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Geomorphology and Sedimentary Framework of the Inner Continental Shelf of Southwestern Maine

by

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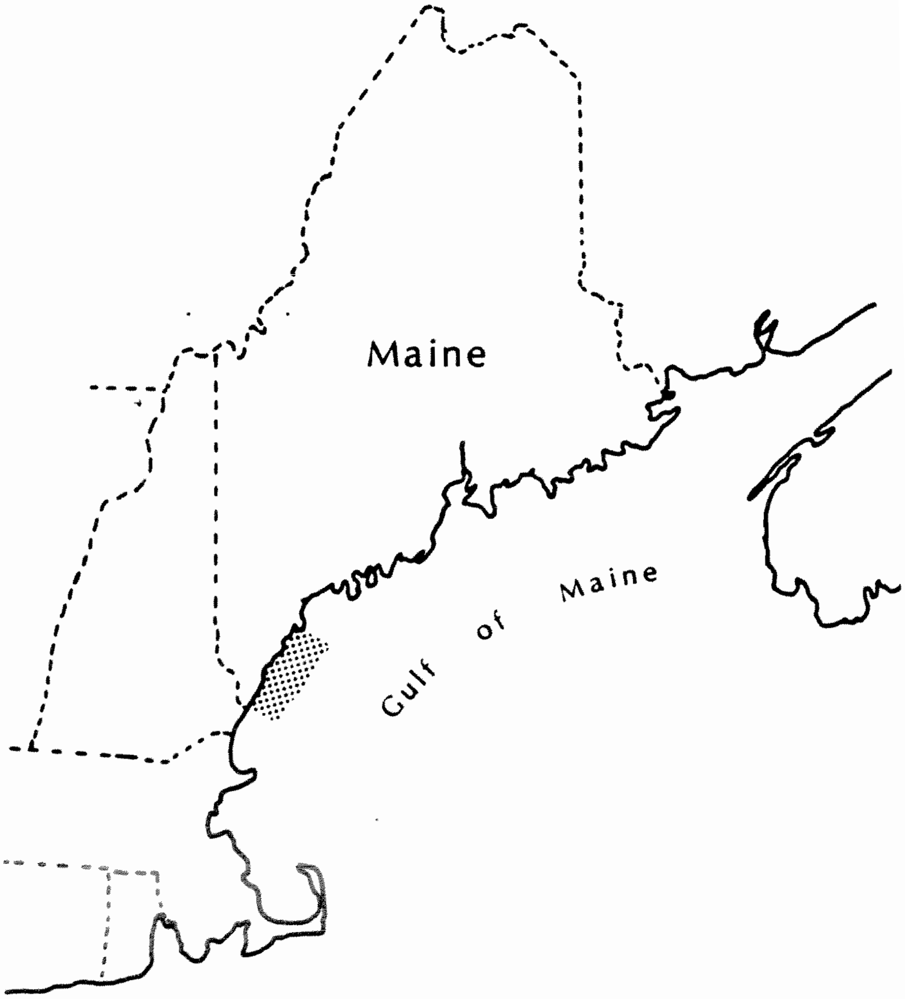

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ABSTRACT

This report summarizes the Year One research in Maine of the Minerals Management Service Continental Margins Program. More than 1000 kilometers of high resolution seismic reflection profiles and 400 bottom samples were collected and investigated to elucidate the sedimentary framework of the southwestern Maine inner shelf. On the basis of this, plus side-scan sonar and submersible observations, the shelf may be divided into four physiographic zones: Nearshore Ramps, Shelf Valleys, Rocky Zones, and Outer Basins. These are distinguished on the basis of surficial sediment texture and composition, geometry of sedimentary deposits, and late Quaternary geological history. The driving force behind shelf sediment deposition, and the process which unifies the shelf stratigraphic framework is sea level change. Following deglaciation, the shelf experienced two marine transgressions and a regression which led to sediment deposition and erosion at various places across the shelf in the past 14,000 years.

INTRODUCTION

This report describes the submarine geomorphology, surficial sediments, and Quaternary stratigraphic framework of the western Gulf of Maine along the inner continental shelf of southwestern Maine (Figure 1). Although reference is made to pertinent terrestrial observations, the research focuses on the nearshore region to a depth of 100 meters. Within this area, bedrock of complex origin ranges in age from Precambrian to Cretaceous; although Paleozoic intrusive and metamorphic rocks are the most common coastal outcrops (Osberg and others, 1985). Bedrock is widely exposed in the coastal zone and exercises a primary control on the morphology of the shoreline (Kelley, in press). The region from Cape Elizabeth south into New Hampshire and beyond has been termed the Arcuate Embayments coastal compartment because numerous bedrock capes punctuate a shoreline otherwise dominated by curved embayments composed of sandy

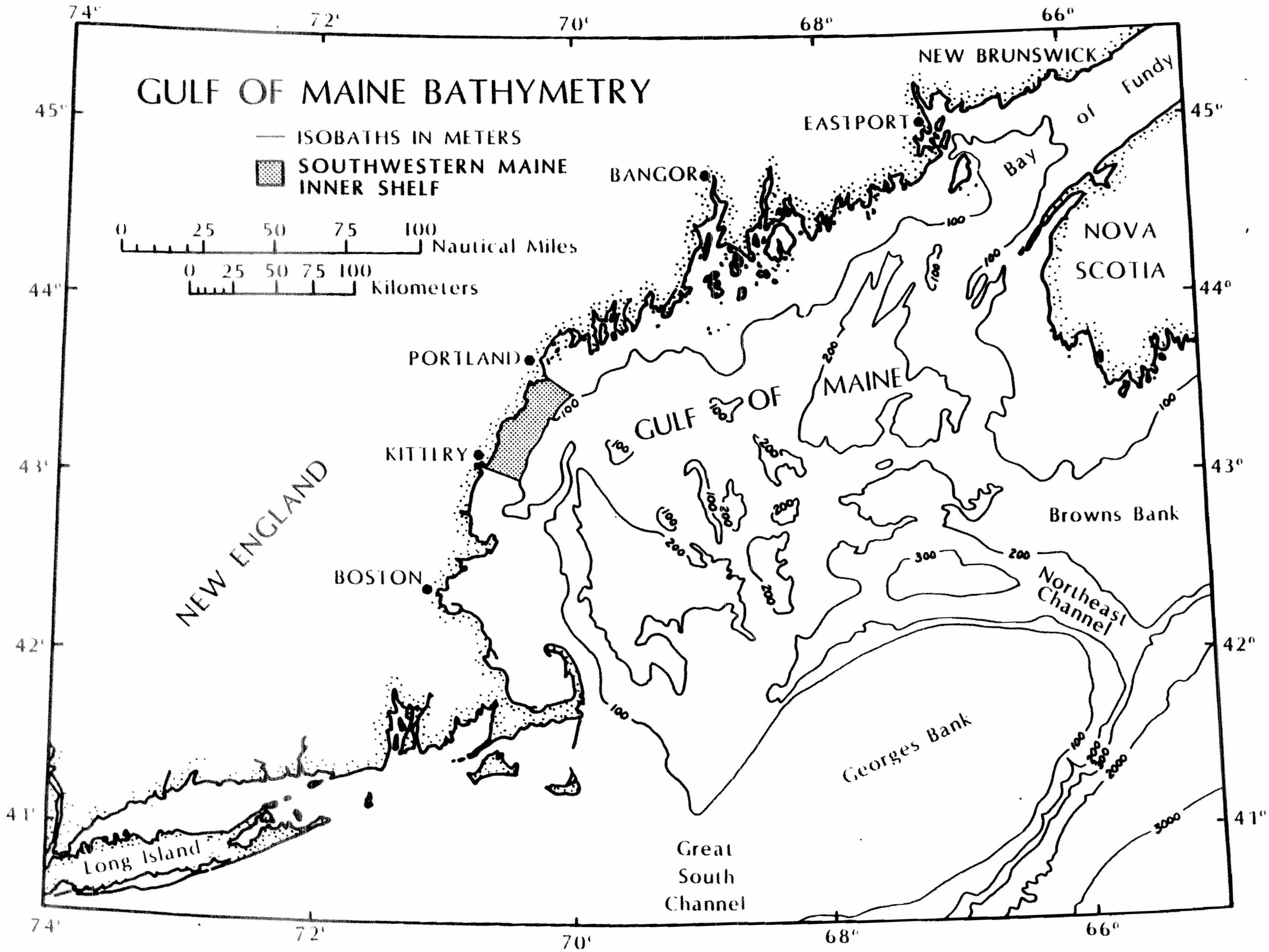


Figure 1. Location of the study area in the western Gulf of Maine.

beaches (Kelley, in press).

Like other shelf areas of New England and the Canadian Maritimes, southwestern Maine has probably experienced numerous Quaternary glaciations, and relatively thin glaciogenic sediment only partly mantles submerged bedrock exposures (Needell and others, 1983; McMaster, 1984; Piper and others, 1983). Unlike the outer regions of the Gulf of Maine and beyond, however, local, relative sea level has fluctuated profoundly in southwestern Maine due to isostatic crustal movements as well as eustatic sea level changes related to growth and disintegration of the Laurentide Ice Sheet (Stuiver and Borns, 1975; Schnitker, 1974; Belknap and others, in press, b). Within the past 14,000 years the study area has experienced a deglaciation, two marine transgressions, and a regression of the sea. It is these changes in sea level, which have permitted a variety of terrestrial and marine processes to repeatedly operate over the inner shelf, that have established the regional stratigraphic framework, and most significantly affected the nature of surficial sediments. The purpose of this paper is to describe the surficial sediments of the area in the context of a stratigraphic framework dictated by Holocene sea level fluctuations.

PREVIOUS WORK

The terrestrial, surficial geology of southwestern Maine was first summarized by Stone (1898) and mapped by Leavitt and Perkins (1935). These workers recognized the glaciated nature of the landscape although confusion existed regarding the formation of some partially stratified coastal moraines. Katz and Keith (1917) mapped the Newington Moraine of New Hampshire and southwestern Maine and interpreted interbedded till and glaciomarine sediment as evidence for a climatic-scale readvance (Table 1). Bloom (1960) mapped the region in more detail and established the late post-glacial nature of the glaciomarine sediment. He called this material the Presumpscot Formation and recognized that the land emerged below present sea level following its deposition (Bloom, 1963). By dating fossil shells in glaciomarine sediment interbedded with till in coastal moraines, Stuiver and Borns (1975) established that retreating ice reached the present shoreline of Maine around 13,200 years ago. They also bracketed the time of deposition of the Presumpscot Formation between 13,200 and 12,000 years before present. Smith (1981) has demonstrated more recently that the stratified morainal deposits of southwestern Maine formed as a result of minor fluctuations in a generally retreating ice sheet and not because of a climatic readvance. He has also mapped the southwestern Maine area in great detail (Smith, 1982) and this mapping has recently been compiled into a State surficial map (Thompson and Borns, 1985). A generalized stratigraphic cross section of Maine's surficial geology, seaward of the limit of marine submergence, has been widely accepted (Smith, 1985). Although complex in detail, the stratigraphic column generally contains a coarse grained diamicton at the base (till, subaqueous outwash, ice contact drift), a fine grained unit in the middle (Presumpscot Formation), and a sandy deposit, locally thick near large rivers, at the top. A ravinement (erosional) unconformity separates the upper sand from the Presumpscot Formation and in the Kennebec River valley, northwest of the study area, the upper sand has been mapped as the Embden Formation

Table 1

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

Study	Location	Data
Katz and Keith, 1917	Southwestern Maine, New Hampshire, Massachusetts	Local, terrestrial mapping of moraines
Bloom, 1960	Southwestern Maine	Regional terrestrial mapping
Bloom, 1963	Southwestern Maine	Study of sea level changes
Farrell, 1972	Saco Bay	Bottom sampling
Oldale et al., 1973	Southwestern Maine shelf	Seismic profiling
Folger et al., 1975	Southwestern Maine shelf	Bottom sampling, seismic profiling
Stuiver and Borns, 1975	Coastal Maine	Study of sea level changes
Hulmes, 1981	Biddeford Pool - intertidal	Vibracores
Smith, 1981	Kennebunk	Terrestrial mapping of moraines
Smith, 1982	Coastal Maine	Terrestrial mapping of moraines
Thompson and Borns, 1985	Maine	State surficial map
Smith, 1985	Southwestern Maine	Regional terrestrial mapping
Kelley et al., 1986	Saco Bay	Seismic profiling
Luepke and Grosz, 1986	Saco Bay - subtidal	Vibracoring and heavy minerals

(Borns and Hagar, 1965). It is of note that in this glaciated landscape, the present drainage system is poorly integrated, and numerous swamps and lakes act as settling basins along stream courses. Derangement of large streams is indicated by buried valleys on land, and numerous waterfalls along the coast (Tolman and others, 1986).

Relatively little work has been published from within the study area (Table 1). Farrell (1972) evaluated the texture of 75 grab samples from inner Saco Bay and concluded that fine sand (3.4 phi mean) dominated the bay bottom to the depth of wave base, or about 20 meters. At greater depths muddier sand was present, but near Prouts Neck (Figure 2) distinctly coarser sand (1.0 phi mean) was common. He inferred that this coarser sand represented a lag deposit of Pleistocene sediment or drowned beach or tidal delta sediments from a lower sea level. He mapped widespread areas of bedrock exposure on the basis of fathometer records and recovered cobbles encrusted with algae near the bedrock.

Oldale and others (1973) collected reconnaissance seismic reflection profiles in the study area and surrounding region and recognized reflections from bedrock, till, and glaciomarine sediment. Folger and others (1975) collected more seismic data and mapped the distribution of bottom sediments on a scale of 1:125,000 on the basis of this and about 60 grab samples. Their map shows sand and gravel nearshore changing to organic-rich clayey silt at about the 100 meter isobath, though they acknowledge that sample density was inadequate to reliably map sediment texture or composition.

Hussey (1970) speculated on the origin of the Wells Beach system by erosion of till and formation of migrating spits and tombolos. Hulmes (1981) collected cores from Biddeford Pool and demonstrated that the spits of that area migrated into position and that lagoonal sediments were deposited directly upon the Presumpscot Formation. She encountered the Presumpscot Formation in 9 cores from Biddeford at depths of less than 6 meters. The U.S. Army Corps of Engineers (Luepke and Grosz, 1986) similarly encountered the Presumpscot Formation beneath less than 5 meters of sand in a dozen cores from inner Saco Bay. Kelley and others (1986) summarized the existing literature on Saco and adjacent Casco Bays and contrasted the two embayments on the basis of their Holocene geologic evolution.

Elsewhere within the region, Ostericher (1965) first employed coring and seismic reflection techniques to examine submarine stratigraphy in coastal Maine. He described reflectors that correlated with bedrock, till, and the Presumpscot Formation, as well as surficial sediment textures from Penobscot Bay. He recognized the regressive unconformity on the surface of the Presumpscot Formation and dated wood fragments from cores of its surface at 7,390 years before present. On the basis of this he concluded that the "post-Presumpscot Formation" lowstand of sea level occurred at that time at a depth of 15-20 meters. Knebel and Scanlon (1985) have re-occupied Ostericher's (1965) lines with better seismic equipment and described details of submerged moraines and provided sediment thickness maps.

Schnitker (1972, 1974) also used seismic reflection methods to examine

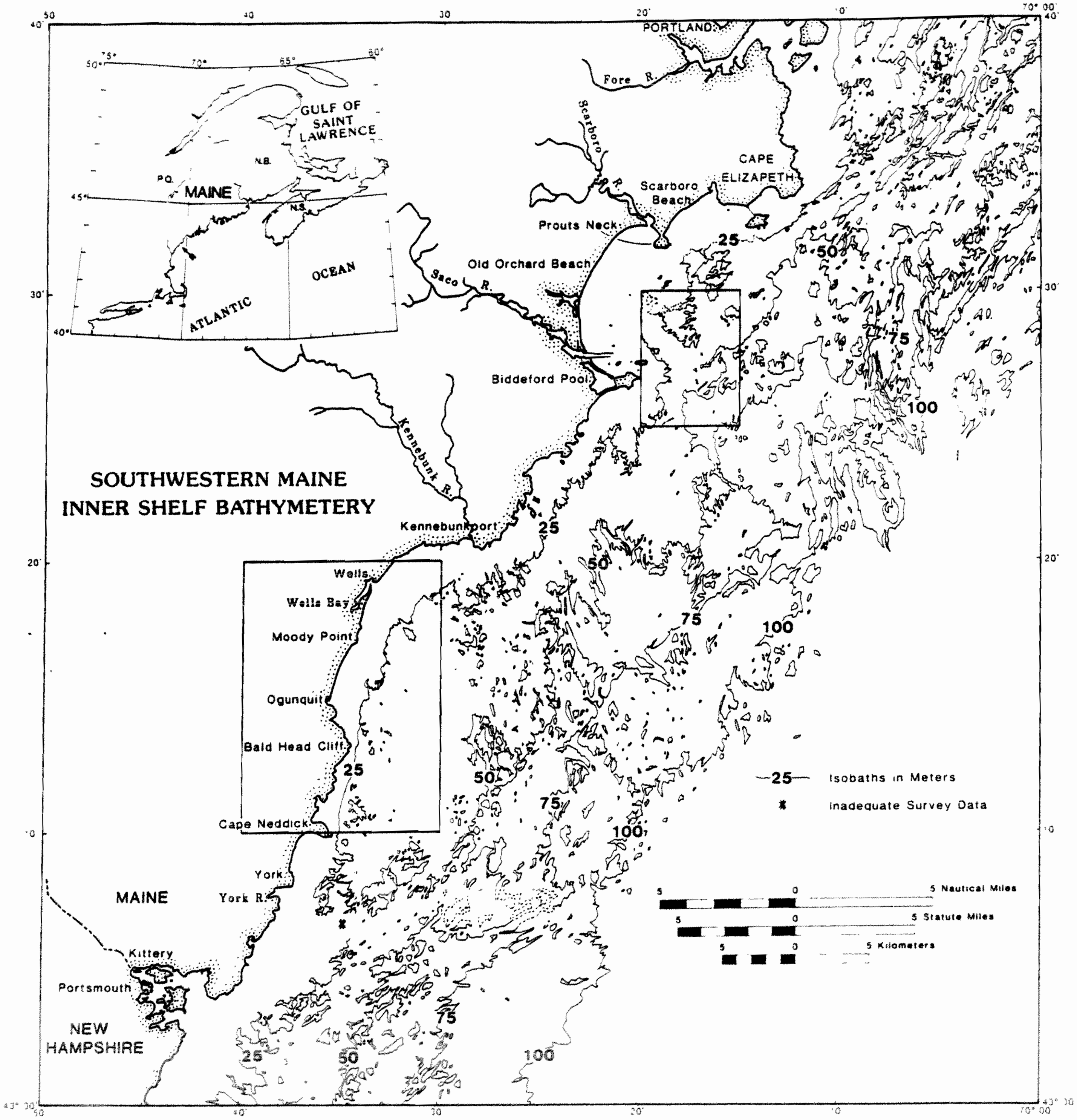


Figure 2. Bathymetric map of the study area with a 25 meter contour interval. Boxed areas are enlarged in Figure 7.

the central coastal region and interpreted subaerially dissected till from the records to a depth of 65 meters, where he recognized a "berm". At depths greater than 65 meters, he interpreted "undissected till" from the seismic records and constructed a widely cited sea level change curve which depicted the relationship of the land and sea between 14,000 years BP and the present. Belknap and others (1986 and in press, a) reinterpreted Schnitker's (1974) "undissected till" as natural gas, but otherwise acknowledged a 65 meter lowstand shoreline and generally accepted the sea level curve (Belknap and others, in press a).

On the northern border of Maine, Piper and others (1983) described the evolution of parts of the Nova Scotian coast on the basis of seismic profiling. Fader and others (1977) mapped the seafloor of the northern Gulf of Maine off the Bay of Fundy using seismic methods and bottom sampling, and King and Fader (1986) extended that work along the Scotian shelf. To the south, Birch (1984a, b) presented a structure contour map of the buried bedrock surface and isopach maps of seismic units representing early Cenozoic sediments, till, the Presumpscot Formation, as well as surficial deposits of sand and mud winnowed from the older units. He recognized a sea level lowstand at 35 meters depth on the basis of truncated deltaic foreset beds at that depth (Birch, 1984b).

METHODS

Bottom Samples

During the summer of 1984, 400 bottom samples were collected from the southwestern Maine inner shelf by means of a Smith-MacIntyre grab sampler (Figure 3). The device reliably collects a $.25m^3$ sample of gravel, sand, or mud with minimal loss of material. Sample stations were more closely spaced nearshore where sand was expected (Farrell, 1972; Folger and others, 1975). The position of all samples was obtained by LORAN-C and depth measured by Raytheon Fathometer.

All samples were frozen immediately after collection and field description. Table 2 summarizes the laboratory procedure by which the samples were analyzed. After standard sample splitting, gravel was screened out of the material for carbon analysis and results are reported for the finer than gravel (2 mm) fraction. While gravel was also screened out of carbonate analysis splits, the weight of gravel was noted and carbonate is reported for the total sample.

The carbon and nitrogen analyses were performed at the University of Maine's I. C. Darling Center on a Carlo-Erba Model 1106 Elemental Analyzer. All crushed samples were treated with acid vapor to remove carbonate. The accuracy of the device when evaluating known standards is better than .02% N and better than .04% C (L. Mayer, personal communication, 1985). Coefficients of variation of 2.75% (carbon) and 1.16% (nitrogen) were calculated from 45 Gulf of Maine sediment samples, and the average standard deviation of 28 triplicate samples from this study was 0.74% carbon. The range in values on the triplicates increases with the overall carbon or nitrogen content of the sediment, and reflects the difficulty in obtaining representative carbonate-free aliquots of very shelly samples.

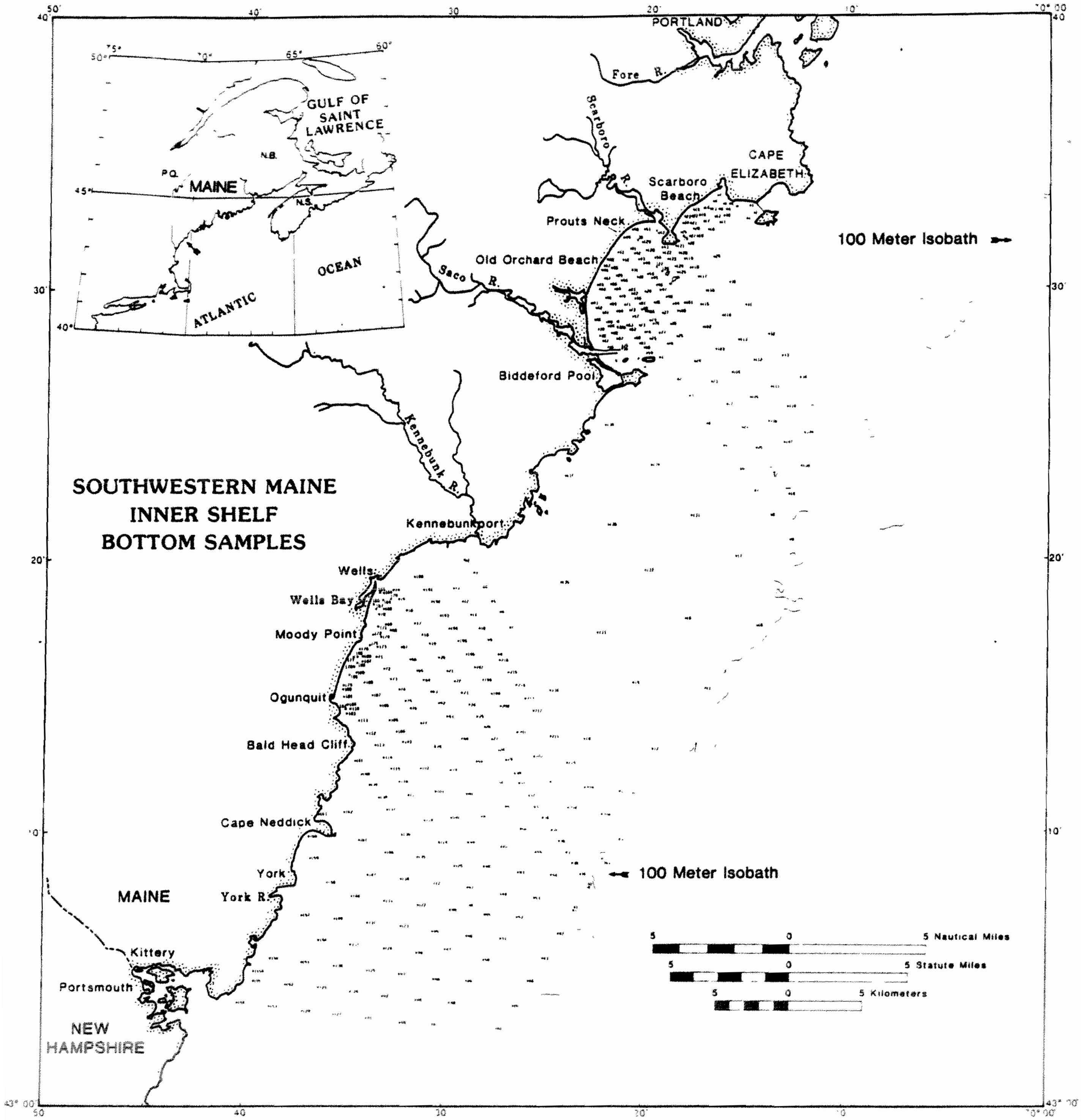


Figure 3. Location of bottom sample stations.

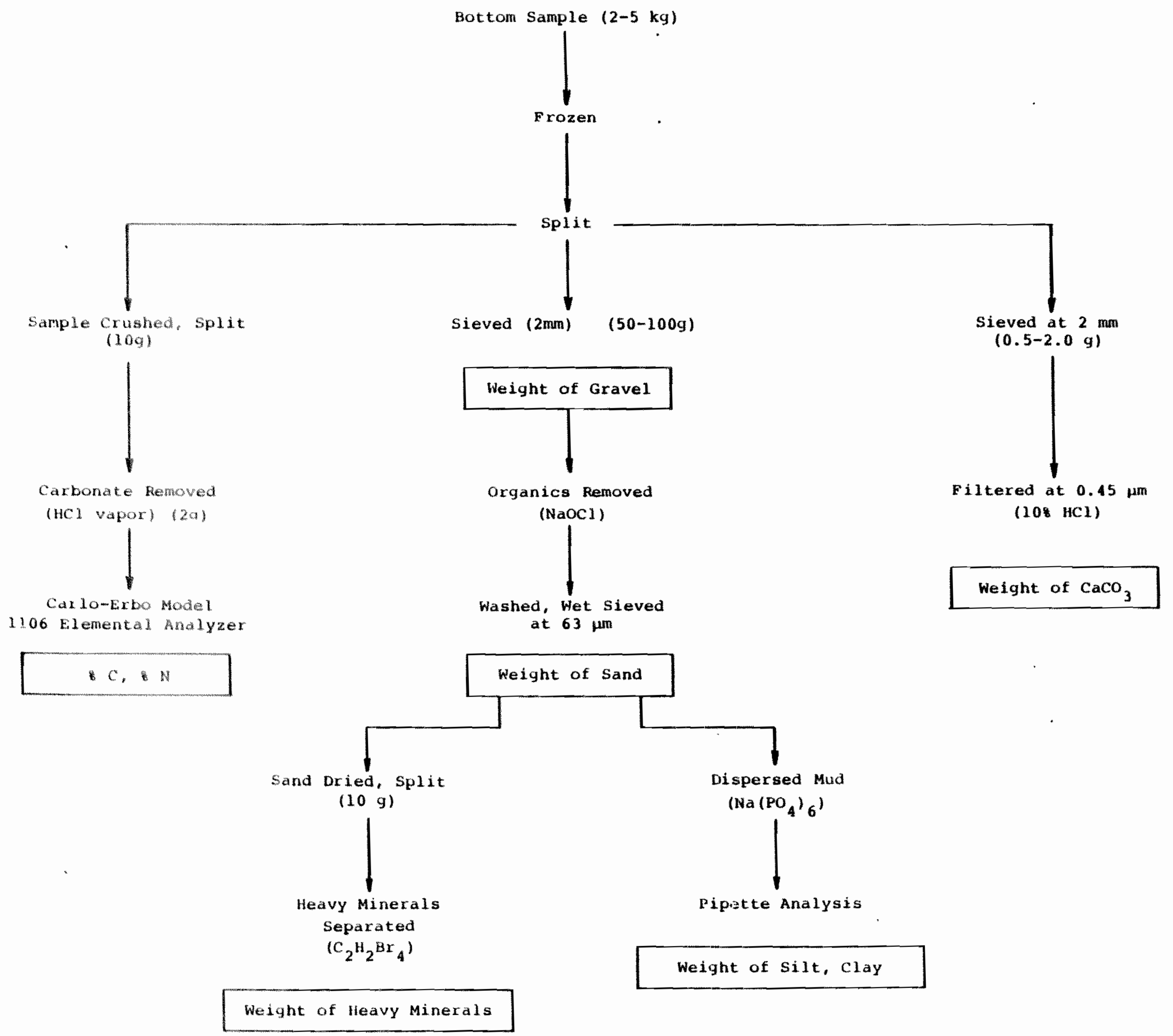


Table 2. Flow diagram for laboratory analyses.

The carbonate analyses were performed by the acid filtration technique of Molnia (1974). Gravel was removed from the sample prior to crushing, although the weight of gravel was incorporated into the calculation of percent carbonate. This technique accurately evaluated known standards to within 0.5%. Eighty-five replicate determinations were made on paired splits of samples to evaluate precision (Figure 4). The decrease in reproducibility with increasing carbonate content reflects the difficulty in obtaining representative splits of coarse-grained, carbonate-rich samples, and not in the reliability of the chemical method.

The textural analyses followed the procedure outlined by Folk (1974). For most samples, percent sand, percent gravel, percent silt, and percent clay were the only parameters evaluated. Selected samples representing specific environments were completely evaluated for mean grain size and related values (Folk, 1974). The proportion of gravel is probably not well represented owing to the difficulty of sampling such large clasts (Folger and others, 1975). For some samples a determination of the weight percent heavy minerals was made by flotation of the low density grains ($p<2.8$) in tetrabromoethane.

Seismic Reflection Profiles

Approximately 1000 km of seismic reflection profiles have been collected from the study area (Figure 5). Navigation was by LORAN-C and position fixes were made every 4 or 5 minutes, with ship speed varying from 3 to 5 knots. Two types of seismic systems were employed in the study: a Raytheon RTT 1000A unit and an O.R.E. Geopulse system. In general the two systems were operated simultaneously, although there were times when only one device was in operation.

The two systems operate in a complementary fashion. The Raytheon unit runs on a 3.5/7.0 kHz frequency and simultaneously at 200 kHz. The 200 kHz signal provides an accurate trace of the bathymetry while the 3.5 kHz signal generates a high resolution record of sub-bottom acoustic reflectors in generally shallow water (<80 m) and muddy substrates. The O.R.E. Geopulse is a wide frequency "boomer" system with reduced resolution but greater penetrating power than the Raytheon. Even on sandy or gravelly bottoms, penetration through greater than 50 m of cover to bedrock was obtained at all depths (<100 m).

The seismic records were used to deduce the nature of the subbottom geology as well as of the surficial material. In the latter capacity, side-scan sonar and bottom sampling provided ground truth "calibration" for interpreting surficial texture as revealed by the relative intensity of the surface acoustic return and overall geometry of the upper acoustic unit. The seismic lines were of great use, thus, to interpolate the surficial geology between the relatively widely spaced bottom samples (Folger and others, 1975).

Interpretation of the subbottom geology was less direct, and inferences drawn from observations on land, in borings and core holes, and from nearby studies were employed to identify the acoustic reflectors. Bedrock was never penetrated by the seismic systems and its surface usually

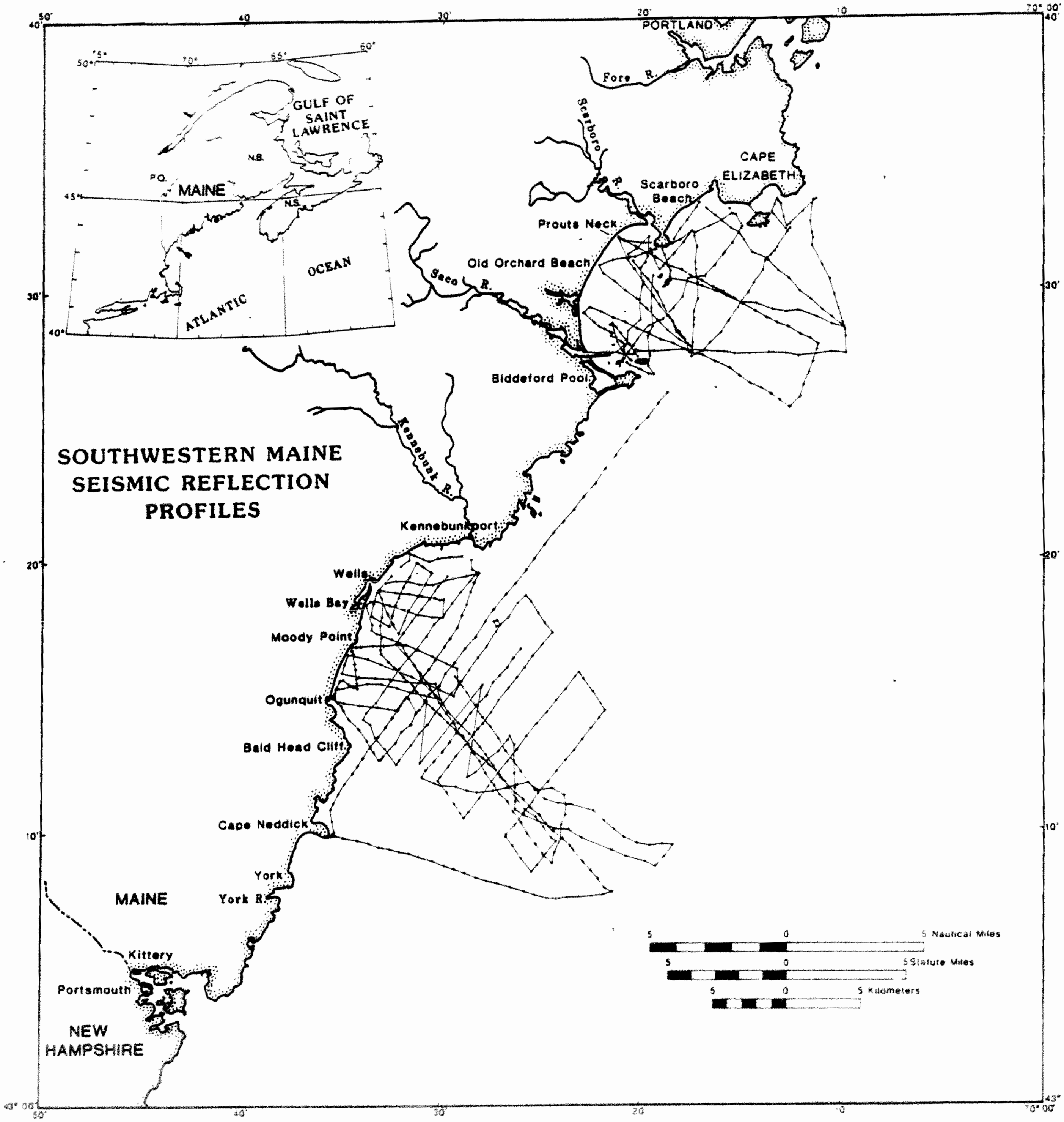


Figure 5a. Location of seismic reflection profiles from the study area. Location was by LORAN-C, and the dots represent some of the navigation fixes taken for plotting purposes.

