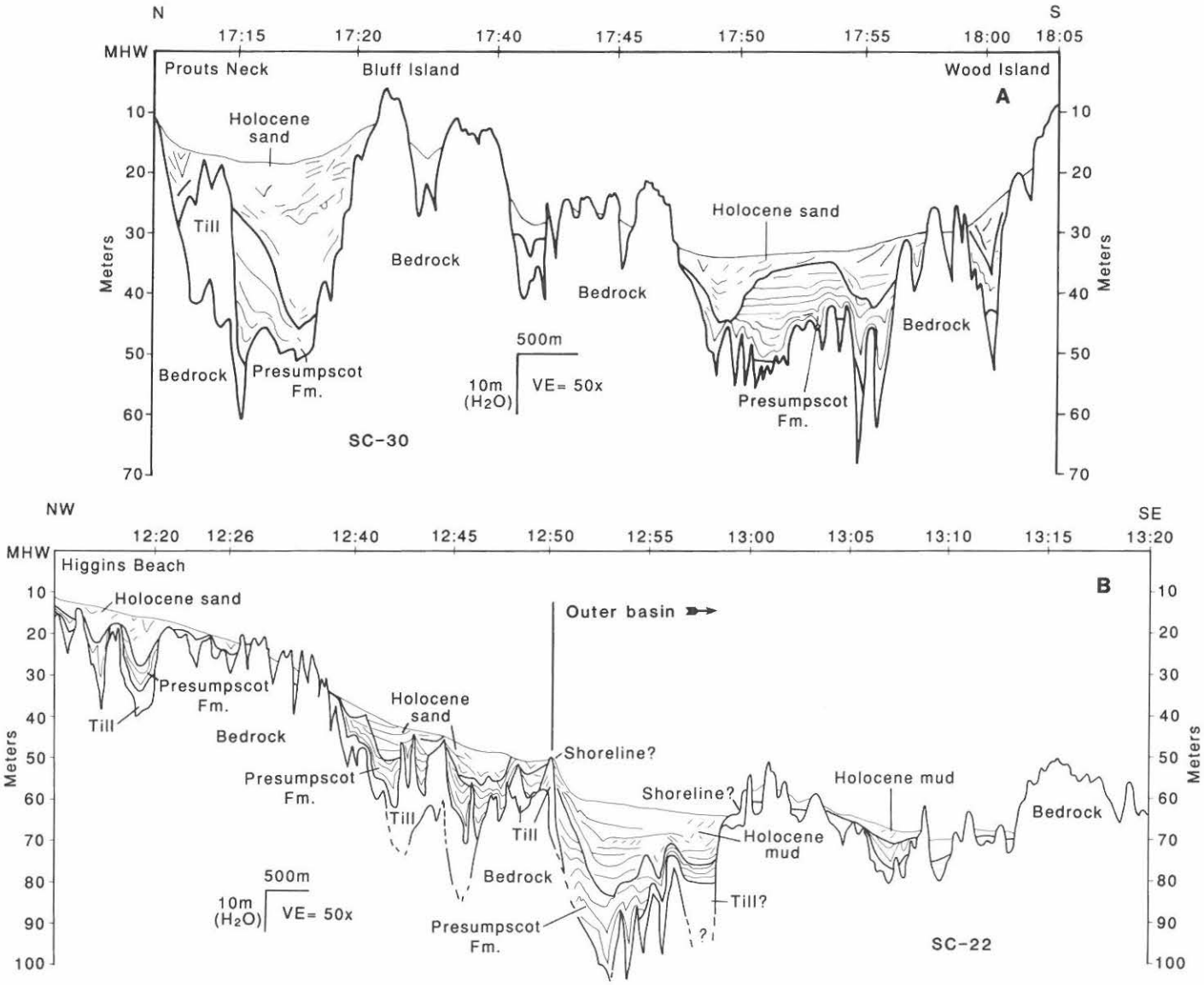


Figure 15. Interpreted seismic reflection profiles from Saco Bay. (a) Cross-section parallel to shore shows the differing depths of the Prouts Neck and Wood Island shelf valleys. Till and possible barrier beach-inlet deposits fill the area between Bluff Island and the mainland; (b) Shore normal seismic reflection profile across the nearshore ramp into the outer basin. Outer basin sediment thickness is greater than other locations in the bay. The shoreline location is not the deepest known from the area and is, thus, not a "lowstand" feature. Location shown in Figure 6.

