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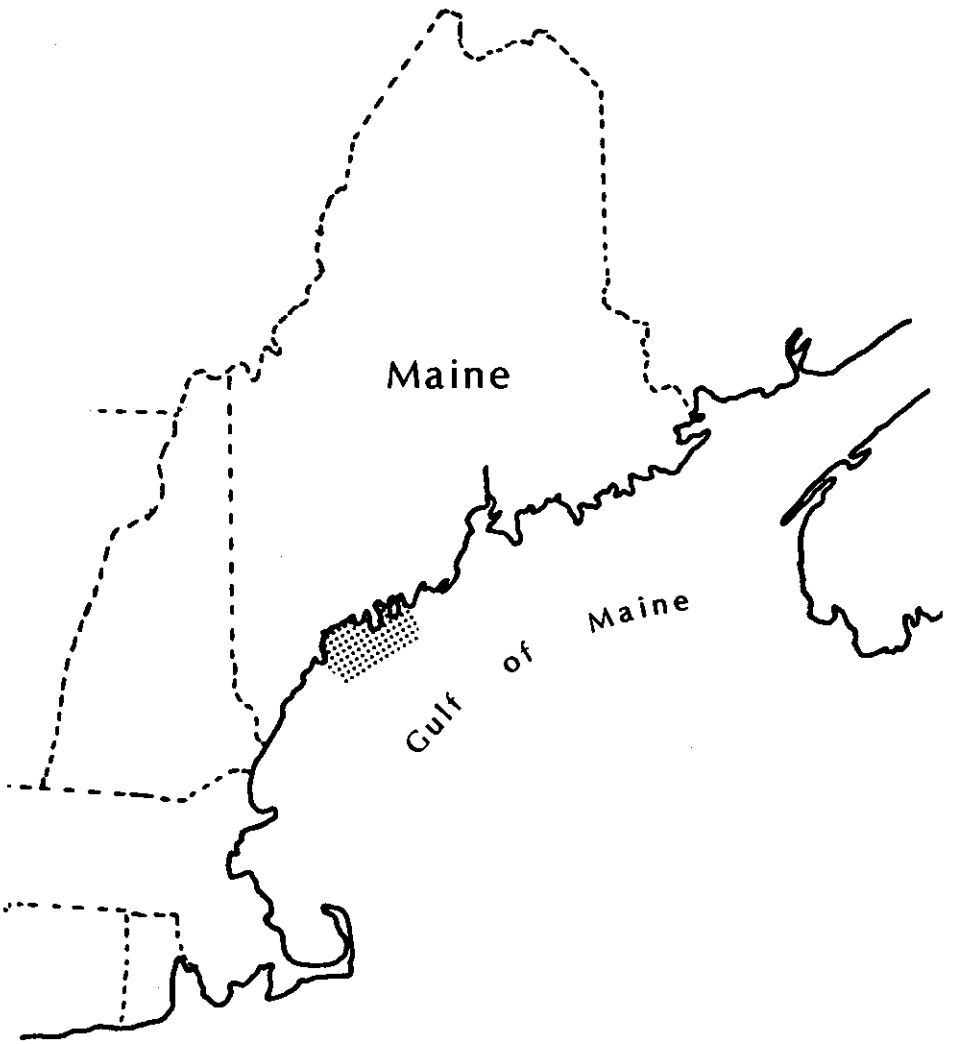
Geomorphology and Sedimentary Framework of the Inner Continental Shelf of South Central Maine

by

Joseph T. Kelley
Daniel F. Belknap
R. Craig Shipp



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GEOMORPHOLOGY AND SEDIMENTARY FRAMEWORK OF THE INNER CONTINENTAL SHELF OF SOUTH CENTRAL MAINE

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ABSTRACT

This report summarizes the Year Two research in Maine of the Minerals Management Service Continental Margins Program. More than 800 kilometers of high resolution seismic reflection profiles and 400 bottom samples were collected and investigated to elucidate the sedimentary framework of the south central Maine inner shelf. On the basis of this, plus side-scan sonar and submersible observations, the shelf is divided into five physiographic zones: Nearshore Basins; 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 one of 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 south central 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 Devonian; although Paleozoic high grade 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 north to Penobscot Bay has been termed the Indented Shoreline coastal compartment because numerous elongate bedrock peninsulas are separated by long, narrow estuaries and neutral embayments. Just as

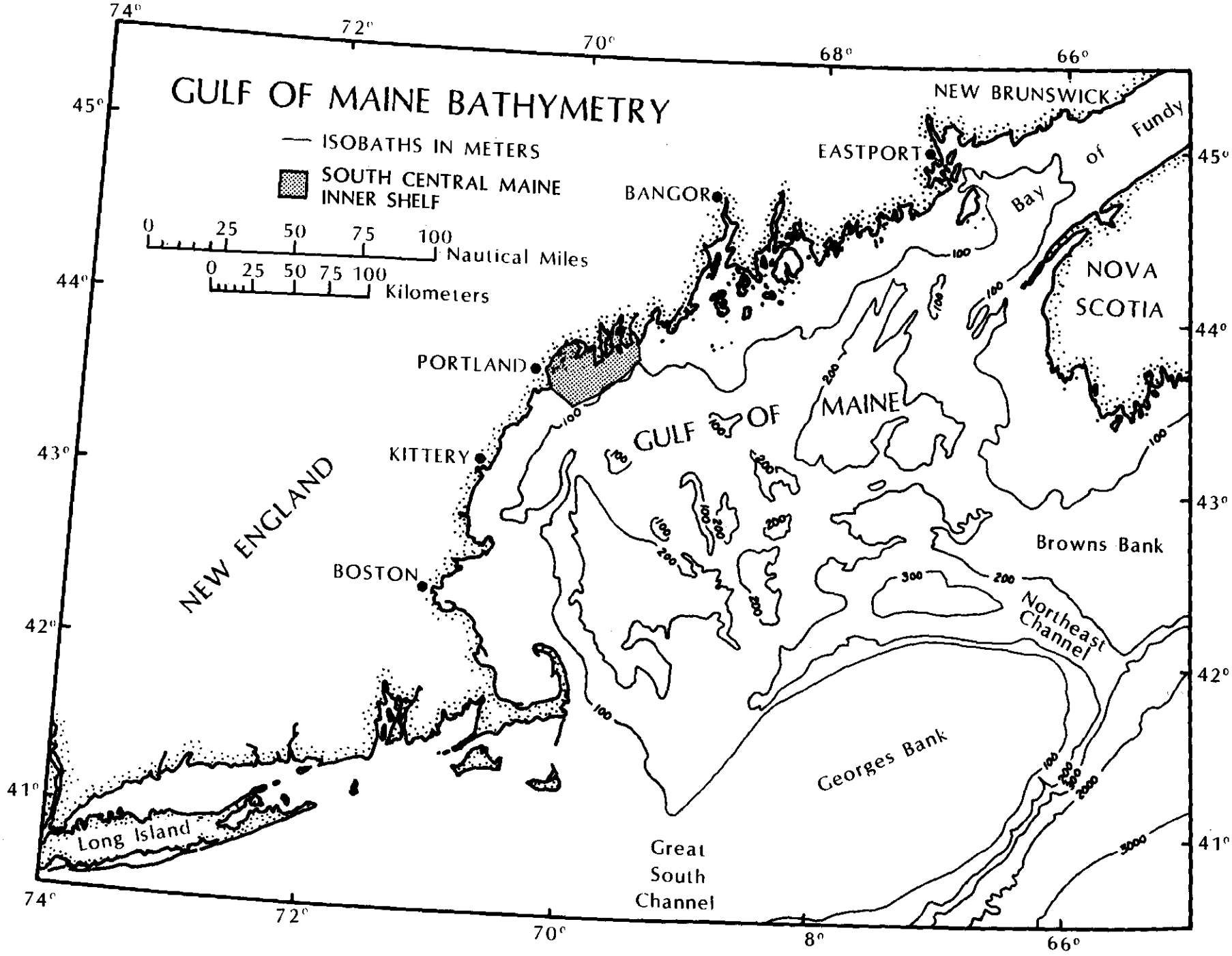


Figure 1. Location of the study area in the western Gulf of Maine.

bedrock exercises a primary influence on the surficial sediments of the southwestern Maine shelf (Kelley and others, 1986b), it similarly controls the distribution and geometry of sediments along the south central inner shelf.

Like other shelf areas of New England and the Canadian Maritimes, south central 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 south central 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 operate repeatedly 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 southern Maine was first summarized by Stone (1899) and mapped by Leavitt and Perkins (1935). 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). Stuiver and Borns (1975) established that retreating ice reached the present shoreline of Maine around 13,200 years ago by dating fossil shells in glaciomarine sediment interbedded with till in coastal moraines. They also bracketed the major time of deposition of the Presumpscot Formation between 13,200 and 12,000 years before present. In the Casco Bay area, Hyland and others (1978) have obtained 11,000 year old dates from tree fragments in the upper Presumpscot Formation. These may have been emplaced by a landslide during the sea-level regression.

Smith has recently mapped the southern Maine area in great detail (Smith, 1982) and this mapping has 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 (Figure 2), the upper sand has been mapped as the Embden Formation (Borns and Hagar, 1965). It is of note that in this glaciated landscape,

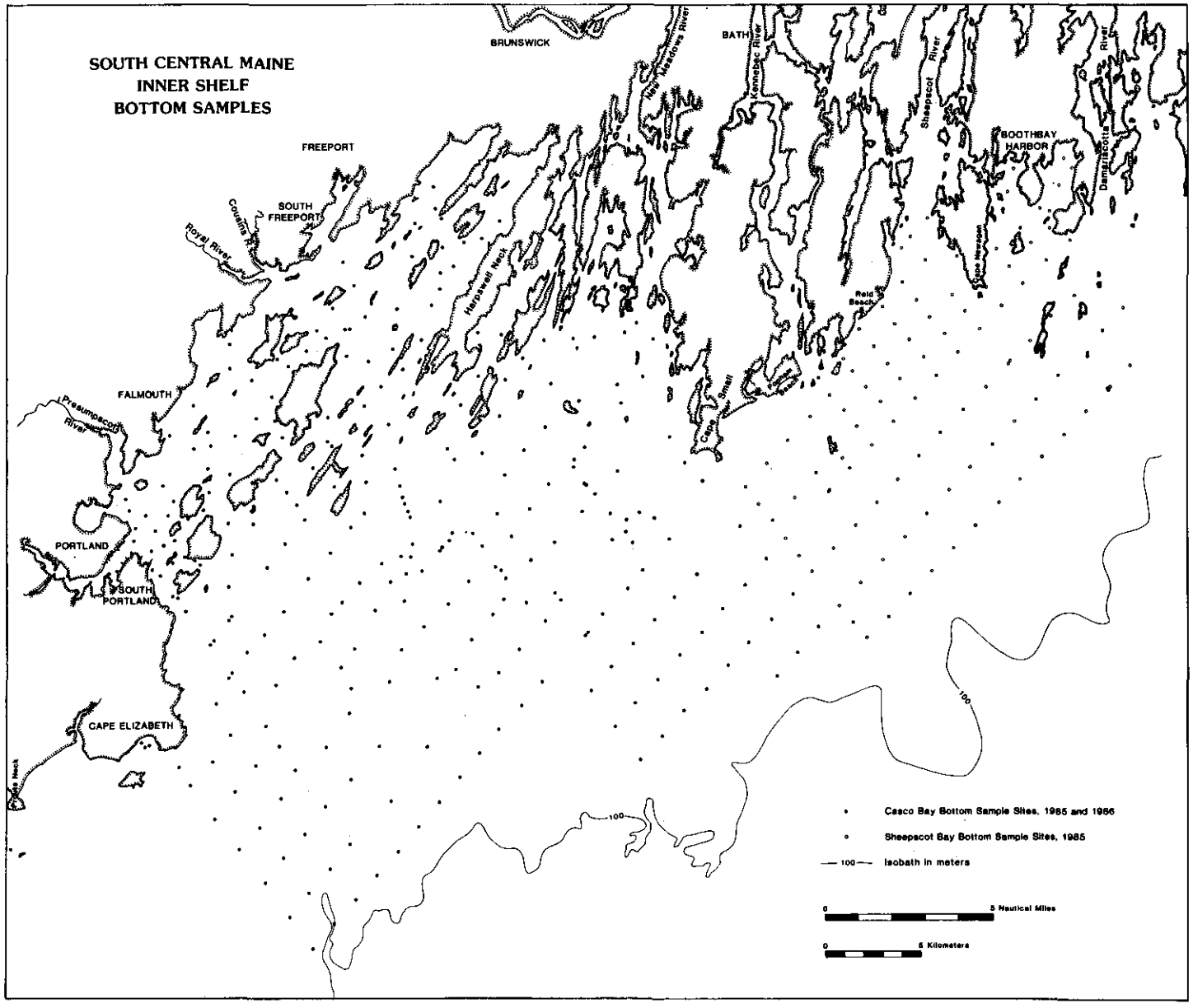


Figure 2. Location of bottom sample stations.

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). Larson and others (1983) collected 58 bottom samples from Casco Bay and found very fine-grained, organic-rich sediment at all stations except tidally scoured channel bottoms and near dredged regions where sand and gravel occurred. Folger and others (1975) also collected several bottom samples from Casco Bay in conjunction with a seismic reflection survey and mapped the inner bay bottom as muddy, and the outer bay as rocky. Although Folger and others (1975) gathered seismic data from the area, Ostericher (1965) was the first to employ coring and seismic reflection techniques to examine submarine stratigraphy in coastal Maine. He described reflectors that correlated with bedrock, till, 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) used seismic reflection methods to examine the inner shelf off the Kennebec River and Sheepscot Bay 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) have 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). Belknap and others (in press, b) have also described a paleodelta at the mouth of the Kennebec River.

On the northern border of Maine, Piper and others (1983) have described the evolution of parts of the Nova Scotian coast on the basis of seismic profiling. Fader and others (1977) have 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) have extended that work along the Scotian shelf. To the south, Birch (1984a, b) has 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).

Several projects are on-going in the Casco Bay area at the present time. Kelley and Hay (1986) have summarized the stratigraphy of the bay and focused on the importance of mass movements as a source of sediment to the marine environment. Kelley and Hay (1986) report on slumping in the

Table 1

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

Study	Location	Data
Bradley, 1957	Sagadahoc-Sheepscot Bay	Bottom samples, crude seismic profiles
Bloom, 1960	Southern Maine	Regional terrestrial mapping
Bloom, 1963	Southern Maine	Study of sea level changes
Folger and others, 1975	Southern Maine shelf	Bottom sampling, seismic profiling
Schnitker, 1974	Sheepscot Bay	Seismic profiling
Stuiver and Borns, 1975	Coastal Maine	Study of sea level changes
Smith, 1982	Coastal Maine	Terrestrial mapping of moraines
Larson and others, 1983	Casco Bay	Bottom sampling
Thompson and Borns, 1985	Maine	State surficial map
Kelley and others, 1986	Casco Bay	Seismic profiling
Belknap and others, 1986	Sheepscot River, Bay	Seismic profiling, cores
Kelley and Hay, 1986	Casco Bay	Field guide to Quaternary geology

Casco Bay-Sheepscot Bay area and relate it to gas deposits and seismicity, and Belknap and others (1986a) similarly describe a major submarine slump from the Sheepscot River.

METHODS

Bottom Samples

During the summer of 1985 and 1986, 413 bottom samples were collected from the south central Maine inner shelf by means of a Smith-MacIntyre grab sampler (Figure 2). The device reliably collects a $.25m^3$ sample of gravel, sand, or mud with minimal loss of material. Sample stations were selected on the basis of extensive side-scan sonar coverage. 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 selected 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 the splits for carbonate analysis, the weight of gravel was noted and carbonate is reported for the total sample. For many of the samples which side-scan sonar observations indicated uniform bottom sediment conditions, a field description of the sediment texture was used.

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 ($\rho<2.8$) in tetrabromoethane.

Seismic Reflection Profiles

Approximately 800 km of seismic reflection profiles have been collected from the study area (Figures 3, 4). 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. 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 sub-bottom

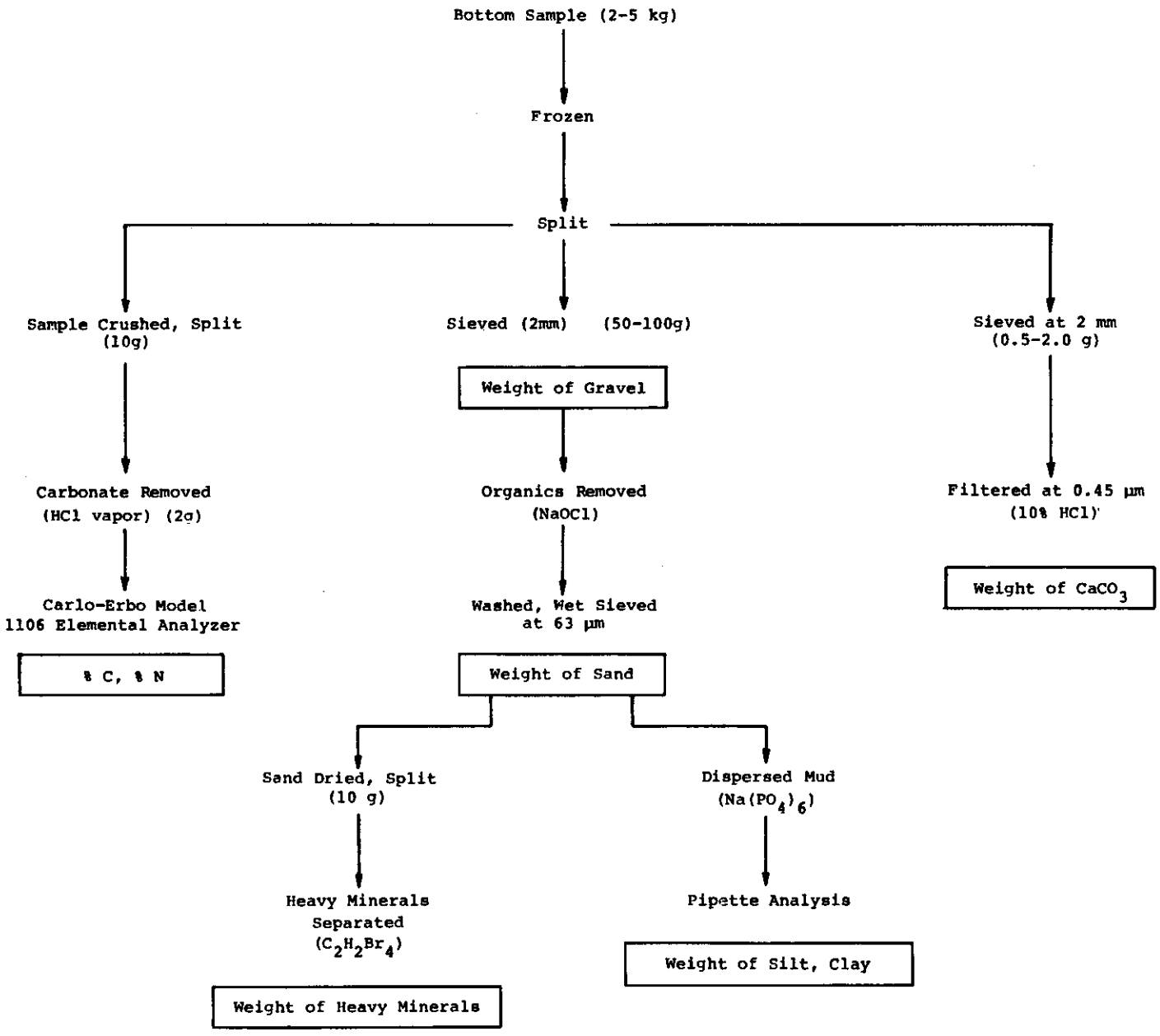


Table 2. Flow diagram for laboratory analyses of selected samples.

