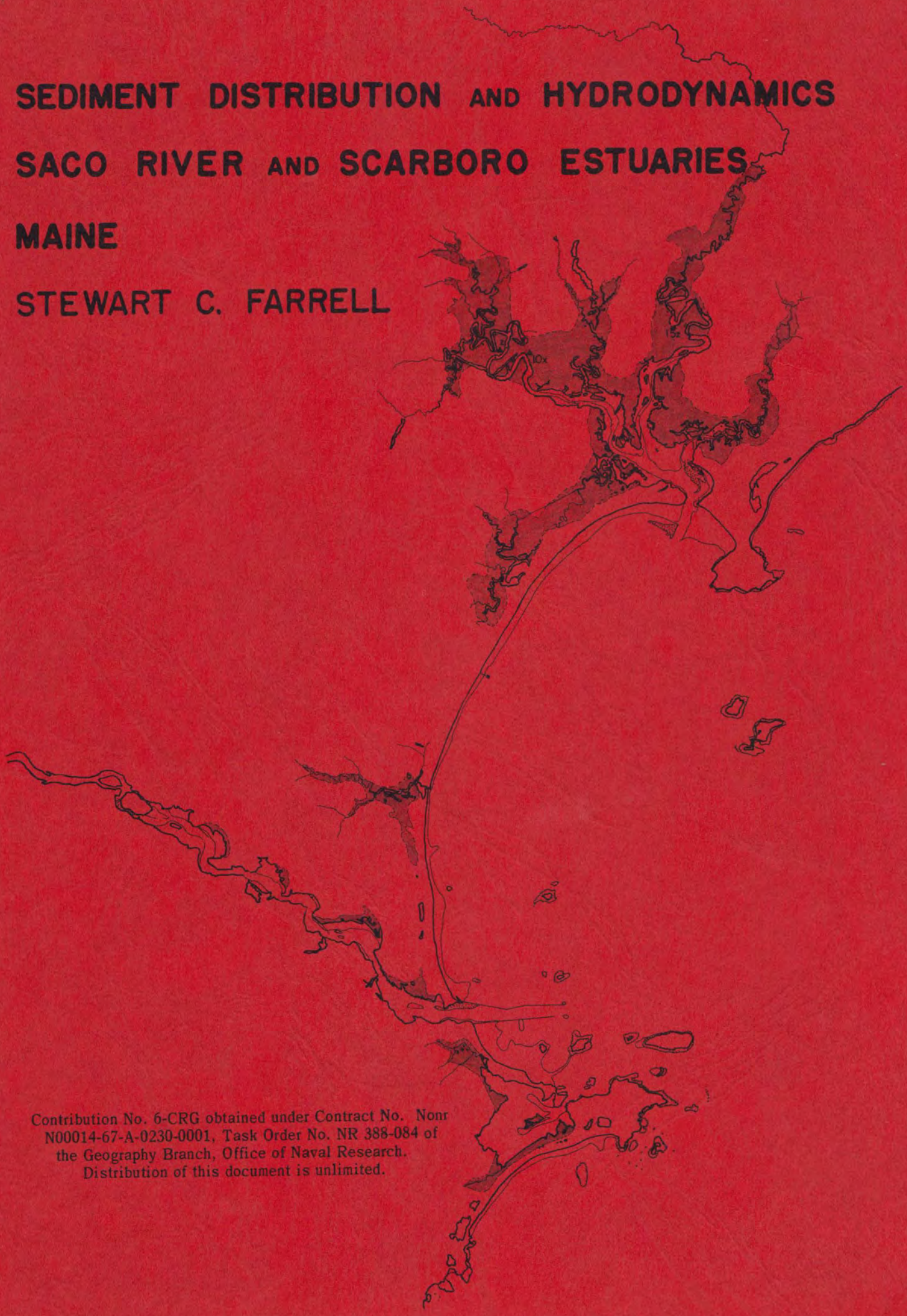
SEDIMENT DISTRIBUTION AND HYDRODYNAMICS SACO RIVER AND SCARBORO ESTUARIES MAINE

STEWART C. FARRELL



Contribution No. 6-CRG obtained under Contract No. Nonr N00014-67-A-0230-0001, Task Order No. NR 388-084 of the Geography Branch, Office of Naval Research.

Contribution No. 6-CRG

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June, 1970

SEDIMENT DISTRIBUTION AND HYDRODYNAMICS SACO RIVER AND SCARBORO ESTUARIES, MAINE

Stewart C. Farrell

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Abstract: The Saco River, a major New England stream with an average runoff of 2919 cubic feet per second, and the Scarboro estuary, a system of three small local brooks, are located at opposite ends of Old Orchard Beach, York County, Maine. The Saco River estuary has a six-mile bedrock channel with no salt marsh or tidal-flat development and with a highly irregular channel bottom profile. The Scarboro estuary system is a complex of well-developed meandering tidal channels, point bars, ebb- and flood-tidal deltas, salt marshes, and tidal flats.

The Saco River estuary is a highly stratified salt-wedge estuary with a slightly inclined salt water-fresh water boundary. The irregular bottom topography creates deep salt-water traps where water of 30°/oo salinity remains throughout the tidal cycle. At ebb, surface fresh water flowing as much as 3.5 feet per second creates sharp shear boundaries between it and the nearly motionless sea water in the deeps.

The Scarboro estuary is a homogeneous, unstratified saline estuary; the minimum salinity in the harbor at low water is 26°/oo. A pronounced time-velocity current asymmetry results in flood transport of sand into the harbor and up on the flood-tidal delta. Flood dominance is most pronounced on intertidal sand flats where sand-wave slip faces migrate only in the flood direction. The

maximum migration rate measured was 3.5 feet during the period of each spring tide. Ebb currents are most effective in the major deep channels. Certain modifications of the flood-tidal delta[1], such as the formation of ebb shields and trailing ebb spits, can also be attributed to the ebb currents.

The grain-size data show a striking difference between the coarser sediments of the intertidal sand bodies of the Saco River estuary (0.5ϕ mean) and the finer sediments of the intertidal sand bodies of the Scarboro

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1. Definitions from Coastal Research Group (1969)

   Ripples: Asymmetric bedforms formed by unidirectional flow. Wavelength of less than 2 feet.

   Megaripples: Wavelength between 2 and 20 feet.

   Linear-megaripples: Megaripples with straight crests.

   Scour-megaripples: Megaripples with undulatory to cuspate crests and well-developed scour pits in front of the slip faces.

   Sand waves: Wavelength greater than 20 feet.

   Ebb spit: Spit formed in an estuary as a result of ebb currents. Commonly attached to the borders of flood-tidal deltas.

   Ebb shield: Topographically high rim or margin around a sand body that protects portions of the sand body from modification by ebb-currents.

   Flood-tidal delta: Sediment accumulation formed inside an inlet by flood-tidal currents.

   Ebb-tidal delta: Sediment accumulation seaward of a tidal inlet. Deposited by ebb-tidal currents.

estuary (1.25ϕ mean). Sediments of the ebb-tidal delta of the Scarboro estuary are much better sorted ($0.35 < \sigma_I < 0.65$) than those of the flood-tidal delta ($0.35 < \sigma_I < 1.0$). This better sorting reflects the nondeposition of suspended fines due to continued reworking of the ebb-tidal delta sand body by waves.

The change from dominant white and gray feldspar in the lower Scarboro harbor to dominant yellow feldspar in the upper tidal creeks, combined with a decrease in the number of polished sand grains and in the quantity of locally derived metamorphic rock fragments away from the estuary entrance, indicates a flood-tide control of transport and deposition within the estuary. The lack of strong fresh-water flow results in material derived from erosion of the latest Pleistocene river deltas and the Presumpscot blue clayey silt being concentrated either as sand in tidal-channel bottom lag deposits and point bars or as silt and clay deposited on the salt marsh or mud flats.

The barrier beach attains its shape due to response to wave refraction. Coarse material is concentrated in a central zone by greater wave energy. A southeast wind combines with refracted swell to move finer sand north to Pine Point. The trend is countered by northeast storm waves generated within Saco Bay, which are of increasing effectiveness on beach processes away from Pine Point toward Camp Ellis.

ACKNOWLEDGMENTS

A study of such a complex area as the Old Orchard crescent could not have been undertaken single-handed. The author would like to thank Miles O. Hayes for supervising this project and Karl Geller and Jack Cysz for their assistance in the field. The financial and equipment support were provided by the Office of Naval Research (Geography Branch), contract N0001-67-A-0230-0001. Special thanks go to Joseph H. Hartshorn and Gregory W. Webb, who critically read the manuscript and offered suggestions, and to Richard Brown and Eugene Rhodes who aided in the drafting and photo reproduction.

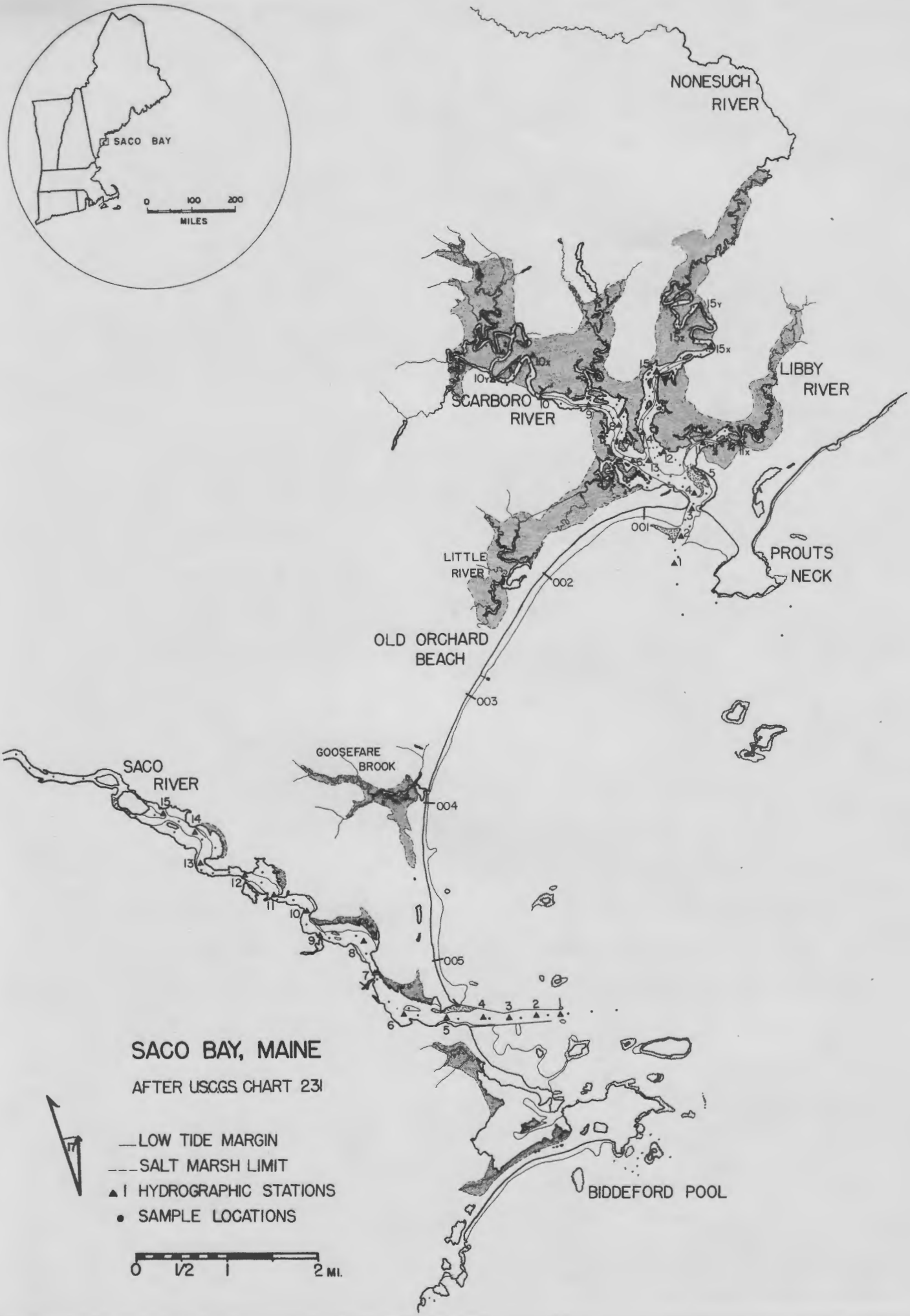
INTRODUCTION

Using a combination of field observations and measurements and laboratory investigation of sampled materials, this study is an attempt to discover the processes responsible for the formation of the assemblage of Holocene sediment bodies present in the Saco Bay, Maine, area. By interpreting the processes and the significant features resulting from them in this and other areas currently under study by the University of Massachusetts Coastal Research Group, a clearer picture of the complex pattern of coastal sand-body development, it is anticipated, will emerge.

The barrier beach at Old Orchard, Maine, is a seven-mile arc of sand (Fig. 1); the two estuaries studied are located at opposite ends of the arc. The Saco River, which feeds the estuary to the south, is a major New England stream rising in Crawford Notch, New Hampshire, and draining 1359 square miles, with an average annual discharge of 2919 cubic feet per second (U.S. Dept. Interior, 1967). The Scarboro estuary is a system of three small brooks--the Scarboro, Nonesuch and Libby Rivers--the largest of which, the Nonesuch, drains an area of about 20 square miles.

The Old Orchard crescent occupies an area which is geologically unique along the Maine coast, inasmuch as the bedrock is virtually unmetamorphosed greenstone, phyllite,

Figure 1. General orientation map of Saco Bay. Common place-names and extent of the various intertidal subregion locations appear here. Hydrographic stations are located by triangles. Sample locations shown by dots do not reflect all samples taken; in particular the 96 grid samples taken from the stippled areas corresponding to three intertidal sand bodies mapped in detail are not shown. The shaded area is salt marsh and the region between the heavy and lighter shorelines is the intertidal zone.


SACO BAY
0 100 200
MILES
NONESUCH RIVER
LIBBY RIVER
SCARBORO RIVER
LITTLE RIVER
PROUTS NECK
OLD ORCHARD BEACH
GOOSEFARE BROOK
SACO RIVER
BIDDEFORD POOL
001
002
003
004
005
SACO BAY, MAINE
AFTER U.S.C.G.S. CHART 231
LOW TIDE MARGIN
SALT MARSH LIMIT
HYDROGRAPHIC STATIONS
SAMPLE LOCATIONS
0 1/2 1 2 MI.

and argillite. The surrounding Paleozoic rocks are all high-grade metamorphic rocks; sillimanite-orthoclase rocks are found just a few miles to the northwest. This isolated zone of soft and easily erodable bedrock, which underlies the depositional basin of Saco Bay, provides a unique rock-fragment tracer in the sands and is of great help in determining sources and transport direction.

The major environments consist of uplands, salt-marsh regions, intertidal and subtidal channels, and the barrier beach zone. The uplands are underlain by Siluro-Devonian metamorphic bedrock that is thinly covered by a variety of glacial tills, postglacial deltas, and marine transgressive clays. These act locally as a minor source of beach sand and a major source of silt and mud. The high salt-marsh region, extensively developed only in the Scarboro estuary, is populated predominantly by Spartina patens, and is cut by tidal creeks which migrate slowly by meander cut-and-fill. The intertidal zone has a great variety of topographic features, depending on the wave and current energy acting on any one particular spot; among these are channel-fringing mud flats, mussel banks, sand flats, ebb- and flood-tidal deltas, and swash bars.

HYDROGRAPHY

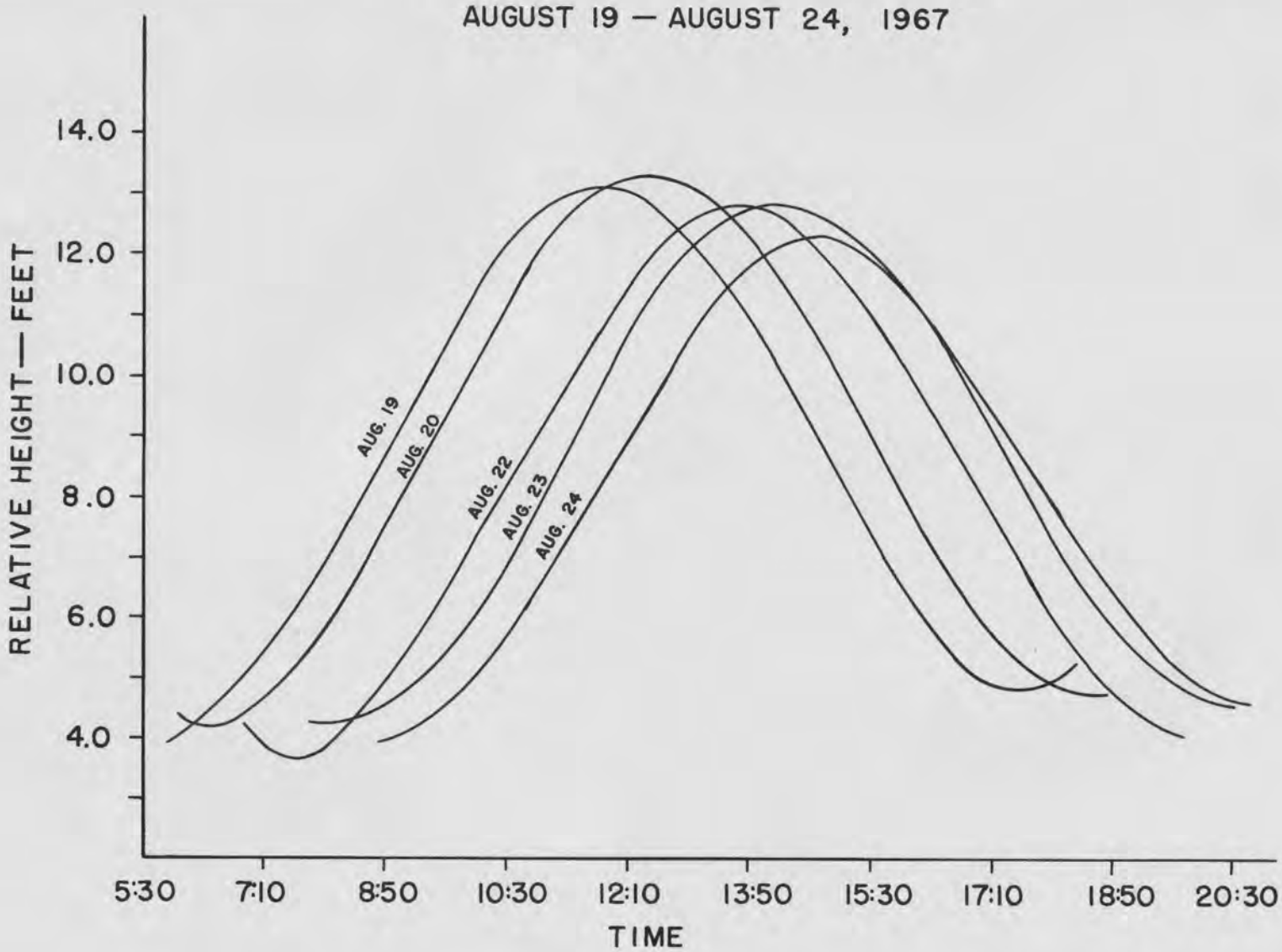
Data on temperature and salinity were gathered on six successive days in August 1967. A total of 36 stations, located in Figure 1, were occupied throughout entire tidal cycles. The tidal curves for the sampling period are shown in Figure 2. Water samples were taken with a Nansen bottle and temperature readings were made with a thermometer at the same time. Salinity readings were made with a hydrometer in the laboratory. A biplane drag vane set, modified after a drag vane apparatus from Chesapeake Bay Institute, was employed to measure current velocities. The current vane set consisted of one 2-square-foot plywood biplane and one 8-square-foot plywood biplane which, in combination with a 17- or 34-lb. weight, were deflected by the current when suspended over the stern of the anchored boat. The angle of deflection from the vertical was measured and the current velocity then read off tables in feet per second. Each station was sampled in vertical section, beginning with water samples at low water. The sequence alternated between water samples and current measurements throughout the day at ninety-minute intervals.

The Saco and Scarboro River systems differ in channel shape and area of intertidal zone, but the real dissimilarity in estuarine water movements and exchanges depends rather on

Figure 2. Graph of tidal fluctuation in Saco Bay for the period August 19-24, 1967. The Saco Bay tide has a slight inequality in successive highs and lows (0.5 to 1.2 feet).

SACO BAY TIDAL CURVES

AUGUST 19 — AUGUST 24, 1967



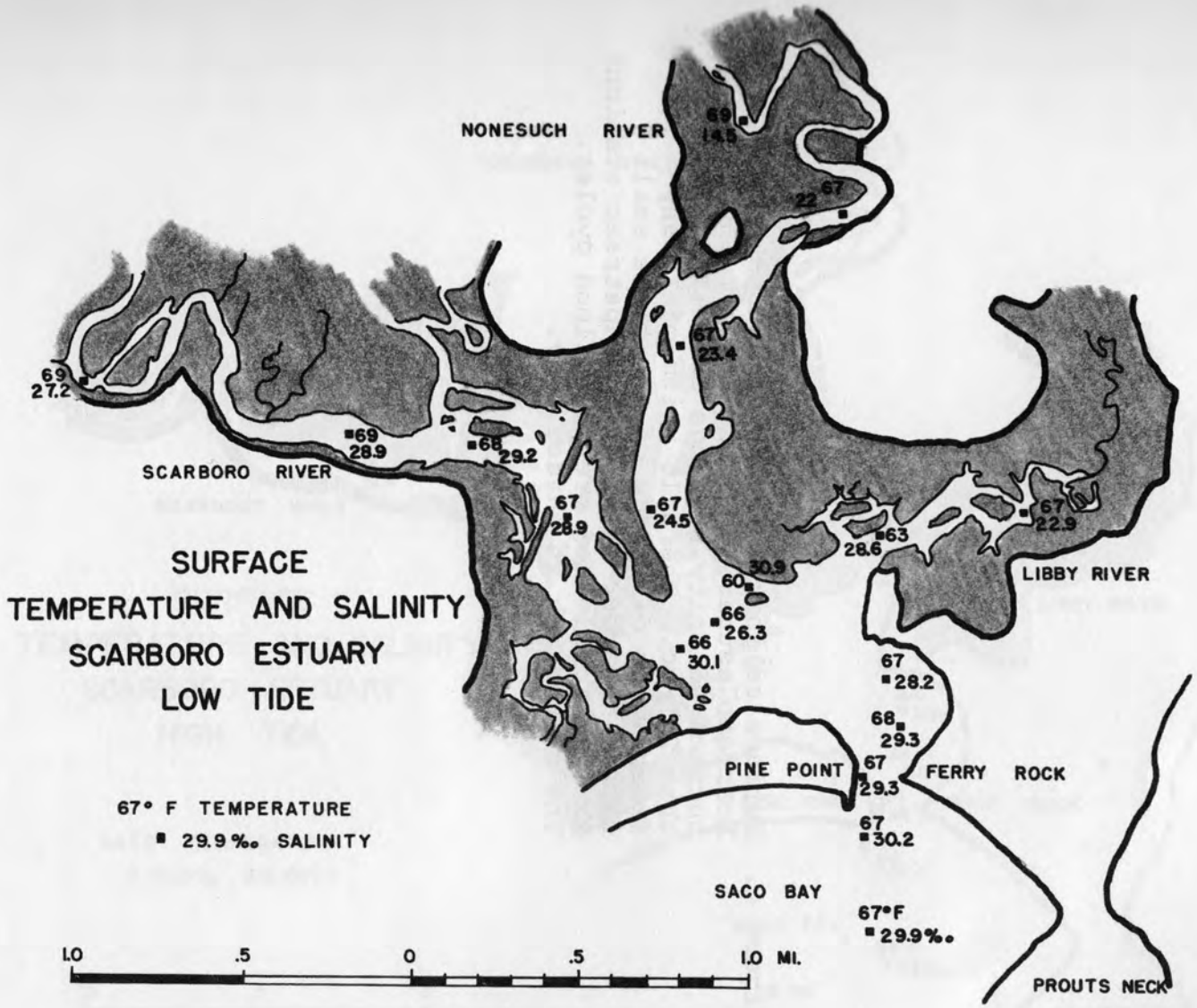
the great disparity in fresh-water influx. This disparity can be better understood by examining each river system separately.

Scarboro Estuary

Temperature and salinity. The Scarboro estuary at low water is little more than three shallow tidal creeks. The relative fresh-water discharge of these creeks can be seen by comparing the values furthest upstream on the surface-salinity and temperature diagrams (Figs. 3 and 4). The Nonesuch River with its 16-mile course drains the largest area of the three. Its influence in diluting the saline water extends into the harbor proper (Fig. 3, station 12). The remaining values throughout the diagram are all indicative of slightly diluted sea water which was warmed up in the summer sun while covering the salt marsh or mud flats.