Combined side-scan sonar and seismic reflection profile data (Fig. 16, and unpublished seismic data) do show that this "gravel plain" is a reworked till deposit as are many similar regions off Wells, Maine (Kelley et al., 1987). The seismic reflection profile clearly indicates that a plug of till chokes the bedrock depression near Prouts Neck. A thick sequence of inferred Holocene sediments containing channel-shaped acoustic reflectors within that sequence, however, implies a more complex origin for the shallow region near Prouts Neck. It is possible that a barrier spit derived from the till, and a tidal inlet may also have once been present in the area and further complicated the texture of the surficial sediment (Fig. 16).

In addition to exposed bedrock and reworked till deposits (gravel plains), numerous small sediment ponds exist within the rocky zone (Kelley et al., 1987). These are individually small, but so numerous that in the aggregate they possess a great deal of sediment. Most of the ponds dip in a seaward direction and many are covered with megaripples. Because the large surface area of bedrock adjacent to the sediment ponds is covered with attached organisms, carbonate content of the sediment ponds is the highest in the region and ranges up to 80% of the surficial sediment (Table 1; Kelley et al., 1987). In general, the rocky zone possesses the coarsest and most carbonate-rich sediment in the study area (Table 1).

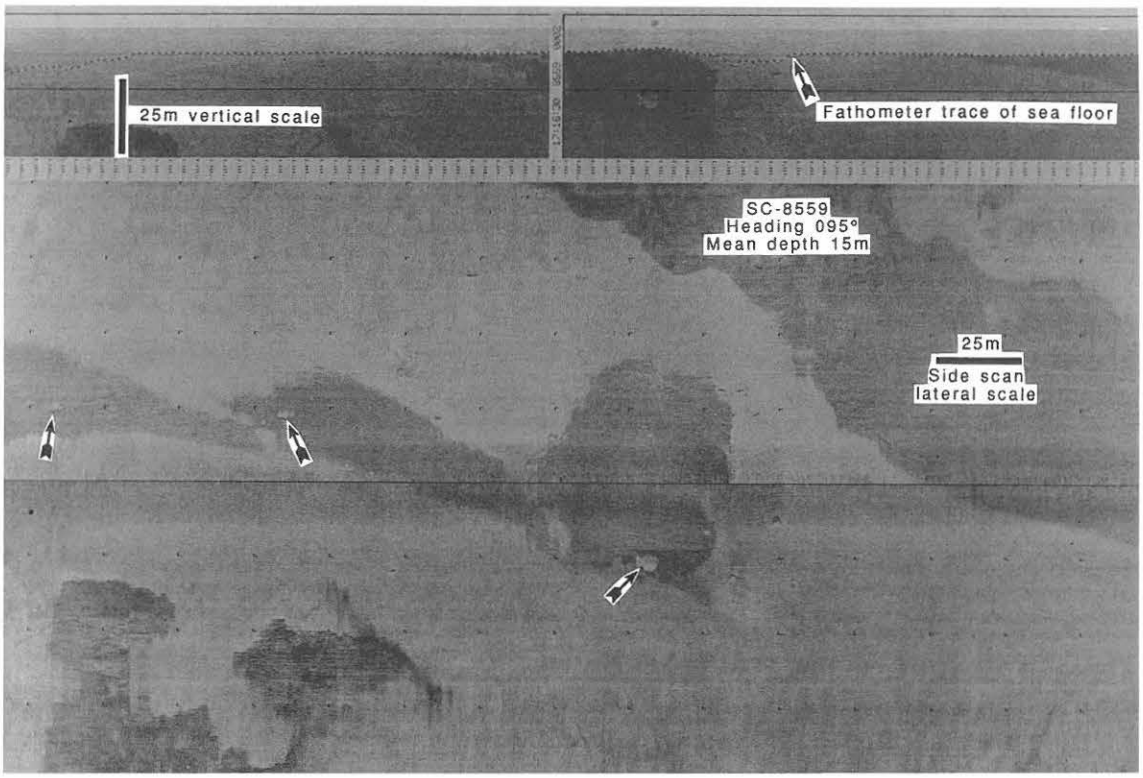


Figure 16. Side-scan sonar image of gravel plain in rocky zone near Prouts Neck. Large boulders (arrows) rest on gravel deposits of eroded till (dark) while lighter areas are sand and mud. Location shown in Figure 6.

Outer Basin

The final physiographic region of Saco Bay is the outer basin (Fig. 7, Kelley et al., 1987). This zone extends seaward of the 100 meter isobath (border of the study area), but possesses a relatively well defined landward border at about 65 m depth (Fig. 6). It is here that the shelf valleys lose their topographic identity and where numerous features interpreted as shorelines exist (Fig. 17).