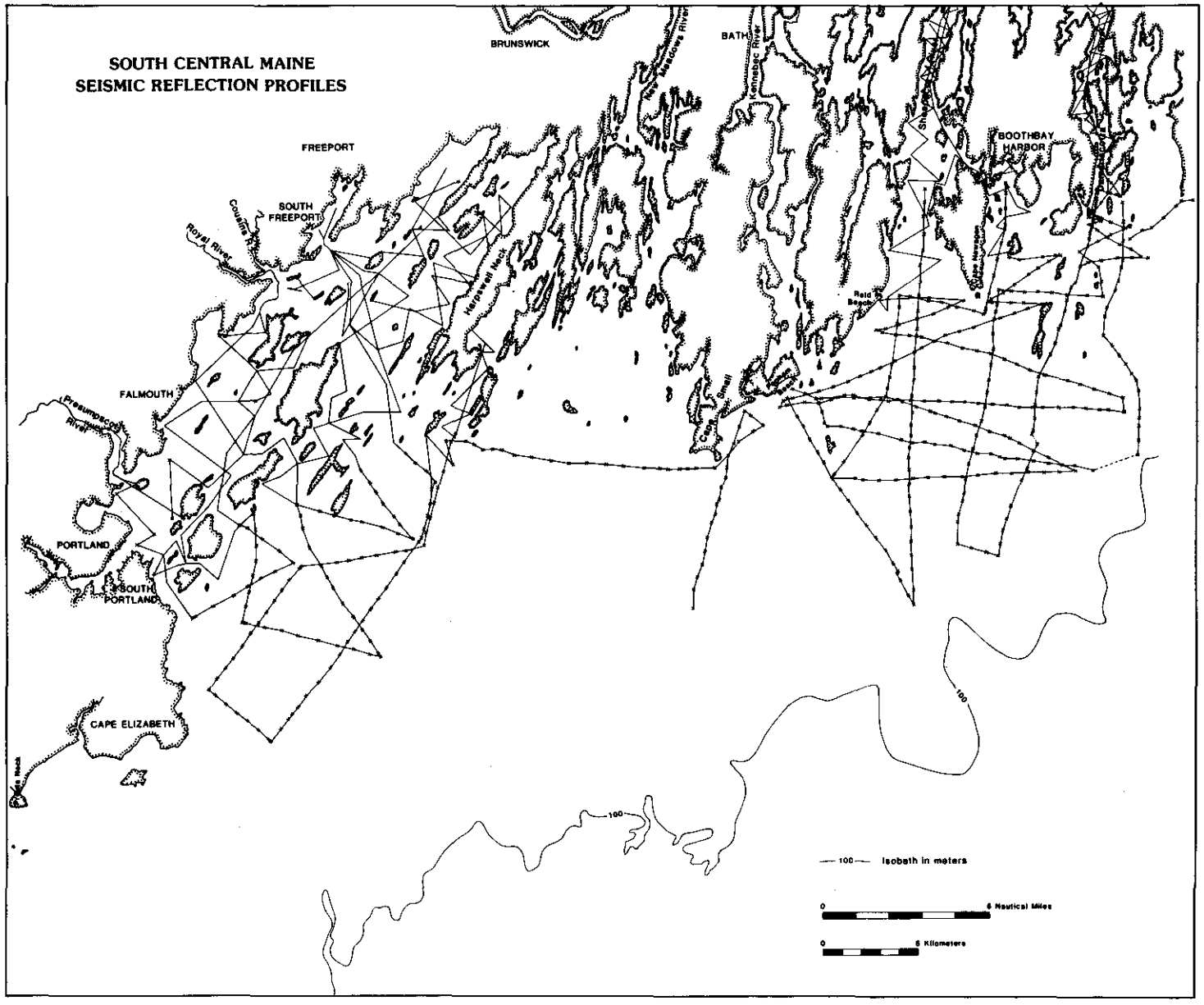
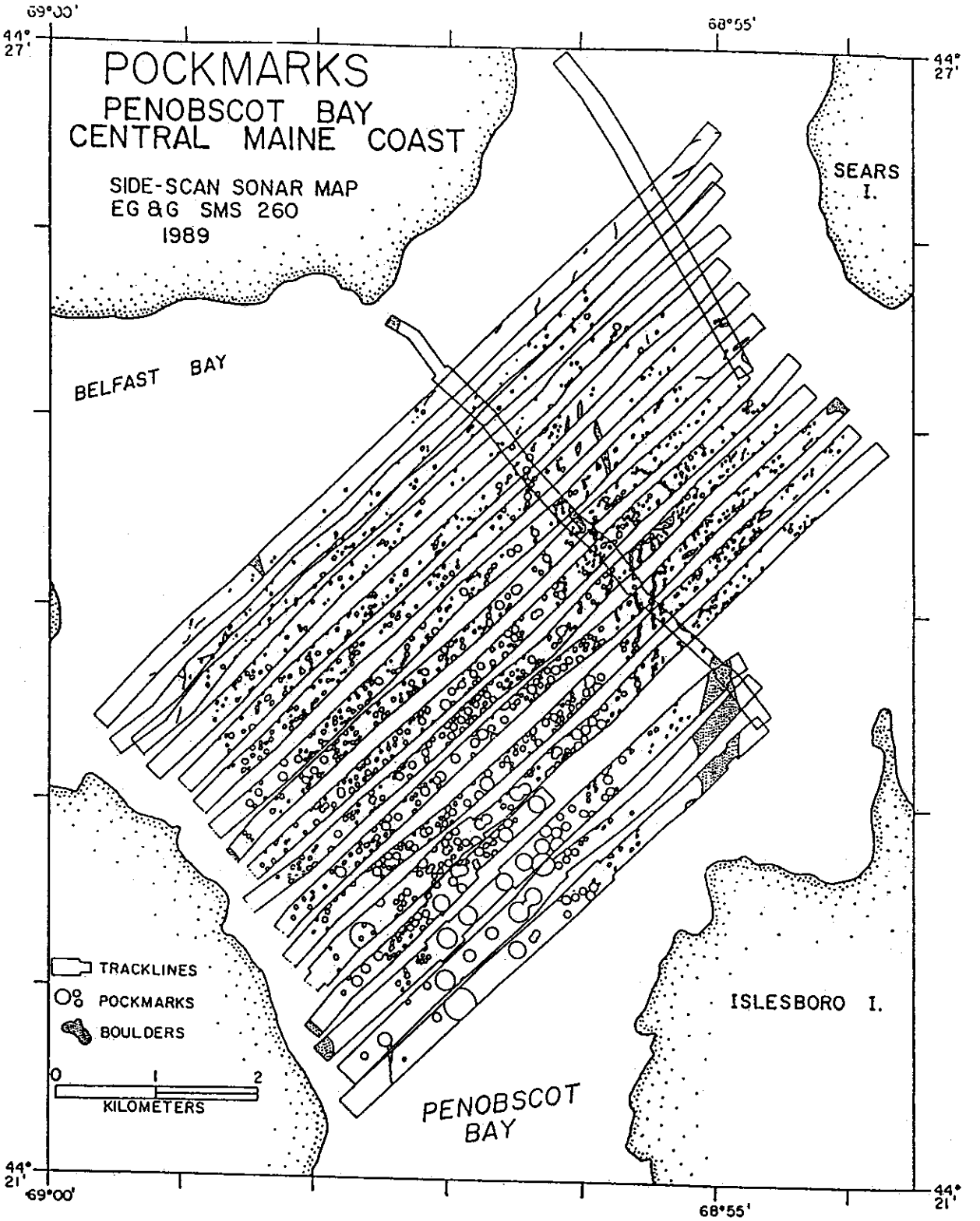


Figure 3. Location of seismic reflection profiles from the study area. Location was by LORAN-C, and the dots represent some of the navigation fixes taken for plotting purposes. LORAN-C does not provide coverage near land, so no position fixes are indicated in estuaries.


POCKMARKS
PENOBSCOT BAY
CENTRAL MAINE COAST
SIDE-SCAN SONAR MAP
EG&G SMS 260
1989
69°00'
68°55'
44° 27'
44° 21'
SEARS I.
BELFAST BAY
ISLESBORO I.
PENOBSCOT BAY
TRACKLINES
POCKMARKS
BOULDERS
0
1
2
KILOMETERS

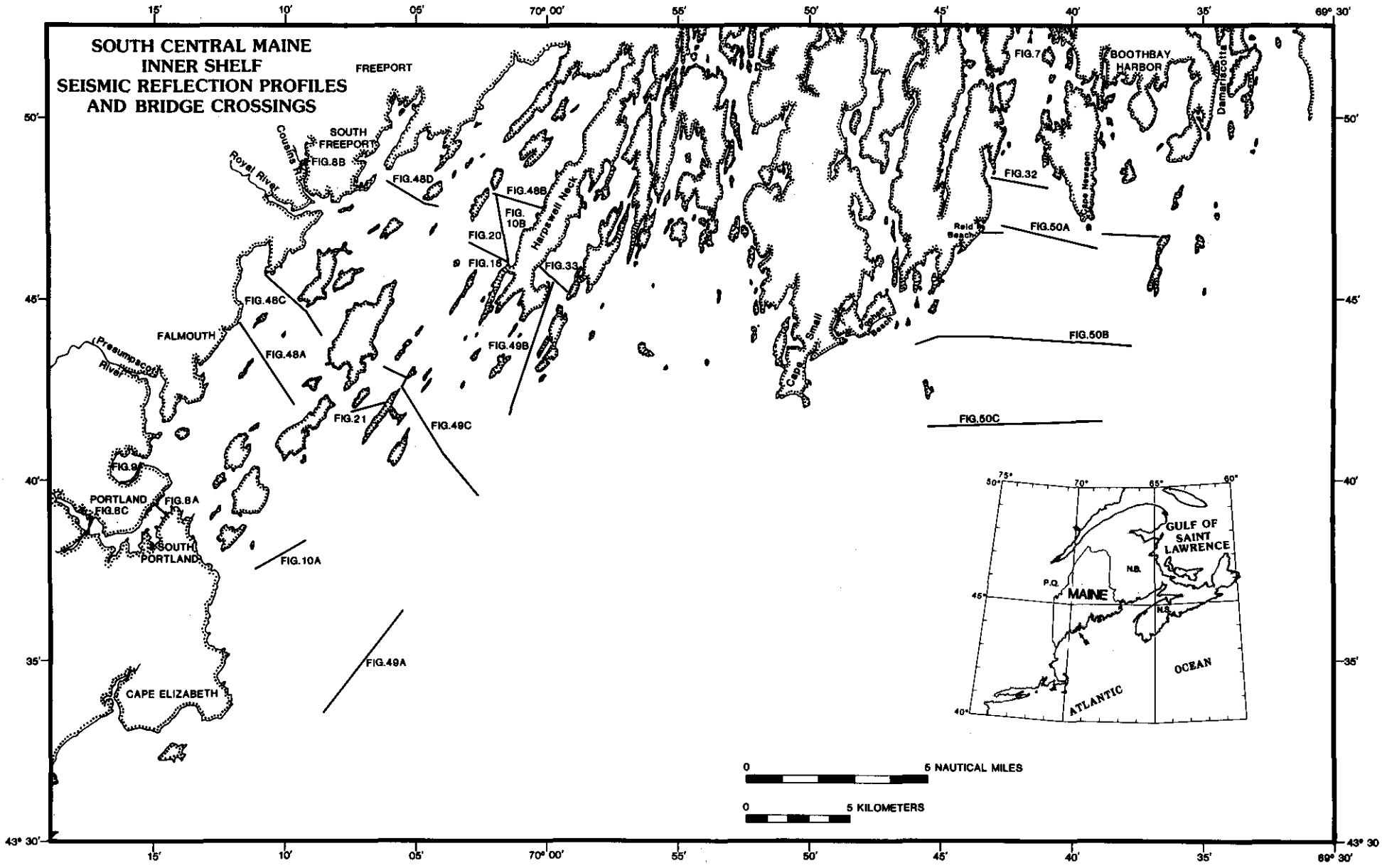


Figure 4. Location of seismic reflection profiles used as figures in text.

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 "hardness" 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 sub-bottom geology was less direct, and inferences drawn from observations on land, in borings and core holes, and from nearby studies were employed to identify anticipated acoustic reflectors (Figures 7-10). In the upper Sheepscot River, Belknap and others (1986) found good correlation between a seismic profile beneath the Wiscasset Bridge and an interpretation of the sub-bottom geology based on borings by Miller and Baker (1982). One difference noted was the presence of natural gas which wiped out portions of the seismic record, but were not recorded from the borings. From within Casco Bay numerous bridge borings and cores associated with Interstate-295 provide detailed information on the bay's sub-bottom geology (Figures 8, 9) (Maine Department of Transportation, 1948, 1967, 1969, 1983). Generally, more than 30 meters of late Quaternary sediment fill the Fore River and Back Cove areas, and refusal in the borings was usually not in bedrock. What is interpreted as till from the engineer's log formed the lowermost unit and was covered by up to 30 meters of glaciomarine sediment (Presumpscot Formation). The upper portion of the Presumpscot Formation was usually channeled and occasionally dessicated and yellowed. This upper material was probably altered during the emergence which accompanied the post-Presumpscot sea-level regression, and locally was replaced by a sandy (fluvial?) unit. Holocene mud unconformably overlies the Presumpscot Formation in the estuaries, although sand and gravel of inferred Holocene age form the uppermost material offshore of the Kennebec River (Belknap and others, in press, b).

On the basis of this detailed understanding of the estuarine sub-bottom geology, interpretation of most of the single-channel seismic records was straightforward (Figure 10). Bedrock was never penetrated by the seismic systems and its surface usually 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 (Figure 10). 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 and prominent moraines were recognized as in nearby locales (Oldale, 1985; Knebel and Scanlon, 1985; Figure 10). 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 or obscured by gas. Where it outcropped near the surface and has been cored (Kelley and Hay, 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

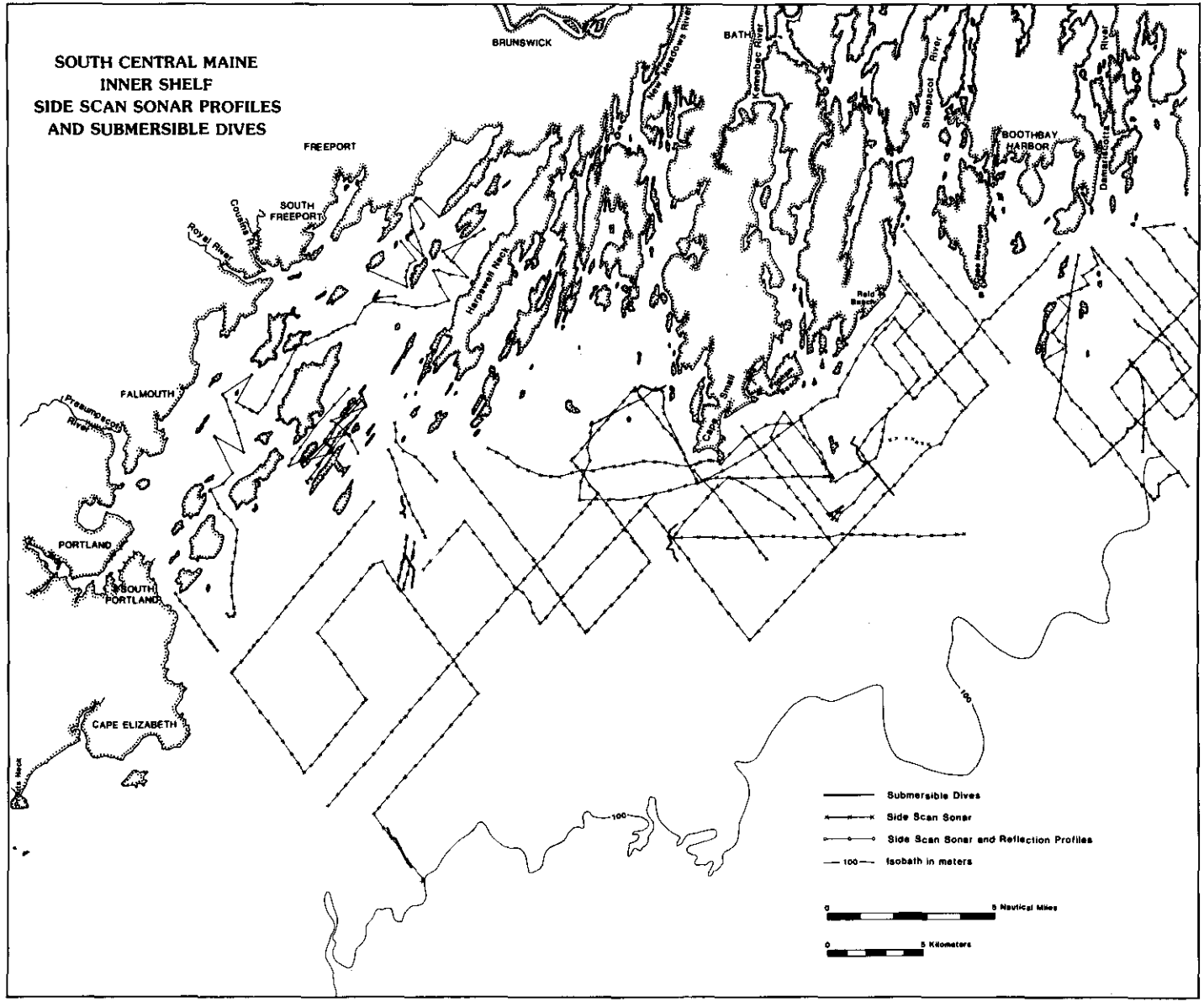


Figure 5. Location of the side-scan sonar tracks and submersible dive sites. Seismic reflection data was also collected in conjunction with the side-scan sonar (indicated by circles).

