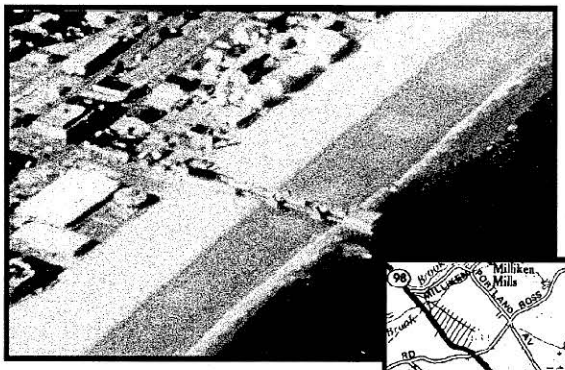
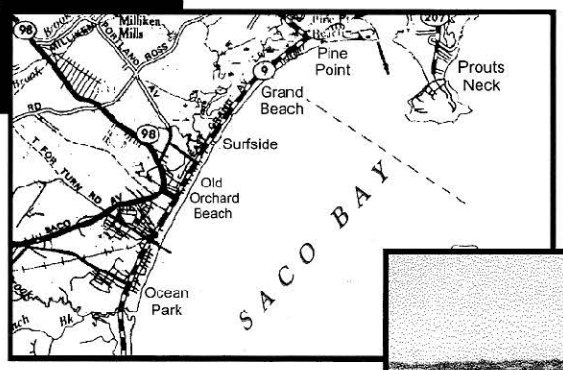
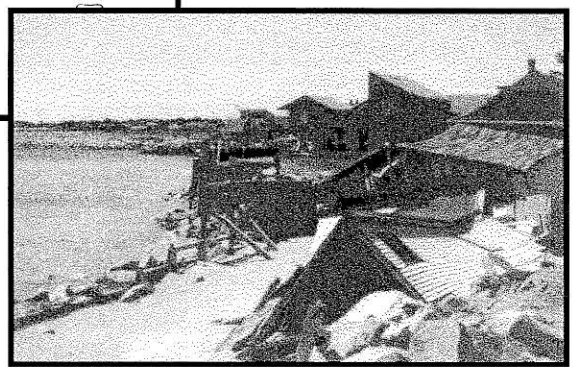
A Sand Budget For Saco Bay, Maine







J.T. Kelley, D.F. Belknap,
D.M. FitzGerald, D.C. Barber, S.M. Dickson,
S. van Heteren, L.K. Fink, and P.A. Manthorp

Maine Geological Survey
Natural Resources Information and Mapping Center
DEPARTMENT OF CONSERVATION

Robert G. Marvinney, State Geologist

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J. T. Kelley
Maine Geological Survey, 22 State House Station, Augusta, ME 04333
D. F. Belknap
Dept. Geological Sciences, University of Maine, Orono, ME 04469
D. M. FitzGerald
Dept. Geology, Boston University, Boston, MA 02215
D. C. Barber
Dept. Geological Sciences, University of Maine, Orono, ME 04469
S. M. Dickson
Maine Geological Survey, 22 State House Station, Augusta, ME 04333
S. van Heteren
Dept. Geology, Boston University, Boston, MA 02215
L. K. Fink
Dept. Oceanography, University of Maine, Orono, ME 04469
P. A. Manthorp
Dept. Geology, Boston University, Boston, MA 02215

ABSTRACT

Saco Bay hosts the largest sand beach and the largest salt marsh system in Maine. We constructed a sand budget for the bay by evaluating the sources and sinks for sand, as well as the pathways in which this material moves. Side-scan sonar and bottom samples were employed to map the offshore areas, while seismic reflection and vibracoring methods were used to examine the volume of sand. On land, ground-penetrating radar and cores were used to measure sand volume and stratigraphy. Historical maps and aerial photographs provided measurements of sand movement over long time frames, and current meters evaluated sand movement both offshore and in the Saco River estuary.

The Saco River is the main source of sand to the bay, and provides an estimated 10,000 to 16,000 m^3 of sand per year to the bay. This sand moves to the north and allows Pine Point to grow. Construction and subsequent enlargement of the north jetty at the Saco River mouth profoundly altered the normal movement and storage of sand between 1867 and 1955. At the present time, 56 million m^3 of sand reside in the shoreface and 22 million m^3 of sand are beneath the beach and dunes. This sand is all utilized by the beach system, however, so that dredging and spoils disposal practices that do not take into consideration the natural storage and movement of sand place the overall system at risk.

INTRODUCTION

Sand beaches are among the most important and valuable areas of the coastal zone, yet they are the most rapidly changing as well. Their attraction as destinations for recreational swimming and boating, and their proximity to protected bays suitable for harbors has led to the large-scale cultural development of most beaches. That development is, in turn, placed at risk by its very presence in a dynamic coastal system. Furthermore, engineering measures taken to protect some cultural features commonly increase the hazard to other developments as well as to the beach system itself. Saco Bay, Maine, is a long-established coastal resort area in northern New England, U.S.A. (Figure 1) that is an outstanding example of these interactions. This paper evaluates the dynamics of sand deposition and erosion on sev-

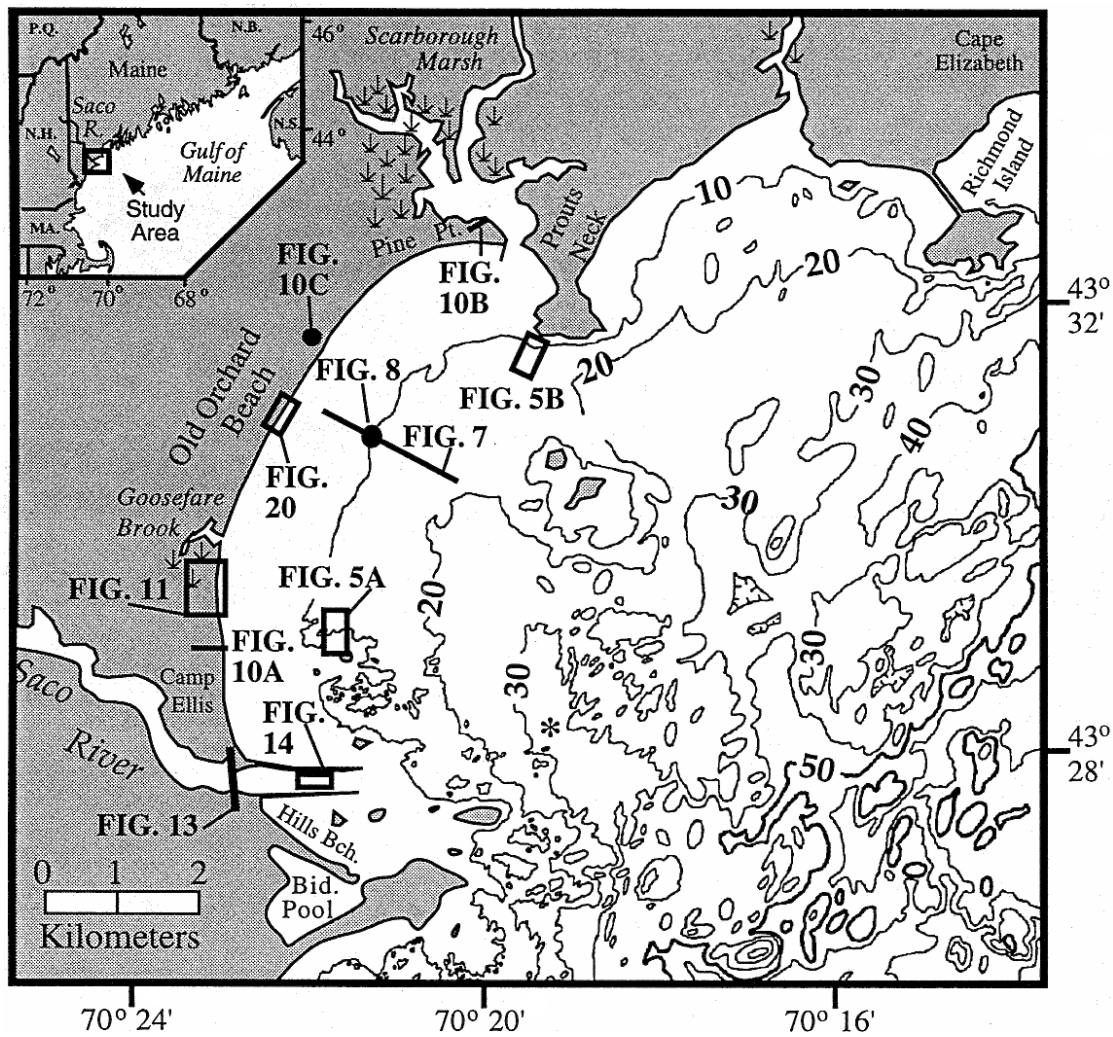

Figure 1: Location of the study area within the Gulf of Maine (inset map), and bathymetric map of Saco Bay. Geographic names and figure numbers refer to those used in this report.

eral time scales as a result of both anthropogenic and natural activities in Saco Bay.

Shoreline change along sandy beaches like those of Saco Bay results from an interaction among the rate of supply of sand, wave and wind climate, especially storm frequency and intensity, rate of relative sea-level change, antecedent geological setting, and activities of humans (Pilkey and others, 1989). The behavior of the beach system over a long period of time, such as the Holocene Epoch, is principally governed by variations in sand supply and rates of relative sea-level rise (Belknap and Kraft, 1981, 1985). The antecedent geological setting may represent a source of sand for the system and exert control on local geomorphology. Along a rock-framed coastline like Maine, bedrock outcrops commonly interrupt longshore sand movement and establish the geometry of an embayment (Nelson and Fink, 1980; Duffy and others, 1989; Kelley and others, 1989a). Over an intermediate time frame, such as the time span since the European colonization of northeastern North America (circa 1609), human activities like dam, jetty, and seawall construction probably rival rising relative sea level as an influence on shoreline behavior. On a time scale of a few years, human activities such as dredging and spoils disposal, along with storm-generated waves, are probably the most important factors in shaping the coast (Pilkey and others, 1989; Fenster and Dolan, 1994).

Saco Bay, Maine is the largest beach system in northern New England (Figure 1). Although its economy is dominated by recreational pursuits today, in the past, industrial activity and commercial fishing were the mainstays of the local economy. As a result of its history, the beach system is influenced by long-term geological processes, coastal engineering structures and practices, and by contemporary recreational activity. Although the beach system is constrained by engineering structures (jetties) at the river mouths on its north and south ends and several high-rise developments in the central beach region, this area is not yet as intensely developed as beaches on the mid-Atlantic and southeastern United States' coast.

Because Saco Bay is a rock-framed pocket beach system, it is self-contained and uninfluenced by far-afield littoral activities. This isolation, coupled with a relatively simple local stratigraphy (Belknap and others, 1989a; Kelley and others, 1989a; Belknap and Shipp, 1991), render the bay amenable to measurement of its sand budget over varying time frames. The purpose of this report is to evaluate the static volume of sand in the major depositional reservoirs of the Saco Bay system, including the dunes, berm, shoreface, and estuary, and to estimate the rate of exchange of sand among these reservoirs on geological, historical, and contemporary time scales. In compiling a sand budget we also address two working hypotheses: (1) that sand for the regional beaches is derived from an offshore glacial source, and after reaching the beach, moves from north to south (USACOE, 1955), or (2) that sand for the beaches is derived from the Saco River and moves along the beach from south to north (Kelley and others, 1989a).

PREVIOUS WORK

Sand Budgets

Many previous studies have attempted to analyze shoreline changes to better anticipate the future behavior of beach systems. In New England and adjacent maritime Canada, a conceptual model depicts the co-evolution of barrier spits and attached bluffs of glacial sediment (Johnson, 1925; Boyd and others, 1987). This model explains the rapid landward migration of the barrier in response to the depletion of its sediment supply (a bluff of glacial sediment) through erosion. Although Saco Bay may once have contained such barriers, the present system does not and appears to be more stable than those systems associated with eroding bluffs (Nelson, 1979).

Bruun (1962) took a quantitative approach to predicting shoreline response to rising sea level. His "rule" assumed a shoreface profile of equilibrium in which the depth offshore, h, is directly related to the distance seaward of the beach, x, times a constant, A:

$$h = Ax^{2/3}$$

To maintain this shape as sea level rises, Bruun (1962) postulated the rule that:

$$s = (a)l/h;$$

where s is the amount of landward migration of the beach, a is the amount of sea-level rise, and l and h are the vertical and horizontal dimensions of the system, respectively. In this formulation, sand is removed from the landward-migrating beach and transferred to the shoreface and seabed to maintain a profile of equilibrium.

Although often applied in planning and engineering designs, the Bruun Rule, even as acknowledged by Bruun himself (1988), is a two-dimensional model that assumes: (1) no longshore movement of sand, and (2) no losses of sand landward of the dune line nor seaward of the "depth of closure" (an arbitrary offshore line). These requirements, including the assumption that a definable sandy profile of equilibrium actually exists, greatly lessen the utility of the rule (List and others, 1991; Dubois, 1992; Pilkey and others, 1993). In an area like Saco Bay, where sea-level rise is not the only factor influencing shoreline change, the Bruun Rule is not applicable.

The most useful, but least applied, approach to understanding the behavior of beach systems involves constructing a sand budget (Komar, 1983). This approach requires that the rate of sand flux to and from outside source(s) is known, as well as the rate of exchange of sand among the depositional reservoirs within the system (Carter, 1988). Some studies have evaluated the rate of sand movement over limited time periods by direct measurement or by indirect calculation of the amount of sand movement using current velocities, and extrapolating the results over longer time periods. On a beach system the size of Saco Bay, such dynamical measurements are prohibitively costly and may be representative of only short-term shoreline processes. We have employed dynamical measurements of beach-profile changes and offshore and estuarine sand transport only to demonstrate the relative direction of sand movement.

Some reports have compared time-series historical maps and bathymetric charts of coastal areas to evaluate changes in sand volume, and to infer directions of sand movement over the past century (Hess and Harris, 1987a, FitzGerald and others, 1989; List and others, 1991). Despite the difficulty in geographically registering old maps, we have employed vintage charts and maps to make historical assessments of sand budget changes (last 130 years), and we have used historical aerial photographs to estimate sand volume changes over shorter time frames (10-40 years).

Few studies have measured the volume of sand in depositional reservoirs of the beach system even though this technique evaluates the integrated products of processes acting over millennia. In many coastal plain settings it is difficult to distinguish between a variety of complex sandy deposits resulting from the repeated Quaternary fluctuations of sea level (Ashley and others, 1991). In generally muddy regions, however, sand deposits are clearly delineated by geophysical methods and coring, and the volume of depositional reservoirs are measurable (Pope and others, 1991). Because Pleistocene sediments in Saco Bay are distinguishable from Holocene sand bodies with geophysical techniques (Kelley and others, 1989a), we have employed these methods, along with core stratigraphy, to measure the total volume of sand within Saco Bay.

Previous Seismic and Stratigraphic Research in the Western Gulf of Maine

Earlier research in the region permits relatively confident assessment of seismic reflectors encountered in Saco Bay. Precambrian and Paleozoic igneous and metamorphic rocks can be traced directly from coastal outcrops into the subsurface and

form the acoustic basement of the area (Belknap and others, 1989a; Belknap and Shipp, 1991). Where bedrock crops out on the seafloor, its strong acoustic reflectivity and fracture patterns are easily recognized on side-scan sonar records (Kelley and others, 1986, 1987, 1989a, b; Kelley and Belknap, 1991). Till unconformably rests on bedrock and is widely recognized from its chaotic internal structure and strong surface return in seismic reflection profiles (Belknap and others, 1989a; Belknap and Shipp, 1991), and irregular, acoustically dark, boulder-littered surface on side-scan sonar records (Kelley and others, 1989a, b; Kelley and Belknap, 1991). Glacial-marine sediment, the Presumpscot Formation (Bloom, 1963), exhibits a variety of acoustic facies in seismic reflection profiles, but is commonly acoustically transparent (GM-M, unit of Belknap and others, 1989a) with widespread, rhythmic, coherent reflectors that drape the underlying topography (GM-D, unit of Belknap and others, 1989a) or with weaker acoustic reflections that are ponded within bathymetric depressions (GM-P, unit of Belknap and others, 1989a). Where this material crops out on the seafloor a lag deposit of sandy gravel with ripples is visible in side-scan sonar records (Kelley and others, 1989a; Kelley and Belknap, 1991). In water depths less than about 60 m, an erosional unconformity exists on the surface of the glacial-marine sediment (Belknap and others, 1989a; Kelley and Belknap, 1991; Kelley and others, 1992). In many areas, acoustically transparent Holocene mud, often charged with acoustically-opaque natural gas, rests on the transgressive unconformity (Kelley and Belknap, 1991; Kelley and others, 1994a; Belknap and others, 1989a). Mud offers almost no acoustic return on side-scan sonar records (Kelley and Belknap, 1991). Seaward of sandy beaches like Saco Bay, a stronger surface return from an acoustic unit often containing clinoform reflectors is indicative of Holocene sand (Belknap and others, 1989a). In side-scan sonar records the sand offers a strong acoustic return and is commonly covered with ripples in large fields or narrow linear bands (Kelley and others, 1989b).

Cores penetrating all of the sedimentary units have established confidence in these interpretations as well as in a chronology for the stratigraphic units (Kelley and others, 1990, 1992, 1994a). Glaciation, deglaciation, and the accompanying relative sea-level changes are the most important influences on the geological column (Figure 2) (Belknap and others, 1987; Kelley and others, 1989b, 1992). A lowstand shoreline was formed around 10,500 yr B.P. near the contemporary 55 m isobath (Shipp and others, 1989, 1991; Kelley and others, 1992). In outer Saco Bay the surface of this feature is covered with sand that we hypothesize was derived from the ancestral Saco River (Kelley and others, 1992). Following the lowstand, sea level rose rapidly to 20 m depth at 9,200 yr B.P., when a significant slowdown occurred (Kelley and others, 1992; Barnhardt and others, 1995). Little record remains of coastal deposits in water depths greater than 20 m. The rate of relative sea-level rise accelerated around 7,000 yr B.P., and then slowed again at 5,000 yr B.P.. Relative sea level continued to slow its rate of rise to 1.2 mm/yr at 4,000 yr B.P. and

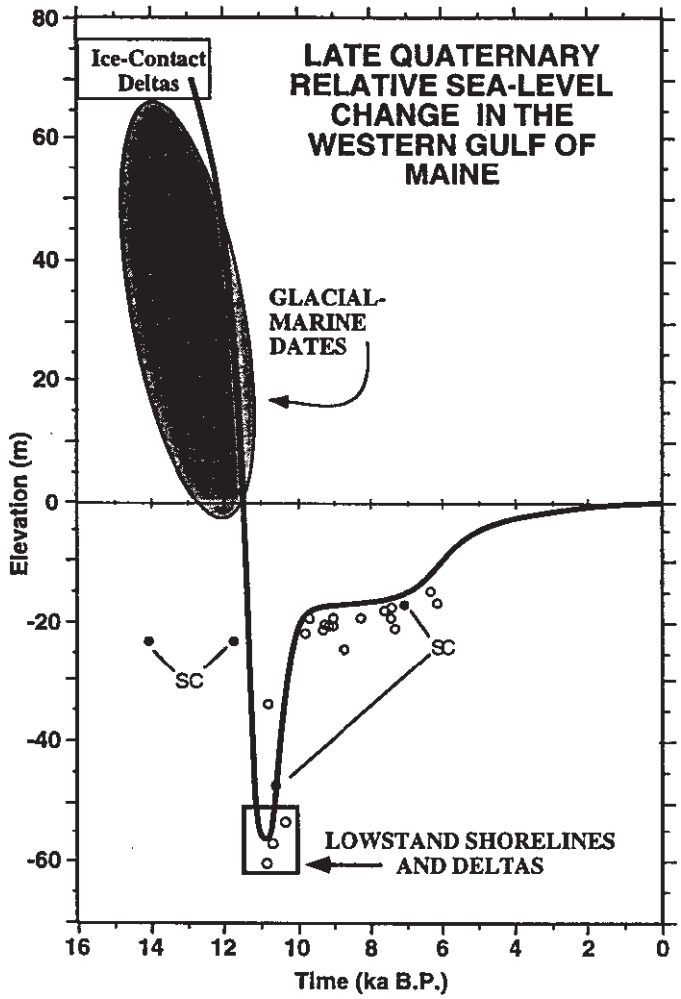

Figure 2: Relative sea-level change graph for the western Gulf of Maine (modified from Kelley and others, 1992; Barnhardt and others, 1995).The gray envelope encircles a large number of glacial-marine dates not gathered for this report (Belknap and others, 1987). Those points labeled SC are from Saco Bay.

0.5 mm/yr at 1,000 yr B.P. in southern Maine (Kelley and others, 1995, Barnhardt and others, 1995; Gehrels and others, 1995).

During the past 5,000 years of slow relative sea-level rise, many of northern New England's coastal beaches and marshes developed (Oldale, 1985; Belknap and others, 1989a,b; Kelley and others, 1995). Barrier evolution before this time of slow relative sea-level rise was mostly transgressive in nature, as suggested by evidence from a number of nearby barriers. At Hills Beach and Fletcher Neck, immediately south of the study area, Hulmes (1980, 1981) found an absence of shallow-marine facies in Biddeford Pool, and a 985 year-old peat sample collected at the seaward side of the beach. She concluded that the barrier had migrated landward approximately 20 cm/yr during the Holocene, in the process reworking proglacial sands. Similarly, the existence of the Wells-Ogunquit barrier system in southern Maine is related in part to the erosion of the Sanford outwash

plain. Sand was transported to the continental shelf during the late Pleistocene regression and subsequently was partially reworked into barriers (Kelley and others 1987, 1989b; Shipp, 1989). Landward migration of this barrier lithosome is indicated by the presence of salt-marsh peat below the barrier facies (Montello and others, 1992). Radiocarbon dates (Hussey, 1959, 1970; Belknap and others, 1989b; Montello and others, 1992; Kelley and others, 1995) suggest that the Wells-Ogunquit system formed at least by 5000 yr B.P., and reached near its present position after 2500 yr B.P., coincident with decelerating rates of relative sea-level rise. Many beach systems in the region display evidence of coastal progradation in the form of seaward-younging beach ridges, closed tidal inlets and abandoned coastal lagoons, and botanically mature salt marshes, possibly as a result of the very slow rate of sea-level rise for the past two thousand years (Duffy and others, 1989; Kelley and others, 1993; Gehrels and others, 1995).