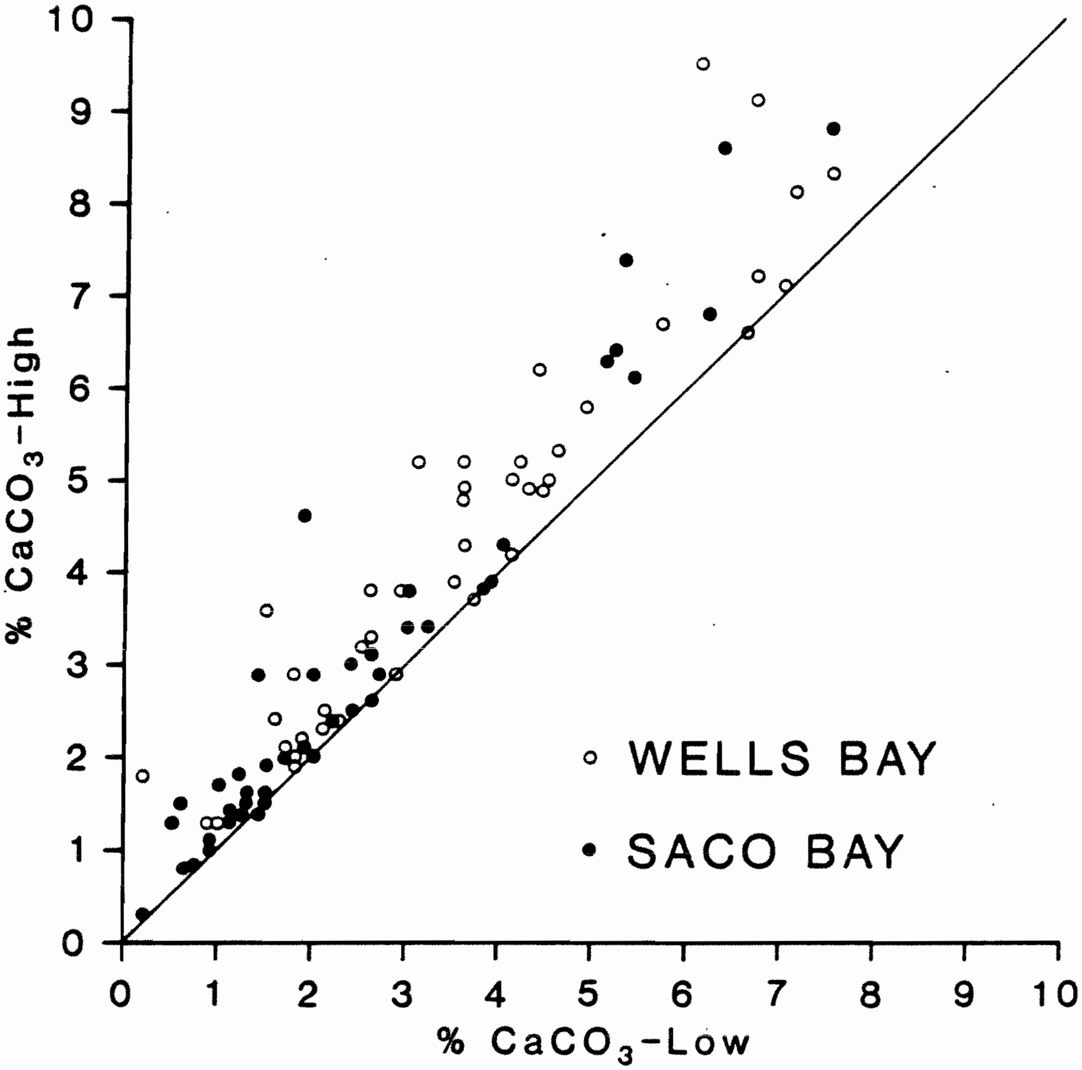
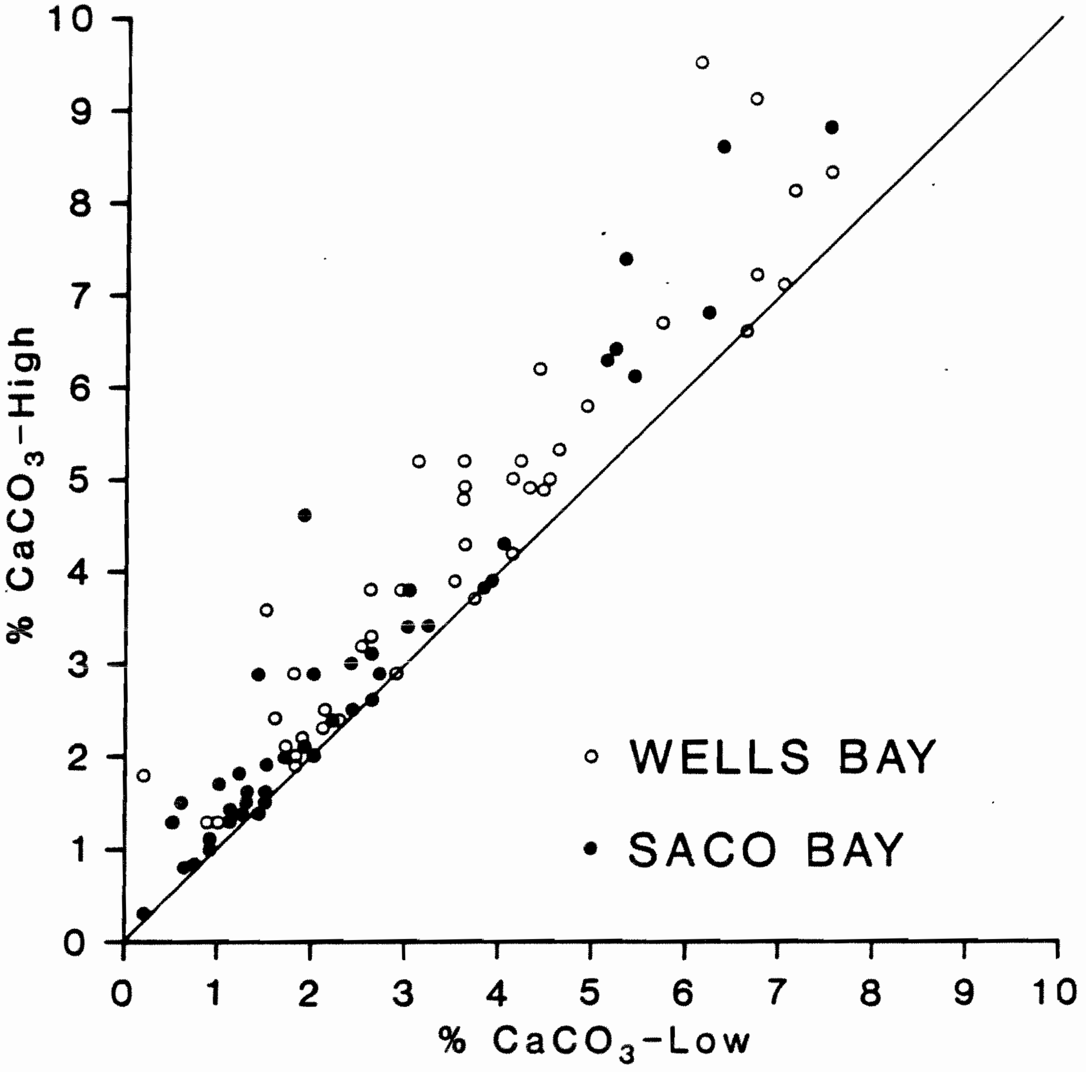


Figure 4. Graph of replicate analyses of $CaCO_3$ splits from 85 samples. The higher value of the pair is always plotted on the ordinate for viewing convenience, and the line plots values of x=y.



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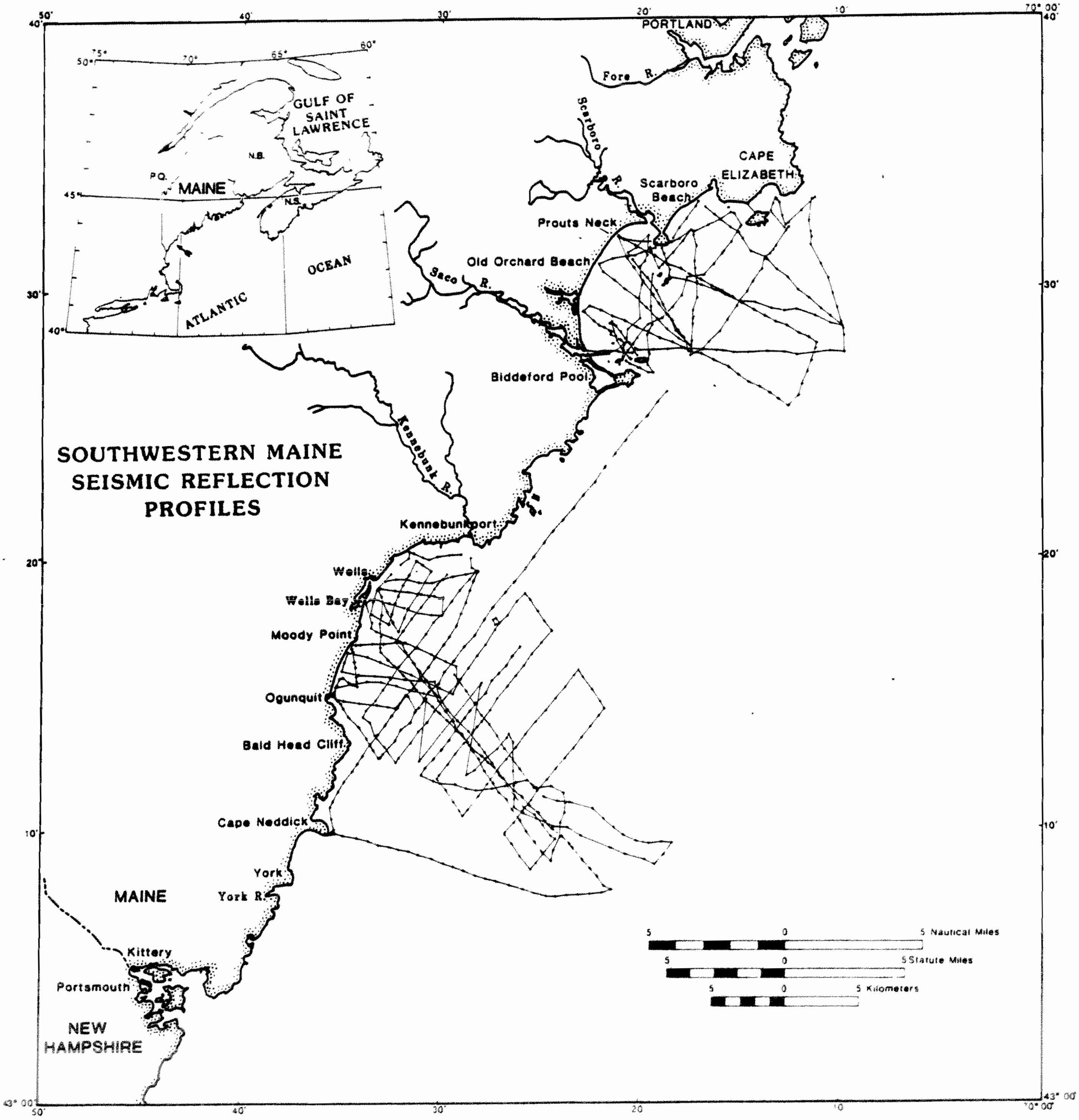

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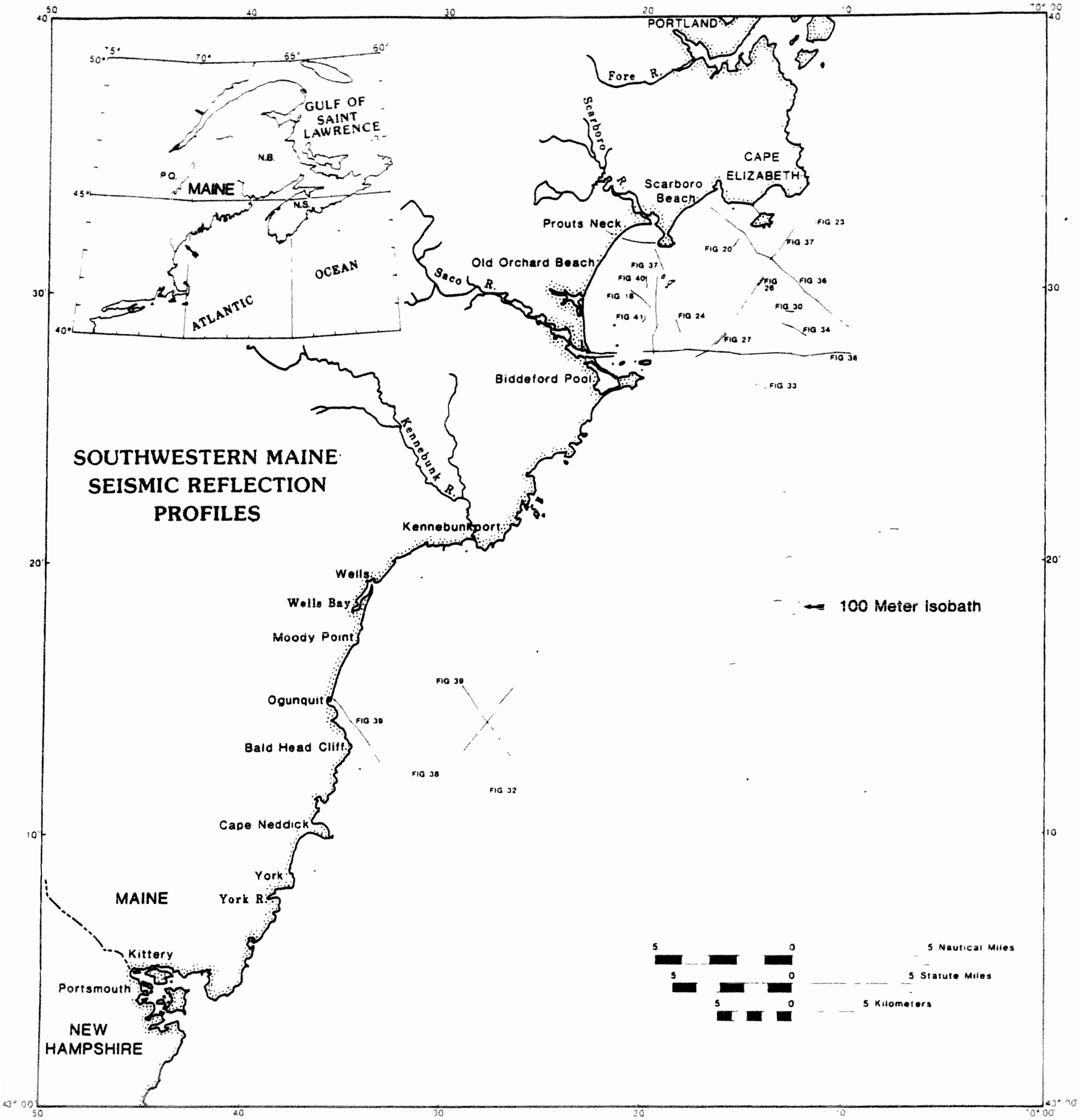

Figure 5b. Location of seismic reflection profiles used as figures in text.

formed the lower-most reflector on a record. Relief on the surface of the bedrock was extreme, and ranged over tens of meters across short horizontal distances. In other nearby areas (Birch, 1984a, b; Fader and others, 1977) early Cenozoic sediment unconformably overlies bedrock. No such deposits were identified in the study area, however. Instead, a seismic unit with chaotic internal reflectors and an irregular surface commonly rested on bedrock. This has been interpreted as till though no prominent moraines were recognized as in nearby locales (Oldale, 1985; Knebel and Scanlon, 1985). Frequently, a relatively transparent acoustic unit with closely spaced basal reflectors mantled the till or bedrock. The hard surface return of this unit was usually flat except in valleys where it was channel-shaped. Where it outcropped near the surface and was cored (Luepke and Grosz, 1986) this unit was identified as the glaciomarine Presumpscot Formation. Because of its readily identifiable characteristics, the glaciomarine sediment has been called Presumpscot Formation far offshore, and well outside the area within which it was originally described (Bloom, 1960). Its upper surface on land marks the regressive unconformity, terminating its deposition, while the offshore surface of the Presumpscot Formation is probably capped by the transgressive unconformity. Overlying the Presumpscot Formation, an acoustically transparent unit of modern mud was identified in some deep water locations (>75 m). Nearshore, a more acoustically opaque unit of sand forms the uppermost deposit. Each of these deposits is relatively smooth on its surface and generally lacking internal reflections. Unlike nearby areas (Kelley and others, 1986) no gas occurrences were recognized in the study area.

Seafloor Observations

Observations on the seafloor itself were made by side-scan sonar profiling as well as by submersible visits (Figure 6). The side-scan system used was the EG&G SMS 960 Seafloor Mapping System. This system automatically provided slant range corrections to the analogue output and was operated successfully at all depths in the study area. It was usually run at a 100 m or 200 m range (to either side of the vessel) and allowed bottom sample ground truth to be widely extrapolated.

One submersible dive was made with the Johnson Sea Link in the summer of 1985 and two dives were made in Saco Bay with the Delta submersible in the summer of 1986. Thousands of still photographs and hours of color videotape were collected during the dives. In addition, several samples and a box core were recovered during the dives. The greatest benefit of the dives was to provide detailed observations on the nature of the seafloor and on contacts between surficial units recognized from side-scan, seismic profiles, or bottom samples. In this report, those observations are referred to as "unpublished field notes".

BATHYMETRY

Unlike the inner shelf of New Hampshire and Massachusetts (Birch, 1984; Folger and others, 1975), the physiography of the study area is extremely irregular (Figures 2 and 7). As a submerged extension of Maine's coastal lowland (Denny, 1982) its bathymetry is dominated by bedrock exposures and glacial deposits. Glaciation has probably exaggerated the

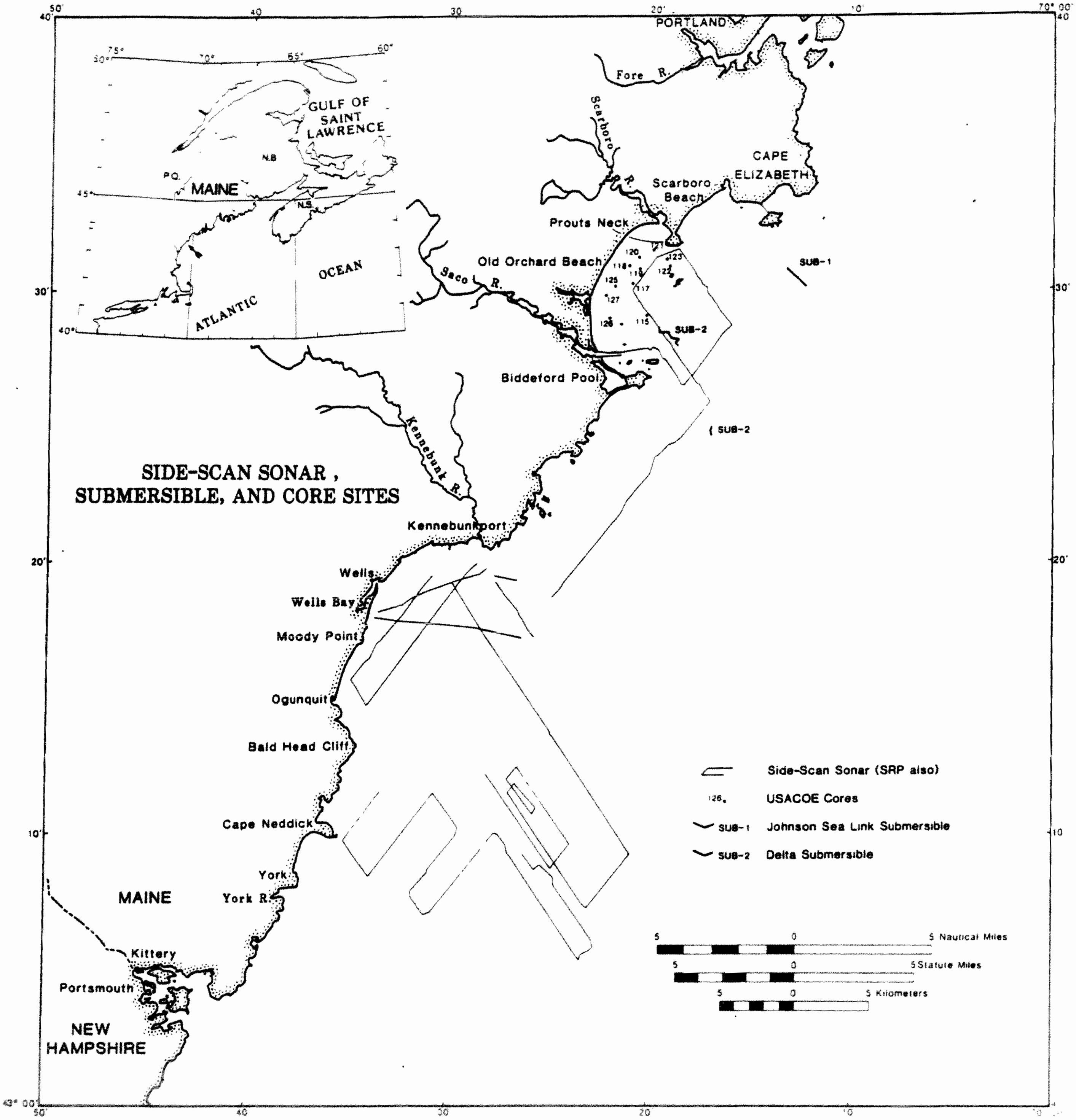

Figure 6a. Location of the side scan sonar tracks, submersible dive sites, and vibracores. Seismic reflection data was also collected in conjunction with the side scan sonar.

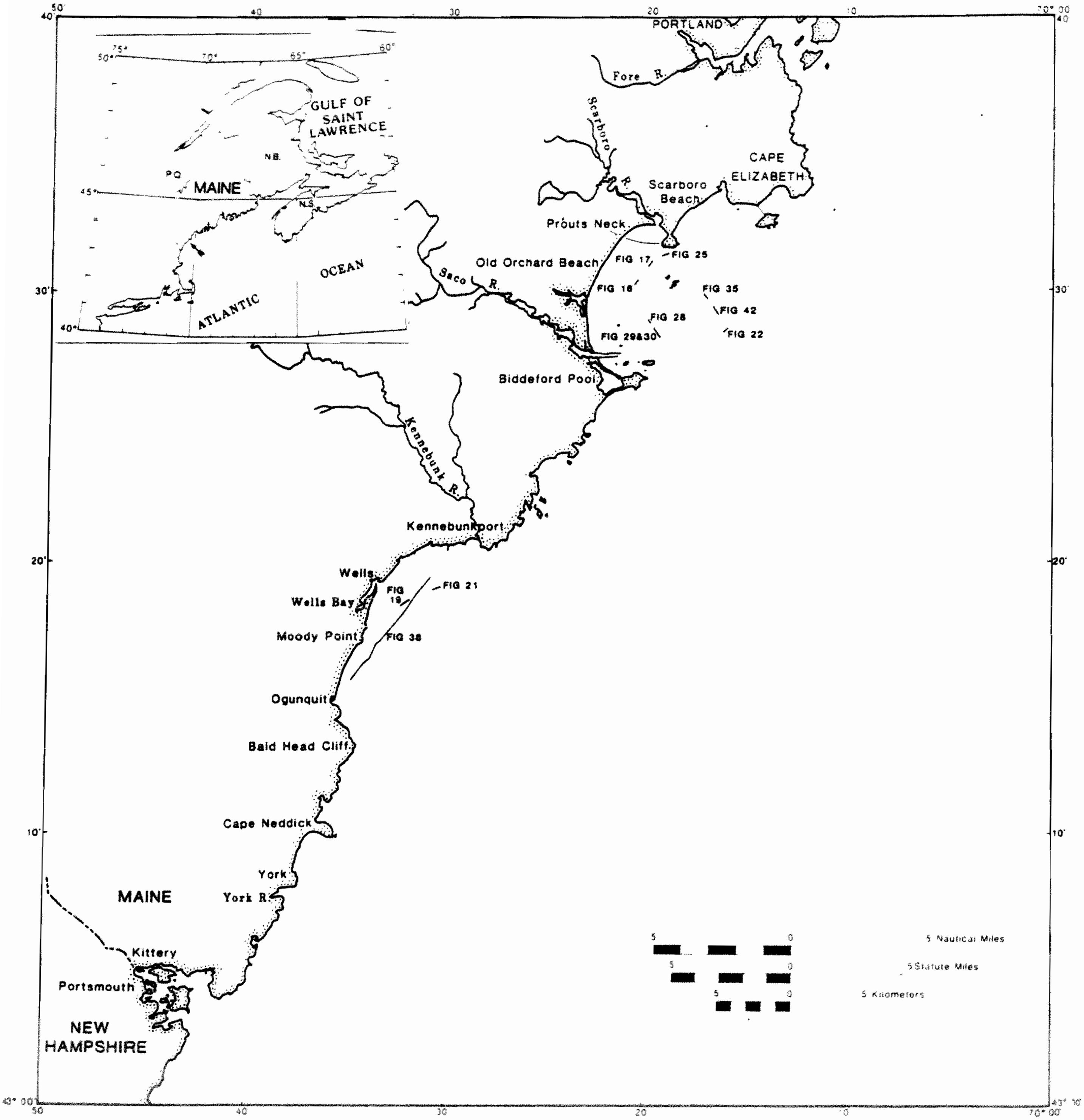

Figure 6b. Location of side-scan sonar tracks used as figures in text.

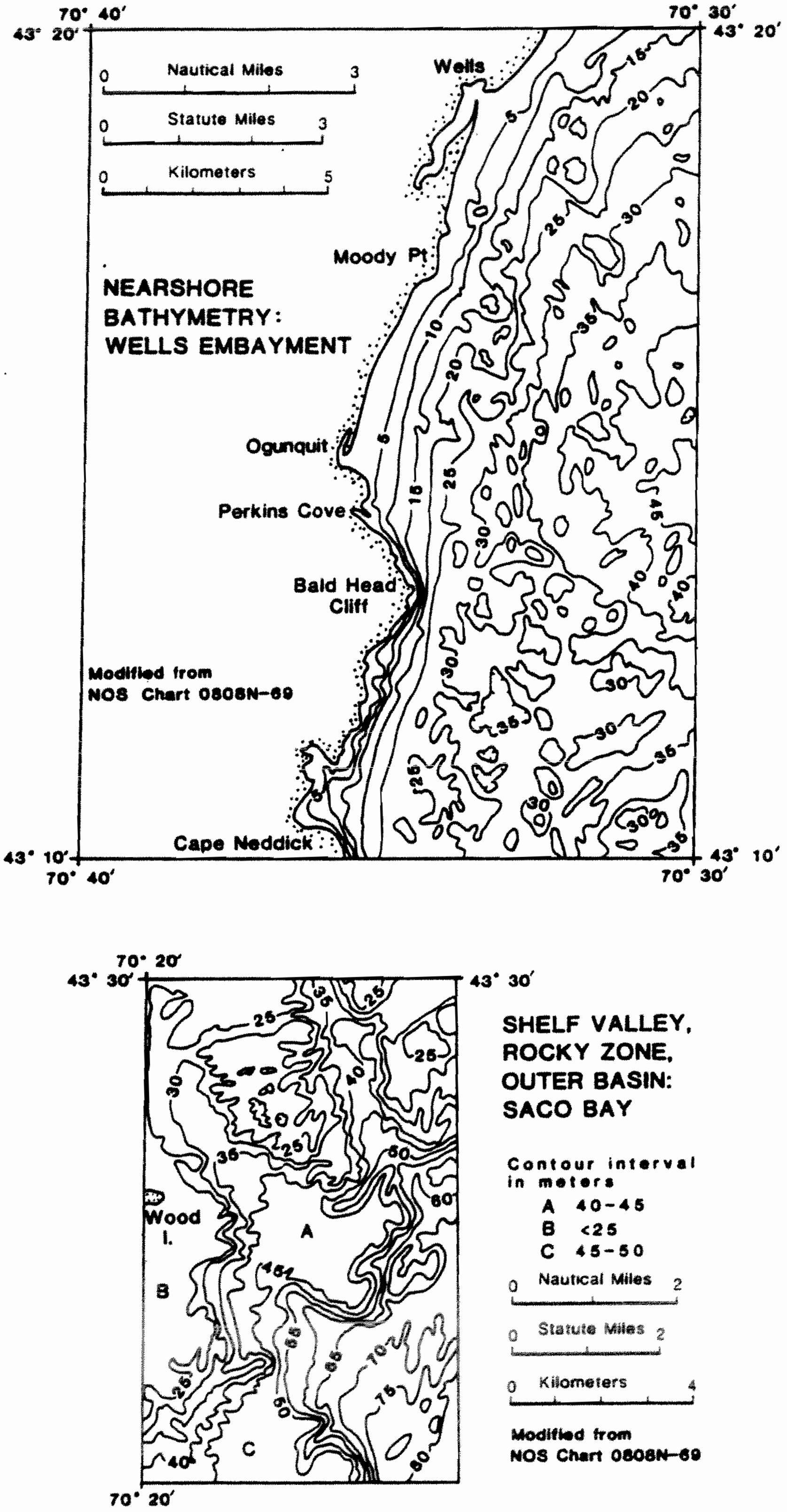

Figure 7. Enlargements from NOS Chart 0808N-69. The locations of these regions are boxed in Figure 1. Even at this scale, contours have been simplified for reproduction where indicated.

local relief by preferentially eroding foliated rocks and leaving resistant knobs of plutonic bodies (Kelley, in press). Although mapped with a 5 m contour interval, some regions of the shelf were too irregular to be mapped (National Ocean Survey, 1970), and most areas were too complex to be reproduced for publication. For this report a 25 m contour interval is used as a base map (Figure 2), and smaller regions are enlarged to depict the major physiographic subdivisions (Figure 7).

Four physiographic zones exist along the inner shelf of southwestern Maine (Figure 8). The Nearshore Ramp is an area of coast-parallel contours seaward of the region's many sandy beaches, but also directly offshore of some high bedrock cliffs (Baldhead Cliff, Figure 8). The Ramp has a gentle slope averaging about 0.5% to the 15 m isobath where it steepens to about 1.5% before flattening out at 30 m depth. Beyond the 30 m isobath the chaotic bathymetry of the Rocky Zone prevails at all places on the southwest inner shelf (Figure 8). The Rocky Zone is the most abundant physiographic component of the study area and is characterized by rapid changes in relief ranging from 5 m vertical bedrock cliffs to areas littered with 3 m diameter boulders (Figure 8). Although bedrock outcrops exist locally in all of the physiographic regions of the shelf, within the Rocky Zone they are the dominant type of bottom.

Extending gradationally from the Nearshore Ramp, numerous Shelf Valleys cut through the Rocky Zone (Figure 8). These valleys are bordered by steep bedrock walls and generally widen in a seaward direction (Figure 7). Their slope averages 0.8%, but no fathometer lines were run along their thalwegs and bedrock appears to outcrop occasionally within the channels. The Shelf Valleys all terminate in the Outer Basins. These extensive areas of very gently sloping seafloor often begin with an abrupt break in slope at 60 m interpreted as a lowstand shoreline and continue into water deeper than 100 m. Bedrock frequently borders the Outer Basin and crops out through the otherwise flat seafloor. On submersible dives, occasional 1 m diameter boulders have been recorded from the surface of the Outer Basin.

BOTTOM SEDIMENT TEXTURE AND COMPOSITION

Bottom sediment texture on glaciated shelves is notoriously heterogeneous (Trumbell, 1972). Virtually all components of the particle size spectrum were encountered in bottom samples from southwestern Maine (Figure 9). Although fewer than 20 samples were true gravels, greater than 100 grabs contained some material coarser than 2 mm in diameter (Table 3). As in other studies (Folger and others, 1975) the abundance of gravel is probably underrepresented by bottom sampling due to the difficulty of collecting large objects in the sampler, and of obtaining enough gravel sized material to perform statistically meaningful grain size analyses. Despite these limitations, several extensive areas of gravel bottom were mapped (Figure 10). Subparallel to the coastline from New Hampshire to Wells a band of gravel exists between a sandy inner area, and a more seaward region of rock. In several other locations offshore of Wells or Kennebunk, smaller bodies of gravel were also mapped adjacent to areas of exposed bedrock (Figure 10).

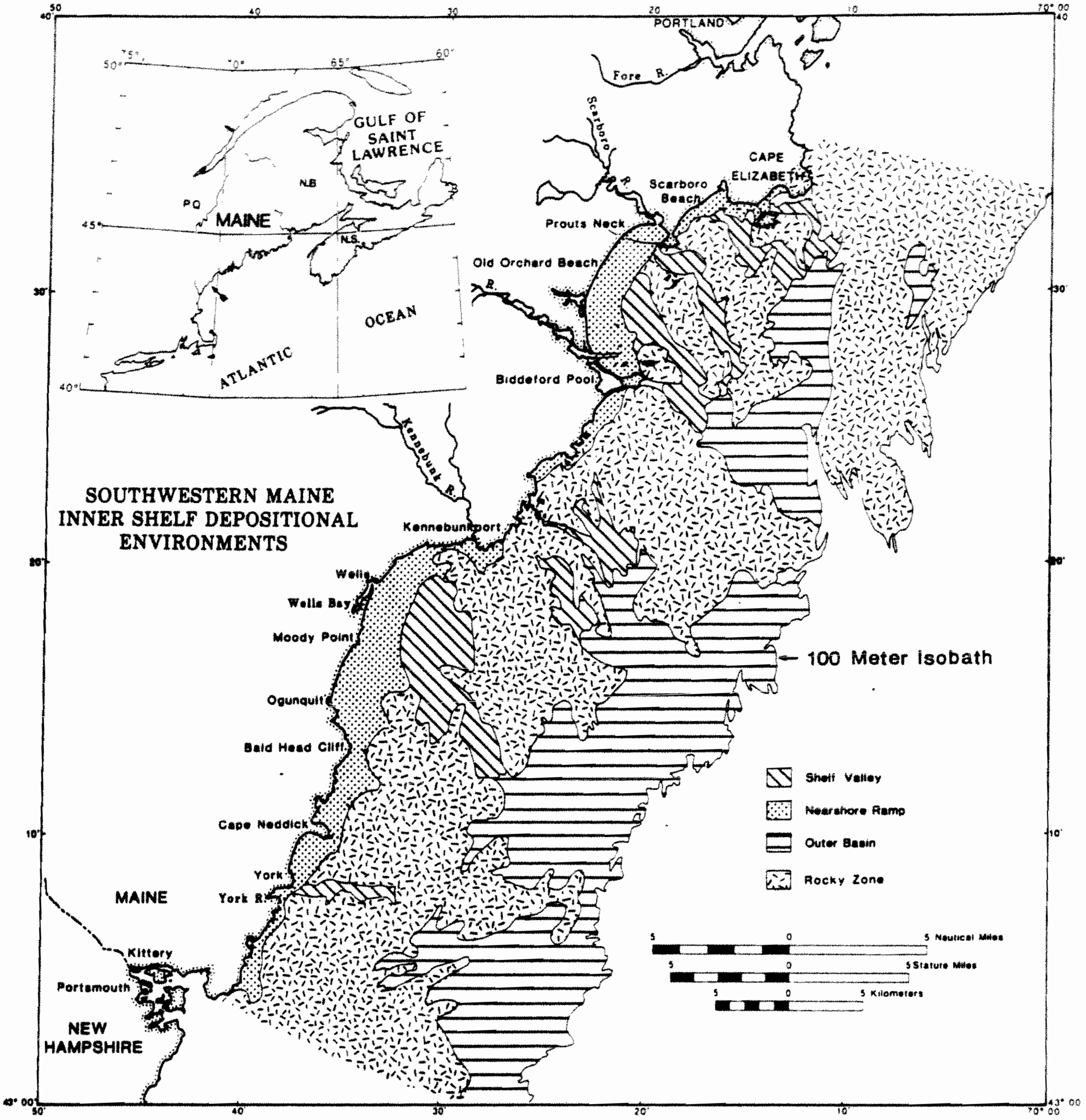

Figure 8. Map depicting the physiographic provinces of the southwestern Maine inner shelf.