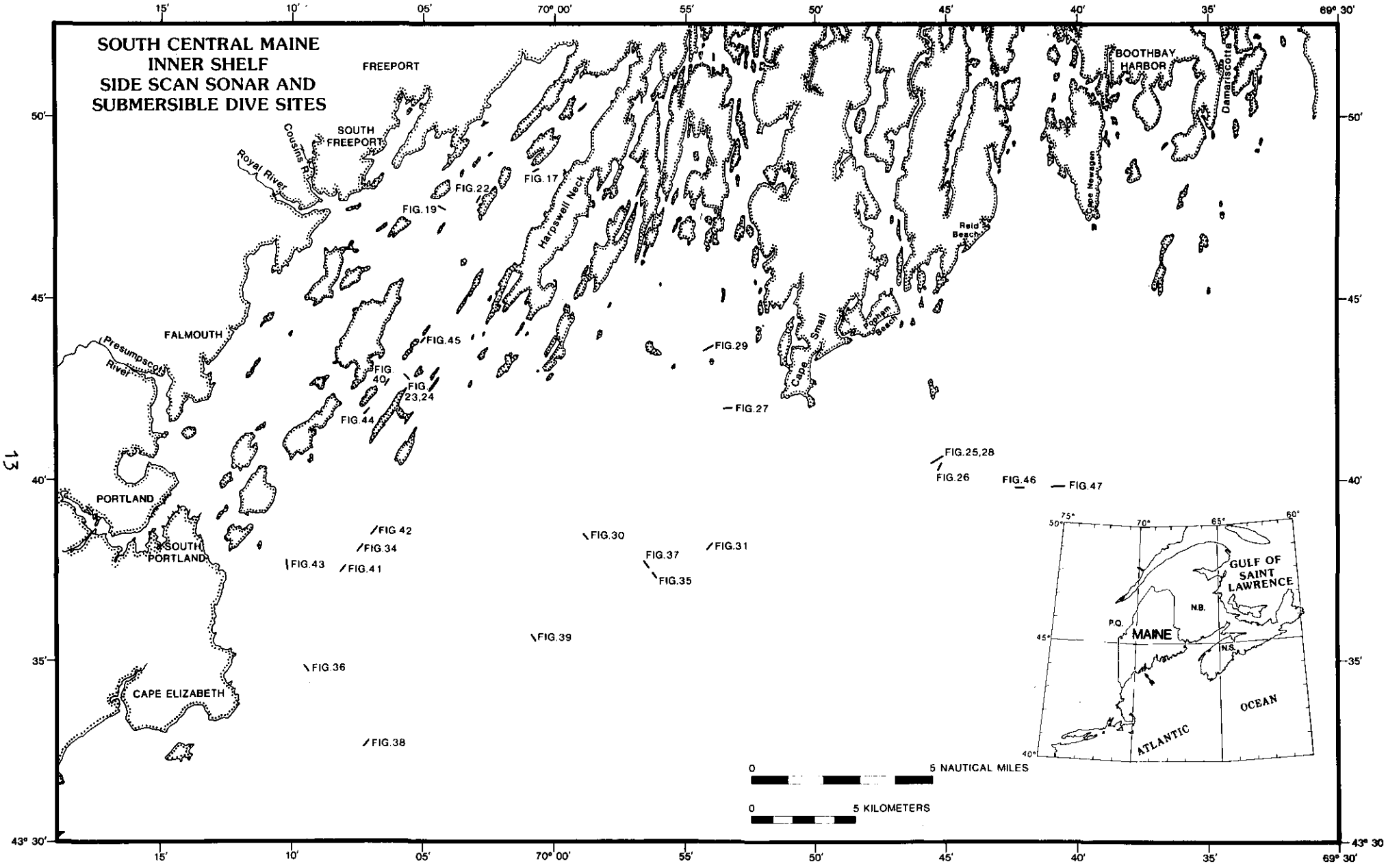


Figure 6. Location of side-scan sonar tracks used as figures in text.

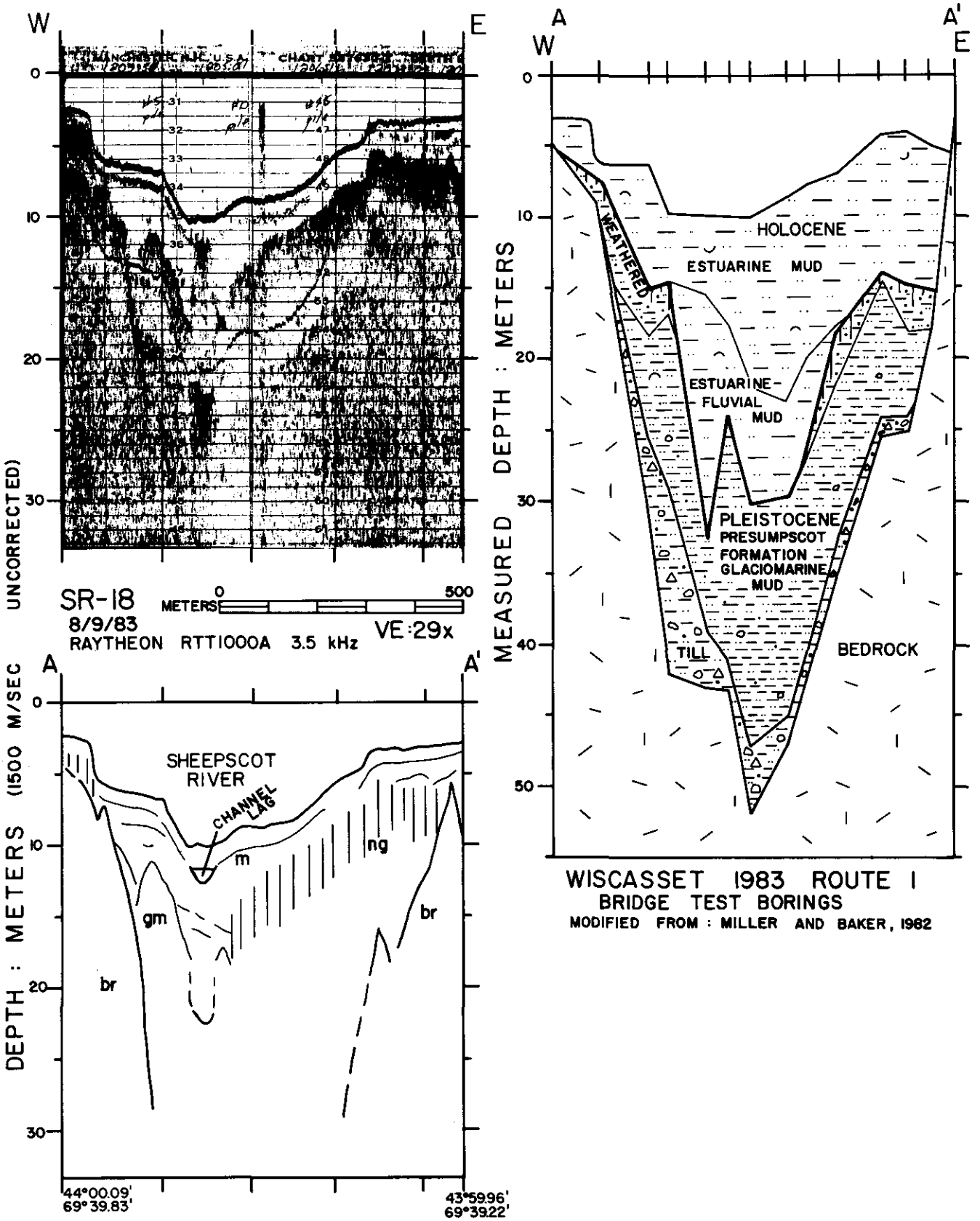


Figure 7. Cross sections of the Sheepscot River in Wiscasset (see Figure 4 for location). This figure is from Belknap et al. (1986).

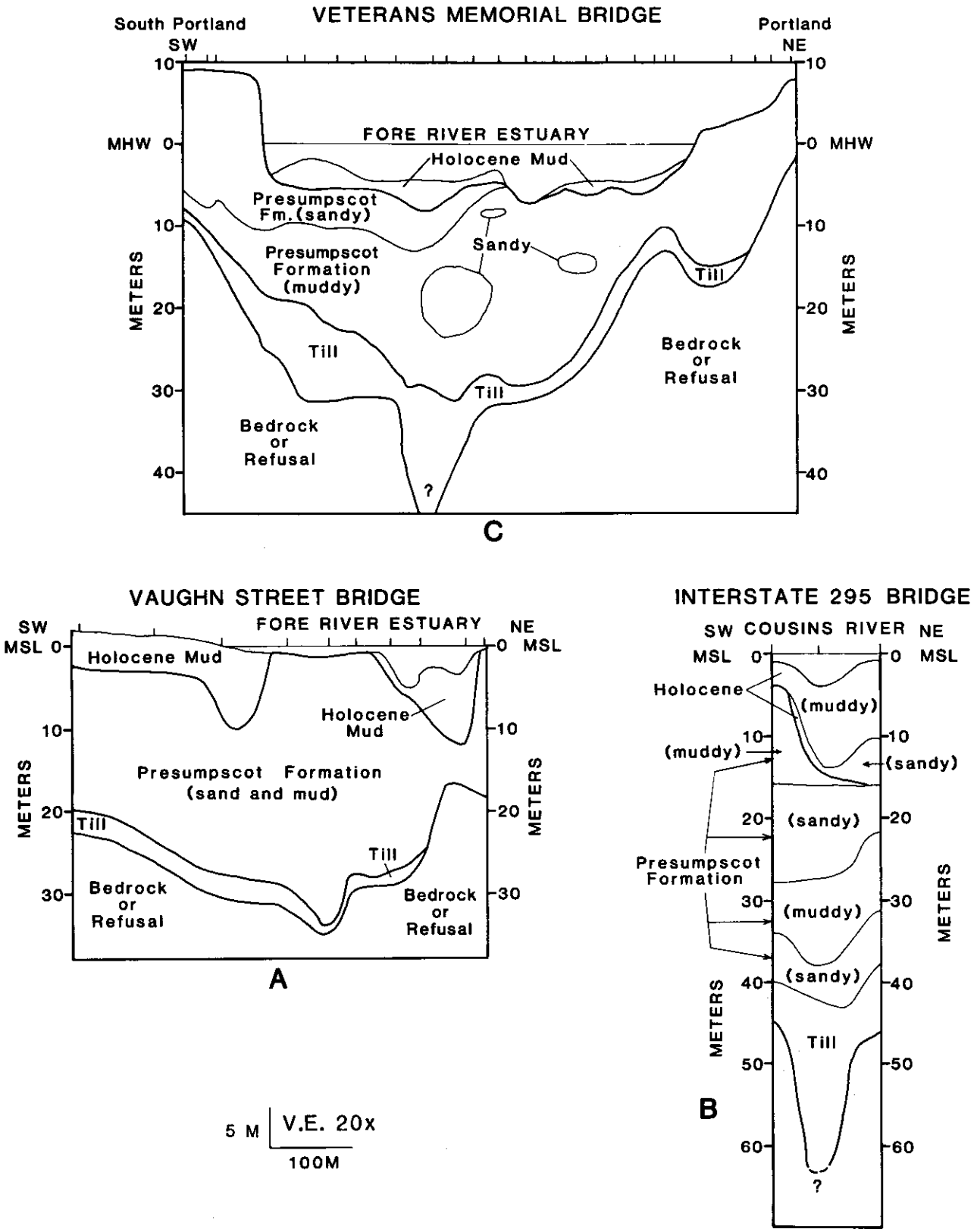


Figure 8. Cross sections of the Fore and Cousins Rivers in Casco Bay. This figure is modified from Kelley et al. (1986).

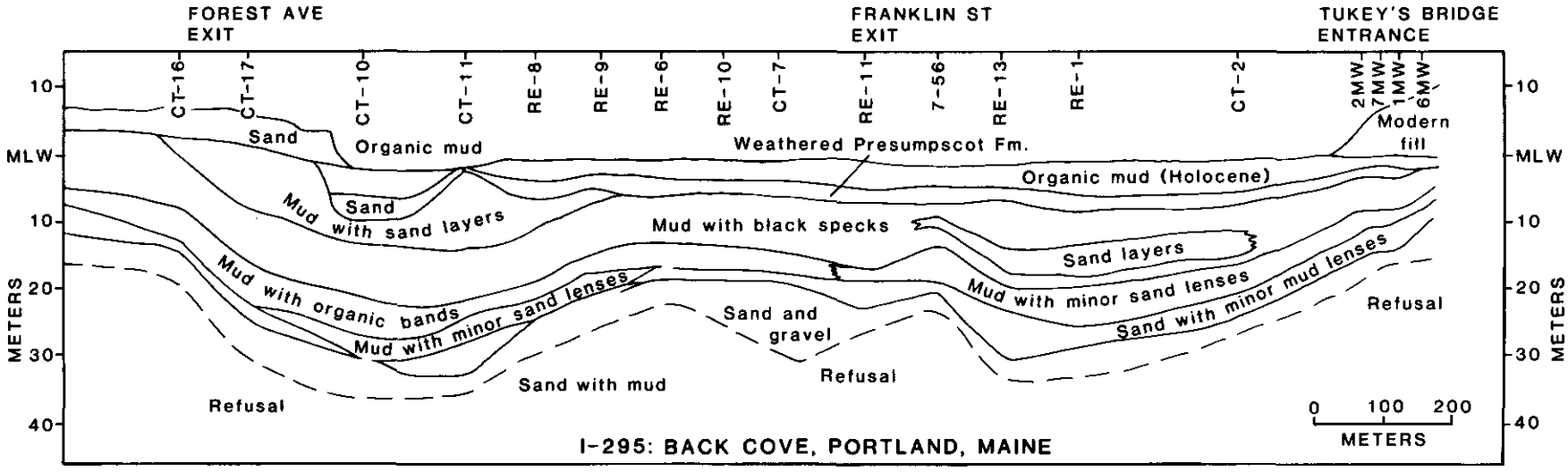


Figure 9. Cross section of the northeastern portion of Back Cove, Portland. The upper sand near Forest Avenue may be 19th century fill.

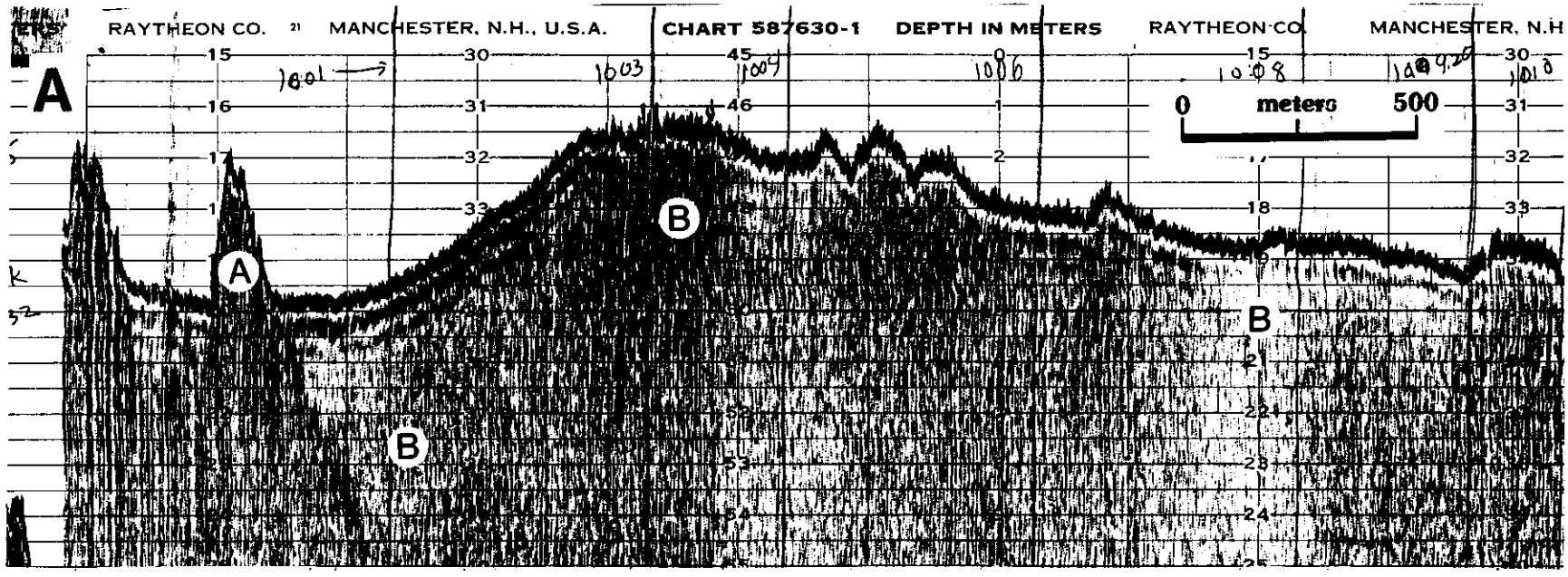


Figure 10a. Seismic profile from Casco Bay showing typical acoustic signatures for the Quaternary deposits of the bay. A feature interpreted as bedrock (A) is overlain by an acoustically chaotic and relatively opaque seismic unit (B) interpreted as till. Side-scan sonar profiles over this area show the surface littered with boulders.