Contemporary relative sea-level rise in the Gulf of Maine ranges from 1.8 mm/yr (since 1927; Seavey Island, ME) to 2.9 mm/yr (since 1921; Boston, MA), as evaluated by tide gauges (Lyles and others, 1988; Belknap and others, 1989b). These short-term rates are greater than any long-term rates the region has apparently experienced in the past 4,000 years. It has been suggested that this acceleration in the rate of relative sea-level rise is partly responsible for contemporary erosion of salt marshes and beaches (Jacobson, 1988; Kelley and others, 1995).

Previous Research on the Distribution and Movement of Sand in Saco Bay

Farrell (1972) prepared the first bottom-sediment map of Saco Bay based on grab samples and fathometer traces. He speculated on eroding glacial deposits as former sand sources in the Prouts Neck area and noted that surficial sand appeared thin in the outer bay. Despite his hydrographic observations (Farrell, 1970, 1972) which revealed that the Saco River is stratified in the summer, he considered the river as the main source of sand to the bay. He noted that the orientation of paleospits in the Goosefare Brook salt marsh suggested a southern, riverine sand source, as did the fining of sand size along the bay's beaches from south to north.

In early reports, the U.S. Army Corps of Engineers (USACOE) also considered the Saco River as a source of sand, at least to its estuary ("The river...during spring freshets carried large quantities of sand, and more particularly logs, sawdust, and other refuse...[to] just below Factory Island (a waterfall at the head of tide)" (USACOE, 1886, p. 5)). In all later work, the Army inferred a glacial origin for the bay's sand: "The beach material in [Saco Bay] is of glacial deposit origin ... Due to the topography of the coast there is apparently no natural source of material other than by local erosion within the confines of Saco Bay" (USACOE, 1955, p. 6). The construction and repeated lengthening of the 2030 m long northern jetty at the Saco River entrance is predicated on the untested assumption that "...a constant movement of sand from north to south along the ocean beach ... has...deposited material in front of the original entrance channel" (USACOE, 1910, p. 3). The Army hypothesized that eroding glacial deposits near the center of Saco Bay shed sand to the north and south: "It appears that the beaches in Saco Bay may have been formed as spits which grew in both directions from the high ground at Old Orchard Beach" (USACOE, 1955, p. 5.). Hulmes (1980, 1981) evaluated the evolution of Biddeford Pool through vibracores and believed that that beach system also originated through the erosion of glacial sediment.

Research employing modern geophysical devices began in the 1980's. Kelley and others (1986) evaluated the seismic stratigraphy of Saco Bay and inferred, based on early lower-resolution seismic profiles, that a relatively thick deposit of sand floored the bay's bottom. They concluded that sand from the Saco River must have been responsible for that great volume of sand as well as for the extensive beaches in the area. Kelley and others (1987) described the bottom sediments in the region in detail based on grab samples, submersible dives, and geophysical observations, and later (Kelley and others, 1989a) synthesized this work with Farrell's (1972). More recently, cores revealing less than one meter of sand over glacial-marine sediment and higher-resolution seismic reflection profiling data revised downward the thickness of sand in Saco Bay (Kelley and others, 1992). Radiocarbon dates from core samples in Saco Bay also suggested that the lower and upper populations of heavy minerals in early cores from Saco Bay (Luepke and Grosz, 1986) represented glacial-marine and fluvial sediments, respectively (Kelley and others, 1992).

Historical Shoreline Changes and Engineering Activities in Saco Bay

Historically, the Saco River has been a major shipping channel, but the tidal delta at its mouth has always been a barrier to navigation. In 1827 some obstructions to navigation were removed, but by 1866 it became necessary to construct a 1311 m long jetty on the north side of the river entrance to block "...a constant movement of sand from north to south along the ocean beach, ...which has ...deposited material in front of the original entrance channel" (USACOE, 1910, p. 3).

A jetty was constructed on the south side of the river entrance in 1897, and the navigation channel was deepened and both jetties were lengthened and raised several times during the early 20th century. The north jetty is presently 2030 m long, 5.2 m above mean low water (MLW) for the first 259 m from land, and 4.6 m above MLW for the remainder. The south jetty is 1463 m long, 3.3 m above MLW for the first 259 m, and 1.7 m above MLW for the remainder (USACOE, 1992).

Shoreline changes accompanied enlargements of the jetties at the river mouth. Camp Ellis grew seaward in the late 19th century due to changes in the hydrodynamic conditions at the river

mouth. As tidal currents at the mouth of the estuary became confined to the dredged, jettied channel, the twice-daily seaward flow across the Saco River's ebb-tidal delta ceased. Regions on both sides of the jetties became dominated by shoaling wave conditions, resulting in the onshore movement of landward-migrating sand bars by 1877 (Farrell, 1972). This same phenomenon was documented at several inlets elsewhere on the East Coast of the United States following jetty construction (FitzGerald, 1988; Dean and Work, 1993).

After the period of accretion owing to onshore migration of the tidal delta and possibly to dredge spoils disposal, beach retreat had become a problem on both sides of the jetties by 1909 (USACOE, 1955). Although the Hills Beach side apparently stabilized, Camp Ellis continued to recede. The Army estimated that between the north jetty at the river entrance and a point 3650 m to the north, between mean high water and the 5.5 m isobath, the shoreline lost 61,933 m^3/yr of sand from 1859 to 1955, a total of 5.945 x 10^6 m^3. This does not include the additional sand introduced to Camp Ellis beach by regular dredging of the Saco River navigation channel (USACOE, 1955).

Shoreline erosion studies have often been conducted at Hills Beach (USACOE, 1920) and Camp Ellis (USACOE, 1935, 1939, 1955, 1961, 1976, 1987), but found no linkage between the jetties and the shoreline changes: "The Division Engineer also concludes that the federal jetties at the mouth of the Saco River have not caused nor accelerated erosion of the shore in the study area [Camp Ellis]" (USACOE, 1955, p. 21). The most recent report (USACOE, 1992, p. 4) states that wave reflection from the north jetty "...contributes to some extent in the erosion" (of Camp Ellis). A $500,000 physical model of Camp Ellis and the river mouth was built by the Corps to evaluate the problem.

Farrell (1972) was the first to compile all the historical maps and aerial photographs of the region's beaches. Nelson (1979) extended this early work on shoreline change and graphically depicted the historical growth of Pine Point, at the northern end of the main central beach system in Saco Bay. Pine Point has continuously grown eastward and seaward since the 19th century. Between 1877 and 1923 it grew 137 meters (Farrell, 1972) partly in response to closing of the Little River inlet to the south when a railroad line was built circa 1875. By 1955 the Scarborough River inlet required dredging for navigation, and in 1957 a jetty was constructed at the southern side of the river entrance. By this time the Scarborough River inlet had narrowed from 762 to 207 m.

Dredging has occurred in the Saco estuary since the early 19th century, in the Scarborough Estuary since 1955, and in the entrance to Biddeford Pool since 1956 (Normandeau Associates, 1994). Sandy spoils have often been placed on nearby beaches, although occasionally dredged material has been disposed "in open water" (Table 1). A recent review of dredging within Saco Bay has chronicled the dredging history of the bay since 1950 (Normandeau Associates, 1994), but differs in detail from older dredging studies (Mahoosuc Corp., 1982) and evaluations of shoreline change (Farrell, 1972; Nelson, 1979).

METHODS

Surficial sediment was evaluated through bottom samples, side-scan sonar records, and seismic reflection profiles (Figures 1, 3a, b). All 134 offshore samples were gathered with a Smith-MacIntyre 0.25 m^3 grab sampler, while 200 samples were gathered in the Saco estuary and vicinity with a Van Veen sampler. Size analyses were performed by sieve, settling tube, and Micromeritics Sedigraph following standard preparation techniques (Folk, 1974) (Figure 3a). An EG&G SMS 260, slant-range corrected side-scan sonar was used to map 30 km^2 of the seabed (Figure 3a), and an ORE Geopulse seismic reflection profiler gathered 370 km of subbottom records (Figure 3b). All navigation positions were measured by LORAN-C and transformed to latitude/longitude coordinates by the computer program, LORCON (J. Stuart, National Ocean Survey, personal communication).

Offshore cores were gathered with both Rossfelder (P5 and P6) and Alpine vibracorers from 16 sites in water depths up to 60 m (Figures 1, 3b). Of these, 6 cores were taken in water depths less than 25 m and are the only cores considered for this study. All cores were photographed and logged prior to grain-size analyses and radiocarbon-dating of fossils. A Lanesky and others (1979) vibracorer was employed on land to provide samples for radiocarbon dating as well as ground-truth information for a ground-penetrating radar (GPR) profiler. A Geophysical Survey Systems System 3 GPR was mounted on a small cart to minimize distance between the 120 MHz transceiver and the ground and to maximize the flexibility of operation. In all, 32 vibracores were gathered along 40 kilometers of GPR lines (Figures 1, 3c). In addition, 10 rotary auger borings were conducted in 1994, identifying barrier, back-barrier, and glacial-marine facies and retrieving sediments for analyses. Beach topography was digitized from mylar flood insurance rate maps which have a 0.66 m contour interval. Beach profiles were made seasonally at 5 stations following the Emery (1961) method.

Evaluation of offshore current velocities and waves involved use of an S4 electromagnetic current meter and four Endeco 105 impeller current meters. Endeco 105 current meters measured mean flow at 30 minute intervals while the S4 evaluated wave period and height, and orbital velocities, in short-term burst sampling, at 1 m over the bottom (Figures 1, 3a). Taut-wire moorings were arrayed with with Endeco meters at 1 and 12 m above the seabed and on one deployment the S4 replaced the Endeco at the 1 m position. Four deployments, summarized in Table 2, were completed in 1991 and 1992, two in a shelf valley in south-central Saco Bay, 1.7 km north-northeast of Wood Island, one in the center of Saco Bay, 3.5 km east-southeast of the Old Orchard Beach pier, and one site 1 km southeast of Prouts Neck. The Old Orchard Beach and Prouts Neck deployments were concurrent.

In the Saco River, current velocity and direction, temperature, and salinity were measured using Marsh-McBirney and Teledyne Gurley current meters and YSI salinometer. Readings

TABLE 1: DREDGING HISTORY OF SACO BAY

SCARBOROUGH RIVER ESTUARY[a]

YEAR	VOLUME DREDGED (m^3)	DISPOSAL SITE	COMMENTS
1956	97,906	open water	initial dredging; most placed on beach[b, c]
1962	114,645	open water	
1965	24,899	open water	
1969	35,922	open water	
1973	144,300	open water	possibly upland[c]
1975	6,948	open water	possibly intertidal[c]

19 year total= 424,620 m^3
Average annual dredge volume = 22,348 m^3

Scarborough estuary filling rate following first dredge = 17,195 m^3/yr

PROJECTED FUTURE DREDGING

TIME FRAME	VOLUME	DISPOSAL SITE
1995[c]	175,743[c]	not determined
1995-2005	191,075[a]	not determined
1995-2045	898,052[a]	not determined

SACO RIVER ESTUARY

YEAR	VOLUME DREDGED (m^3)	DISPOSAL SITE	COMMENTS
1827	???	???	initial clearing of river, building of piers, buoys
BY 1872	84,073	???	
1886	12,515	???	channel deepened to 1.8 m
1912	65,279	???	channel deepened to 2.1 m
1919	"large quantity"	beach	assume minimum 60,000 m^3
1928	63,437	???	channel deepened to 2.5 m
1939	60,824	???	
1940	48,151	???	
1965	28,279[a]	upland	
1969	66,765[a]	beach	expanded anchorage
1969	55,893[a]	beach	differs from Mahoosuc, 1982
1973	28,279[a]	nearshore	
1978	61,144[a]	beach	differs from Mahoosuc, 1982
1978	38,215[a]	beach	
1982	5,579[a]	beach	expansion of anchorage
1992	10,000[e]	beach	new anchorage
1992	65,706[a]	beach	
1992	19,107[a]	in channel[d]	

SACO RIVER ESTUARY (continued)

122 year total = 773,246 m^3
Average annual dredge volume = 6,338 m^3

Saco estuary filling rate following last expansion (10 yr) = 8,481 m^3/yr

PROJECTED FUTURE DREDGING

TIME FRAME	VOLUME	DISPOSAL SITE
1995-2005	84,073[a]	not determined, probably beach
1995-2045	420,365[a]	not determined, probably beach

BIDDEFORD POOL

YEAR	VOLUME DREDGED (m^3)	DISPOSAL SITE	COMMENTS
1956	57,177	open water[a]	improvement
1956	2,707	upland[a]	initial dredge
1971	287	upland[a]	
1976	306	upland[a]	
1979	382	upland[a]	initial dredge
1988	860	open water[a]	
1988	35,095	open water[a]	disposal site monitored[f]
1989	12,233	beach[f]	
1992	9,439	offshore[a]	improvement

33 year total = 118,486 m^3
Average annual dredge volume = 3,590 m^3

Biddeford Pool filling rate following last expansion (10 yr) = 4,819 m^3/yr

PROJECTED FUTURE DREDGING

TIME FRAME	VOLUME	DISPOSAL SITE
1995-2020	25,232[a]	not determined
1995-2045	50,464[a]	not determined

[a] (from Normandeau Associates, 1994; most values and disposal sites differ from Mahoosuc Corp., 1982)
[b] (some or all of this filled in Pine Point, Farrell, 1972)
[c] (Mahoosuc Corp., 1982)
[d] (projected by U.S. Army Corps of Engineers, 1994, personal communication)
[e] (personal communication, Maine State Department of Environmental Protection)
[f] (Maine Geological Survey)

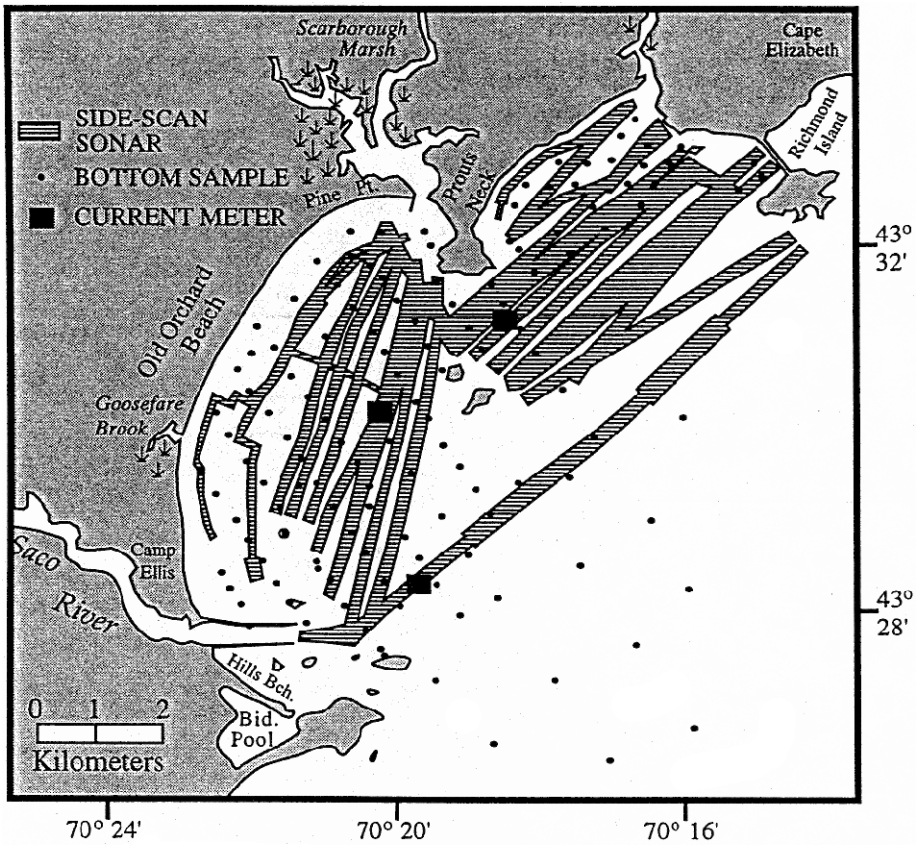

Figure 3a: Location of data collected for this report. (a) Area of side-scan sonar swaths shown with ruled pattern, with bottom sample locations located as filled circles. The three black boxes locate current meter sites.

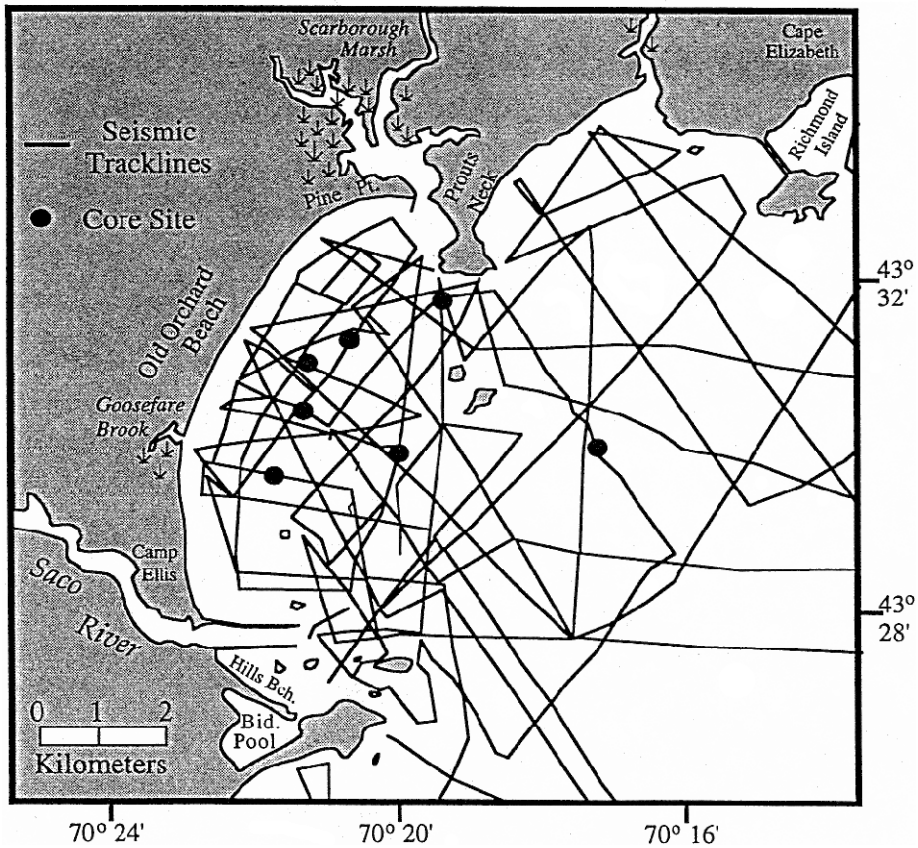

Figure 3(b): Location of seismic reflection lines and vibracore sites (filled circles).

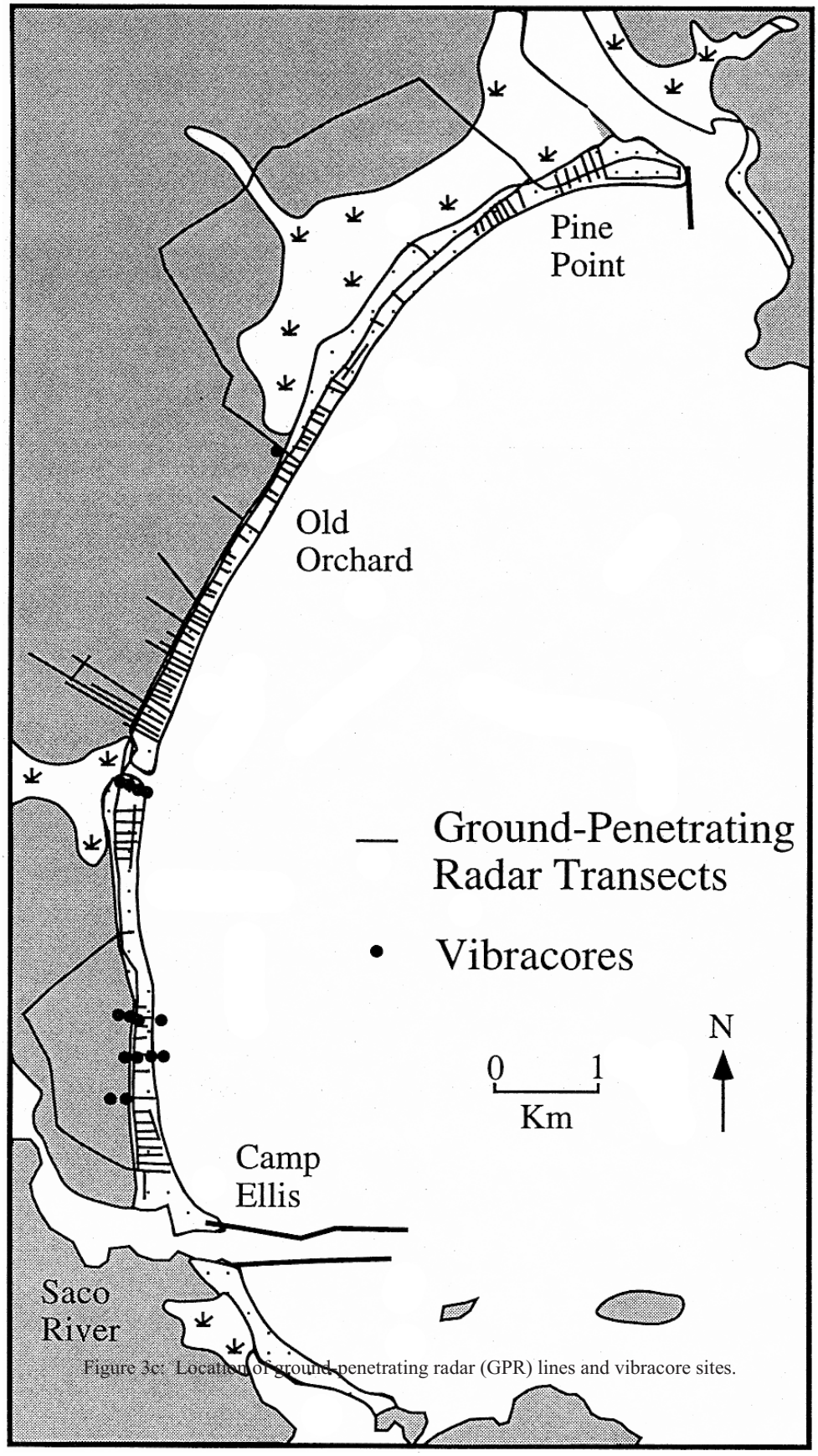

Figure 3c: Location of ground-penetrating radar (GPR) lines and vibracore sites.