One anomaly in the salinity appeared at station 13, a depression in the sand flats behind a small marsh island. Here two streams drain a small pool at a rate of 7 cubic feet per second until reversed two hours after low tide. The cold temperature (60° F) and high salinity ($30.9^{\circ}/oo$) of the pool at first presented a problem of interpretation until an extensive gravel bed was discovered from 8 to 11 feet below the marsh area known as Winnock Neck. The gravel

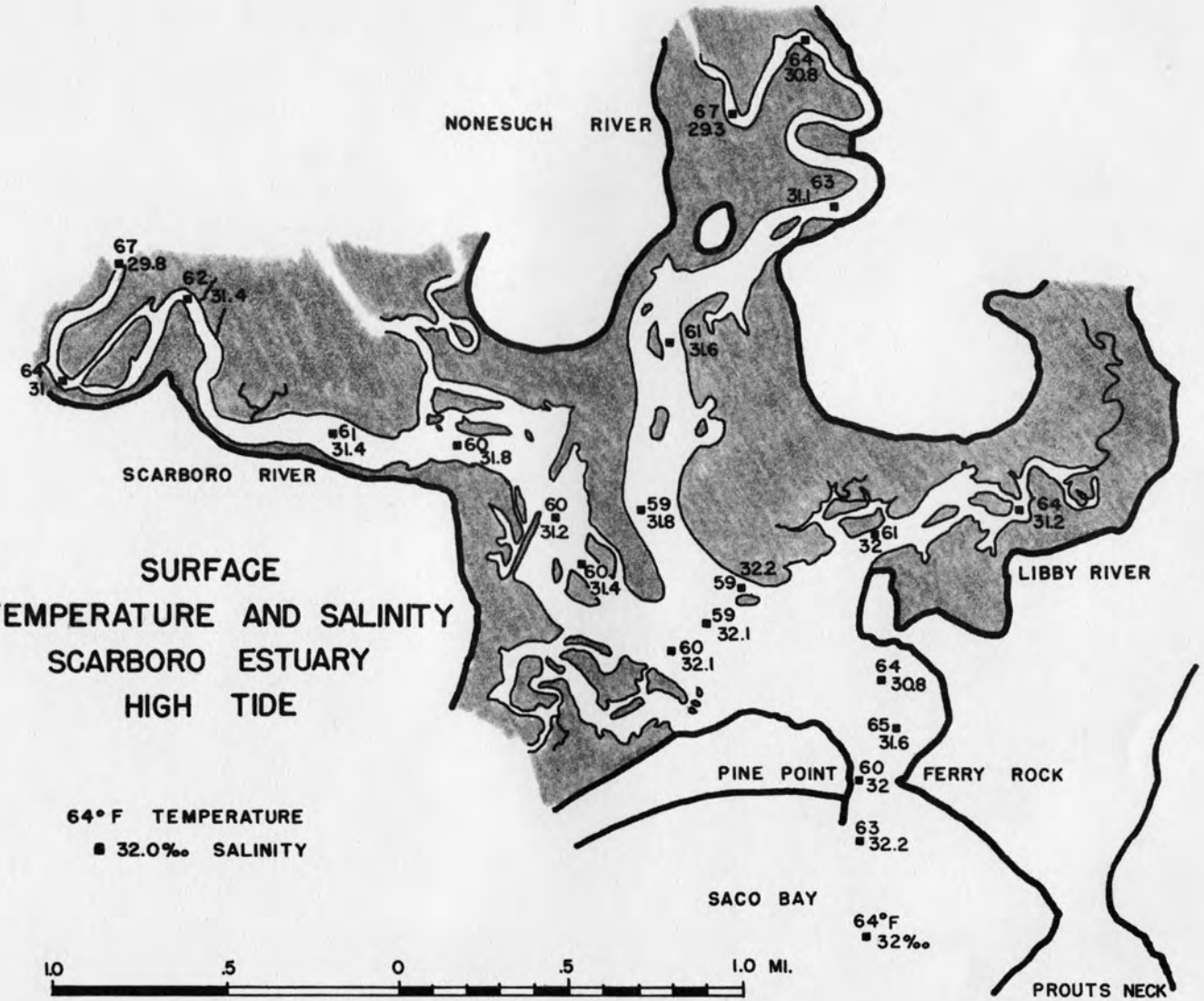
Figure 3. Surface salinities and temperatures of the Scarboro estuary at low tide. The low fresh-water discharge is not capable of diluting the salt-water dominated estuary. However, minor salinity fluctuations do occur in the upper reaches of the three streams as a result of variations in discharge. The salt marsh is shaded gray.



SURFACE
TEMPERATURE AND SALINITY
SCARBORO ESTUARY
LOW TIDE

67° F TEMPERATURE
29.9 ‰ SALINITY

Figure 4. Surface salinities and temperatures of the Scarboro estuary at high tide. Twenty-two surface salinity readings are all greater than 29°/oo. The salt prism masks any fresh-water discharge of the three small rivers. Warmer water at the upstream stations is a residual from previous flood cycles. The salt marsh is shaded gray.



SURFACE
TEMPERATURE AND SALINITY
SCARBORO ESTUARY
HIGH TIDE

bed, a reversable ground-water storage system, accounts for the continued rate of flow of cold sea water.

The high-tide surface salinity diagram points out the uniformity of the water mass in the entire estuary (Fig. 4). The cold saline water moves in, covers the flats, warms up (in the summer), and flows out; this pattern continued during the period of my observation.

The vertical salinity and temperature profiles, which extend from the ebb-tidal delta up the Scarboro River for 2.5 miles, demonstrate the lack of any stratification (Figs. 5 and 6). Some temperature-controlled density layering may occur, but it was only noticeable in special cases, such as when the summer sun caused at least a 10° F rise in the temperature of the tidal-flat waters. Williams (1963) called such an unstratified estuary a neutral estuary of the homogeneous or mixed type; Pritchard (1967) classified this estuary type as vertically homogeneous with no lateral variations.

Current velocity. Evidence for stratification is also lacking in the current-velocity profiles (Figs. 7 and 8). The increase or decrease in average current velocity of individual station current profiles can be explained by the channel morphology and gradient. Velocity fluctuations between stations reflect relative channel constriction or opennness of flow; for example, stations 1 to 4 are all in

Figure 5. Longitudinal profiles of temperature and salinity in the main channel of the Scarboro estuary. The vertical sampling interval was 3 feet to a depth of 9 feet and 6 feet at greater depths.

(A) A.M. low water. Station 6 is located where the Nonesuch River empties into the main estuary. The slightly fresher water dilutes the sea water to 26°/oo at this point.

(B) Half tide (flood). The cold sea water pushes in, weakly defining a density wedge as the flood progresses. Salinities of the warmer water range from 28°/oo to 29.5°/oo.

TEMPERATURE & SALINITY, SCARBORO ESTUARY, MAINE

AUGUST 20-22, 1967

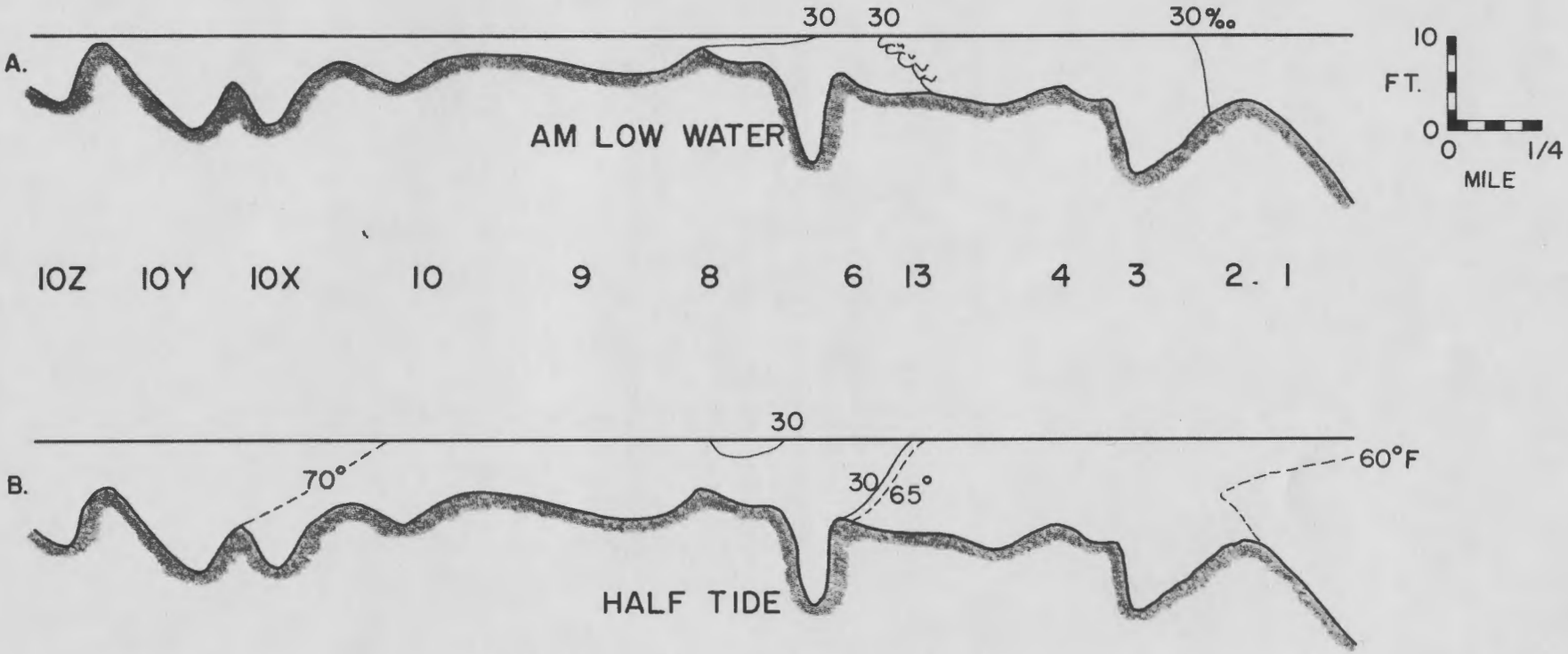


Figure 6. Longitudinal profiles of temperature and salinity in the main channel of the Scarboro estuary, August 20-22, 1967.

(A) At high water the tidal prism can be roughly defined by the 60° F isotherm. Water warmer than 65° F remains from previous tidal cycles; water between 60° and 65° F represents mixed water from the present and previous tidal cycles.

(B) Halfway to low water, homogeniety is almost complete between 61° F and 66° F and from 30.8°/oo to 32.3°/oo salinity.

(C) P.M. low water is a repeat of the morning low with slightly lower salinities in the upper Scarboro (29.3°/oo versus 30.3°/oo).

TEMPERATURE & SALINITY, SCARBORO ESTUARY, MAINE

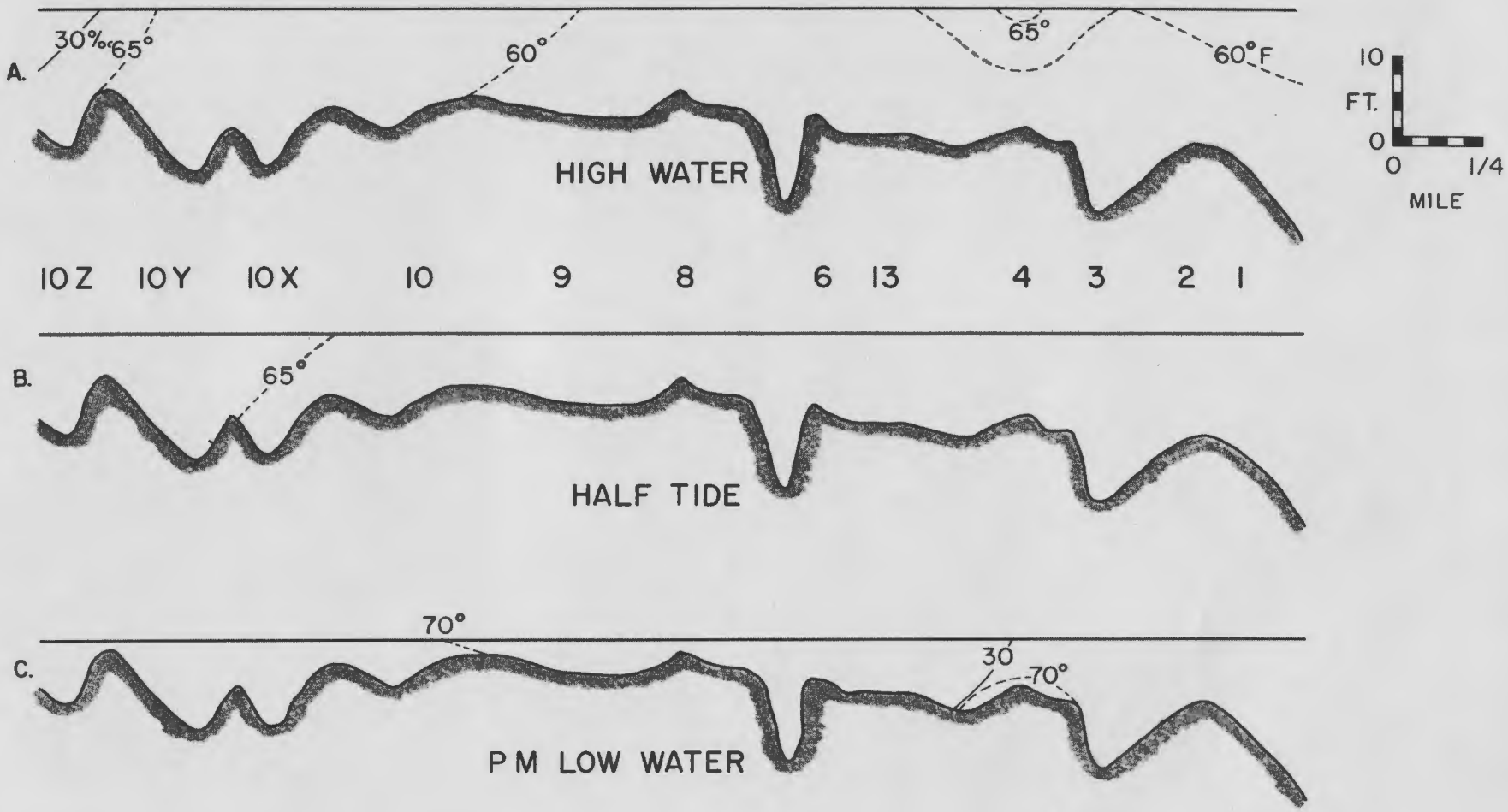


Figure 7. Longitudinal profiles of current velocity during flood tide in the main channel of the Scarboro estuary.

(A) Early flood currents in the Scarboro are uniform vertically and decrease upstream. The Scarboro River gradient is sufficient to keep water running downstream in an ebb direction at 2.4 feet per second 90 minutes after low water at station 10, 2.75 miles from the sea.

(B) Late in the flood, high velocities develop in the constriction between Ferry Rock and Pine Point (station 3). The lack of stratified flow is apparent.

CURRENT VELOCITIES — SCARBORO ESTUARY, MAINE

AUGUST 20-22, 1967

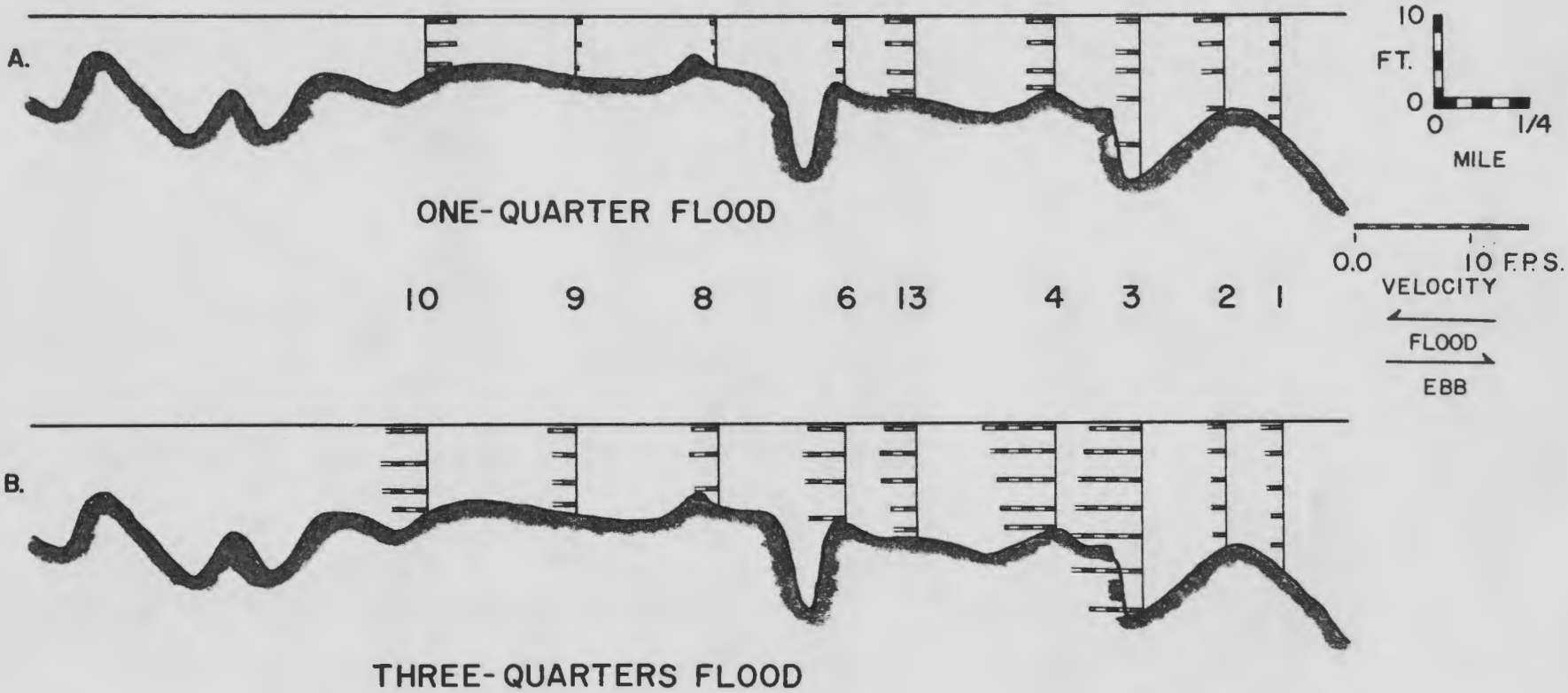
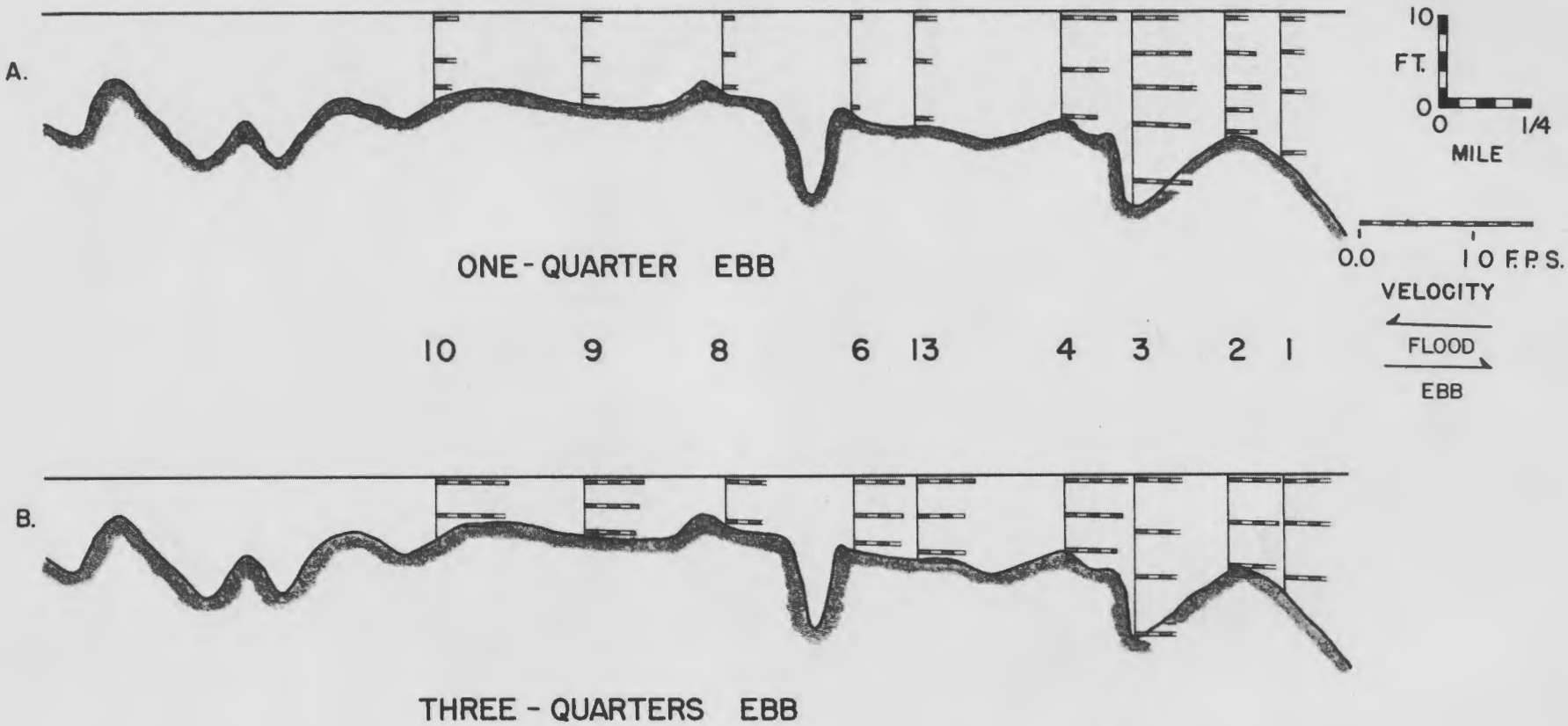


Figure 8. Longitudinal profiles of current velocities during ebb tide in the main channel of the Scarboro estuary, August 20-22, 1967.

(A) The ebb velocities rise rapidly in the outer channel (stations 1 to 4) but remain low in the estuary while the flats are still covered.

(B) High channel flow develops late in the ebb after the flats are exposed. Ebb-oriented bedforms are created marginal to these channels (station 4).

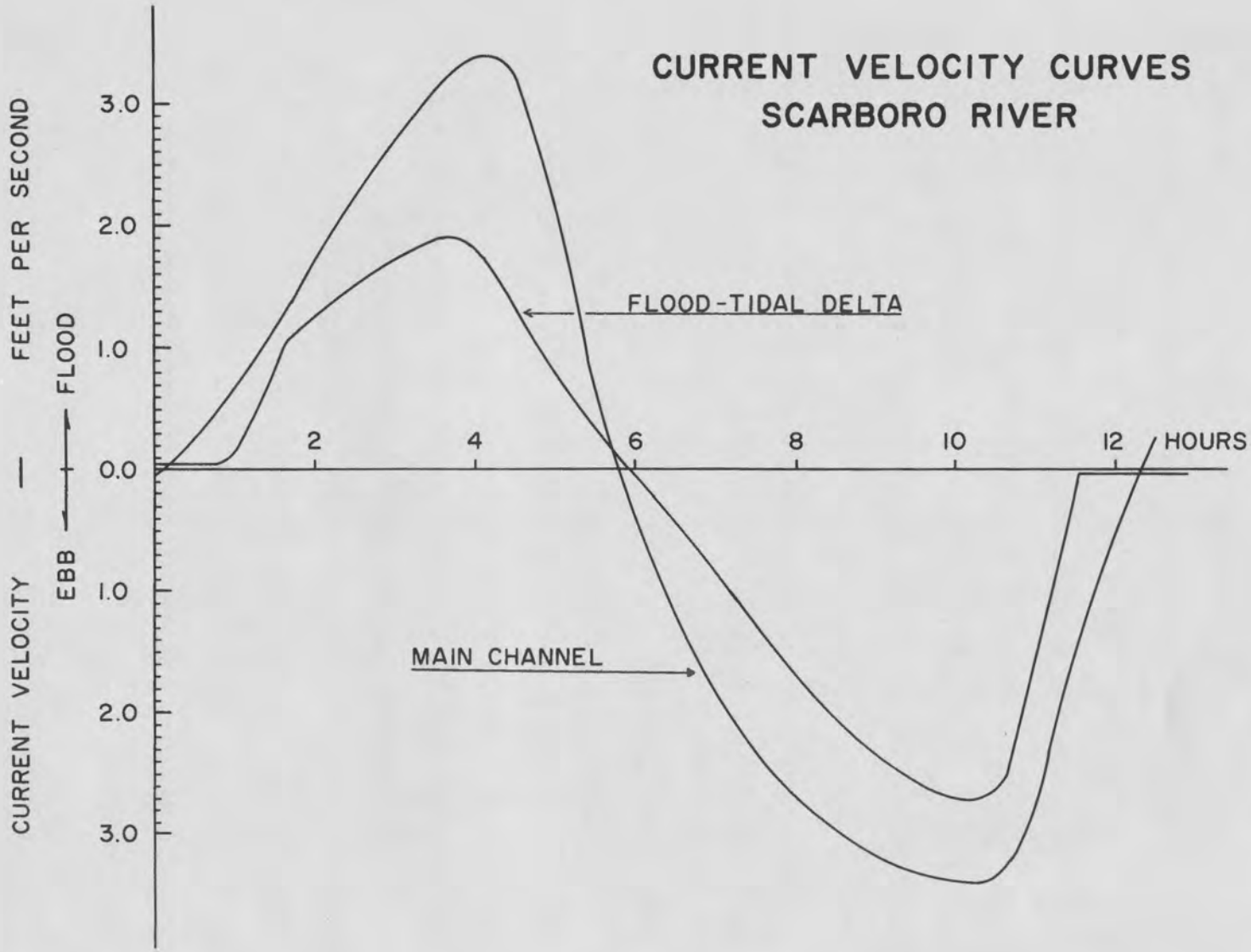
CURRENT VELOCITIES — SCARBORO ESTUARY, MAINE



the dredged channel where flow is constricted to a uniform 200-foot width and 8-foot depth.

A plot of velocity versus time at any individual station for a tidal cycle shows the pronounced tidal current asymmetry (Fig. 9) which is known to exist in other New England estuaries. An asymmetric maximum in current velocities occurring in both flood and ebb tides is largely responsible for flood-oriented bedforms remaining even after the completion of the ebb tide. This time-velocity asymmetry is expressed in Figures 7 and 8. As can be seen in the current velocity profile (Fig. 7), even 1.5 hours after low water an ebb current persisted in the upstream stations (stations 9 and 10), with average velocities of about 2.0 feet per second. All flats were still uncovered and the currents were confined to the channels. By 4.5 hours after low water the velocities in the channels increased to 4.0 feet per second, which was more than sufficient for lower flow regime transport of material in large ripples or even megaripples (Guy and others, 1966). By this time all flats were covered by at least 2 feet of water. The flood currents carried sand up out of the channels and out on to the flats in the ripple bedform phase; average current velocity was 1.2 feet per second. As the sand was carried into shallower water, it was distributed into large linear sand waves.