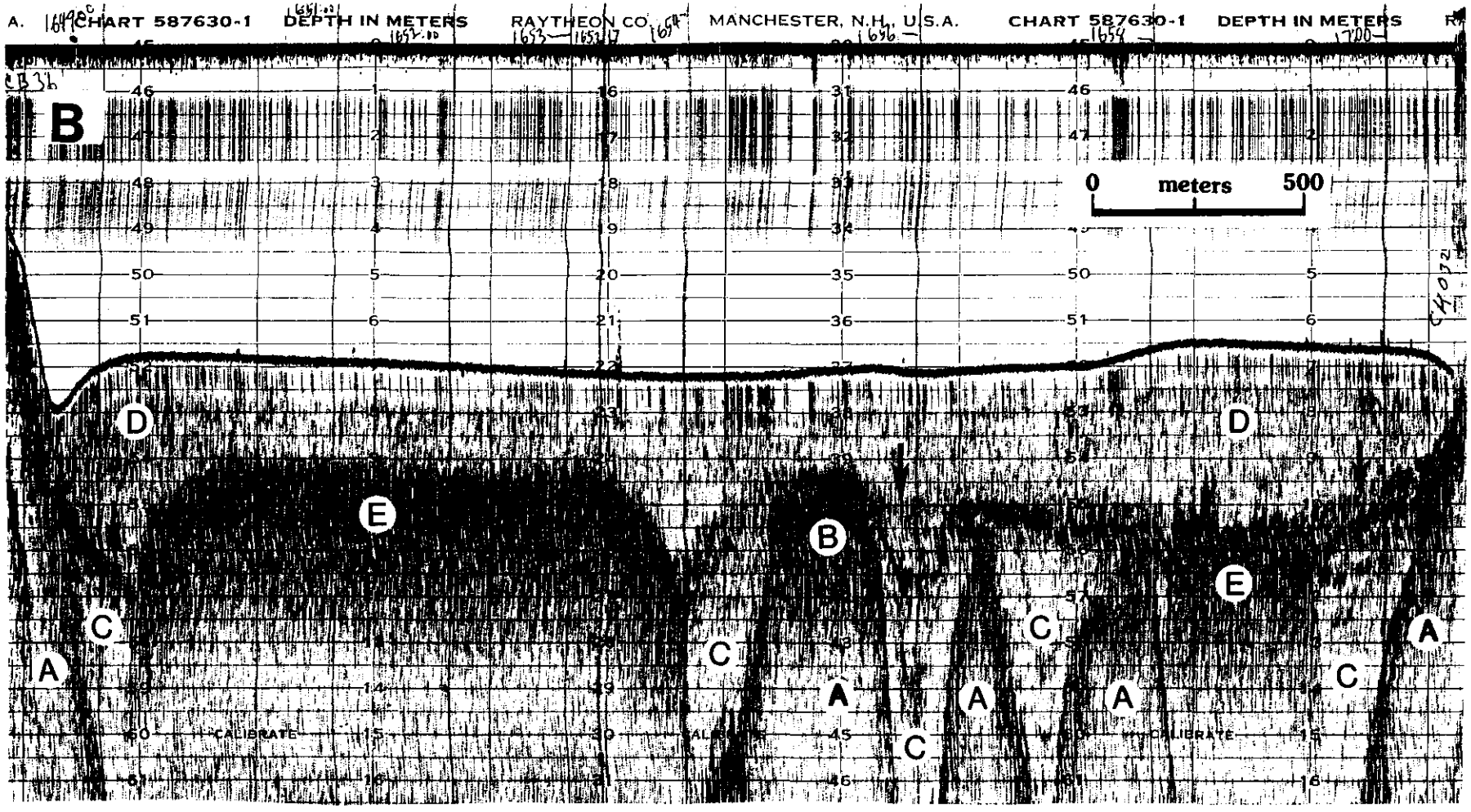


Figure 10b. Seismic profile from Casco Bay showing typical acoustic signatures for the Quaternary deposits of the bay. Bedrock (A) and glaciomarine sediment (C) were observed along the shoreline at the beginning and end of the track and are easily traced offshore. A seismic reflector interpreted as till (B) is poorly observed over a bedrock pedestal. The surface of the glaciomarine Presumpscot Formation (C) has been cored in this area and is more dried out and coarser grained than the underlying mud. Thus it forms a strong reflector (arrows) which is occasionally channelled. Where deep channels have been cut into the Presumpscot Formation, a thick accumulation of Holocene mud (D) fills the gullys and is itself charged with natural gas (E).

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 many locations. Nearshore, a more acoustically opaque unit of sand forms the uppermost deposit off the Kennebec River. Each of these deposits is relatively smooth on its surface and generally lacking internal reflections. Unlike nearby areas to the south (Kelley and others, 1986a, b) gas occurrences were recognized in the study area in virtually all locations.

Seafloor Observations

Observations on the seafloor itself were made by side-scan sonar profiling as well as by submersible visits (Figures 5, 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 in Casco Bay with the Johnson Sea Link in the summer of 1985 and five dives were made in Casco and Sheepscot Bays 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 submersible notes".

BATHYMETRY AND SURFICIAL SEDIMENT

Physiographic Zones

Unlike most areas of the United States, there are no adequate bathymetric charts yet available for the study area. For this reason bathymetric contours were traced from navigation chart NOS 13288 and transformed from English to metric units (Figure 11). In addition, a 10 meter contour interval bathymetric chart from part of Casco Bay (National Ocean Survey, 1970; Figure 12) and details from National Ocean Survey Provisional Chart #71 (Bath, Maine) were used to provide detailed physiographic observations (Figure 13). Although the provisional chart possesses a two meter contour interval, much of the region is inadequately surveyed or too complex for reproduction at that scale.

On the basis of the limited bathymetry, five physiographic zones are defined on the south central Maine inner continental shelf (Figure 14; Table 3). The Nearshore Basins are shallow (<30 m), generally low relief regions adjacent to the mainland. These basins are separated from other areas by extensive shoals or chains of islands, as in inner Casco Bay (Figure 14). The contact between the basins and the intertidal upland is

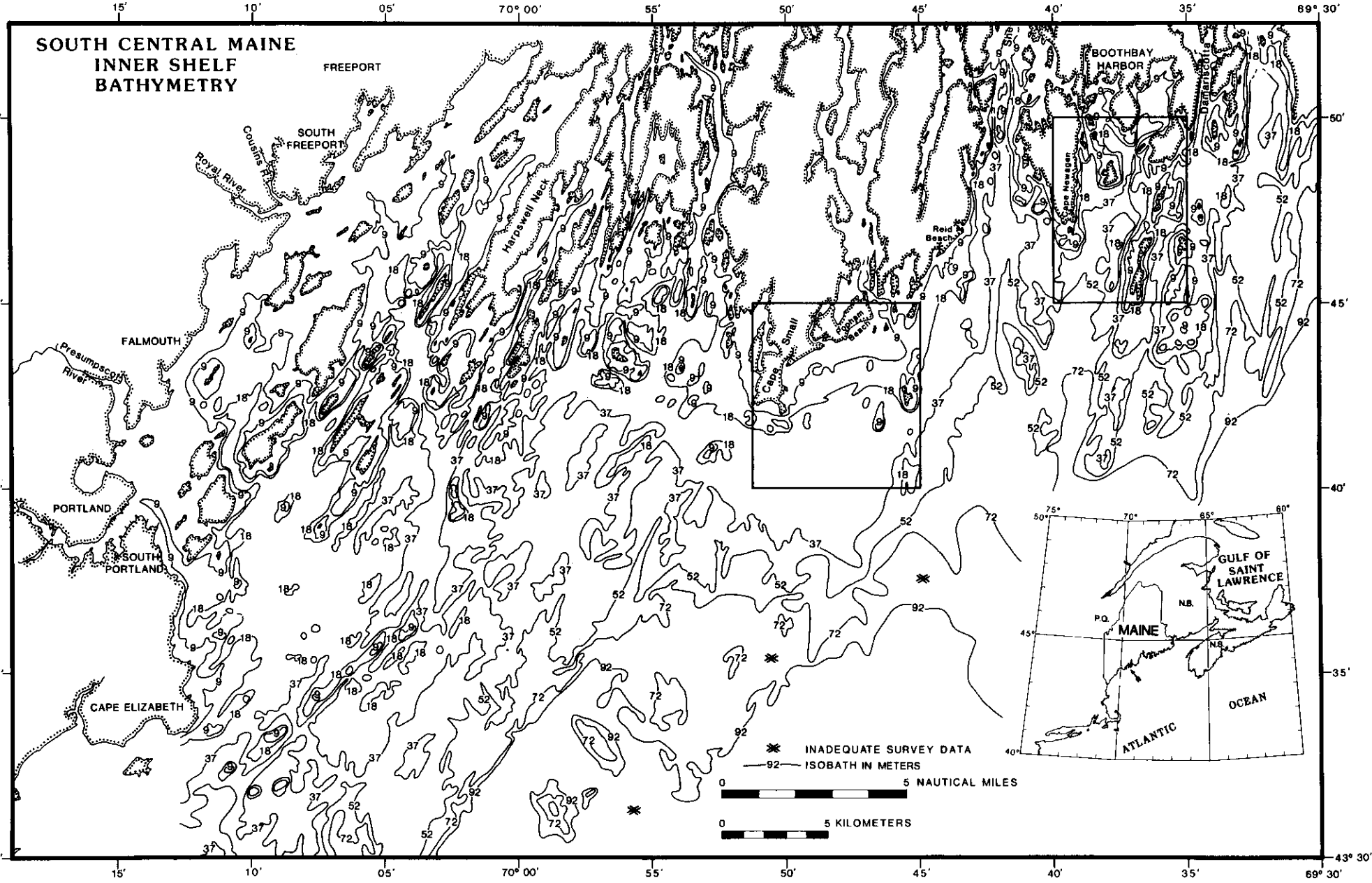


Figure 11. Bathymetry of the study area. Bathymetric contours traced and transformed from English units on navigation chart NOS 13288. Boxed areas shown in detail in Figure 13.

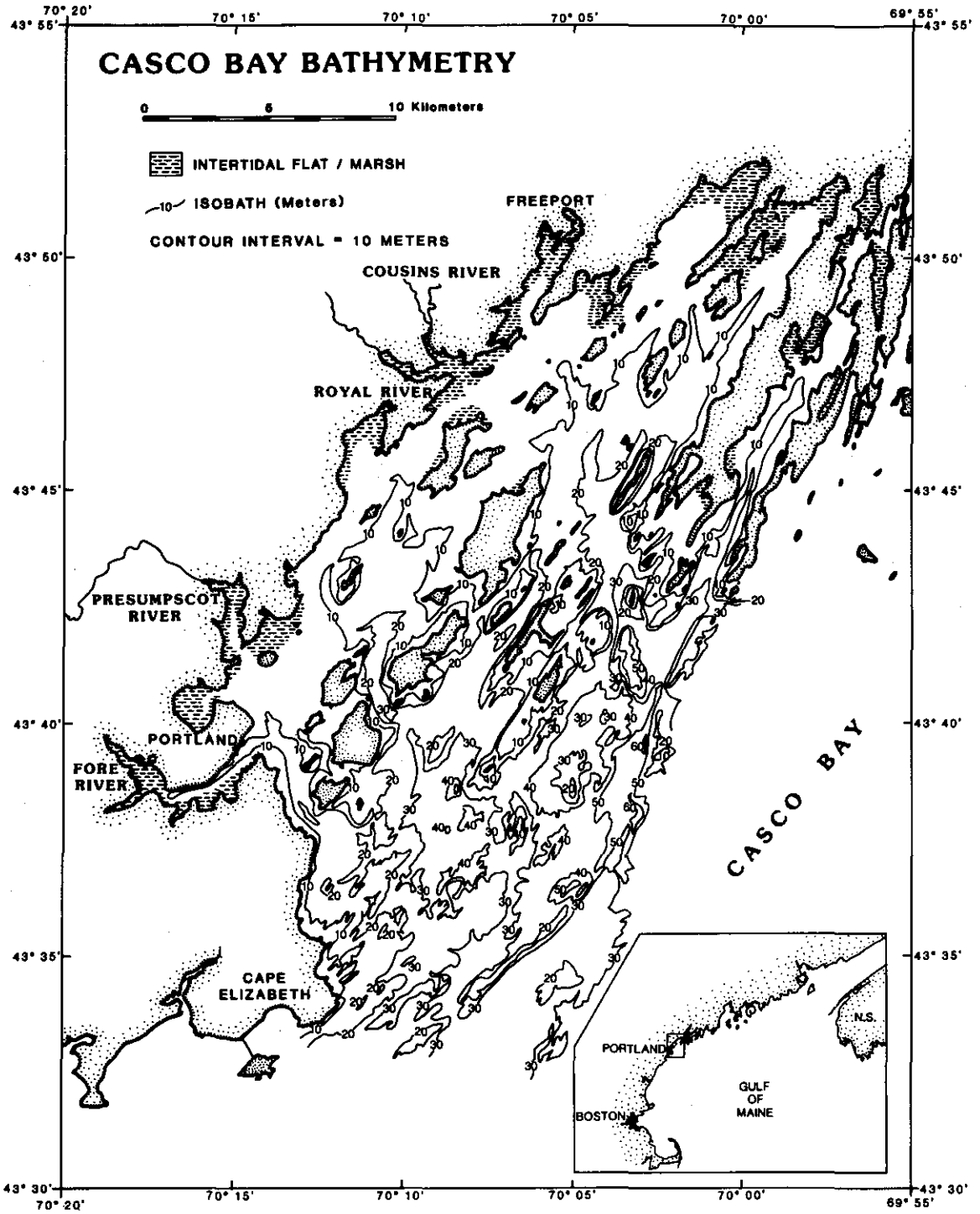


Figure 12a. Bathymetry of Casco Bay modified from NOAA chart NOS-0808N-69. Many small ledges and islands were deleted for simplicity. Intertidal regions transferred from NOAA chart 13290.

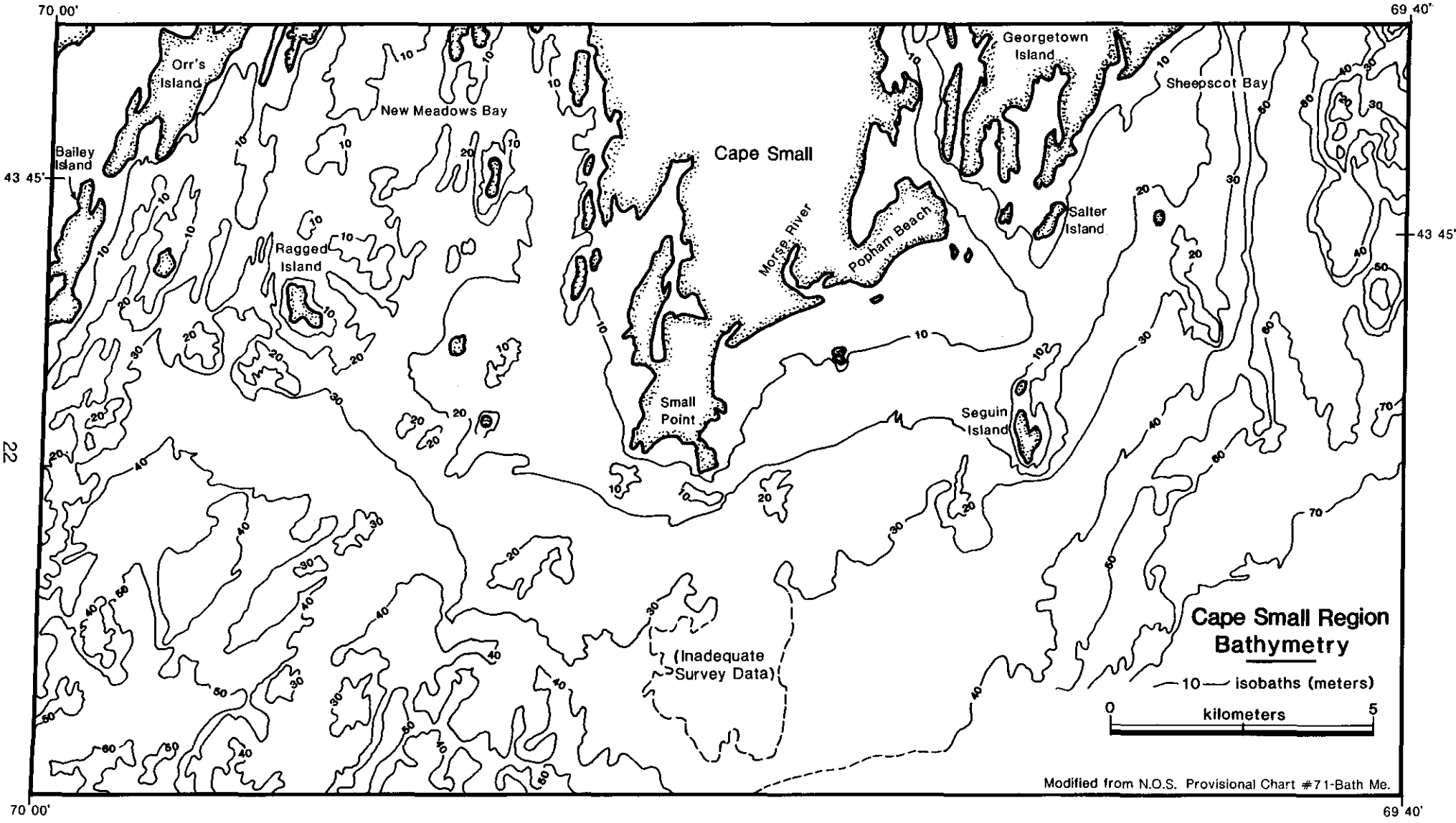
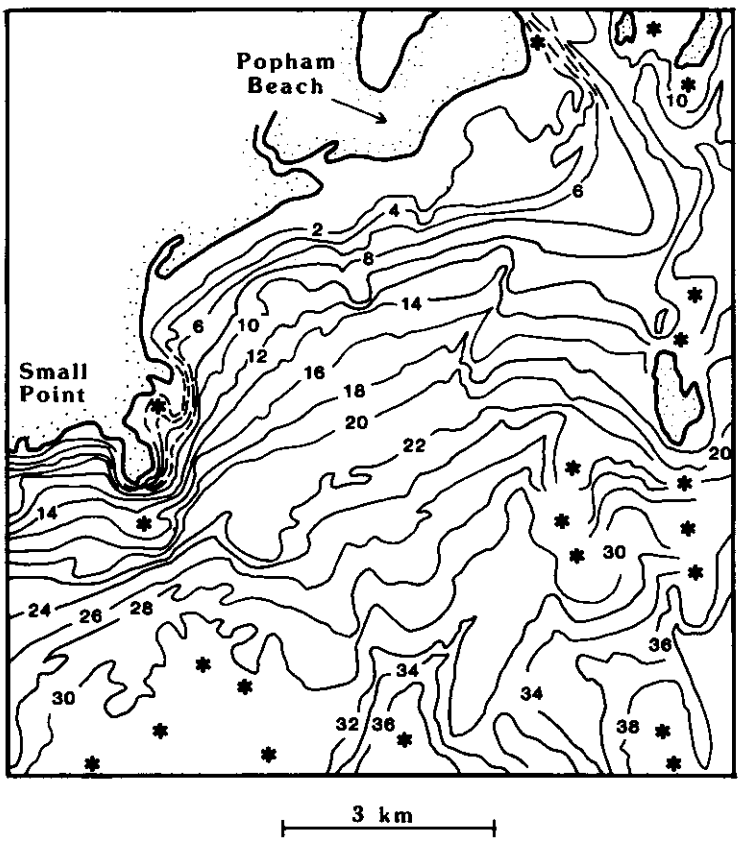


Figure 12b. Bathymetry of the Cape Small area modified from National Ocean Survey Provisional Chart #71, Bath, Maine.