TABLE 2: CURRENT METER DEPLOYMENTS

LOCATION	LATITUDE	LONGITUDE	WATER DEPTH	DATES	TYPE
Shelf Valley	43° 28.0' N	70° 19.2' W	30 m	8/2-9/18/91	Endeco 12 m Endeco 1 m
Shelf Valley	43° 28.0' N	70° 19.2' W	30 m	3/5-3/20/92	Endeco 12 m S4 1 m
Central Saco Bay	43° 29.8' N	70° 19.8' W	22 m	7/15-8/18/92	Endeco 12 m Endeco 1 m
Prouts Neck	43° 30.9' N	70° 17.9' W	22 m	7/15-8/18/92	Endeco 12 m Endeco 1 m

NOTE: Mooring locations in Saco Bay are shown in Figure 3a.

were taken at three locations through the water column (1 m off the bottom, mid-depth, and 1 m below the surface) at 5-10 stations in the Saco estuary over complete tidal cycles during spring freshet, tide-dominated, and mean conditions. In addition to data gathered directly by this project, data on wind velocity and wave height from the Portland Large Navigation Buoy (LNB; R. Marine, National Weather service, personal communication), 11 km to the east-northeast of Saco Bay, were analyzed. Stream gauge data for the Saco River at Cornish, ME, were utilized as well (Bartlett and others, 1993; U.S. Geological Survey, personal communication).

All data were transferred to a Geographic Information System (GIS)(ARC/INFO) for analysis of sediment volumes and archival purposes. Historical aerial photographs were analyzed on an analytical stereoplotter and historical shoreline positions were transferred to the GIS for analysis (Dickson and Kelley, 1993). Areal and volumetric quantities quoted in this paper are based on GIS-computed values.

RESULTS

Surficial Sediment

Bedrock is exposed over 8% of the bay, and crops out on the shallow, submerged margins of all islands in the bay seaward of the peninsulas at Biddeford Pool and Prouts Neck. Bedrock is exposed along the shoreline in several places in Cape Elizabeth and in many small, isolated shoals scattered throughout the bay (Table 3; Figure 4). Rock is most extensive in the shallow water near Bluff and Stratton Islands in the central bay, regions previously included as Rocky Zones on physiographic maps (Kelley and others, 1987; 1989a; 1989b). All outcrops of bedrock contain some coarse-grained talus and carbonate sediment filling in large cracks (Neptunian dikes), and most rocky areas are closely associated with mixed rock and gravel, and gravel deposits (Figures 4, 5a; Kelley and others, 1989a). Mixed rock and gravel, occupying 30% of the bay bottom, is the most common seafloor environment; it increases in abundance offshore. One reason for the unusual abundance of this seafloor type is the broad definition of the map unit, which is required by the extreme heterogeneity of the seafloor and the resolution of the side-scan sonar. Within the beach and dune areas, bedrock outcrops are limited in number as well as size.

Rippled coarse sand and gravel covers 9% of the Saco Bay in water depths from 5 to 45 m (Figures 4, 5a, b). Four distinct locations of these coarse-grained ripples (CGR) are identified. Three locations contain large oscillatory ripples with mean wavelengths of 1.3 m and amplitudes of 20 cm (similar in size to those measured by Belknap and others, 1988). The finest mean grain size from oscillatory CGR sites was 1 phi (0.5 mm) (medium-coarse sand), while the coarsest samples contained cobbles (Barber, 1995). Extensive fields of ripples lie generally south of Prouts Neck and Richmond Island (Figures 4, 5b). Elongate CGR ribbons range from 100 m to 250 m in width and 0.5 km to 2.0 km in length. Some connect to larger bedform fields while others occur in isolated, subparallel groups. A more restricted occurrence for the rippled bottom is adjacent to bedrock outcrops, or over locations where bedrock is buried by less than 5 m of sediment (Figure 5a). Kelley and others (1989a) inferred that in these locations erosion of glacial-marine sediment directly overlying rock, and carbonate detritus from encrusting organisms, provide coarse material from which the ripples form.

TABLE 3: AREAL EXTENT OF SEAFLOOR TYPES MAPPED IN SACO BAY

BOTTOM TYPE	AREAL EXTENT (m^2)	% OF AREA MAPPED IN FIGURE 4
Bedrock	12,100,00	8.0
Mixed rock and gravel	45,700,000	30.5
Gravel (smooth)	4,600,000	3.0
Coarse sand and gravel (rippled)	13,900,000	9.3
Medium and fine sand	25,100,000	16.8
Muddy sand	25,000,000	16.7
Sandy mud	18,500,000	12.3
Mud	5,100,000	3.4

NOTE: Geographic distribution of these bottom types is shown in Figure 4.

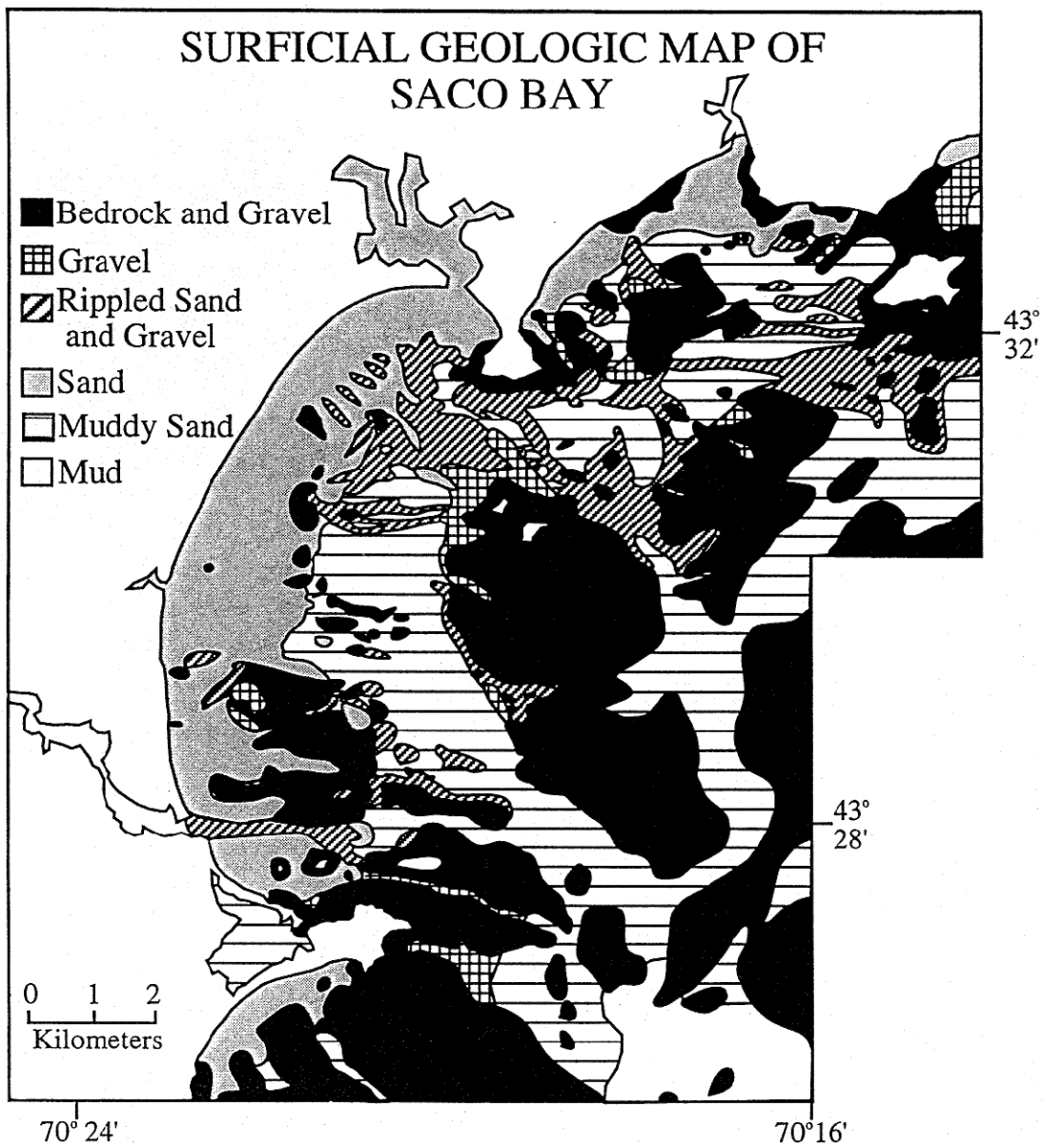

Figure 4: Surficial sediment map based on the side-scan sonar and bottom sample observations. The muddy sand also includes sandy mud and the rippled gravel also contains coarse sand.

Direct observations from a submersible confirm the presence of carbonate-rich, coarse clastic halos around bedrock outcrops (Belknap and others, 1988). A final location with a rippled seafloor is located within the estuary of the Saco River where strong tidal currents produce unidirectional megaripples (discussed below).

Medium to fine sand occurs in water depths less than 15 m directly offshore of many beaches of the region (Figure 4). This shoreface area is large (17% of the bay, Table 3) and relatively featureless except where broken up by rock outcrops. A northward fining trend in grain size of offshore sediment between 5 and 7 m depth parallels a similar trend observed onshore by Farrell (1972; Figure 6). Medium to fine sand nearshore grades offshore into muddy sand in most places by the 20 m isobath. Muddy sand covers the previously mapped Shelf Valleys which slope gently offshore into the deeper Gulf of Maine (Kelley and others, 1989a). At about the 40 m isobath, muddy sand within the Shelf Valleys grades into sandy mud which, in turn, grades to mud around 65 m depth (Kelley and others, 1987). Seismic records show that the large area of muddy sand mapped between Prouts Neck and Cape Elizabeth (Figure 4) delineates an area where till and glacial-marine sediment crop out on the seafloor. Many large (1 m) boulders rest on the surficial mud of the area and may be a lag deposit (Kelley and others, 1989a). Although occupying more than 30% of the bay, little analysis was made of muddy areas for this project.

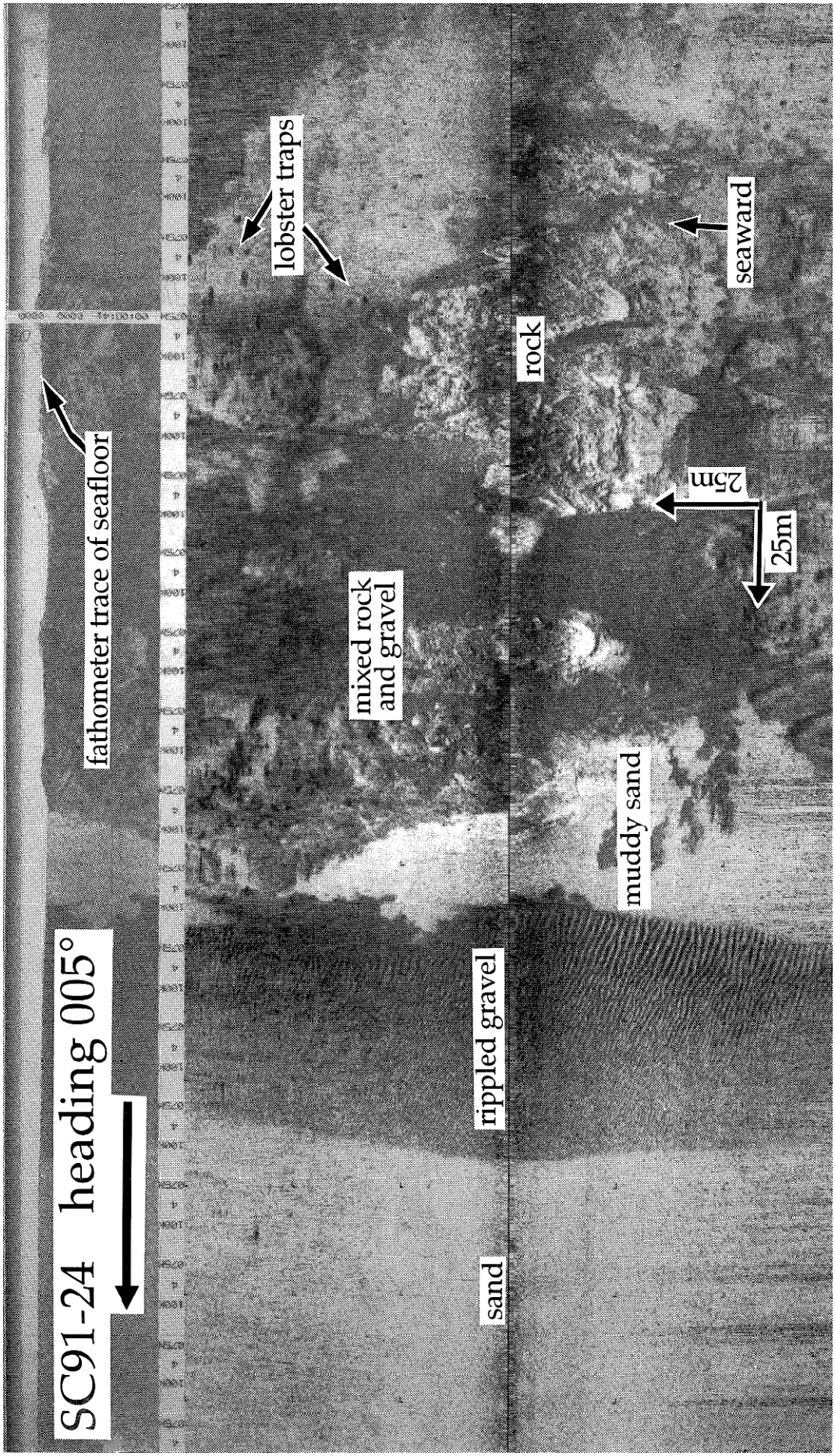

Figure 5(a): Side-scan sonargram of rippled bottom and mixed rock and gravel near bedrock outcrop.

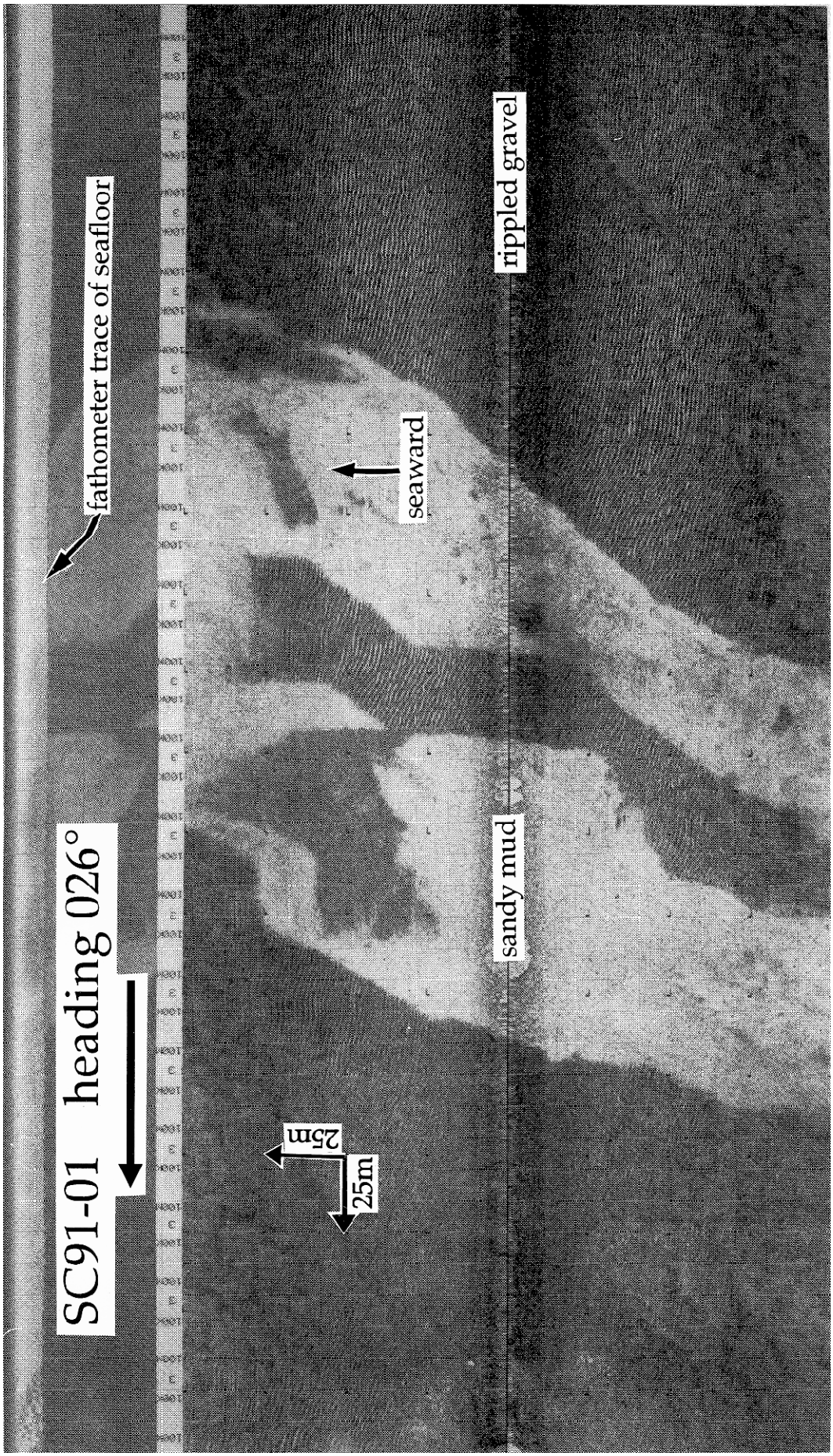

Figure 5(b): Side-scan sonargram of ribbons of ripples on an otherwise smooth bottom. Figures are located in Figure 1.

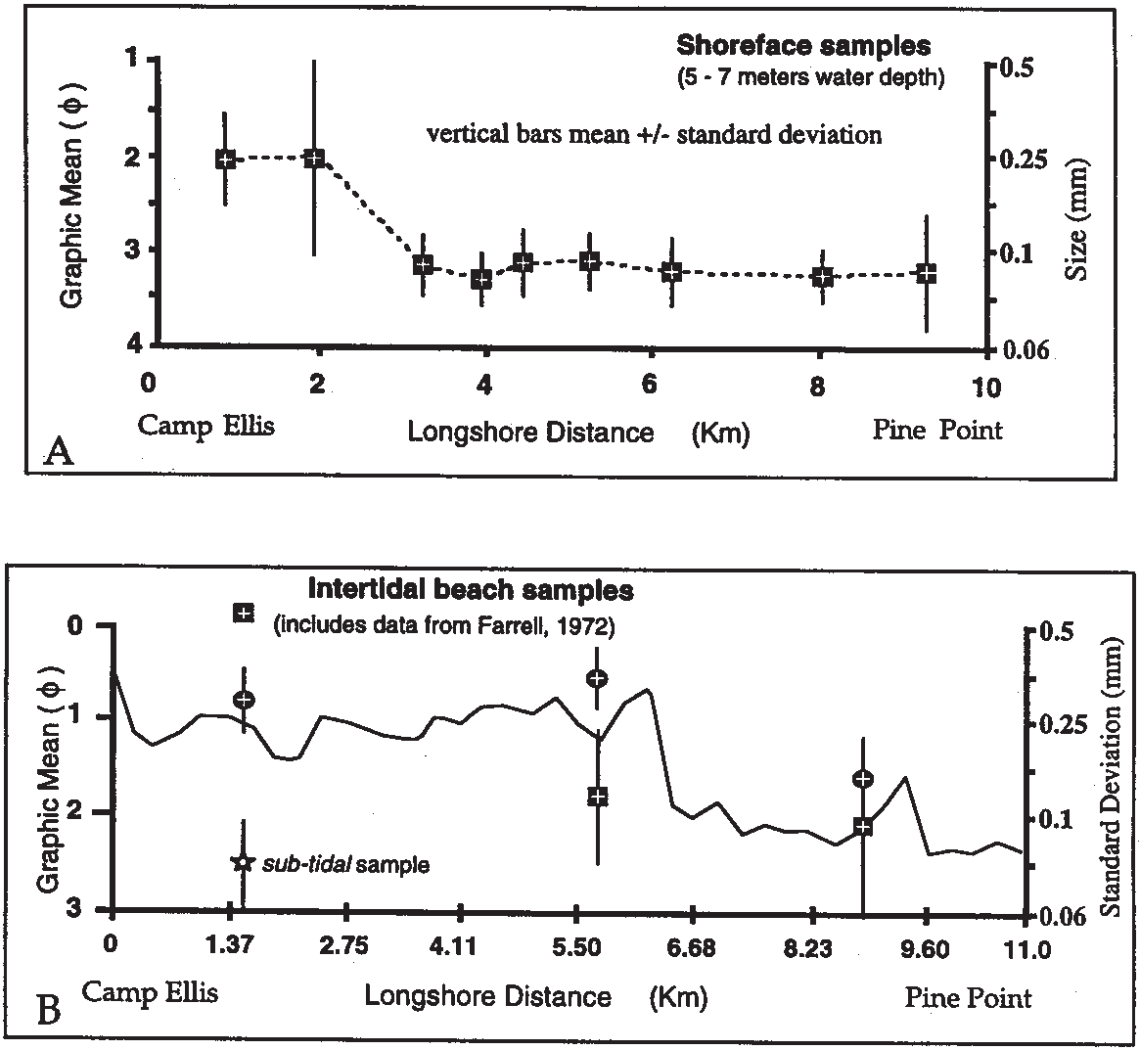

Figure 6: Trends in grain size along the shoreface and intertidal beach from Camp Ellis to Pine Point (modified from Barber, 1995).