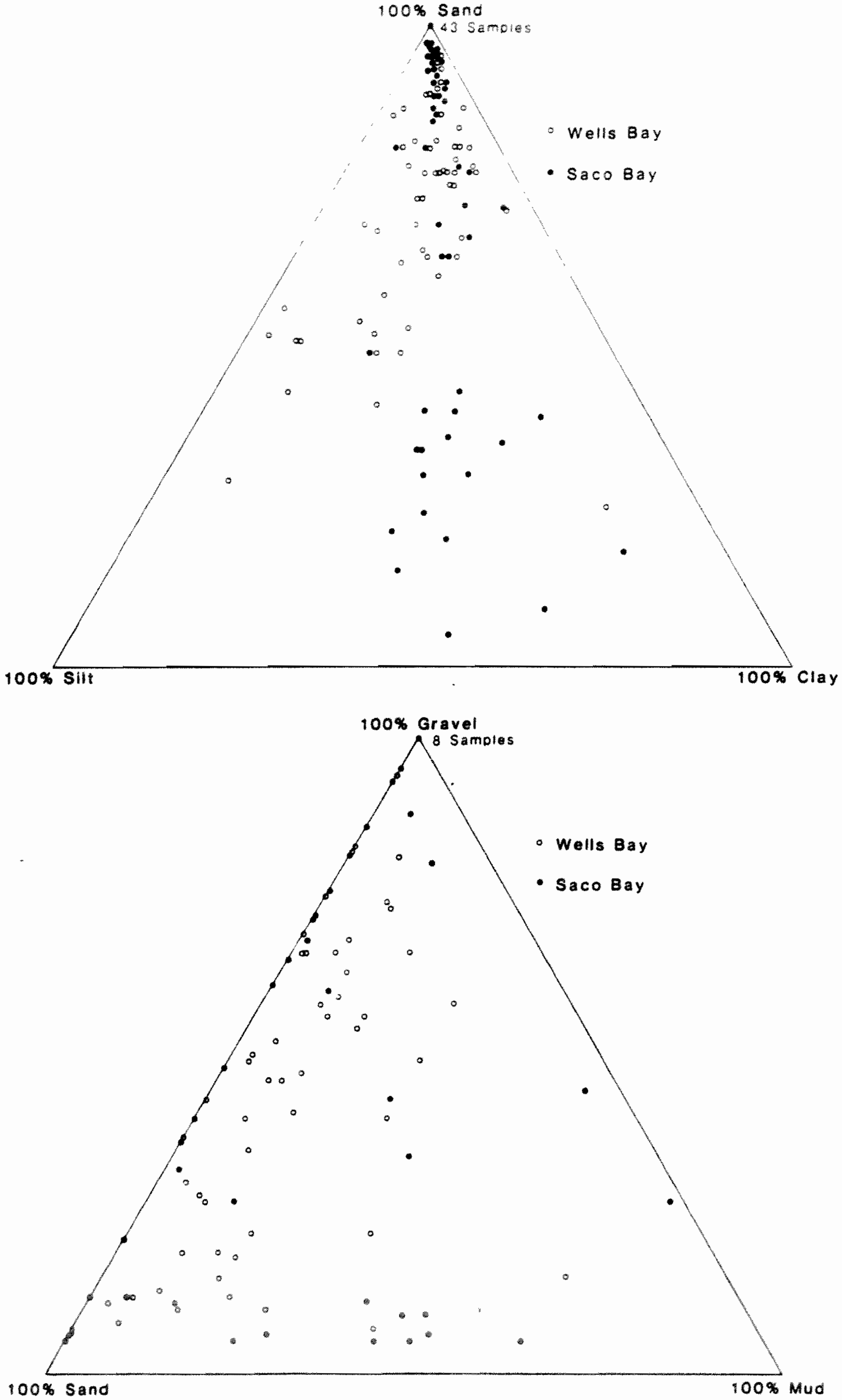

Figure 9. Ternary diagrams depicting the texture of sediment samples from the southwestern Maine inner shelf.

Table 3. Bottom sediment location, composition, and texture.

Station	Location (LORAN-C)		Depth (meters)	Color (munsell)	Sediment Description	CaCO$_3$ (%)	N (mg/g)	C (mg/g)	C/N	Snd (%)	Slt (%)	Cly (%)	Grav (%)	Hea (%
SC1	13400.0	26000.0			H									
SC2	13399.8	25991.6	38	A	gM-P	4.8	2.0	15.3	7.7	33	32	30	5	
SC3	13399.8	25983.0	52	B	gM-P	4.2	1.2	9.4	8.0	48	23	24	5	
SC4	13400.0	25974.3	67	B	mS	2.0	.7	5.7	8.4	72	9	19	0	
SC5	13399.7	25965.9	78	A	sM	4.1	1.3	9.9	7.7	40	30	30	0	
SC6	13399.8	25957.0	74	B	sM	5.4	2.2	17.1	7.7	21	44	35	0	
SC7	13399.9	25948.7	56		H									
SC8	13400.0	25940.1	69	C	mG-P					8	6	6	80	
SC9A	13399.8	25930.2	81		H-P									
SC9	13399.9	25930.0	81	C	mS	2.3	0.9	6.8	7.7	67	11	22	0	
SC10	13429.9	25920.1	88	D	sM	3.2	1.8	13.5	7.5	39	15	46	0	
SC11	13459.5	25920.1	91	B	sM	3.3	1.7	12.6	7.6	24	38	38	0	
SC12	13489.7	25920.2	91	B	sM-P	4.5	1.4	10.9	7.6	30	29	41	0	
SC13	13509.7	25920.0	88		H									
SC14	13509.7	25940.1	67		H									
SC15	13480.9	25939.9	85	E	sM	7.0	1.9	14.6	7.6	15	46	39	0	
SC16	13450.9	25939.8	102		mG-P	7.6	1.8	8.3	4.5	5	4	47	44	
SC17	13420.7	25940.1	72		gM	10.5	0.1	1.7	11.0	2	22	50	26	
SC18	13389.9	25940.1	99	B	sM	5.3	2.2	16.6	7.7	18	14	68	0	
SC19	13389.8	25947.3	91	D	sM-P	4.6	1.9	15.0	7.8	34	35	31	0	
SC20	13389.6	25956.3	89	E	M-P	6.6	2.6	19.7	7.7	9	29	62	0	
SC21	13389.9	25965.0	79	B	sM	3.7	1.8	14.1	7.9	36	29	35	0	
SC22	13389.9	25973.8	72	E	sM	3.7	2.0	15.0	7.5	35	22	43	0	
SC23	13389.9	25982.2	47		H									
SC24	13390.0	25991.1	48	B	sM	6.2	0.9	12.6	14.5	20	37	43	0	
SC25	13390.0	26000.0	27		H									
SC26	13389.9	26004.6	28		H									

Color Code:

A = 5Y 3/2
B = 5Y 4/2
C = 2.5Y 3/2
D = 2.5Y 4/2
E = 5Y 4/1

F = 5Y 5/3
G = 5Y 4/3
H = 5Y 3/1
I = 5Y 5/2
J = 5Y 2.5/2

K = 5Y 1/2
L = 5Y 5/1
M = 10YR 3/2
N = 5Y 4/4
O = 5Y 2.5/1

Textural Designation:

H = hard bottom, no sample
G = gravel
M = mud
S = sand
P = pebbles in sample

Table 3. Continued.

Station	Location (LORAN-C)		Depth (meters)	Color (munsell)	Sediment Description	$CaCO_3$ (%)	N (mg/g)	C (mg/g)	C/N	Snd (%)	Slt (%)	Cly (%)	Grav (%)	Heavy (%)
SC27	13389.9	26008.8	31	F	gS-P	5.8	0.3	2.4	8.4	53	23	19	5	
SC28	13390.0	26013.5	27	B	gS	4.5	0.8	6.4	8.0	45	25	24	6	
SC29	13390.2	26017.0	26	G	gS	7.9	0.7	5.4	8.1	67	15	12	6	
SC30	13389.8	26022.5	16		H-P	86.0								
SC31	13389.8	26025.3	13	B	gS	3.7	0.1	0.7	10.7	94	0	0	6	
SC32	13389.8	26029.0	9	B	S	1.4	0.1	1.0	8.0	94	3	3	0	
SC33	13390.0	26032.2	8	C	gM	5.3	1.4	9.8	7.0	44	30	17	9	
SC34	13411.5	26011.9	5	B	S	1.4		0.3	14.4	97	2	1	0	
SC35	13410.0	26012.3	9	B	sM	4.4	1.8	25.8	14.7	49	33	18	0	
SC36	13415.2	26015.5	3	A	S-P	9.2		0.4	14.0	99	1	0	0	
SC37	13415.0	26018.1	5	E	S-P	2.0				91	5	4	0	
SC38	13415.1	26020.0	5	B	S	1.6	0.2	1.2	6.3	96	2	2	0	
SC39	13414.8	26021.4	5	B	S	1.6	0.2	1.3	6.0	94	2	4	0	
SC40	13413.0	26024.0	5	H	S	1.5	0.1	0.9	6.8	98	0	0	2	
SC41	13409.9	26023.5	8	A	gS-P	1.0		0.4	8.5	94	0	0	6	
SC42	13410.1	26026.4	7	B	S-P	1.9	0.2	1.3	6.4	91	2	3	4	
SC43	13410.1	26028.6	6	B	S	1.7	0.1	0.9	9.5	100	0	0	0	
SC44	13405.1	26029.0	7	B	S	1.9	0.1	1.0	7.0	94	2	4	0	
SC45	13404.8	26031.3	6	A	S	1.3	0.3	2.8	11.4	100	0	0	0	
SC46	13399.9	26032.1	6	B	S	2.6	0.2	1.4	9.2	100	0	0	0	
SC47	13397.6	26032.1	6	A	mS	1.9	1.8	15.6	8.8	88	4	7	0	
SC48	13395.3	26033.2	5	B	S	1.9	0.1	0.7	13.9	100	0	0	0	
SC49	13385.1	26032.6	6	B	S	2.2	0.1	1.0	10.0	97	2	1	0	
SC50	13379.9	26031.9	5	I	S	1.8				100	0	0	0	
SC51	13377.1	26029.8	6	I	S					96	1	3	0	
SC52	13373.2	26025.3	3	I	S	0.9				100	0	0	0	
SC53	13375.0	26022.7	14	B	mS	1.9				77	6	17	0	
SC54	13379.8	26022.1	14	C	S-P	0.6				100	0	0	0	
SC55	13384.9	26020.2	15	C	S-P	1.8				100	0	0	0	
SC56	13394.8	26018.0	20	F	S	2.0				93	4	3	0	
SC57	13399.9	26014.4	20	F	mS	2.3				89	5	5	0	
SC58	13404.9	26010.4	10		H									
SC59	13404.8	26004.8	6		H									
SC60	13404.6	26005.4	13		gS-P	26.9	0.4	31.0	84.9	83	8	4	5	
SC61	13404.9	26007.5	14	B	mS	3.0	0.5	5.3	11.0	65	19	16	0	
SC62	13404.9	26013.1	13		G-P	13.2	0.2	1.4	7.8	18	0	0	82	
SC63	13405.0	26015.2	8		H									
SC64	13404.9	26020.9	12	B	mS	2.0	0.2	1.7	8.5	72	4	24	0	

Table 3. Continued.

Station	Location (LORAN-C)		Depth (meters)	Color (munsell)	Sediment Description	$CaCO_3$ (%)	N (mg/g)	C (mg/g)	C/N	Snd (%)	Slt (%)	Cly (%)	Grav (%)	Hea (%)
SC65	13404.9	26023.7	9	F	S	1.6	0.2	1.2	7.4	100	0	0	0	
SC66	13405.1	26026.0	7	B	S	2.0	0.1	0.9	11.9	97	2	1	0	
SC67	13400.2	26030.0	7	B	S	1.7	0.1	0.9	8.5	92	3	5	0	
SC68	13399.8	26027.3	7	B	S	2.0	0.1	1.1	8.0	100	0	0	0	
SC69	13399.7	26024.5	7	B	S	2.7	0.1	0.6	10.8	100	0	0	0	
SC70	13399.7	26022.3	13	F	S	2.2	0.1	1.0	7.3	91	3	6	0	
SC71	13399.8	26019.8	15	F	S	1.5	0.1	1.0	8.2	95	3	2	0	
SC72	13399.7	26017.1	14	F	mS	1.9	0.2	1.1	7.1	89	5	6	0	
SC73	13399.8	26012.2	20	B	gS-P	2.2	0.2	1.9	8.3	61	3	9	27	
SC74	13399.8	26009.2	20		sG-P	0.3	0.2	1.6	10.6	28	0	0	72	
SC75	13399.8	26006.5	19		S-P	1.2	0.1	0.8	17.7	97	0	0	3	
SC76	13394.7	26001.6	32	B	sG-P	2.5	0.5	4.7	9.7	34	9	23	34	
SC77	13395.0	26005.2	30	F	mS-P	3.2	0.8	6.7	8.9	81	10	9	0	
SC78	13394.8	26008.0	29	B	mS	2.3	0.5	4.1	8.0	69	14	15	0	
SC79	13394.8	26010.1	26	F	S	1.9	0.2	1.8	9.4	91	4	5	0	
SC80	13396.3	26014.6	22		mS	1.9				86	6	8	0	
SC81	13394.9	26015.8	21	F	mS	2.6	0.2	1.5	9.0	90	3	7	0	
SC82	13394.9	26020.4	18	F	mS	2.2				85	7	8	0	
SC83	13394.9	26022.9	15	F	S	2.8				100	0	0	0	
SC84	13395.0	26025.8	12	F	S	2.0	0.2	3.0	14.6	100	0	0	0	
SC85	13395.3	26027.9	9	F	S	1.8	0.2	1.3	6.8	93	3	4	0	
SC86	13395.1	26030.8	6	F	S	1.6				100	0	0	0	
SC87A	13405.2	26014.7	13		S-P	1.6		0.6	29.4	96	0	0	4	
SC87B	13410.1	26014.7	6		H-P									
SC88	13410.3	26016.8	12	E	mS	3.1				88	6	6	0	
SC89	13410.2	26019.1	11	B	mS					81	9	10	0	
SC90	13409.9	26021.3	8		H									
SC91	13384.8	26029.8	10	C	S	1.8	0.1	0.8	10.7	100	0	0	0	
SC92	13385.2	26027.7	12	J	S	1.2		0.6	14.7	97	1	2	0	
SC93	13385.2	26025.7	13	B	S	1.2	0.1	1.0	10.3	100	0	0	0	
SC94	13384.8	26022.6	15	A	sG-P	4.3	0.1	0.7	11.9	66	1	1	32	
SC95	13385.0	26017.4	20	G	sG-P	16.8	0.2	2.6	11.6	32	5	20	43	
SC96	13384.9	26015.5	15	H										
SC97	13385.0	26012.7	23	B	sG-P	53.7	0.6	48.8	88.8	31	1	0	68	
SC98	13384.8	26010.3	18	H										
SC99	13384.9	26007.8	29	H										
SC100	13385.0	26005.4	18	H										
SC101	13380.4	26005.3	29	H										

Table 3. Continued.

Station	Location (LORAN-C)		Depth (meters)	Color (munsell)	Sediment Description	$CaCO_3$ (%)	N (mg/g)	C (mg/g)	C/N	Snd (%)	Slt (%)	Cly (%)	Grav (%)	Heavy (%)
SC102	13379.9	25996.0	24	H										
SC103	13380.2	25987.5	35	H										
SC104	13380.2	25978.5	53	H										
SC105	13380.3	25969.9	71	A	gS-P	4.1	0.9	11.7	13.3	51	15	23	11	
SC106	13379.9	25961.2	89	B	M	7.8	3.0	22.6	7.6	5	44	51	0	
SC107	13379.9	25952.4	87	B	sM	4.0	2.1	15.5	7.5	34	34	32	0	
SC108	13379.9	25943.6	96	B	sM	4.6	2.0	15.6	7.6	30	35	35	0	
SC109	13370.2	25949.7	94	B	mS	2.8	0.6	5.1	8.2	64	15	21	0	
SC110	13370.1	25958.4	83	B	gM	4.2	1.3	9.7	7.6	47	12	32	9	
SC111	13370.3	25967.3	62	B	gS	2.2	0.8	6.1	7.5	72	6	17	5	
SC112	13370.1	25976.0	66	B	sM	5.0	1.9	14.7	7.7	42	24	34	0	
SC113	13370.3	25984.6	38		H-P									
SC114	13370.2	25993.6	40		sG-P	4.7	0.1	1.0	12.3	32	2	6	60	
SC115	13375.2	26001.9	23		H-P									
SC116	13370.2	26002.5	38	B	sM	7.0	2.1	15.8	7.5	40	26	34	0	
SC117	13369.9	26007.5	25		sG-P	0.6	0.1	1.5	19.5	35	0	0	65	
SC118	13370.2	26011.6	24	B	gS-P	2.9	0.2	1.7	8.9	77	2	10	11	
SC119	13370.0	26014.2	23	H	mS	2.9				78	7	15		
SC120	13370.1	26016.7	20	A	mS	2.3	0.4	3.4	7.9	64	16	20	0	
SC121	13369.8	26018.7	15		R									
SC122	13374.9	26020.3	15	G	S	1.9	0.1	1.3	9.1	95	1	4	0	
SC123	13374.9	26017.8	17	A	sG-P	2.6	0.1	1.0	9.9	24	0	0	76	
SC124	13375.1	26015.7	17		H-P									
SC125	13375.0	26013.3	10		H									
SC126	13380.1	26017.4	3		H									
SC127	13380.3	26019.8	12	A	S	5.9	0.1	1.0	7.4	96	1	3	0	
SC128	13380.2	26024.7	11		sG	1.9	0.1	1.7	21.2	60	0	0	40	
SC129	13379.9	26027.0	9	B	S	1.1	0.1	0.8	14.0	100	0	0	0	
SC130	13380.4	26028.5	9	G	mS	1.2	0.0	0.4	40.4	87	6	7	0	
SC131	13425.8	25960.0	43		sG	1.1	0.0	0.4	20.0	63	0	0	37	
SC132	13453.2	25960.0	66	B	mS	2.9	0.8	5.9	7.7	81	14	5	0	
SC133	13481.7	25959.9	58		H									
SC134	13510.2	25960.1	52		H									
SC135	13482.5	25979.9	58	I	mS-P	2.2	0.8	5.8	7.7	66	16	18		
SC136	13454.8	25979.9	53	B	mS-P	4.8	1.5	11.3	7.8	69	12	18		
SC137	13457.7	26000.0	16		H	1.0								
SC138	13433.1	26000.1	17		H									
SC139	13426.7	25980.0	33		G-P		0.1	0.8	15.4	5			95	

Table 3. Continued.

Station	Location (LORAN-C)		Depth (meters)	Color (munsell)	Sediment Description	$CaCO_3$ (%)	N (mg/g)	C (mg/g)	C/N	Snd (%)	Slt (%)	Cly (%)	Grav (%)	Hea (%
SB1	13340.0	26006.8	16	K	S-P	17.6				100	0	0		
SB2	13337.1	26006.2	8	B	S	5.7				100	0	0		
SB3	13336.8	26007.4	9	B	S	1.9				100	0	0		
SB4	13344.9	26013.3	14	B	S	1.8								
SB5	13342.4	26013.3	12	B	S	3.0								
SB6	13345.3	26015.8	11	B	S	2.2								
SB7	13344.9	26018.2	6	I	S	1.4								
SB8	13347.4	26018.3	8	I	S	1.7								
SB9	13347.3	26014.9	14	B	mS	3.0								
SB10	13347.7	26013.1	16	B	mS	2.5								
SB11	13350.0	26012.7	19	B	mS	2.9								
SB12	13350.1	26015.0	15	B	S	1.7				100	0	0	0	
SB13	13349.9	26017.4	12	B	mS	1.9								
SB14	13352.7	26019.1	13	B	mS-P	2.7								
SB15	13355.2	26021.1	10		S-P	5.2				94	0	0	6	
SB16	13355.0	26018.6	15	B	G-P	7.3				14	0	0	86	
SB17	13354.9	26016.1	15		H									
SB18	13355.1	26013.9	20		sG-P	2.3				52	0	0	48	
SB19	13360.1	26014.9	20	B	sG-P	9.3				28	0	0	72	
SB20	13360.0	26017.1	15	B	S	1.6	0.2	1.3	7.5	95	3	2	0	
SB21	13359.9	26019.7	10		H									
SB22	13357.7	26020.2	11	B	mS	1.9								
SB23	13360.0	26022.3	6	L	S	3.0				100	0	0	0	
SB24	13362.4	26021.8	7	B	mS	2.4								
SB25	13365.3	26020.0	7	A	gS-P	2.8	0.0	0.7	44.5	88	0	0	12	
SB26	13364.9	26019.0	8		H									
SB27	13362.3	26017.0	16		H-P									
SB28	13364.9	26016.5	20	B	gS-P	4.2				79	0	0	21	
SB29	13360.1	26006.6	20		H									
SB30	13360.4	25997.4	40	B	mS	7.6	1.9	14.4	7.7					
SB31	13360.3	25988.3	27		sG	7.9				39	0	0	61	
SB32	13359.9	25979.8	59	B		4.7	1.0	7.8	8.3	95	0	0	5	
SB33	13360.1	25971.1	56			2.7								
SB34	13359.8	25962.2	107	B		2.4								
SBR1	13372.6	26026.4	2			0.9								
SBR2	13369.0	26029.7	2	B		1.6								
SBR3	13371.0	26032.3	2	I		2.2								

le 3. Continued.

Station	Location (LORAN-C)		Depth (meters)	Color (munsell)	Sediment Description	$CaCO_3$ (%)	N (mg/g)	C (mg/g)	C/N	Snd (%)	Slt (%)	Cly (%)	Grav (%)	Heav (%)
WB1	13510.0	26010.1	17		G-P	69.5				1	0	0	99	
WB2	13509.9	26009.9	17		G-P	38.1				1	0	0	99	
WB3	13509.8	26005.0	20		H-P									
WB4	13509.8	25999.2	23		H									
WB5	13510.0	25994.1	30		H									
WB6	13509.4	25988.9	43	J	mS	4.3	1.4	12.4	9.0	69	17	14	0	
WB7	13509.8	25983.9	43		H									
WB8	13519.7	25981.5	29		H									
WB9	13519.9	25986.9	34		G	1.0				0	0	0	100	
WB10	13520.0	25992.1	37	G	gS-P	6.5	0.2	4.4	19.3	69	11	7	12	
WB11	13519.8	25997.1	34	G	mS	4.5	0.5	4.6	9.6	77	13	10	0	
WB12	13519.8	26002.0	27	B	G	15.7	1.4	6.6	4.7	12	1	6	81	
WB13	13519.8	26007.4	27	A	mS	4.2	1.6	7.3	4.7	54	32	14	0	
WB14	13540.0	26023.6	12	E	S	1.8	0.1	0.8	10.6	100	0	0	0	
WB15	13540.3	26019.0	17		H									
WB16	13540.0	26014.8	18		H									
WB17	13540.0	26010.3	30	B	mS-P	4.5	1.3	6.6	5.0	77	10	13	0	
WB18	13540.2	26005.6	31		H	3.5								
WB19	13539.9	26002.2	37	E	mS		1.3	6.8	5.4	78	14	8	0	
WB20	13539.9	25996.7	42	E	mS	2.9	0.9	5.2	5.9	69	24	7	0	
WB21	13540.0	25991.9	42	A	sG-P	2.6	0.7	3.8	5.6	46	5	8	41	
WB22	13539.9	25907.5	44	G	mS-P	3.3	0.6	4.0	6.3	77	9	14	0	
WB23	13540.1	25983.1	44	B	mS	3.1	1.4	5.7	3.9	73	15	12	0	
WB24	13540.1	25978.4	40		H-P									
WB25	13540.0	25973.9	50	B	sG-P	3.1	1.0	5.2	5.3	17	2	7	74	3.5
WB26	13539.9	25969.8	52	A	sG-P	2.1	1.0	5.0	5.3	31	2	13	54	
WB27	13540.0	25965.3	49	A	mS	2.3	0.3	2.1	7.6	90	4	6	0	3.4
WB28	13540.1	25961.0	51	A	sG-P	2.1	0.1	0.8	11.8	32	2	0	66	
WB29	13539.8	25956.9	30		H									
WB30	13539.8	25951.9	47		H									
WB31	13540.3	25948.1	53		sG	2.2	0.6	6.3	9.9	47	3	4	46	
WB32	13539.9	25943.2	72	B	mS	1.4	0.4	3.1	7.1	86	6	8	0	
WB33	13540.2	25939.1	65	B	gS-P	3.5	0.5	3.4	6.4	65	7	10	18	
WB34	13540.0	25934.8	60	B	S	1.1	0.0	1.4		94	2	4	0	
WB35	13539.9	25929.8	79	A	mS	3.1	0.7	7.3	10.3	63	22	15	0	4.4
WB36	13539.9	25925.6	81	B	mS	2.9	0.4	5.1	12.6	78	5	17	0	
WB37	13539.8	25924.3	80	B	mG-P	2.9	8.3	8.2	1.0	25	13	13	49	
WB38	13540.1	25916.9	87	A	mS-P	3.9	1.5	7.7	5.3	52	41	3	4	

Table 3. Continued.

Station	Location (LORAN-C)		Depth (meters)	Color (munsell)	Sediment Description	CaCO$_3$ (%)	N (mg/g)	C (mg/g)	C/N	Snd (%)	Slt (%)	Cly (%)	Grav (%)	Hea (%
WB39	13540.0	25912.4	76		H									
WB40	13539.9	25907.6	97	B	mS-P	5.1	1.0	9.2	9.2	51	42	7	0	
WB41	13549.9	25906.5	76		H									
WB42	13559.9	25905.5	69		H									
WB43	13570.0	25904.5	82	B	mG-P	5.7	0.8	8.1	9.9	16	12	14	58	
WB44	13579.7	25903.5	87	B	mS	5.8	1.0	8.8	8.8	61	18	21	0	
WB45	13589.9	25902.5	90	B	mS	4.7	1.4	7.2	5.2	53	26	21	0	
WB46	13599.7	25901.5	91	B	sM	7.2	2.4	15.7	6.5	41	36	23	0	
WB47	13619.7	25920.3	75	B	gM	6.7	1.6	12.9	8.1	22	48	15	15	
WB48	13609.8	25920.4	70	B	gS-P	2.8	0.8	6.9	8.9	45	11	22	22	
WB49	13599.5	25920.2	78	B	sM	4.5	1.1	9.3	8.5	49	32	19	0	
WB50	13589.8	25920.2	76	B	mS-P	4.7	1.2	10.0	8.3	65	18	17	0	
WB51	13579.7	25920.2	63	B	G-P	3.3				6	0	0	94	
WB52	13569.9	25920.2	55	M	sG-P	5.5				63	0	0	37	
WB53	13560.0	25919.9	38		H									
WB54	13549.8	25920.1	56		H									
WB55	13549.6	25929.3	72	B	mS	2.6	0.4	4.0	9.5	84	4	12	0	2.2
WB56	13549.8	25938.3	68	G	mS-P	2.6	0.6	5.7	9.0	75	9	16	0	4.6
WB57	13549.7	25947.1	59	B	sG-P	1.6	0.8	6.4	8.6	17	3	7	73	
WB58	13549.6	25955.9	50	A	sG-P	2.2				45	3	6	46	
WB59	13549.9	25964.6	41		G	25.9	0.4	3.9	9.5				100	
WB60	13549.7	25973.4	49		H									
WB61	13549.7	25981.9	49	A	sG	5.8	0.5	4.7	9.9	29	5	10	56	
WB62	13549.8	25986.8	48	A	mS	2.3	0.4	3.6	10.2	81	13	6	0	
WB63	13549.9	25991.7	45		sG-P	2.4				55	2	8	35	3.8
WB64	13549.8	25995.7	44	A	mS-P	3.4	0.8	6.9	9.2	71	4	25	0	
WB65	13549.8	25999.9	41	A	mS	3.7	0.5	4.7	9.7	79	7	14	0	
WB66	13549.9	26004.0	39	A	mS-P	2.9	0.6	5.1	8.9	77	8	15	0	1.5
WB67	13549.8	26008.6	30		H									
WB68	13549.9	26015.5	19		H									
WB69	13550.0	26017.9	17		H									
WB70	13550.1	26021.9	10		H									
WB71	13560.2	26013.7	19		H									
WB72	13560.2	26009.2	23		G-P	0.3	0.0	0.7	33.8	0	0	0	100	
WB73	13560.1	26004.9	32	B	gS-P	1.7	0.1	1.7	12.4	65	4	4	27	
WB74	13559.9	26000.9	33	G	sG-P	2.7	0.2	1.6	8.9	47	2	1	50	
WB75	13560.1	25996.7	33		H									
WB76	13560.0	25992.1	38		H-P									

Table 3. Continued.

Station	Location (LORAN-C)		Depth (meters)	Color (munsell)	Sediment Description	$CaCO_3$ (%)	N (mg/g)	C (mg/g)	C/N	Snd (%)	Slt (%)	Cly (%)	Grav (%)	Heavy (%)
WB77	13560.0	25987.8	41	A	mS	2.5	0.3	3.5	10.4	87	2	11	0	4.9
WB78	13560.2	25978.8	42	A	mS	2.6	1.1	9.4	8.4	63	13	24	0	
WB79	13560.1	25969.8	38		G-P	3.4	0.0	0.8		0	0	0	100	
WB80	13560.0	25960.6	52		H									
WB81	13560.0	25951.8	54		gS-P	3.3	0.7	5.6	8.4	69	3	13	15	
WB82	13560.0	25939.8	45	B	gS-P	2.0	0.3	2.7	10.7	72	3	6	19	
WB83	13560.0	25929.9	63		gS-P	3.2	0.4	3.7	9.0	65	17	8	10	
WB84	13570.1	25929.9	55		H									
WB85	13580.0	25929.9	47		H									
WB86	13590.1	25930.1	17		H									
WB87	13600.0	25930.3	63	A	mS-P	2.7	0.5	4.1	9.1	82	8	10	0	3.5
WB88	13610.2	25929.9	44		H									
WB89	13620.1	25930.2	65	A	mS-P	3.6	0.8	6.7	8.7	64	14	22	0	5.1
WB90	13629.9	25930.1	62	A	mS-P	3.0	0.7	6.4	9.0	67	12	21	0	4.5
WB91	13640.1	25940.0	26		H									
WB92	13630.3	25940.3	44	A	sG-P	1.4	0.5	4.8	8.9	28	2	7	63	
WB93	13620.1	25940.4	52		H									
WB94	13610.1	25940.1	55	A	sG-P	3.3	1.9	8.8	4.7					
WB95	13650.1	25940.2	60	A	mS-P	7.6	0.3	2.6	9.3	89	6	5	0	2.4
WB96	13590.0	25940.1	38	E	sG-P	47.3	0.3	47.7	15.4	43	5	0	52	
WB97	13519.8	25540.2	211		H-P	0.1	0.9	14.9						
WB98	13569.9	25940.1	40	G	sG-P	1.0	0.1	0.9	14.9	48	3	0	49	
WB99	13570.0	25949.6	21		H									
WB100	13570.2	25959.4	33		H									
WB101	13569.8	25969.0	32		G-P					0	0	0	100	
WB102	13569.9	25978.3	28		H-P					0	0	0	100	
WB103	13569.9	25988.1	29		H									
WB104	13569.8	25992.6	26		G					0	0	0	100	
WB105	13569.8	25997.3	32	G	gS	1.5	0.2	1.6	9.5	86	2	1	11	
WB106	13569.6	26002.2	30	B	S-P	0.7	0.1	0.8	8.6	100	0	0	0	7.5
WB107	13570.0	26006.9	24		G-P	0.5				0	0	0	100	
WB108	13570.1	26011.6	22	F	S-P	2.0	0.2	1.5	9.5	93	2	5	0	1.8
WB109	13570.1	26016.3	13	B	S	1.3	0.0	0.5	11.2	100	0	0	0	2.9
WB110	13580.0	26010.0	12	E	S	1.5	0.0	0.4	33.9	100	0	0	0	2.7
WB111	13579.8	26005.5	20	B	S	1.4	0.0	0.5	12.3	100	0	0	0	3.2
WB112	13579.8	26000.4	29	A	sM-P	8.9	3.2	24.0	7.6	49	29	22	0	
WB113	13579.6	25996.1	30	B	S-P	1.9	0.1	1.1	19.1	0	0	0	100	
WB114	13579.9	25990.9	31	G	S-P	0.4	0.0	0.7	16.7	0	0	0	100	

Table 3. Continued.

Station	Location (LORAN-C)		Depth (meters)	Color (munsell)	Sediment Description	$CaCO_3$ (%)	N (mg/g)	C (mg/g)	C/N	Snd (%)	Slt (%)	Cly (%)	Grav (%)	Hea (%
WB115	13579.7	25986.2	29		sG-P	0.8	0.0	0.5	40.4	25	0	0	75	
WB116	13579.7	25981.4	32	G	sG-P	0.7	0.1	1.0	11.5	17	0	0	83	
WB117	13579.6	25976.1	30	B	G	1.5	0.1	1.3	9.2	0	0	0	100	
WB118	13579.8	25967.3	32	N	G-P	10.3				17	0	0	83	
WB119	13579.7	25957.5	33	O	H-P									
WB120	13579.7	25948.5	26		H-P									
WB121	12589.7	25950.0	26		mS					82	3	15	0	2.6
WB122	13599.9	25950.0	39		H-P									
WB123	13609.8	25950.2	32	G	sG-P	3.2	0.4	3.1	8.3	28	1	5	66	
WB124	13619.9	25950.0	45	A	sG-P	4.3				34	3	7	56	
WB125	13630.0	25950.0	50	B	gS-P	7.4	0.6	4.8	8.2	77	3	10	10	
WB126	13639.9	25950.1	26		H									
WB127	13650.0	25950.0	43	B	gS-P	3.4	0.5	4.4	8.6	61	7	10	22	
WB128	13659.8	25959.9	43		H									
WB129	13649.7	25960.1	26		H									
WB130	13639.9	25960.0	23		H									
WB131	13630.0	25960.3	25		H									
WB132	13620.0	25960.1	27		mS					86	12	2	0	0.8
WB133	13610.0	25960.2	23		H									
WB134	13599.9	25960.2	24		H									
WB135	13589.7	25960.4	29	N	gS-P	2.0	0.0	0.6	15.5					
WB136	13590.0	25969.5	40	A	sG-P	1.7	0.1	6.3	71.4	31	3	7	59	
WB137	13589.8	25979.0	30	G	mS-P	2.4	0.0	0.6	20.7	81	10	7	3	3.3
WB138	13589.9	25983.9	35	A	gS-P	2.4	0.2	1.6	9.5	65	3	4	28	
WB139	13590.0	25988.7	35	A	S-P	1.7	0.2	1.6	9.4	91	3	5	0	
WB140	13590.1	25993.4	32	G	sG-P	3.5	0.1	1.0	15.8	31			69	
WB141	13589.8	25998.1	22	G	S	3.1	0.0	0.7	15.7	100	0	0	0	1.3
WB142														
WB143														
WB144														
WB146	13599.3	25970.7	30		H									
WB147	13609.8	25970.2	33	A	H-P	0.9	0.1	1.0	11.4					
WB148	13619.7	25970.1	23		H									
WB149	13629.8	25970.1	16		H									
WB150	13639.8	25970.0	13		H									
WB151	13649.9	25970.3	13		H									
WB152	13660.0	25970.1	12		H									
WB153	13670.0	25970.2	19		H-P									

le 3. Continued.