CAPE SMALL BATHYMETRY

—— isobath (meters)

* complex bottom

Figure 13a. Detailed bathymetric map made from National Ocean Survey Provisional Chart #71, Bath, Maine. Location of detailed bathymetry boxed in Figure 11. A region offshore of Popham Beach possesses sub-parallel bathymetric contours similar to that seen off most of the region's beaches.

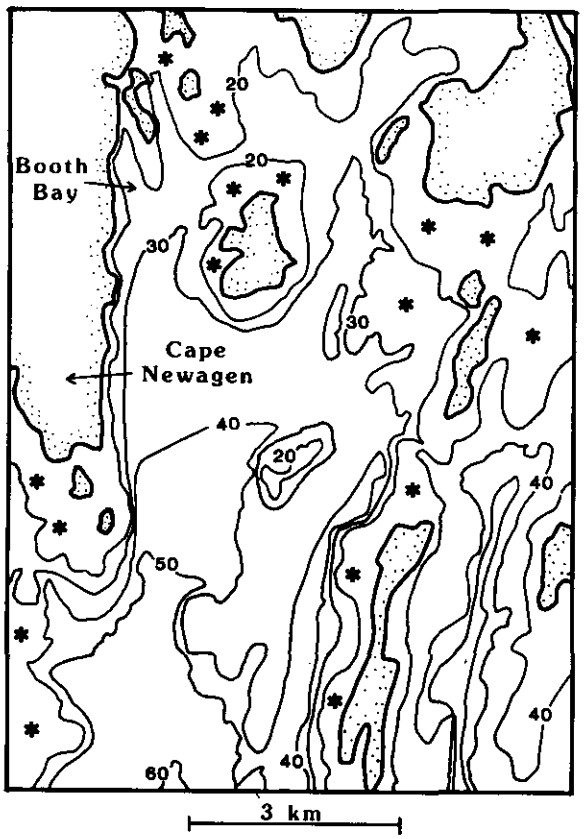


Figure 13b. Detailed bathymetric map made from National Ocean Survey Provisional Chart #71, Bath, Maine. Location of detailed bathymetry boxed in Figure 11. A Shelf Valley extends seaward of Boothbay Harbor as well as from many of the other embayments of the region. Location of these maps is found in Figure 2.

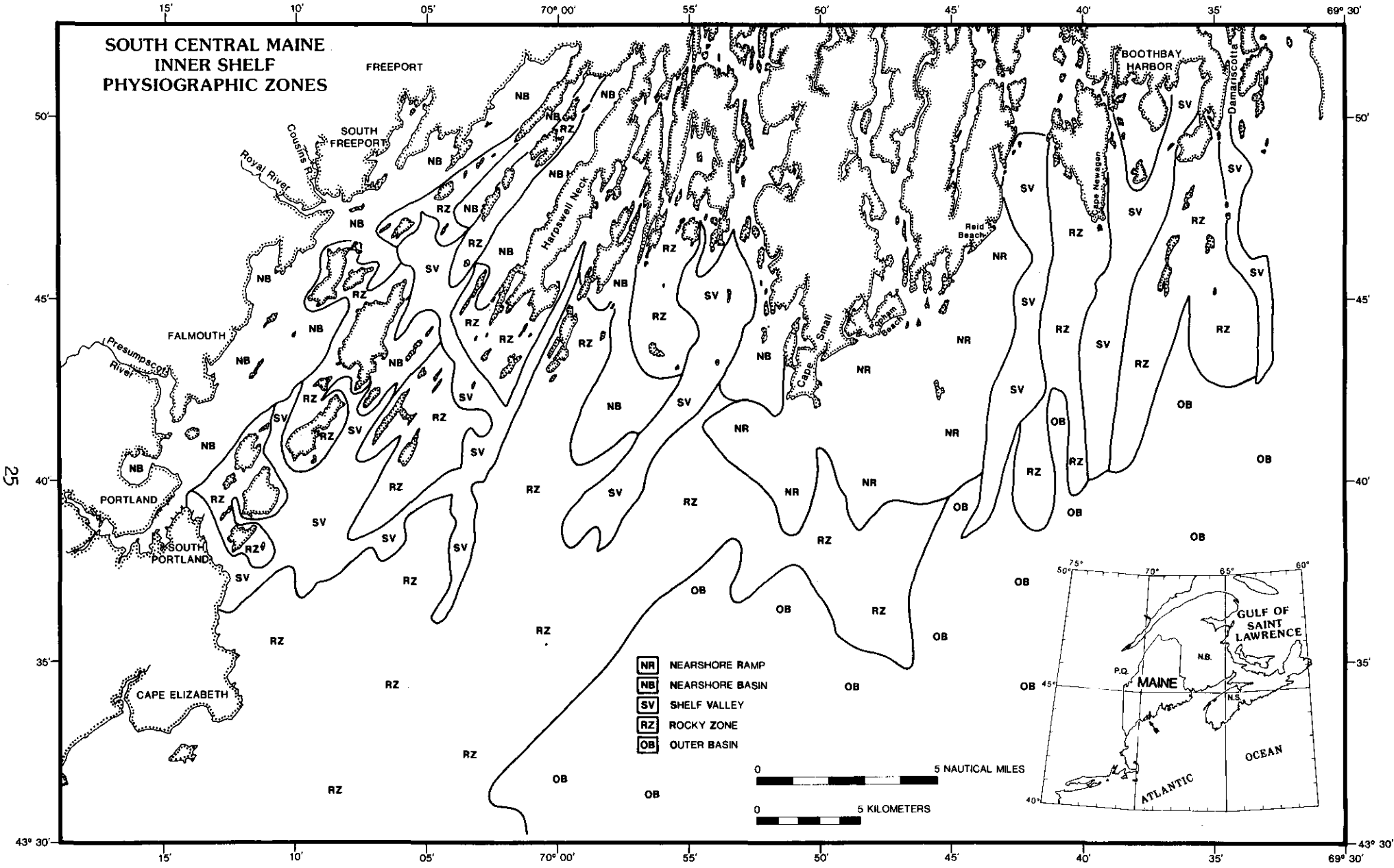


Figure 14. Map depicting the physiographic provinces of the south central Maine inner shelf.

gradational along mudflats in very protected areas, but may be abrupt with greater than 5 meters of nearly vertical relief in more exposed locations near islands. While the seafloor of the basins is generally smooth, it is often cut by channels in narrow constrictions between islands and is irregularly punctuated by bedrock exposures.

The Nearshore Ramp is an area of coast-parallel contours seaward of the sandy beaches at the mouth of the Kennebec River (Figures 13, 14). The entire area offshore of Cape Small (Figure 13a) forms a broad swell which has been previously described as a paleodelta (Belknap and others, in press, b). On its east and west margins this feature drops rapidly into the New Meadows and Sheepscot River Shelf Valleys. Bedrock outcrops sporadically in the Nearshore Ramp, often as linear ridges paralleling the regional north-northeast bedrock strike. The Nearshore Ramp abruptly abuts bedrock on part of its seaward margin, but otherwise is bordered by the Outer Basin.

Shelf Valleys are long, narrow depressions which extend from Nearshore Basins to uncertain terminations in deep water (Figures 13, 14). Part of the uncertainty is based on a lack of adequate bathymetry off Sheepscot Bay, while in Casco Bay the Shelf Valleys terminate in an apparent cul-de-sac (Figure 14). The valleys are very steep-walled along their margins and frequently encounter irregular areas along their otherwise smooth seaward slopes.

Rocky Zones are regions of extreme local relief ranging from 5 meter vertical bedrock cliffs, to extensive areas of boulders (Figure 14). The highly foliated nature of bedrock in south central Maine, in contrast to the inner shelf of the southwestern part of the State (Kelley and others, 1986b) is especially characterized by long narrow bedrock ridges and troughs. Although sediment is often found in the troughs, it is of minor abundance compared to the extensive ledges.

The final physiographic zone is the Outer Basin which generally forms the seaward border of the study area (Figure 14). This is the least known portion of the study area, largely due to a lack of good bathymetric control. On the basis of small scale charts (1:1,000,000) it appears to extend to Platts Basin in the deeper Gulf of Maine.

Bottom Sediment

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 south central Maine (Figure 15). Although fewer than 10 samples were true gravels, greater than 100 grabs contained some material coarser than 2 mm in diameter. 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. Because of these limitations, only small patches of gravel bottom are mapped (Figure 16). These are located in outer Casco Bay, within the Rocky Zone, and in the inner bay adjacent to rock outcrops of the Nearshore Basin. Numerous outcrops of gravel certainly exist in the study area,

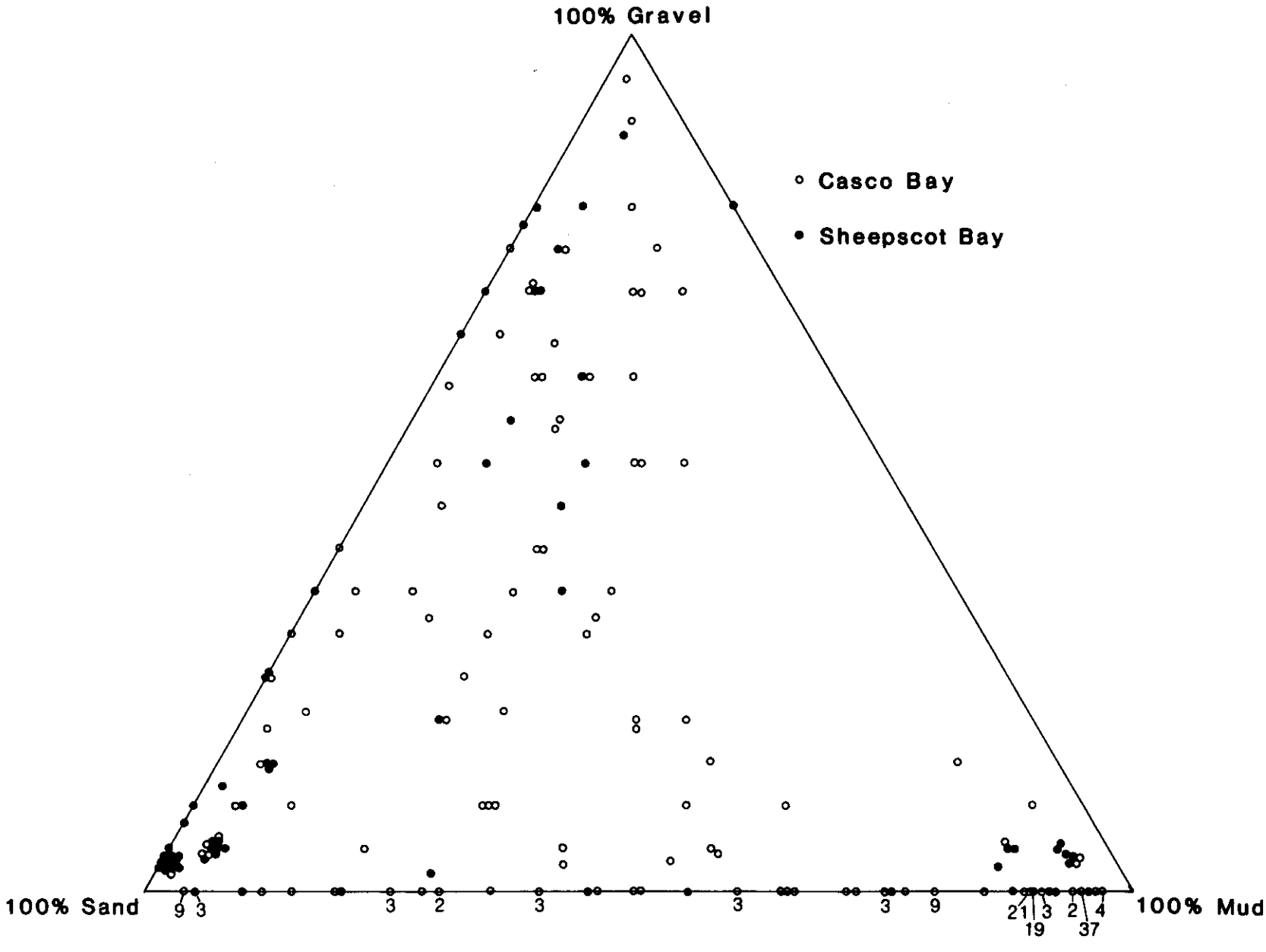


Figure 15. Ternary diagram depicting the texture of sediment samples from the south central Maine inner shelf.

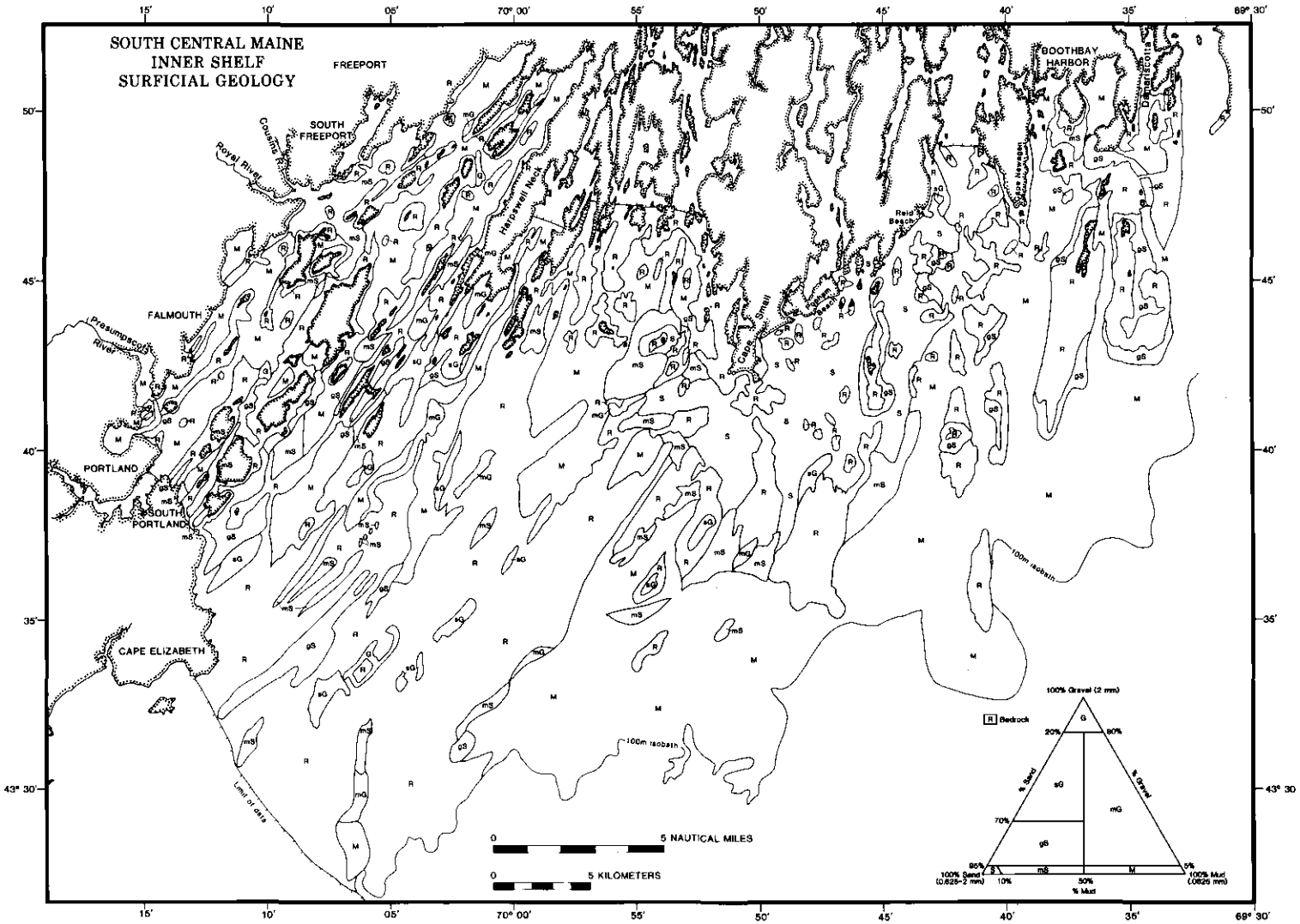


Figure 16. Map of sediment texture on the south central Maine inner continental shelf. Hatched lines indicate the extent of data up river valleys.

especially within the Rocky Zone, but cannot be presented at the scale of existing maps. These gravel deposits usually form a narrow band along bedrock ridges or exist as an apron surrounding rock outcrops (Kelley, unpublished submersible notes).

Sandy gravels, gravelly sands, and muddy gravels are much more common surficial materials along the south central Maine inner shelf than "clean" gravels. Gravelly sands are especially abundant surrounding rock outcrops in the Sheepscot Bay area, and in long narrow bedrock depressions in outer Casco Bay. Sandy and muddy gravels are much less common and occur only in bedrock depressions and channels in the Rocky Zone of Casco Bay (Figure 16).

A single extensive deposit of sand is mapped offshore of the Kennebec River mouth (Figure 16). This is the Nearshore Ramp physiographic zone and the offshore sand extends without discontinuity onto the extensive sand beaches and bays of the area (Bradley, 1957). As discussed below, this sand is actively being worked by waves and currents, and is very well sorted. Along most borders, the extensive sand in the Nearshore Ramp grades into muddy sands. These areas of muddy sand are extensive, and themselves grade into mud deposits in the Outer Basins. Muddy sands also cover a large section of Casco Bay's Nearshore Basin directly offshore of the combined mouth of the Royal and Cousins Rivers and in the axes of Shelf Valleys (Figure 16).