Figure 9. Illustration of the time-velocity asymmetry of the flood- and ebb-tidal currents. The flood current velocities rise to a maximum late in the tidal cycle and are highest when the intertidal sand bodies are covered. Strongest ebb currents occur when the intertidal sand bodies are exposed. This resulting current asymmetry directs intertidal zone transport in the flood direction up to 2 miles from the estuary entrance.


CURRENT VELOCITY CURVES
SCARBORO RIVER
CURRENT VELOCITY — FEET PER SECOND
EBB ← → FLOOD
3.0
2.0
1.0
0.0
1.0
2.0
3.0
2
4
6
8
10
12
HOURS
FLOOD-TIDAL DELTA
MAIN CHANNEL

In contrast, as the tide fell the velocities increased, slowly at first, then rising to 4 or 5 feet per second late in the ebb. The low velocities were not high enough nor did they act long enough to erase or reverse the orientation of the flood features on high flats and deltas. However, stronger spring-tidal ebb currents did create lunate ripples on the high flats and generally resulted in scour-megaripples being formed on the channel margins. The majority of the flood-oriented bedforms could not exist through the ebb cycle if the ebb-tide velocity were at its maximum while the flats were still covered.

Saco River Estuary

Temperature and salinity. The Saco River channel configuration is quite unlike that of the Scarboro River. The portion of the river under tidal influence is a rock channel which cuts across bedrock structural trends to form a series of narrow, deep rock gorges separated by shallower sand-floored reaches. The rock gorge has severely limited mud-flat and marsh development to miniscule fringing marsh banks. The 6-mile, tidally influenced portion of the channel terminates at the Factory Island rapids (station 15).

Man's major influence on the Saco River has been the construction of numerous flood-control and power dams and, in 1857-67, of 1100 yards of harbor-entrance jetties. The

dams have served to cut down the transport of sand-sized sediment, while the jetties have resulted in the destruction of a well-developed ebb- and flood-tidal system that existed in 1603, according to the description of Champlain (Locke, 1880).

Five stations per day, spaced about one-quarter of a mile apart in the channel of the Saco River, were occupied over a period of three days. The data gathered were used to derive the vertical profiles for temperature and salinity. These profiles exhibit a marked difference from those of the Scarboro River.

The low-water temperature and salinity profile (Fig. 10A) shows a nearly horizontal stratification gently inclined upstream. This stratification is altered where ledges and shallow reaches between deeps act as density barriers, confining masses of more saline water in the deeps, two of which contained normal sea water. Only the easternmost deep at station 7 contained water of relatively lower salinity, due to its narrowness, length, and much greater current velocities.

As shown on Figure 11A, by high tide the salt wedge had intruded to station 11, 4½ miles upstream. The steep boundaries present earlier (Fig. 10B) flattened out and were gently inclined upriver. The less dense and warmer

Figure 10. Longitudinal profiles of temperature and salinity during flood in the main channel of the Saco River estuary.

(A) The early morning low-water profile was run just after the tide had started to flood. The salt wedge can be seen moving into the estuary from the extreme right. The stippled patterns indicate water salinities of less than 5°/oo or greater than 25°/oo.

(B) At half tide the salt wedge had pushed 1.5 miles up the estuary as a well-defined, density-controlled water mass. The 10°/oo and 15°/oo isohalines were displaced upriver by the movement.

TEMPERATURE & SALINITY, SACO RIVER, MAINE

AUGUST 23–25, 1967

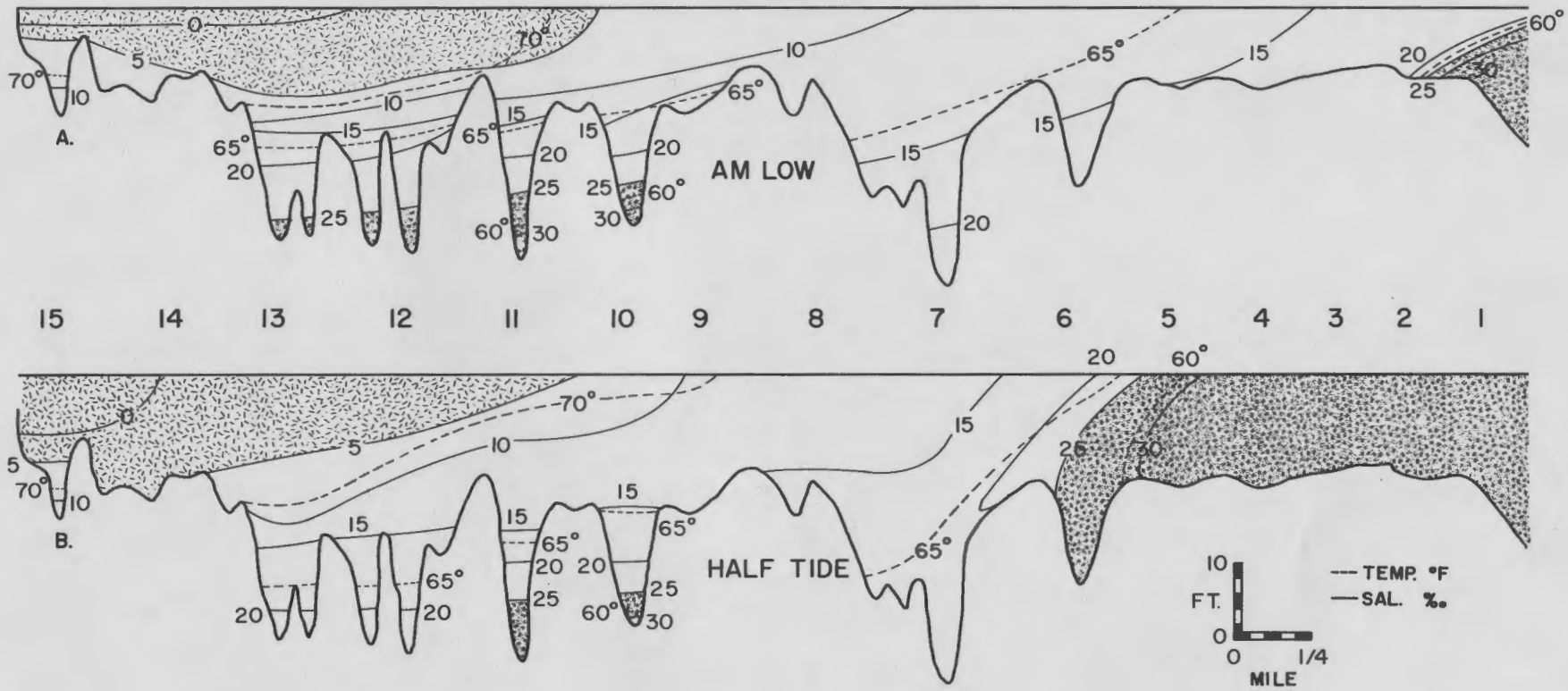
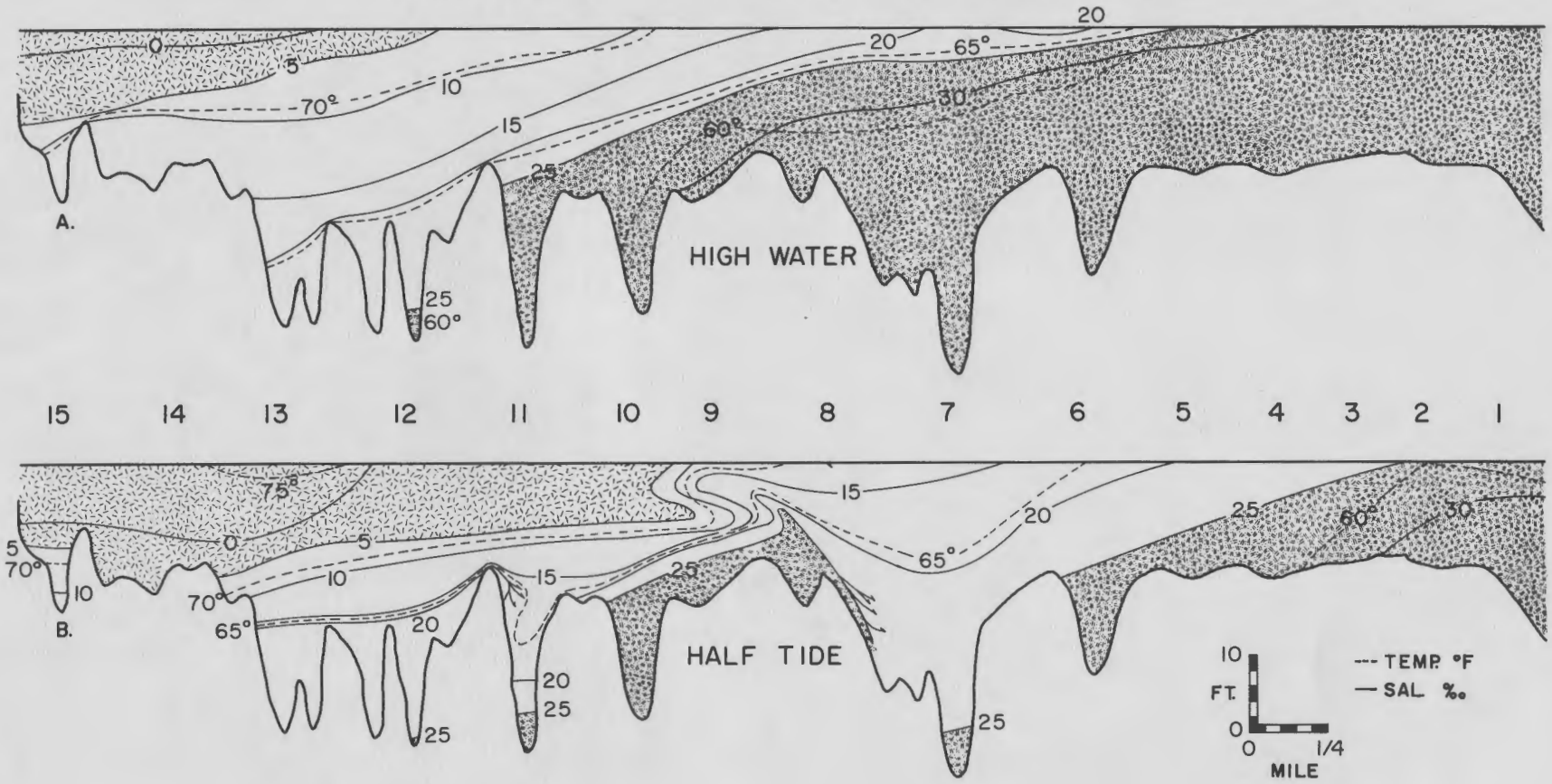


Figure 11. Longitudinal profiles of the temperature and salinity in the main channel of the Saco River estuary, August 23-25, 1967.

(A) High water. The cold sea-water prism occupied three-fifths of the estuary, and fresh water was beginning to flow out over the salt wedge.

(B) By half tide vertical mixing was at its maximum from stations 9 to 5. Extreme turbulence caused the horizontal stratification to break down in the mid-region.

TEMPERATURE & SALINITY, SACO RIVER, MAINE



river water, trapped close to station 15 during mid-flood while the tide was rapidly rising, was able to move downstream with the approach of high water and the correlate decrease in rate of water level rise. This created an ebb current which began on the surface up to an hour before maximum high water at stations 14 and 15; at maximum high water a 0.8-foot per second current was already ebbing at station 15.

By the time the maximum level of this particular tide was reached, cold salt water had occupied more than half of the estuary (Fig. 11A). Halfway to low water in the afternoon (Fig. 11B), the isohalines became contorted by the turbulence and mixing resulting from the ebb flow. The salt wedge withdrew to stations 1 and 2. At this time, the water coming through the gap at station 10 flowed out into a broad, open sandy reach where it was subject to extensive eddy mixing. The sudden deceleration of the previously confined flow within the rock walls at station 10 caused the overturning and mixing of the water column. The outlet for this wide river reach is the main rock gorge centered at station 7. The hydraulic acceleration as the river entered this gorge was evident in the lack of surface wind ripples and the appearance of boils along a surface boundary just above the gorge. As the water

emerged from the bedrock channel it was partially mixed, with salinity values between 14°/oo and 26°/oo in a 40-foot water column, whereas at station 10 it was stratified, with salinities from 3°/oo to 27°/oo through only a 15-foot column.

The afternoon low water (Fig. 12) copied the morning low water except that the salt wedge had completely withdrawn. This is attributable to the taking of the morning low-water samples just after the tide had turned, as opposed to the taking of the afternoon samples just before the flood tide commenced. The trapped salt water in the upper river deeps was clearly defined by the isohalines. The intense mixing of water around station 7 is seen both in the lack of stratification and in the partial density inversion of the water column.

Current velocity. The significance of the current distribution hinted at by the above temperature and salinity diagrams can be examined more fully in current velocity profiles. For example, low-water and high-water slacks do not conform to maximum or minimum water levels. Ninety minutes after low water, at one-quarter flood (Fig. 13A), the river water contined to flow in the ebb direction at the upstream end of the estuary while at the same time the salt wedge was moving into the region of station 6. At

Figure 12. Longitudinal profile of the low-water temperature and salinity in the main channel of the Saco River estuary, August 23-24, 1967. Deep pools contain cold, salt water greater than $25^{o}/oo$. This pattern is a repetition of that found at low water in the morning. The tide had not yet reversed its flow at the harbor entrance (station 1), therefore, the salt wedge had not reappeared (as in Fig. 10A).

TEMPERATURE & SALINITY, SACO RIVER, MAINE

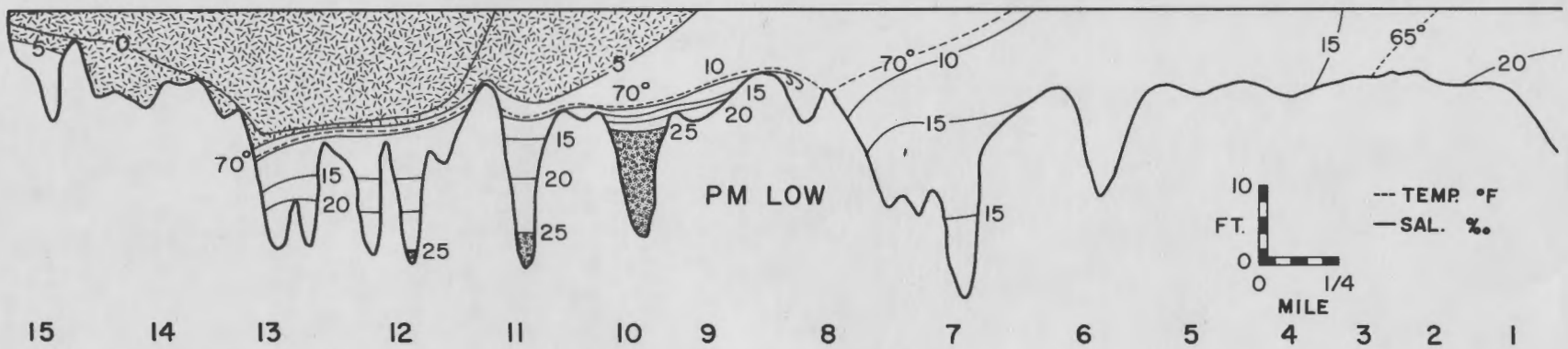
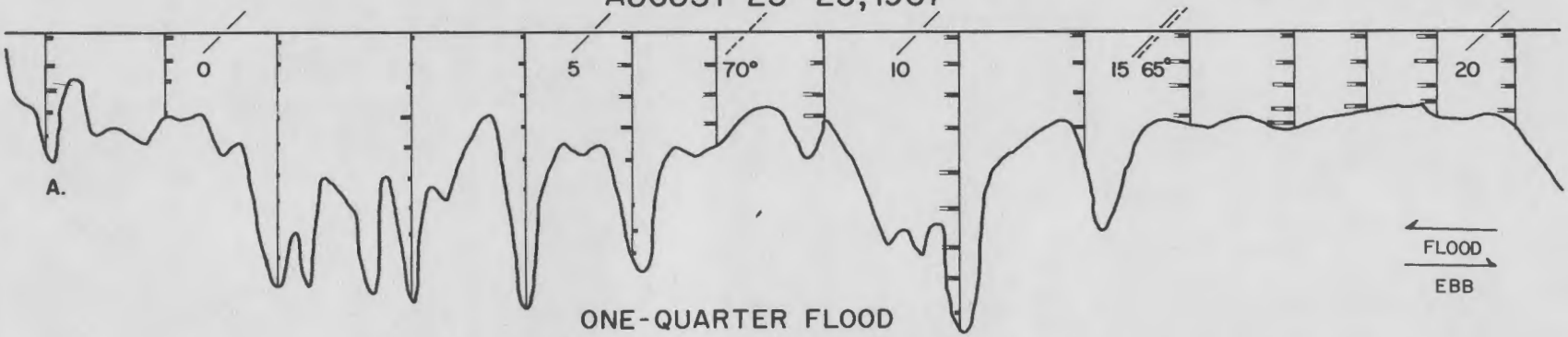


Figure 13. Longitudinal profiles of current velocity during flood in the main channel of the Saco River estuary.

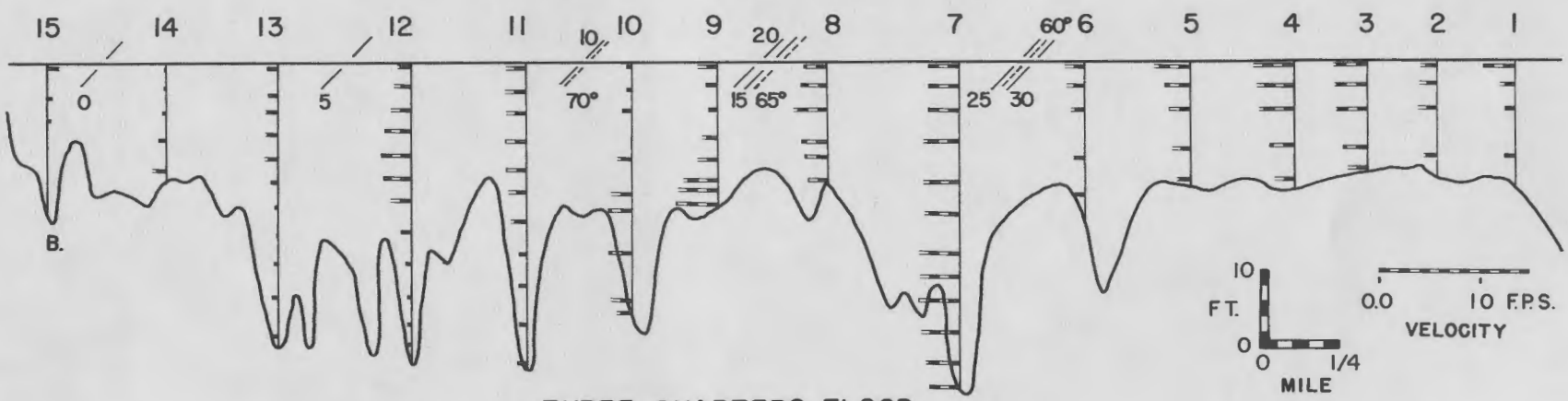
(A) One and one-half hours after low tide the upper four stations still maintained an ebb flow. Flood velocities were quite uniform vertically and decreased uniformly upstream.

(B) Three-quarters through the flood-tidal cycle, ebb-oriented flow from the Saco River still persisted at station 15. Density-controlled flow had developed at stations 9 and 10. The topographic influence of the ledges on the current profiles is demonstrated at stations 11, 12, and 13. Salinity and temperature measurements were made at the surface simultaneously with the current measurements. Isohaline and isothermal boundaries are shown along the surface line of the two current profile diagrams.

CURRENT VELOCITIES, SACO RIVER, MAINE
AUGUST 23-25, 1967



ONE-QUARTER FLOOD



THREE-QUARTERS FLOOD

each of the downstream stations the vertical profiles exhibited the highest current velocities nearer the bottom, reflecting the density-controlled flow of the salt wedge as it moved in along the channel bottom.

Four and one-half hours after low tide, at three-quarters flood, all current directions except those at station 15 were flood-oriented (Fig. 13B). By this time the salt wedge had penetrated to station 9 and bottom density flow was well displayed (station 9). River water remained ponded between station 14 and the dam while the tide was rising rapidly. As the flood period approached high water, this collected river water no longer could be held back and it commenced to flow out over the salt-water mass.

Ninety minutes after high water, a strong fresh-water current, with a surface flow of up to 5 feet per second had developed, while less than 6 feet down current velocities at five stations were less than 1.0 feet per second. The effect was most pronounced at station 9 where the velocity of 5 feet per second existed only in the top 3 feet of the water column. So pronounced was this fresh water-salt water boundary that a diver approaching it from below in the virtually still sea water could observe the brown river water flowing overhead in violent turbulence. The actual boundary was so well defined that it was limited to a

6-inch width. Occasionally, vortices distorted the boundary to a depth of 4 or 5 feet below the boundary surface. This caused wave-form undulations to spread upstream until the vortex subsided and the straighter plane of shearing flow re-established itself.

As the ebb progressed, the shear boundary extended deeper and deeper, finally placing the entire water column in motion (Fig. 14B). The surface velocities were still greater than bottom velocities, which ranged from 1 to 3 feet per second, except where the water surged over the thresholds of shallow ledges.

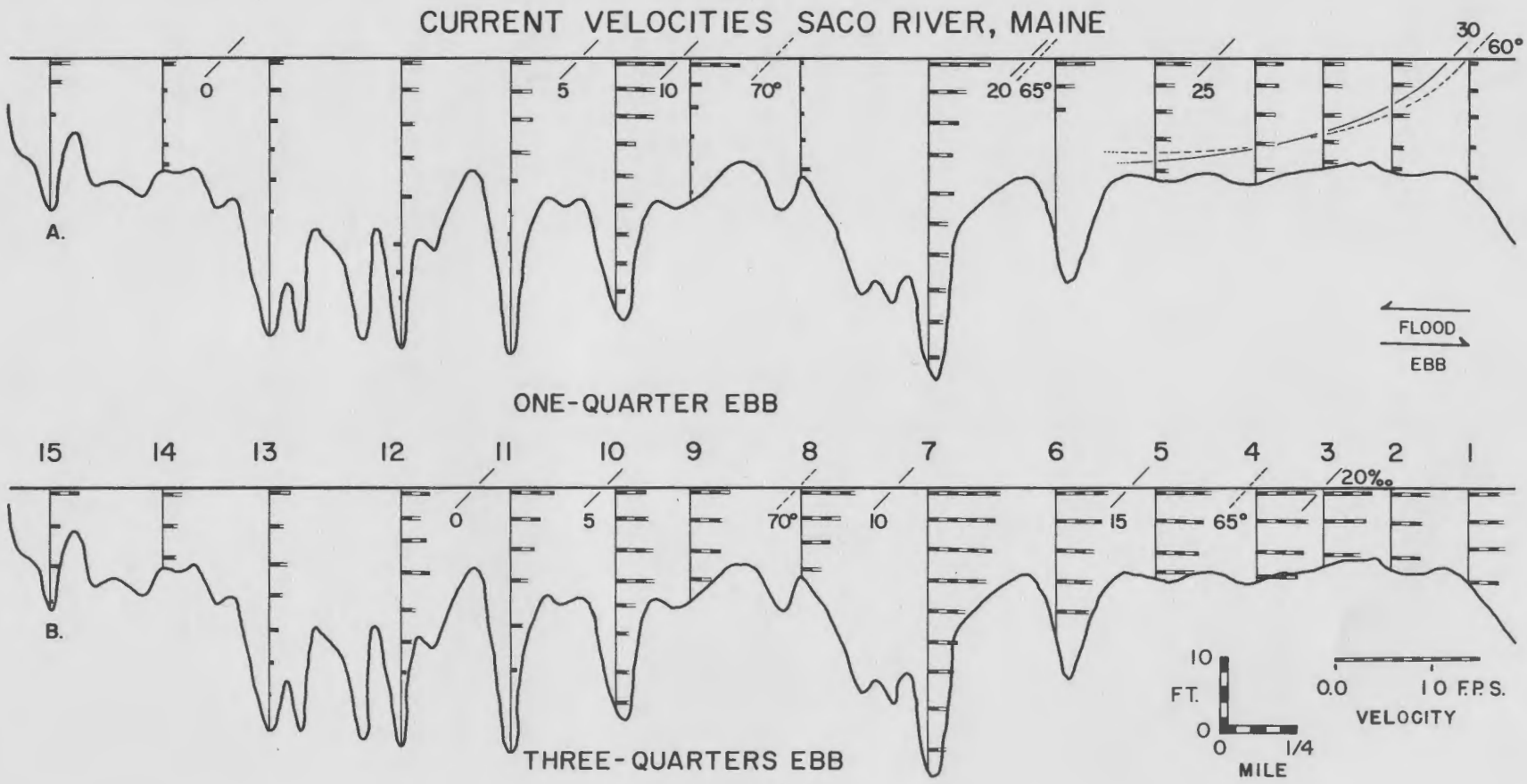
Current velocities of deep areas were controlled by the intervening rock ledges. Although strong currents did not occur below a ledge depth of 12 to 20 feet, flood-directed movement was detectable at stations 11 and 12 ninety minutes after high water. These weak currents probably represented saline density adjustments as the salt water sought the deepest levels, a process shown in both morning and afternoon low-water salinity profiles (Figs. 10A and 12).

This system may be classified as a "horizontal to inclined salt wedge estuary" after Williams (1963) or a "highly to moderately stratified tidal estuary" after Pritchard (1967). The highly irregular bottom topography of the Saco River channel is unlike that of any other of the seven northern New England estuaries which have been

Figure 14. Longitudinal profiles of ebb-period current velocities in the main channel of the Saco River estuary, August 23-25, 1967.

(A) One-quarter of the way into the ebb-tidal cycle the strength of flow varied greatly among the stations. Individual stations exhibited both the ebb- and flood-current directions as density adjustments occurred in the deep pools (stations 11 and 12).