Station	Location (LORAN-C)		Depth (meters)	Color (munsell)	Sediment Description	$CaCO_3$ (%)	N (mg/g)	C (mg/g)	C/N	Snd (%)	Slt (%)	Cly (%)	Grav (%)	Heavy (%)
WB154	13679.8	25980.2	6		H									
WB155	13670.0	25980.1	12	B	S-P	10.9	0.1	0.8	12.6	100	0	0	0	
WB156	13659.7	25980.0	9		H									
WB157	13640.0	25980.1	24	B	sG-P	7.7	0.4	5.6	15.0	25	5	2	68	
WB158	13624.8	25980.2	23	A	G-P	14.5				7	0	0	93	
WB159	13625.0	25989.9	10		H									
WB160	13621.1	25995.2	3	E	S	3.7	0.0	0.4		100	0	0	0	4.4
WB161	13615.0	25980.3	28	A	mG	0.4	0.4	3.1	7.0					
WB162	13604.0	25990.1	23	A	gS-P	8.7	0.1	1.0	8.9	78	6	3	13	
WB163	13613.5	25996.5	3	A	gS-P	13.7	0.0	0.4	50.9	86	3	3	8	
WB164	13543.7	26024.6	8		S	1.3	0.0	0.4	29.9	100	0	0	0	1.5
WB165	13545.3	26026.4	5		S	1.2	0.0	0.3		100	0	0	0	
WB166	13549.9	26025.3	5		S	0.9	0.0	0.3	38.3	100	0	0	0	
WB167	13549.9	26023.8	8		S	1.2	0.0	0.4	9.9	100	0	0	0	
WB168	13547.0	26021.9	11		S	0.1	0.1	0.6	10.3	100	0	0	0	
WB169	13545.9	26023.8	9		S	1.8	0.1	0.6	9.1	100	0	0	0	2.1
WB170	13513.3	26022.0	13	B	S-P	1.5	0.0	0.6	15.6	100	0	0	0	3.3
WB171	13553.0	26019.5	15	E	S	1.3	0.1	0.9	1.0	100	0	0	0	5.1
WB172	13556.7	26018.9	16		H-P									
WB173	13557.5	26016.0	14		H									
WB174	13554.7	26017.1	18	B	sG-P	6.5	0.2	1.4	7.1	53	2	5	40	
WB175	13560.0	26017.0	13		H									
WB176	13564.2	26020.0	7		S	1.5	0.0	0.2		100	0	0	0	
WB177	13567.9	26019.8	5		S	1.8	0.0	0.2	15.2	100	0	0	0	
WB178	13569.8	26018.1	9		S	1.4	0.1	0.4	8.7	100	0	0	0	0.2
WB179	13576.8	26017.1	4		S	1.3	0.0	0.4	23.9	100	0	0	0	1.6
WB180	13577.9	26015.3	6		S	1.7	0.0	0.2		100	0	0	0	0.5
WB181	13579.9	26014.3	7		S	1.4	0.0	0.2		100	0	0	0	1.0
WB182	13581.8	26011.7	8		S	1.4	0.0	0.2		100	0	0	0	3.6
WB183	13582.0	26009.8	10		S	1.5	0.0	0.4	14.8	100	0	0	0	3.6
WB184	13579.9	26011.7	10		S	1.0	0.0	0.2		100	0	0	0	
WB185	13573.7	26016.6	8		S		0.0	0.3	24.1	100	0	0	0	
WB186	13567.9	26017.7	12		S	1.1	0.0	0.5	11.3	95	1	4	0	1.7
WB187	13566.1	26017.3	13											
WB188	13566.3	26019.0	9		sG-P	1.3	0.0	0.3	13.4	57	0	0	43	
WB189	13564.2	26017.8	14		S	1.4	0.0	0.3	8.6	100	0	0	0	3.9
WB190	13530.0	26020.0	12		H									
WB191	13529.9	26014.9	23		mS	3.3	0.6	4.5	7.1	64	18	18	0	

Table 3. Continued.

Station	Location (LORAN-C)		Depth (meters)	Color (munsell)	Sediment Description	$CaCO_3$ (%)	N (mg/g)	C (mg/g)	C/N	Snd (%)	Slt (%)	Cly (%)	Grav (%)	Hea (%
WB192	13530.0	26010.2	29	A	mS	2.0	0.5	4.1	8.6	87	10	3	0	1.
WB193	13530.0	26005.0	31		gS-P	2.3	0.5	4.3	7.8	67	10	4	19	
WB194	13530.0	26000.0	35	A	mS-P	2.8	1.0	8.2	7.9	68	23	9	0	
WB195	13529.9	25994.9	30		H-P									
WB196	13530.0	25990.0	35		sG-P	2.2	0.1	1.1	11.6	66	4	0	30	
WB197	13530.0	25985.0	44		mS-P	3.2	0.7	5.2	7.6	77	5	18	0	4.1
WB198	13530.1	25980.1	26		H-P									
WB199	13530.1	25975.1	30		H									
WB200	13530.0	25970.0	32		H									
WB201	13530.1	25960.2	38		H									
WB202	13529.9	25950.4	56	A	sG-P	1.2	0.7	4.1	5.8	34	2	6	58	
WB203	13529.8	25940.4	72	B	mS-P	3.8	0.7	5.3	7.7	81	6	13	0	5.7
WB204	13529.5	25930.1	79	B	mG	3.4	0.5	4.3	8.3	34	14	12	40	
WB205	13529.7	25920.4	82	B	mG-P	14.6	0.9	7.0	7.5	16	11	7	66	
WB206	13529.6	25910.1	88	B	mS	2.9	0.8	6.7	8.3	58	27	15	0	
WB207	13520.0	25910.0	102		sM	6.3	2.2	16.1	7.3	29	62	9	0	
WB208	13520.0	25920.0	87		H									
WB209	13519.8	25930.2	85		sM-P	8.1	1.7	13.0	7.5	43	47	10	0	
WB210	13520.1	25940.2	77		sM	5.5	1.2	9.0	7.8	52	31	17	0	
WB211	13520.0	25950.1	67		sG-P	11.2	0.7	5.6	8.1	31	2	1	66	
WB212	13520.0	25960.1	50		sG-P	6.2	0.8	6.4	7.8	42	7	4	47	
WB213	13520.0	25965.0	40		H									
WB214	13520.2	25970.2	40		H									
WB215	13520.1	25975.1	46		gS-P	4.2	0.2	2.0	8.6	82	2	4	12	
WB216	13520.1	25980.0	33		H									

Table 4. Mean value of compositional and textural parameters from the four physiographic zones on the shelf.

Mean Values of Textural and Compositional Parameters

Bay	Environment	%C	%N	C/N	%$CaCO_3$	%Mud	%Sand	%Gravel
Saco	Shelf Valley	5.37	0.65	8.26	2.99	23.3	67.0	9.7
Wells	Shelf Valley	4.77	0.70	6.81	3.54	20.0	64.9	14.8
Combined	Shelf Valley	5.04	0.68	7.41	3.32	21.2	65.2	13.9
Saco	Outer Basin	3.14	1.72	7.64	4.28	61.2	37.8	1.0
Wells	Outer Basin	9.46	1.11	6.51	4.61	29.9	52.9	17.2
Combined	Outer Basin	7.23	1.34	7.06	4.48	41.6	47.3	11.1
Saco	Rocky Zone	2.57	0.33	7.79	8.39	11.8	51.1	37.1
Wells	Rocky Zone	4.14	0.47	8.81	7.46	7.1	41.2	51.7
Combined	Rocky Zone	3.59	0.42	8.55	7.82	9.0	45.3	45.7
Saco	Nearshore Ramp	1.49	0.18	8.28	2.25	5.7	92.3	2.1
Wells	Nearshore Ramp	2.25	0.28	8.04	2.40	2.8	88.8	8.4
Combined	Nearshore Ramp	1.77	0.22	8.05	2.31	4.5	90.8	4.7

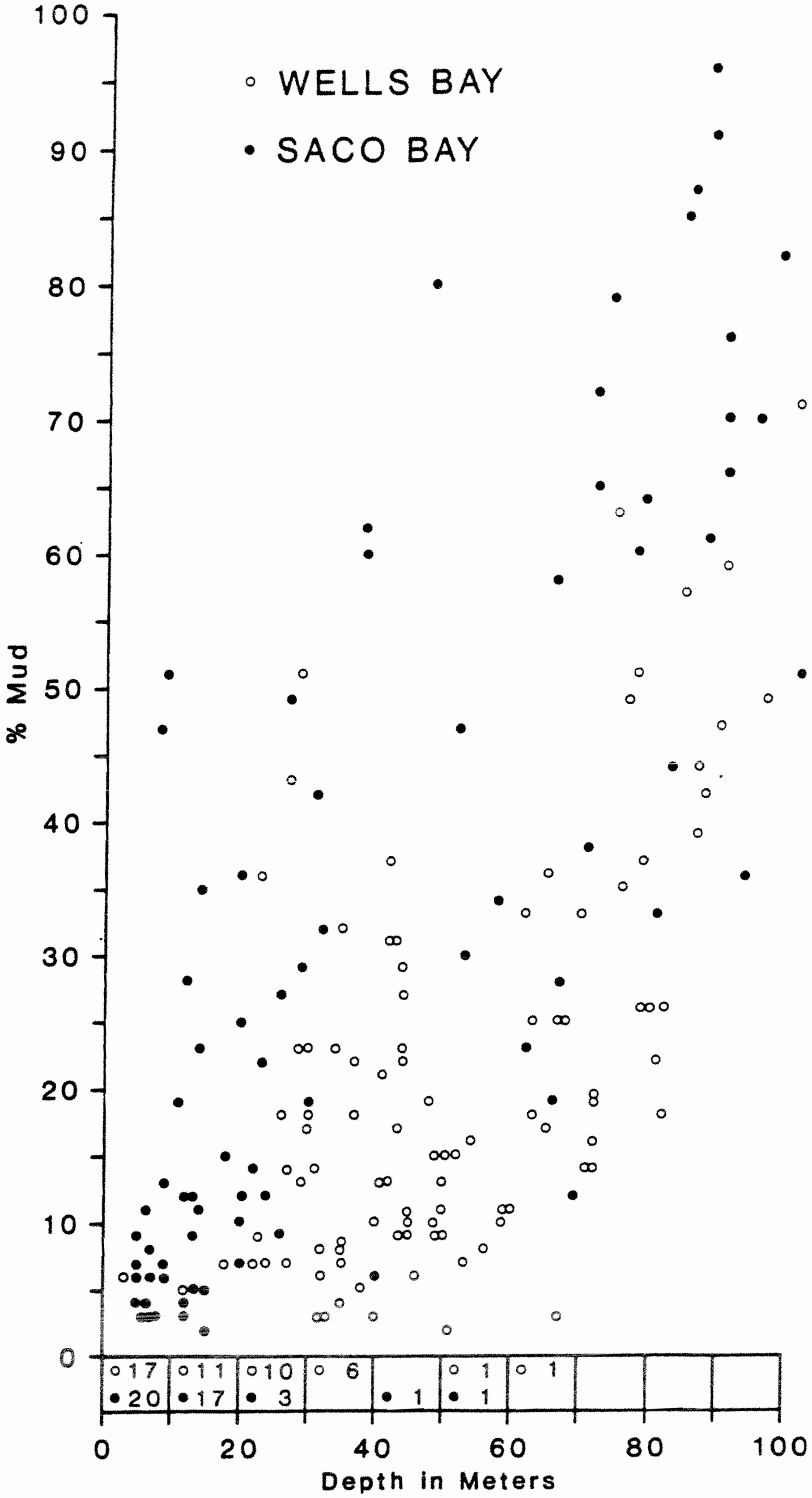

Figure 11. The percentage of mud versus depth of the samples. The values along the abscissa refer to the number of samples with no mud.

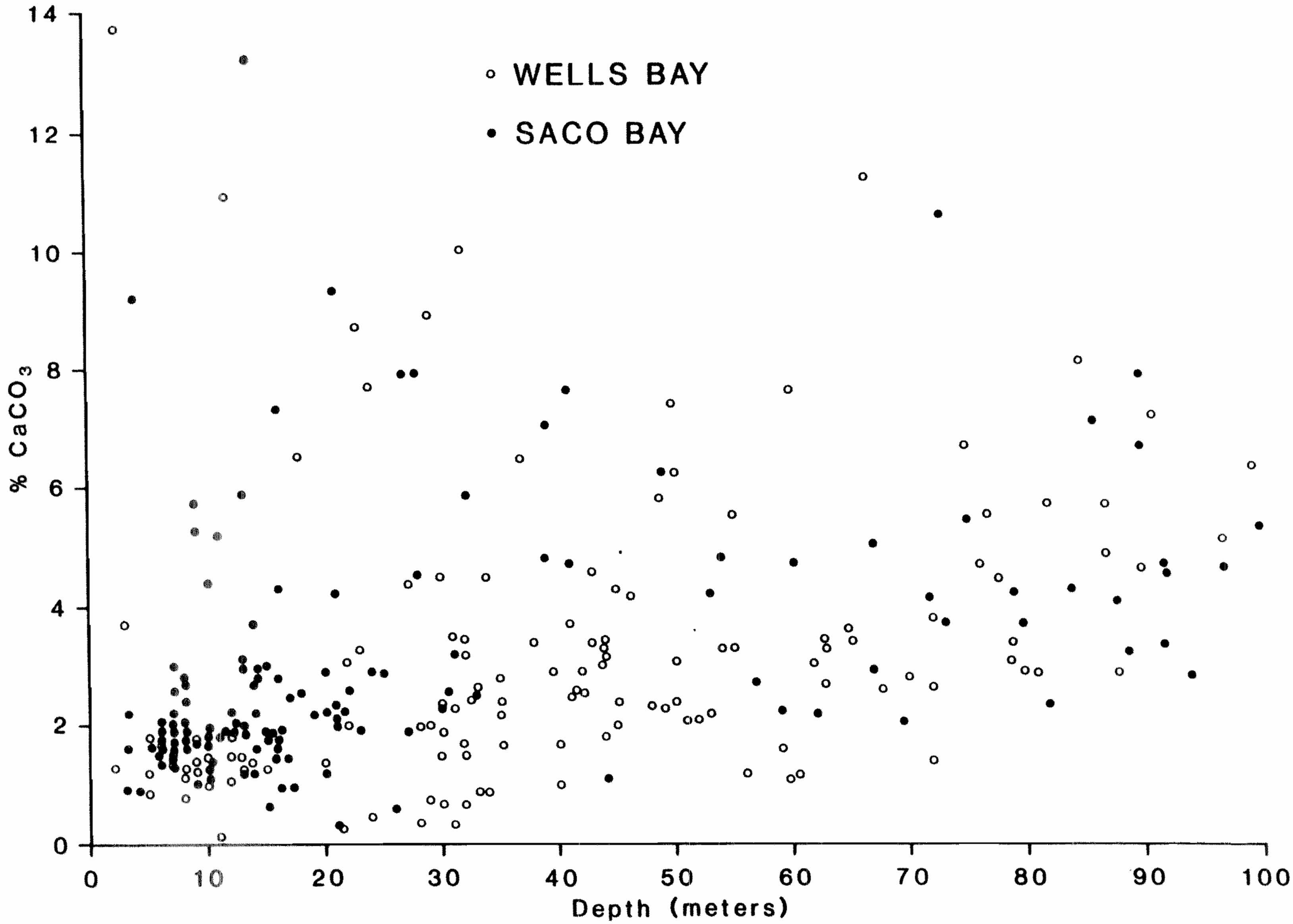

Figure 12. Carbonate content of the finer than 2 mm fraction versus sediment depth.

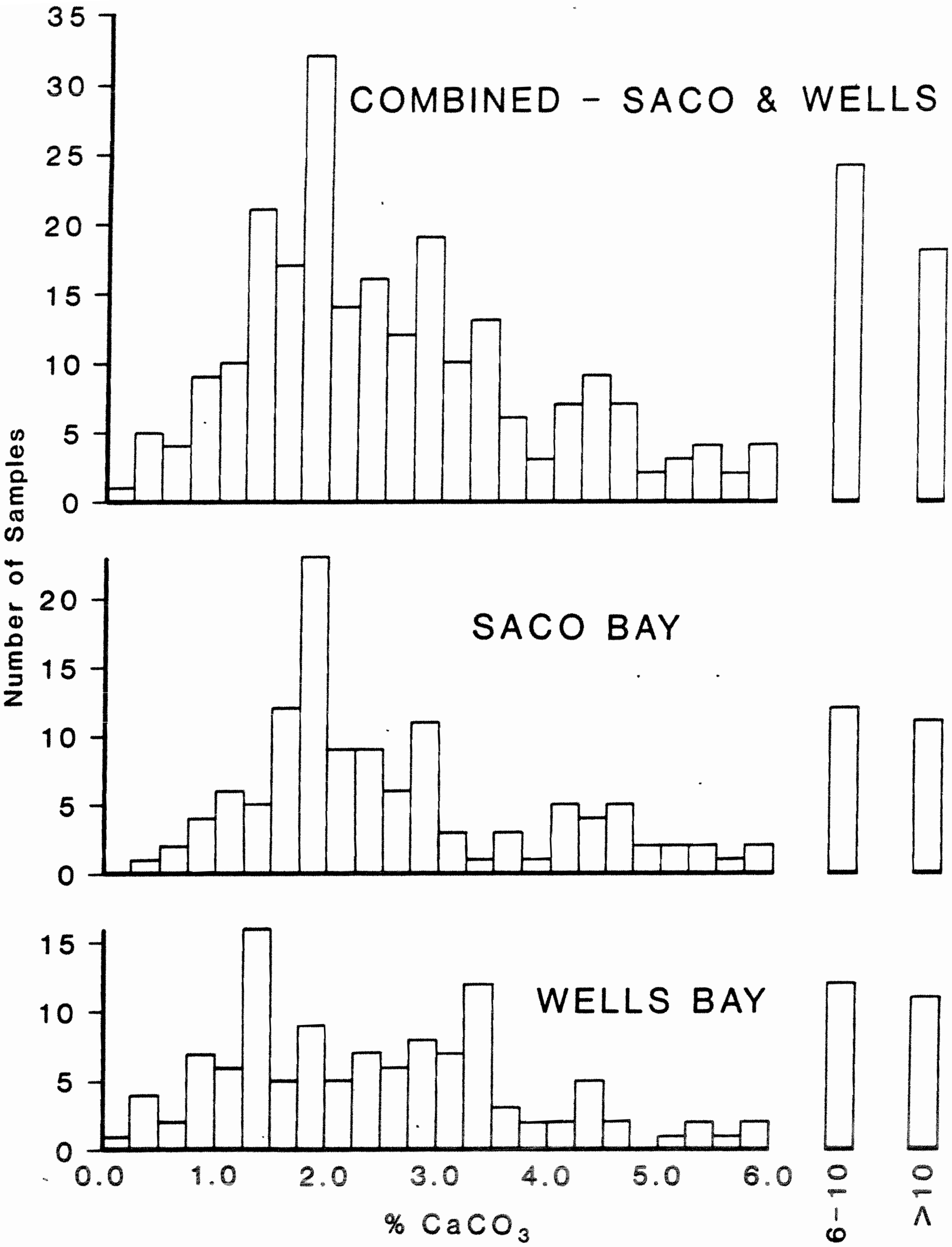

Figure 13. Histograms showing the abundance of carbonate from Wells and Saco Bay sediments.

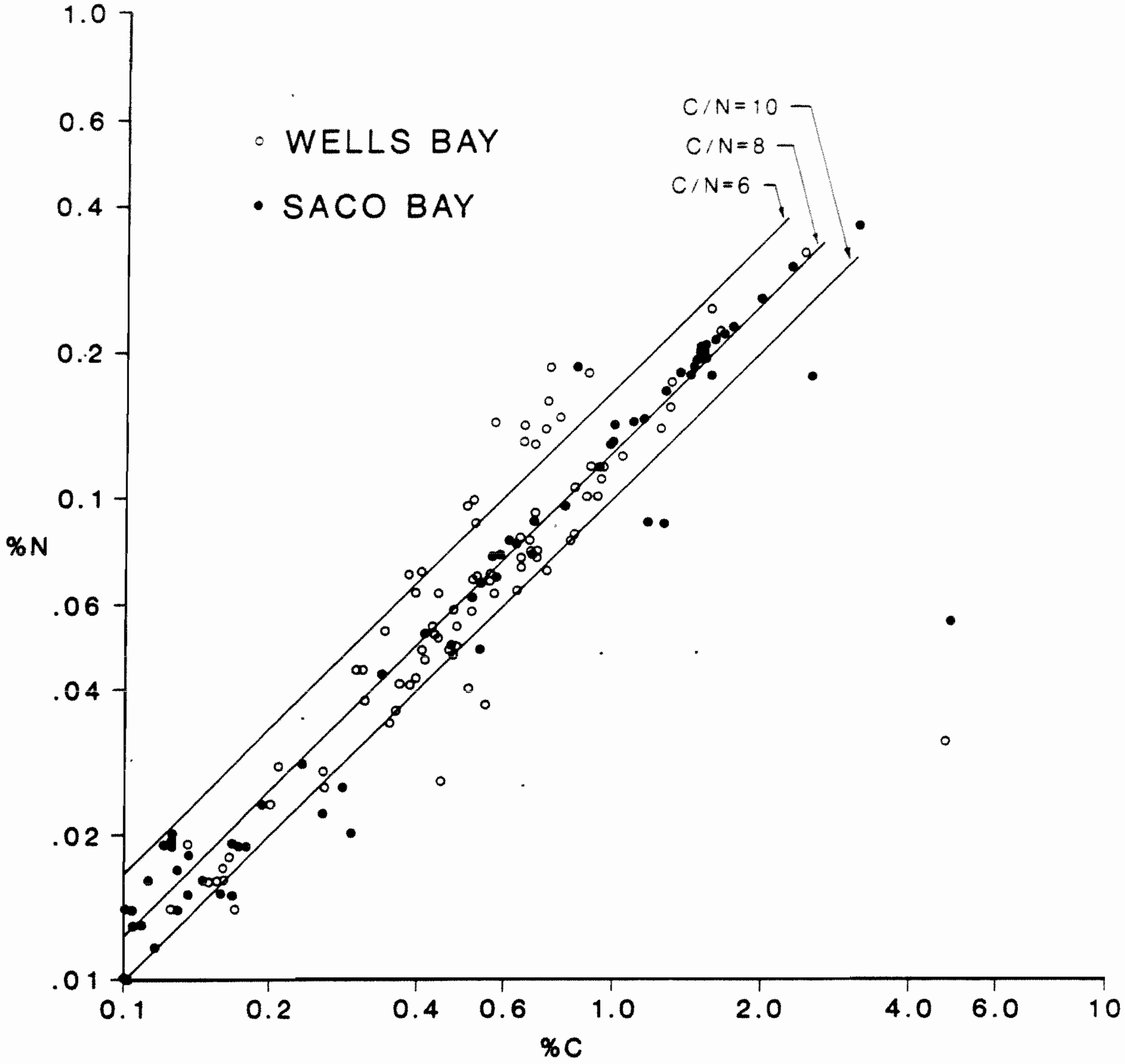

Figure 14. Log-log graph of carbon and nitrogen values from Saco and Wells Bay sediment.

lower C/N ratios than usually seen in Gulf of Maine sediment (L. Mayer, pers. comm.). This may be due to incomplete carbonate removal or elevated Nitrogen values related to sewage discharge in the highly developed Wells Beach area. Generally, the remainder of the samples show relatively low carbon and nitrogen values in the sandy Nearshore Ramp and Rocky Zone, with higher values in the muddier Shelf Valleys and Outer Basins (Table 4). The overall abundance of carbon, like that of carbonate, is polymodal, reflecting variations between physiographic zones (Figure 15).

The abundance of heavy minerals (s.g. >2.9) in the study area was evaluated only in sandy samples from the Nearshore Ramp. The mean value of the 37 samples investigated was 3.1%, with a range from 0.2% to 7.5% in the Wells Embayment. Luepke and Grosz (1986) found an average concentration of heavies in Saco Bay of 0.9%, but they included muddy samples from within cores as well as sandy surficial material.

The composition of the heavy mineral fraction was not evaluated for this report, but Luepke and Grosz (1986) found garnet, pyroboles, and metamorphic minerals to be the most abundant species present. It is anticipated that a comparison will be made of the heavy mineralogy of a longer stretch of the Maine coast following the completion of the Year Three study.

GEOPHYSICAL AND SUBMERSIBLE OBSERVATIONS

Bottom sediment properties correlate well with environmental settings defined by bathymetry (Table 4). Nevertheless, considerable variation exists within the physiographic zones that is best accounted for by subdividing the zones into facies on the basis of side-scan sonar and seismic reflection records, as well as direct observations from submersibles (Table 5).

Nearshore Ramp

Geophysical observations permit a subdivision of the Nearshore Ramp into an inner, relatively steeply deepening region marked by oscillation megaripples, an outer area of gentler slope which generally lacks bedforms, and rocky outcrops with associated mud and gravel (Table 5). A side-scan sonar profile parallel to Old Orchard Beach (Figure 16) displays the contact between the inner region where megaripples possess a wavelength of 1.75 m, and the more uniform outer area. The abrupt contact between the two areas may be controlled by wave base under summer wave conditions. In other areas the contact is less abrupt, and in several locations "rippled scour depressions" similar to those described elsewhere (Cacchione et al., 1984, Morang and McMaster, 1980) extend from shallow water across the outer area (Figure 17).

Although most of the Nearshore Ramp is sandy with slight local relief, occasional exposures of bedrock or till interrupt this uniformity. Where bedrock is exposed at the seafloor, gravel or mud is also frequently found. Seismic profiles show that the mud and gravel are probably derived from eroded Pleistocene sediment which usually rests on bedrock (Figure 18). Offshore of Wells Beach an extensive gravel area extends from a rocky part

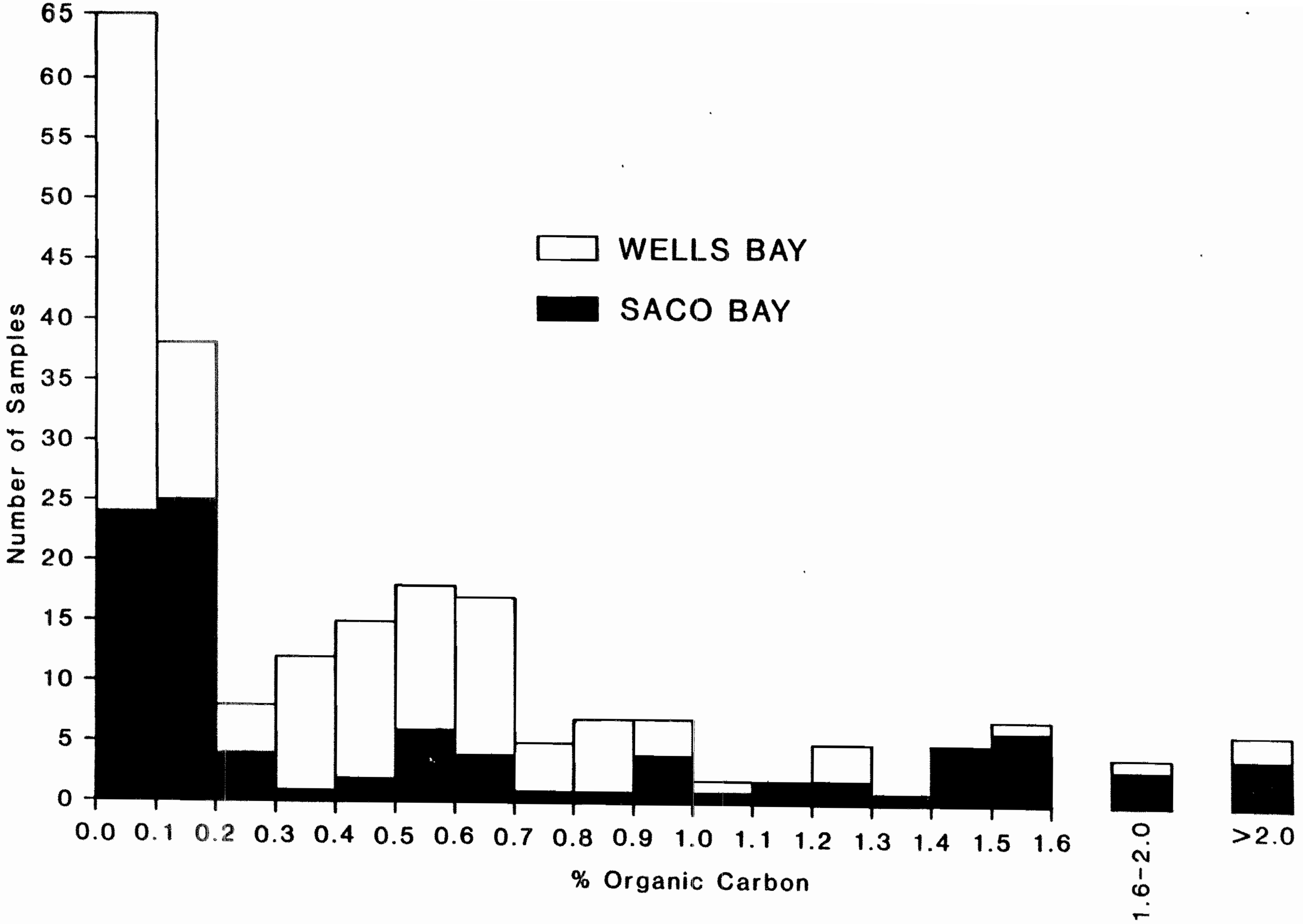

Figure 15. Histogram showing polymodal abundance of carbon in samples.

Table 5. Subdivision of the physiographic zones into facies of differing properties.

Physiographic Zone/Facies	Depth(m)	Topography	Texture	Morphology	Composition	Origin
NEARSHORE RAMP						
Inner Sand	0-15	steep slope	fine to coarse, well sorted sand	megaripples	low $CaCO_3$, C, N	reworked fluvial (Saco); or glacial (Wells)
Outer Muddy Sand	15-30	gentle slope	fine to coarse muddy sand	ripples, flat surface	low $CaCO_3$, C, N	reworked fluvial (Saco); or glacial (Wells)
Rocky	0-30	high local relief	muddy sand, gravelly sand	chaotic, disturbed	high $CaCO_3$, low C, N	reworked glacial-glaciomarine; modern carbonate
ROCKY ZONE						
Exposed Bedrock	0-100	high relief	no sediment	circular outcrop pattern	high $CaCO_3$	modern carbonate veneer
Gravel Plain	30-65	low relief	muddy sandy gravel with boulders	chaotic	high $CaCO_3$ low C, N	reworked till
Sediment Ponds	30-65	low relief, seaward dip	sandy gravel; muddy gravel	megaripples	high $CaCO_3$ low C, N	reworked paleo-shoreline; reworked glaciomarine

Table 5. Continued.

Physiographic Zone/Facies	Depth(m)	Topography	Texture	Morphology	Composition	Origin
SHELF VALLEY						
Thalweg	30-65	U-shaped channel	muddy sand	bioturbation	high C, N low $CaCO_3$	paleochannel, now rarely active
Rippled, Scour Zones	30-65	elongate patches in channel	gravelly sand	megaripples	low C, N high $CaCO_3$	recently scoured area
Channel Margin	30-65	high relief	rocky, sandy gravel	megaripples, talus pile	low C, N very high $CaCO_3$	modern carbonates and reworked glacial material
OUTER BASIN						
Muddy Basin	65-100	flat, smooth	sandy mud, muddy sand	bioturbation	high C, N high $CaCO_3$	modern hemipelagic sediment, turbidites?
Lowstand Shoreline	55-85	moderate relief concave up	gravelly sandy mud	?	high C, N high $CaCO_3$	shoreline cut into glacial, glacio-marine sediment modern mud
Rocky	55-100	high relief, chaotic	muddy gravel gravelly mud	?	high C, N high $CaCO_3$	reworked glacio-marine, modern mud

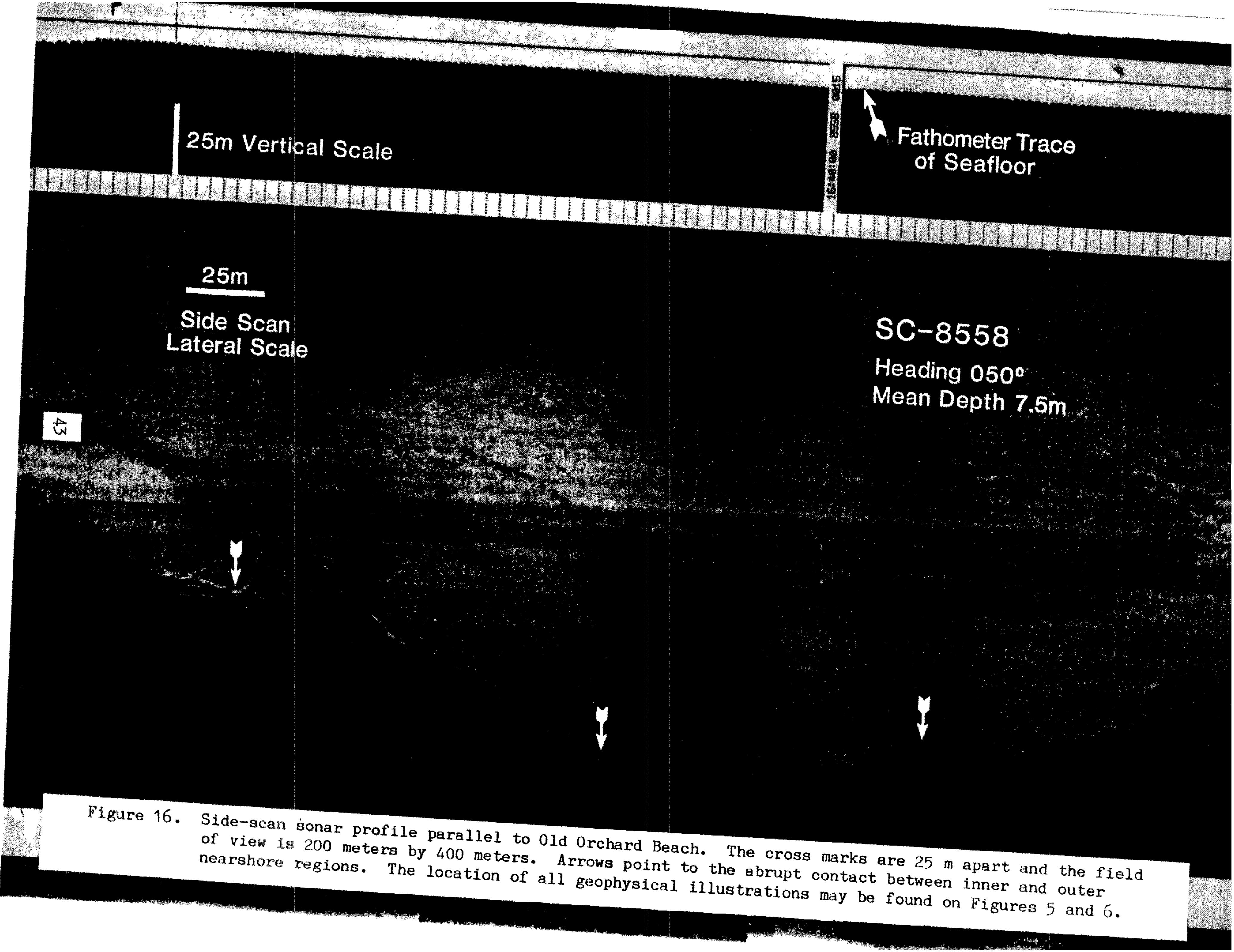

Figure 16. Side-scan sonar profile parallel to Old Orchard Beach. The cross marks are 25 m apart and the field of view is 200 meters by 400 meters. Arrows point to the abrupt contact between inner and outer nearshore regions. The location of all geophysical illustrations may be found on Figures 5 and 6.