Mud comprises the most extensive sort of surficial sediment cover in the study area (Figure 16). Most of the region shown as mud is in the Outer Basins where side-scan data presented below suggests it is a thin cap over bedrock or other sediment. Along the Shelf Valleys and in the Nearshore Basins, however, mud blankets most traces of bedrock and the resulting physiography is of very low relief.

GEOPHYSICAL AND SUBMERSIBLE OBSERVATIONS

Bottom sediment properties correlate well with environmental settings defined by bathymetry. 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 3).

Nearshore Basins

The Nearshore Basins are bedrock depressions partly filled with Quaternary sediment and relatively well protected from waves by peninsulas, chains of islands, and shallow ledges. Most of the seafloor in the Nearshore Basins is smooth and muddy (Figures 17-24; Table 3). The monotony of this bottom texture is locally disturbed by regions covered by a dense network of grooves with numerous dark patches (Figure 17). The grooves are 1 meter wide and occur as parallel pairs of tracks 25 meters apart. Because of this regularity we assume they formed as a result of commercial dragging by fishermen. The dark patches associated with the grooves have not been observed directly, but are probably mussel bars. That they are not bedrock exposures is demonstrated by seismic profiles

Table 3. Subdivision of the physiographic zones into facies of differing properties.

Physiographic Zone/Facies	Depth(m)	Morphology	Texture	Structure	Composition	Origin
NEARSHORE BASIN						
Smooth muddy	5-15	flat	soft mud, dark patches?	bioturbated, fishing gear marks	high C, N low $CaCO_3$	Holocene mud
Channels	5-25	steep sided, slump scars	mud - gravel	slumped blocks	?	modern slumping due to tidal currents?
Rocky	0-25	high local relief	muddy, sandy gravel	chaotic	high $CaCO_3$ low C, N	reworked glacio-marine, modern carbonate
NEARSHORE RAMP						
Inner Sand	0-15	steep slope	fine to coarse, well sorted sand	megaripples	low $CaCO_3$, C, N	reworked fluvial
Outer Muddy Sand	15-30	gentle slope	fine to coarse muddy sand	ripples, flat surface	low $CaCO_3$, C, N	reworked fluvial
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

Table 3. Continued.

ROCKY ZONE (cont.)						
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
SHELF VALLEY						
Thalweg	30-65	U-shaped channel	muddy sand	bioturbation common	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 common	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

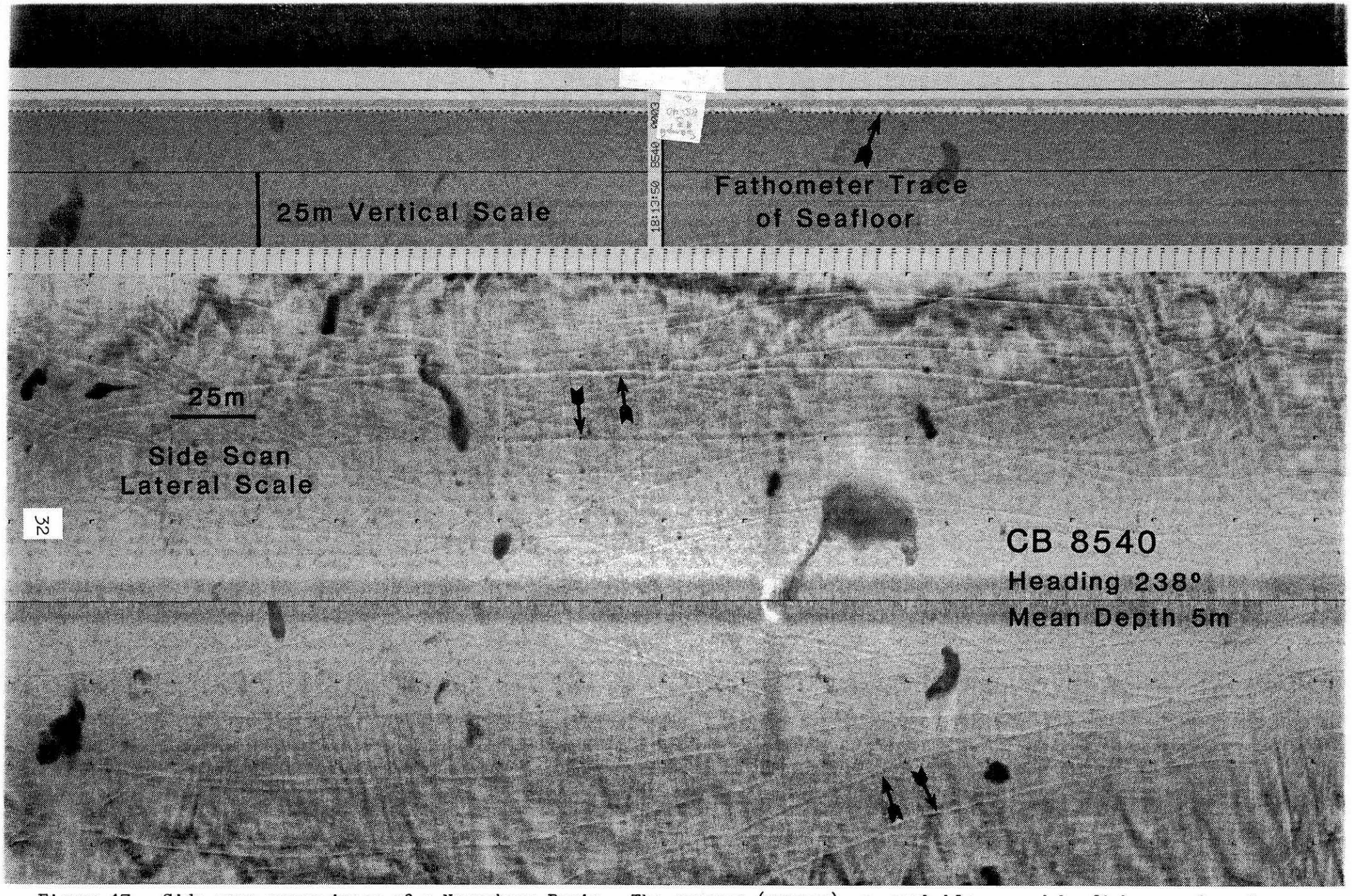


Figure 17. Side-scan sonar image of a Nearshore Basin. The grooves (arrows) are probably caused by fishermen dragging the bottom. The dark patches have not been certainly identified, but may be mussel bars. All side scan sonar tracklines are located on Figure 6. On all images the tickmarks are 25 meters apart so that 100 or 200 meters of seafloor are seen on either side of the central ship's track. In the upper part of the image, the fathometer trace of the ship is recorded with the spacing between dark horizontal lines equal to 25 meters.

from the Nearshore Basins which show several meters of acoustically transparent Holocene mud near the surface (Figure 18).

Where bedrock projects above the seafloor, small rocky-gravel areas exist (Figure 19). Seismic profiles suggest that winnowed glaciomarine sediment or till is the source of the coarse sediment near the rock outcrops. Channeling near the rock exposures forms the "moats" or small depressions that expose the coarse, Quaternary sediment (Figures 18, 20). The coarse material is rich in carbonate derived from organisms encrusting the bedrock (Kelley, unpublished submersible notes). Although coarse grained, carbonate-rich aprons surround all outcrops in all parts of the study area, these are usually too small to be mapped (Figure 16).

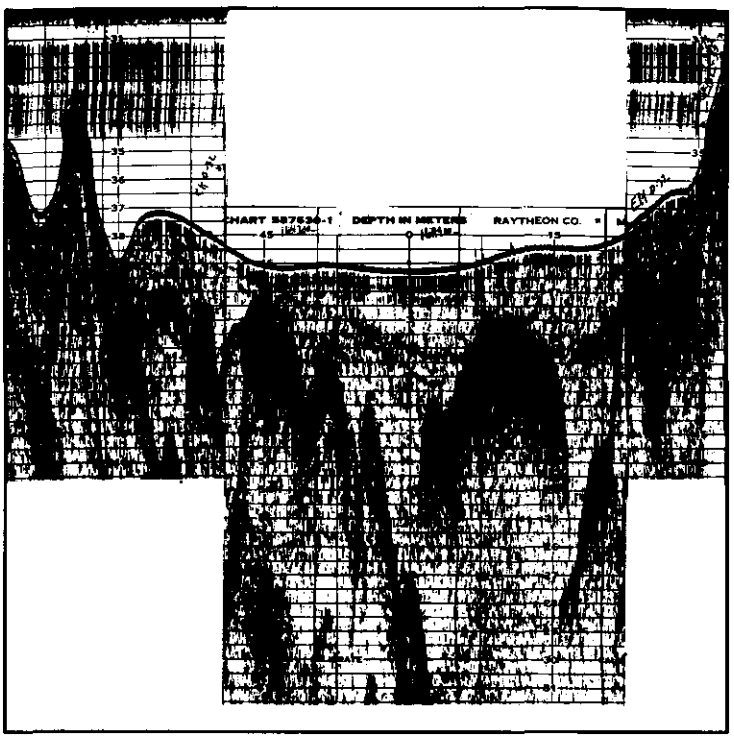
In addition to rocky and muddy facies in the Nearshore Basins, channels also exist (Figures 18, 20, 21). These are usually cut into acoustically transparent Holocene mud deposits which unconformably overlie the Presumpscot Formation. Tidal currents presumably maintain the channels and may also cause slope failure along the channel margins (Figures 20-24). Inferences of slope failure are discerned from the seismic reflection profiles (Figures 20, 21, 23), and have been directly observed in side-scan sonar images (Figures 22, 24). It is not known whether slope failure results from oversteepening due to rapid sediment accumulation or loss of shear strength due to natural gas in the sediment, or both. Slumps range in size from 100 m^2 to 1000 m^2 and possibly larger (Figure 22, 24). When the slumps occurred and whether they were triggered by storm waves, earthquakes, or other events is not known.

Nearshore Ramp

The Nearshore Ramp exists as a single unit on the south central Maine inner shelf and forms a broad topographic swell around Cape Small (Figures 11, 12b, 13a). This is near the mouth of Maine's largest river, the Kennebec, and the only large sand beaches of the area are also located here (Kelley, in press). The Nearshore Ramp, as in southwestern Maine (Kelley and others, 1986b), may be divided into inner, outer, and rocky regions (Table 3).

The inner region is covered with medium-coarse sand formed into large fields of megaripples (Figures 25, 26). The wavelength of the megaripples ranges up to 2.5 meters (Figure 25) and often increases near bedrock outcrops. While the size of the bedforms is larger near bedrock, the features cover at least several square kilometers of the area offshore of Popham and Reid Beaches. Currents appear to play a role in megaripple formation and small fields of bedforms often exist in scoured regions where local bathymetry focuses currents (Figure 27). Similarly, bedrock exposures also deflect currents and result in pockets with no megaripples in areas otherwise covered with the bedforms (Figure 28).

The outer Nearshore Ramp is generally devoid of megaripple fields, but ripples smaller than the side-scan sonar resolution (0.25 m) may exist. The Nearshore Ramp merges gradationally into Shelf Valleys and Outer Basins (Figures 13a, 14) and generally muddier sediment is found at the seaward edge of the Nearshore Ramp (Figure 29). As in other areas, bedrock exposures are often surrounded by aprons of gravelly mud which appear to be



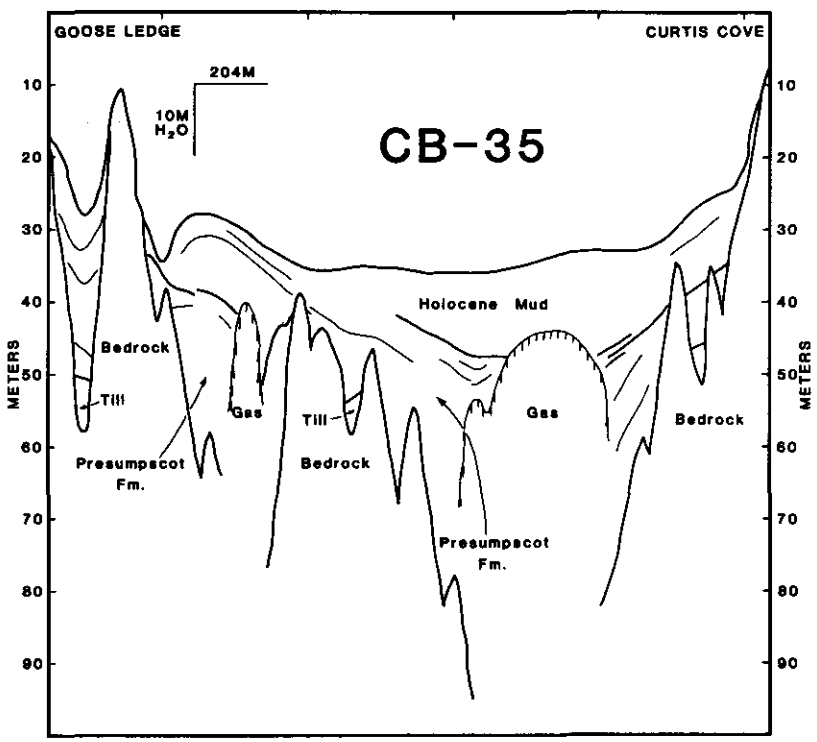


Figure 18. Original and interpreted 3.5 kHz record from Nearshore Basin. The acoustically transparent Holocene mud is channelled near rock outcrops. It is underlain by glaciomarine mud, which is locally channelled. These channels are filled with muddy, gas-rich mud. All seismic reflection profiles are located on Figure 4.

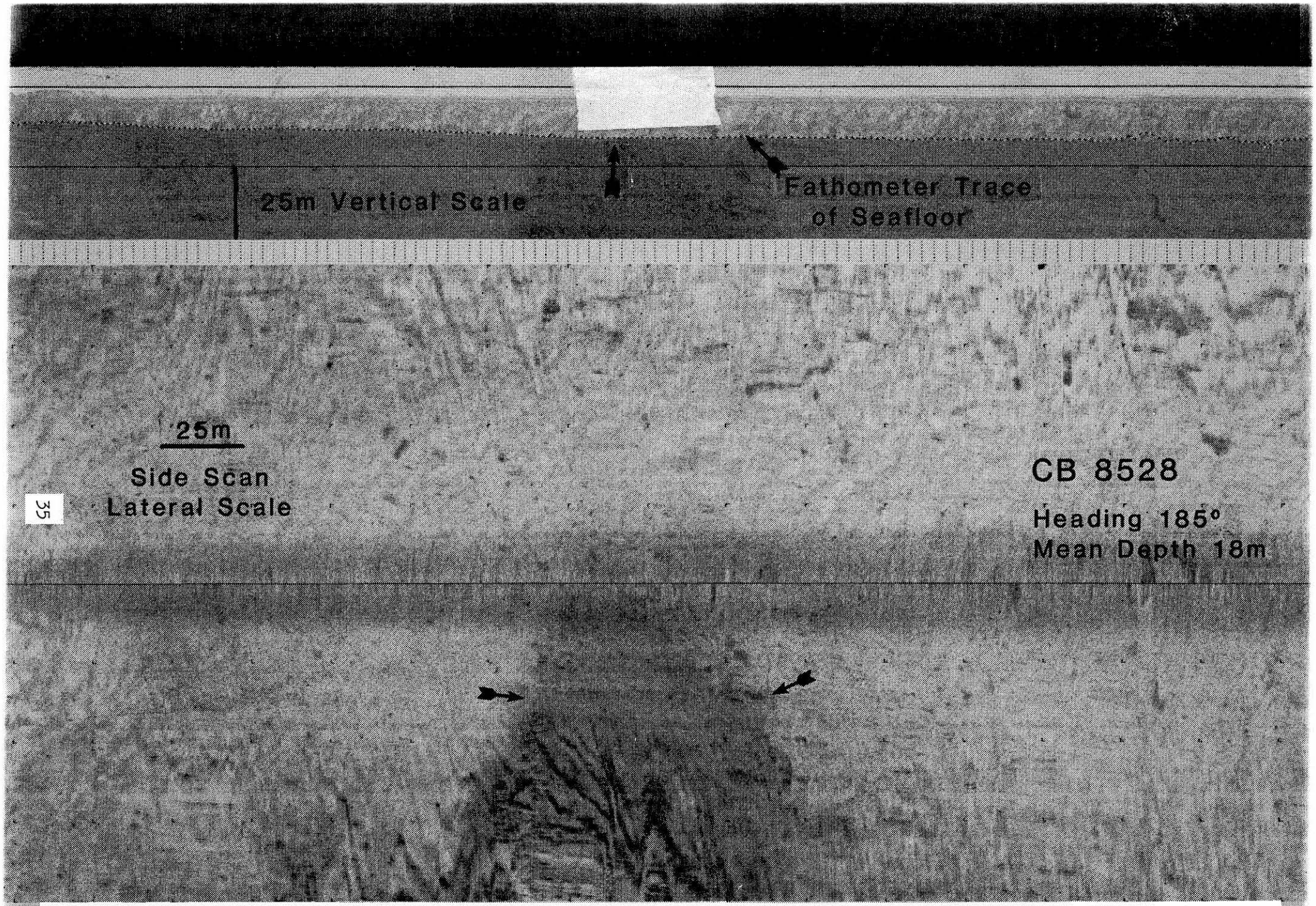
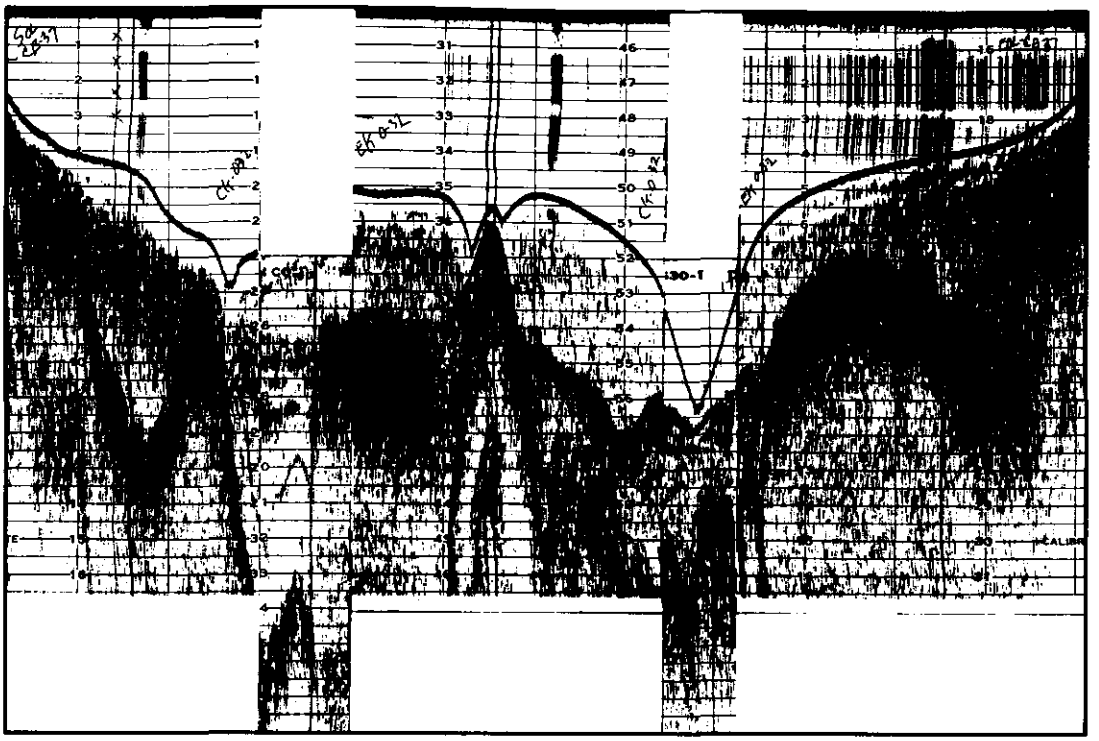


Figure 19. Rocky outcrop at bottom of side-scan sonar image is surrounded by coarse-grained sediment (dark, arrows). This appears to be Pleistocene sediment exhumed by current scour which forms a depression (arrow on fathometer trace) near the rock.