Shallow Stratigraphy and Offshore Sand Volume

Shore-normal seismic reflection profiles reveal an irregular bedrock basement overlain by a relatively thick, acoustically transparent unit interpreted as glacial-marine sediment (Figure 7). The surface of this unit is marked by a relatively strong acoustic reflector which dips very gently seaward (1:275, Figure 7) and is cut by apparent channels in a few places. Overlying the strong reflector is a wedge that only locally can be resolved into more than one unit. This wedge begins at 20 m water depth and thickens to approximately 10 m at the shoreline.

Vibracores penetrated each of the unconsolidated units and confirmed the presence of glacial-marine material (Pgm) at depth as was previously recognized in other cores from the area (Kelley and others, 1990, 1992) (Figure 8). Holocene sediment unconformably overlies the Pleistocene material and the strong acoustic reflector correlates well with the change from glacial-marine mud to fine sand at 3 m depth in core VCSC92-02. Above the unconformity the basal sand becomes muddy (32% sand, with a range of 9 to 48%; Barber, 1995) Radiocarbon dates on woody material (6,110 50 yr B.P.) deposited with salt marsh foraminifera (Trochammina inflata), and an articulated mollusc (Macoma balthica; 7,060 35 yr B.P.) establish a mid-Holocene, estuarine setting (He). The stratigraphic reversal of the radiocarbon dates (Figure 8) is best explained by reworking and later deposition of the older Macoma shell. The sediment becomes sandier toward the top of the core (Hs), but Crassostrea fragments suggest maintenance of the estuarine (back-barrier?) environment until about 55 cm in the core. Here an abrupt increase and coarsening in the sand content occurs and marks the apparent ravinement unconformity (Figure 8). A shell horizon at 15 - 20 cm, commonly seen on many other cores about this depth, probably represents a storm deposit (Davidson-Arnott and Greenwood, 1976; Hunter and others, 1979; Barber, 1995).

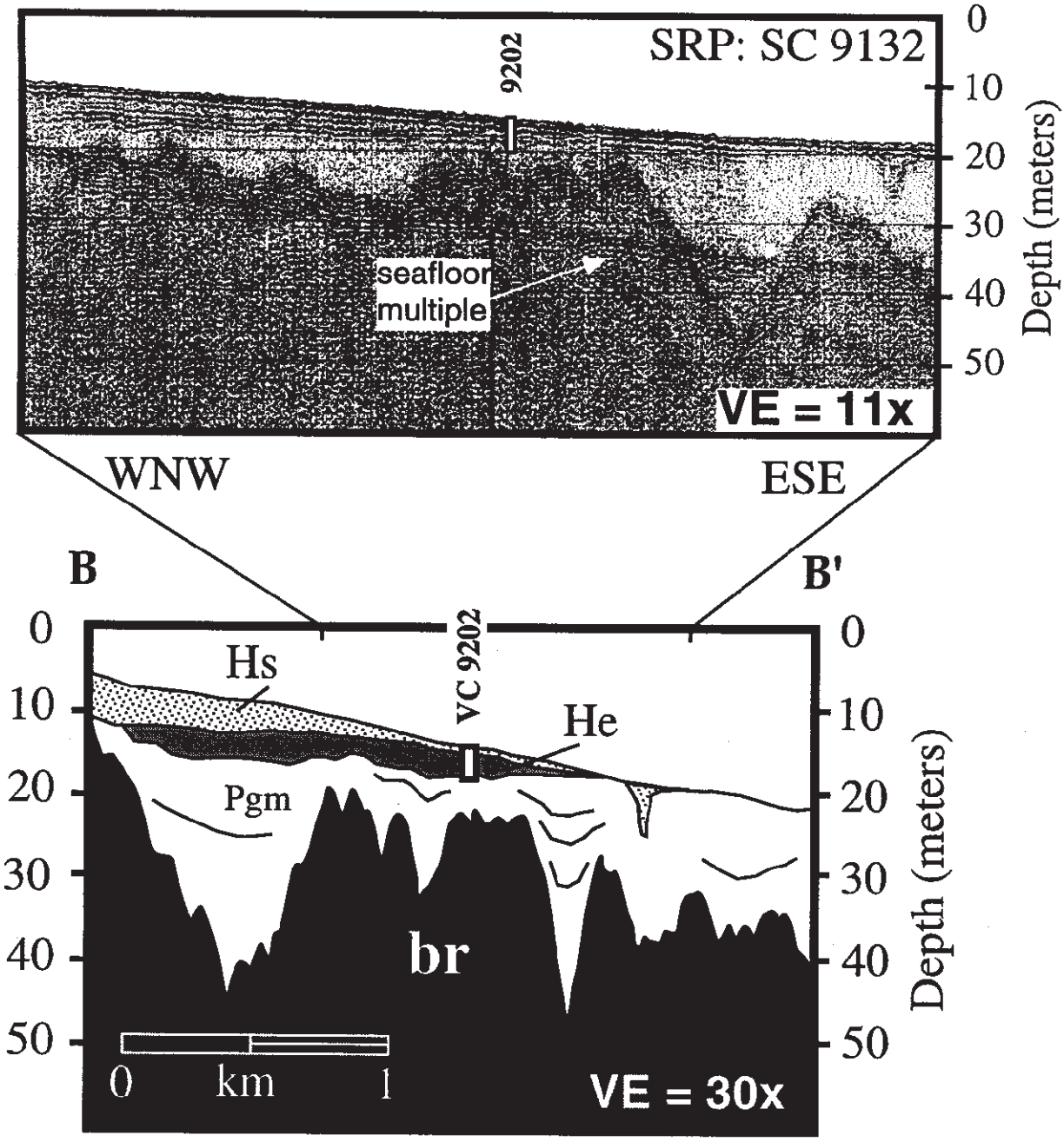

Figure 7: Original (top) and interpreted (bottom) seismic reflection profile (SRP) 9132 from the Old Orchard Beach shoreface. Seismic line location is shown in Figure 1. Vibracore 9202 is depicted in Figure 8. Units are as follows: Hs - Holocene sand; He - Holocene estuarine sediment; Pgm - Presumpscot Formation, glacial-marine sediment; br - bedrock. VE is vertical exaggeration.

The other shore-normal seismic profiles depict a wedge-shaped body of Holocene sand extending out to the 15 - 20 m depth (Barber, 1995), where muddy surficial sediment marks the outcrop of glacial-marine material on the seafloor (Figure 4). There are several exceptions to the generalized wedge-shape of the Holocene shoreface sand body (Figure 9a). Anomalously thick accumulations of sand (>5 m) occur in two ellipsoidal bodies, one at the mouth of the Saco River jetties, and the other parallel to the river one kilometer north. Another unusually thick deposit of sand (7 m) occurs south of Pine Point, where the shoreface extends farther seaward than elsewhere in the bay. In locations with shallow bedrock, thinner deposits ex-

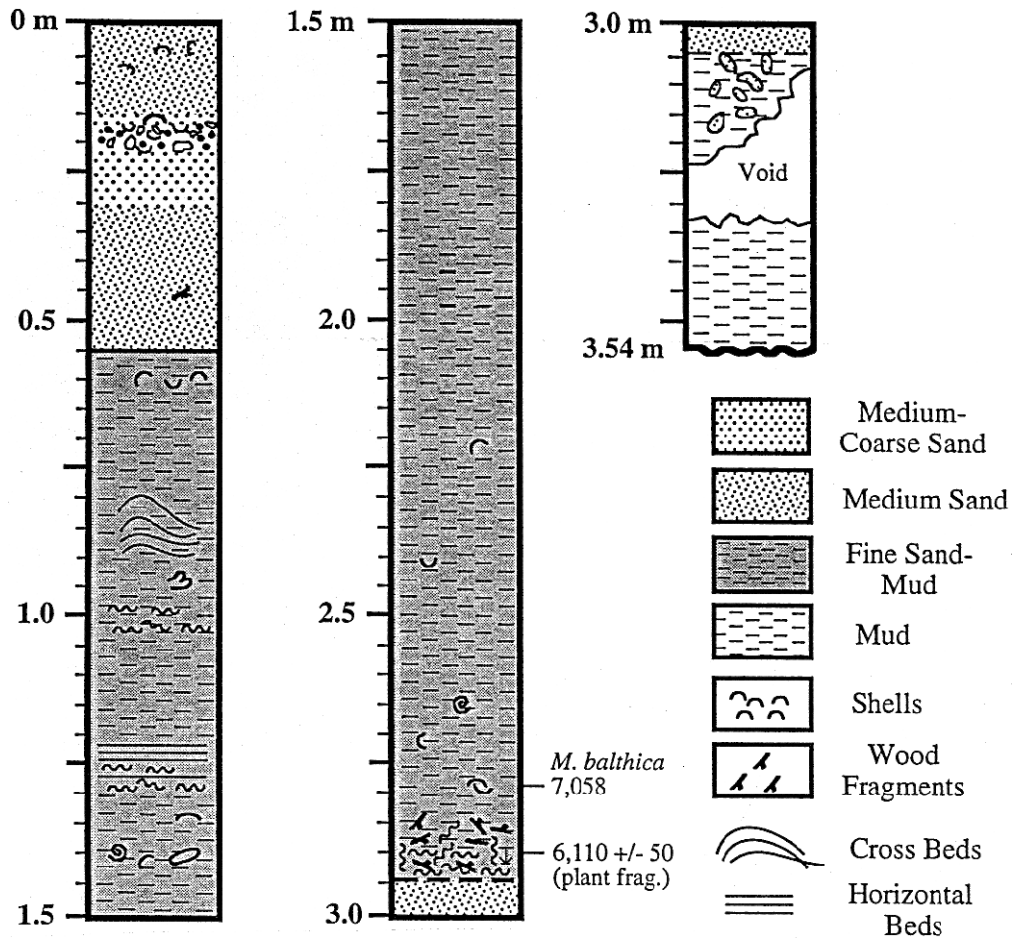

Figure 8: Log of vibracore 9202. Water depth = 14.1 m (MHW datum). Seismic line over core site is shown in Figure 7.

ist, with the exception of a J-shaped accumulation over 1 m thick in the central bay.

On the basis of side-scan sonar images, seismic records and cores, the Holocene wedge of sediment was estimated using the GIS to occupy a volume of 6.63 x 10^7 m^3 (Figure 9a). After subtracting the average mud content of the cores from this volume, the best estimate of clean Holocene sand in the shoreface is approximately 5.62 x 10^7 m^3.

Shallow Stratigraphy and Onshore Sand Volume

Ground-penetrating radar (GPR) profiles reveal a complex barrier and back-barrier stratigraphy on a base of glacial-marine muds (Presumpscot Formation; Figure 10). Bedrock was found in approximately 10 locations by the GPR. Northwest of Goosefare Brook the basal strata imaged by radar are formed by glacial-deltaic sands that were deposited during the late Wisconsinan ice retreat, circa 14 to13 ka. These sands may have extended into the present bay, and, as such, may have formed a source of some of the sand now present in the barrier system (van Heteren and others, 1994a).

The barrier and back-barrier sediments are subdivided into three units on the basis of morphologic, vibracore, and GPR data (van Heteren and others, 1996; Figure 10a). The sandy lower barrier unit forms a discontinuous buried beach ridge that extends from the Saco River entrance to Goosefare Brook, along the southern part of Saco Bay. Back-barrier deposits of muddy fine sands were identified. Also present along the southern part of the bay are elongated ponds, which occupy sites of former back-barrier lagoons. These relict lagoons and associated salt marshes and tidal flats formed behind the middle barrier unit as spits accreted northward from several bedrock pinnacles and other elevated anchor points. Locally, parts of this system are now buried, but south of Goosefare Brook, recurves of two generations of paleospits extend into the modern salt marsh behind the barrier (Figure 11; Farrel, 1972; Nelson, 1979; Kelley and others, 1989a; Millette, 1993, 1997). Both northerly and seaward spit accretion are observed in the sigmoidal reflectors seen in GPR records in the northern portions of Old Orchard Beach, particularly at Pine Point. The back-barrier region behind this section of the barrier has always had an open connection to Saco Bay at the Scarborough River inlet. No separate early

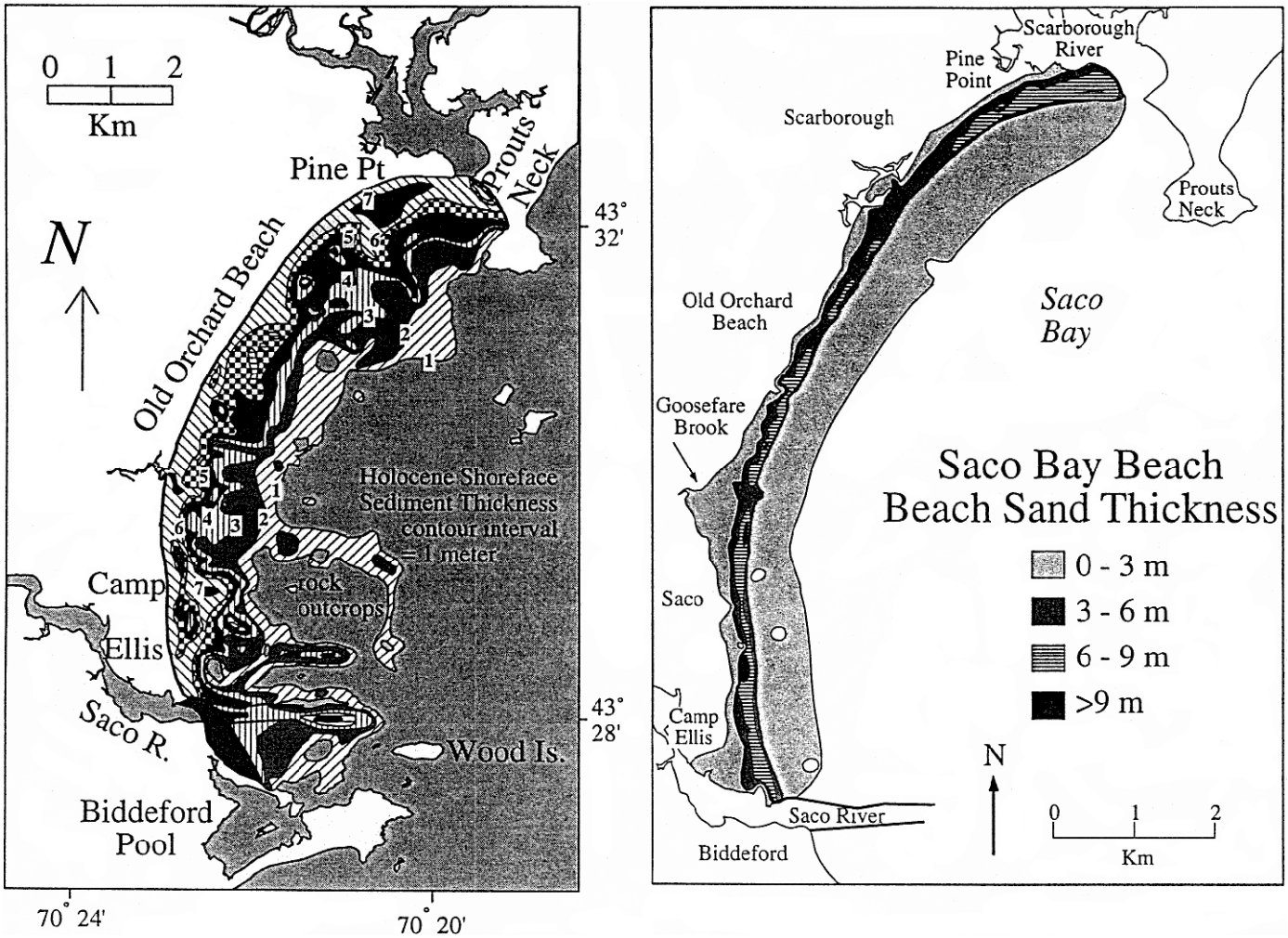

Figure 9. Holocene sediment isopach (thickness) maps: (a) isopach map of Holocene sediment along the shoreface (from Barber, 1995). (b) Holocene sand isopach map for the beach, dunes and back-barrier regions of Saco Bay (from van Heteren, 1996). Patterns represent thickness of sediment between contour lines. Shoreface thickness exceeds 7m near Pine Point and dunes are over 9m thick in some locations.

paleolagoon was identified, as in southern sections. The present barrier represents, for the most part, a net seaward widening of the middle barrier unit (the spit system) at a later time. At Pine Point there has been significant lonsgshore spit accretion as part of the development of the upper barrier unit (Figure 10b).

GPR records, rotary auger and core data from north of Old Orchard Beach demonstrate that back-barrier peat and clastic facies have infilled low-lying Pleistocene paleotopography. The back-barrier deposits, in turn, are overlain by, and interfinger with, washover and eolian barrier facies (Figure 10c). High-marsh peat from beneath the central portion of the barrier just north of Old Orchard Beach yields a radiocarbon age of 2,850 75 yr B.P.. This date constrains the age of this portion of the barrier as it transgressed its own back-barrier deposits. The presence of peat underneath the barrier lithosome implies a component of onshore migration of the barrier during this stage of development, and not exclusively longshore accretion of a spit.

The combined data for the Saco embayment suggest that the shoreline evolved through repeated, but not necessarily synchronous, landward and alongshore (primarily northward) movement of the sandy barrier. This sedimentation history and morphologic development probably resulted from changes in the balance between the rates of relative sea-level rise and sediment supply (van Heteren and others, 1996; van Heteren, 1996).

On the basis of the regional topography, GPR records, vibracores, and rotary-auger drilling, we used the GIS to estimate that 2.2×10^7 m^3 of sand exists in the dune, beach and other barrier deposits (Figure 9b; van Heteren and others, 1994a). The generally muddy and spatially more restricted back-barrier deposits were not included in this calculation.

Included in the calculations are wedges of sand that extend both landward into the salt marsh (washover and tidal inlets facies) and seaward to a theoretical depth at which the entire barrier lithosome has been eroded at the ravinement surface. The

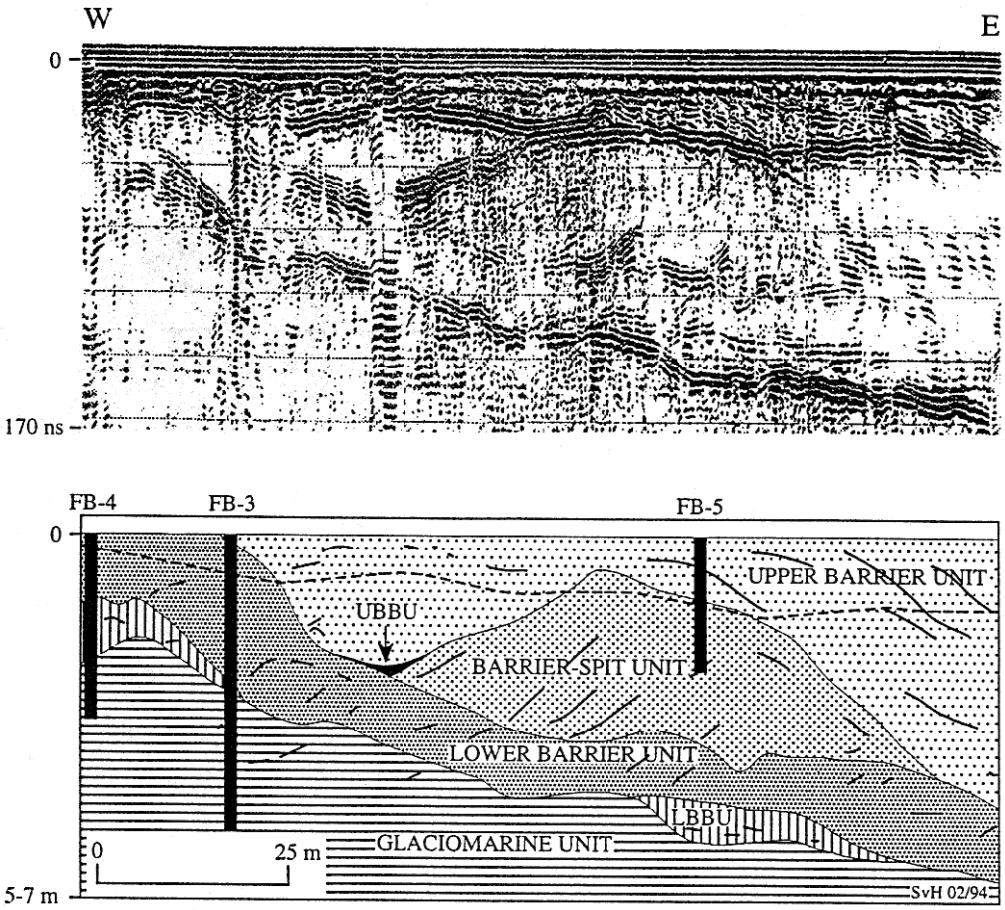

Figure 10. Ground-penetrating radar (GPR) data from Saco Bay beaches. Locations are shown in Figure 1. (a) Interpreted and original GPR record across the back barrier and part of the barrier beach near Ferry Beach State Park (from van Heteren and others, 1994b).

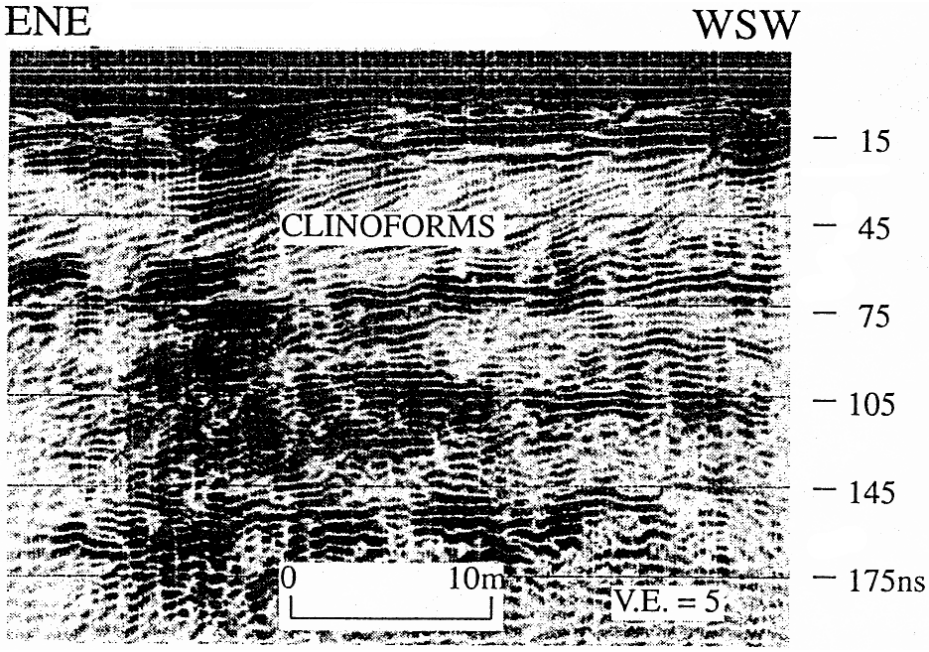

Figure 10(b): Original GPR record from Pine Point showing clinoform reflectors dipping towards the Scarborough River estuary.