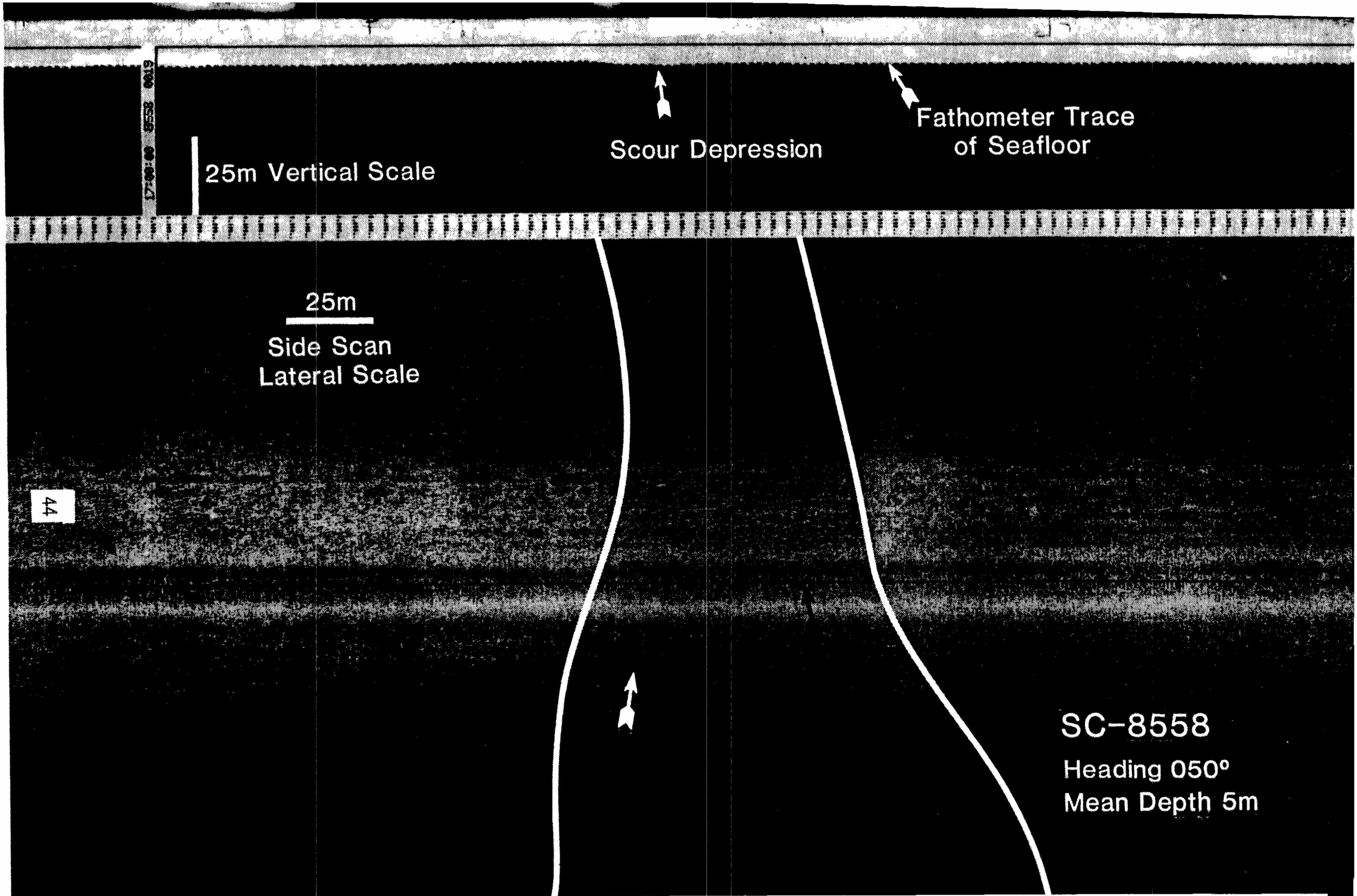

Figure 17. Side-scan sonar profile parallel to Old Orchard Beach shows a rippled surface in a 1-2 meter deep depression (arrows) which extends normal to the shoreline. The field of view is 200 meters by 400 meters. In the side-scan view the scour depression is a channel, bordered by lines, with arrows suggesting flow direction.

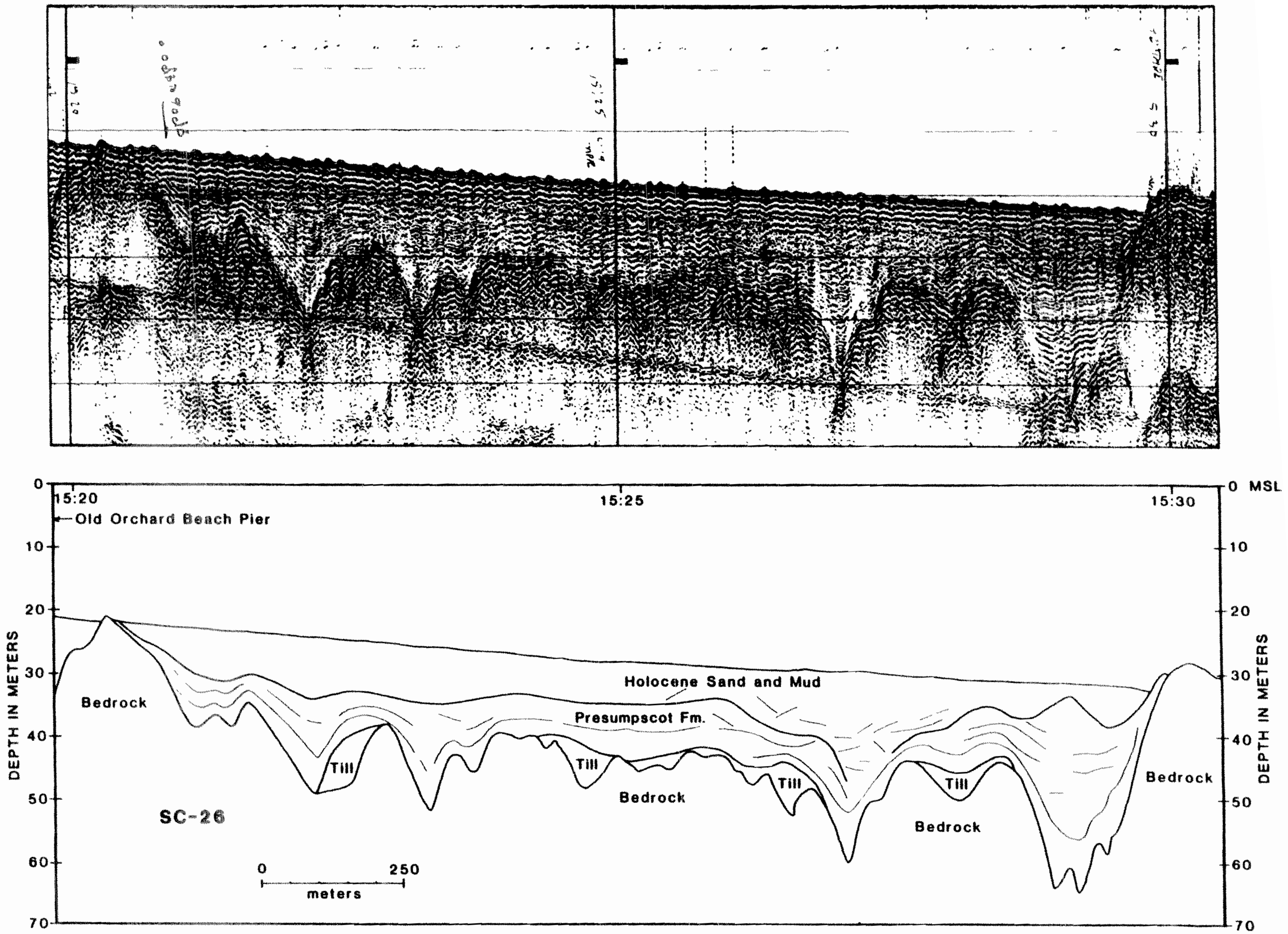

Figure 18. ORE Geopulse seismic profile SC-26 normal to the shoreline of Saco Bay. In areas where bedrock is exposed on the seafloor, glacial sediments frequently outcrop also. Core 117 was collected within a few hundred meters of the 15:20 time mark and shows probable Pleistocene sediment 3 meters beneath the surface (Figure 45).

of that beach (Figure 19). Since this is wholly surrounded by sandy material (Figure 9) it is nonetheless included in the Nearshore Ramp.

One additional feature was observed in the Nearshore Ramp, although not enough occurrences of it were noted to warrant defining another facies (Figure 20). Offshore of Higgins Beach, and adjacent to the Shelf Valley of the Spurwink River, a 3 m high mound of material was seen in the seismic records. This appears to overlie till and its opacity to the 3.5 kHz signal suggests it is composed of gravel. This is tentatively identified as a paleoshoreline although more data will be necessary to confirm this suggestion.

Rocky Zone

The Rocky Zone is the largest physiographic element of the southwestern Maine inner shelf (Figure 8). To account for variation in bottom sediment properties from this area, three subenvironments are defined: exposed bedrock, gravel plains, and sediment ponds (Table 5).

Bedrock exposures occur throughout the study area but are most concentrated in shallow water (<25 m) surrounding Bluff, Stratton, Boon, and other islands. These are regions of complex bathymetry (NOS, 1970) and represent shoals surrounded by deep water that have relatively recently been drowned by the sea. Where the bedrock is foliated, fracture patterns similar to those on land are apparent (Figure 21). Encrusting organisms are common here and carbonate production is probably high on the large surface area of the irregular, exposed bedrock.

Within areas of exposed bedrock, sediment ponds exist in the bedrock depressions (Figure 21). Sandy and muddy gravels rich in carbonate are common in these locally small, but abundant environments. In some locations the ponds are covered by megaripples with 1-2 m wave lengths (Figure 22). The crests of these bedforms usually trend NW-SE and may have formed during winter storms. Over many rocky regions in the study area, and elsewhere in Maine (Kelley and others, 1986) the sediment ponds dip in an offshore direction (Figures 23, 24).

Extensive areas of the Rocky Zone covered with coarse-grained sediment are called gravel plains (Table 5). These regions typically are of low relief, although boulders up to 5 m in diameter have been observed (Figure 25). Bottom samples from these areas are the most variable encountered in the entire shelf area, and side-scan observations show that patches of bedrock, gravel, sand, and mud are frequently juxtaposed. Seismic reflection profiles suggest that many of the gravel plains are deposits of "thin drift", as mapped on land (Thompson and Borns, 1985).

Shelf Valleys

Shelf Valleys are the major sedimentary regions which extend through the Rocky Zone and connect the Nearshore Ramp to the Outer Basin. They are bedrock channels which have been filled to varying degrees by glacial and post-glacial sediment. The physiographic form of the valleys disappears at about 65 m depth, and although many of the valleys have smooth seaward gradients (NOS, 1970), some are interrupted and wrap around irregular

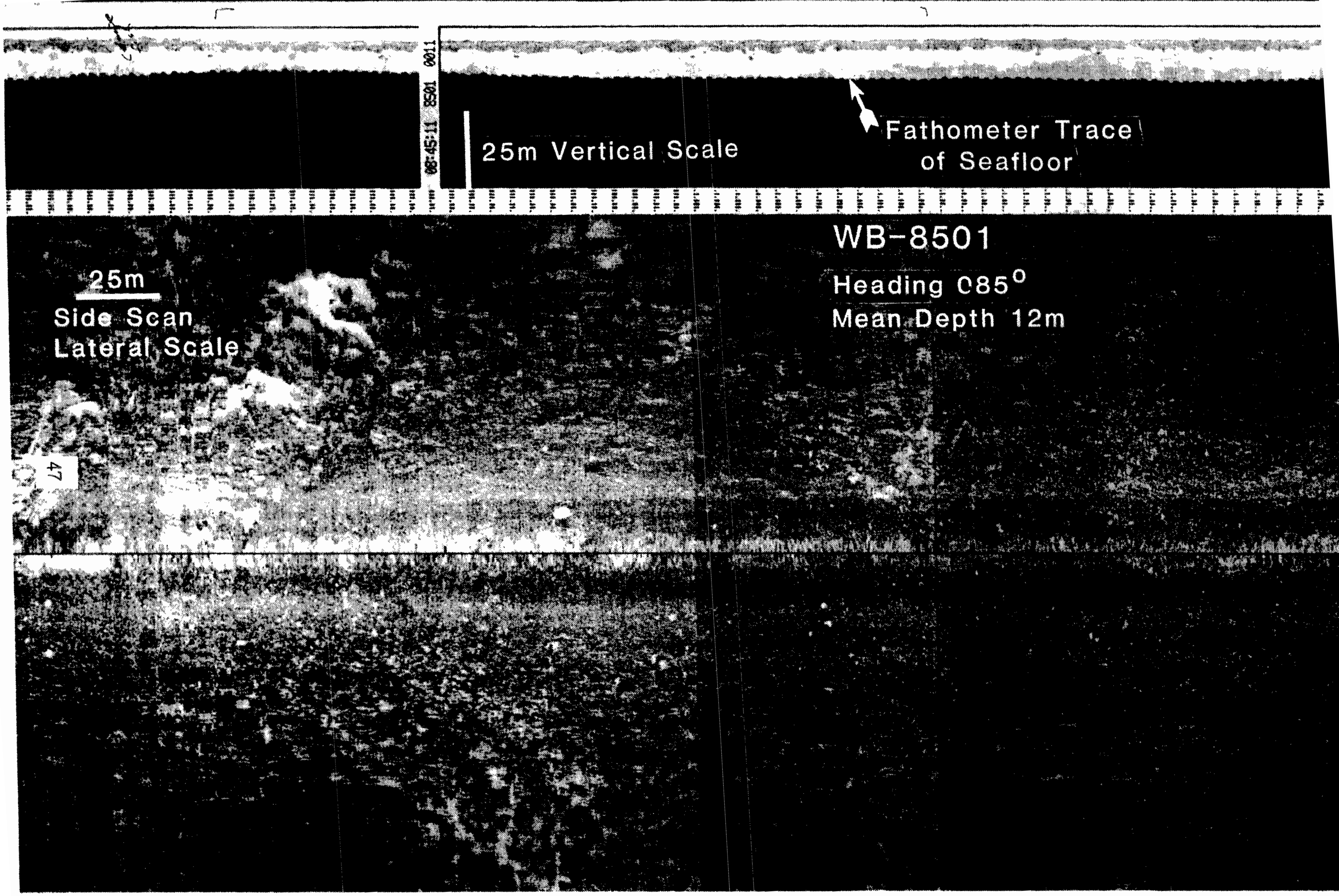

Figure 19. Side-scan sonar profile normal to Wells Beach. The field of view is 200 meters by 400 meters. The dark regions are sand and gravel and the light dots are shadows cast by boulders.

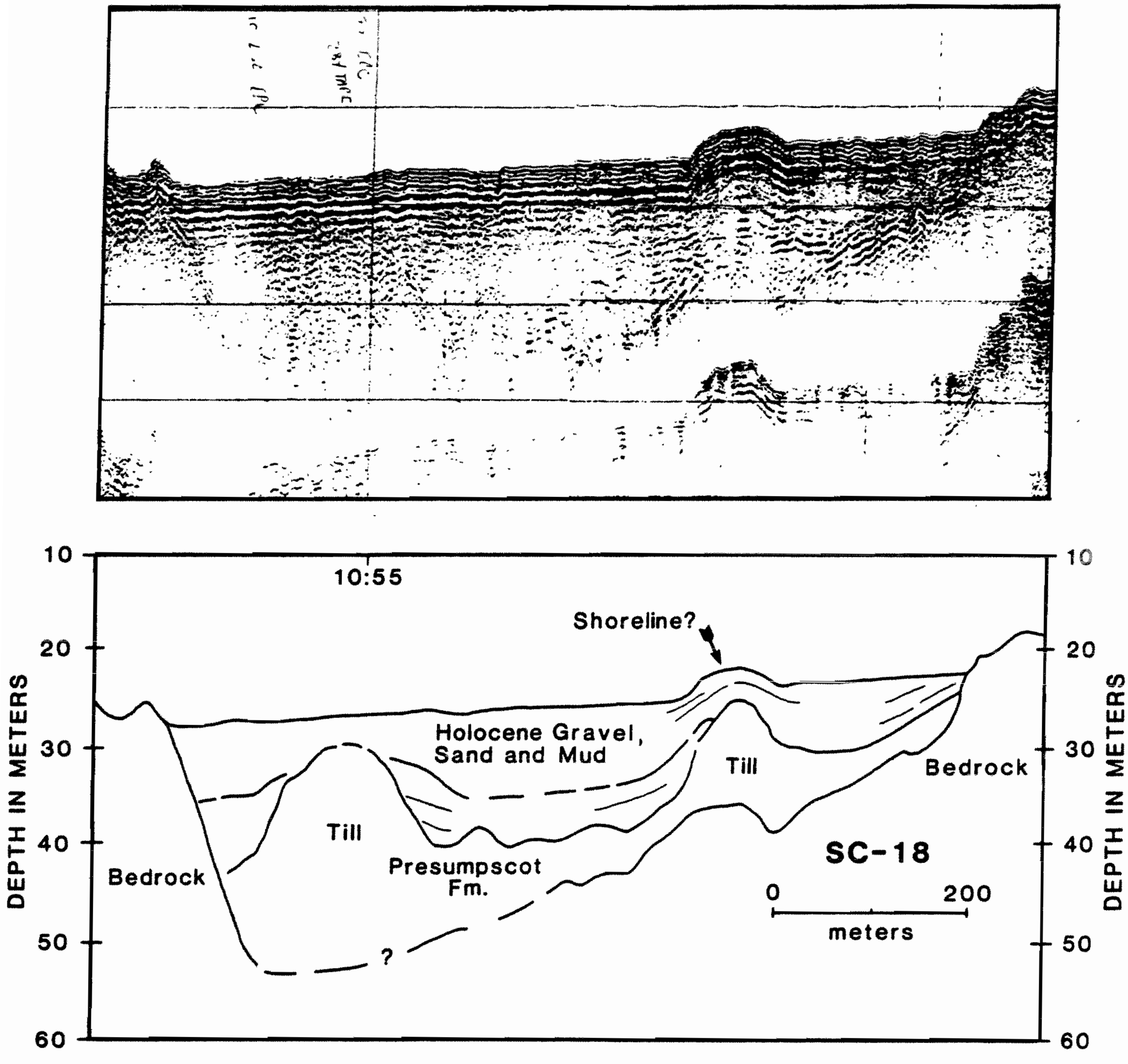

Figure 20. ORE Geopulse seismic profile offshore of Higgins Beach. The line is normal to a Shelf Valley on the edge of the Nearshore Ramp. Arrow points to possible former shoreline feature.

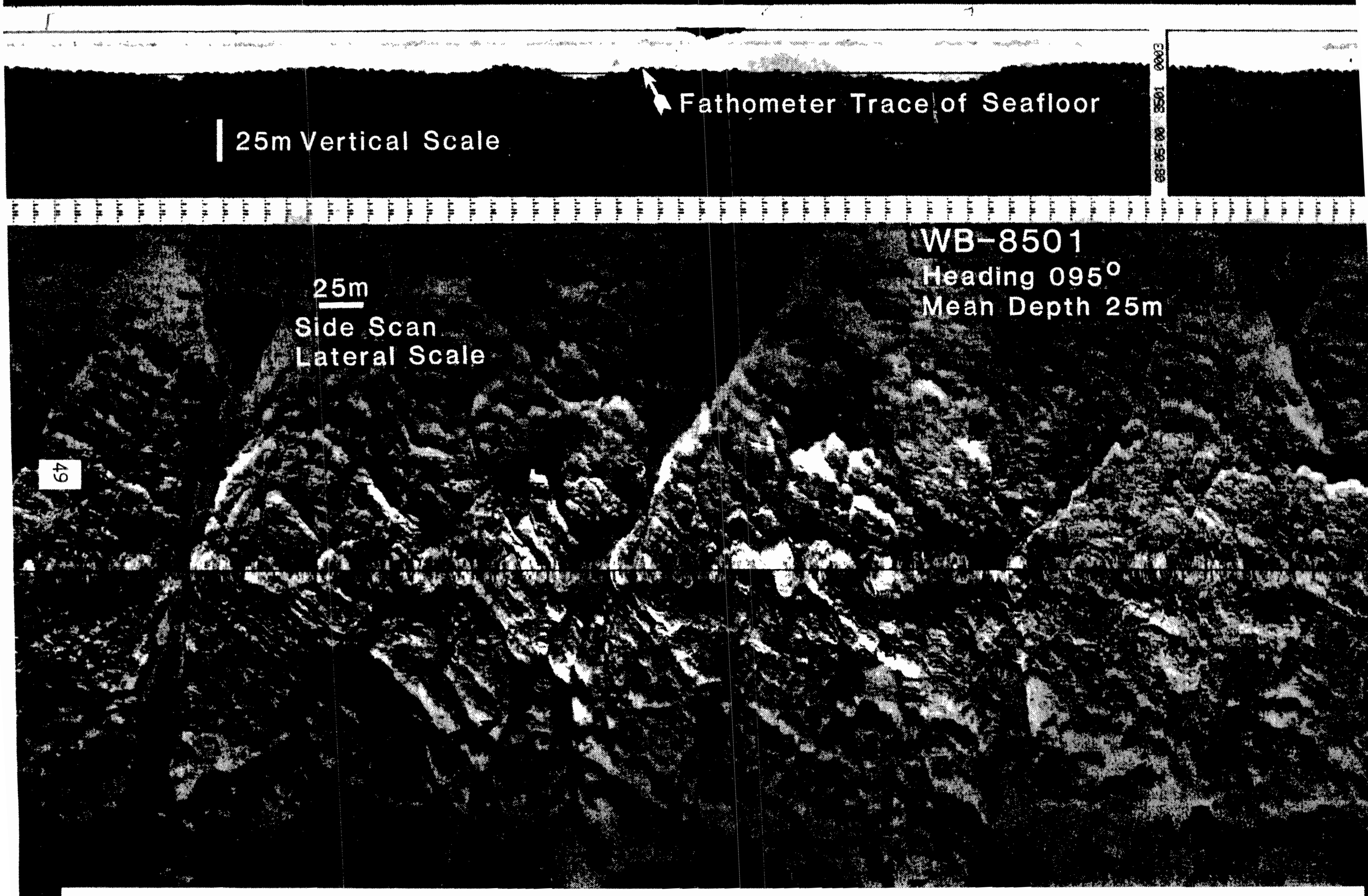

Figure 21. Side scan sonar image of extensive bedrock exposure in Wells Embayment. The strong fracture pattern is evident (arrows) and the irregular surface permits considerable carbonate production by encrusting organisms. The depth ranges from 22 to 28 meters and the field of view is 800 meters by 800 meters.

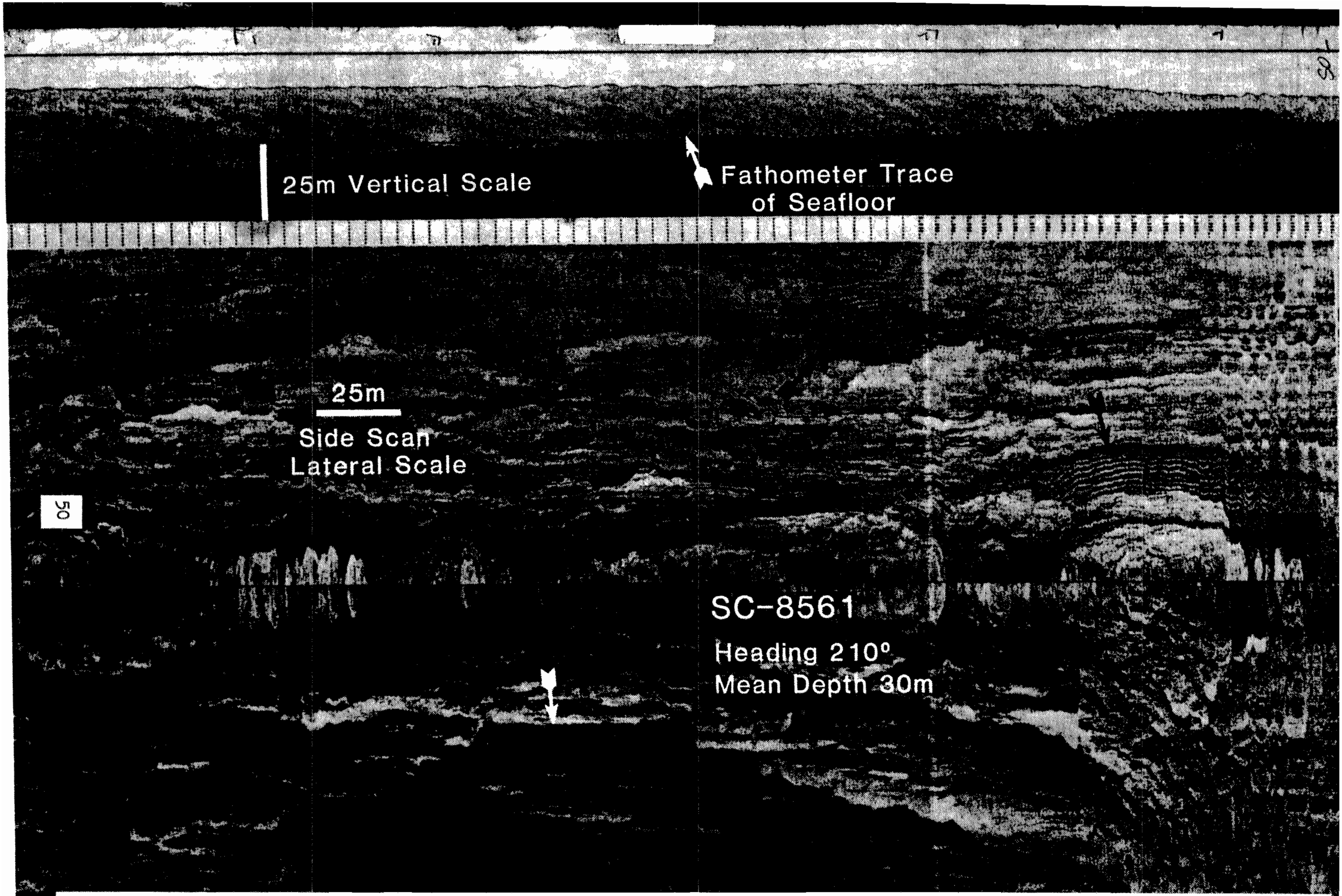

Figure 22. Side-scan sonar image of rocky area with sediment ponds near Stratton Island, Saco Bay. The surface of sediment ponds in this area frequently dips seaward (Figure 23) and is mantled by megaripples with wavelengths up to 2 meters. The field of view is 375 meters by 200 meters and the depth ranges from 18 meters (right side) to 40 meters (left side).

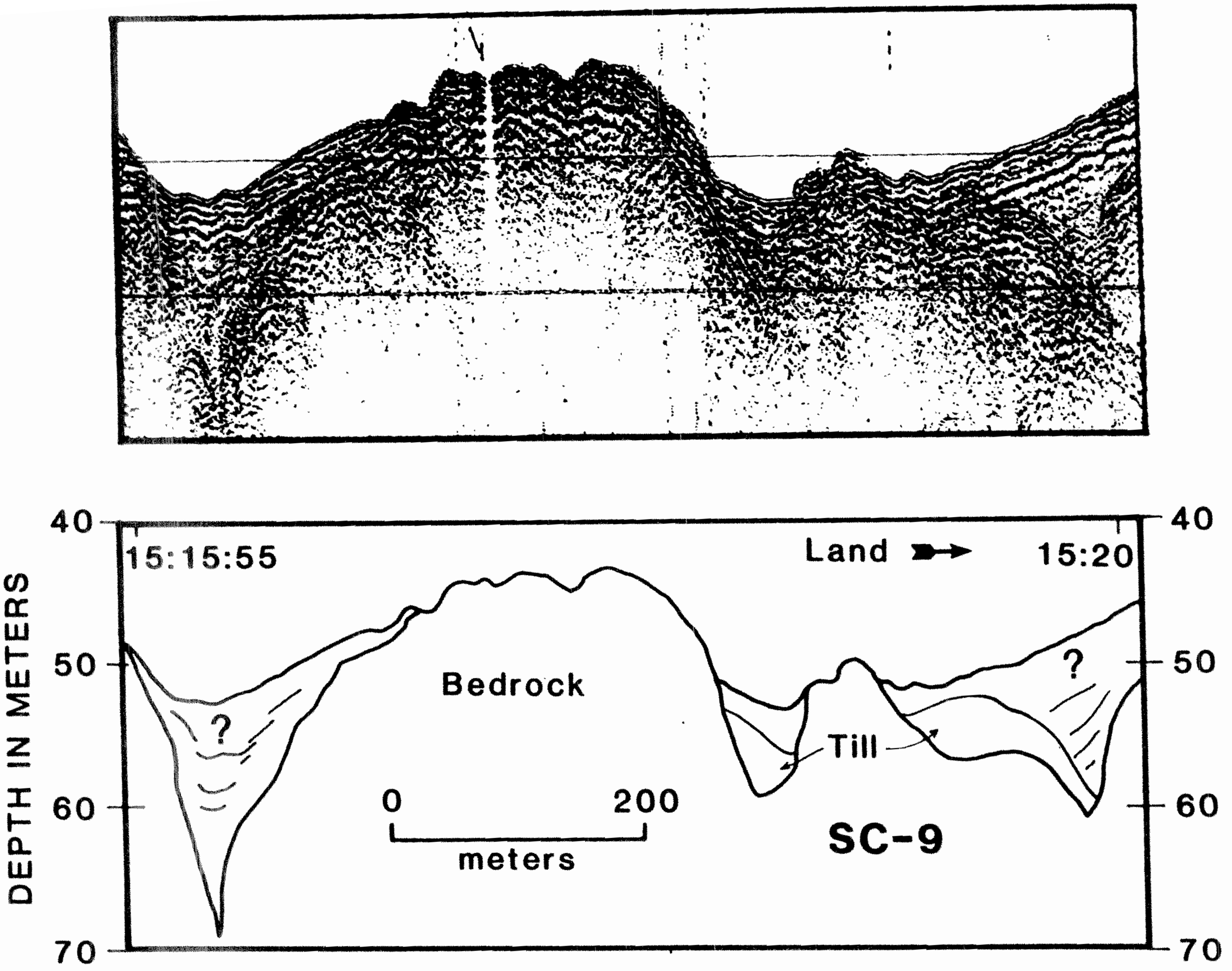

Figure 23. Geopulse seismic profile across seaward dipping sediment ponds in Saco Bay.

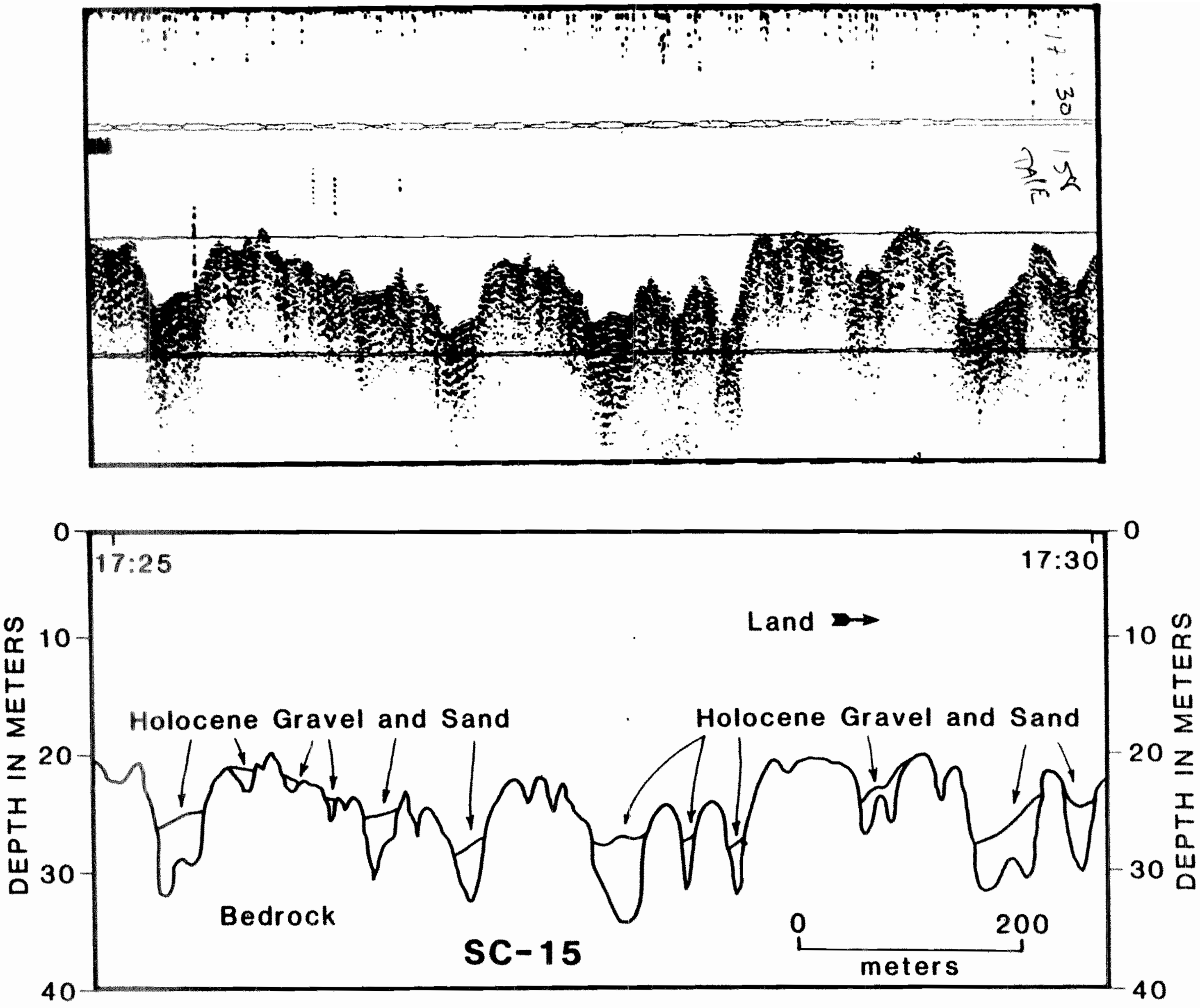

Figure 24. Geopulse seismic profile across seaward dipping sediment ponds in Saco Bay.