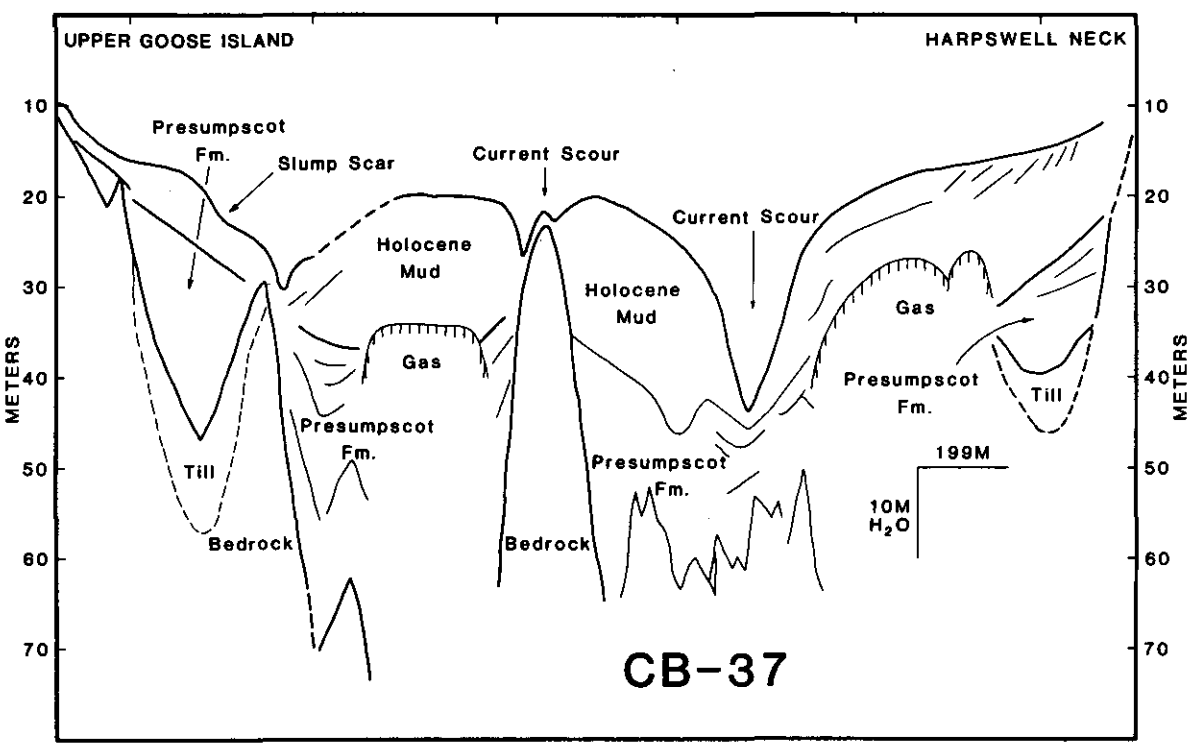
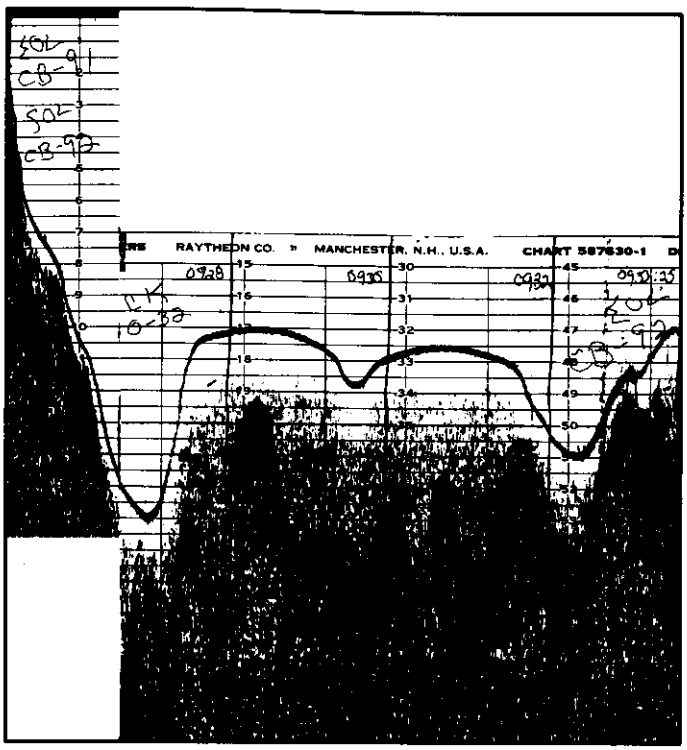


Figure 20. Seismic reflection profile from Nearshore Basin. Current scour is evident as moats near rock exposures as well as deep channels. Gas in the acoustically transparent Holocene sediment may lead to loss of shear strength and slumping.



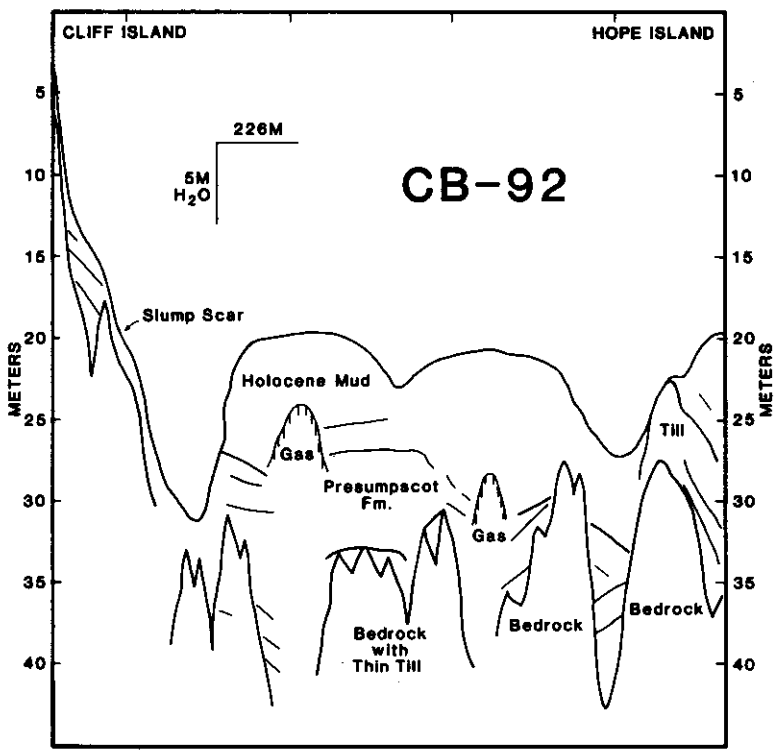


Figure 21. Seismic reflection profile showing steep-sided channel cut in Holocene mud from a Nearshore Basin.

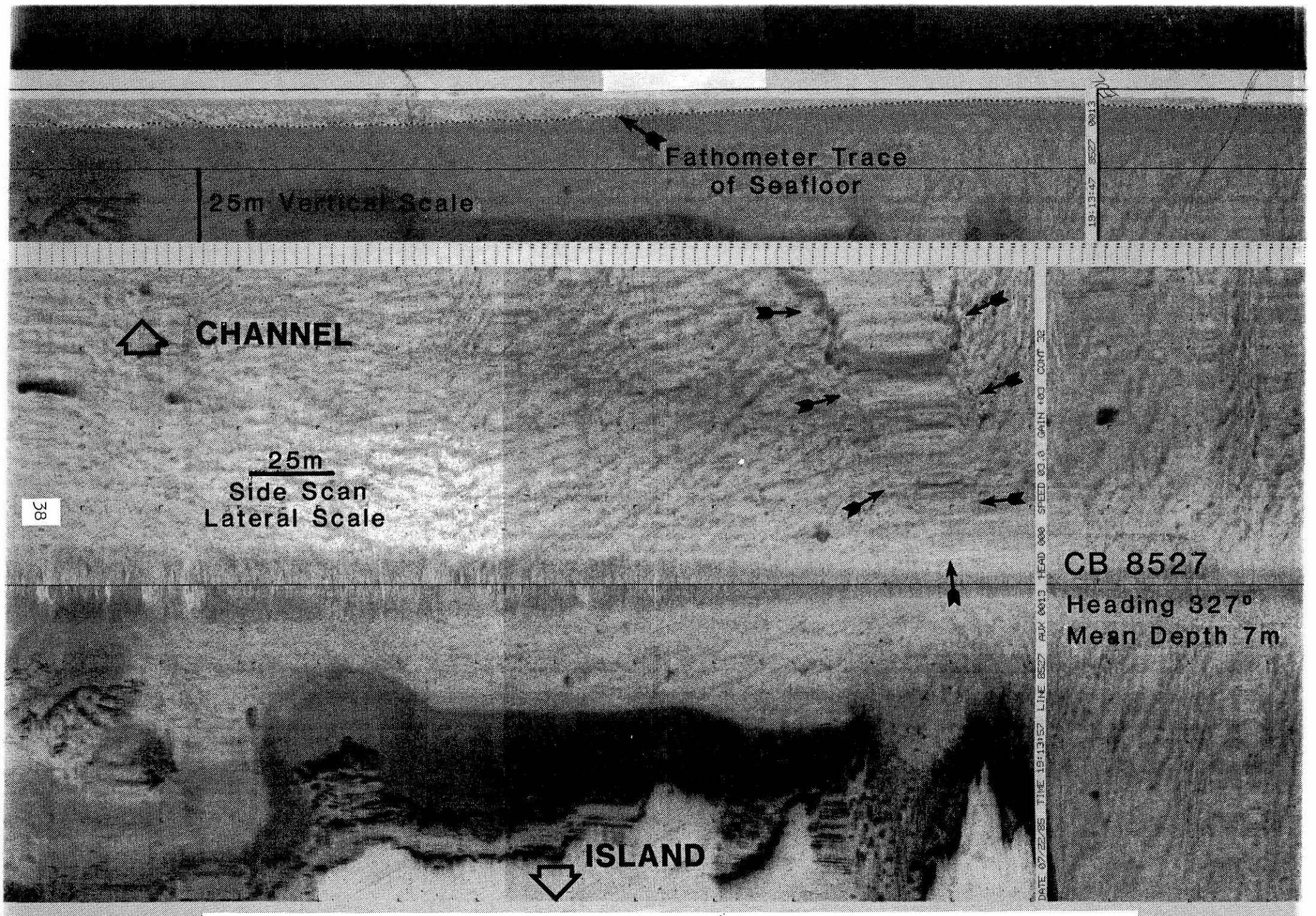
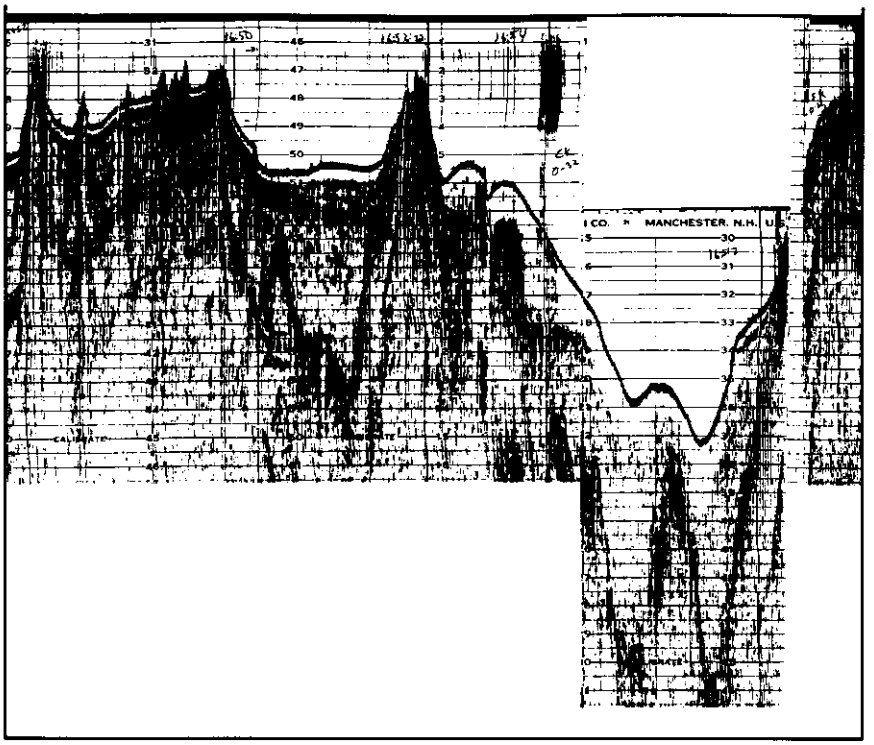


Figure 22. Side-scan sonar image of a small slump (arrows) in a Nearshore Basin.



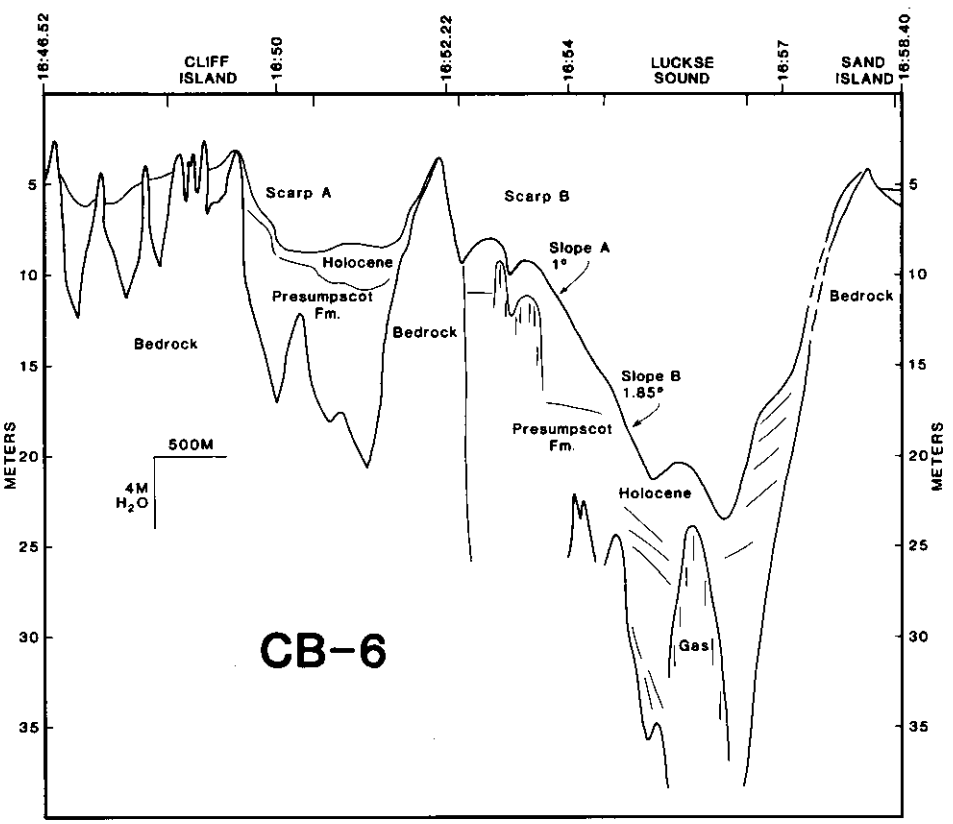


Figure 23. Seismic reflection profile across a Nearshore Basin with a large slump (Scarp B). See side-scan sonar image of same area in Figure 24.