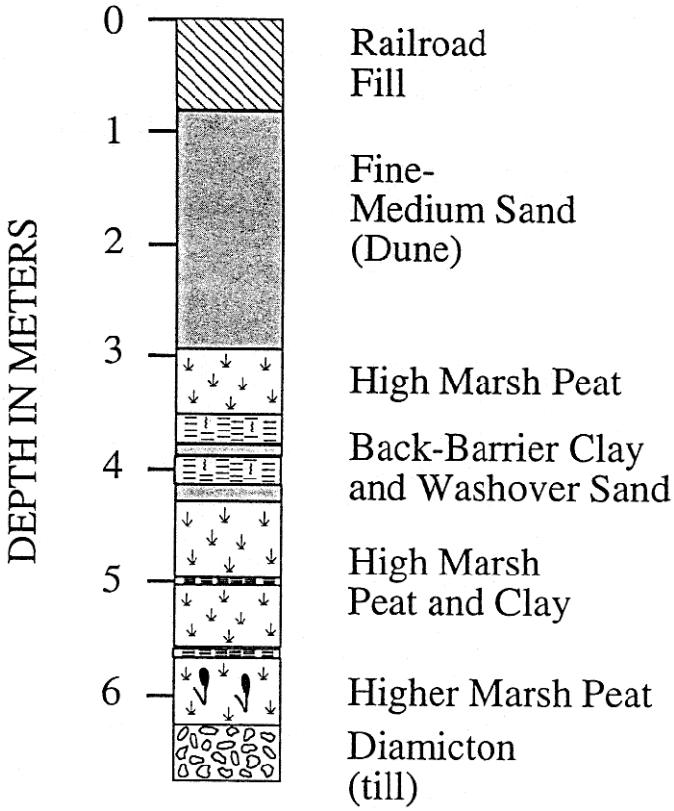

Figure 10c: Log of rotary auger core SB94-RA9.

most prominent area of sand accumulation within the littoral system is Pine Point. Here a 500 m wide and 2 km long sand body has an average thickness of 6 m and reaches a maximum of 9 m. Elsewhere, sand deposits between 6 and 11 m in thickness occur in an elongate 100 m wide belt that extends almost continuously between the Saco and Scarborough Rivers. The belt coincides with the area of highest dunes. Lesser quantities of sand are found in areas with elevated bedrock or in dune areas disturbed by human development.

Dynamic Estuarine Regime

The lower Saco River (10 km) is cut into bedrock at various locations, and its morphology is characterized by relatively deep gorges (5 - 8 m) separated by wide, shallow reaches (2 - 4 m) bordered by marshes and tidal flats (Figure 12; Kelley and others, 1994b). Most of the river is floored by medium to coarse sand except in gorges, where cobbles and boulders predominate (Manthorp and others, 1994; Manthorp, 1995).

Bottom samples, hydrographic measurements, and side-scan sonar observations indicate that two distinct regimes exist in the Saco River estuary. During normal river stages, which encompass most of the year, the estuary is highly stratified with well-defined thermoclines and haloclines (Figure 13). Under these conditions the upper two-thirds of the estuary is domi-

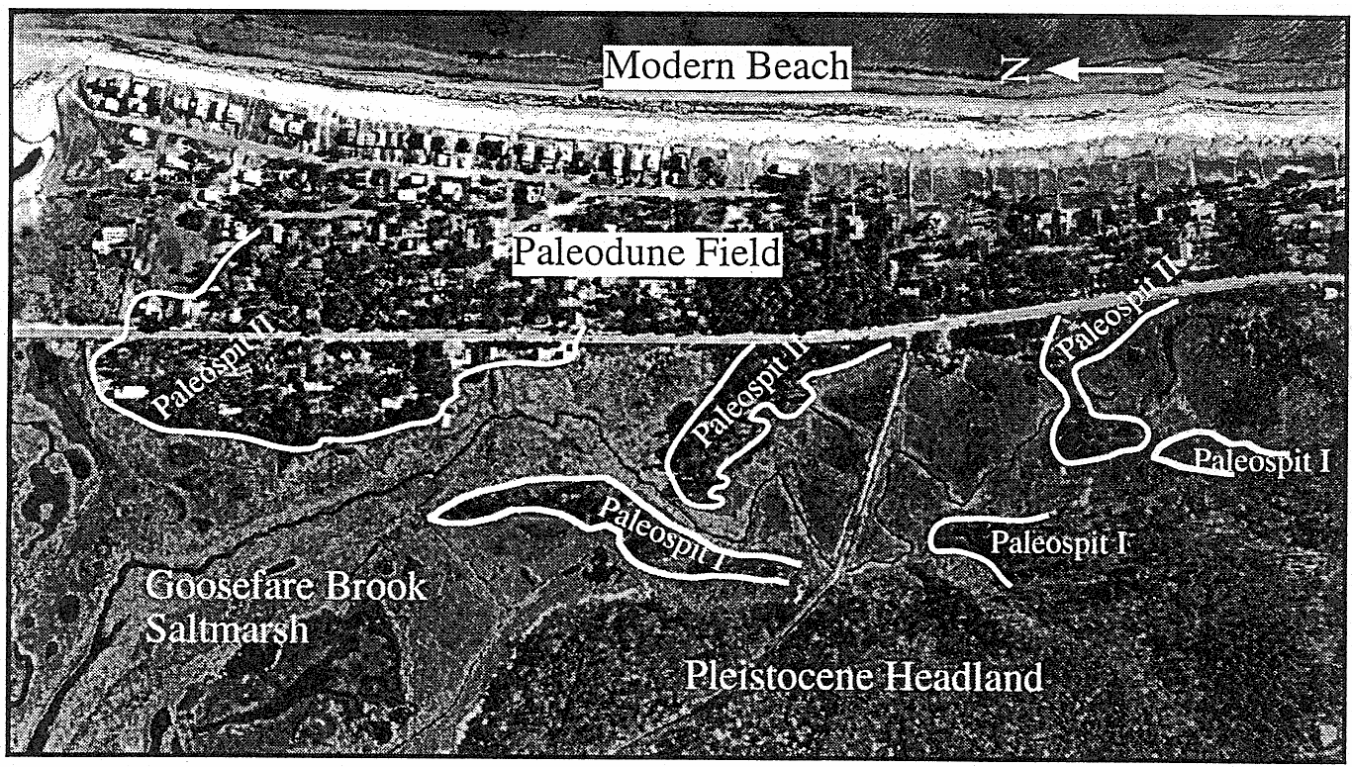

Figure 11: Paleospits in the Goosefare salt marsh are visible in this 1991 aerial photograph. Two generations of spits appear to exist, with the earlier attached to a former seacliff and the later spit at and beneath the present barrier. Some of the latter's subsurface features were imaged in Figure 10a. (modified from Kelley and others, 1989a)

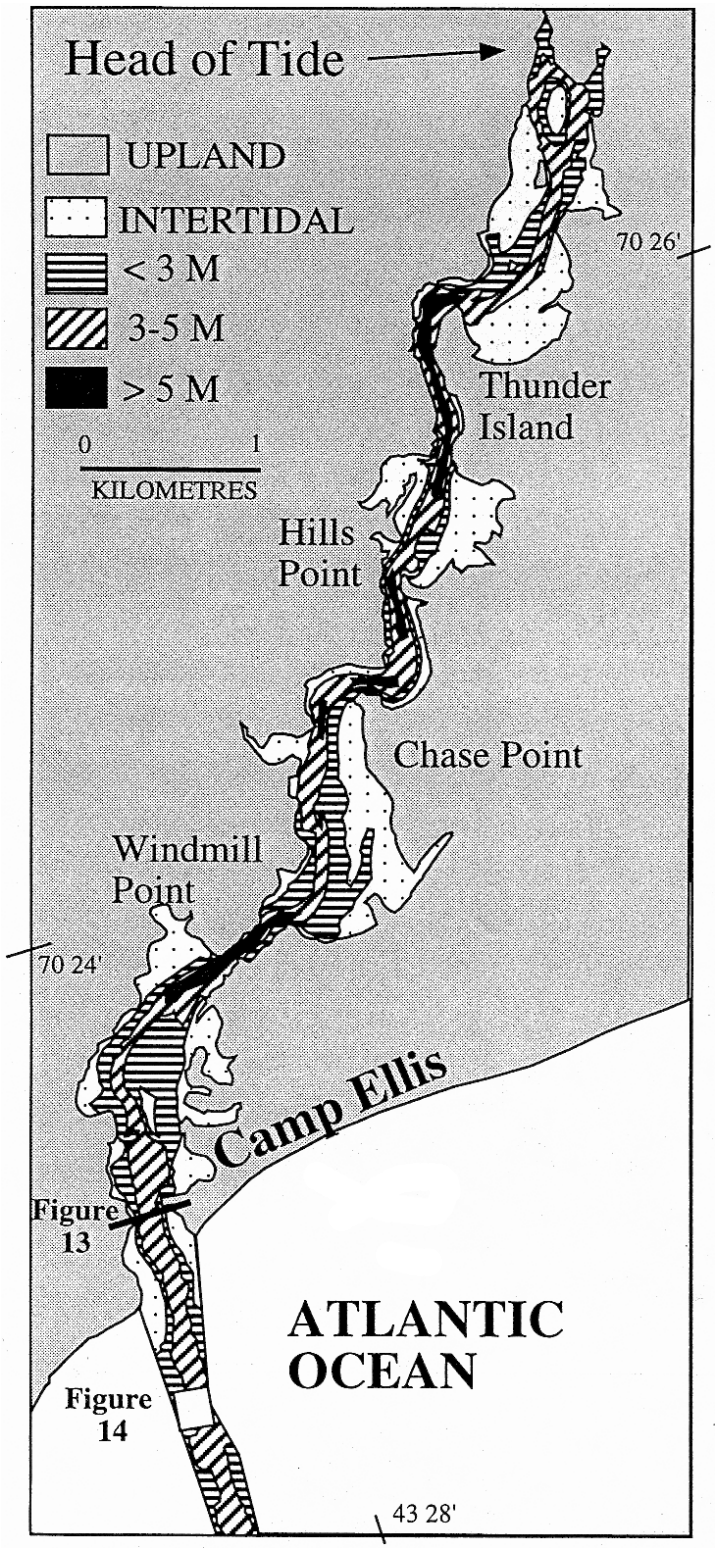

Figure 12: Bathymetry of the Saco River Estuary and location of Figures 13 and 14. Bathymetric data from NOAA chart 13287.

nated by ebb flow with stronger average and bottom currents (by 3 to 63 cm/sec; Figure 13). The lower portion of the estuary experiences dominant average ebb flows; however, bottom currents exhibit stronger flood velocities (4 to 16 cm/sec; Figure 14a). Bedforms are restricted to thalweg regions and reflect distinct areas of flood and ebb dominance.

During spring freshets, the freshwater discharge, which increases by more than an order of magnitude (Barber, 1995), supplants the saltwater tidal prism, resulting in total domination of the estuary by riverine processes (Manthorp and others, 1994; Figure 13). Flow is in an ebb direction at all stages of the tide and at all depths. This condition may persist for several weeks. During this period, medium to coarse-grained sands floor much of the estuary and ebb-oriented bedforms occupy more than 50% of the channel bed out to the seaward end of the jetties (Figure 14b).

No complete sand discharge records exist for the Saco River, but temporally limited data exist on the suspended sand content at a gauging station 35 km above the head of tide (Barber, 1995; Bartlett and others, 1975-93). Regression of the suspended sand volumes, from the limited times of observation to all stages of river discharge, yields an estimate of 6,100 m^3/yr of sand discharged by the river. This is a minimum estimate since the bedload discharge was not evaluated.

Dynamic Beach Regime

Geomorphological and GPR observations demonstrate that during the latest Holocene, sand traveled from south to north in Saco Bay (Figures 10, 11). The orientation of paleospits (Kelley and others, 1989a) and their continuity (van Heteren and others, 1994a, 1996) along the southern part of the beach are indicative of an important quantity of sand derived from the Saco River. GPR observations at Pine Point also depict the northeastward growth of that spit into the Scarborough River Inlet (Figure 10b; van Heteren and others, 1994a, 1996; van Heteren, 1996). Fining grain sizes from south to north along both the beach and nearshore are also suggestive of net northerly transport (Figure 6; Farrell, 1972).

Historical measurements of shoreline positions also document a continuing movement of sand from south to north. Charts depict a very large ebb-tidal delta at the mouth of the Saco River in 1866 (Figure 15a). This sand body was destroyed by construction of the north jetty, and sand moved ashore (Farrell, 1972). After 1896 the beach and nearshore area north of the jetty underwent erosion. Bathymetric changes between high water and the 5.5 m isobath from 1859 to 1955 indicate loss of 5.95 x 10^6 m^3 of sand in the southern part of the bay (USACOE, 1955). The Little River inlet closed between 1871 and 1877, probably in response to the northward movement of that sand (Farrell, 1972; Figure 15b). The simultaneous northward growth of Pine Point required at least 1.36 x 10^6 m^3 of sand moving from the south. Even more sand lies off of Pine Point in the active ebb- and

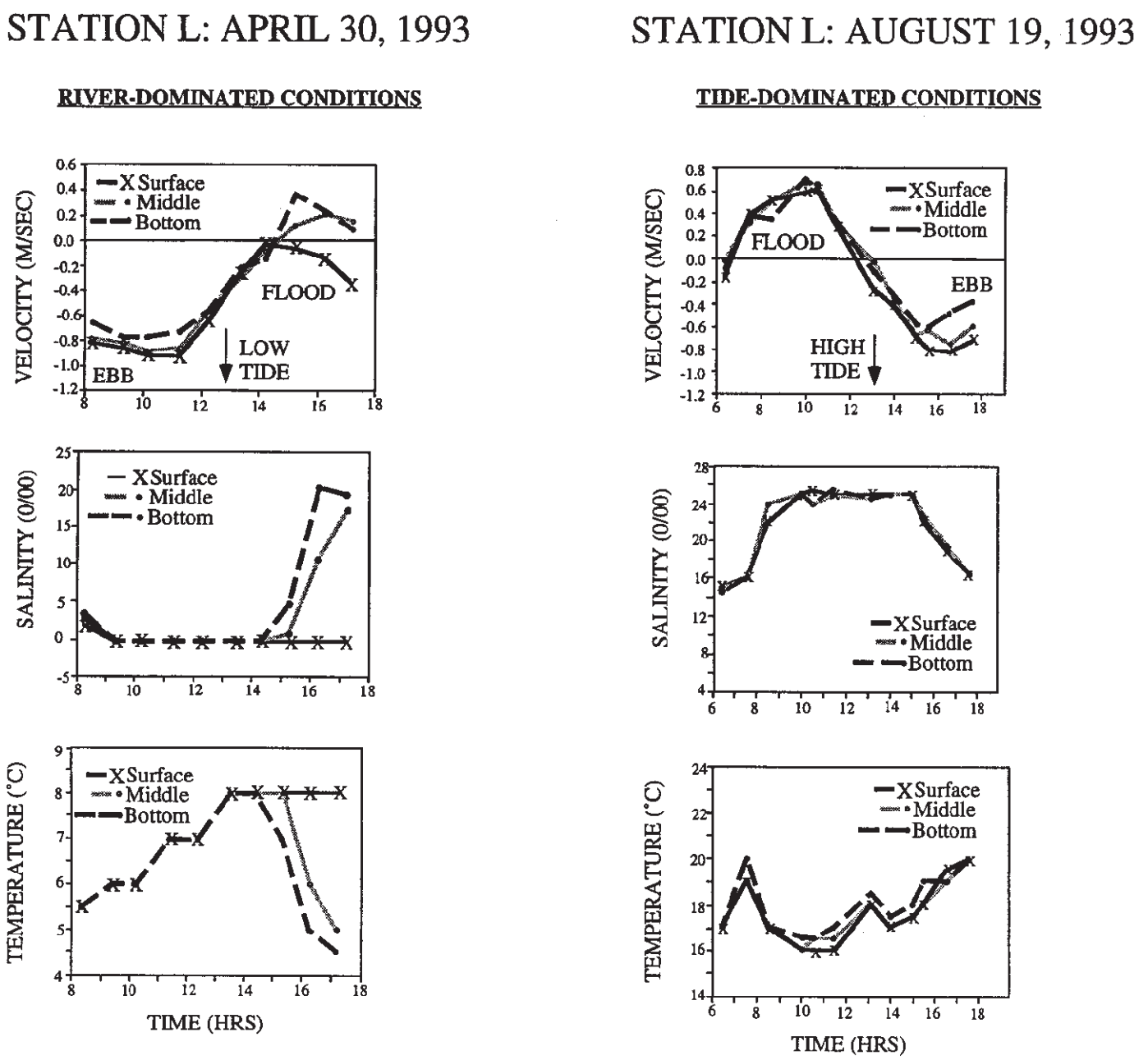

Figure 13: Hydrographic data from the Saco River Estuary during spring and summer (from FitzGerald and others, 1993, and Manthorp, 1995).

flood-tidal deltas of the Scarborough River inlet and the flood tidal delta of the abandoned Little River inlet (Figure 16).

Comparison of aerial photographs from the past 40 years document the continued erosion of the beach near the north jetty at Camp Ellis (Figure 17a) and the continued accretion of the beach at Pine Point (Figure 18a). At Pine Point, the spit has grown southeastward towards Prouts Neck in a seaward direction 40 - 80 meters. Comparison of 1976 and 1991 beach profiles suggests that this erosion and progradation is continuing (Figures 17b; 18). At Camp Ellis the beach erosion led to construction of seawalls by 1953 (USACOE, 1955) in an attempt to reduce the loss of property. As a result, the rate of landward retreat has abated somewhat from earlier values. Since then unarmored shorelines have retreated 10 - 30 m (Figure 17a).

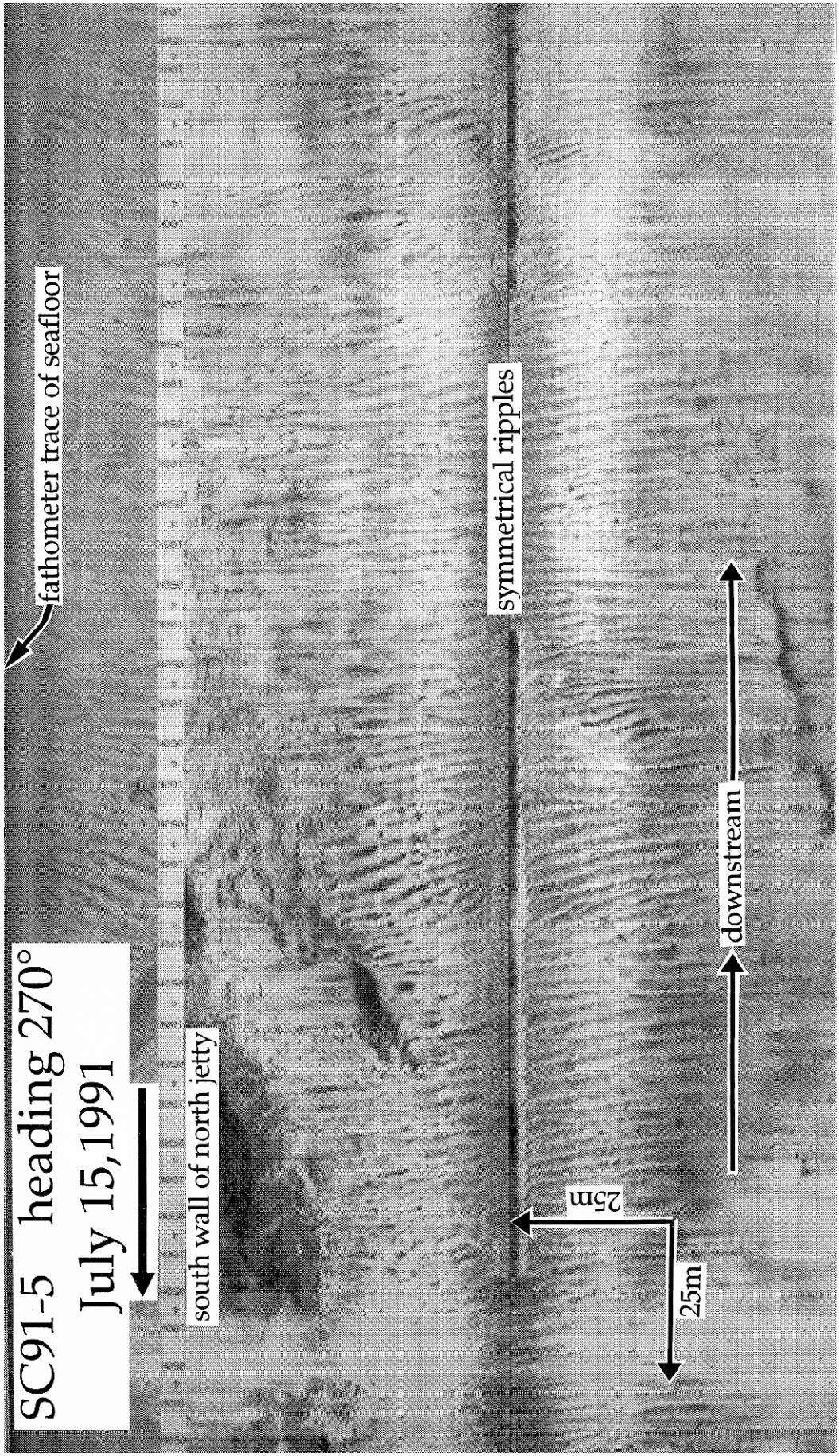

Figure 14(a): Side-scan sonar images of the Saco River Estuary: (a) Record from near the end of the jetties in July, 1991.