(B) Three-quarters of the way through the ebb-tidal cycle, strong ebb flow had developed at all stations. The influence of channel topography on individual station velocity profiles can best be observed at station 10. Isohaline and isothermal boundaries are shown along the surface line of the two current profile diagrams.


CURRENT VELOCITIES SACO RIVER, MAINE
0
5
10
70°
20
65°
25
30
60°
A.
FLOOD
EBB
ONE-QUARTER EBB
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
5
70°
10
15
65°
20‰
B.
10
FT.
0
0
1/4
MILE
0.0
1.0 F.P.S.
VELOCITY
THREE-QUARTERS EBB

studied by the University of Massachusetts Coastal Research Group. The Merrimack River estuary, for example, which has a fresh water inflow twice that of the Saco River estuary, has a far more regular bottom than the Saco River. Consequently, neither deep pools of trapped sea water nor swift currents over rock ledges develop. As in the Saco, a salt wedge intrudes beneath the surface of the Merrimack River, ponding fresh water on the surface at the upstream end of the estuary during flood. As the tide begins to fall, fresh water streams over the motionless salt water as a result of the rapid ebb flow (Hartwell and Hayes; in Coastal Research Group, 1969). Thus, bottom topography does not appear to be a controlling factor in determining estuary type, but it is, rather, the relation between fresh water discharge and tidal-prism volume which is a controlling factor. As pointed out by Williams (1963), the ratio of width to depth is another important factor.

Comparison with other New England estuaries

The one factor that causes the intense salinity stratification in the Saco River estuary, as opposed to its absence in the Scarboro estuary, is the volume of fresh water which enters the head of each estuary. As in the Merrimack River estuary, two conditions produce stratification in the Saco: the density difference between fresh and sea water and the decrease in water density with increasing

temperature. A change in salinity of $30^{o}/oo$ is 25 times as effective in inducing density stratification as a 10° F change in temperature in fresh water alone. (Sea water at 60° F = 1.025 g/cc; fresh water at 60° F = 0.999 g/cc, at 70° F = 0.998 g/cc.) Direct combination of the salt- and fresh-water masses is further inhibited by the mixing energy necessary to dilute a solution (the sea water) with a given amount of additional solvent (the fresh water). The volume of entering fresh water in relation to the tidal volume of the estuary will therefore determine the degree of stratification possible. Stratification will be best developed in a high tidal-range estuary when a relatively large volume of fresh water enters it. The Essex and Parker (Mass.), Hampton (N.H.), Scarboro and Cousins (Me.) estuaries, in contrast to the Saco, have fresh water input of less than 50 cubic feet per second and, as a result, have no stratification (see Coastal Research Group, 1969). Pritchard (1967) indicated four influences on estuarine hydrography: tidal range, estuary width, estuary depth, and fresh-water influx. The tidal range along the New England coast remains constant at 8 to 10 feet. Width to depth ratios of the six estuaries are also of the same order of magnitude at 100:1; the Saco has a width-depth ratio of 30:1. The fresh-water inflow is therefore the dominant hydrographic control. It appears that, for the estuaries studied by

the University of Massachusetts Coastal Research Group, the volume of fresh water needed to cause stratification is dependent upon the total volume of water entering and leaving an estuary during a tidal cycle. Given the 8- to 10-foot tidal range of the northern New England coastline, this volume of inflowing fresh water must be from 10 to 20 percent of the total tidal volume (Table 1).

Table 1

The ratio of fresh-water discharge to tidal prism volume (in percent) for three stratified estuaries[2]

River	Discharge (cu ft/sec)	6 hr. fresh-water volume $x10^6$ ft^3	9 ft. tidal prism $x10^6$ ft^3	Ratio
Saco	3000	64.8	285.1	22.8%
Merrimack	6000	129.6	748.8	17.6%
Royal	300	6.5	48.8	13.3%

For example, the Royal River in Maine has only 300 cubic feet per second discharge while the Saco has 3000 cubic feet per second, yet the two estuaries are equally well stratified (Barry S. Timson, personal communication, 1970) since the Royal River estuary is about one-tenth the

2. The Merrimack River estuary was studied by Hartwell and Hayes (in Coastal Research Group, 1969) and the Royal River is under study by Barry S. Timson.

tidal-prism volume (surface area of the estuary times the tidal range) of the Saco River estuary. The Merrimack River has twice the mean annual discharge of the Saco River, but it also has a tidal-prism volume of greater than two times that of the Saco estuary. In summary, fresh water-salt water stratification is the factor that causes the real dissimilarity between the Saco and the Scarboro estuaries on the Old Orchard crescent.

INTERTIDAL SAND BODIES AND BEDFORMS

As the changing elevation of the tide causes water masses to move back and forth in the estuaries, the friction between the moving water column and the unconsolidated channel bottom causes the accumulation of sediment in bedforms which reflect dominant direction of movement, water depth, and current velocity. In New England estuaries, these bedforms are best seen on large sand deposits located near their inlets. These intertidal sand bodies and their bedforms in the Saco Bay area provide good evidence of flood-dominated sediment transport to compare with that provided by the hydrography of the area.

Camp Ellis bar

All that remains of the former intertidal sand bodies that once surrounded the mouth of the Saco River is the Camp Ellis bar. This sand body is tied to the barrier

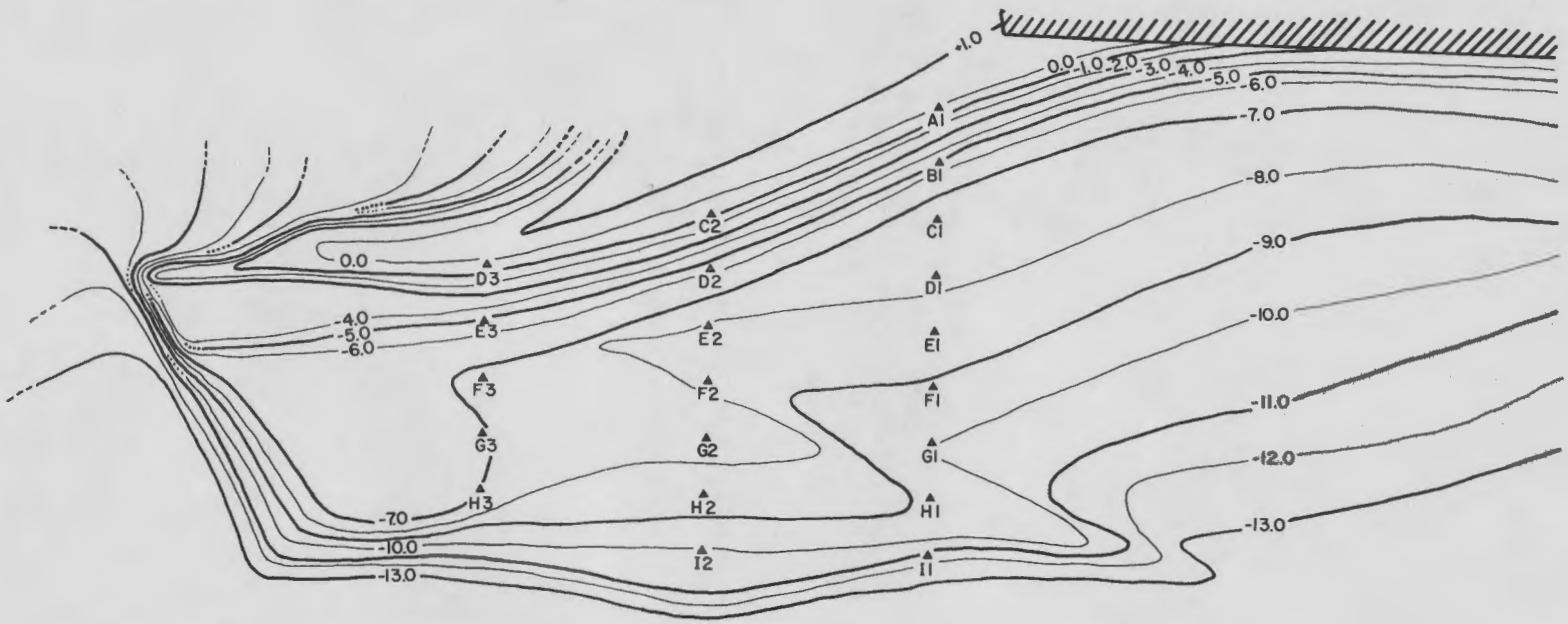
beach at the base of the river-entrance jetty and now extends upriver beyond two old piers in the Camp Ellis boat basin (Fig. 15). The crest of this flood-oriented spit (Fig. 16) is above normal high water and deposition on the crest occurs only during storm surges. Extending into the river from the base of the spit beach face (altitude -7.0 feet, Fig. 16) is a flat terrace. A long ebb spit trails away from this terrace. The channel margin of the ebb spit is covered with a field of linear-megaripples (wavelength 8 to 10 feet, amplitude 0.8 foot) composed of coarse feldspathic sediment, which reverse their slip-face orientations with each tidal cycle. Cuts through the linear-megaripples show details of the reversals of the slip-face orientations (Figs. 17C,D; Fig. 18B). Seventy percent of the crossbeds remain flood-oriented. Thus the ebb current is capable of reversing the exterior form while still leaving a record of the flood current preserved in the megaripple crossbedding. The flood-tidal current asymmetry is diminished by the fresh-water flow and it is probably the original topographic height of the flood-oriented linear-megaripples that prevents the late ebb-stage currents from erasing the flood-oriented crossbedding.

Figure 15. Oblique aerial photograph of the Camp Ellis bar at low tide, August 16, 1968. Flood direction is from the bottom to the top of the picture. Flood-dominated growth of this bar is extensively modified by ebb currents. Ebb-oriented linear-megaripples, which reverse to a flood orientation during flood, can be seen covering the channel margin.

N

Figure 16. Topographic map of the Camp Ellis bar. The bar was initiated by a major northeast storm in November, 1962. It is a flood-directed structure attached to the barrier beach.

INTERTIDAL TOPOGRAPHY – CAMP ELLIS TIDAL BAR



CONTOUR INTERVAL 1.0 FT.
MAPPED AUGUST 9, 1967
▲ SAMPLE GRID POINTS
DATUM IS MEAN SEA LEVEL

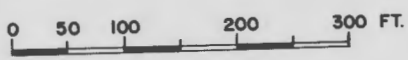
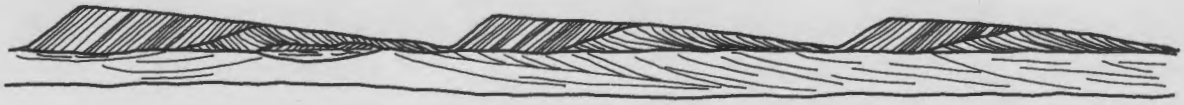


Figure 17. Internal structures of bedforms (linear-megaripples) of Scarboro and Camp Ellis bars. Drawings of four selected trenches show a "herringbone" pattern of cross-bedding. The Scarboro bedforms, located in front of the Pine Point jetty, were formed by a spring tide ebb current. The same ebb tide caused much less modification of bedforms on the Camp Ellis bar in the Saco River.

INTERNAL STRUCTURES OF BEDFORMS
IN
SCARBORO AND CAMP ELLIS BARS

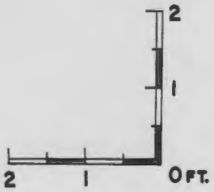
AUGUST 12, 1968



A EBB-ORIENTED STRAIGHT-CRESTED MEGARIPPLES
SCARBORO SWASH BAR

B EBB-ORIENTED STRAIGHT-CRESTED MEGARIPPLES
SCARBORO SWASH BAR

C EBB-ORIENTED STRAIGHT-CRESTED MEGARIPPLES
UPPER PART OF CAMP ELLIS BAR



D EBB-ORIENTED STRAIGHT-CRESTED MEGARIPPLES
LOWER PART OF CAMP ELLIS BAR

Figure 18. Photographs of internal structures of bedforms of the Scarboro and Saco River estuaries. Ebb-oriented linear-megaripples show flood-oriented crossbedding. August 12, 1968.

(A) Scarboro swash bar. Wavelength is 5.8 feet; amplitude is 0.5 foot. Sketch A of Figure 17.

(B) Camp Ellis bar at Saco River. Wavelength is 5.5 feet; amplitude is 0.7 foot. Sketch C of Figure 17.

A

B

Scarboro ebb-tidal delta

Vertical aerial photographs taken on July 27, 1967, show areas of the Scarboro estuary subjected to detailed mapping and sampling (Figs. 19 and 20). The estuary was essentially unmodified by man until 1956, when a dredging and jetty construction project was undertaken by the Corps of Engineers in order to provide an 8-foot-deep, self-flushing channel. The dredging was first done in October of 1956, repeated in 1962 when the jetty was constructed, and carried out a third time in 1966 as a maintenance project (U.S. Army Corps of Engineers, 1956, 1962, 1966). The topographic map of June 25, 1967 (Fig. 21) is of a large swash bar just south of the inlet and its extension to the dredged channel.

Prior to 1956 the end of Pine Point was an accretional series of vegetated storm-beach ridges. The growth of the point, dating from the end of the Presumpscot marine transgression-regression and well-documented over 350 years of habitation, was aided in 1956 by the deposition of some 187,000 cubic yards of dredged spoil, building the ridge and swale area of Pine Point to +12 feet M.L.W.

Aside from man's influence, three natural forces operate around the mouth of the Scarboro estuary: littoral drift, surf, and ebb- and flood-tidal currents. Littoral

Figure 19. Vertical aerial photograph of the Scarboro ebb-tidal delta complex taken July 27, 1967. The linearity of the swash bar (left) breaks up into longitudinal lobes of sand under the influence of tidal currents in the Scarboro estuary inlet. (Photograph courtesy of U.S. Army Corps of Engineers.)

0 600 1200 1800

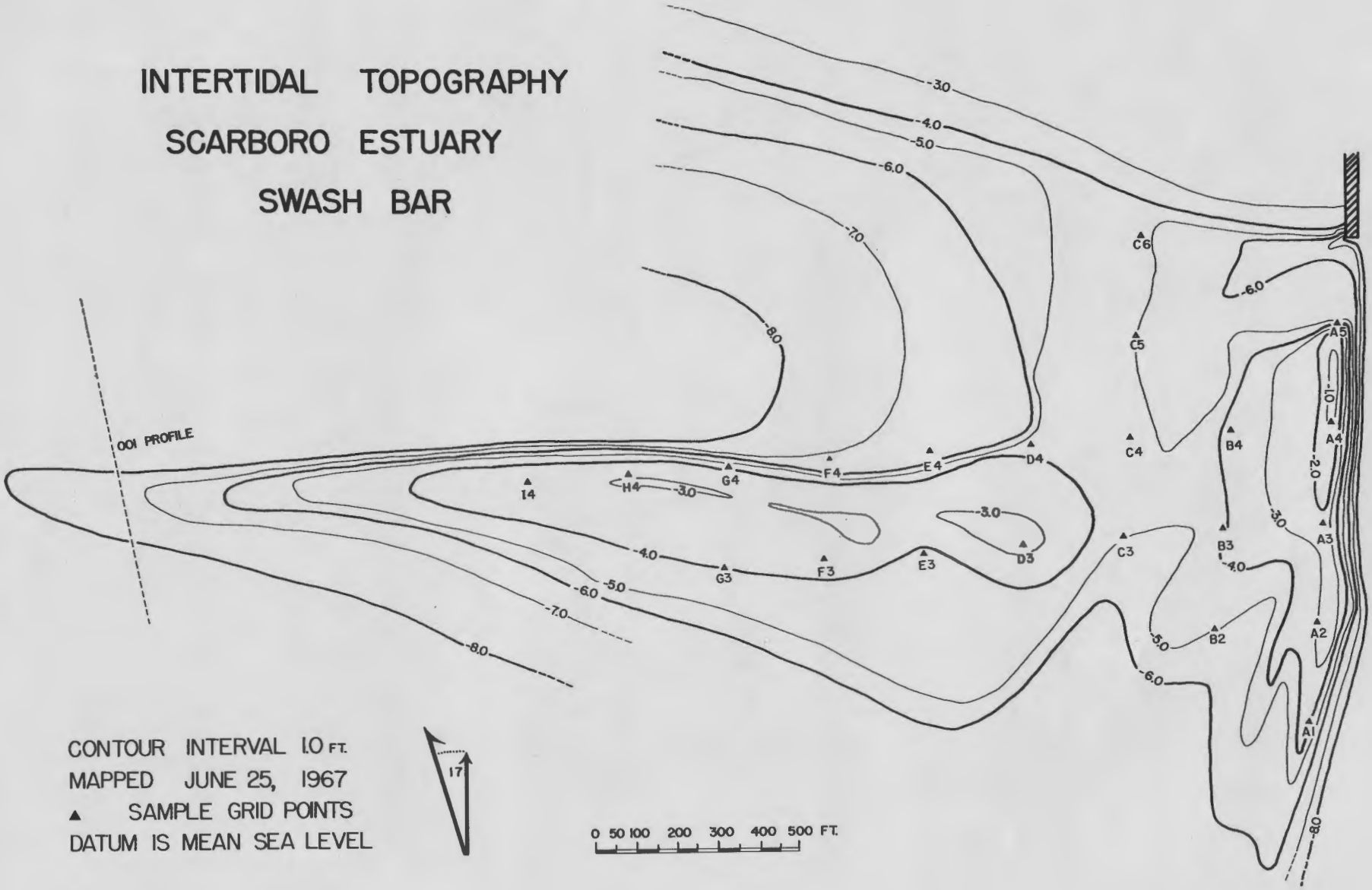
FEET

Figure 20. Vertical aerial photograph of Scarboro estuary flood-tidal delta taken July 27, 1967. This is the only intertidal sand-wave field in the Saco Bay area. (Photograph courtesy of U.S. Army Corps of Engineers.)


0
600
1200
1800
FEET

Figure 21. Intertidal topography of Scarboro estuary swash-bar complex. This sand body changes from a swash bar at the west end, where profile 001 crosses it, to a subaqueous sand lobe that surrounds the entrance to the Scarboro channel. Ebb-oriented megaripples (Fig. 19) were formed in the vicinity of sample stations A5 to B4 and scour-megaripples in the runnel trough at station C6. The ridge (H4, F3, D3) reflects wave influence from the southeast.

INTERTIDAL TOPOGRAPHY
SCARBORO ESTUARY
SWASH BAR



CONTOUR INTERVAL 1.0 FT.
MAPPED JUNE 25, 1967
▲ SAMPLE GRID POINTS
DATUM IS MEAN SEA LEVEL

drift is responsible for transport of material toward Pine Point, where it is incorporated into the tidal delta. The southeasterly wave direction, with 1- to 3-foot-high, 3- to 5-second-period waves, is significant in building the swash bar during most periods of calm weather. This surf crosses the bar crest, resulting in 125 feet of slip-face movement during 1967-68, as documented by subaqueous profiles run across the swash bar simultaneously with the Old Orchard #1 beach profile. Ebb and flood of an 8.8-foot tide led to the formation of megaripple bedforms and the modification of the wave-built topography of the channel-margin zone between the swash bar and the ebb-delta lobe. The main lobe of the ebb-tidal delta, a spoon-shaped bar of sand off the channel entrance, is totally subaqueous and is formed by deposition of ebb-channel bedload material carried beyond the harbor entrance into deeper water. The ebb-tidal delta, then, is the result of the interaction of two separate and distinct processes--the surf and tidal currents.

The tidal exchange across the portion of the bar near the jetty also results in the formation of lunate ripple bedforms (0.8-foot average wavelength) during ebb flow. During spring tides, greater current velocities attending the increased tidal range cause linear-megaripples

(7.2-foot average wavelength; 0.6-inch amplitude) to form along the high margins of the estuary channel (Fig. 17). These are ebb-oriented, but cross sections show that 40 to 50 percent of their volume is of flood-oriented cross-bedding (Figs. 17 and 18). Scour-megaripples, which also show ebb orientation and which show no preserved flood crossbedding, develop along the channel margin and in the large runnel between the swash bar and beach (Fig. 19). The waves construct the swash bar largely from sand transported toward Pine Point by littoral drift, while the ebb and flood of the tide combine and interfere with the waves to produce the features marginal to the channel.

Scarboro flood-tidal delta

A flood-tidal delta has developed directly north of the constriction in the estuary channel at Ferry Rock (Fig. 24, page 75) due to the sudden deceleration of currents passing through this constriction. The flood-tidal delta, known locally as Turner's Bar, was mapped by plane table, and the contour map (Fig. 22) depicts a large sand-wave bedform locality on the delta, the only intertidal one in the thesis area. During the summers of 1967 and 1968 careful measurements were made from a pair of stakes to show sand-wave migration; the daily tidal range on the day of each wave-migration reading is given with the

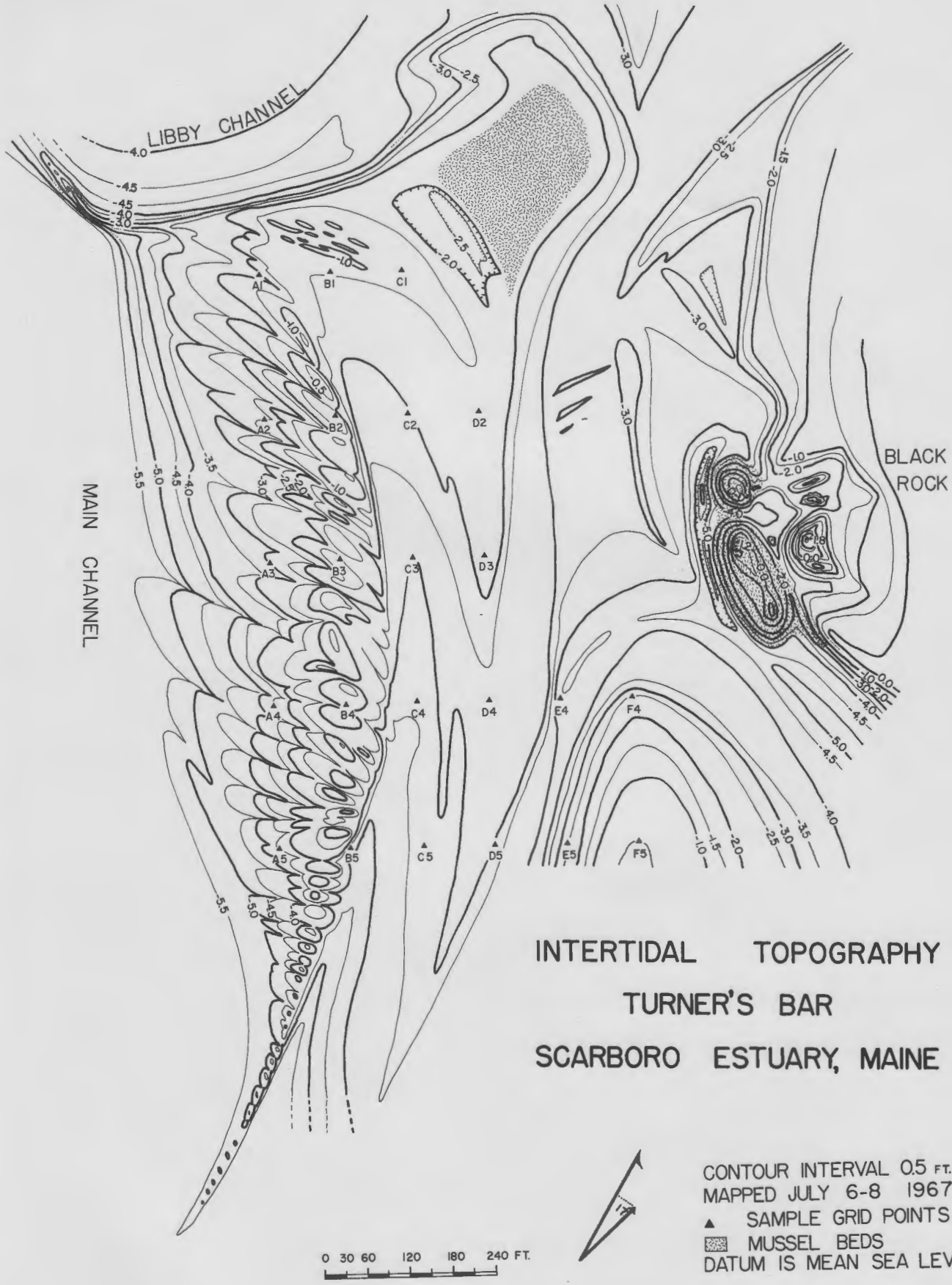
Figure 22. Intertidal topography of the Scarboro estuary flood-tidal delta (Turner's Bar). This delta can be divided into four parts:

(1) The active sand-wave area nearest the main channel, containing 35 slip faces.

(2) The ebb shield and spit at sample stations B1 and C1. The Libby River channel joins the main channel at the northwest and forms this ebb spit.

(3) The sandy clam flat between the sand waves and the east shore. Mussels are beginning to establish themselves on this flat.

(4) Black Rock and minor channels. The Libby River divides and flows out past the mussel-encrusted Black Rocks to the east of the sand flats. Previous records hint at a former main channel past this rock outcrop and hugging the Prouts Neck side of the shore to Ferry Rock.



INTERTIDAL TOPOGRAPHY
TURNER'S BAR
SCARBORO ESTUARY, MAINE

CONTOUR INTERVAL 0.5 FT.
MAPPED JULY 6-8 1967
▲ SAMPLE GRID POINTS
MUSSEL BEDS
DATUM IS MEAN SEA LEVEL

migration rates on Table 2.