While most of the outer basin is flat and covered with sandy mud, occasional bedrock and till outcrops exist (Kelley et al., 1987). Typically, a halo of shelly gravel surrounds the bedrock exposures, and bottom samples from features interpreted as shorelines contain sandy gravel. However, a submersible dive on one shoreline feature recorded soft mud over the area. As might be expected, the deep outer basins possess the finest grained, most organic-rich sediment in the study area (Table 1). These areas also contain relatively high concentrations of calcium carbonate which may reflect a low rate of inorganic sediment input.

Sediment volume is much greater in the outer basin than in any other location in Saco Bay (Fig. 15b). At least 40 m of Quaternary sediment, most interpreted as glaciomarine material, fill a deep bedrock basin. Till is interpreted to exist beneath the shoreline on the outer basin margin, and till of unknown thickness fills at least one deep portion of the outer basin (Fig. 15b). In the absence of cores it is difficult to pinpoint the Pleistocene-Holocene contact. In the deeper water of the outer basin, continuous sediment accumulation probably marked the Pleistocene-Holocene transition, and the strong coherent acoustic reflector selected as the boundary (Fig. 17) is very tentative. If the strong reflector represents coarse-grained sediment influenced by waves and nearshore processes at the time of the sea level lowstand, then 10-30 m of Holocene sandy mud may overlie Pleistocene sediment in the outer basin.

In general, the sand content of sediments increases in a landward direction across Saco Bay, reflecting an increase in wave and tidal energy toward the shoreline. Gravel outcrops occur in all regions where coarse-grained Pleistocene sediments are exposed by erosion. These exposures are most common near bedrock outcrops, but also occur on the axes of shelf valleys where downcutting and erosion of Holocene sandy mud may occur. High organic carbon and nitrogen values are associated with muddy sediments similar to many other places. Carbonate values are less easily understood, however. While it is clear that high carbonate values occur near bedrock outcrops which host encrusting organisms, it is not clear why such high values were encountered in the outer basins.