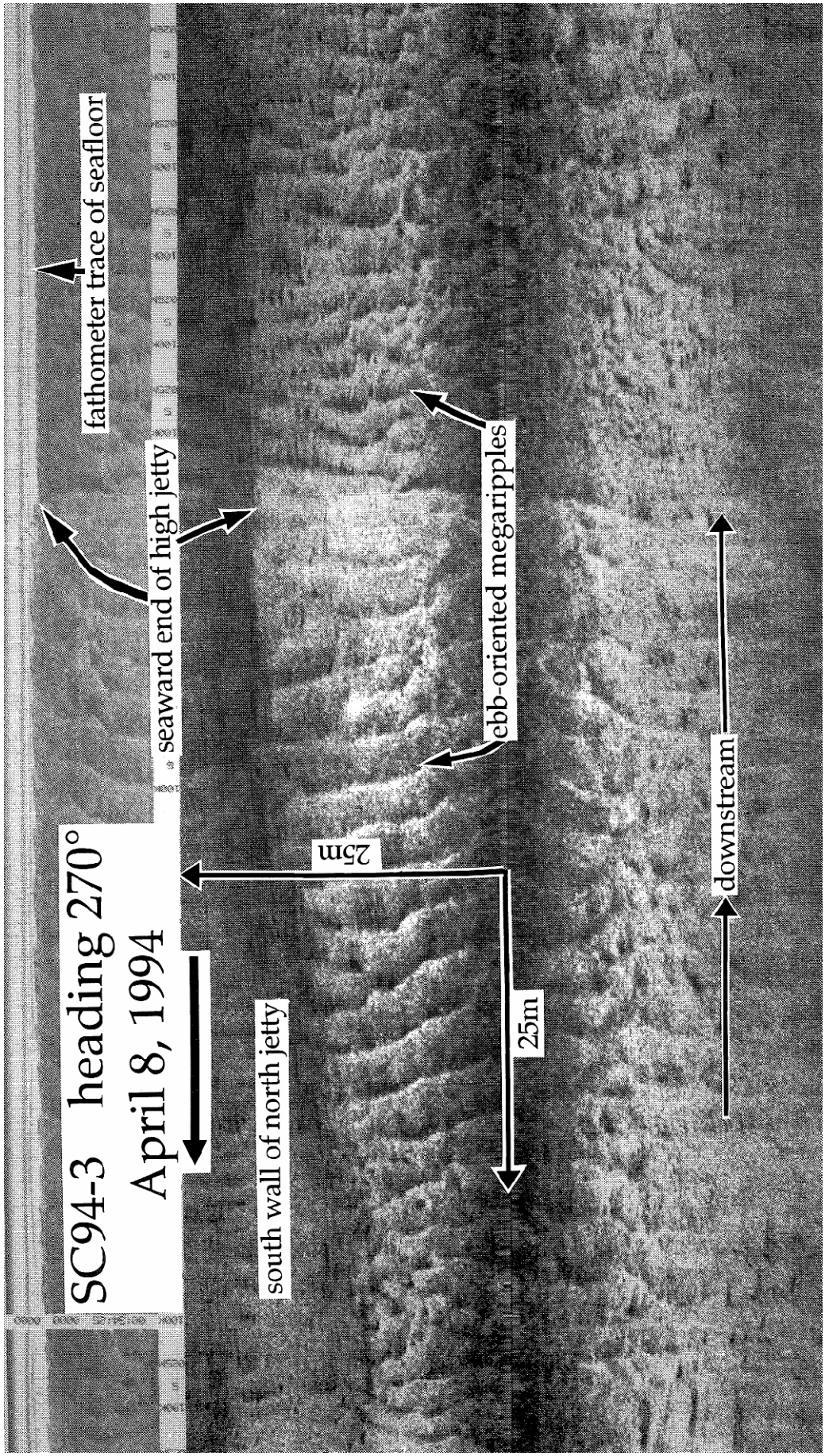

Figure 14(b): A record from the same place as Figure 14(a) showing ebb-oriented bedrorms on April 8, 1994.

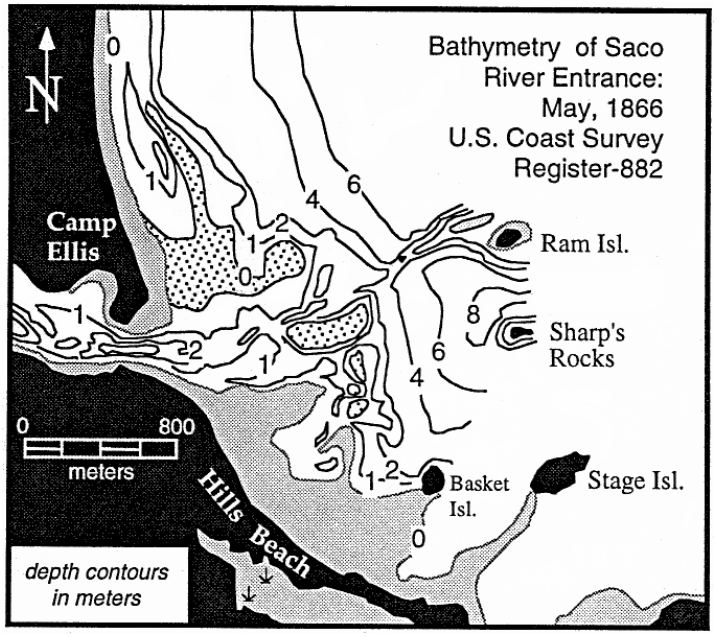

Figure 15(a). The shoreline and nearshore bathymetry of the Saco River mouth in 1866 (USACOE, 1955).

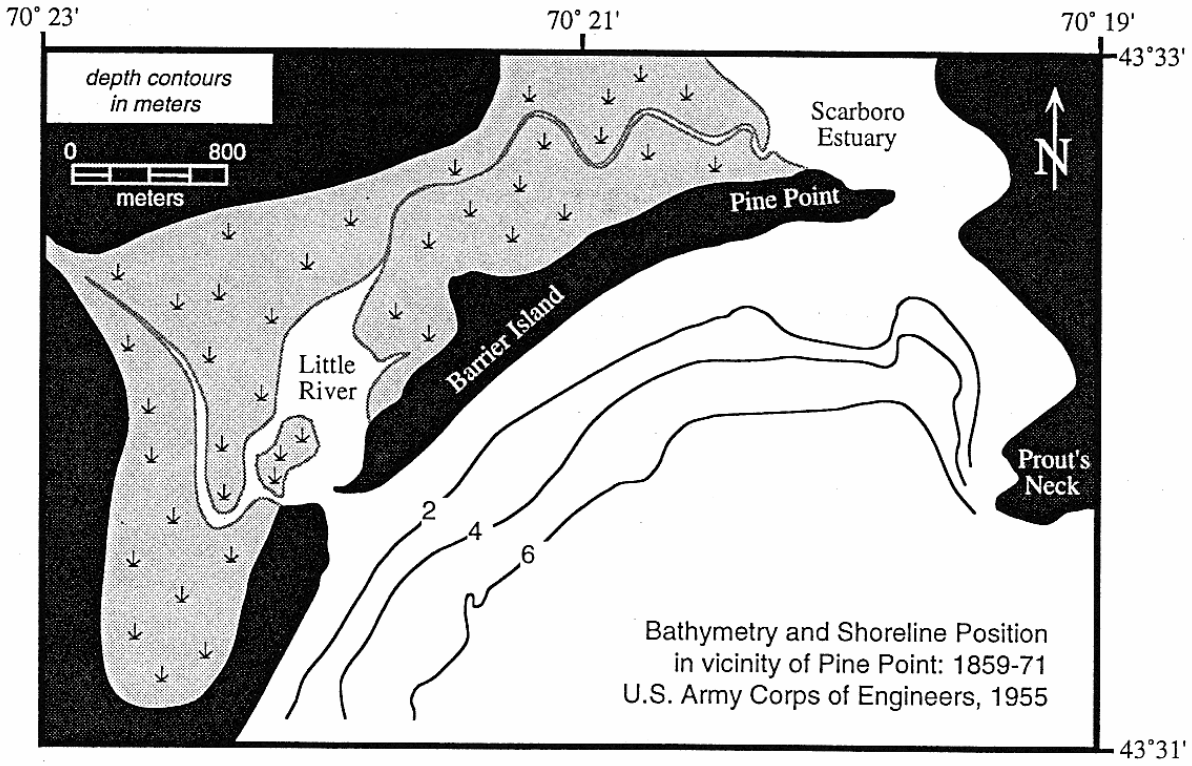

Figure 15(b): The shoreline and nearshore bathymetry near Pine Point between 1859 and 1871 (USACOE, 1955).

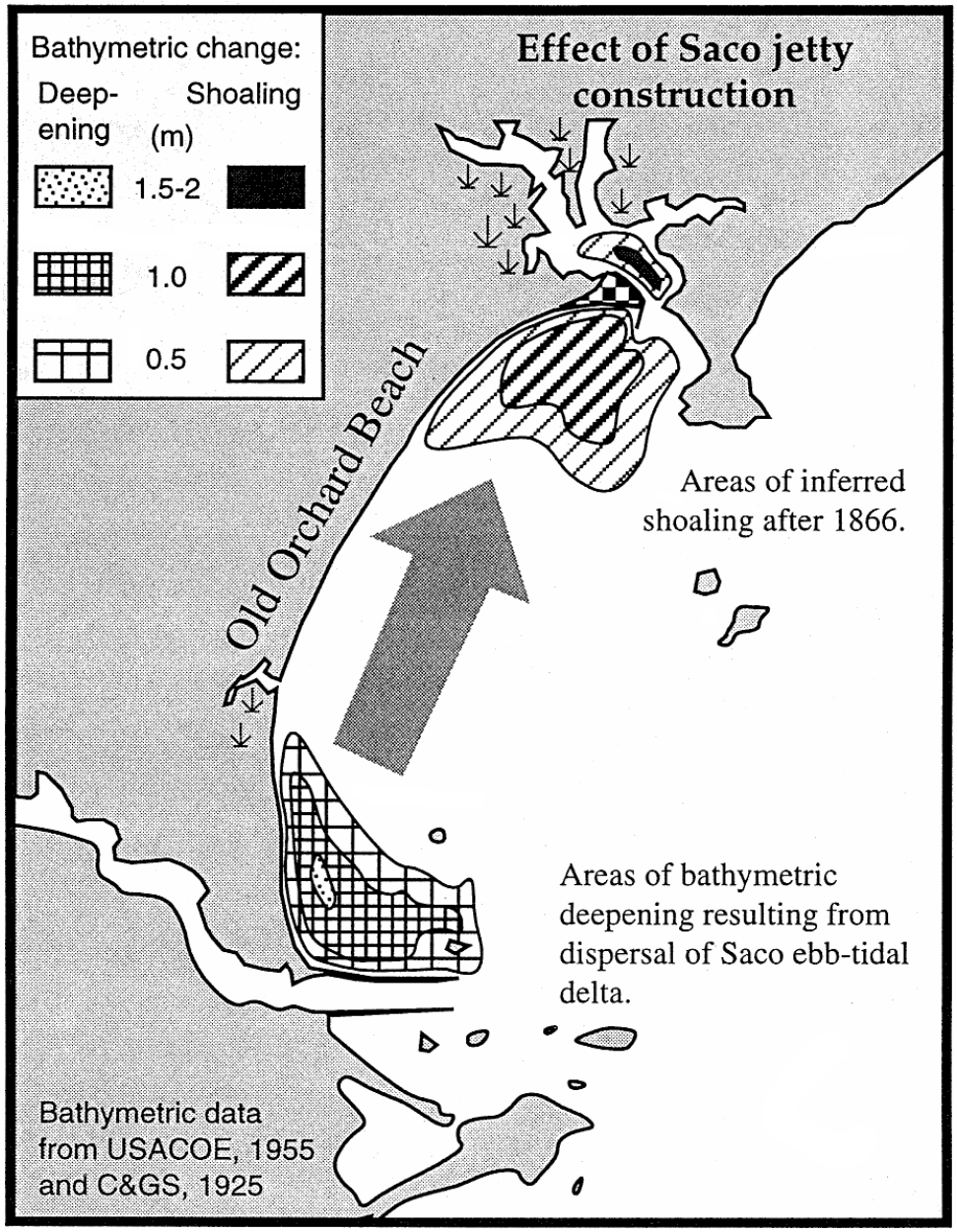

Figure 16: Inferred bathymetric changes resulting from the construction of the north jetty at the Saco River mouth. Bathymetry near the Saco River was evaluated by the U.S. Army Corps of Engineers (1955); bathymetric changes at the Scarborough River mouth are projected on the basis of existing bathymetry and the known volume of material added to Pine Point and lost from Camp Ellis. Checkered pattern shows area of new beach added to Pine Point.

Dynamic Offshore Regime

Current meters, deployed at 1 and 12 m above the bottom in 20 - 30 m water depth, measured mean currents (Pugh, 1987), tidal currents, wave orbital motion, and wind-driven circulation (Table 2; Figure 3a). Fair-weather tidal currents had speeds less than 15 cm/sec and were rotary, resulting in a tidal ellipse. The greatest speeds in the ellipse were into and out of Saco Bay (northwest-southeast) along the axis of the shelf valley, but never strong enough to transport sand and gravel (Dickson and others, 1993a, b).

High frequency (4 - 5 sec), reversing wave-orbital currents capable of entraining sand and gravel were observed on several occasions. Orbital currents up to 48 cm/sec were measured beneath 2 m storm waves with a period of 10 seconds during a

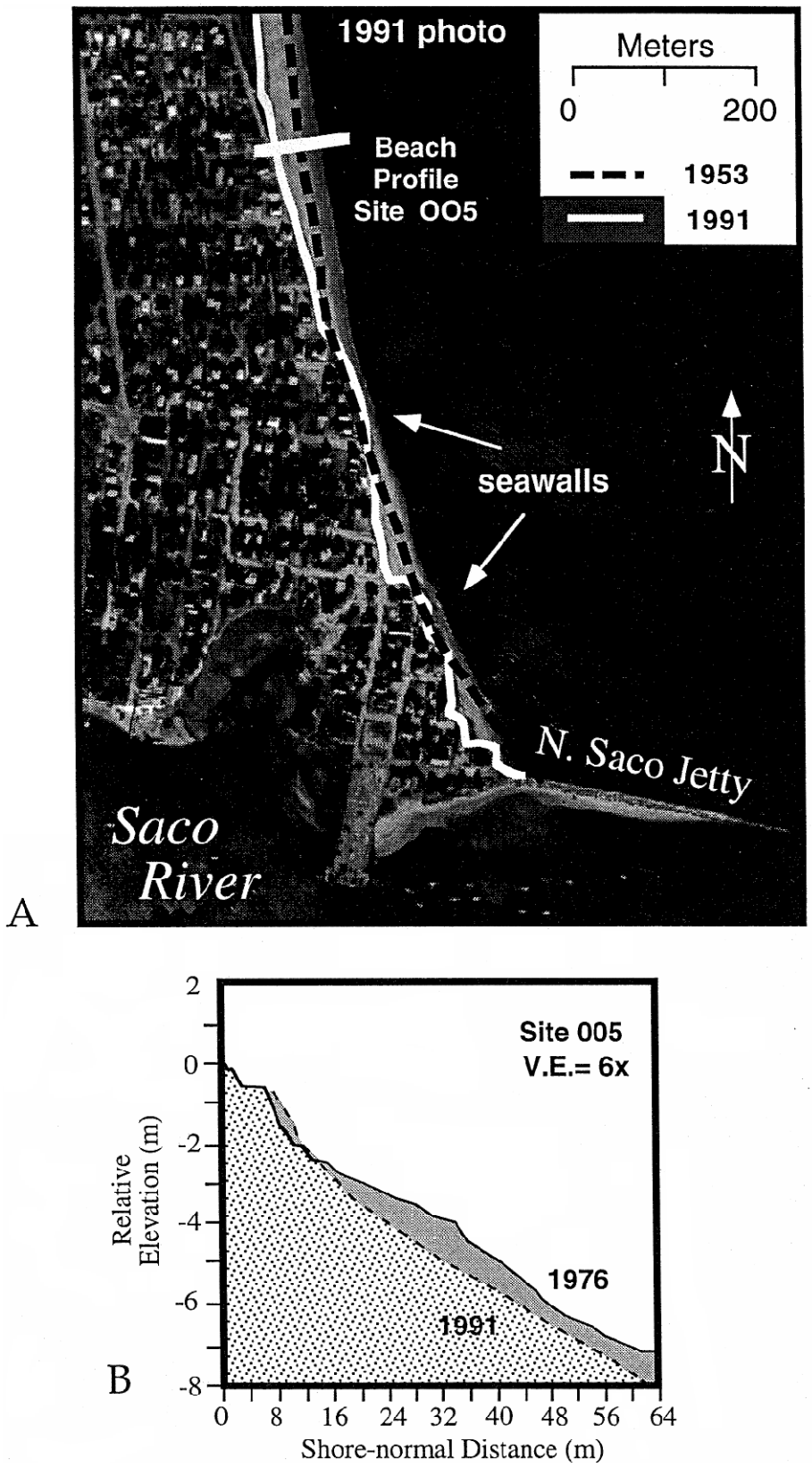

Figure 17: Shoreline change at Camp Ellis, 1953-1991. (b) Beach profile comparing elevations from 1976 to 1991. Profile location shown in (a) above (L. K. Fink, written communication, 1992).

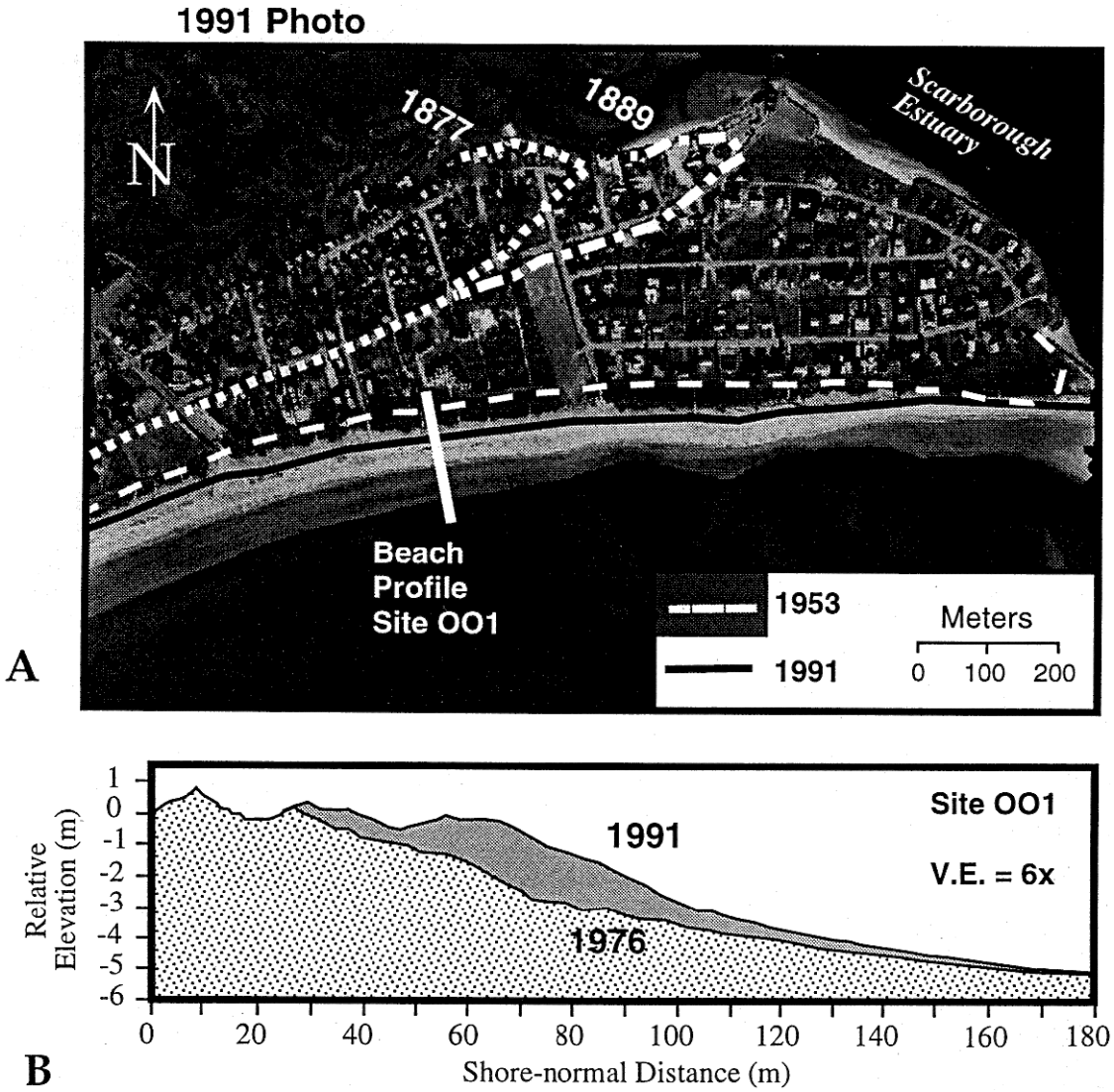

Figure 18: (a) Shoreline change at Pine Point, 1953-1991. (b) Beach profile comparing elevations from 1976 to 1991. Profile location shown in (a) above (L. K. Fink, written communication, 1992).

March 19, 1992 northeaster (Dickson and others, 1993a). Although these currents were fast enough to transport the shoreface sand, their reversing directions (northwest-southeast, or onshore-offshore) probably led to little net sand movement.

Wind-driven circulation was also observed to generate currents capable of moving sand. A northeast storm on August 4 - 5, 1991 created an offshore-directed bottom current of 20-35 cm/sec for up to 12 hours (Dickson and others, 1993a). This probably resulted from an onshore wind-driven surface current that induced a coastal set-up leading to the offshore-directed, downwelling storm current.