Table 2

Migration of sand waves
(in feet)

Date	Tidal Range	Feet From Stake 1	Movement During Interval	Feet From Stake 2	Movement During Interval
August 5, 1967	10.6	---	---	---	---
8, 1967	11.3	1.4	1.4	1.8	1.8
12, 1967	9.8	4.6	3.2	5.1	3.3
15, 1967	8.2	7.9	3.3	8.7	3.4
22, 1967	9.5	11.2	3.3	13.5	4.8
29, 1967	6.1	12.0	0.8	14.1	0.6
Sept. 30, 1967	8.1	19.3	7.3	21.1	7.1
Oct. 1, 1967	9.8	30.2	10.9	33.1	11.9
June 29, 1968	9.4	---	---	---	---
July 3, 1968	9.4	---	---	0.8	0.8
7, 1968	10.6	1.5	1.5	2.1	1.3
9, 1968	11.0	3.1	1.6	4.1	2.0
17, 1968	9.6	9.7	6.6	12.0	7.9
22, 1968	10.5	9.9	0.2	12.2	0.2
August 12, 1968	9.7	18.5	8.6	21.6	9.4
14, 1968	9.3	18.6	0.1	22.2	0.6

The fourteen-day cycle in tidal ranges goes from a spring-tide maximum of 12.4 feet to a neap-tide minimum of 4.9 feet. The average variation is from 11.6 feet to 5.8 feet. The sand waves moved almost exclusively during the 5-day period of spring tides, with no movement taking place during neap tides. During a spring tidal cycle, the average migration was 3.5 feet; thus, if this is considered an average rate, the bedform moves 90 feet in a year.

An idea of the sediment volume transported over this delta can be gained by computing the average sand-wave volume. Bedform wavelength averages 35 feet, amplitude 0.5 foot, and the length of the crest about 120 feet. This is an average of 2100 cubic feet of sediment per wave. If, as in 1967, 35 sand waves are migrating at once, than a total sand volume of 73,500 cubic feet or 2,720 cubic yards moved in one year onto the flood-tidal delta alone. A series of photographs illustrates this sand wave migration during various tidal ranges (Fig. 23).

On the extreme landward end of the delta an ebb-dominated area consists of an ebb shield and ebb spit (terminology by Coastal Research Group, 1969). This topographically high, blunted end of the flood-tidal delta, which faces the ebb current, is similar to the landward portion of flood-tidal deltas in other New England estuaries. The ebb-tidal current strikes the obstruction and is forced to go over or around it. As the water depth decreases and the current increases, ripples become megaripples and, in the final stages before emergence, some plane-bed flow may develop. After the delta has emerged, the swift current streams around one or both sides of the sand body, carrying with it sand to form an ebb-oriented trailing spit, which is

Figure 23. Series of photographs showing sand-wave migration and modifications to the ebb spit, summer, 1968; Scarboro flood-tidal delta.

(A) Oblique aerial photograph looking west from Black Rock to Pine Point, showing general view of sand-wave field.

(B) The stake was implanted in the slip face of one of the sand waves. June 29, 1968.

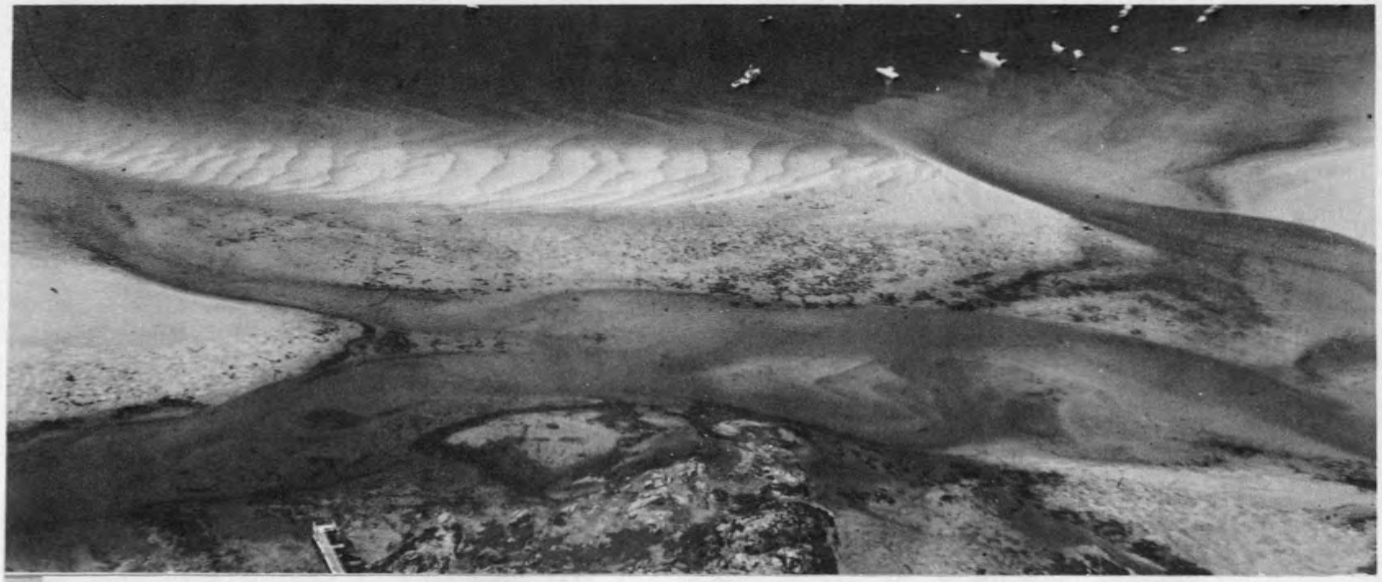
(C) Under the weak influence of a neap tide period, only 0.8 foot of movement was recorded by July 3, 1968.

(D) Continuing this neap tide period, 1.5 feet of movement had occurred by July 7, 1968.

(E) Responding to the increased velocities and depths occurring during the subsequent spring tide, 9.7 feet of migration took place by July 17, 1968.

(F) By August 15, 1968, two spring tide periods after the start on June 29, 1968, the sand-wave slip face had moved a total of 18.6 feet.

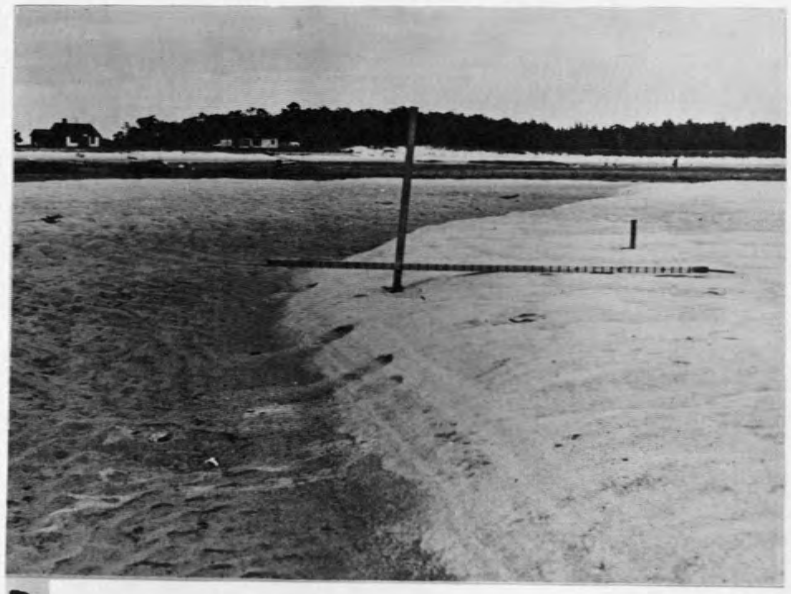
(G) Ebb-oriented scour-megaripples (wavelength, 6 feet; amplitude, 1.2 feet) formed on the ebb spit.



A

B

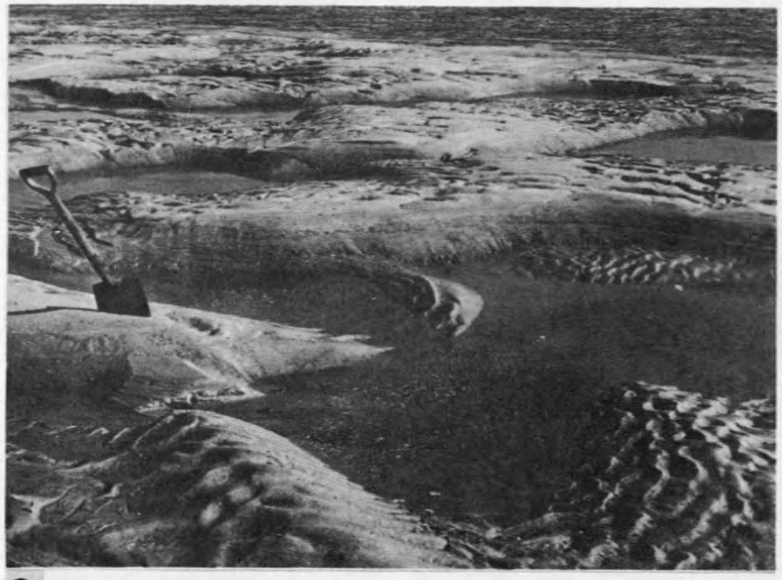
C



D

E

F



G

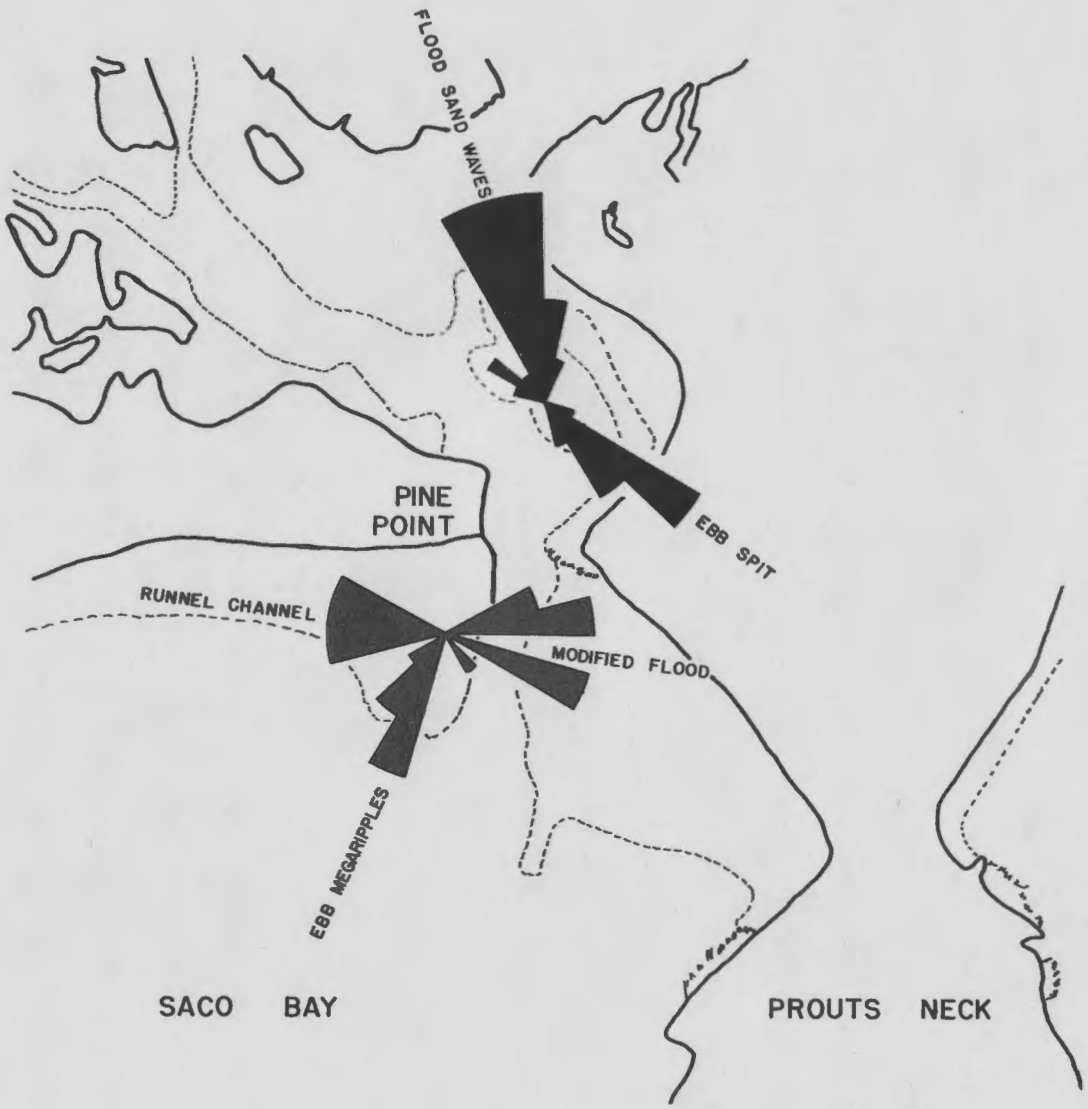
usually covered with ebb-oriented scour-megaripples (Fig. 23G). The ebb-shield is thus an ebb-modified subdivision of an otherwise flood-oriented sand body.

Scarboro estuary bedform orientations

A composite of 82 average slip-face orientations (Fig. 24), based on five readings at each locality on Turner's Bar, the ebb-tidal delta complex, and the lower harbor channel margins, points out the dominance of the flood transport direction. The crest of Turner's Bar, with 35 sand-wave slip faces, has a flood-oriented slip face mode of N. 15° W. Ebb-oriented scour-megaripples, on the other hand, are found only on the ebb spit and channel margin.

A fanning-out of the ebb flow exiting from the Pine Point-Ferry Rock constriction causes a diversity in slip-face orientations. One ebb-current direction maximum is shown by linear-megaripples on the bar crest. A second maximum orientation trends west and arises from scour-megaripples in the runnel trough. Modified flood directions are found as preserved crossbedding in ebb-oriented linear-megaripples. This crossbedding, however, does not extend below the bedform depth (Fig. 17), indicating a slow rate of upbuilding with constant reworking and planation.

Figure 24. Rose diagrams of intertidal slip-face orientations of the Scarboro estuary. The flood-oriented bedform readings are all straight-crested sand waves or preserved planar crossbedding (modified flood on figure). Bedforms on the ebb spit and runnel channel are scour-megaripples with festoon crossbedding. The ebb-oriented linear-megaripples are developed on the high margins of the swash bar of the ebb-tidal delta near the estuary channel. All measurements made at low tide.



INTERTIDAL SLIP FACE ORIENTATIONS SCARBORO HARBOR AREA

N

SCALE

0 yards 500

ROSE PLOTS OF 82 READINGS AT LOW WATER

Until the tidal current-velocity asymmetry is considered, the preponderance of flood-oriented bedforms, which migrate up the general stream gradient, poses a difficult problem. The high velocities late in the flood stage produce bedforms which remain undisturbed throughout the early ebb when velocities are low. These sedimentary structures are preserved on the higher flats and tidal deltas because they are already exposed by the time the ebb currents are strong enough to reverse the slip-face orientation. The shielding effect of the elevated upstream end of the tidal delta adds to this, all providing an excellent explanation for sedimentary current indicators that are oriented 180° to stream gradient within the intertidal zone (Daboll, 1969). Critical examination of the sediment comprising these bedforms yields more evidence favoring transport of sand in the upstream direction by tidal currents.

SEDIMENTS

The analysis of sediment size distribution and grain texture (roundness, polish, and mineralogy) in the Saco Bay area contributes further to the precise determination of the various sources of the estuarine sediments. Especially significant is its aid in delineating tidal control

of sedimentation in the Scarboro estuary. The Saco River sediment contains coarse yellow feldspar (greater than 2.0ϕ) and fine white feldspar (less than 2.0ϕ). Since these two feldspar species can be separated by the natural environment (by selective sorting), and because of their presence on both the beachfront and in the Scarboro estuary, they are of interest to this analysis.

Ninety-six samples from the 210 which were analyzed for size were sieved and subsamples collected for the three sizes 0ϕ, 2ϕ, and 4ϕ. The three fractions were mounted either in Canada balsam and kept for permanent preservation after counting or placed on a millimeter slide and counted but not saved. The point count was divided into nine groups: rock fragments, quartz, feldspar (yellow, gray, and white), shell fragments, mica (biotite and muscovite), and heavy minerals. Notations were also made on iron staining, polish, and roundness for the quartz and feldspar fractions.

Mineralogy

Useful information from Saco Bay sediment mineralogy is obtained in spite of the problem introduced by glacial mixing of suites from various source areas. The situation is, moreover, complicated by the late Pleistocene and Holocene submergence (locally to the present 210-foot contour)

and the subsequent reemergence of the coastline which has left the present coastline in a state of disequilibrium regarding sediment distribution. Examination of the heavy mineral suite shows no marked presence or absence of any particular mineral in the samples studied. Concentrations vary depending on wave and current sorting action. For example, high wave energy on pocket gravel beaches will concentrate garnet and magnetite while amounts of tourmaline, zircon, rutile, and amphibole seem to remain uniform in their distribution percentages throughout the bay.

Metamorphic rock fragments. Very distinctive chlorite-grade schists, sandy dolomites, greenstones, and argillites all outcrop in or near the bay. The Silurian and Siluro-Devonian formations are listed in the partial stratifraphic column (Table 3). Especially useful in sand-size fragment identification are the Berwick, Spring Point, and Scarboro Formations, as the rock fragments from these units are easily distinguished from the higher grade metamorphic rocks outside the Old Orchard area.

Table 3

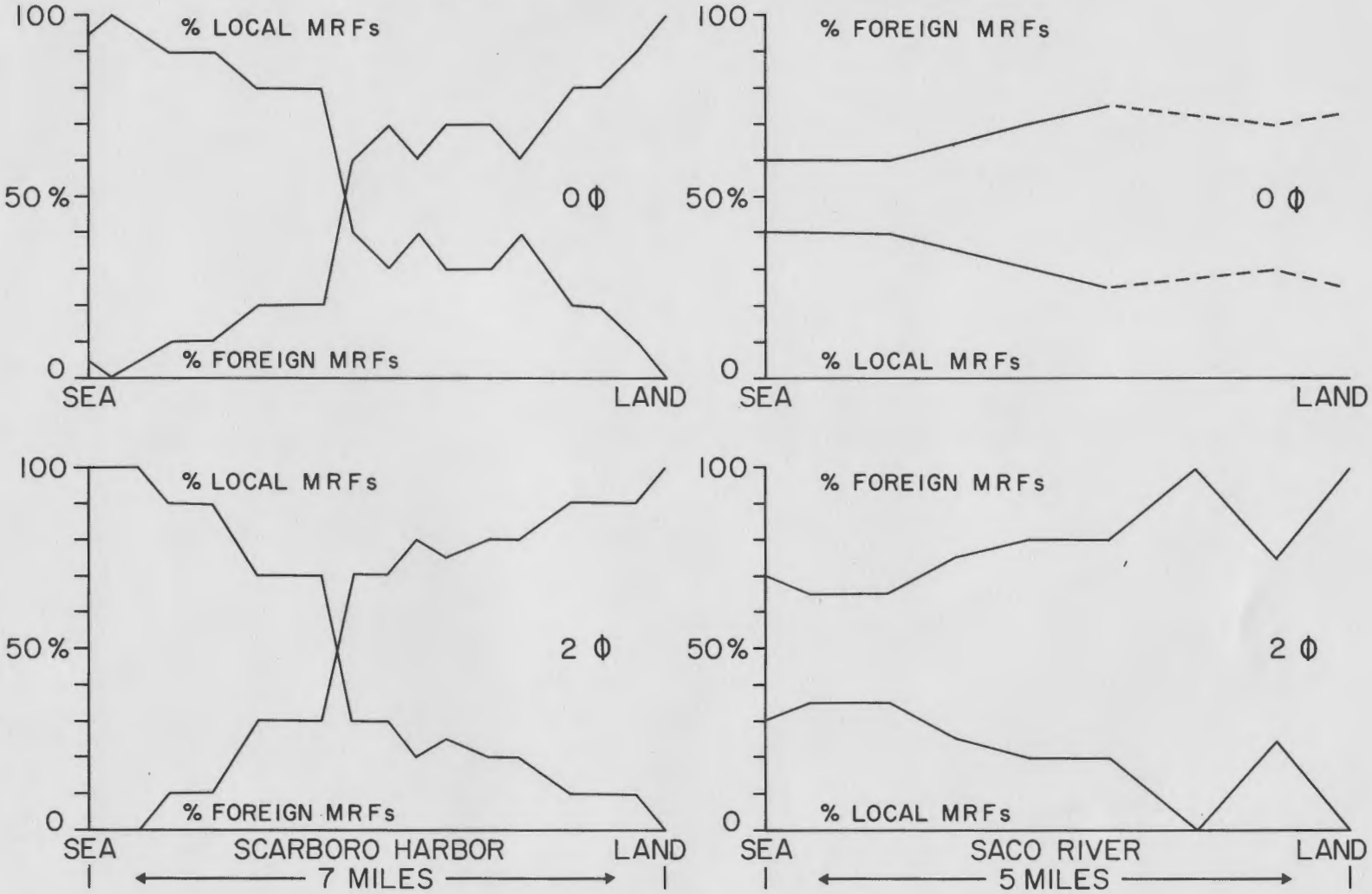
Partial stratigraphic column for Saco Bay area in York and Cumberland counties, Maine (from Maine State Geologic Map, 1967)

Map Symbol	Formation Name	Characteristics
Dg	Biddeford Granite	Biotite and mus-biotite granite
DSps	Scarboro Fm	Sulfide-rich phyllite
DSlm	Spurwink Fm	Limestone with phyllite interbeds
DSsg	Spring Point Greenstone	Mafic volcanic tuffs and flows
DSsq	Cape Elizabeth Fm	Thin-bedded phyllite and quartzite
DSq	Berwick Fm	Calcareous shales
Sa	Eliot Fm	Shale and siltstone
Scq	Kittery Fm	Calcareous siltstone and shale

The percentage of local metamorphic rock fragments (MRF's) undergoes a radical change from 100 percent of a sample in the outside approaches to the Scarboro harbor to 0 percent six miles up the Nonesuch River near the salt-fresh water boundary. Figure 25 demonstrates this dramatic shift in MRF content for both 0ϕ and 2ϕ fractions in the Scarboro and Saco Rivers. The Saco system, vastly larger than the Scarboro and with its source area in high-grade crystalline rocks, has a far greater volume of igneous rock fragments and high-grade MRF's to mix with locally derived sediments. The Scarboro system, with its inconsequential fluvial discharge and strictly local drainage basin, gains a significant contribution of MRF's by the breakup of nearby Prouts Neck sea cliffs

Figure 25. Percentage of local versus foreign metamorphic rock fragments in the Scarboro and Saco River estuaries from the inlet to the upper limit of tidal influence. The abrupt change in metamorphic rock fragment type in the Scarboro estuary sands shows most dramatically the landward transport of sand by flood-tidal currents over the lower and largest portion of the estuary. The crossover occurs at the same place that flood-oriented bedforms, feldspar polish, and coarse gray feldspar cease to be significant. The Saco River, with its greater bedload of sediment, masks the contribution made by disintegration of local outcrops and dilutes the amount of change in MRF types.

PERCENTAGE OF LOCAL VS. FOREIGN METAMORPHIC ROCK FRAGMENTS
IN
SCARBORO HARBOR AND SACO RIVER SANDS

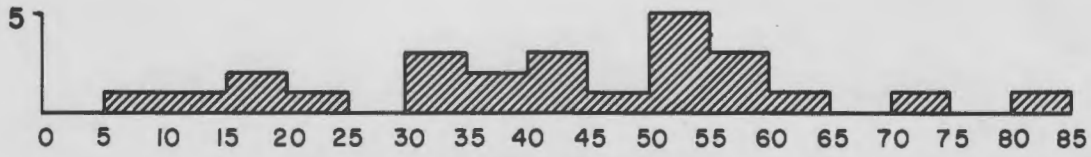


and estuary channel-bottom bedrock. This added source also contributes to a contrast in sediment feldspar mineralogy between the Saco and Scarboro estuaries as illustrated in the bar graphs (Fig. 26).

Feldspars. At Pine Point in the Scarboro system, the beach is composed of fine quartz and mica plus a small percentage of white feldspar, while the bars offshore have abundant coarse quartz and MRF's, with a little feldspar of a gray-white color. For both areas, the 0ϕ fraction consists, in descending order of percentage occurrence, of quartz, local rock fragments, white and gray feldspar, shell fragments, and heavy minerals. Histograms for the 0ϕ interval show a segregation in the yellow and gray feldspars for the Scarboro estuary (Figs. 27 to 29). The upper estuary sands have significantly more yellow feldspar than gray, while the lower harbor has virtually no yellow feldspar and up to 16 percent gray feldspar in the 0ϕ fraction. Binocular microscopic examination of 30 samples from Pleistocene deltas in the Scarboro valley and from Saco River flood-plain deposits seems to indicate a uniform percentage of gray and gray-white feldspar of from 2 to 6 percent of the total feldspar content. The remaining feldspars are 10 to 25 percent yellow and pink potassium feldspars. The sediment in the lower Scarboro harbor has been depleted in the coarse (0ϕ) yellow feldspars and enriched in the coarse gray and gray-white feldspars eroded from pegmatite

Figure 26. Percentages of yellow feldspar in 0ϕ and 2ϕ (combined) sands in the Saco River and Scarboro estuaries. The Saco sediment owes its yellow color to an average of 50 percent yellow feldspar out of the total feldspar content. The Scarboro sand lacks this yellow constituent and consequently is grayish-yellow in color.