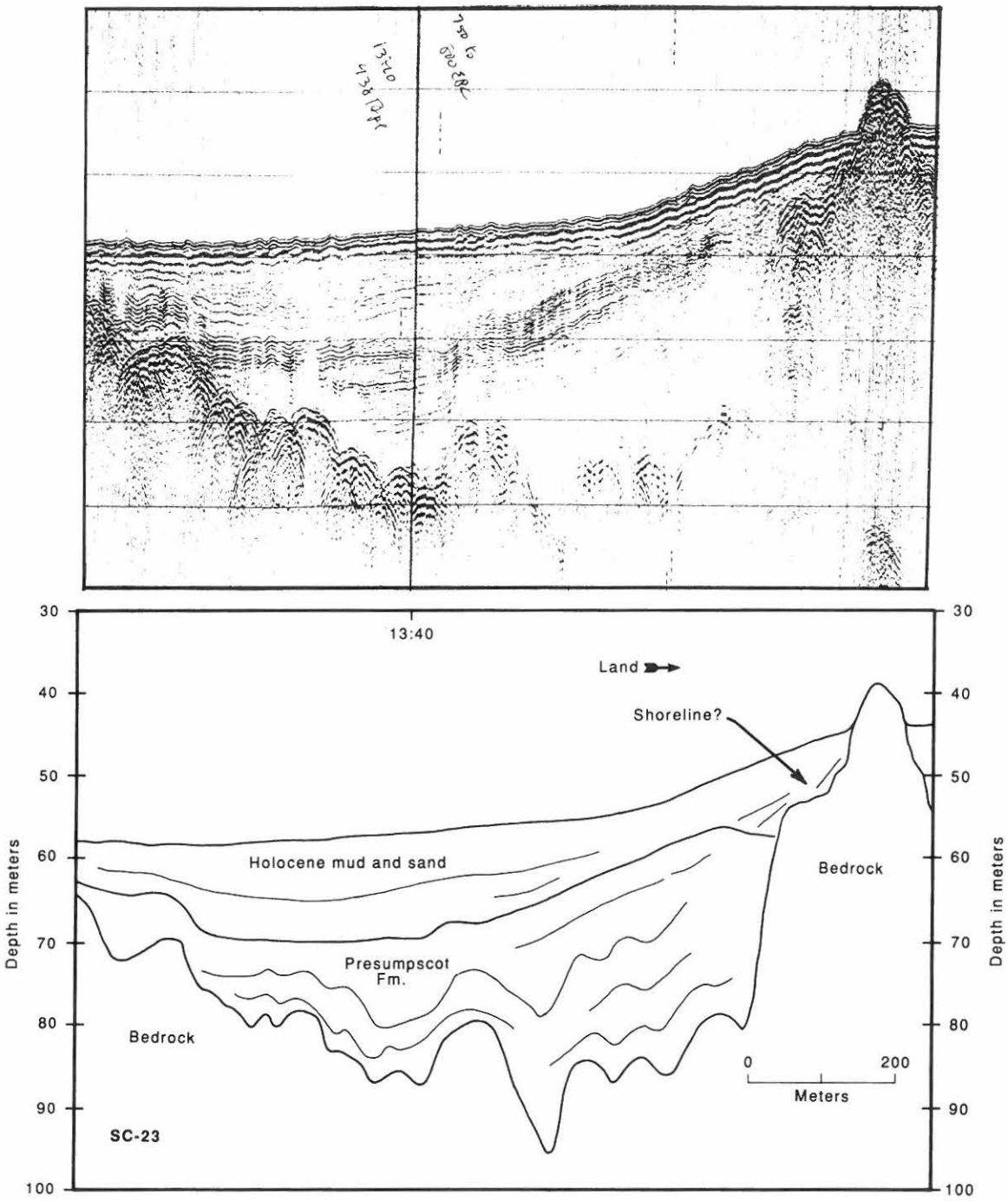


Figure 17. Seismic reflection profile across shoreline bordering outer basin. This is not the deepest shoreline known, but shows the prominent reflector interpreted as the Holocene-Pleistocene contact. Location shown in Figure 6.