Similar conditions were initially produced on August 19-21, 1991 when Hurricane Bob tracked across Saco Bay (Figure 19). The approach of the storm, with onshore-directed winds, produced a downwelling, offshore-directed flow at 12 m above the bottom for 12 hours until the eye of the storm crossed the coastline. Then, a reversal of the wind direction led to 24 hours of onshore (northwest) bottom flow, overwhelming the ebb-tidal current of August 20. The offshore currents reached 30 cm/s, while the onshore currents ranged from 15 - 20 cm/s. The duration of upwelling was approximately twice as long as the downwelling, and persisted about half a day after the winds had slackened. Significantly, no beach erosion accompanied the hurricane, rather, Old Orchard Beach accreted sediment (Dickson and others, 1993b).

DISCUSSION

Origin and Direction of Movement of Saco Bay Sand

The Army inferred that an eroding glacial deposit in Saco Bay supplied local beaches with sand (USACOE, 1955). Once

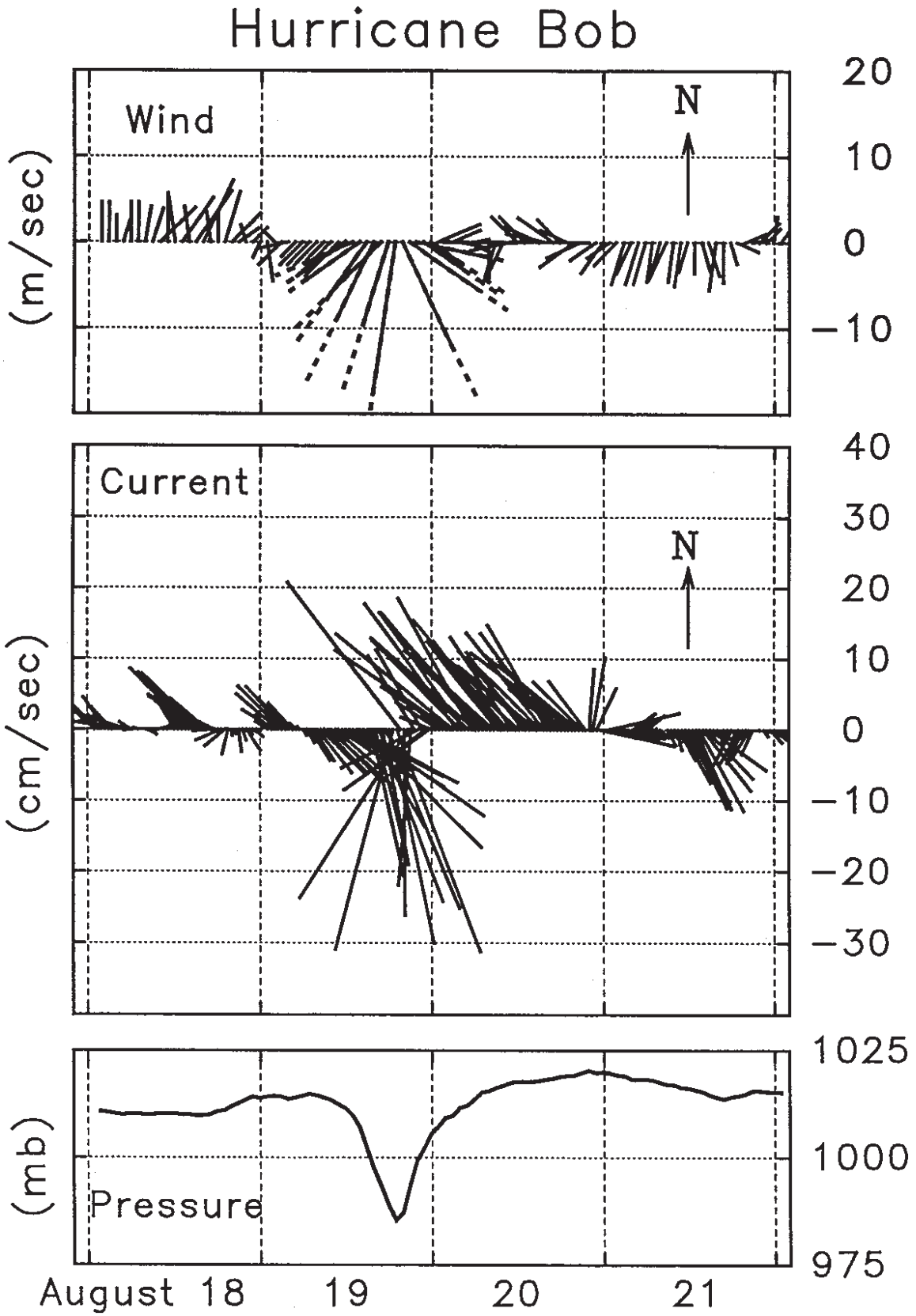

Figure 19: Wind velocity, current velocity, and atmospheric pressure preceding, during, and following Hurricane Bob (from Dickson, in prep.). Dashed wind vectors represent gusts.

eroded on the seafloor, they believed that the sand moved landward to a nodal point near Old Orchard Beach and then traveled north to Pine Point and south to Camp Ellis. The north jetty at the mouth of the Saco River was constructed to intercept the inferred north-to-south movement of sand in the littoral drift (USACOE, 1910, 1955).

Support for this hypothesis includes the orientation of a small modern spit on the northern side of Goosefare Brook, indicating southerly sand transport. In addition, hindcast meteorological and oceanographic data (Jensen, 1983) indicate that the northeast-east is the direction from which the largest storm wind and waves approach the outer bay during the winter. The Army assumed that the more common summer waves, which are derived from the southeast-southwest, are too small to be important relative to winter storm waves, and that they are blocked by Biddeford Pool and by the north jetty. The Army cites recent shoaling adjacent to the north jetty as evidence for north to south littoral sand transport, and the success of the north jetty in protecting the navigation channel from filling. Finally, unfilled depressions in the Saco estuary and dams on the Saco River have been cited as evidence for a lack of contemporary river contribution to the bay (Maine State Planning Office, 1979).

Our surficial sediment observations in Saco Bay contradict the early, unsupported assumptions of the Army that there is a significant source of glacial sand in the bay. Most of the sand in the bay is part of the shoreface profile of equilibrium (Figure 4) and so cannot provide new sand to the shoaling Saco River channel or to the beaches. Muddy or rocky material crops out over most of the remainder of the bay (Table 3; Figure 4). A lag deposit near Prouts Neck probably represents a reworked till or glacial-marine deposit that may once have been important as a source of sand and gravel. Side-scan sonar records provide evidence of wave and current reworking of some of this offshore seabed (Kelley and others, 1989a; Dickson and others, 1993a; Figure 5b), but the potential source area for sand is small (4 km^2) (Figure 4). An unreasonable and unobserved amount of erosion would be required to produce the volume of sand added just to Pine Point in this century. Furthermore, the offshore sediments are largely mud at depth (Kelley and others, 1992) and covered with only a veneer of coarse sediment. Sand at nearby Pine Point, by contrast, is fine-grained (Figure 6; Farrell, 1972; Barber, 1995).

Current meter observations clearly indicate that the Saco River is capable of transporting sand downstream of the dams from the head of tide at all times of the year, and that all sediment transport is ebb-oriented during times of high discharge (Figure 13). Bedform analysis by side-scan sonar depicts offshore-oriented megaripples at the jetty mouth and imply offshore sand transport during the spring freshet (Figure 14). Suspended sand transport upstream of the dams suggests that at least 6,100 m^3/yr of sand moves through the base-draining dams at the head of tide (Barber, 1995). This minimum estimate excludes bedload transport, but is only slightly less than the historical infilling rate at the Camp Ellis anchorage of 6,300 m^3/yr or of the modern infilling rate of 8,500 m^3/yr (Table 1). The infilling rates are also minimum estimates of the sand introduction to the bay from the Saco River because an unmeasured volume of sand leaves the river mouth and enters the bay during freshets. We assume that the intertidal deposits of the Saco estuary are in equilibrium or are accumulating sand at very slow rates.

Paleospit orientation suggests south-to-north littoral sand movement (Figure 11), which is also indicated by GPR records (Figure 10; Farrell, 1972; Kelley and others, 1989a; van Heteren and others, 1996). The small, south-oriented spit at Goosefare Brook is paired with a north-oriented spit on the other side of the inlet and is an artifact of local wave refraction. A strong argument for net northward sand movement is in the historical observations of Pine Point's growth and Camp Ellis' concurrent erosion. Almost 6 x 10^6 m^3 of sand left the river mouth area in the century following construction of the north jetty (USACOE, 1955). At the same time 1.3 x 10^6 m^3 of sand was added to the subaerial beach and dunes at Pine Point. If the region offshore of Pine Point, which today represents the largest single deposit of sand in Saco Bay, accreted only 0.5-1.0 m vertically during that same time, it would account for an additional 3.5 x 10^6 m^3 of sand. Additional sand exists in the relict flood-tidal deltas of the Little River (Figure 15) and Scarborough River (Farrell, 1972). Thus, to account for the sand lost near Camp Ellis, it is necessary for a significant net northerly littoral transport to exist. The continuing build-out of Pine Point and erosion of Camp Ellis suggests this is an ongoing process (Figures 17, 18). During the last dredging of the Camp Ellis anchorage (1992), the 65,000 m^3 of sand introduced to the beach quickly disappeared, and woody, shelly estuarine sand blocked Goosefare Brook and was observed all along the remainder of the beach system (Figure 20) for months after spoils disposal (L. Mitchell, Saco City Administrator, personal communication, 1992).

Offshore sands of Saco Bay are affected by combined flows generated by storms. Exactly how much volume is transported from the beach offshore or from the offshore to the beach is difficult to quantify. However, directions of movement can be inferred from current meter data. Currents created from waves, tides and wind shear all combine to produce speeds sufficient to transport sand. Time-averaged flows are determined primarily by tidal stage and wind direction. Under rough seas these average flows can indicate the direction of sediment transport. For example, northeasterly winds and an ebbing tide were found to generate offshore-directed bottom currents. These currents should transport sand away from the toe of the beach to the lower shoreface. Sand loss is particularly likely to occur from the beach to the shelf valley at the southern part of the bay and onto muddier offshore sediment. Sand entering the valley may be topographically contained there, or incorporated into more cohesive muddy sediments, and thus not easily reworked back onshore. In the shallow shoreface, on the other hand, conditions are commonly conducive to onshore transport of sand. It was

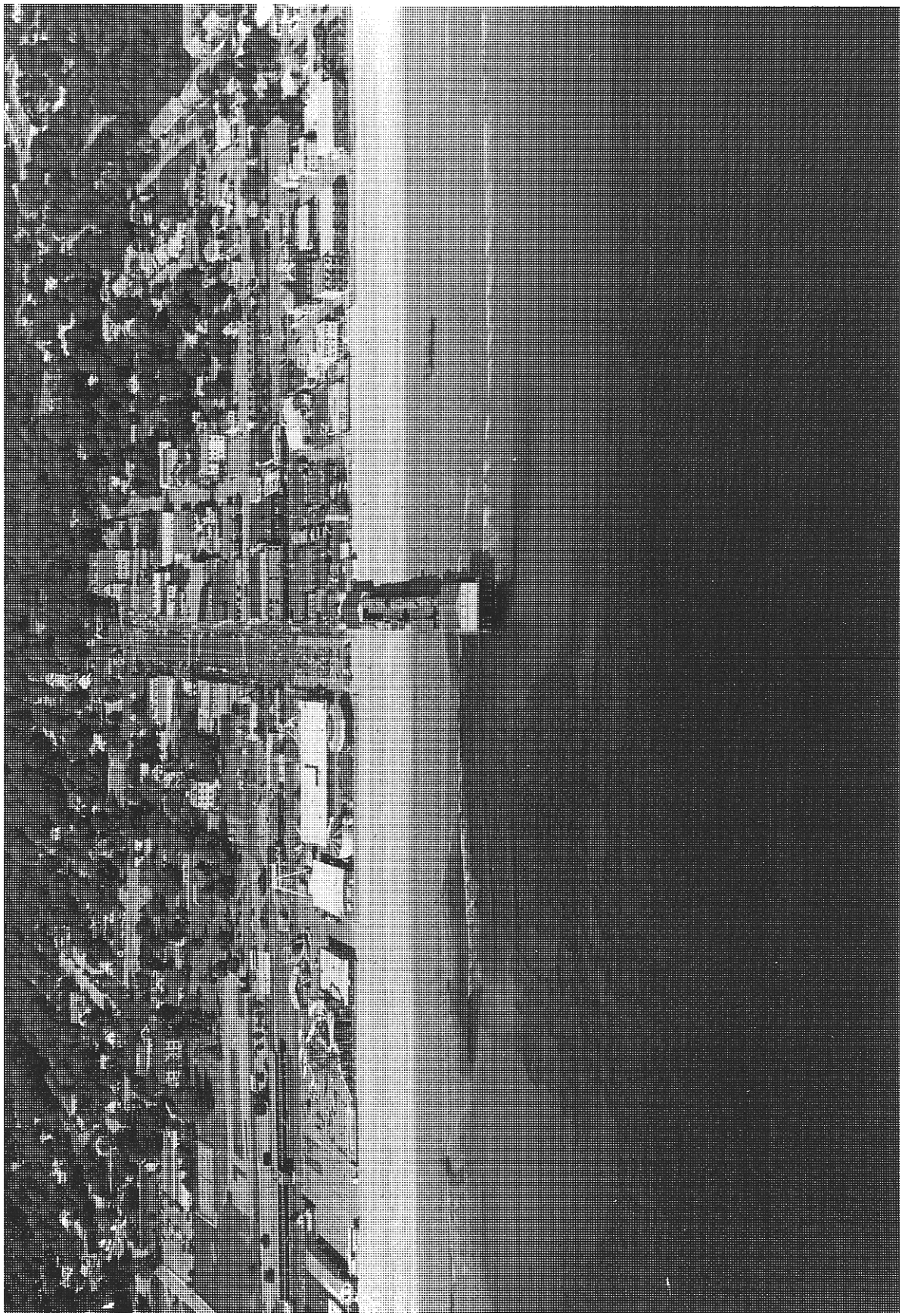

Figure 20: Aerial photograph of central Old Orchard Beach. Dark material (arrow) is composed of wood and shell fragments from Saco River dredge spoils put onto Camp Ellis beach and moved north by currents (September, 1993).

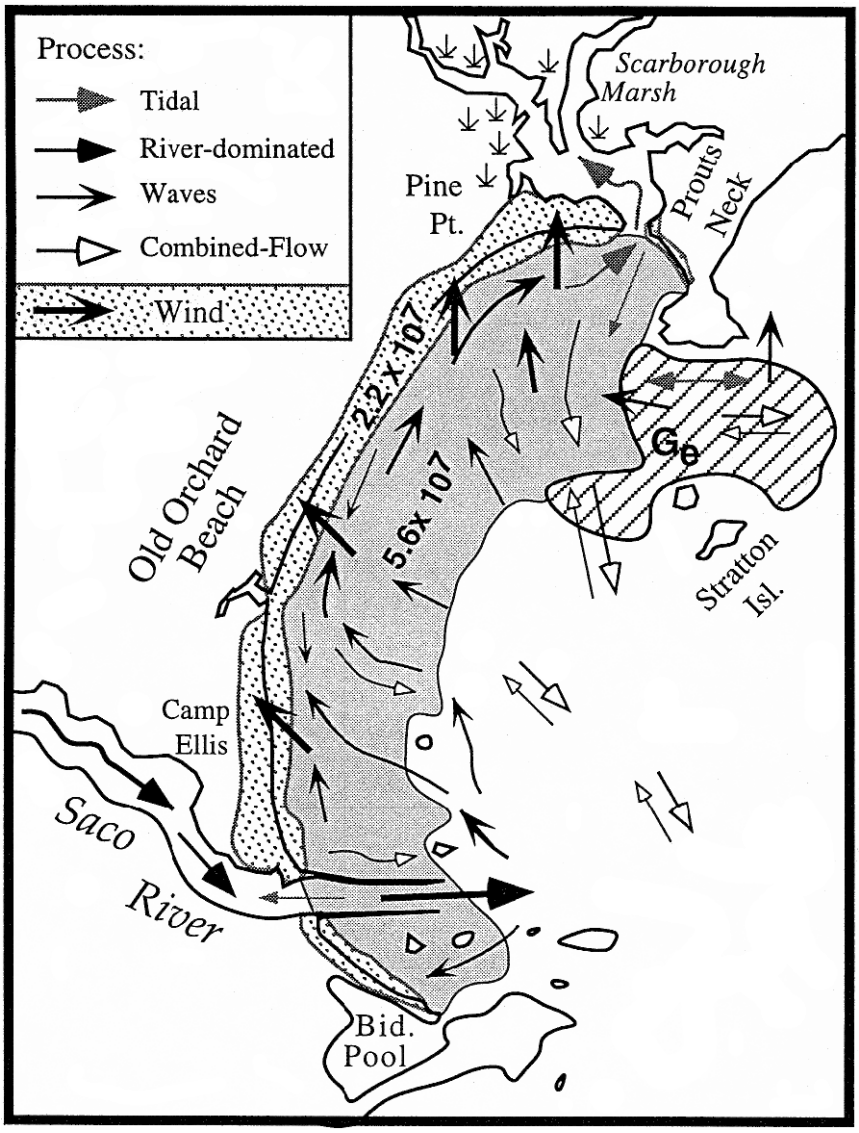

Figure 21: Sand pathways in Saco Bay.

seen that not all storm conditions lead to offshore transport. In the case of Hurricane Bob, current meter data suggest that strong northwesterly winds and a flooding tide combined to cause currents that transported sand onto Old Orchard Beach. Seismic profiles and cores demonstrate that there is a seaward thinning wedge of shallow shoreface sands, and virtually no sand below about 16 m water depth. At present we cannot rule out offshore transport into the shelf valley, but there appears to be a relatively efficient recycling of sediment onshore to the littoral system. In short, the offshore currents are variable and influenced by meterological and oceanographic conditions. The currents may in turn rework beach sands offshore at some times and offshore sands onto the beach at other times. The cumulative effect of this variability is best observed in the geologic and historic record of evolution of the coast.

A Sand Budget for Saco Bay: 7,000 yr B.P. to 130 yr B.P.

The largest deposit of sand in the bay, 5.6 x 10^7 m^3, resides in the shoreface and ebb-tidal deltas (Figure 9). The second largest body of sand, 2.2 x 10^7 m^3, is in the berm and dunes, including old washover deposits (Figure 9). Although we have not measured the volume of sand in the estuaries, we assume that such a volume is small relative to beach and offshore volumes because: (1) the Saco estuary possesses very little accommodation space for sand, and (2) the Scarborough estuary is generally muddy (Farrell, 1972).

The rate of introduction of sand to the system from the Saco River today is probably greater than either the value estimated on the basis of the upstream sand discharge of the river (6,100 m^3/yr) or the value based on the infilling rate of the anchorage

(6,000-8,500 m^3/yr; Table 1) because: (1) the discharge value involves only suspended sand; and (2) the infilling value neglects sand passing through the jetties into the bay. This latter observation is further supported by the infilling rate of nearby Biddeford Pool (3,600 - 4,800 m^3/yr; Table 1), which probably derives its sediment from the Saco River as well. On the basis of this consideration, and considering the infilling rate of the Scarborough River anchorage (17,000 m^3/yr; Table 1) we have selected 10,000 m^3/yr to 16,000 m^3/yr as a range within which the current value probably falls (Figure 22a). The prehistoric sand discharge rate of the Saco River, assuming a constant climate, was probably closer to the larger end of this range because some sand may be trapped behind dams.

The only possible offshore source of sand is located south of Prouts Neck and is today covered with rippled coarse sand and gravel (Figure 4). That region, underlain by both till and glacial-marine sediment (Kelley and others, 1989a) and covered by ripples (Figures 4, 5b) occupies about 4 km^2. All cores here contain coarse-grained sediment at the top, with finer material at depth (Kelley and others, 1990; Luepke and Grosz, 1986). The average sand content of the only core analyzed is 58%, which is a relatively high value for glacigenic sediment in Maine (approximately 33 %, W. Thompson, personal communication, 1995; Kelley, 1989). If this area were originally 5 m above present sea level (somewhat higher than nearby Bluff and Stratton Islands) and eroded to its present average depth of 20 m, it could account for almost 3.3 to 6.0 x 10^7 m^3 of sand (assuming a sand content of 33% and 58%, respectively). A contribution of this magnitude is unlikely, however, because the sand in this area is coarse grained (modal size of 2.8 phi; Kelley and others, 1990), and all the nearshore sand is finer grained (3.2 phi; Figure 6). As this deposit eroded it would have quickly been capped by a lag deposit preserving deeper parts of the unit as observed elsewhere (Forbes and others, 1991; Stea and others, 1994). Since there is no evidence of a more extensive lag deposit, it is reasonable to conclude that 10 m or less of erosion occurred in this area. Erosion of a deposit of the present area and texture (33 - 58%) to 10 m depth would yield 1.3 x 10^6 m^3 to 2.3 x 10^6 m^3 of sand. Owing to the proximity of Scarborough Beach to the northeast of the area of rippled coarse sand and gravel, and the southern direction from which the prevailing summer winds originate, at least 50% of this sand probably went to the Scarborough Beach system. This leaves only 0.65 - 1.15 x 10^6 m^3 of sand to contribute to the Old Orchard Beach system. The importance of this source of sand has probably decreased with time as the lag deposit on the surface thickened and its depth and distance offshore increased.

At the rate of sand introduction estimated for the Saco River, 10,000 m^3/yr to 16,000 m^3/yr, the 7.8 x 10^7 m^3 of sand in the entire beach system would be delivered in between 7,800 and 4,900 years (Figure 22a). Offshore sand, which might have been locally important earlier in the bay's history, would not affect these values by more than a few hundred years because of the small quantity of material available from that source. Further evidence supporting the scenario that the Saco River formed the bay's beaches between 4,900 and 7,800 yr B.P. and the present includes (1) radiocarbon dates on back-barrier fauna collected in offshore cores range from about 6 - 7 ka (Figure 8); (2) recent reconstructions that demonstrate that the Wells barrier beaches (25 km to the south) formed within that interval (Kelley and others, 1995), and (3) a slowdown in the regional rate of relative sea-level rise that occurred at that time (Barnhardt and others, 1995).