PERCENTAGES OF YELLOW FELDSPAR IN SACO RIVER AND SCARBORO HARBOR COARSE SAND FRACTIONS



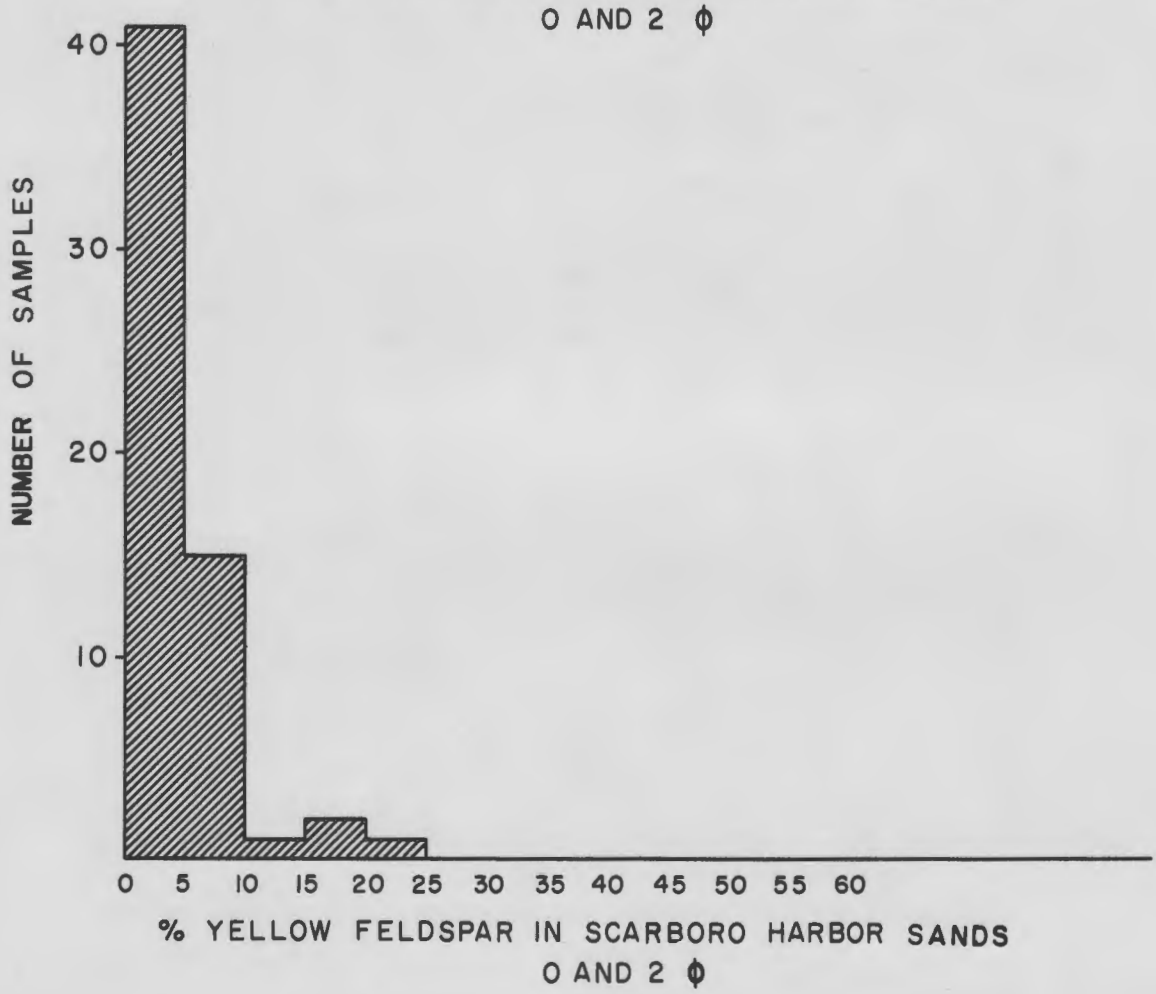


Figure 27. Percentages of gray versus yellow feldspar in upper and lower Scarboro Harbor 0ϕ-size sand. For 0ϕ ranges in the Scarboro Harbor the percentage of gray feldspar (derived from local schists and pegmatites) decreases upstream while the yellow feldspar (derived from Pleistocene delta deposits) increases. The upstream lag deposits are especially rich in the coarse yellow feldspar.

PERCENTAGES OF GRAY vs YELLOW FELDSPAR IN UPPER AND LOWER SCARBORO HARBOR SANDS

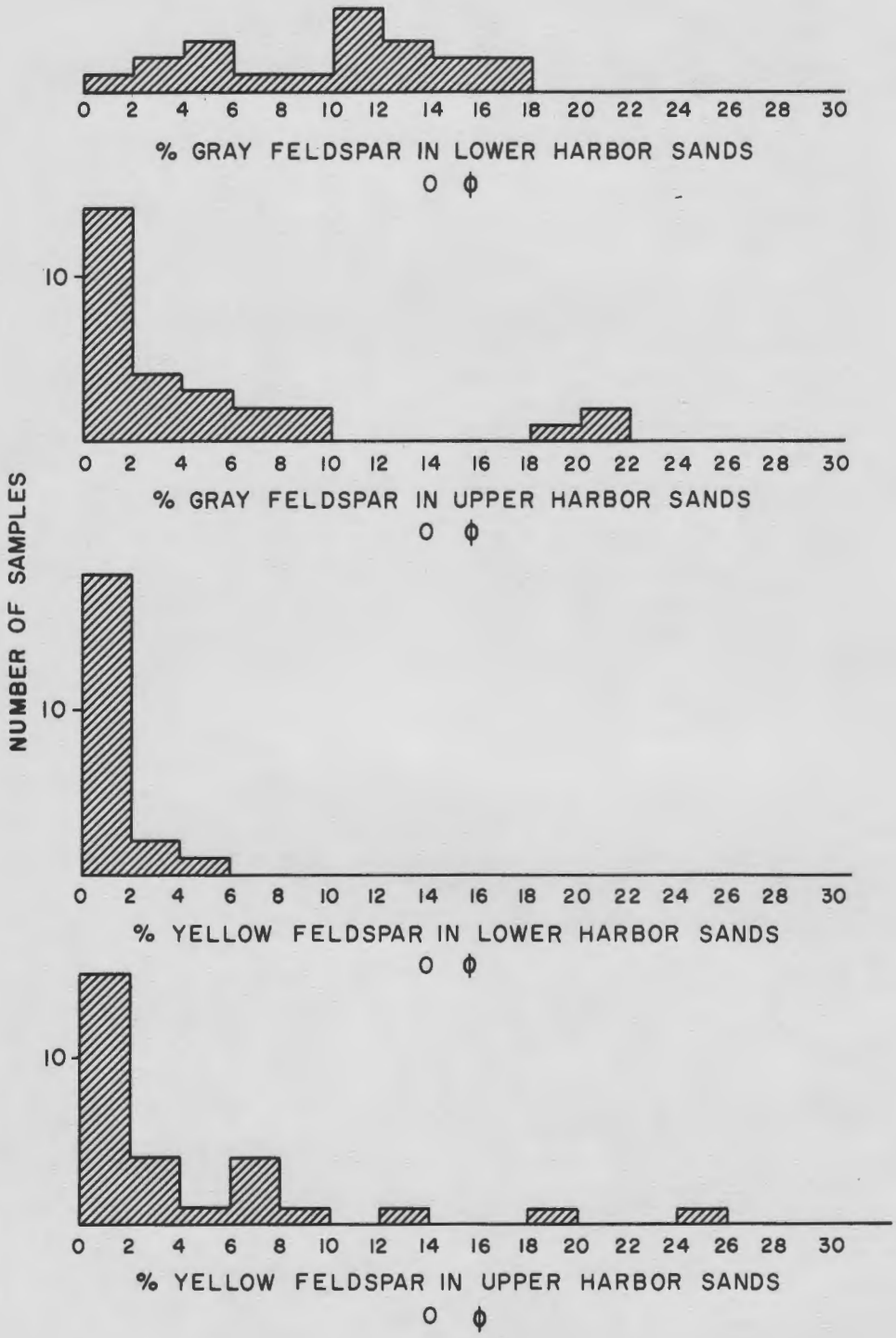


Figure 28. Percentages of gray feldspar in the 2ϕ fraction in upper and lower Scarboro Harbor sands. The gray feldspar content in the 2ϕ fraction shows little difference from one end of the Scarboro estuary to the other.

PERCENTAGES OF GRAY FELDSPAR IN UPPER AND LOWER SCARBORO HARBOR SANDS

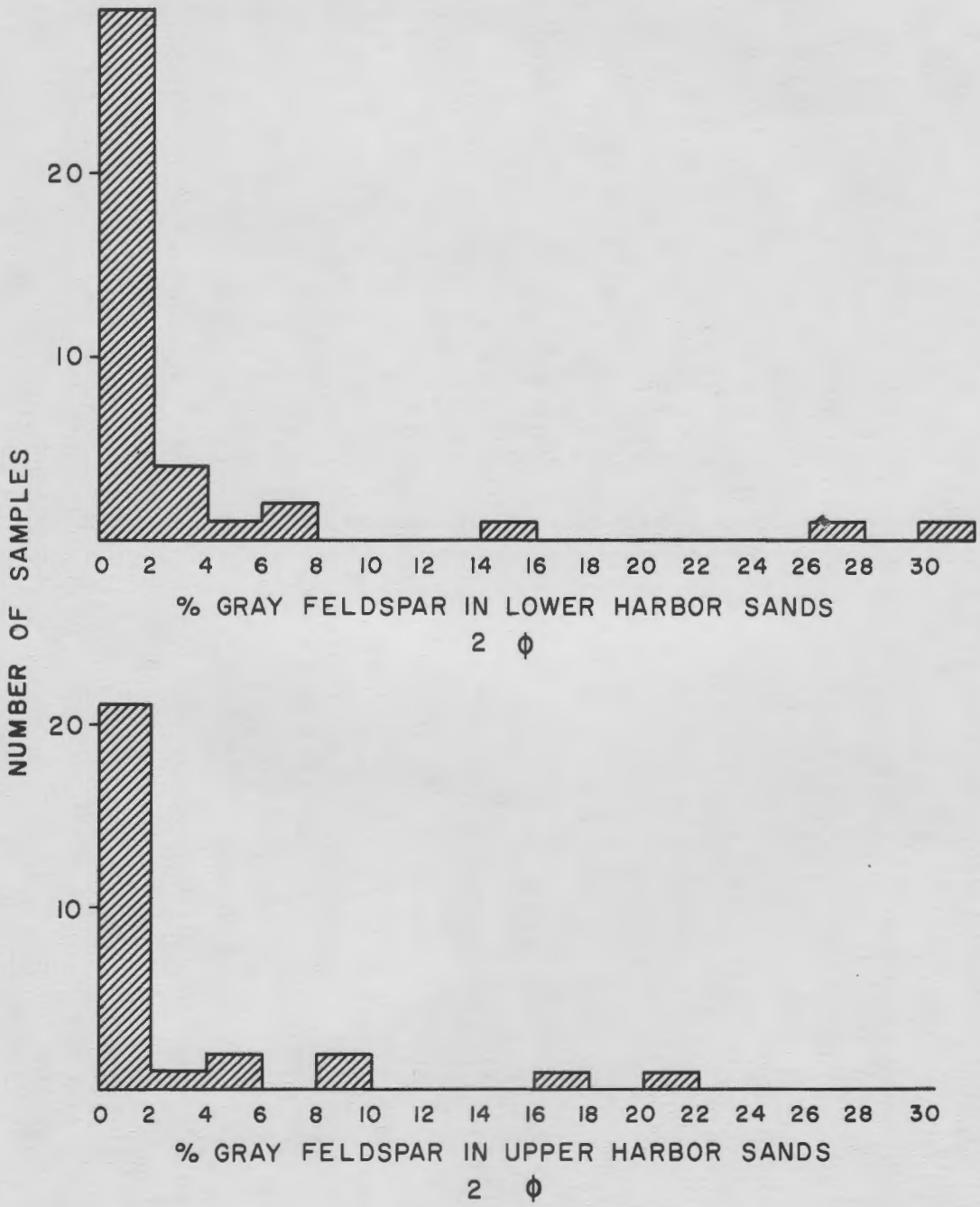
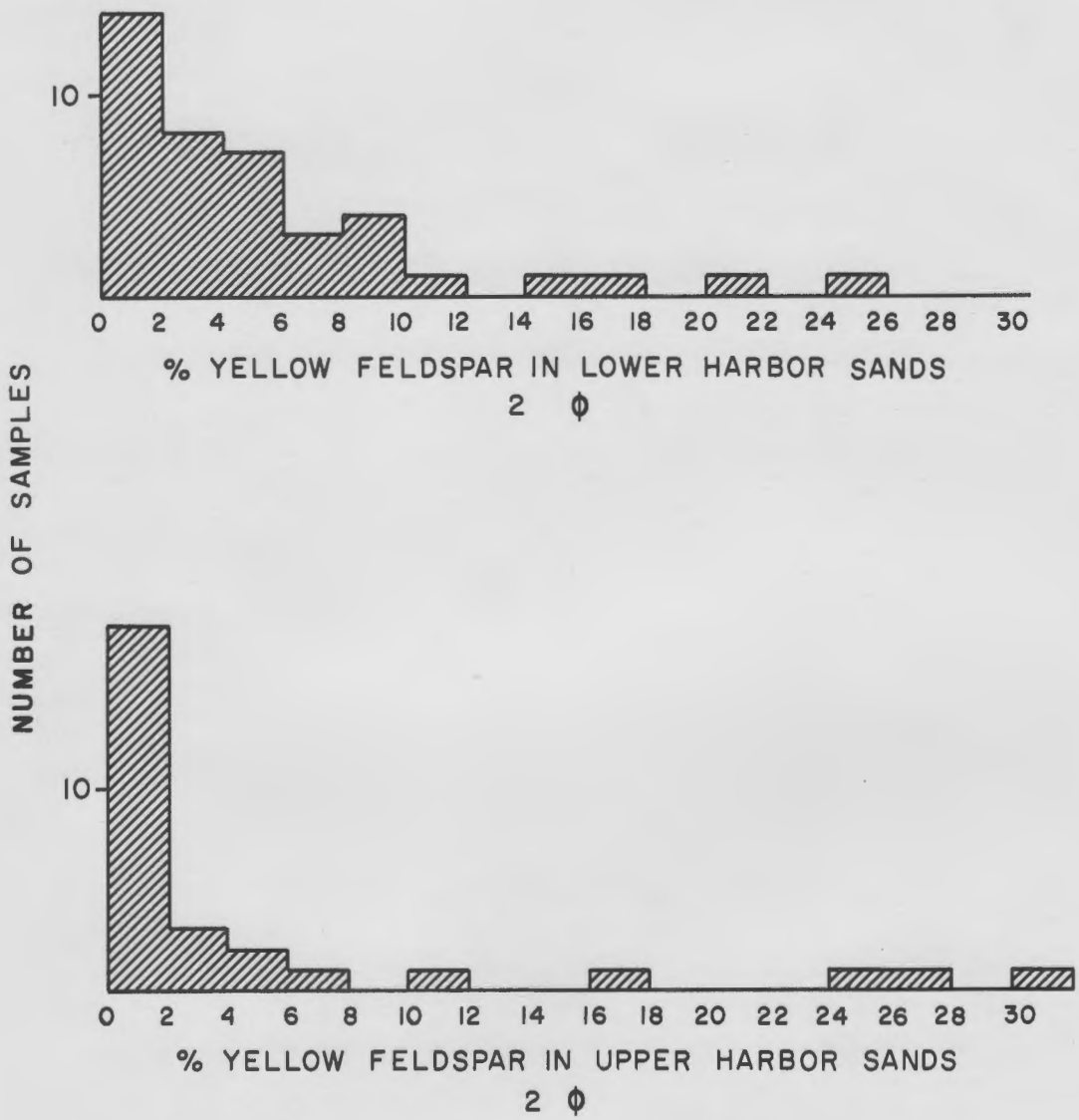


Figure 29. Percentages of yellow feldspar in the 2ϕ fraction in upper and lower Scarboro Harbor sands. The 2ϕ yellow feldspar content of the lower estuary is greater than that from the upper estuary Pleistocene deposits due to the addition of Saco River sediment transported to the Scarboro harbor by littoral drift. Yellow feldspar is much more abundant in the Saco River sediments than in any of the Pleistocene deposits accessible to the Scarboro drainage system.

PERCENTAGES OF YELLOW FELDSPAR IN UPPER AND LOWER SCARBORO HARBOR SANDS



veinlets in the local sea cliffs. The yellow feldspar, which appears to be most abundant in coarser sizes (greater than 0ϕ), is selectively left behind in the central zone of Old Orchard Beach.

In finer fractions there appears to be no enrichment of the gray feldspar, probably because disintegration of the local bedrock has not progressed far enough to produce abundant sizes less than 2ϕ. The finer yellow feldspar, which is present in the Old Orchard beach sediment, is transported to Pine Point and is incorporated in the deposits of the Scarboro estuary. The effect of long-shore transport and flood-tidal current deposition has been to change the feldspar mineralogy of the 0ϕ sizes. This shows up in Figures 27 to 29 and points to the accretion in Scarboro Harbor of material not derived from the watershed of the Scarboro estuary.

Grain texture

Polish and roundness. The degree of polish and roundness of the quartz and feldspars in the 0ϕ fractions underlines the distinct separation between upper and lower Scarboro estuary sediments already noted in the discussion of feldspar mineralogy. A typical sample from the Scarboro harbor entrance contains subangular to subrounded feldspar grains which are polished to a marked degree. The quartz,

too, is free of the iron-staining typical of upper estuary sand, and the sharp edges and points have been modified by polishing and rounding. The percentage of polished and stain-free grains drops from 70 percent of the 0ϕ fraction in the harbor entrance to near zero 3 miles upstream from the Pine Point entrance. The 50-percent crossover point between local and foreign metamorphic rock fragments is also 3 miles from the harbor entrance (Fig. 25). The equivalence of both sand mineralogy and the appearance of polished feldspar and quartz grains in the flood- and ebb-tidal deltas agrees well with the bed-form and hydrographic data which indicate a dominance of transport and deposition of sediment by flood-tidal currents in the lower portion of the Scarboro estuary.

Grain size. The grain-size parameters for the 210 samples help establish the relative influence of energy conditions and sediment supply on the overall sand-size distribution of the intertidal sand bodies and of the tidal channels. Fifty of the samples contained more than 5 percent of material finer than 4ϕ and warranted pipette analysis. The remainder were washed, dried, split into 27-gram samples, and run in the University of Massachusetts two-meter settling tube, in which sample release starts the chart drive and a curve is drawn as a plot of cumulative

weight versus time. The recorder was allowed to run until the chart showed that at least 98 percent of the sample had fallen through the tube. Most samples ran to a full 100 percent recovery, but some contained a small amount of fines that remained suspended in the tube. The fall time for the sizes equivalent to ¼ϕ intervals between 1ϕ and 4ϕ were derived from tables (Zeigler and Gill, 1959). These fall times were checked against calculations by Schultz and others (1954) and were used to calibrate the settling curves. Using a plastic overlay with the ¼ϕ fall times marked on it, the ¼ϕ intervals were picked off the curve as cumulative weight percent. This settling tube and size analysis technique were developed by Fayez S. Anan. The grain size data were run on the university's CDC 3600 computer using a grain-size program devised by E.G. Rhodes. This program calculates grain-size parameters using both graphic statistics (Folk, 1965) and the method of moments.

Intertidal sand bodies in Saco Bay.--A clear distinction among the several intertidal sand bodies with respect to their grain size statistics is evident on scatter plots of graphic standard deviation versus graphic mean and graphic skewness versus graphic mean (Figs. 30 and 31).

Figure 30. Graph of sorting (inclusive graphic standard deviation) versus graphic mean for 96 surface sediment samples from three intertidal sand bodies in Saco Bay. The Camp Ellis bar of the Saco River has a range of grain sizes coarser than the Scarboro flood-tidal delta, but the overall standard deviation of the bar is similar to the flood delta. The ebb-tidal delta has the best sorting, presumably as a result of wave action.

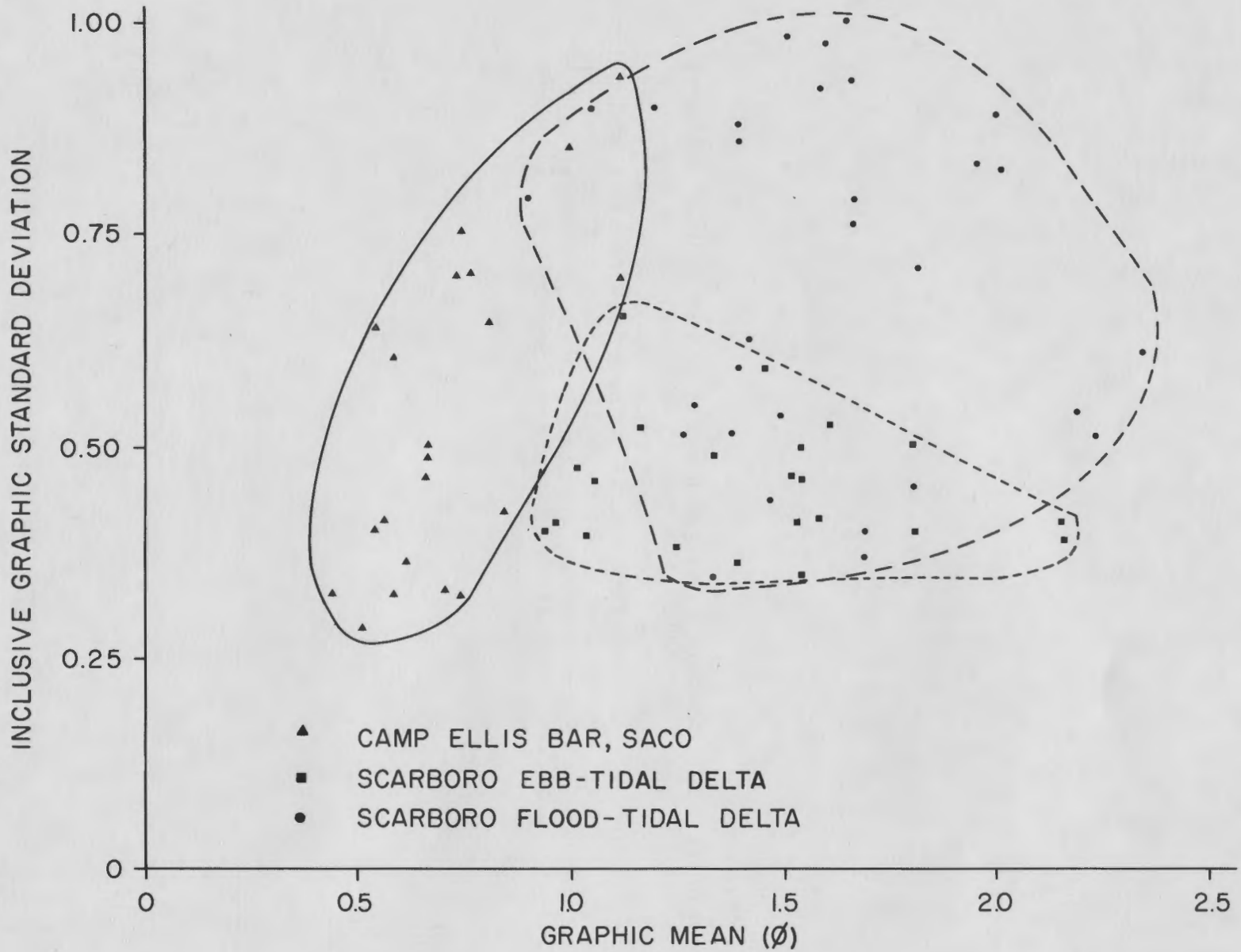
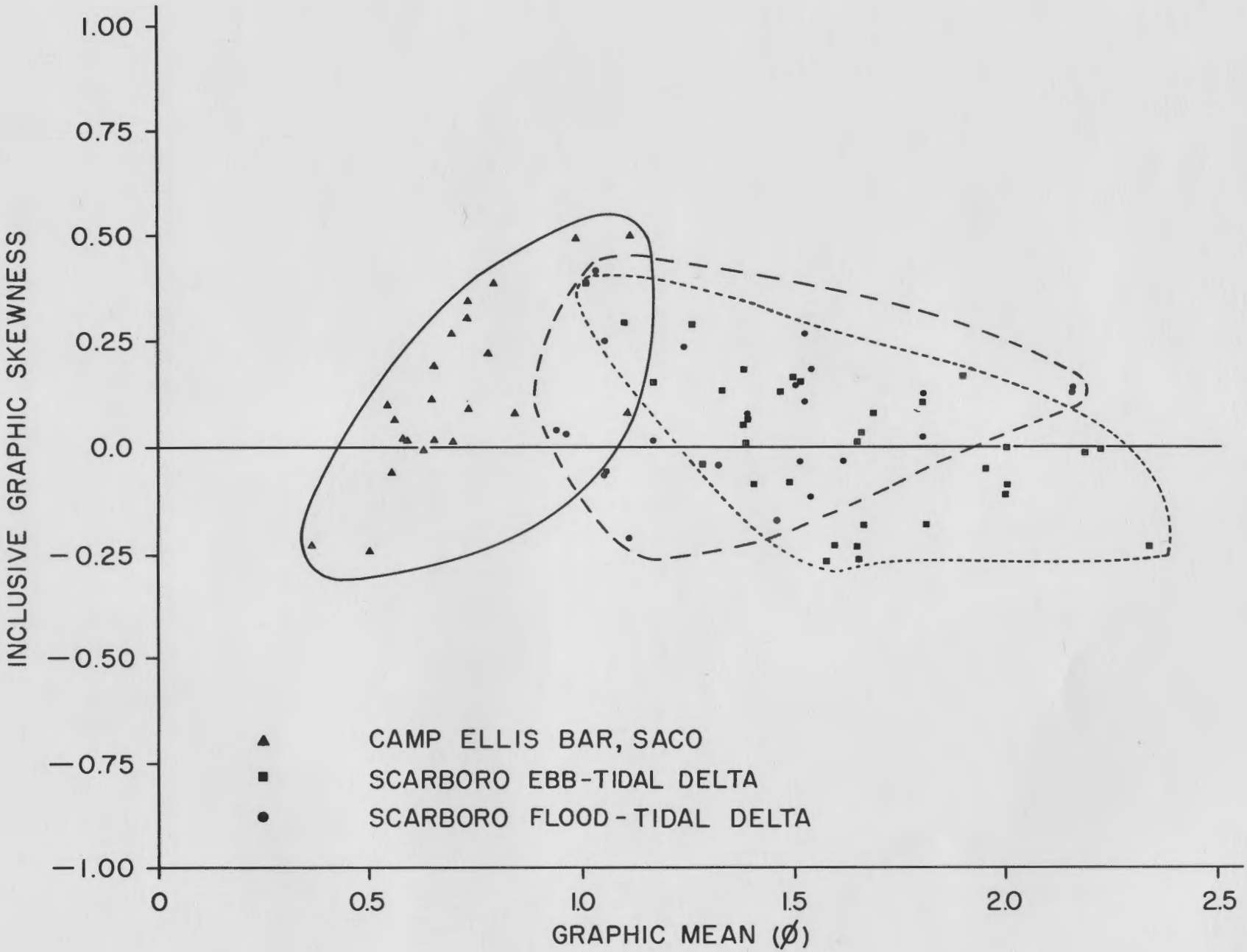

INCLUSIVE GRAPHIC STANDARD DEVIATION
1.00
0.75
0.50
0.25
0
0
0.5
1.0
1.5
2.0
2.5
GRAPHIC MEAN (Ø)
CAMP ELLIS BAR, SACO
SCARBORO EBB-TIDAL DELTA
SCARBORO FLOOD-TIDAL DELTA

Figure 31. Graphic mean versus inclusive graphic skewness for three intertidal sand bodies in the Saco Bay area. Graphic skewness of the samples for the three sand bodies does not discriminate among the three deposits. The differences in mean size are, however, distinct enough to separate the coarser Saco-Camp Ellis bar from the other two.