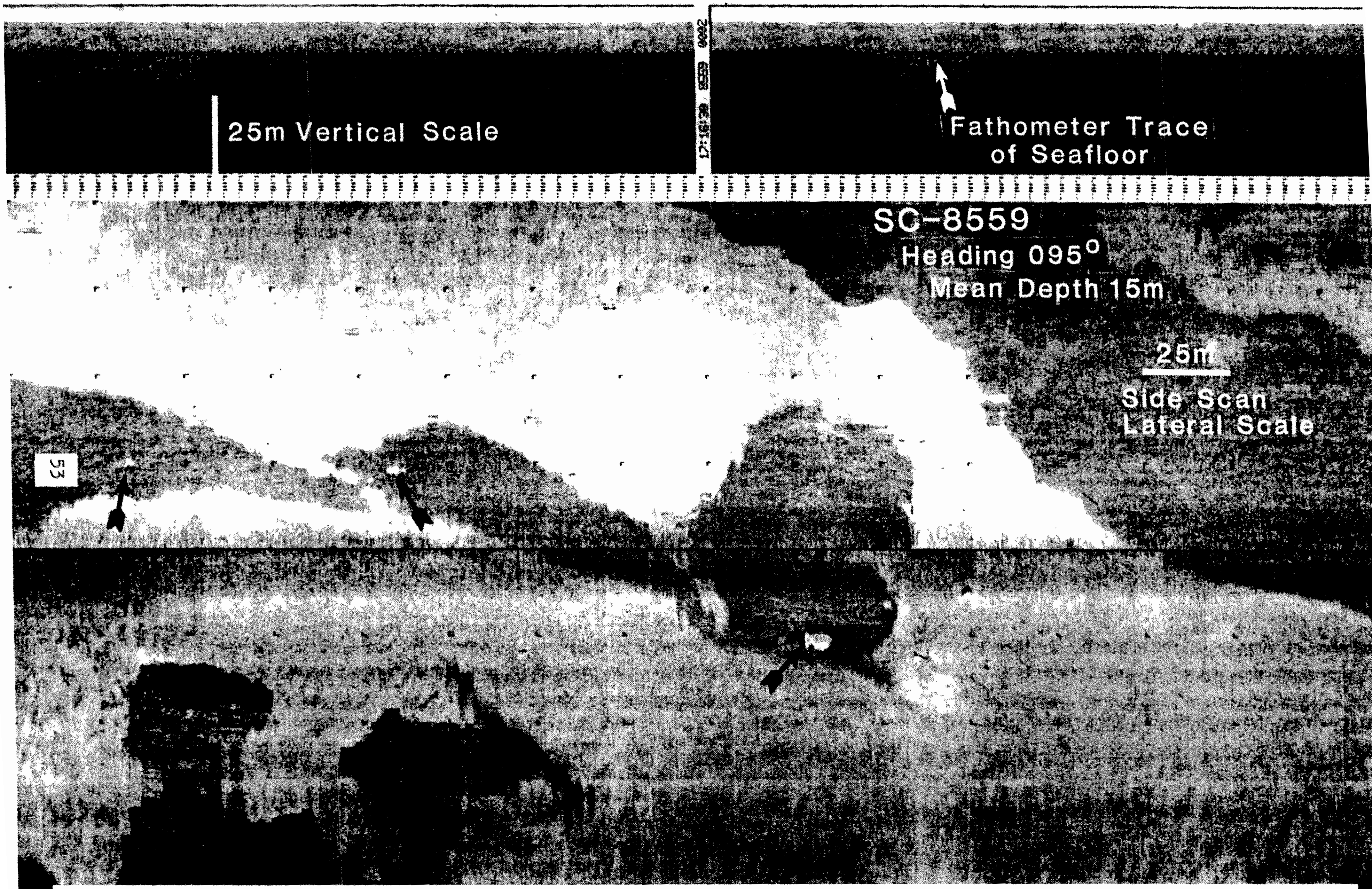

Figure 25. Side-scan sonar image of gravel plain between Prouts Neck and Bluff Island. Water depth is 12 meters and the field of view is 400 meters by 200 meters. Arrows point to boulders in muddy gravel areas (dark) surrounding sandy area (light). Bedrock outcrops at the lower left portion of the image.

obstacles of apparent bedrock. While some valleys may be traced directly to modern rivers (Saco, Spurwink), others have no obvious terrestrial source.

The most abundant environment in the valleys are thalwegs floored by muddy sand (Table 5). These are relatively featureless on side-scan imagery and have a U-shape or flat bottom in cross section (Figures 26, 27). Submersible observations in one of Saco Bay's Shelf Valleys reveal a muddy seafloor with numerous burrows and animal traces (Kelley, 1986, unpublished submersible notes).

Distributed along the central axes of the channels are relatively small areas of apparent current scour (Figure 28). The seafloor here is marked by megaripples and gravelly sand and often the scour areas are in small depressions in the channel floor. As the contact between the scour zone and channel thalweg is approached the megaripples become small ripples draped by increasing amounts of mud (Kelley, 1986, unpublished submersible notes). Though the origin of the scours is not clear, many of the patches are elongate in a "downstream" direction near, or behind, bedrock outcrops (Figure 28).

Along the edge of the Shelf Valleys, the channel margin environment represents a transition to a rocky interfluve. The channel margin is usually sandy muddy gravel with occasional boulders and abundant carbonate. On side-scan imagery it appears as a dark apron around the bedrock, and sometimes shows patches of megaripples (Figure 29). Seismic reflection profiles across these areas (Figures 25, 27, 30) show subbottom reflectors outcropping at the valley walls and thus the coarse material may be exhumed, older sediment.

Outer Basins

The Outer Basins are distinct regions of very low relief extending from about 55 meters depth to greater than 100 meters outside the study area (Figure 8). The landward border of the Outer Basins is frequently a rocky escarpment, but in some locations is a more gentle break-in-slope with a concave-up profile (Figures 31, 32). On the margin of a broad basin the relief is very gentle (Figures 31, 32) and direct observations from submersible indicate a muddy surface in Saco Bay (Kelley, 1985, unpublished submersible notes). The depth of the break-in-slope ranges from 55 to 75 meters. Near areas of bedrock, mounds of sediment appear piled up against the rock on seismic reflection profiles, but the overall cross section remains similar (Figures 33, 34). Where several of the features occur near one another, their depths are generally equivalent, although the overall depth range remains between 55 and 75 meters in the study area. These features have been interpreted as shorelines formed during the sea level lowstand (Schnitker, 1974; Kelley and others, 1986) although no cores have yet been obtained from them. Bottom samples from the shoreline features in rocky areas are typically gravelly, shelly sands.

Most of the Outer Basins have a smooth, very gently sloping bottom. The sediment is usually muddy, although sand was locally common and sandy sediment often existed beneath the surface mud (Kelley, 1985, unpublished field notes). Side-scan images from these areas are very monotonous except

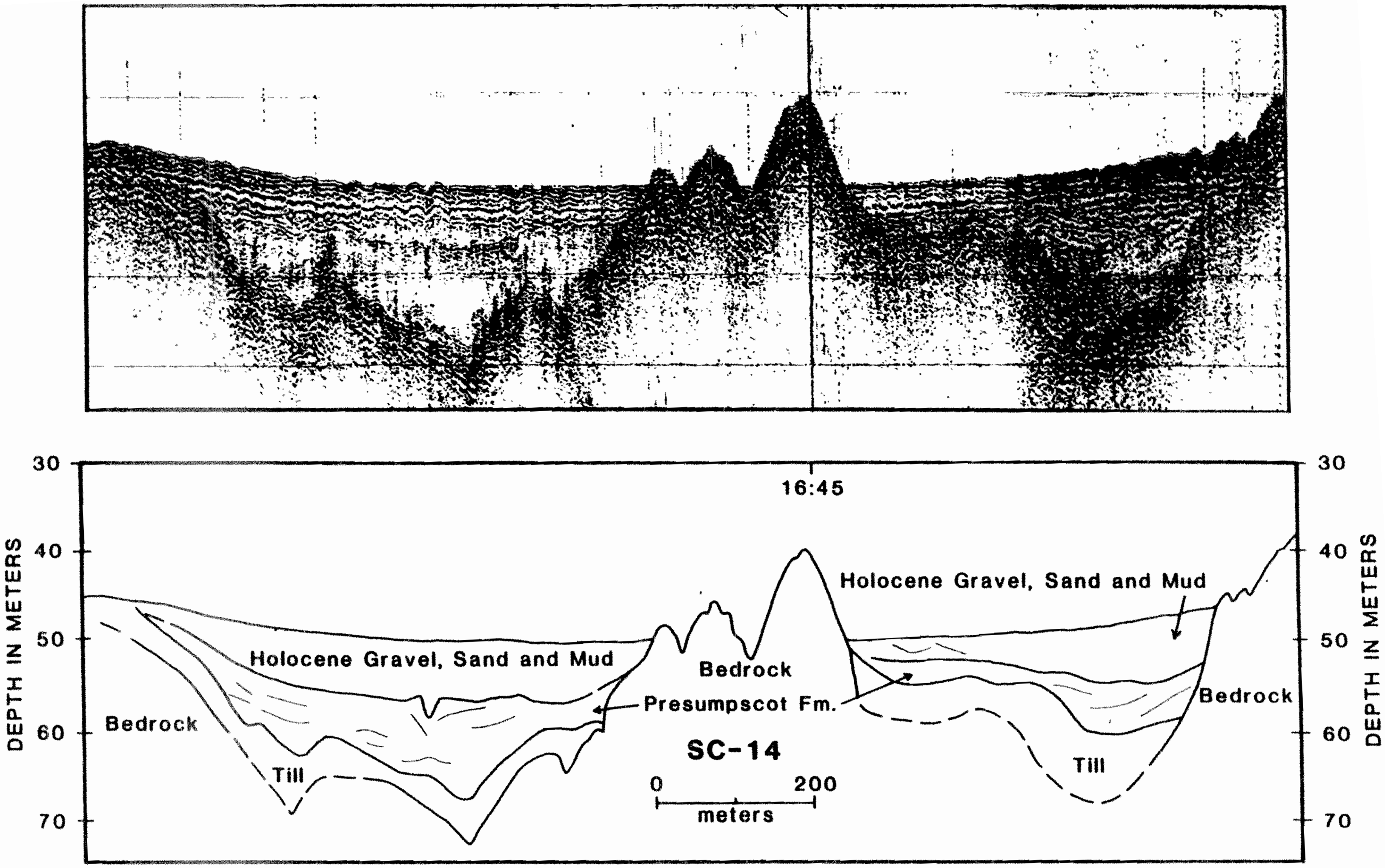

Figure 26. Seismic reflection profile SC-14 across Shelf Valley with U-shaped cross section.

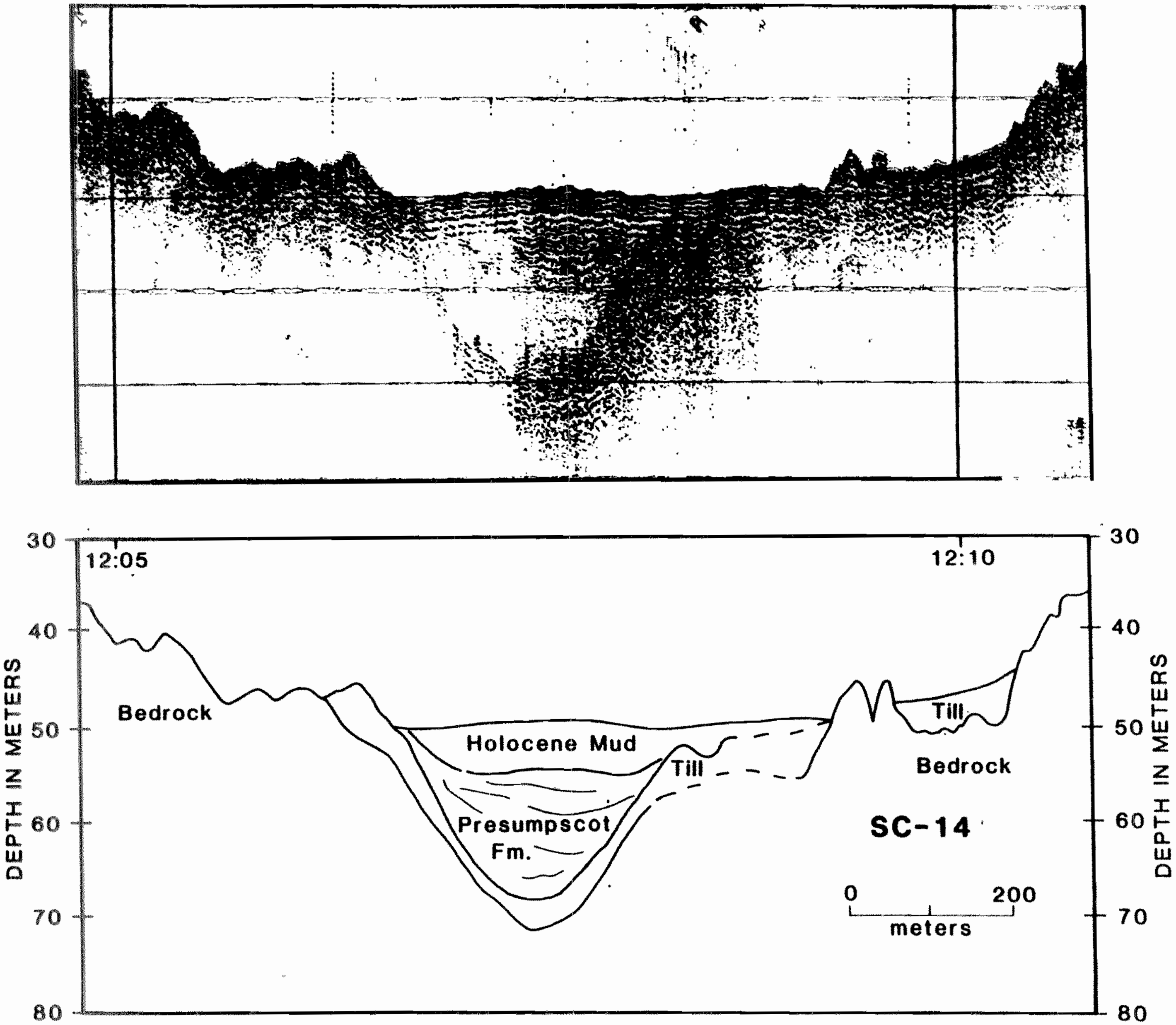

Figure 27. Seismic reflection profile SC-14 across Shelf Valley with flat bottom cross section.

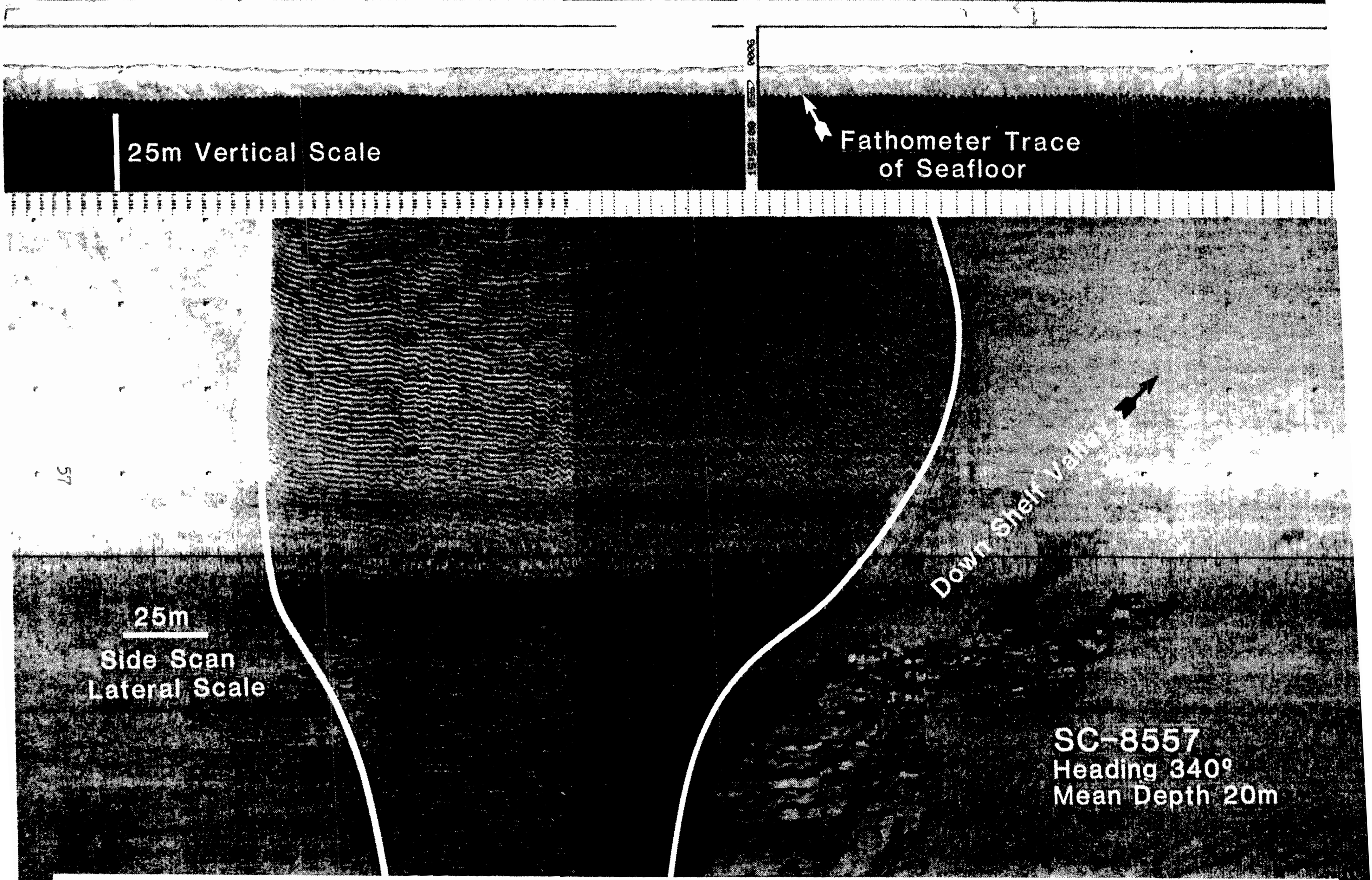

Figure 28. Side-scan sonar image of scour zone in Shelf Valley. The megaripples have a one meter wavelength and stretch obliquely downstream from a bedrock outcrop. The crests of the bedforms are parallel to storm waves approaching from the northeast. The field of view is 400 meters by 200 meters, and the depth is 21 meters.

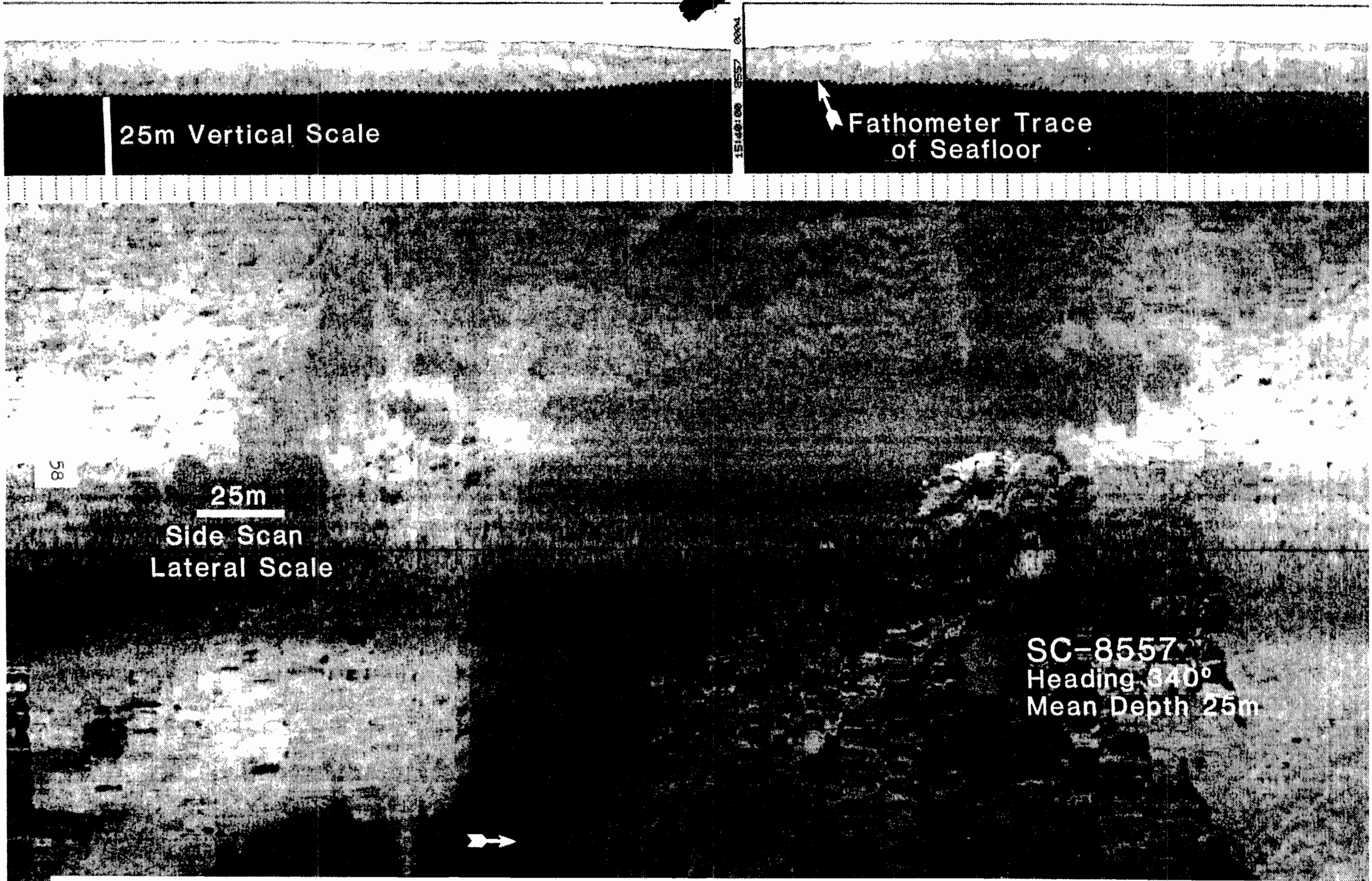

Figure 29. Side-scan sonar image of interfluve where two shelf valleys merge in Saco Bay. Light area is sandy mud; arrow points to megaripples in dark region of shelly gravel. Figure 30 shows simultaneous seismic reflection profile. The field of view is 400 meters by 200 meters, and the depth ranges from 22 meters to 25 meters.

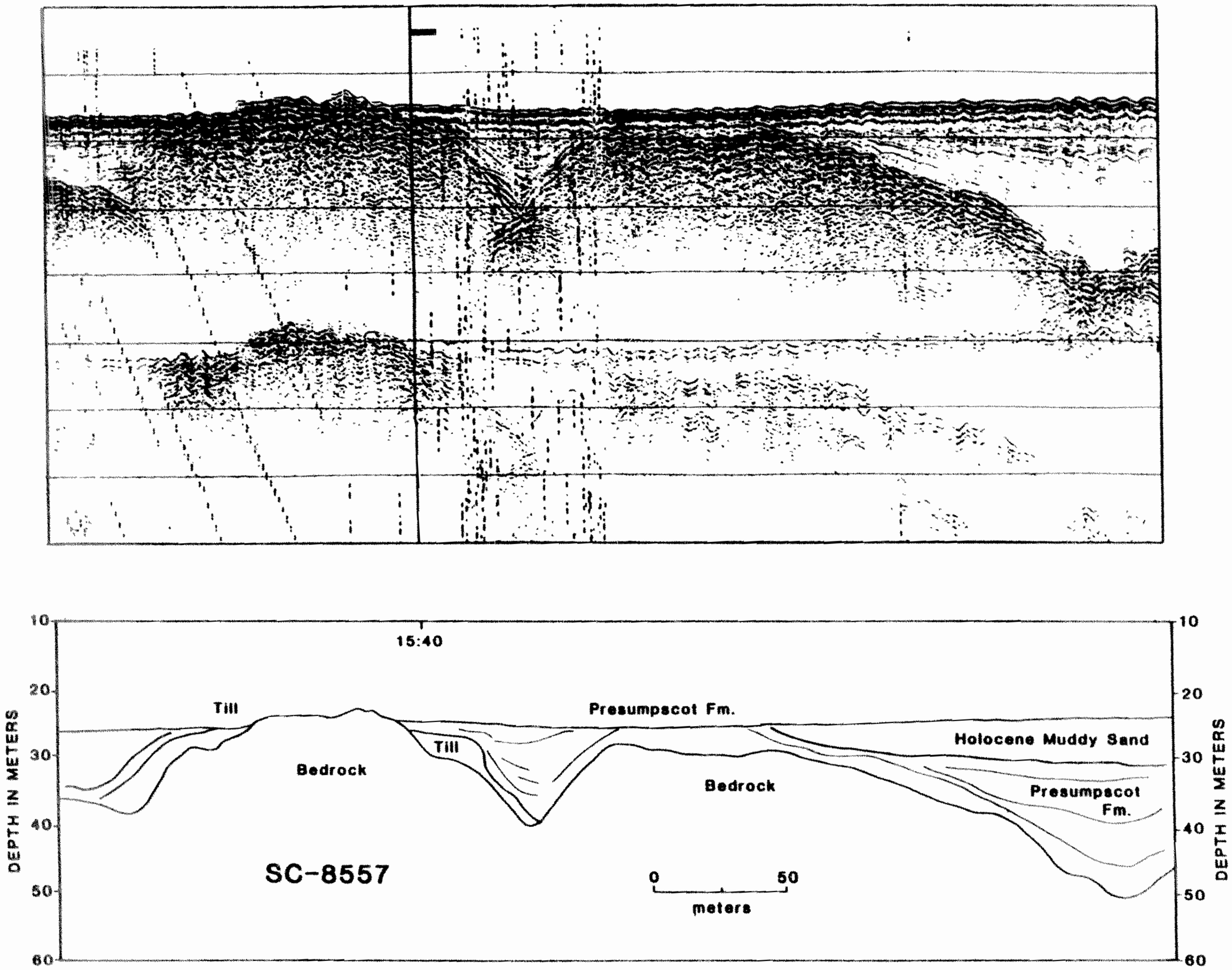

Figure 30. Seismic reflection profile showing bedrock interfluve at junction of two shelf valleys. Note that the area of outcrop of major subbottom reflectors corresponds to gravelly seafloor of side scan sonar image in Figure 29.

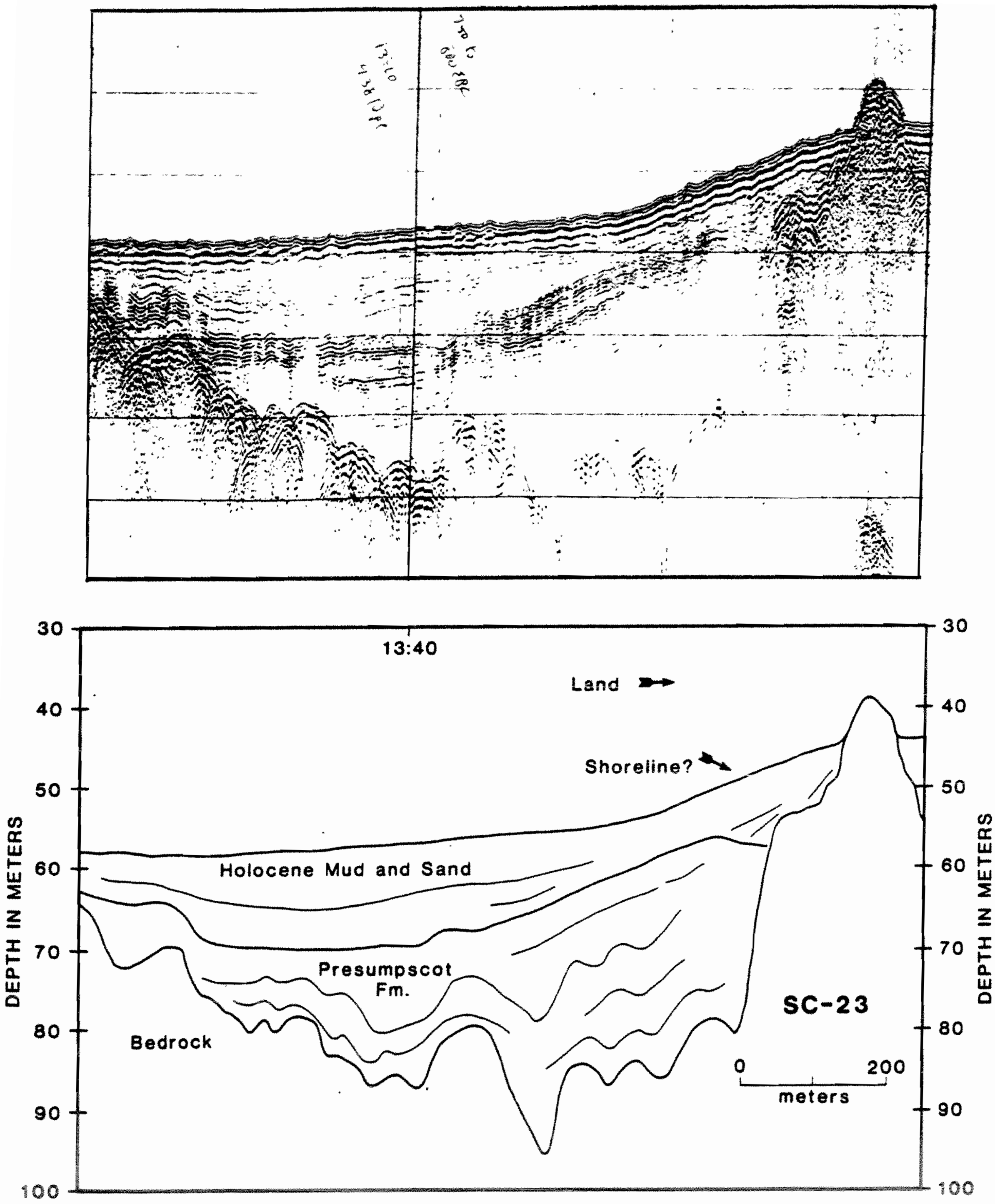

Figure 31. Seismic reflection profile across lowstand shoreline in Saco Bay. This feature was crossed by a submersible dive in 1985. Only soft mud was observed on the surface.

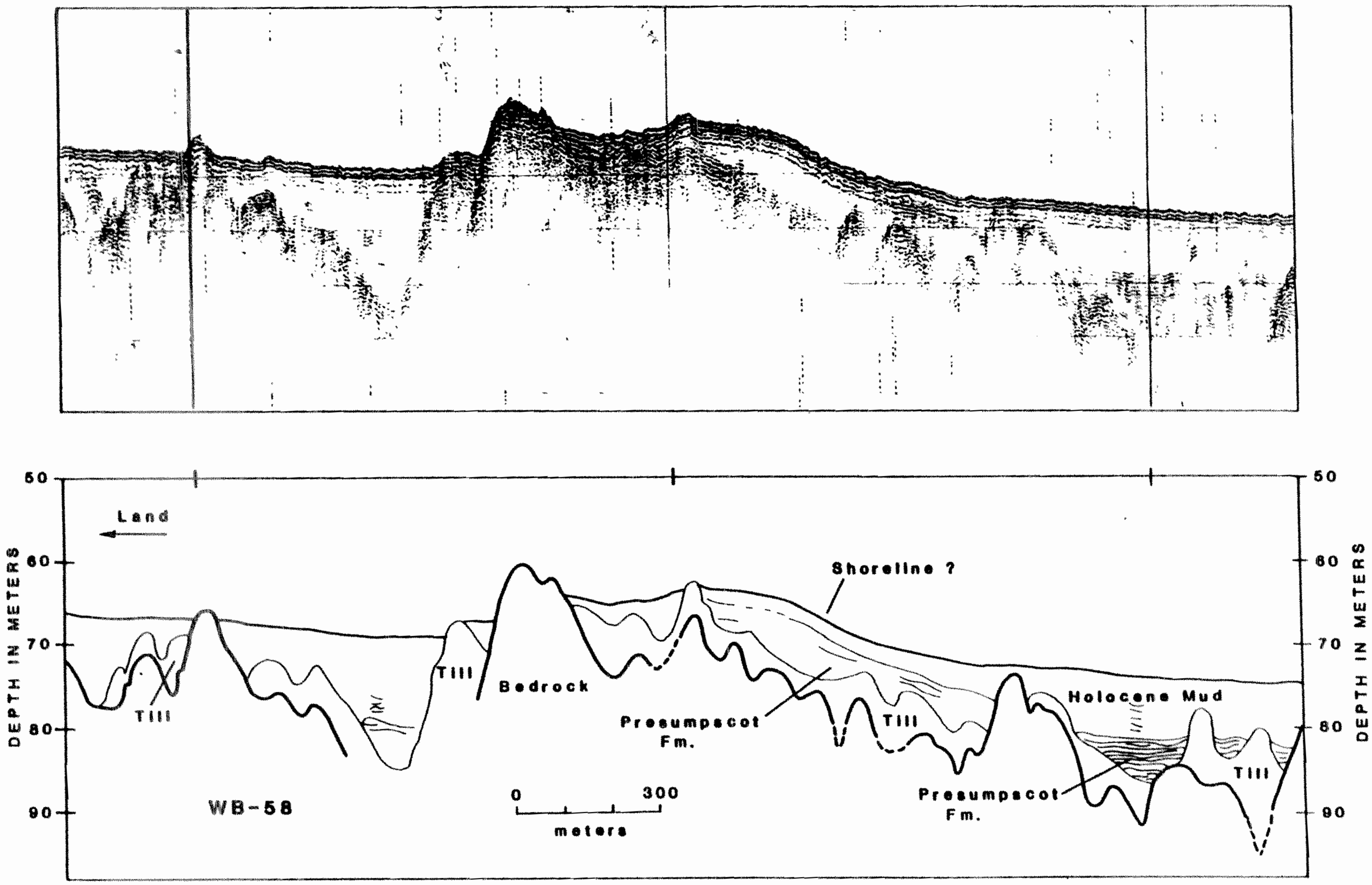

Figure 32. Seismic reflection profile across lowstand shoreline in Wells Bay.

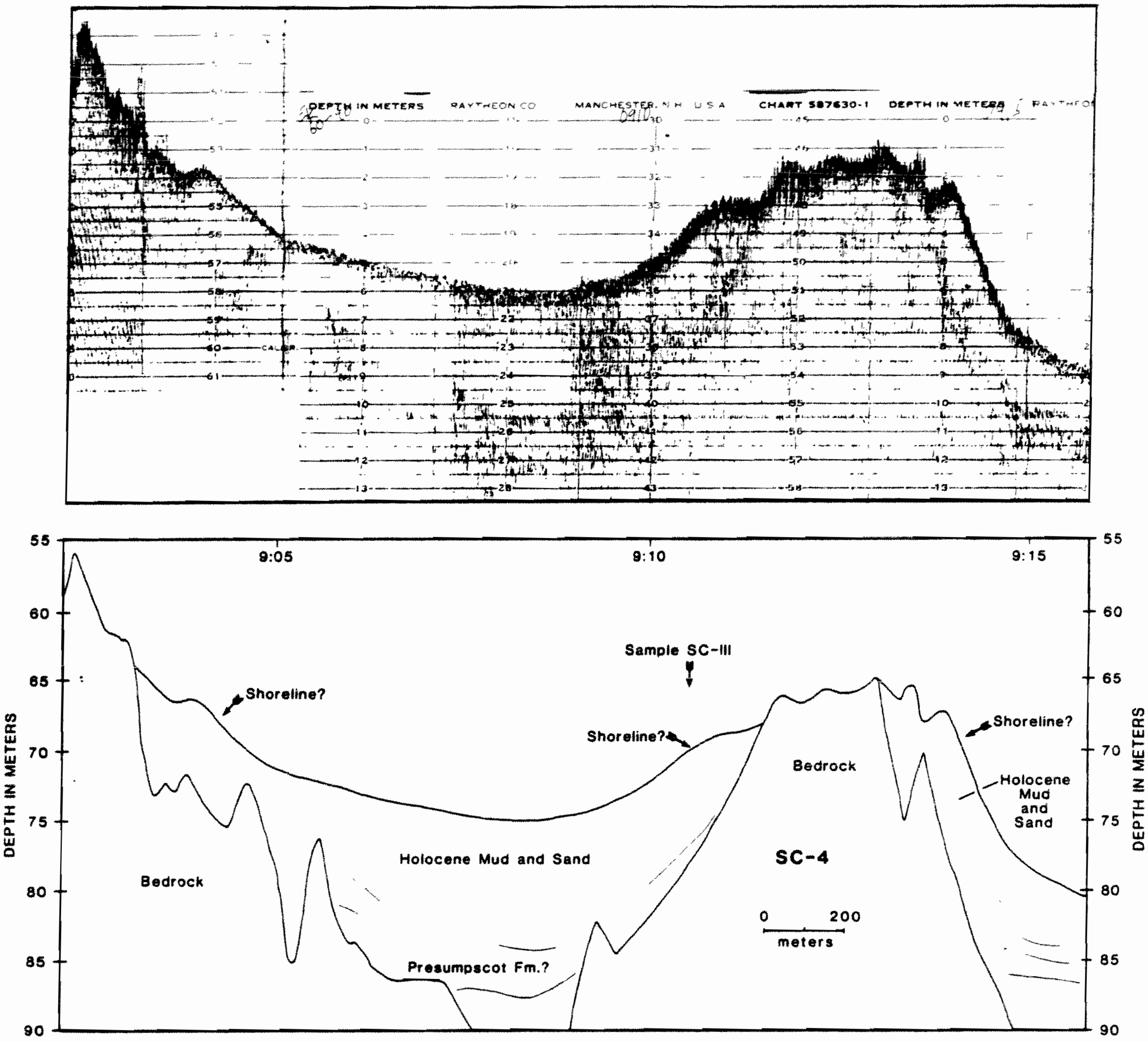

Figure 33. Seismic reflection profile (3.5 kHz) across mounds of sediment in Saco Bay. A bottom sample was collected from one mound and was composed of gravelly sand.