EVOLUTION OF SACO BAY

Prior to the last glacial advance, valleys incised into bedrock already existed in Saco Bay, as well as in other locations in the region (Tolman et al., 1986). The retreating ice margin, which reached the southern Maine coast 13,800 yr B.P. (Smith, 1985), left a considerable volume of till in some of the deeper bedrock valleys (Fig. 15) and in the outer basin. No laterally extensive moraines have been found in this study area or to the south (Kelley et al., 1987), however, to support the ice-margin orientations suggested by Oldale (1985b). Accompanying retreat of the ice, glaciomarine sediment (Presumpscot Formation, Bloom, 1960) was draped across the sea floor and accumulated to considerable thickness (10-30 m) in bathymetric lows like the

shelf valleys and outer basin (Figs. 8, 11, 15). The strong, coherent reflectors near the base of the acoustic unit identified as the Presumpscot Formation (Figs. 8, 15) mimic the underlying topography and imply rapid sediment deposition from suspension (Piper et al., 1983). Above this horizon there are fewer reflectors within the seismic unit identified as the Presumpscot Formation. This more acoustically transparent material probably accumulated relatively slowly in deep water between 12,500 and 13,000 yr B.P. (Fig. 2).

Following general retreat of the ice from Maine (Smith, 1985), crustal rebound led to emergence of the marine sediments and establishment of a new drainage network on the former sea floor. Because the major paleovalley in Saco Bay, which exists beneath the Scarborough Marsh (Kelley et al., 1986), was choked with till and glaciomarine sediment, the Saco River was forced to locate a new channel in its present valley. As relative sea level fell between 12,000 and 9,500 yr B.P. (Fig. 2), the Saco River, as well as the other smaller streams of the area (Scarborough River, Spurwink River), at first deposited sand and gravel over the muddy sediments of Presumpscot Formation in a fashion similar to that described by Borns and Hagar (1965) for the Kennebec River valley. With falling sea level and an increasingly steep gradient, the Saco and other local rivers began to downcut into till, glaciomarine mud, and regressive sands in their valleys (Fig. 18). Meander scars visible along the banks of the Saco today (Fig. 3) and possibly near the mouth of the Scarborough River (Nelson, 1979) probably date from that time. The material eroded by the Saco River was deposited in progressively deeper water until the time of maximum sea level lowering, 9,000-9,500 yr B.P. (Fig. 2; Belknap et al., 1987a).

It has been suggested that around 9,500 yr B.P., sea level in Maine was at a location 65 m deeper than today (Schnitker, 1974; Belknap et al., 1986, 1987a,b; Kelley et al., 1986, 1987; Shipp et al., this volume). Oldale et al. (1983) and Birch (1984b) have indicated a maximum lowering of 50 and 35 m respectively, for Massachusetts and New Hampshire. This discrepancy between southern and northern New England shelf areas may be a result of differing regional response to isostatic movements resulting from deglaciation. In Saco Bay, 65 m is the greatest depth of a clearly marked shoreline. Seaward of this depth a large volume of Holocene sediment is inferred from seismic reflection profiles (Fig. 15). This was derived from fluvial contributions of the Saco River (and possibly from Casco Bay), as well as from local erosion. The strong reflectors 10-15 m (or greater) beneath the surface of the outer basin are interpreted as a coarse-grained unit deposited when those depths were inside the influence of wave base.

Sea level rose rapidly following the maximum lowstand (Fig. 2). Nevertheless, constructional and erosional shoreline features are interpreted from the 20-65 m depth range (Kelley et al., 1986, 1987). They may owe their preservation to the rapid rate of transgression which minimized the period of time they were within the depth range of wave influence (Belknap and Kraft, 1981). By 6000 yr B.P., sea level was 20 m beneath its