1.00
0.75
0.50
0.25
0.0
−0.25
−0.50
−0.75
−1.00
INCLUSIVE GRAPHIC SKEWNESS
0
0.5
1.0
1.5
2.0
2.5
GRAPHIC MEAN (Ø)
CAMP ELLIS BAR, SACO
SCARBORO EBB-TIDAL DELTA
SCARBORO FLOOD-TIDAL DELTA

The average mean size and the range of mean sizes for samples from the two Scarboro tidal deltas are identical, but the sediments of both are considerably finer than those of the Camp Ellis bar. The finer size of the Scarboro samples reflects the loss of the coarse fraction, particularly the yellow feldspar and large quartz grains, during littoral transport to Pine Point.

The best sorting of the three sand bodies is in the Scarboro ebb-tidal delta complex (Fig. 29), where surf action serves to sort out fines and give a low σ_I value (0.35 to 0.65 = well-sorted; Folk, 1965). On the other two sand bodies, the absence of wave sorting allows fine material to settle out during tidal slack water, with the resulting larger sorting coefficient (σ_I up to 1.0 = moderately sorted) (Fig. 30).

Graphical representation of the coarse sediment (mean size 0.6ϕ) of the Camp Ellis bar is shown in the cumulative curves and frequency distributions (Figs. 32 and 33). The frequency distributions (Fig. 33) make it apparent that the sediment from the Camp Ellis bar is coarser than the sediment of the two Scarboro tidal deltas. Apparently, it is a selectively sorted coarse deposit derived from the available Saco River bottom-sediment sizes. The Saco river-bottom sand is better sorted than the Saco River flood-plain sediments, which

Figure 32. Cumulative weight-percent curves for samples from three intertidal sand bodies of the Saco Bay area. The coarse size and unimodal distribution for the Saco Camp Ellis bar is apparent from the cumulative curves. The bimodal nature of sample B1 (D) can be shown on the cumulative percent curve, but is better illustrated in a frequency distribution curve (Fig. 33).

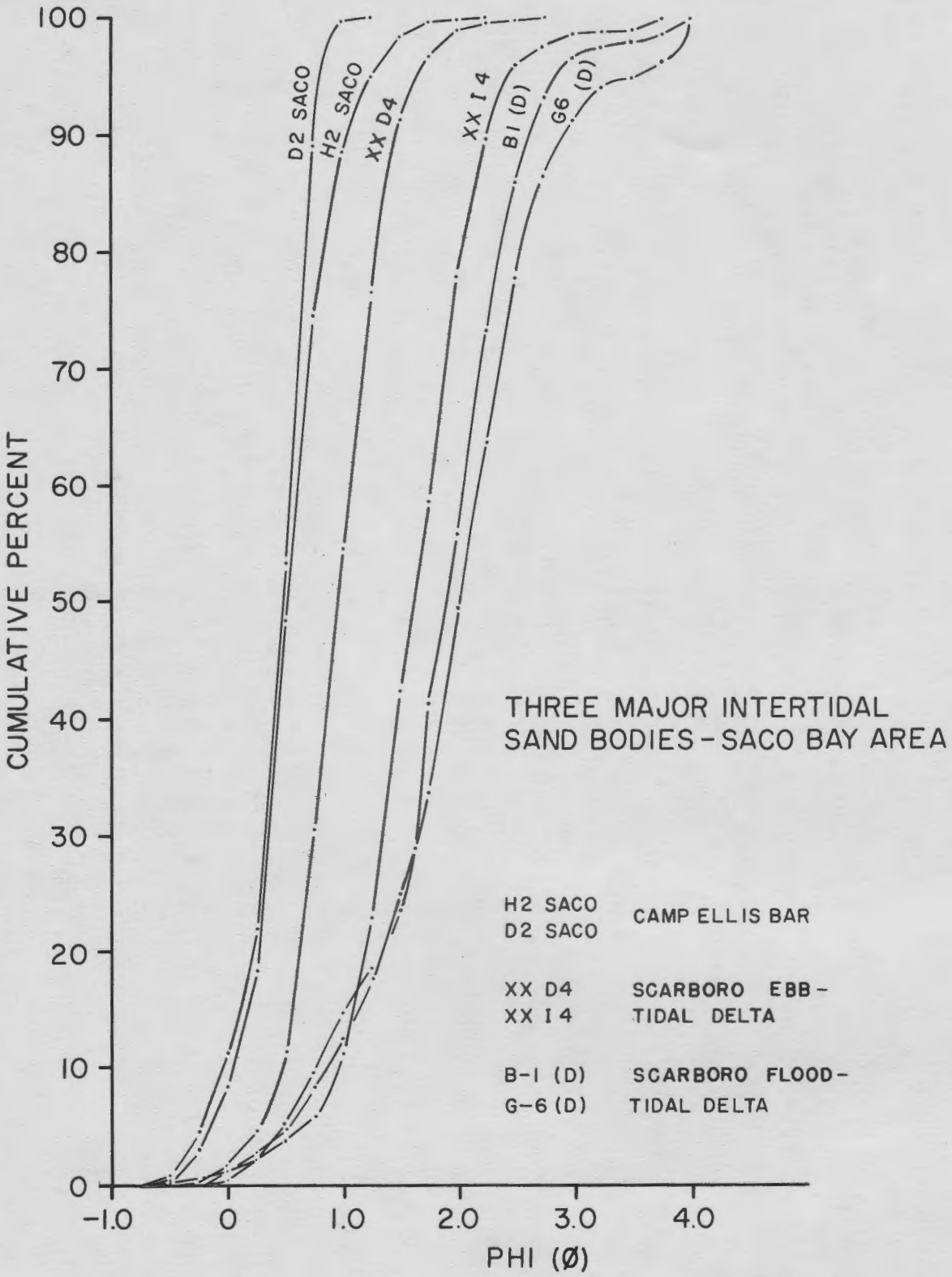
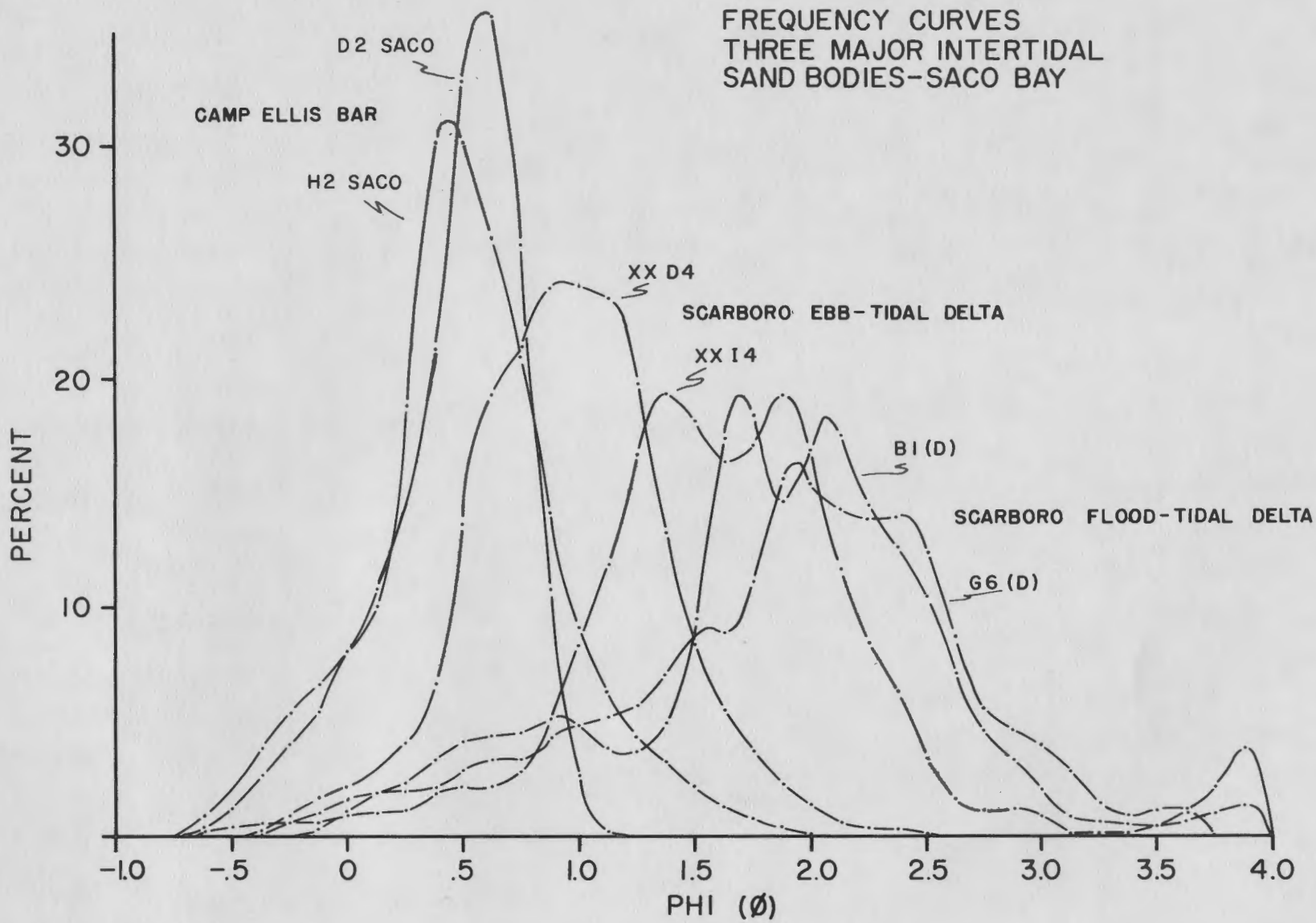

100
90
80
70
60
50
40
30
20
10
0
CUMULATIVE PERCENT
-1.0
0
1.0
2.0
3.0
4.0
PHI (Ø)
D2 SACO
H2 SACO
XX D4
XX I 4
B1 (D)
G6 (D)
THREE MAJOR INTERTIDAL
SAND BODIES - SACO BAY AREA
H2 SACO
D2 SACO
CAMP ELLIS BAR
XX D4
XX I 4
SCARBORO EBB-
TIDAL DELTA
B-1 (D)
G-6 (D)
SCARBORO FLOOD-
TIDAL DELTA

Figure 33. Frequency distribution curves for three intertidal sand bodies, Saco Bay area. The unimodal Camp Ellis bar sand (H2 and D2) contrasts markedly with the bimodal Scarboro sediment (XXI4 and B1(D)). The Camp Ellis bar sands (H2 and D2) are much better sorted than the river bottom sands because the tidal-current reworking removes the fine material present in the bottom sediments. The broadening and splitting of modes in the Scarboro sediment may arise either from differences in wave and tidal-current transporting strengths or from marked differences in sizes transported by neap and spring tides.


FREQUENCY CURVES
THREE MAJOR INTERTIDAL
SAND BODIES-SACO BAY
D2 SACO
CAMP ELLIS BAR
H2 SACO
XX D4
SCARBORO EBB-TIDAL DELTA
XX I4
B1 (D)
SCARBORO FLOOD-TIDAL DELTA
G6 (D)
PERCENT
30
20
10
-1.0
-.5
0
.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
PHI (Ø)

characteristically contain 5 to 10 percent coarse silt. The Saco River flood plain and the associated Pleistocene deposits contain the entire range of grain sizes represented in the intertidal environment, but it remains for the differing energies of the nearshore processes to sort the available range of sediment sizes into various deposits, from the -3ϕ gravel ridges on Old Orchard Beach at profile 004 to the clay muds deposited in cut-off Scarboro estuary meander loops.

The possibility of longshore drift of material around the headlands was considered as a potential source for Saco Bay sediment. Examination of the pocket beaches on Prouts Neck and Biddeford Pool revealed a sediment composition unlike any sand-size material deposited in or available to the Saco Bay basin. The coarse sand-sized material (0ϕ) is 70 percent metamorphic rock fragments, 20 percent shell fragments, minor amounts of feldspar, igneous rock fragments, and 3 to 5 percent heavy minerals. Fathometer profiles indicate that at the apex of the headlands the outcrop plunges down to 48- to 60-foot depths about 20 feet from shore. Bottom samples from Saco Bay tentatively demonstrate that wave sorting is effective only to 55 feet. In addition, bedrock bottom or cobble pavement from the foot of the headlands out to 100-foot

depths provides conclusive evidence that no sediment is being transported into or out of Saco Bay by littoral processes.

Tidal creeks and their margins.--The Pleistocene sediment outcrops along the Nonesuch River and marginal to other tidal creeks are another potential source for Scarboro estuary sediment. Comparison of upper tidal-channel samples in the Scarboro tidal creek with the exposed Pleistocene bank deposits along some parts of this tidal creek shows an interesting lag deposit of the very coarsest portion of the Pleistocene sand and silt (Figs. 34 and 35). The tidal currents measured in the Scarboro tidal creek three-quarters of a mile above the Boston and Maine Railroad trestle have maximum velocities of about 3.0 feet per second. This maximum velocity decreases gradually upstream to 0.79 feet per second at the Route 1 bridge. Since this current reverses its direction four times a day and since none of this coarse sediment is found between scoured deeps in meander bends, it is thought that this lag deposit material is not being transported downstream to the main portion of the estuary. The modal size of these lag deposits ranges from 0.48ϕ to 1.59ϕ. Each deposit is well sorted about its individual mode (Fig. 34). The Pleistocene material (the Presumpscot Formation) has modes of 2.95ϕ and 3.92ϕ, with long tails out to 9ϕ. The lag

Figure 34. Cumulative weight-percent curves for Scarboro River channel-bottom lag deposits and eroded Pleistocene deposits. S38 and NS7A are coarse channel-bottom lag deposits derived from the coarse fraction of the eroding Pleistocene bank deposits. S2 is the Presumpscot Formation (blue clay) and S1 is a fine sand and clayey silt associated with late Pleistocene deltas present in the Cumberland County area.

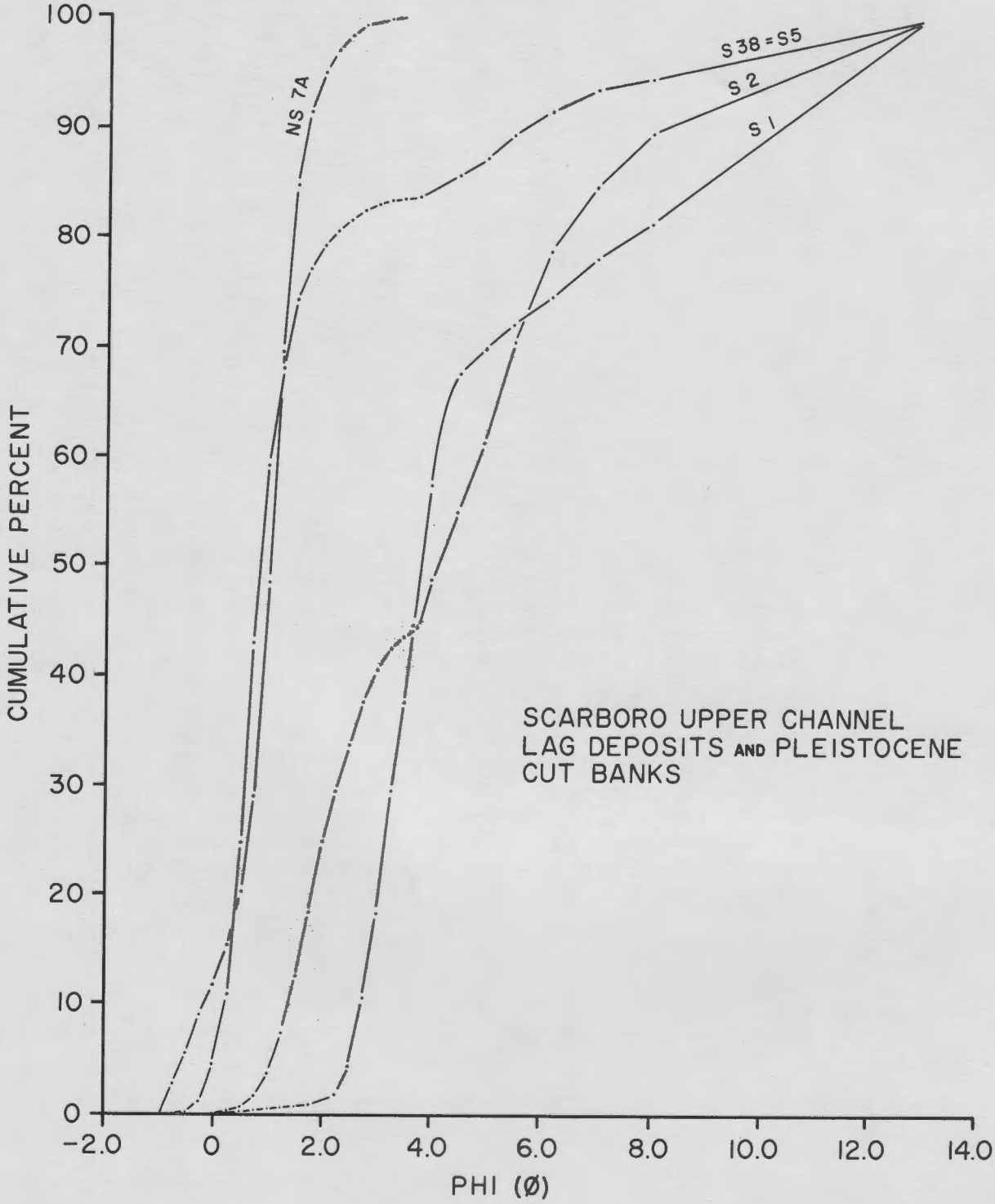
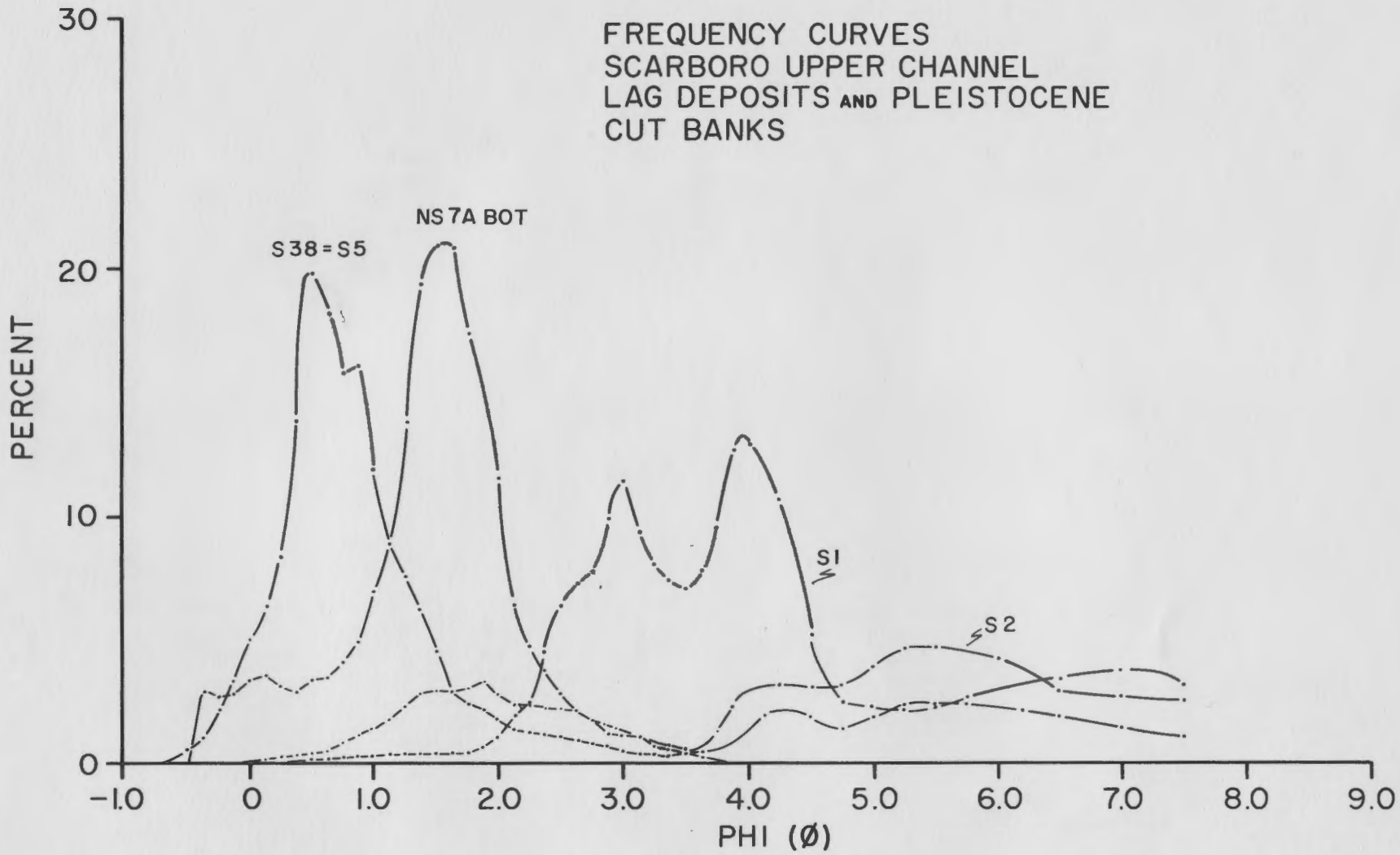

100
90
80
70
60
50
40
30
20
10
0
CUMULATIVE PERCENT
-2.0
0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
PHI (Ø)
NS 7A
S 38 = S5
S 2
S 1
SCARBORO UPPER CHANNEL
LAG DEPOSITS AND PLEISTOCENE
CUT BANKS

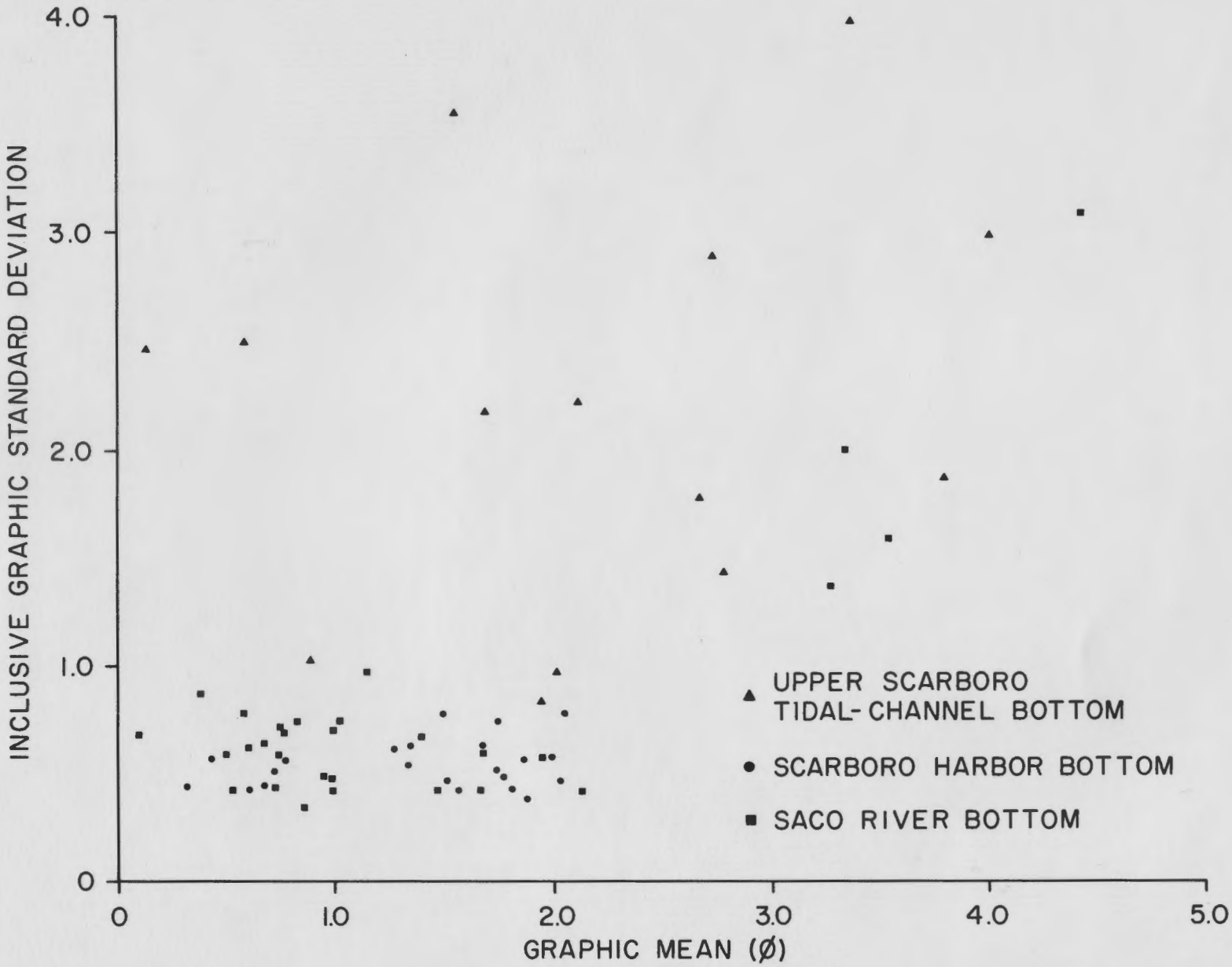
Figure 35. Frequency distribution curves for Scarboro River channel-bottom lag deposits and eroded Pleistocene deposits. The coarse lag deposits are quite well sorted. Current variations allow fine sand, silt, and clay to be included as a fine tail along with the coarse mode. The coarse lag material is present in the bank deposits. Samples S38 = S5 and NS7A Bot are examples of the lag concentrates. S2 is from the Presumpscot Formation which outcrops along the Scarboro tidal creek. S1 is from a fine silty clay which overlies the Presumpscot at the same locality.