An important component of the progradation of the overall beach system has been the growth of sand dunes. Cores and auger holes indicate that the eolian material ranges from 2 m to 4 m in thickness. Neglecting the recently added material at Pine Point (Figure 18), the volume of dune sand ranges from 4.0 to 8.0 x 10^6 m^3. If this deposit formed within 7,800 to 4,875 years, the rate of eolian deposition ranged from 500 m^3/yr (2 m thick dunes forming in 7,800 years) to 1,600 m^3/yr (4 m thick dunes forming in 4,900 years). Our best estimate lies in the middle of this range, around 1,000 m^3/yr (Figure 22a). It is likely that dunes formed quickly, and have been efficiently recycled throughout the late Holocene.

A Sand Budget for Saco Bay: 1859 to 1955

During the time interval 1859-1955, human activities caused important changes in the location of sand storage within Saco Bay. The rate of sand introduction from the Saco River averaged from 10,000 to 16,000 m^3/yr, but the construction of the north jetty at the mouth of the river caused 61,200 m^3/yr of sand to move away from the Camp Ellis area (USACOE, 1955) towards Pine Point (Figure 22b). This rate of human-induced, net sand movement exceeded the long-term, natural rate of transport by at least a factor of four. We assume that this sand traveled with wave-generated longshore currents until reaching Pine Point. Alternatively, a longer-term process of onshore-offshore seasonal cycles of sand movement coupled with slow northward drift could have caused this transfer of sediment.

By 1957, Pine Point had expanded 550 m from its long-term position (Farrell, 1972) and gained 1.4 x 10^6 m^3 of sand. Of this, between 1.0 and 2.0 x 10^5 m^3 were added to sand dunes from 1859-1991, assuming 2 or 4 m aggradation, respectively. This yields rates of dune growth between 840 and 1,690 m^3/yr, somewhat greater than the long-term average of the beach. Probably this is because of the finer sand size in the area and much wider spit, upon which the dunes at Pine Point developed, compared with the remainder of the beach system.

Elsewhere in the bay during this time interval, houses and commercial establishments were built on most of the sand dunes of the beach system. Seawalls were later constructed along the outer edge of most of the frontal sand dunes of the beaches, inhibiting or eliminating the exchange of sand between the beach and dunes.

We estimate that 3.5 x 10^6 m^3 of sand accumulated offshore of Pine Point, shoaling that area by 0.5 to 1.0 m, and that the re-

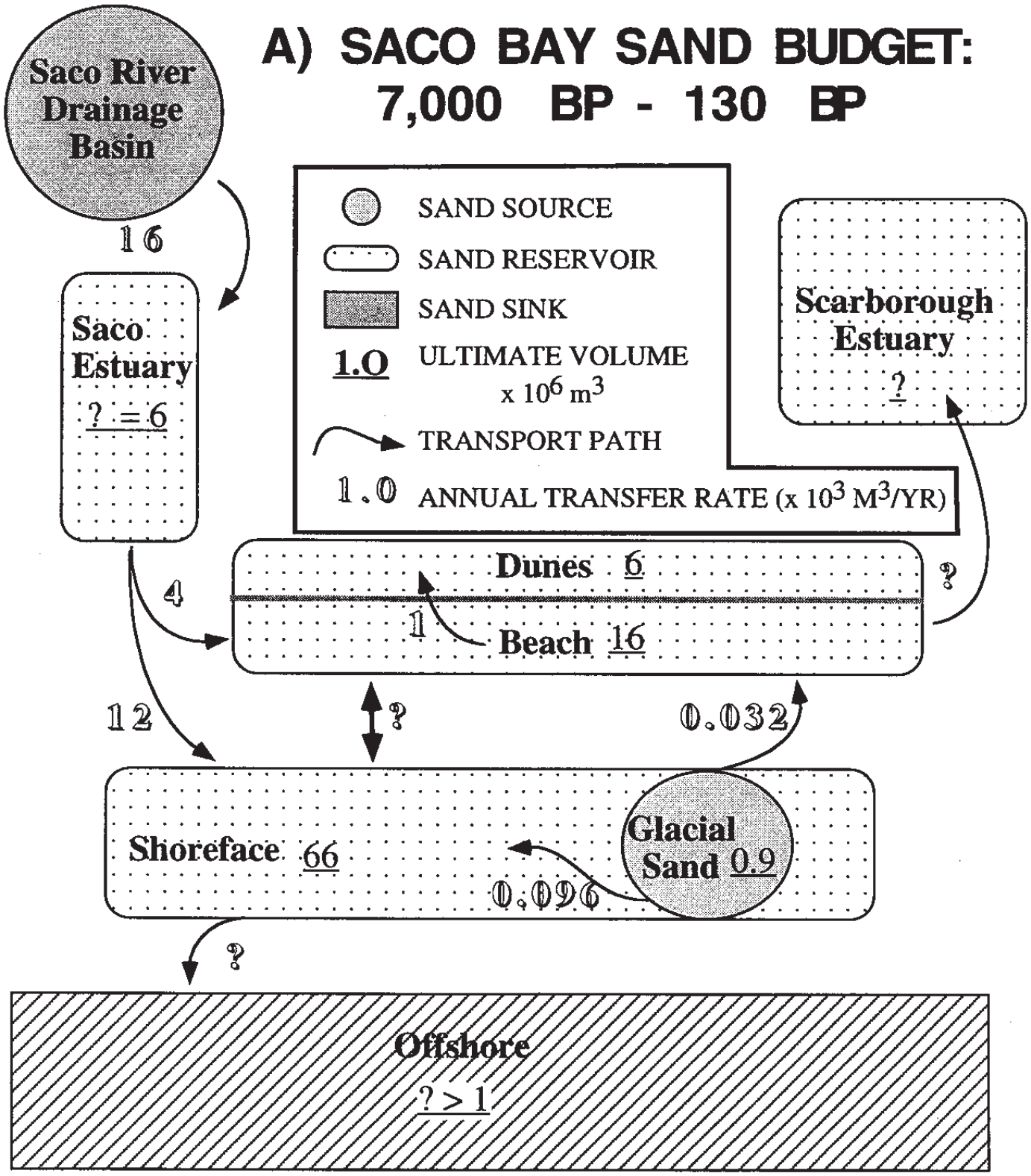

Figure 22(a): Sand budget for Saco Bay from 7,000 yr B.P. to 130 yr B.P.

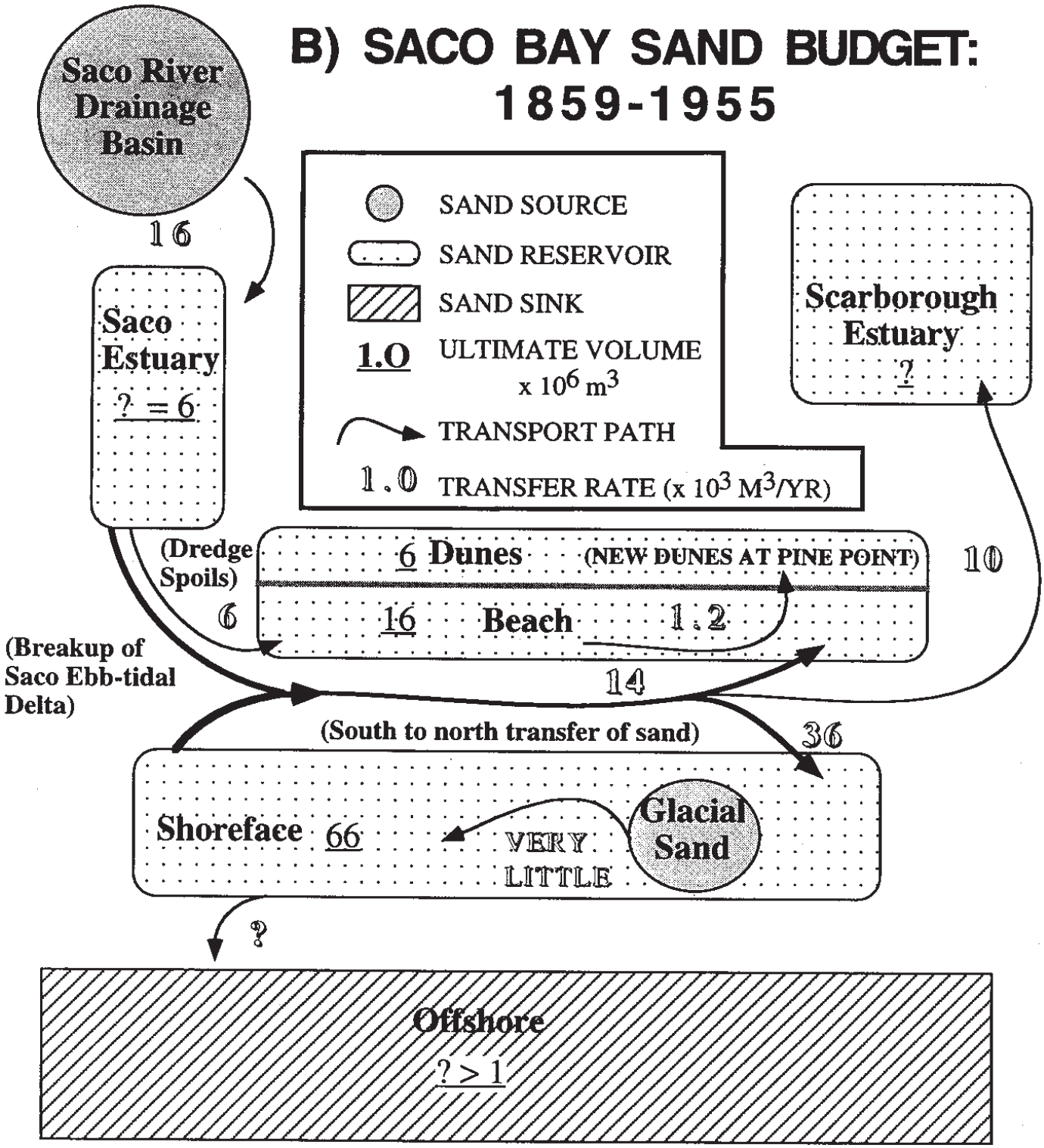

Figure 22(c): Sand budget for Saco Bay from 1859-1955.

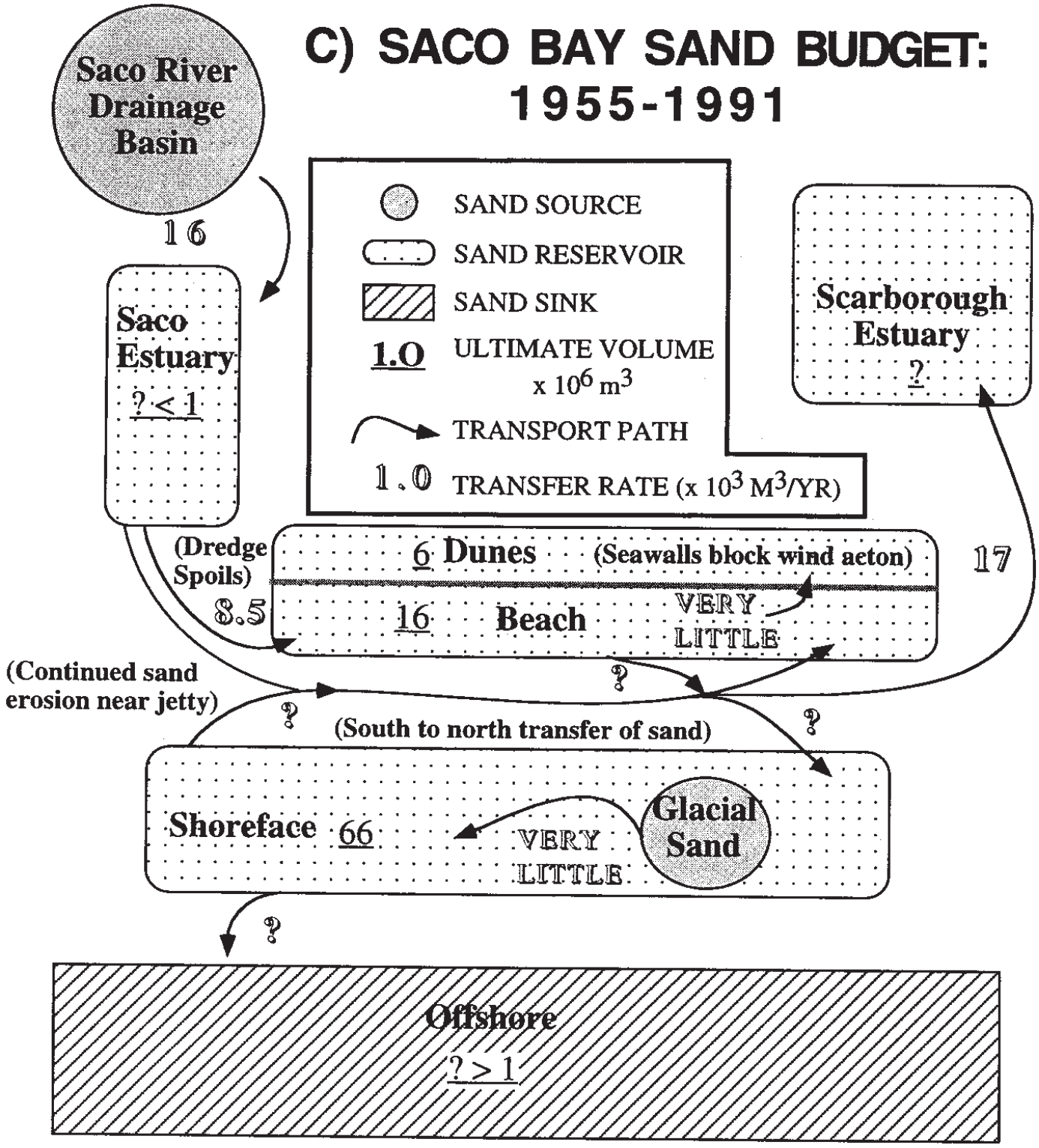

Figure 22(c): Sand budget for Saco Bay from 1955-1991.

maining 0.8 x 10^6 m^3 was dispersed along the shoreface, lost seaward, or remains buried in tidal delta deposits (Figure 22b). This results in an annual input from the beach to the shoreface of 3.6 x 10^5 m^3 between 1859-1955.

A Sand Budget for Saco Bay: 1955 to 1991

During the most recent time interval under consideration, 1955-1991, engineering structures continued to alter sand depositional patterns in the bay. Despite the construction of a jetty at the end of Pine Point to prevent further shoaling of the Scarborough River Inlet, an average of 2.23 x 10^4 m^3/yr of sand has been dredged from that channel (Table 1). After the initial dredging, we estimate 1.7 x 10^4 m^3/yr of sand reaches the inlet. Army records are unclear about the ultimate disposal site of all this sand, but indicate that most of it went to an offshore, "open water" site (Figure 22c; Table 1).

Almost all of the 8,500 m^3/yr of sand dredged from the Saco River has been directly deposited on the adjacent beach at Camp Ellis (Figure 22c). This sand has rapidly moved to the north and blocked the Goosefare Brook inlet following disposal events. The most recent closure of the inlet in 1993 required the use of heavy construction equipment to re-establish the channel (L. Mitchell, Saco City Administrator, personal communication). This channel is required to accommodate effluent from the Old Orchard sewage treatment facility on Goosefare Brook.

The beach at Pine Point has continued to build out, even as the beach at Camp Ellis has continued to recede (Figures 17, 18). The infilling rate in the Scarborough River channel, 1.7 x 10^4 m^3/yr, is more than twice the average rate of dredged sand disposal on the beach at Camp Ellis. This implies that the difference, approximately 8,500 m^3/yr, comes from: (1) sand that is delivered by the Saco River and bypasses the anchorage, (2) spoils from the Scarborough River which re-enter the inlet, or (3) continued sand reworking from the southern beach and shoreface. Regardless of the ultimate source, Pine Point appears to receive a minimum of 8,500 m^3/yr of sand from both the shoreface and from the longshore drift.

The Present Status of Saco Bay, and Recommendations for Beach Management

Saco Bay is presently facing political and economic issues concerning its beaches and harbors that are strongly influenced by geologic processes of sand movement, but also by engineering and land-use practices. The erosion of Camp Ellis continues as onshore, refracted and jetty-reflected waves strip away sediment and attack wooden bulkheads and sand embankments. This erosion will continue, since the jetties have starved the former ebb-tidal-delta system of sand. It is likely that the zone of shoreline retreat will extend farther north as a new geological equilibrium is attempted, extending the Camp Ellis scenario of houses falling into the sea, block by block, along the beach. Pine Point, on the other hand, will continue to accrete sand, although at a decreased rate as the supply from the south declines. Inside the Scarborough River, partial cutoff of sand from the beach by the short jetty will contribute to local erosion. The central part of the Saco Bay system (Ocean Park, Old Orchard Beach, and Surfside) appears relatively stable and bypasses sand, yet as relative sea level continues to rise, shoreline retreat is likely in this part of the system as well.

Inlets, such as Goosefare Brook, and the former Little River inlet, are and were links to the back-barrier marsh systems, that open, close, and migrate over historical and geologic time periods. During severe storms, new inlets could form from a process of land-to-sea breaching, as documented in Cape Cod (Oldale, 1992) and elsewhere. Former inlet locations are particularly vulnerable to this breaching because of their morphology, hydrology, and underlying geologic and stratigraphic control.

Several factors could disturb the present sediment budget. First, construction of seawalls, businesses, houses, highrises, and other invasive coastal structures have already resulted in a loss of natural sand exchange pathways between the beach and dunes. Dune sand is a major reservoir that the beach system must occasionally draw on to survive great storms and rising relative sea level. Walling up all of the Saco Bay dune sand would remove between 5% and 10% of the total sand budget of the system (assuming 2 or 4 m dune thickness, respectively). Such a loss would leave the beach system with no flexibility in the future and transform it over time into a coast lacking beaches like the New Jersey shore. New Jersey will spend more than 1 billion dollars replenishing its beaches in the next decade (Pilkey, personal communication). Ultimately, such unchecked development in Maine would result in the loss of the primary aesthetic and economic draw to the area, the uninterrupted stretch of clean sandy beaches.

Second, an increased rate of relative sea-level rise could cause increased shoreline retreat, eroding present properties and structures. This recession is a natural process of re-establishing profiles of equilibrium. When interfered with by engineering structures, or where dunes have been removed or built upon, sea-level rise can become an accelerating process of instability.

Our recommendations for management are straightforward. Sediments dredged from either the Saco or Scarborough River should be returned to the south end of the system, at Camp Ellis. This is initially more expensive than offshore disposal, but wise relocation of sandy dredged material decreases the need for later nourishment and provides some protection to the beaches. Even with beach nourishment, erosion is likely to occur. In the long run, public acquisition of endangered properties in Camp Ellis for a park is an optimal solution. Properties near present and historical inlets should be recognized as especially vulnerable to shoreline changes, and development of any type, but especially highrise structures, should be precluded.

CONCLUSIONS

Sediment budgets are difficult to fully quantify, but provide a guide to sources, pathways, and sinks of material. We have examined these transport pathways on several time scales: geologic (past 7,000 yrs), historic (past 100 years), and modern (past 40 years). It is clear that an examination of the geologic and geomorphic data, coupled with measurement of representative processes of sediment transfer, give a more complete and accurate description of the forces modifying the beaches and inlets of Saco Bay than existing models. Physical and numerical models are useful tools, but are often incomplete, and commonly ignore geologic information on past changes in a system. We feel that a mistake was made in the early years of USACOE manipulation of the Saco River mouth. Sand is dominantly moving south to north in the system, and is supplied by the Saco River, not the reverse. Thus, the jetties are interfering with the overall supply of sediment to the beaches, rather than protecting the river mouth from a fictitious infill derived from north to south sand movement. Our primary conclusions from this project are listed below.

The Saco River is the primary source of sand to the Saco Bay beach system, and has been so through the late Holocene. This fact is documented by hydrographic observations in the river, side-scan sonar mapping of flow-oriented river bedforms, and textural data from the river sediments. An offshore glacial sediment deposit may have been a locally important source of coarse-grained sediment before the middle Holocene, but offshore side-scan sonar and seismic-reflection records and bottom sediment texture reveal that it is no longer important. Our best estimate is that the Saco River contributes between 10,000 to 16,000 m^3/yr of sand to the bay, mostly during the spring freshet. All sand accumulating in the Saco River navigation channel and federal anchorages comes from the Saco River.

The net direction of sand movement in the bay has been and remains from south to north. This is documented by the orientation of paleospits visible in aerial photographs and in ground-penetrating radar records. It is further supported by changes inferred from historical bathymetric and topographic maps which depict the transfer of almost 6×10^6 m^3 of sand from the Camp Ellis area to Pine Point between the middle 19th and 20th centuries. Contemporary movement of sand from south to north is indicated by the rapid disappearance of dredged sand placed on Camp Ellis, and the coincidental closure of Goosefare Brook inlet and the appearance of the same dredged material all along the beach. The continued erosion of Camp Ellis may be directly contributing to the further growth of Pine Point.

The fragile balance between erosion and accretion along much of the Saco Bay shoreline supports regulations restricting further large-scale alteration of the coastal zone. There is no way at present to predict whether the erosion in the southern part of the bay will be restricted to that area or extend north of Goosefare Brook. The large-scale engineering and development of most of the bay's sand dunes leaves little room for flexibility as relative sea level continues to rise, possibly at increasing rates.

The long-term nature of shoreline retreat in the southern part of the beach, the history of property destruction, and the presence of the north jetty at the river mouth suggests that buildings in jeopardy may need to be moved. Although the rate of retreat has slowed since the early 20th century, the sediment budget does not balance in some locations. Beach nourishment and building relocation are long-term solutions that should be considered to manage the dynamic shoreline of Saco Bay.

If the Scarborough River inlet is dredged again, as planned, sandy spoils should be returned to the Camp Ellis beach. Although initially more costly than local disposal, the avoided cost of a longer return time for the sand and the savings in property protected as it returns justify moving sand to Camp Ellis, from whence it ultimately came.

The removal of the jetties at the Saco River mouth is justified geologically, but probably not economically. For the long term, however, the jetties' detrimental effects on the beach will require continual maintenance dredging and nourishment, and/or public acquisition of properties in Camp Ellis. The day may come when the public will be faced with the question of whether it wants a harbor at Camp Ellis or a beach in southern Saco Bay.

ACKNOWLEDGMENTS

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