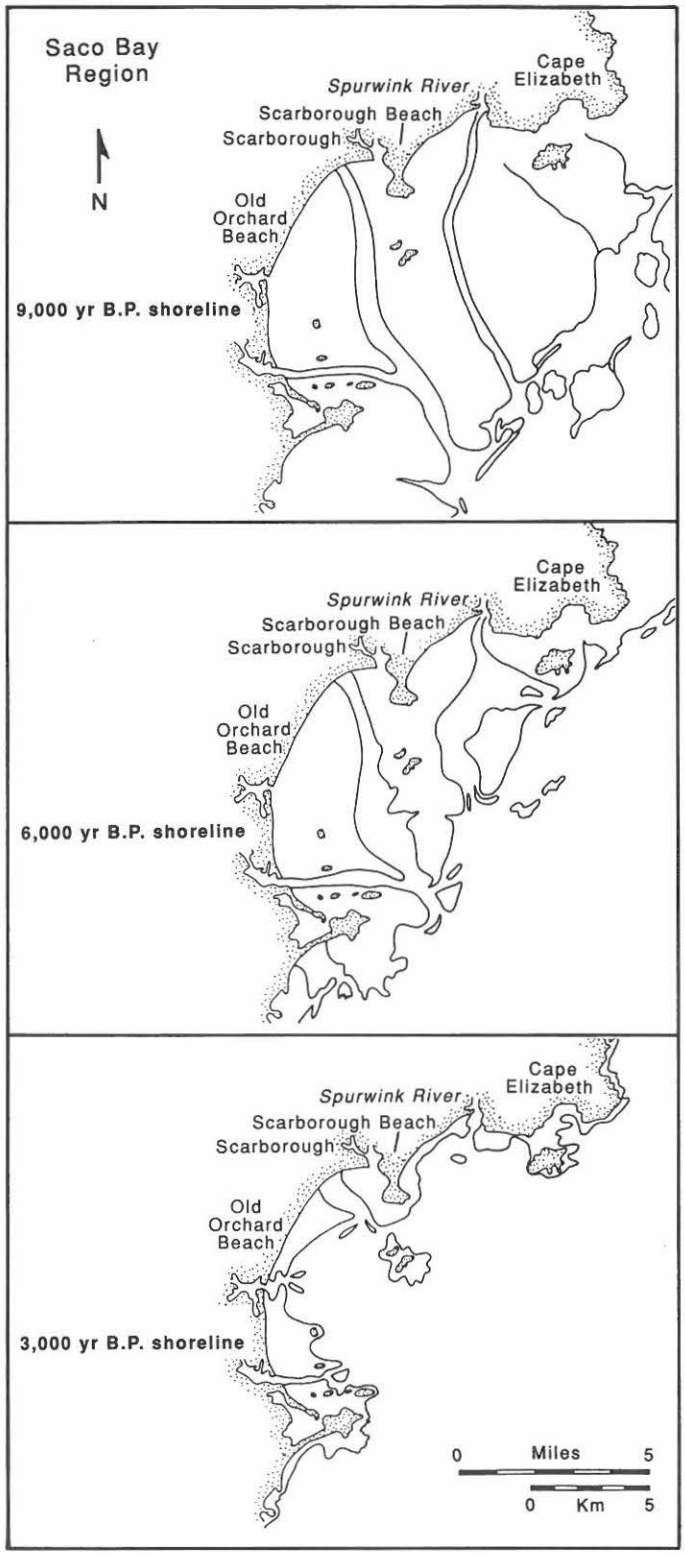


Figure 18. Paleogeographic reconstruction of Saco Bay based on sea level curve of Belknap et al. (1987a; Fig. 2).

present location and the transgression had transformed the Saco, Scarborough, and Spurwink Rivers into relatively broad estuaries (Fig. 18). While the spits in the paleogeographic reconstruction are hypothetical, the large island at the mouth of the Spurwink River and the long peninsula extending from Prouts Neck were probably sediment-covered bedrock knobs at that time (Fig. 18). Mainland beaches, deriving their sediment from bluff erosion instead of barrier spits, were probably the most common littoral environment at the time. As sea level rose, the fine-fraction of their surficial cover was transported down shelf valleys to the outer basin, and only the exposed bedrock with occasional boulders and sediment ponds remain as the extensive, shallow rocky zone today (Fig. 7). Although eroding bluffs undoubtedly fed sediment into the nearshore system at 6000 yr B.P., sand from the Saco River was also a major source of beach sand. If summer wave conditions were similar to today's (Fig. 3), longshore currents would have moved sand to the northeast to form a connected system of beaches as far north as Cape Elizabeth. Few shoreline features remain from this period owing to the slower rate of sea-level rise than occurred previously, and the more complete erosion of the antecedent topography (Belknap and Kraft, 1981).