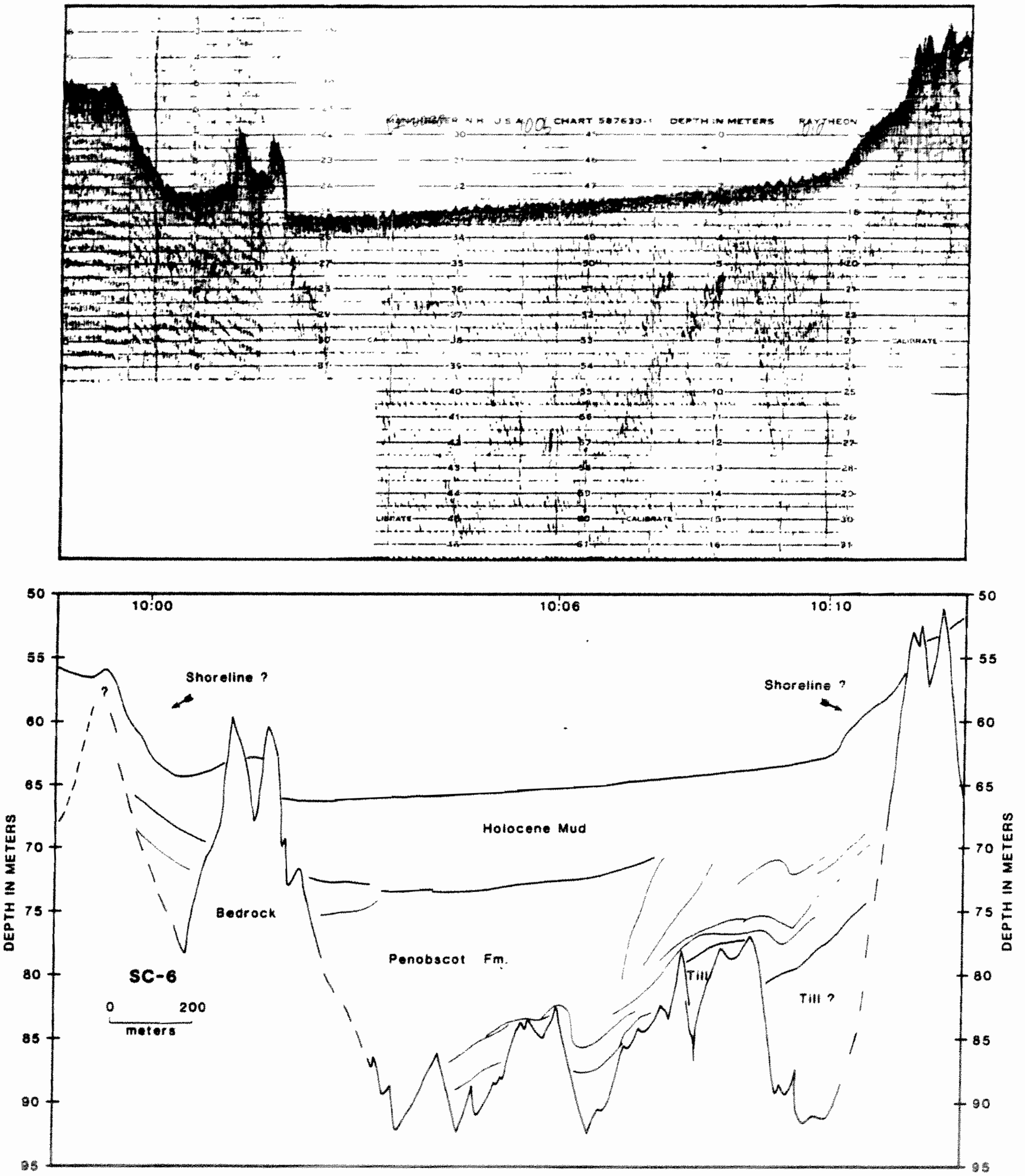

Figure 34. Seismic reflection profile (3.5 kHz) across a narrow basin with lowstand shorelines on either side.

where bedrock outcrops (Figure 35). Near rocky areas, gravelly muds surround outcrops and carbonate concentrations are high. A submersible dive was made on one rocky outcrop in a muddy basin north of Saco Bay and several centimeters of mud covered the gravelly, shelly mud apron around the rock. Similarly, the bathymetry of much of the outer areas of the study area suggested a rocky bottom, yet small quantities of mud were returned in the sampler, suggesting a thin mantle of mud overlying bedrock was collected.

SEISMIC REFLECTION PROFILES

The two seismic reflection profiling (SRP) systems employed in the study permitted recognition of numerous subbottom reflectors, many of which have been interpreted as the submarine equivalent of terrestrial units mapped by Thompson and Borns (1985). Confidence in the interpretation of the reflectors is enhanced by cores and borings from the study area, as well as by comparison with similar research results from nearby locations (King and Fader, 1986; Birch, 1984; Knebel and Scanlon, 1985; Belknap and others, 1986; Oldale, 1985).

The lowermost seismic unit in this study has no internal reflectors and yields a strong, continuous, high relief return from its surface. This unit is interpreted as, largely, pre-Cenozoic bedrock, and often it could be traced from outcrops on land at the start or finish of a trackline. No strong evidence for Cenozoic sediment as has been reported elsewhere was recognized (Birch, 1984; King and Fader, 1986).

Overlying the bedrock, a relatively thin unit with discontinuous internal reflectors and a strong surface return was frequently observed. Although this unit's thickness exceeded the ability of the seismic equipment to fully penetrate it in some places, usually it was only a few meters thick, and locally was often absent. This unit is interpreted as till, with subdivision into lodgment or reworked facies possible only when the unit is exposed on the seafloor.

Directly overlying till or bedrock is the thickest, most widespread seismic unit in the study area. Its lower surface drapes over whatever lies beneath it and it possesses continuous internal reflectors with relatively high relief. This unit is interpreted as the offshore equivalent of the glaciomarine Presumpscot Formation, first mapped on the adjacent coast by Bloom (1960). Strictly speaking, the Presumpscot Formation is "emergent marine mud", but others have recognized it from seismic reflection profiles, cores, and borings (Ostericher, 1965; Knebel and Scanlon, 1985; Birch, 1984; Hulmes, 1983; Luepke and Grosz, 1986). In appearance on seismic reflection profile data, the Presumpscot Formation is similar to the Emerald Silt (facies A, B; King and Fader, 1986), but the difference in the time of formation makes correlation impossible at present. The surface of the Presumpscot Formation is a strong continuous reflector which generally slopes seaward. In Shelf Valleys, it is frequently channel-shaped in cross section. This surface is interpreted as an early Holocene transgressive unconformity, although in places the regressive unconformity may also be preserved. In cores, this surface contains sand and gravel in a muddy matrix, and on land is frequently

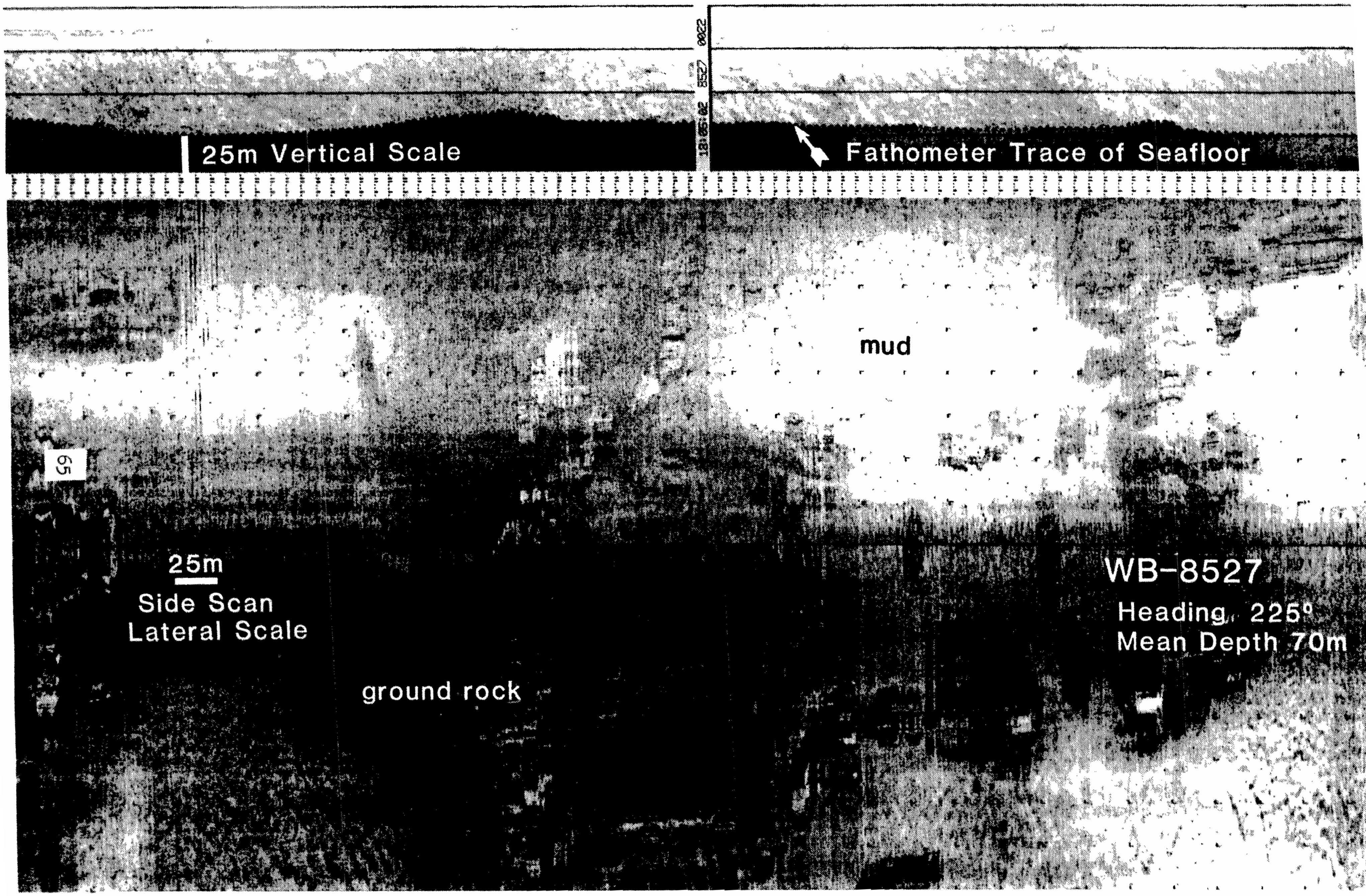

Figure 35. Side-scan sonar image of Outer Basin offshore of Wells. Shelly gravel aprons surround bedrock outcrops in an otherwise monotonous muddy plain. The field of view is 400 meters by 800 meters.

desiccated (Bloom, 1963).

Overlying the Presumpscot Formation are a variety of sediment types, described above as surficial sediments, that are of Holocene age. Some of these are drowned littoral materials, derived from fluvial sources or reworked from older deposits.

The seismic reflection profiles permit an understanding of the location of major late Quaternary centers of sediment deposition as well as insight into the origin of surficial sediment characteristics and the processes which formed them. Although the seismic tracklines are of sufficient density to permit construction of a structure contour map of regional sediment thickness (Figure 47), the lack of cores from most environments on the shelf precludes isopach maps of the stratigraphic units at the present time.

TILL

What has been interpreted as till is very irregularly distributed throughout the study area. The largest deposits occur in topographic lows, and reach thicknesses up to 30 meters. These were best observed in the Outer Basin where bedrock could not always be clearly detected beneath till (Figure 36), and in the Shelf Valleys (Figure 36, 37). Contrary to speculation by Oldale (1985) no morphologic features resembling submarine moraines were identified in the study area. In most places where till is recognized at the sediment-water interface, the seafloor has been planed into a boulder-strewn surface of very low regional relief (Figures 38, 39). Widespread areas offshore of Wells (gravel plain) appear to have formed by wave planation just as the existing high bluffs along the coast are today eroding (Figure 38). Some of the large deposits of till that are covered by younger material rest on bedrock knobs and may be minor moraines similar to those described by Smith (1984) or possibly "lift-off" moraines (King and Fader, 1986). That is especially true for the locations where till was inferred to exist beneath shorelines adjacent to deep Outer Basins.

GLACIOMARINE SEDIMENT (PRESUMPSCOT FORMATION)

The most widespread unit recognized in the seismic survey correlates with the Presumpscot Formation described by Bloom (1960, 1963) from southwestern Maine. Like till, the glaciomarine sediment is thickest in the low areas of the Outer Basins and axes of Shelf Valleys. Although it rarely exceeds 30 meters in thickness, it is commonly greater than 10 meters thick (Figures 31-35). Near its base, seismic reflectors within the Presumpscot Formation drape over the irregular, underlying topography (Figure 40). This has been attributed by others (King and Fader, 1986; Piper et al., 1983) to deposition of sand and mud from suspension near a melting ice margin. Less commonly within this study area the lower portion of what is called Presumpscot Formation is acoustically transparent (Figure 41). The upper surface of the seismic unit correlated with the Presumpscot Formation is a reflector which commonly truncates lower reflectors (Figure 41). This is most likely the unconformity marking the early Holocene marine transgression across the shelf. Although it dips gently seaward

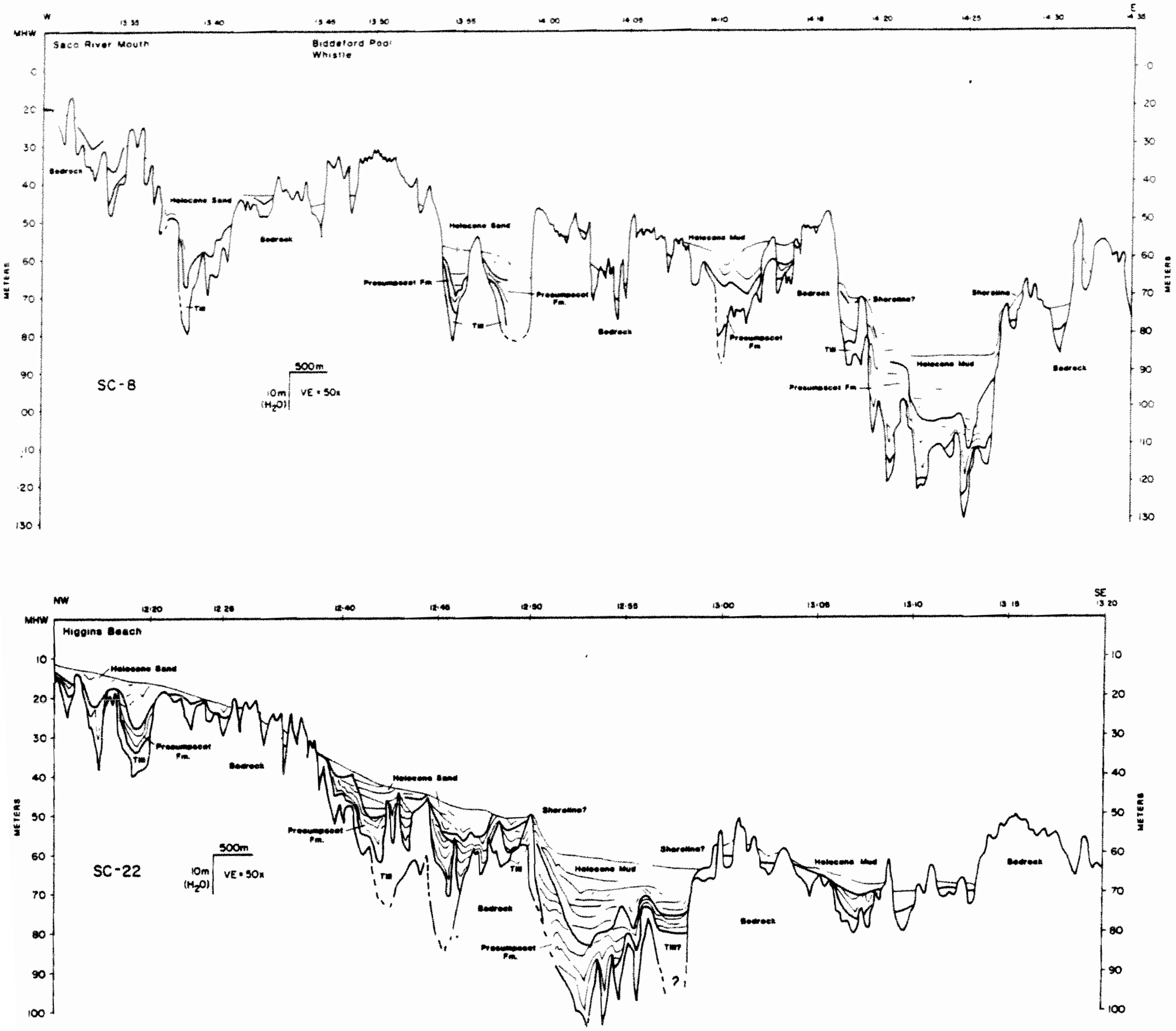

Figure 36. Digitized seismic reflection profiles normal to the shoreline of Saco Bay. Location of lines indicated in Figure 5. Each of these profiles crosses all the major physiographic zones of the shelf. It is of note that the Outer Basin in this area slopes gently from northeast to southwest so that its depth as well as that of bordering shorelines is greater in line 8 than in line 22.

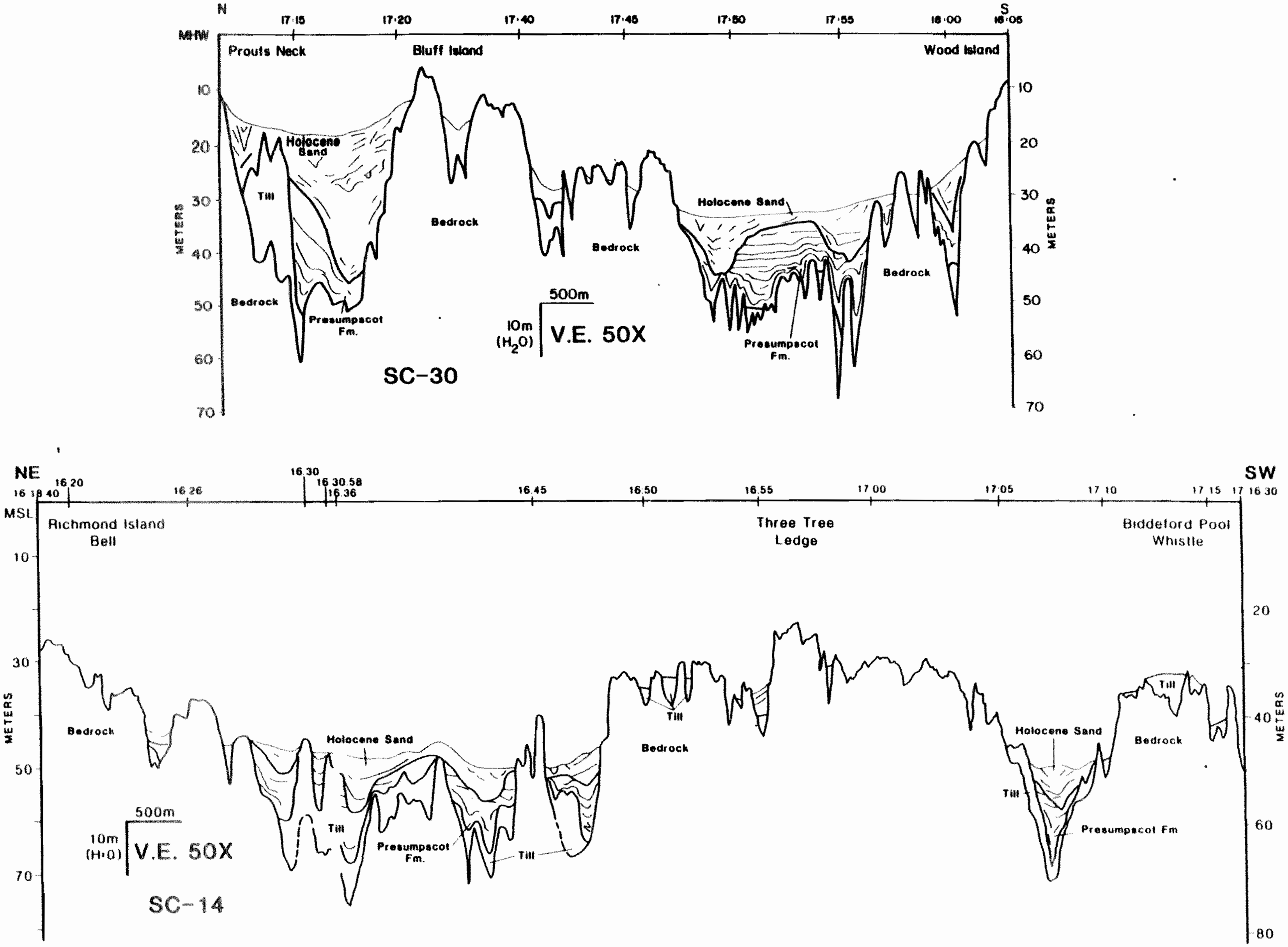

Figure 37. Digitized seismic reflection profiles parallel to the coast of Saco Bay. Line 30, which is inshore of the shore-normal profiles (Figure 36), shows 15 meter difference in depth in the two sides of the inner bay. Near Prouts Neck, nearly 40 meters of till, Presumpscot Formation sediment, and coarse grained Holocene material link the mainland to till outcrops on Stratton and Bluff Islands. Shelf Valley channels in the Presumpscot Formation are at very similar depths on both line 30 (45 meters) and line 14 (57 meters).

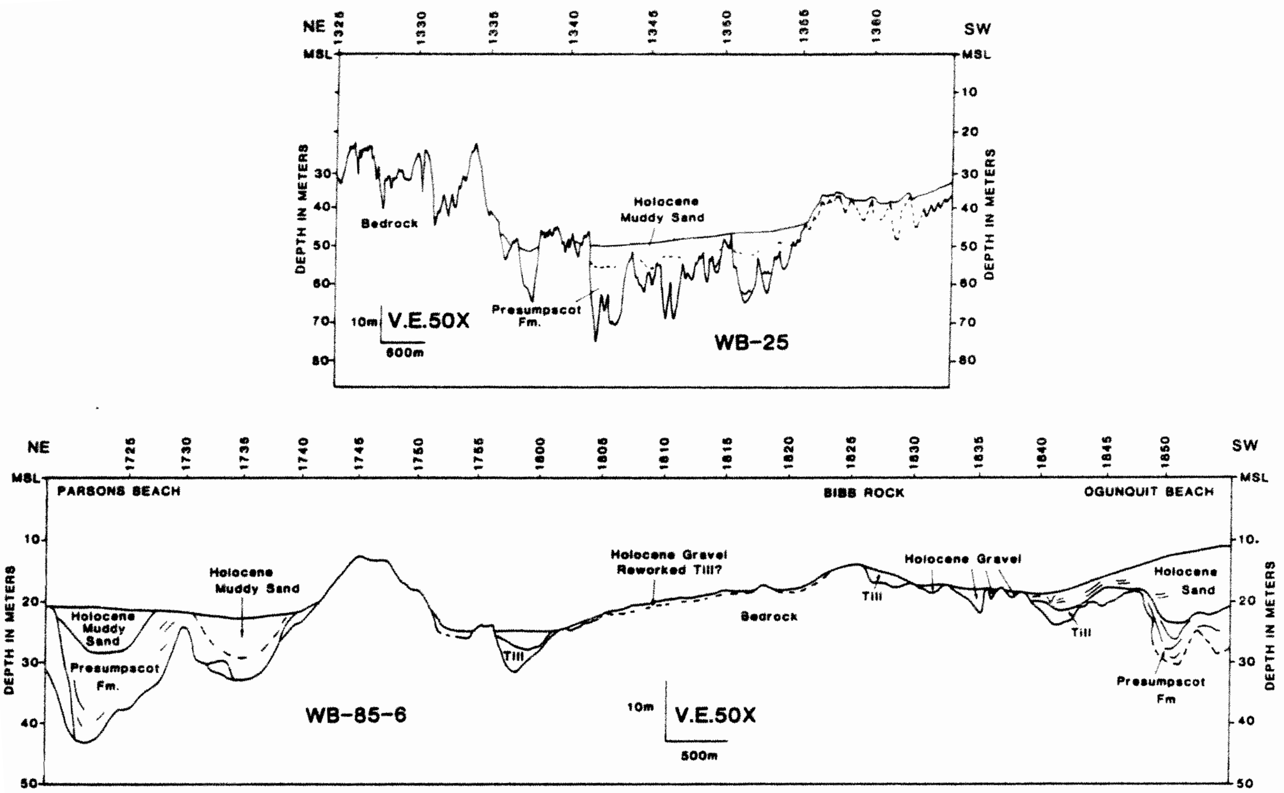

Figure 38. Digitized seismic reflection profiles parallel to the coast of Wells Bay. The paucity of sediment in this area is apparent in each of these lines. Sediment is concentrated largely in the shelf valleys. Along the nearshore line (line 6) it was possible to clearly distinguish rock from gravel only where the bedrock projects through the low relief, gravel plain.

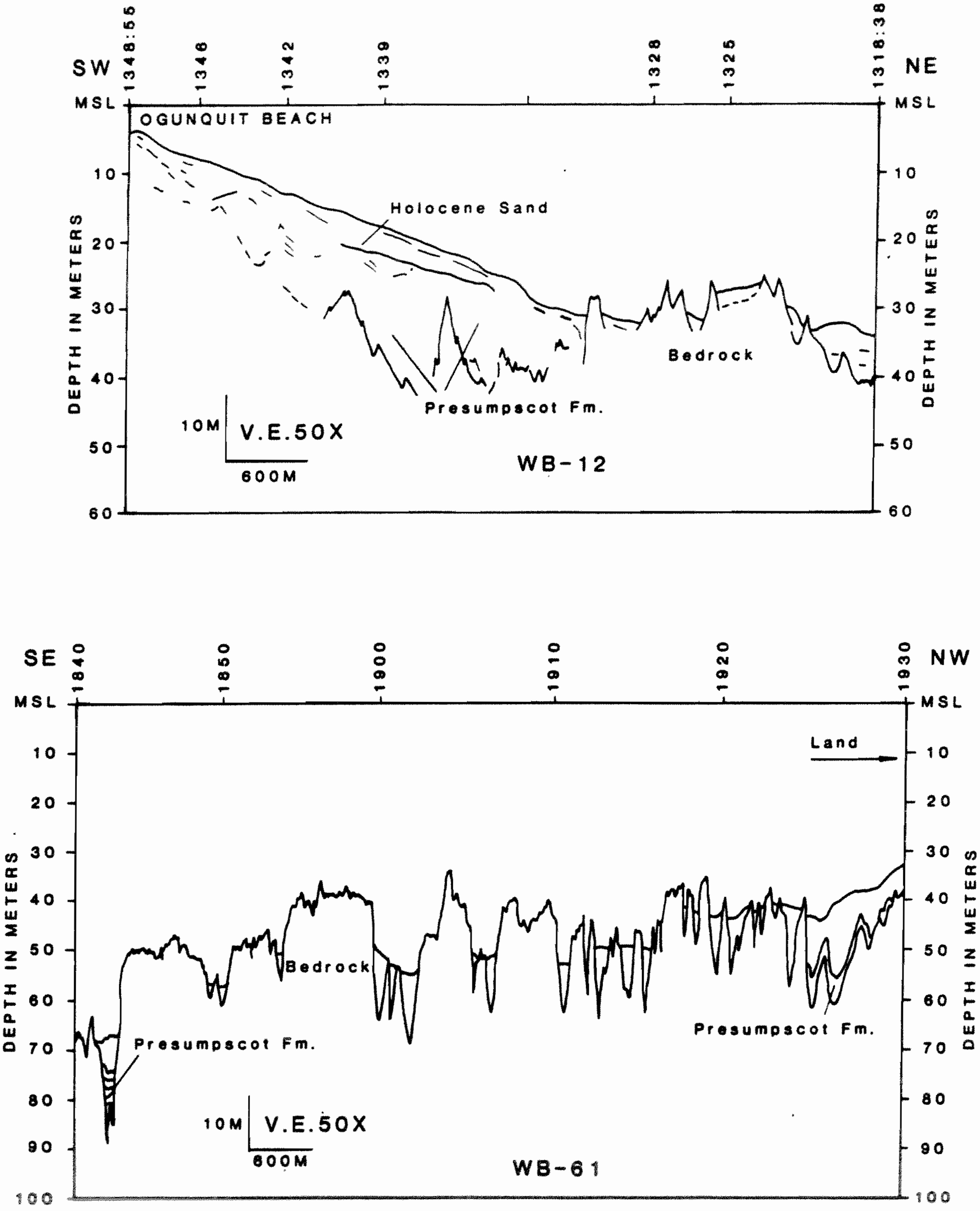

Figure 39. Digitized seismic reflection profiles normal to the shoreline of Wells Bay. These two lines show an unusually thick sediment section offshore of the Ogunquit Beach area (line 12) and a crossing of the 65 meter isobath with no shoreline (line 61) but rather a steep bedrock scarp.

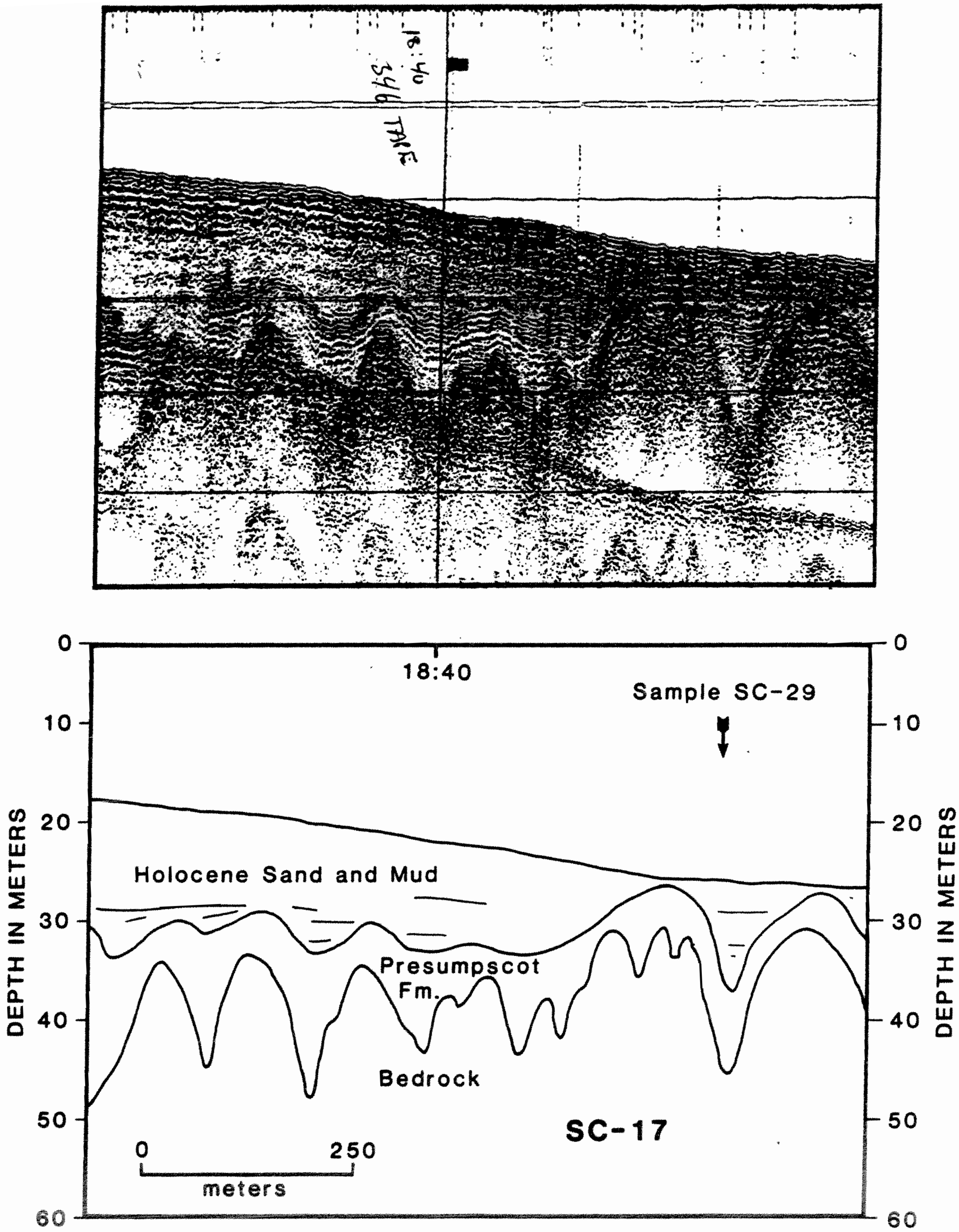

Figure 40. Seismic reflection profile from central Saco Bay. The undulating nature of reflectors at the base of the Presumpscot Formation is striking. The surface of the Presumpscot Formation is not clearly seen here possibly because the overlying sand provides too little acoustical contrast to produce a reflector. That the glaciomarine sediment is near the surface is evidenced by the gravelly nature of sample SC-29 (it is surrounded by sand) which was collected where the Presumpscot Formation appears to outcrop on the seafloor over a bedrock pedestal.