FREQUENCY CURVES
SCARBORO UPPER CHANNEL
LAG DEPOSITS AND PLEISTOCENE
CUT BANKS
NS 7A BOT
S38 = S5
S1
S2
PERCENT
30
20
10
0
-1.0
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
PHI (Ø)

deposit is made up, then, of the coarsest part of the eroding bank deposits (about 2 to 5 percent of the S1 and S2 samples--Fig. 35), with a small percentage of the silt-sized fraction as a fine-skewed tail. The modal sizes (2.95ϕ and 3.92ϕ) of these eroded Pleistocene deposits are transported to various environments such as point bars in the channels and mud flats along the sides. Some of this fine sand and silt is deposited on top of the marsh during each storm surge and becomes a silt layer in the marsh peat; some silt is incorporated in mussel-bank deposits by the *Mytilus edulis* clam. A scatter plot of the mean grain size versus graphic standard deviation for the upper tidal-creek mussel-bank, channel-side, and bottom sediments appears in Figure 36. The mean size range of the channel-margin, mussel-bank, and mud-flats samples lies completely within the bimodal size range distribution of sample S1 (Fig. 35).

The Scarboro salt marsh is developed on the weathered, probably eroded Presumpscot blue-clay surface (Bloom, 1960). The tidal creeks cut down into this clay and expose it in the deeper scour areas, where it is either bare or veneered by from 1 to 6 inches of coarse lag deposit. The upland area of the Scarboro drainage system is mantled by the Presumpscot, which is locally as much as 90 feet thick (Bloom, 1960). However, in the area between the Nonesuch

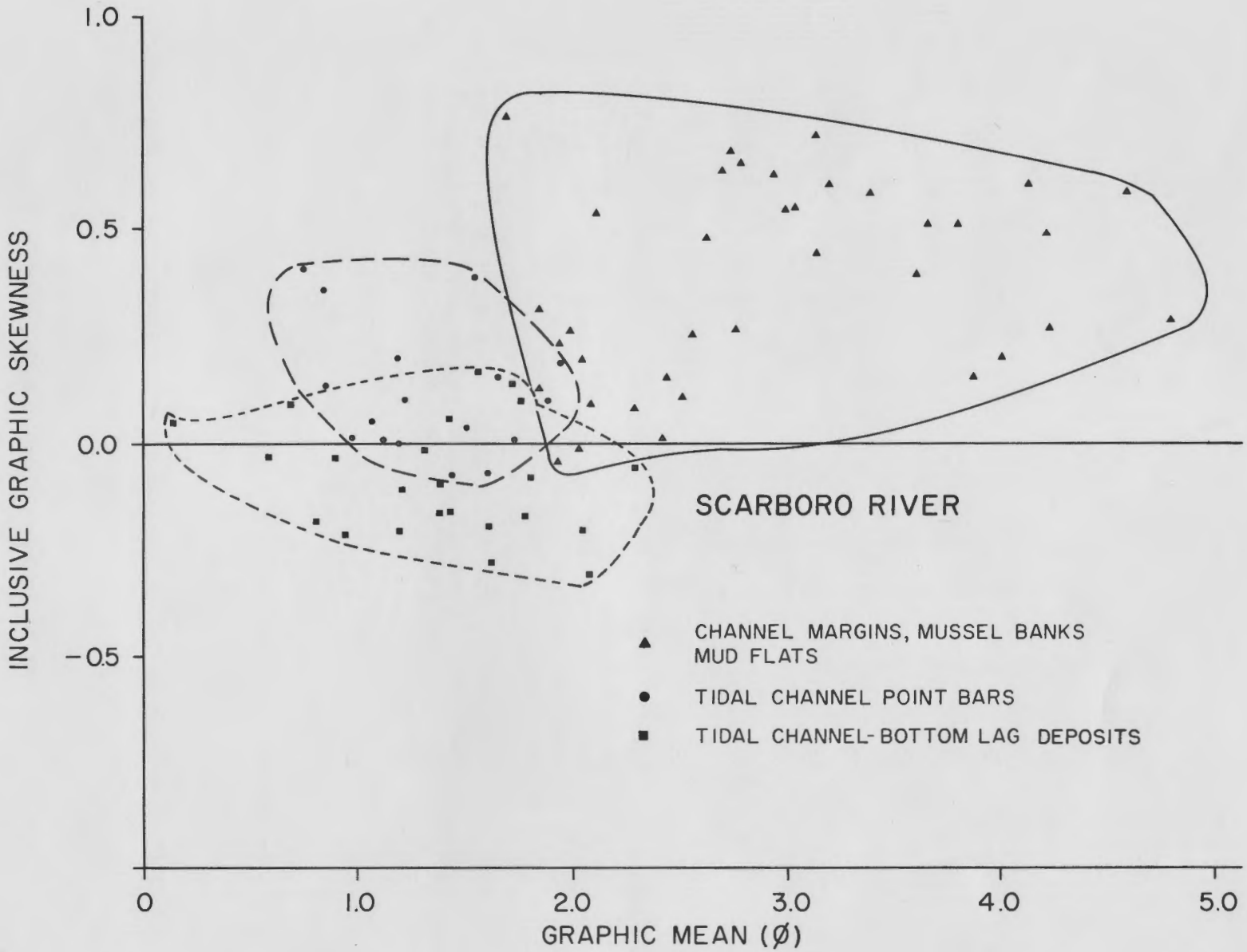
Figure 36. Plot of inclusive graphic standard deviation versus graphic mean for Saco River and Scarboro estuary bottom sands and upper Scarboro tidal-channel bottom deposits. The Scarboro harbor-bottom sediment averages finer than the Saco River bottom sediment, yet both are equally well sorted. The scatter of the bottom lag deposits of the upper tidal channel reflects the variable current velocities and the presence of clay galls.


INCLUSIVE GRAPHIC STANDARD DEVIATION
4.0
3.0
2.0
1.0
0
0
1.0
2.0
3.0
4.0
5.0
GRAPHIC MEAN (Ø)
UPPER SCARBORO TIDAL-CHANNEL BOTTOM
SCARBORO HARBOR BOTTOM
SACO RIVER BOTTOM

River and the Libby River along Route 207, part of an extensive late Pleistocene delta is exposed in the bank of the Nonesuch. The sizes here range from fine gravel (-3.0ϕ) to moderately sorted sand of mean size about 1.5ϕ. The Libby River embayment is developed on Presumpscot clay (S1 is a sample of material) but closer to Prouts Neck white littoral sands surround shallow bedrock (the Spring Point Greenstone).

Feldspar percentages (Figs. 27 to 29) were obtained from the bottom deposits in the Nonesuch tidal creek. They show that even in this, the most active creek, the flood-tidal transport of local metamorphic rock fragments masks the upland sediment sources to about 3 miles upstream from the harbor entrance. The swiftest and deepest Nonesuch channel bottoms are floored by the coarse lag concentrate (NS7A BOT, Fig. 35), eroded clay galls, and shells. In these channels, though, the point bars are made up of coarser sands while the fine sand and silt collects either on the salt marsh or in meander cutoffs and small side channels. Except where currents are strong enough to create large ripples (greater than 1 foot wavelength), the point bars contain 3 to 10 percent silt and clay (Fig. 37). Unless clay galls are removed, even the channel lags contain 1 to 10 percent clay, which is not deposited as particulate clay but rather as an aggregate.

Figure 37. Graph of inclusive graphic skewness versus graphic mean for Scarboro River tidal channel-bottom lag deposits, point bars and channel margins, mussel banks, and mud flats. The combination of mean size and skewness separates the mud flat environment from the point bars and bottom lag deposits. The entire range in sediment sizes of these three environments is represented in the blue clay of the Presumpscot Formation.


1.0
0.5
0.0
-0.5
INCLUSIVE GRAPHIC SKEWNESS
0
1.0
2.0
3.0
4.0
5.0
GRAPHIC MEAN (Ø)
SCARBORO RIVER
CHANNEL MARGINS, MUSSEL BANKS
MUD FLATS
TIDAL CHANNEL POINT BARS
TIDAL CHANNEL-BOTTOM LAG DEPOSITS

Sediment distribution

Comparison of these separate deposits reveals a unified pattern of sedimentation for the study area. Erosion of the Scarboro uplands provides abundant silt and clay. Limited stream competence allows only small amounts of sand to be moved downstream into the lower harbor. The clay and silt is carried in suspension and is deposited along channel margins, on mud flats, in abandoned channels, and rarely over the entire salt marsh. Increased sedimentation occurs during high tidal or storm surge slack-water periods. Storms usually are accompanied by heavy rain which swells the brooks, causing greater amounts of silt to be brought down. Because the storm surge floods the marsh and since the grass acts as a sediment trap, silt and clay are readily deposited on the marsh during the time of surge slack water. The sand-size material is transported downstream as channel bedload, as evidenced by point-bar deposits positioned downstream from each tidal creek meander slip-off slope. Downstream transport of point-bar sand occurs largely during unusual periods of high runoff. About two-thirds of the way from the upper salt-marsh limit to the sea this sediment is mixed with bedload material being transported upstream by flood tides. Seaward of this zone of mixing, the upland contribution is lost in the volume of landward-moving material.

The source of this sand, carried into the harbor as a result of the tidal current asymmetry, is, ultimately, the Saco River. How it gets from the Saco River to the Scarboro estuary and loses its coarse yellow feldspar fraction in transit is illuminated by studying storm winds, wave refraction, and beach longshore drift.

THE LITTORAL SYSTEM

The movement of sand to the tidal-delta deposits of the Scarboro harbor is initiated in the surf zone by wave-generated longshore drift that transfers the sand from south to north along Old Orchard Beach. Drift measurements taken weekly during the summer of 1967 in conjunction with the beach profile measurement reveal a pattern of northerly drift at profiles 001 and 002, which contrasts with a southerly drift at 004. The southerly drift drops to near zero around profile 005, where it is weakly moving north again. The central area at 003 has both northerly and southerly drift values of more or less equal frequency and magnitudes, the drift direction depending on particular circumstances. During storms the normal drift direction is reversed (Table 4) and runs from north to south. This reversal, which should counteract usual longshore sand movement, fails to explain the growth of Pine Point to the north,

a phenomenon which conflicts with the theory that northeast storms are the dominating agent shaping northern New England beaches.

Table 4

Drift measurements
made at five Old Orchard Beach profiles
-Summer, 1967

Drift velocities (in feet per second) and directions

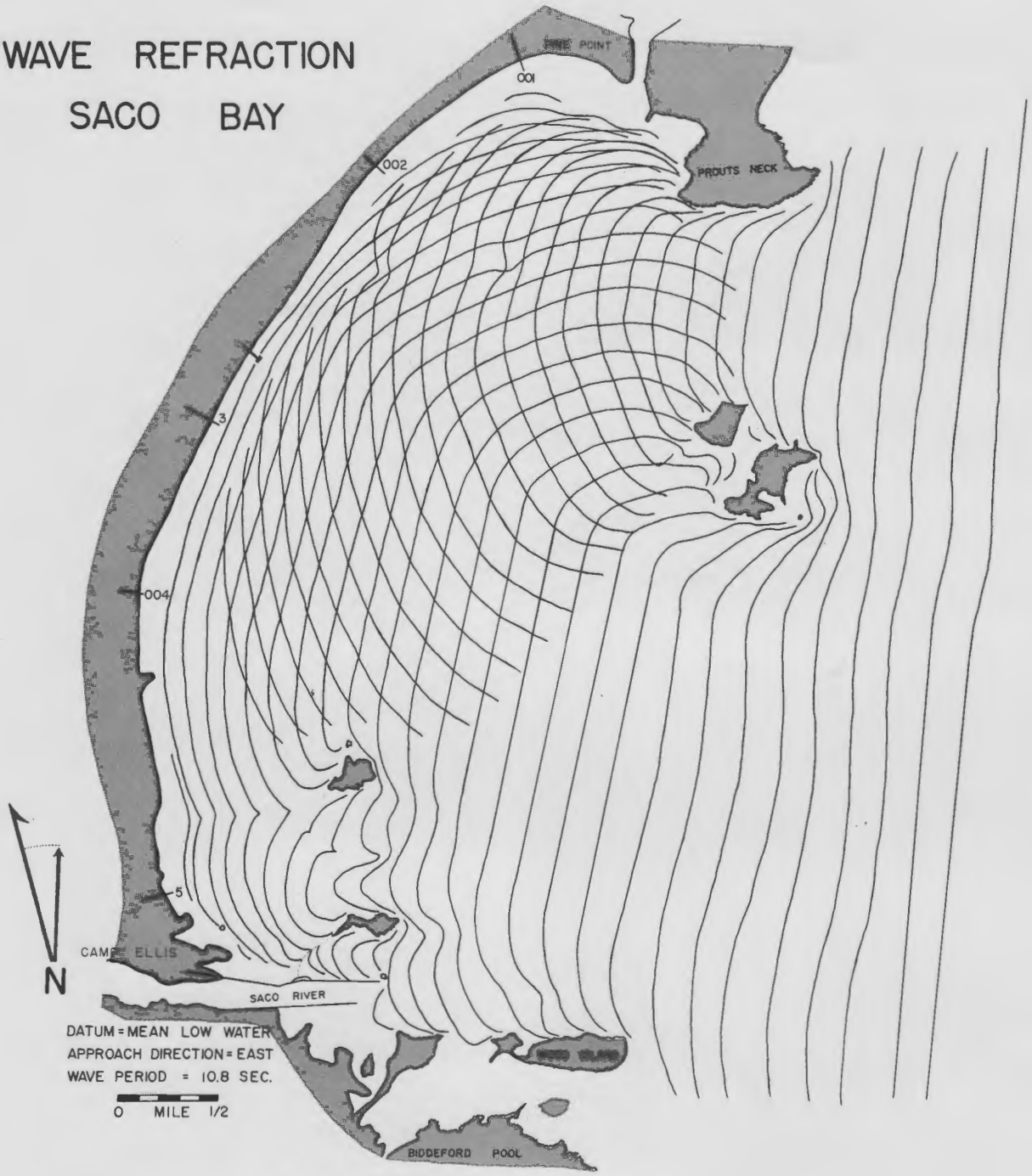
Pro. 001	Pro. 002	Pro. 003	Pro. 004	Pro. 005	
0.36 No.	0.08 No.	0.33 So.	0.50 So.	0.00	6/13
*0.36 No.	*0.43 So.	*0.78 So.	*0.78 So.	*0.13 No.	6/20
0.09 So.	0.29 No.	0.08 No.	0.67 So.	0.00	6/22
0.07 No.	0.36 No.	0.33 So.	0.91 So.	0.23 No.	7/17
0.35 No.	0.25 No.	0.00	0.58 So.	0.15 No.	7/24
0.23 No.	0.42 No.	0.08 No.	0.75 No.	0.02 No.	7/31
0.33 No.	0.05 So.	0.35 No.	0.55 So.	0.17 No.	8/14
0.11 No.	0.24 No.	0.19 No.	0.47 So.	0.06 No.	8/28

(Values marked by * were measured during a storm 6/20/67)

In an attempt to explain this conflict, a wave-refraction diagram for Saco Bay was constructed (Fig. 38), using the methods outlined by King (1959). An easterly approach direction was chosen. A wave period of 10.8 seconds was used because the 10.8-second period is typical of large swells from the Gulf of Maine (Jack Cysz, oral communication, 1969). Using this as a pattern, the effects of a shorter wave with the period of from 5 to 7 seconds typical of northeast storms can be better understood. This shorter

Figure 38. Wave-refraction diagram for Saco Bay for easterly approaching storm waves with a 10.8-second period. The offshore islands in Saco Bay strongly influence approaching wave fronts. Maximum surf energy is concentrated in the zone 003 to 004.

WAVE REFRACTION
SACO BAY



wave length delays the topographic influence until shallower depths are reached and produces a sharper radius of curvature for the refracting wave, with a greater divergence of wave orthogonals. This disperses wave energy along the beach in the Pine Point area, decreasing the intensity of attack at any given locality. The train of 5- to 7-second waves, however, strikes the central beach region with little bending and little loss of energy due to dispersion. It should be noted that nowhere do wave orthogonals converge as waves approach the beach; therefore, the net effect of wave refraction is to diminish the energy of any wave train as it strikes the shore, rather than to intensify it.

On a sand coast where waves are the primary energy source for generating a littoral drift, the net result of sediment transportation is to form a beach which is oriented perpendicular to the refracted wave orthogonals for the dominant approach direction (Bascom, 1964; Bird, 1968). An equilibrium condition exists when wave orthogonals approach perpendicular to the beach, because the surf energy is not directed at an angle along the beach to produce drift (Weigel, 1964). The curved crescent of Old Orchard beach is a close fit to the refracted wave crests for the easterly 10.8-second period wave approach

direction (Fig. 38). The equilibrium condition at Old Orchard breaks down both at Pine Point, where waves sweep north, and at profiles 002 to 004, where waves passing between Stratton Island and Prouts Neck cause southerly drift.

During a northeast storm, the average wind intensity is between 40 and 60 mph and the duration is from 6 to 12 hours. The southerly beach drift measured during the 1967 summer storm (Table 4) can be explained by the effects of northeast winds blowing across the fetch of Saco Bay. A 50-mph northeasterly wind blowing for 10 hours would form a 5.2-foot wave at profile 005, which has a 5-mile fetch, a 4.8-foot wave at profile 004 (4-mile fetch), a 4.1-foot wave at profile 003 (3-mile fetch), a 3.6-foot wave at profile 002 (2-mile fetch), and a 3.1-foot wave at profile 001 (1-mile fetch) (based on calculations of King, 1961, p. 120, after Bretschneider, 1954). The wave period ranges from 2 seconds for the 3.1-foot wave to 4 seconds for the 5.2-foot wave. The short period and low amplitude allow waves to proceed almost to the beach before being refracted and thus they are effective transporters of sediment in the swash zone. The continued change in orientation of the shoreline from parallelism at Pine Point to a near-perpendicular alignment at Camp Ellis, combined with the length

of fetch, concentrates this wave action around profiles 004 and 005. At Pine Point there is no northeast fetch, while at Camp Ellis, across 5 miles of bay fetch, the beach is oriented perpendicular to the wave orthogonals. The resulting equilibrium of Camp Ellis beach is evidenced by the lack of drift during a northeast storm (Table 4). The drift to the north at Pine Point (Table 4) results from the refraction of northeast storm waves around Prouts Neck (Fig. 38) and their consequent approach of the beach from the south. Following a northeaster, the winds blow offshore as the high-pressure system moves into the area. During the stable weather conditions after the high-pressure system arrives, fresh breezes blow from the south.

In summary, the littoral drift system at Old Orchard Beach is influenced by three wave directions. Figure 38 illustrates the close fit of the Saco Bay shore to refracted wave orthogonals of large, long-period storm waves. The growth of Pine Point is influenced by both refracted northeast storm waves and southeasterly fairweather waves. Camp Ellis, to the south, is protected by offshore islands from direct attack from large sea waves and is not influenced by the southeast waves because of Biddeford Pool headland. This region of Old Orchard beach is dominated by the northeast storms, which are able to blow across the 5-mile

Saco Bay fetch. This generates a wave which reinforces the weakened sea wave and was sufficient in March of 1969 to damage several beach front homes.

This general system of drift transport and size sorting is quite similar to that found from the Merrimack River south to Crane Beach, Mass. There the coarse feldspar-rich sand at the Merrimack River mouth is acted on by northeast storm waves and the resulting littoral currents and is size-sorted so that the sediment reaching Crane Beach is fine and highly quartzose. The Merrimack River-Plum Island-Crane Beach system is more exposed and has larger waves, but this energy increase and the absence of protecting offshore islands do not diminish the remarkable similarity in appearance of the Plum Island beach to Old Orchard beach between profiles 003 and 004 and the similarity between Crane Beach and Pine Point beach.

CONCLUSIONS

The Saco River estuary and the Scarboro estuary appear at first glance to be totally separate systems merely draining into the same bay. It has been shown, however, that the two are not independent entities, but that each is a part of the total Saco Bay environment and responds to its processes. Some of these processes and effects were found to be:

1. The Saco River, a highly-stratified salt wedge estuary, has a slightly-inclined salt-water fresh-water boundary.
2. Saco River fresh water ponds behind the encroaching salt wedge. As the rise of the tide decreases in rate late in the flood cycle, this water begins to flow out over the top of the still-flooding salt water. Strong shear boundaries develop as the ebb tide commences, strong vertical mixing being confined to station 7 in the lower deep rock gorge.
3. The Scarboro is a homogeneous mixed estuary. Some temperature stratification occurs in summer as the water is heated on the shallow flats. During flood tide, cold salt water is placed in extensive ground-water storage in the post-Pleistocene fluvial gravels beneath the Winnock Neck marsh.
4. The Saco River is not transporting sand-size sediment, except during great floods. Together with the jetty construction of 100 years ago, this has acted to starve the beach of material to replace that which has moved north.

5. The grain-size distribution and mineralogy of the Presumpscot formation indicate that the formation is the source of the coarse lag deposits in upper estuary tidal channels as well as of the fine material brought down to the intertidal zone by fresh-water streams.
6. The fresh-water streams are not presently able to transport more than a small fraction of the sand-size material coming into the Scarboro estuary. All of the mud, however, is silt and clay which presumably has been derived from the weathering and erosion of the Presumpscot blue clay.
7. A strong time-velocity asymmetry of tidal currents exists in the Scarboro estuary. This asymmetry allows material to be transported to the tidal flat area by flood currents and not be removed by the ebb currents.
8. Of the tidal-delta sand bodies, only the Scarboro flood-tidal delta has a well-developed sand-wave field, ebb shield, and trailing ebb spit. The intertidal portion of the Scarboro ebb-tidal delta is a swash bar facing the southeast waves. The Saco tidal deltas that existed in 1850 have been destroyed by jetty construction; the Camp Ellis bar is a small vestige of those much greater sand deposits.

9. Longshore drift has selectively removed and transported the finer quartz-white feldspar fraction north from the Old Orchard beachfront. The severe storms concentrate coarse yellow sand in the center of the beach arc, while the southeast waves winnow out the finer fraction.
10. Bedform orientation, the distribution of feldspar populations, metamorphic rock fragment content and type, lack of fresh-water runoff, feldspar polishing, and longshore drift all point to a flood-tide transport of sand-size material into the lower Scarboro estuary.

REFERENCES CITED

Bascom, W., 1964, Waves and beaches, the dynamics of the ocean surface: Garden City, New York, Doubleday and Company, Inc., 267 p.

Bird, E.C.F., 1968, Coasts: Canberra, Aust., Australian National University Press, 264 p.

Bloom, A., 1960, Late Pleistocene changes in sea level in southwestern Maine: Maine Geol. Survey, 143 p.

Coastal Research Group, Univ. of Mass., 1969, Coastal environments, N.E. Massachusetts and New Hampshire, Field Trip Guidebook: Eastern Section of Soc. of Econ. Paleon. and Min., 462 p.

Daboll, J.M., 1969, Holocene sediments of the Parker River estuary, Massachusetts: Cont. No. 3, Coastal Research Group, Dept. of Geology, University of Massachusetts, 137 p.

Folk, R.L., 1965, Petrology of sedimentary rocks: Austin, Texas, Hemphill's, 159 p.

Guy, H.P., Simons, D.B., and Richardson, E.V., 1966, Summary of alluvial channel data from flume experiments, 1956-61: U.S. Geol. Survey Prof. paper 462-I, 96 p.

King, C.A.M., 1961, Beaches and coasts: London, Edward Arnold Limited, 403 p.

Locke, J.S., 1880, Shores of Saco Bay: Boston, 243 p.

Pritchard, D.W., 1967, What is an estuary--physical viewpoint: in Lauff, G.H., editor, Estuaries; Am. Assoc. Adv. Sci. Pub., 83, p. 3-5.

Schultz, E.F., Wilde, R.H., and Albertson, M.L., 1954, Influence of shape on the fall velocity of sedimentary particles: Colorado Agricultural and Mechanical College, Fort Collins, Colorado.

Trefethen, J.M., and Dow, R.L., 1960, Some features of modern beach sediments: Jour. of Sed. Petrology, v. 30, p. 589-602.

U.S. Army Corps of Engineers, 1956, Project Scarboro: Waltham, Massachusetts, Department of the Army, New England Division, Corps of Engineers.

_____ 1962, Scarboro jetty and dredging project: Waltham, Massachusetts, Department of the Army, New England Division, Corps of Engineers.

_____ 1966, Scarboro maintenance project: Waltham, Massachusetts, Department of the Army, New England Division, Corps of Engineers.

_____ 1968, Saco River project: Waltham, Massachusetts, Department of the Army, New England Division, Corps of Engineers.

U.S. Congress, 1962, Beach erosion control study, Hills Beach, Biddeford, Maine: House Document no. 590.

U.S. Department of the Interior, 1967, Water resources data for the state of Maine, Oct., 66 to Sept., 67: Department of Interior document.

Weigel, R.L., 1964, Oceanographical engineering: Englewood Cliffs, New Jersey, Prentice-Hall Inc., 532 p.

Williams, J., 1963, Oceanography; an introduction to the marine sciences: Boston, Little, Brown, 316 p.

Zeigler, J., and Gill, R., 1959, Tables and graphs for the settling velocity of quartz in water above the range of Stoke's law: Woods Hole Oceanographic Inst., Ref. no. 59036.