Between 6000 and 3000 yr B.P., the shoreline continued to move landward. The large shelf valley extending from Pine Point was probably the largest estuary in the embayment at the time, just as its successor, the Scarborough Marsh, is today. This embayment was bordered by a large till deposit between Bluff Island and Prouts Neck which probably persisted until sea level overtopped the large island at the Spurwink River mouth, and waves could directly attack the till. Side-scan sonar and seismic reflection profiles show till to exist at the sea floor near Prouts Neck today, and channel-shaped reflectors are common in inferred Holocene sediments near Bluff Island (Kelley et al., 1987; Figs. 14, 15). Thus, it seems likely that the till was breached near Bluff Island some time around 3000 yr B.P. and an inlet and barrier spit evolved from the till deposit. Eventually, with continued rise in sea level and depletion of the sediment supply, the area was drowned, leaving a chaotic sea floor (Fig. 14) much elevated over the shelf valley of the ancestral Saco-Scarborough Rivers to the south (Fig. 15a).

Around 3000 yr B.P., local sea level stood at -3 m and significantly slowed its rate of rise (Oldale, 1985; Belknap et al., 1987a). This permitted the barrier spits to grow laterally and vertically. Lagoons were created and cut off from the sea by spit progradation near Goosefare Brook and at Scarborough Beach (Fig. 4). While the source of beach sand near Goosefare Brook was certainly the Saco River, Scarborough Beach probably received sand from eroded till bluffs near Prouts Neck and Higgins Beach (Fig. 3).

Pine Point may have become a barrier island when the till or regressive sand near Prouts Neck was finally breached and an inlet opened at the present mouth of the Scarborough River. To the south, Biddeford Pool is thought to have formed around the same time by the breaching of a till deposit (Hulmes, 1981). The Scarborough Marsh and the marshes at the mouth of the Spurwink River probably grew over the mud and sand flats of their river valleys once their sediment supply equalled the rate of sea level rise, perhaps by 3,000 yr B.P.

CONCLUSIONS

Variations in sediment supply and sea level change have been the primary factors influencing Saco Bay in the late Quaternary. The stratigraphic column of the bay reflects deposition of coarse and fine grained sediment by ice and marine processes respectively during the late Pleistocene marine transgression (Kelley et al., 1987). Introduction of sand by the Saco River was a major event during the early Holocene marine regression which ended about 9,000 years ago. Since then, waning sediment introduction from the Saco and increased supply of sand and mud by erosion of Pleistocene sediment have permitted the beach and marsh systems to persist despite the late Holocene transgression.

Future research in Saco Bay is needed to resolve numerous problems identified during this project and pertinent to the growing human population of the bay. What is the major source(s) of sand to the beaches today and are the beaches losing more sand than they receive? Are the rippled scour depressions on the nearshore ramp and along the shelf valleys indicative of sand transport offshore during storms (e.g. Cacchione et al., 1984)? Shape analysis of sand grains would be useful for provenance analysis of the sand populations recognized (Farrell, 1972) and might be used to trace the path of grains. Cores with radiocarbon dates from the backbarrier salt marshes would firmly establish the time of formation and rate of growth of the numerous spits of the area (Fig. 4). Cores from the shelf valleys and outer basin would further permit recognition of the Holocene-Pleistocene boundary and identify with greater confidence the origin of sub-bottom reflectors and nature of the offshore shoreline deposits. While it seems that there is a general transfer of sand and mud from nearshore along the shelf valleys to the outer basin today (Fig. 3), this hypothesis needs testing by sediment trap studies and investigations of the direction of submarine bedform migration and current velocities during storm and non-storm conditions.

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