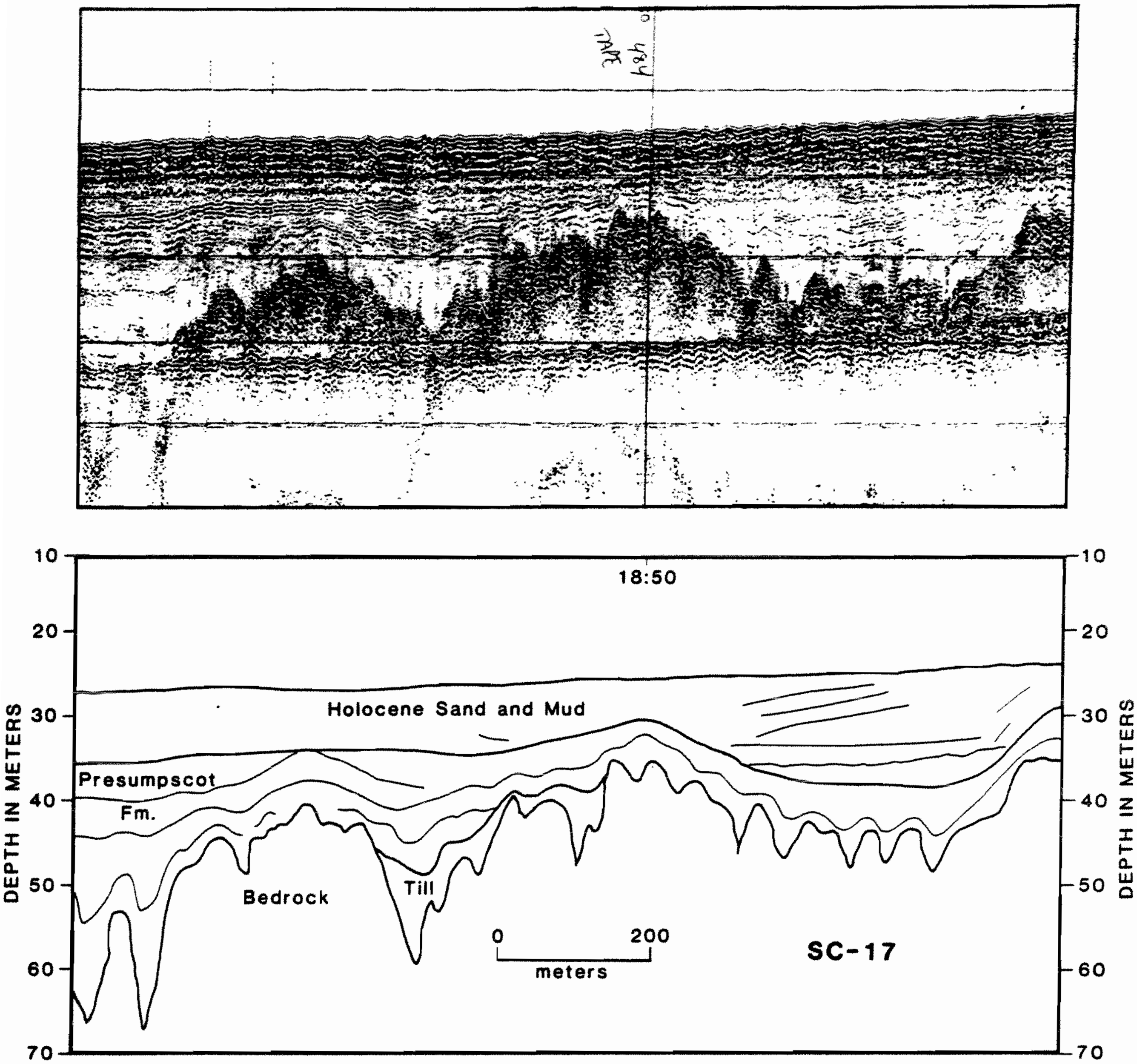

Figure 41. Undulating reflectors within the Presumpscot Formation do not extend to the base of the unit in this Saco Bay seismic reflection profile. Rather, an acoustically transparent material rests on bedrock. Truncation of undulating reflectors by the strong reflector representing the transgressive unconformity is apparent on the left side of the illustration.

down the axes of Shelf Valleys, it is commonly channel-shaped or absent in the thalwegs of paleochannels (Figure 42).

In cores from the study area (Figures 43-45) (Hulmes, 1980; Luepke and Grosz, 1986) and nearby (Kelley et al., 1986; Belknap et al., 1986) the surface of the Presumpscot Formation is an indurated, compact clay frequently capped by gravel which occasionally contains wood (Knebel and Scanlon, 1985). Where this surface intersects the present seafloor (Figure 30) gravel rubble or coarse grained megaripples are found. The surface of the Presumpscot Formation is most commonly exposed at the seafloor wherever bedrock knobs project through the sediment-water interface such as at the margins of Shelf Valleys.

Origin of Surficial Sediments

The coastal geomorphology of Maine is controlled by bedrock, which determines the geometry of each coastal compartment, and glacial sediment availability, which dictates the sediment texture of coastal environments (Kelley, in press). Modern processes interact with bedrock and available sediment to create the landforms extant on the present shoreline. The inner shelf of Maine is similarly influenced by bedrock, glacial sediment, and modern processes, but the distribution of sediment across the shelf has also been strongly affected by late Quaternary sea level changes. The initial transgression and regression were major times of sediment introduction to the shelf, while the present transgression appears to be largely a period of sediment reworking.

During the late Pleistocene transgression (Transgression 1, Figure 46) which accompanied deglaciation, bedrock probably exercised some control on sediment deposition by creating a series of pinning points which grounded the ice and led to till deposition (King and Fader, 1986). Glaciomarine sediment was deposited seaward of the grounded ice margin and poured into bedrock basins which had probably formed by pre-glacial fluvial action. The location of till on bedrock high points (and of gravel plains) and the undulating nature of nearby reflectors within the Presumpscot Formation supports this idea. The present coastline apparently acted as a major pinning point for the retreating ice, and major stratified coastal moraines reflect interaction between marine and glacial processes (Stuiver and Borns, 1975; Smith, 1985). The variety of facies present in coastal moraines (Figure 46) cannot be compared to the "till" recognized on seismic reflection profiles, furthermore, the absence of morphologic forms similar to those described by Oldale (1985) suggests they may never have been present at all on the present shelf.

Landward of the present coast the glaciomarine sequence ends at the marine limit and is marked by extensive glaciomarine deltas (Figure 46; Thompson and Borns, 1985). Following deposition of these features, sea level fell very rapidly across the landscape due to isostatic uplift. A deranged drainage network was incised in the former seafloor as numerous buried valleys remained choked with sediment (Tolman et al., 1986). A few large rivers with headwaters in mountainous areas began downcutting into glacial sediment, and sandy marine-fluvial sediment was deposited over the Presumpscot Formation muds (Kelley and others, 1986). In the Kennebec

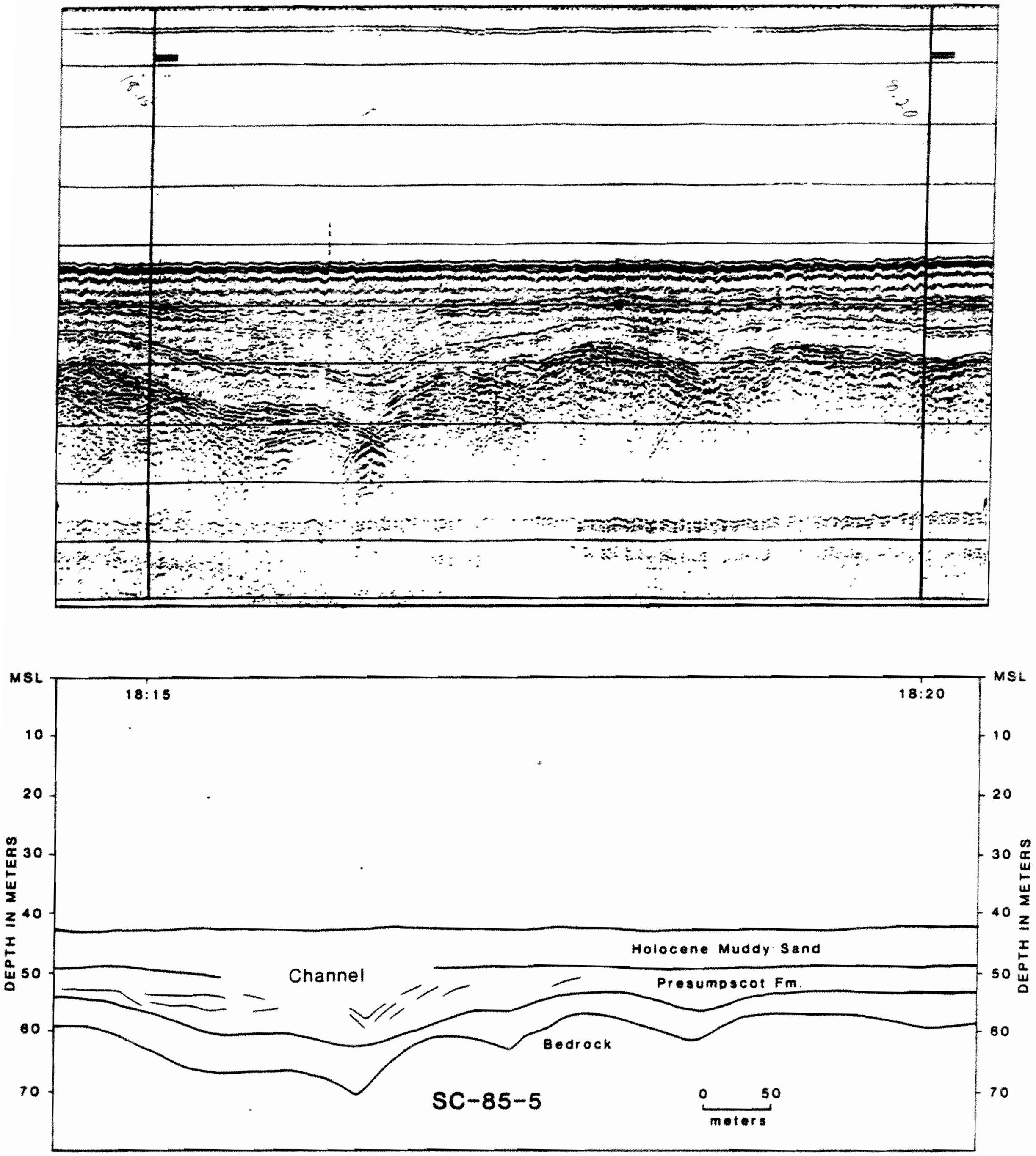

Figure 42. Seismic reflection profile down the axis of a shelf valley in Saco Bay. The lower reflector within the seismic unit identified as the Presumpscot Formation mimics the topography of the underlying bedrock and is characteristic of the glaciomarine sediment. The major reflector above it dips gently seaward and appears to be the late Holocene transgressive unconformity. Where this reflector disappears, a channel cuts into the Shelf Valley from out of the plane of the section.

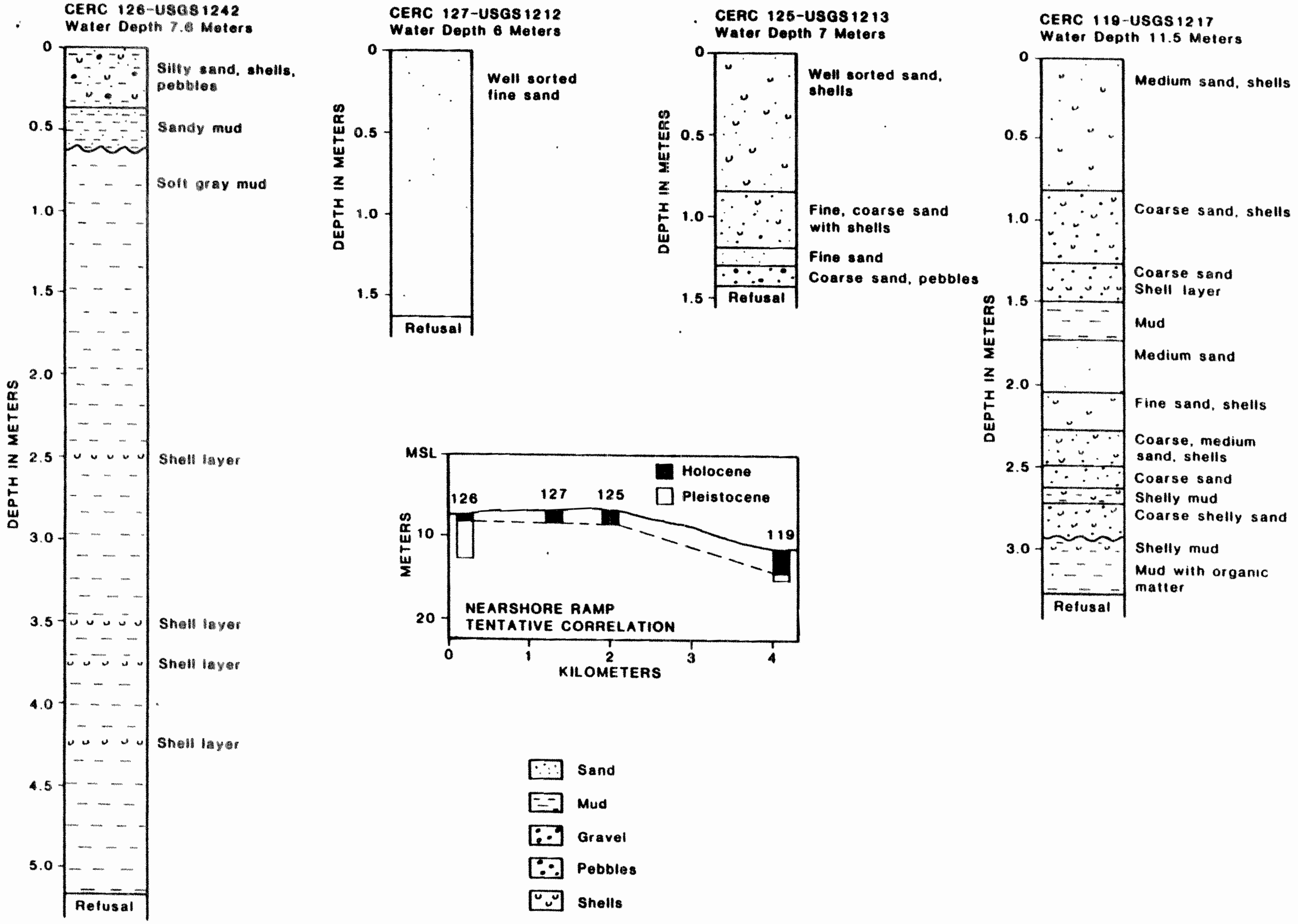

Figure 43. Vibracores collected from the Nearshore Ramp in a line parallel to Old Orchard Beach. The correlation is inferential, and based on similar lithologies described from borings by Bloom (1963).

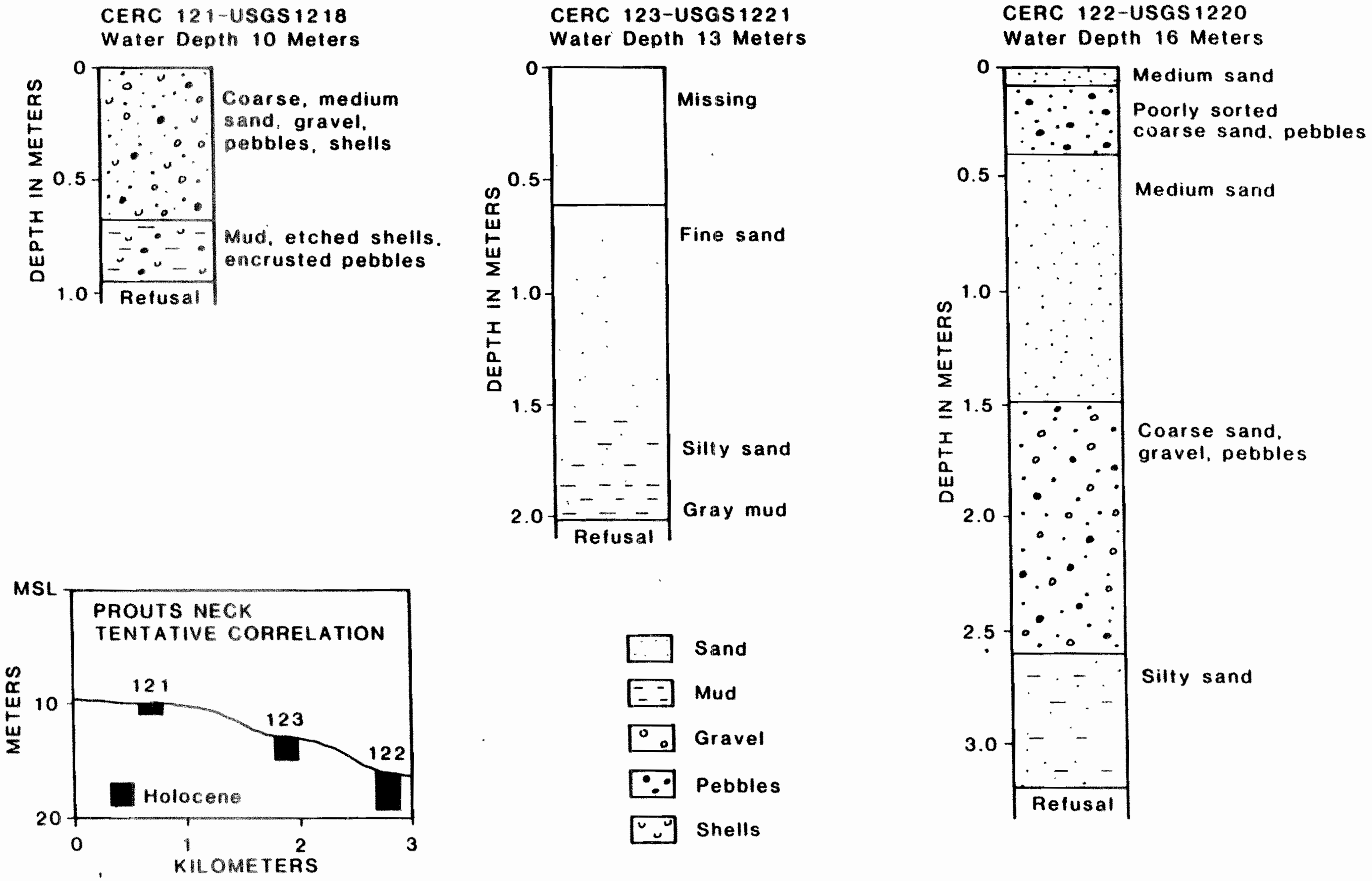

Figure 44. Vibracores from the Prouts Neck area of Saco Bay. Coarse-grained sediment here may be derived from till (Figures 25 and 37) or Holocene beach/tidal inlet sediment (Farrell, 1972).

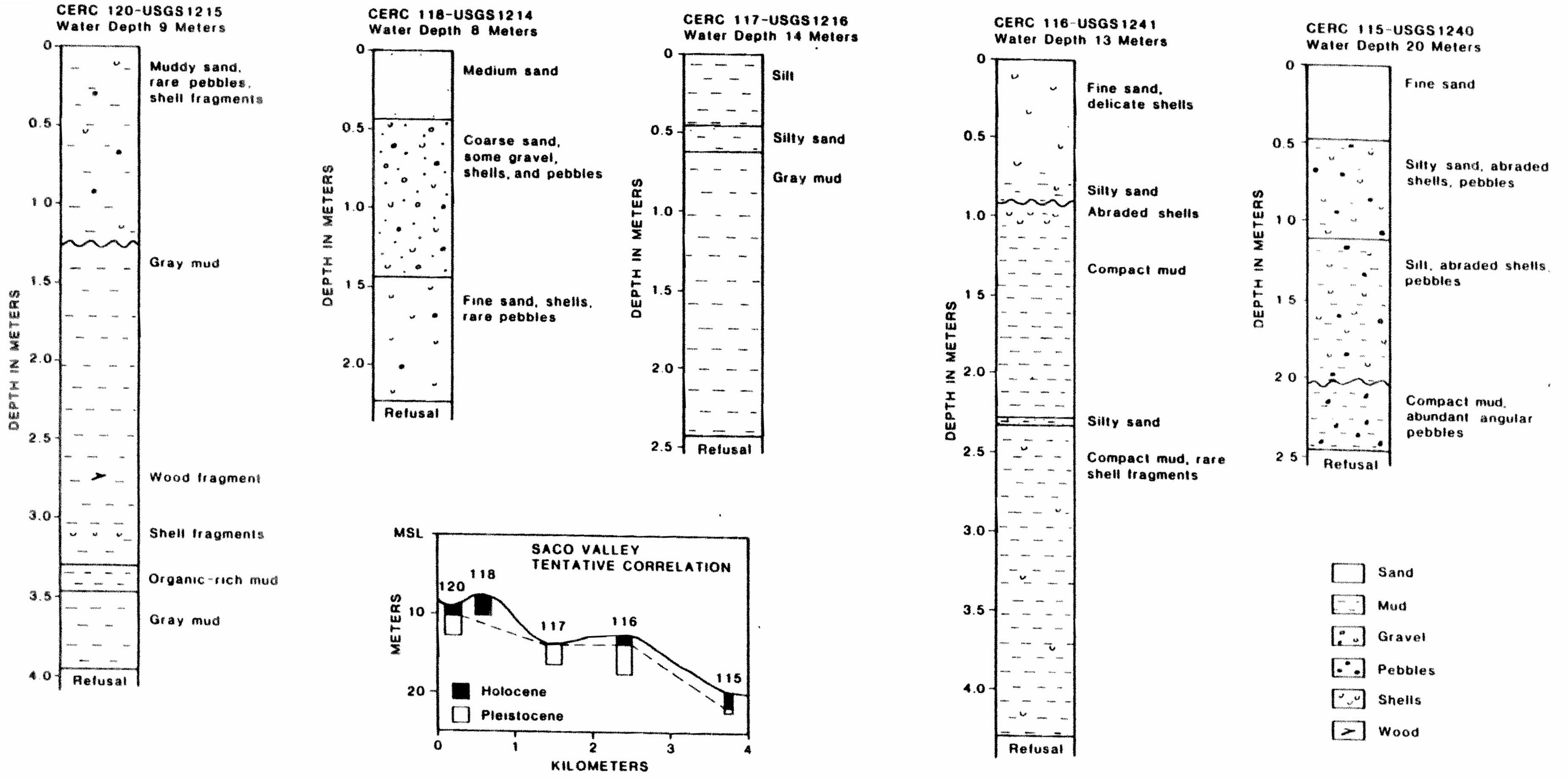

Figure 45. Vibracores along the axis of the ancestral Saco River valley. Correlation is inferential and based on similar lithologies described from borings by Bloom (1963).

STRATIGRAPHIC CROSS-SECTION :
SOUTHWESTERN COASTAL MAINE

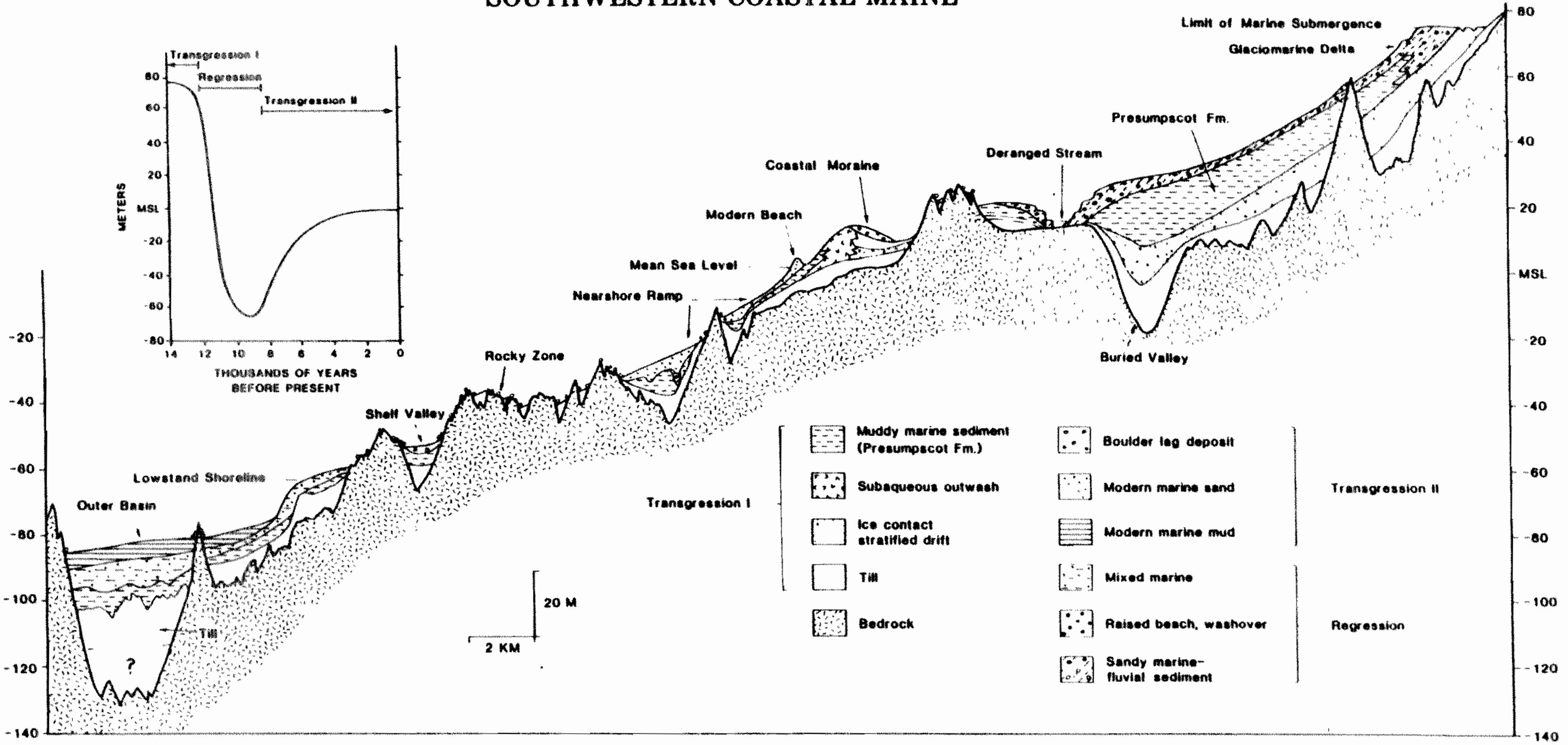

Figure 46. Idealized stratigraphic section extending from the marine limit on land to the lowstand shoreline and Outer Basins. Terrestrial portion is modified from Smith (1982). Offshore units are interpreted from seismic reflection profile and side scan sonar data.

River valley this material is called the Embden Formation (Borns and Hagar, 1965) although similar material may also be seen in the Saco River area (Thompson and Borns, 1985). Smaller streams which originate within the marine limit are not generally associated with this sandy material (Kelley and others, 1986).

Terraces were etched into sandy alluvium as sea level fell below the present coast, and sandy sediment poured into the present shelf area as the regression reached the lowstand limit. A large stream like the Saco River undoubtedly transported more coarse clastic sediment to the sea than did the other minor streams entering the study area (Kelley and others, 1986). Mixed with the early Holocene fluvial contributions to the shelf were sediments locally reworked as the surf zone crossed the present shelf. In addition to sediment reworked from interfluves, material was removed from Shelf Valleys as relatively high gradient streams cut into the previously buried channels. Although sea level is inferred to have rapidly fallen and left few raised beaches (Belknap et al., 1986; Thompson and Borns, 1985), sufficient reworking of sediment occurred to leave most bedrock ridges and high points seaward of the marine limit covered only with "thin drift", or less than 3 meters of material (Thompson and Borns, 1985).

The exact time of sea level lowstand in southwestern Maine is not known, and is probably a time-transgressive phenomenon within the Gulf of Maine (King and Fader, 1986). While the depth of the lowstand is also inferred to be variable within the region (King and Fader, 1986; Oldale and others, 1983; Birch, 1984; Knebel and Scanlon, 1985), notches cut into glacial sediment as well as constructional features interpreted as beaches were recognized on virtually every seismic profile crossing the 65 meter isobath in the study area. While samples collected from these areas today are generally sandy shelly gravels, and strong coherent seismic reflectors were observed within the landforms, the basins seaward of them are more acoustically transparent and presently floured by mud. Thus, at the time of the sea level lowstand, the fine grained sediment load of rivers may have escaped into the deeper Gulf of Maine while coarser sediment remained nearshore.

Following the marine lowstand, sea level rose very rapidly during the early Holocene across the already-wave-washed shelf (Figure 46; Belknap and others, in press). Material not removed during the prior regression was again subject to wave and current action. The currently extensive areas of bedrock on the shelf were finally exposed at this time, and till outcrops were planed off at the surf zone. Some of this reworked sediment, plus the continued, albeit probably reduced, load of streams added increasingly finer sediment to the Outer Basins. As the transgression moved up the Shelf Valleys, the reflector interpreted as an unconformity on the surface of the Presumpscot Formation was probably formed.

Dating of basal salt marsh peats behind the Wells barrier spit and in other places in the region (Belknap and others, 1987) indicate relative sea level rise began to slow down around 3,000 years ago (Figure 46). This permitted the general buildup of barrier spits and marshes that presently characterize the coastline around Wells, Old Orchard, and elsewhere. As the barriers in the Wells area moved landward, they may have done so as a system of evolving spits tied to eroding glacial deposits (sediment sources) (Hussey, 1970). Thus the Nearshore Ramp contains numerous patches of gravel and rock and probably little sand at depth. Because of the proximity of the Saco River, Old Orchard Beach may have migrated more slowly, although a relatively thin veneer of sand rests on the eroded surface of the Presumpscot Formation within Saco Bay (Figure 45). In all parts of the southwestern shelf, spits may have formed any time sediment from eroding bluffs was available and then drowned when it ran out. One example is inferred from Saco Bay (Figure 20) but others have been inferred (Farrell, 1972; Hussey, 1970).

Although all the physiographic elements of the present shelf have been in place for thousands of years, modern processes continue to influence the surficial sediment. Megaripples on the inner Nearshore Ramp (Figure 16) reflect contemporary wave action just as the rippled scour depressions (Figure 17) probably represent reworking of nearshore sand by water escaping the surf zone during major storms (Morang and McMaster, 1980; Cacchione and others, 1984). This may ultimately result in sand starvation and beach erosion in southwestern Maine in light of the post-colonial construction of dams on rivers and the modern construction of seawalls on eroding bluffs. Although the scour depressions have not been traced into deep water, the rippled areas near bedrock outcrops in channel thalwegs (Figure 28) and the coarse-grained rubble on Shelf Valley margins (Figure 29) may also result from scouring of the seafloor by seaward moving jets of water during storms. It appears that the Shelf Valleys are not only acting as conduits for nearshore sediment escaping the coastal zone, but are themselves being stripped of sediment wherever rock outcrops focus currents. Since glaciomarine sediment and till commonly rest on bedrock, these deposits are being exhumed by scouring action. Resuspension of glaciomarine mud is in fact the most likely source for mud currently accumulating in the Outer Basins and Shelf Valley thalwegs. During two submersible dives in Saco Bay, high levels of turbidity made bottom observations impossible more than a few inches away from viewing areas. While dragging by modern fishing boats in Outer Basins may be partly responsible for resuspending mud, it cannot account for the sandy muds seen in the Outer Basins or the sand layers observed there beneath modern mud. It is conceivable that mass movements of sand and mud move down Shelf Valleys and lead to the graded deposits commonly observed in deep water.

Aside from some very shallow water sand that may be introduced to the shelf by the Saco River, the only new sediment accumulating today is carbonate detritus. The very large surface area of exposed bedrock available to encrusting algae and fauna (Figure 21) has led to a surprisingly high carbonate content in sediment near rock (Table 4). In conjunction with gravel, carbonate is the only sediment returned from many samples collected near bedrock outcrops. In general, the inner shelf of southwestern Maine may be viewed as sediment-starved with only a few small areas containing greater than 40 meters of Quaternary sediment (Figure 47).

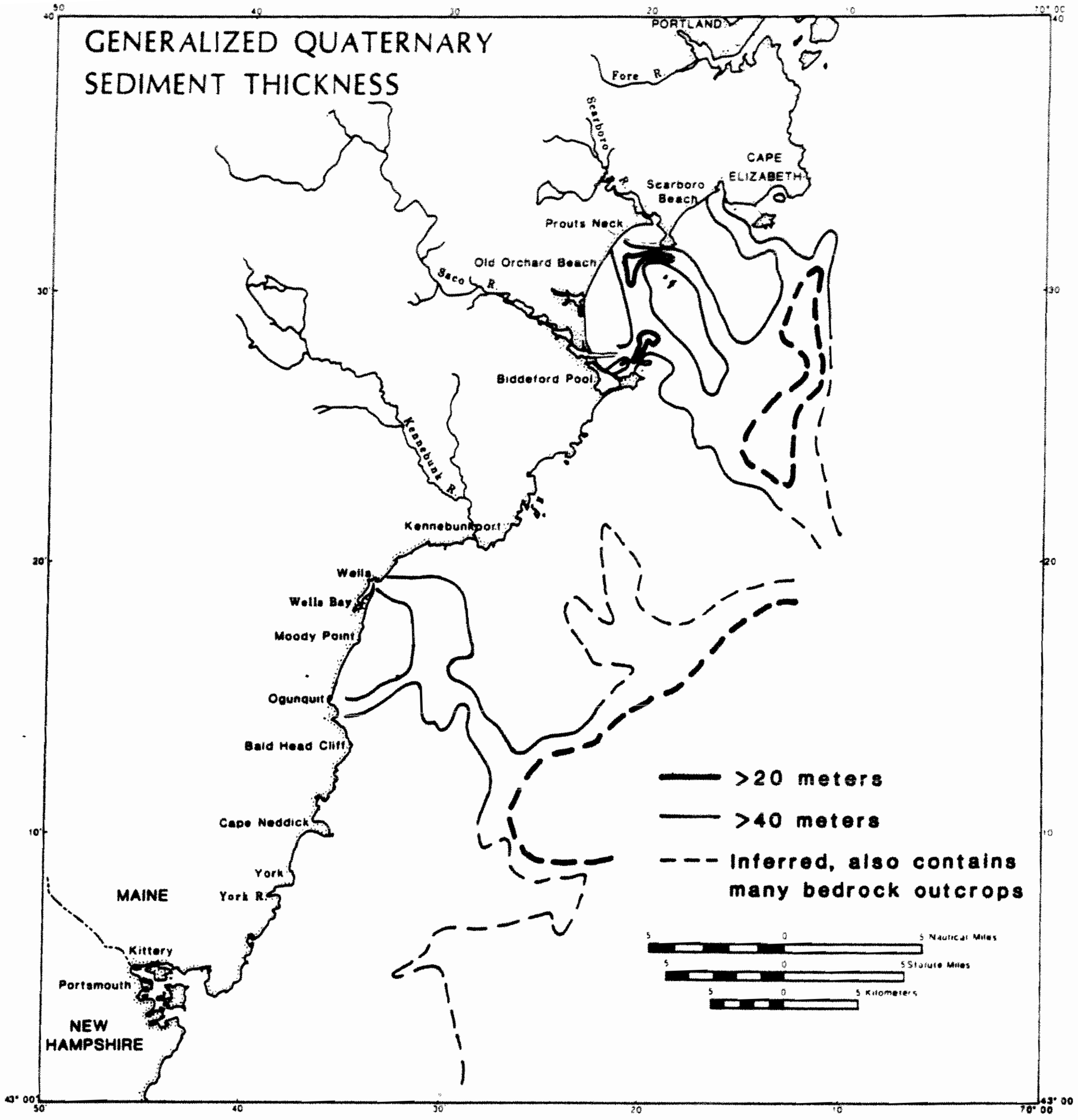

Figure 47. Inferred thickness of Quaternary sediment on the inner shelf. Bedrock sills exist throughout the study area, and even within the 20 meter contour interval there are places with less than 20 meters of sediment. Where line is dashed, inadequate data exists to confidently map thickness, or data indicates pockets of thick sediment with numerous shallow bedrock exposures.

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