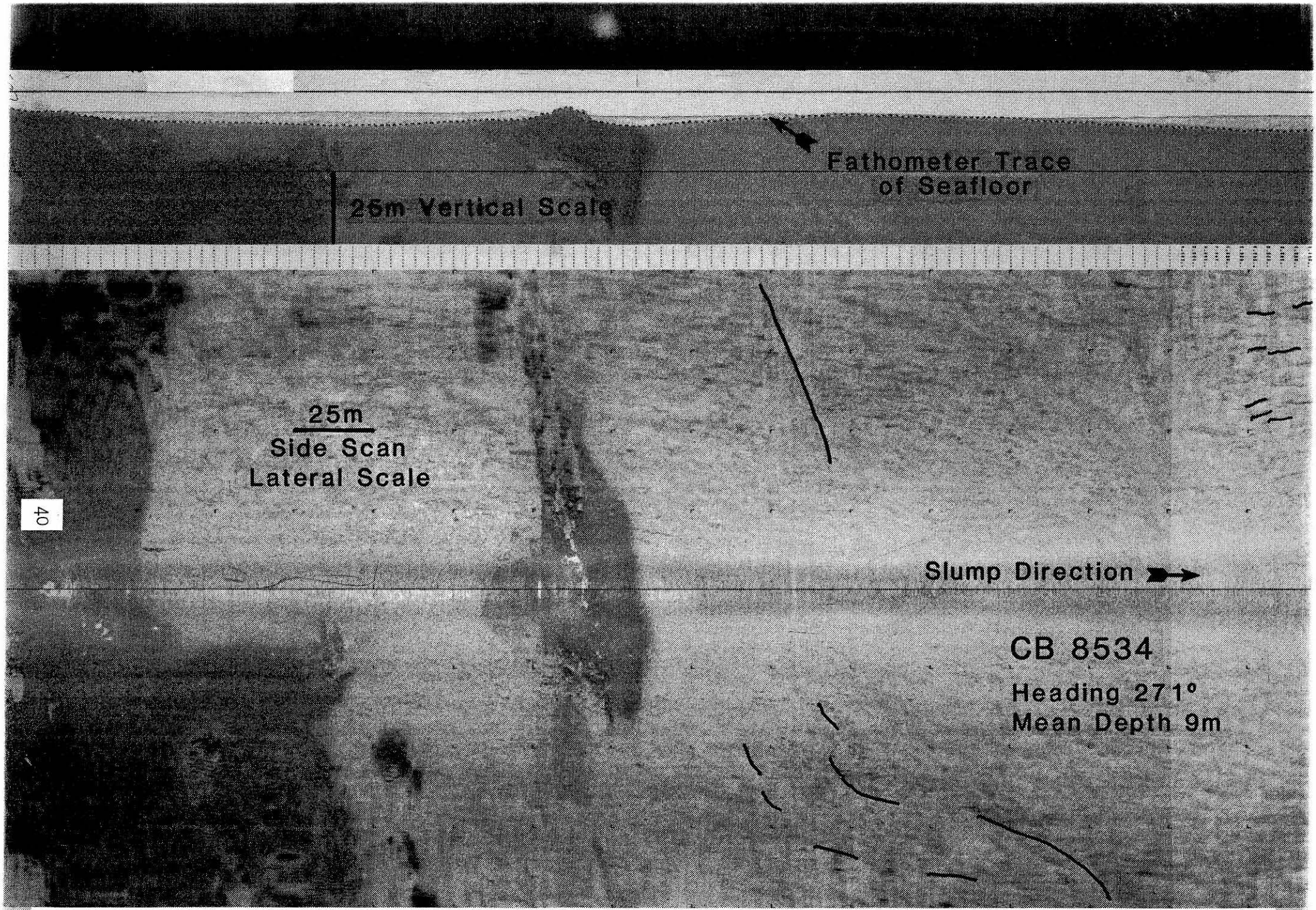


Figure 24. Side-scan sonar image of small part of large slump in Nearshore Basin. The inferred zone of detachment is marked by lines and inferred pressure ridges are slightly out of the field of view on the right side of the image. See Figure 23 for seismic reflection profile over same area.

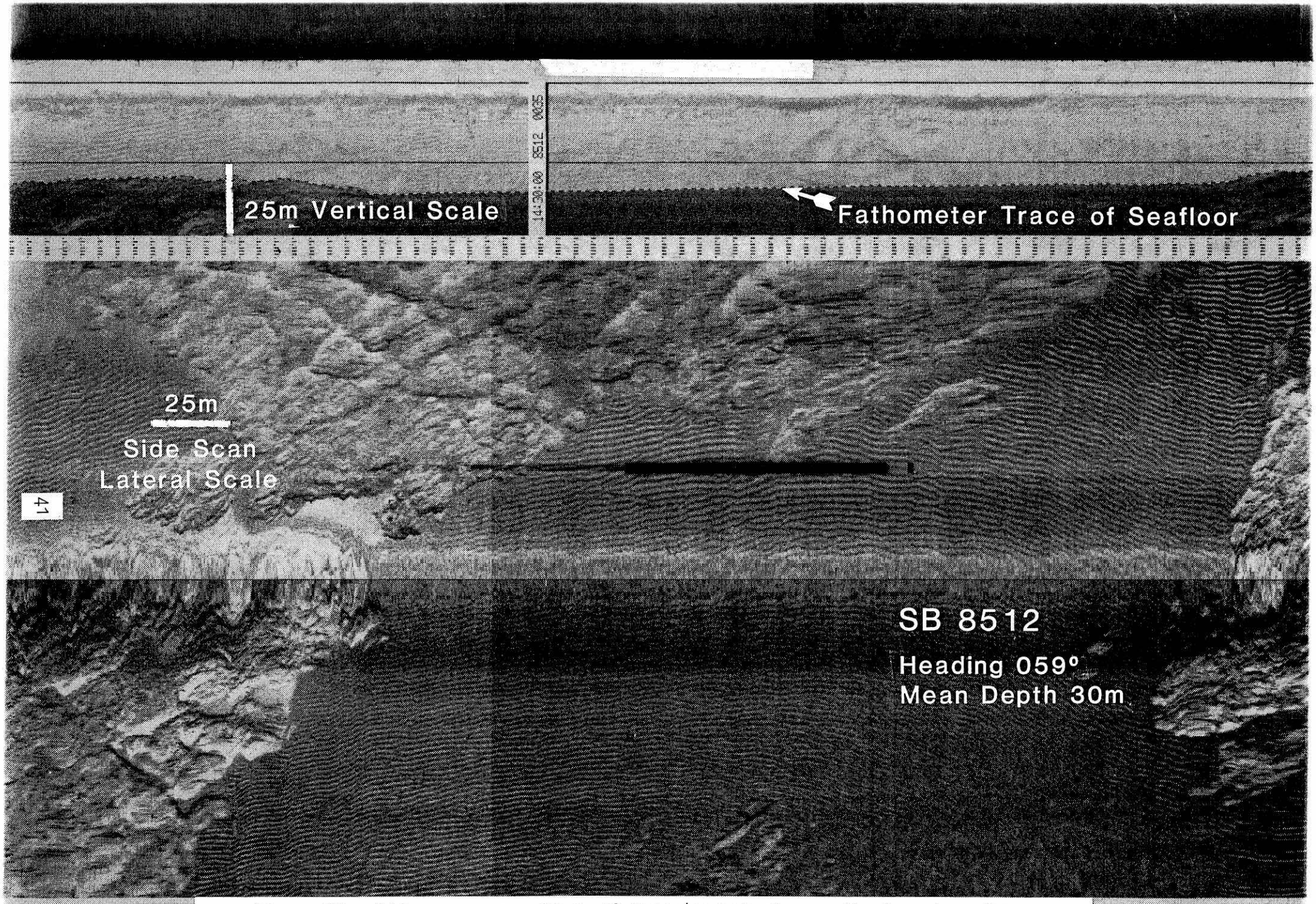


Figure 25. Side-scan sonar image of large megaripples on the Nearshore Ramp.

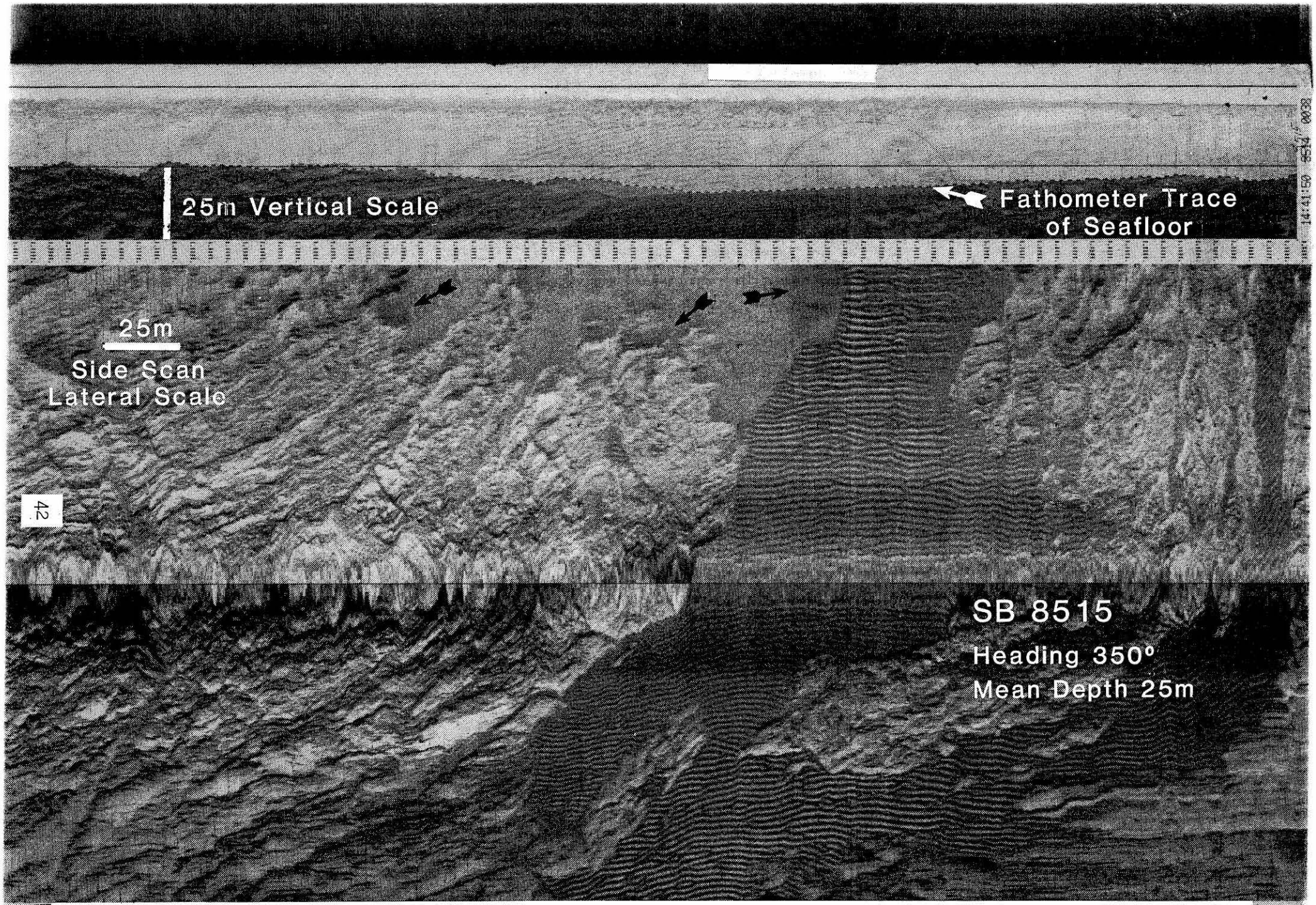


Figure 26. Side-scan sonar image of megaripples and muddy gravel (arrows) in rocky part of Nearshore Ramp.

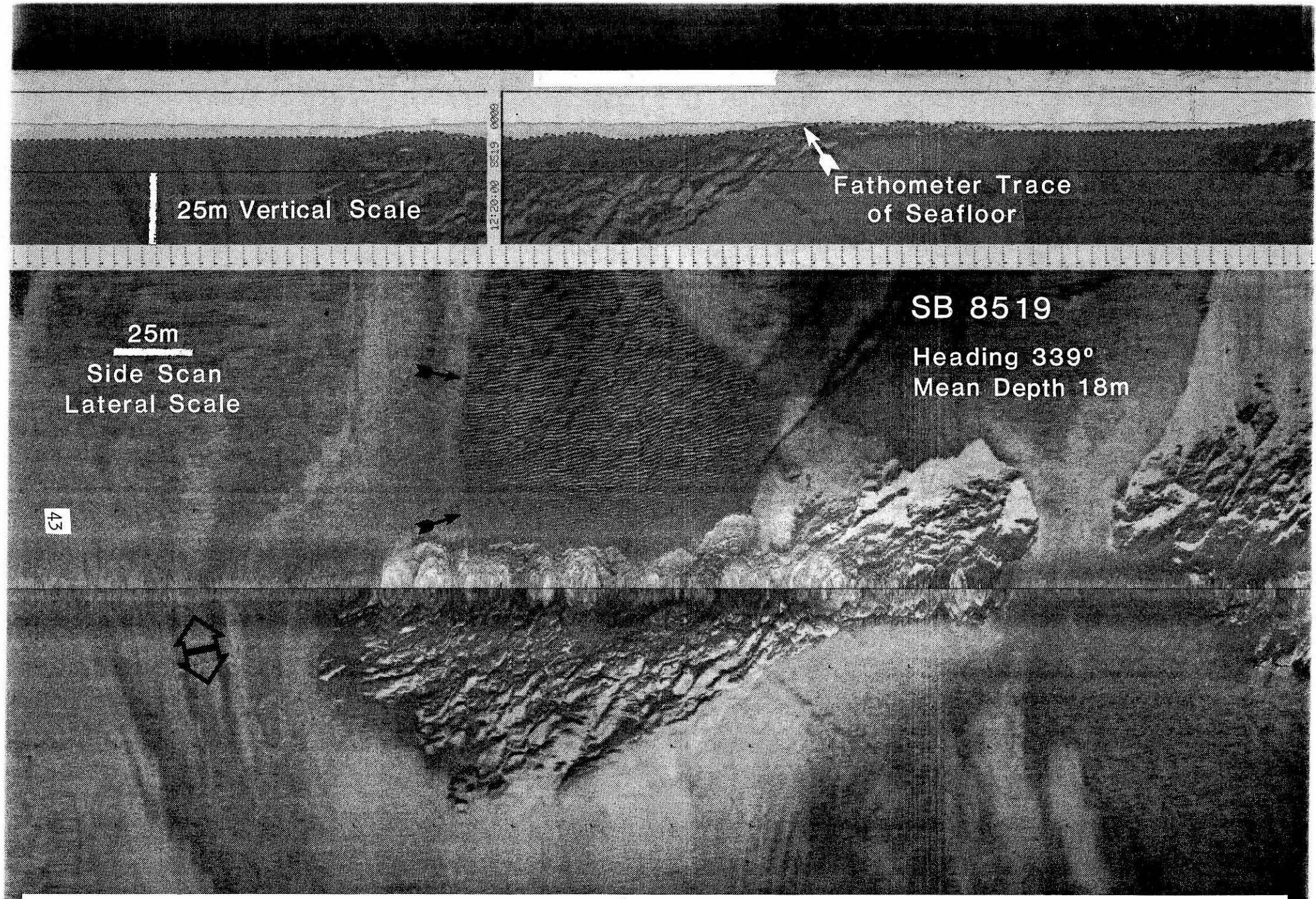


Figure 27. Side-scan sonar image of small megaripple field (arrows) adjacent to bedrock outcrop. From the shape of gravel (dark) and sand (light) deposits in the area, it appears that tidal currents violently effect the area and are strengthened near the rock outcrop.

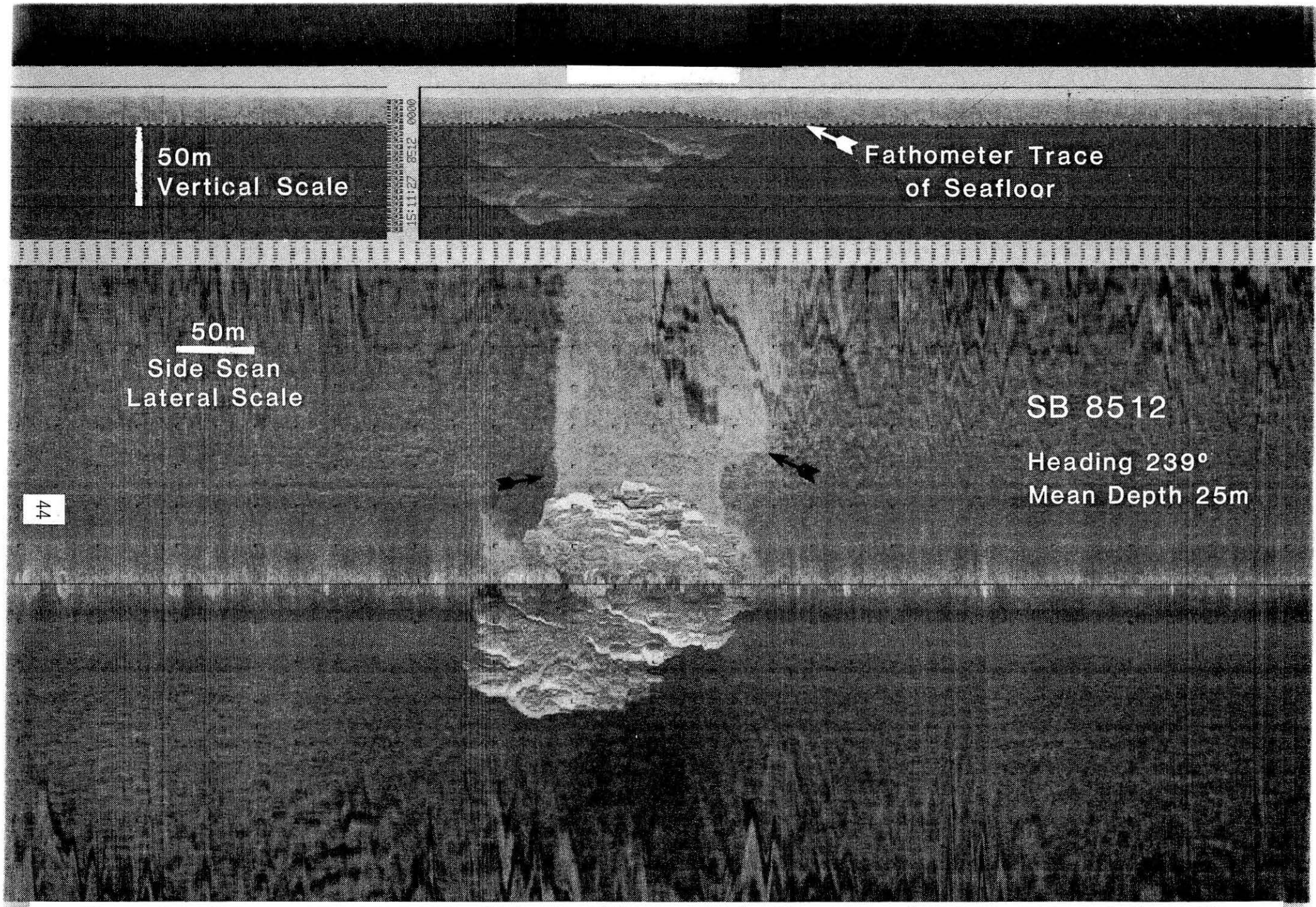


Figure 28. Side-scan sonar image of muddy region (light, arrows) adjacent to rock outcrop and megaripple field. The rock outcrop here appears to shield the adjacent area from current action.

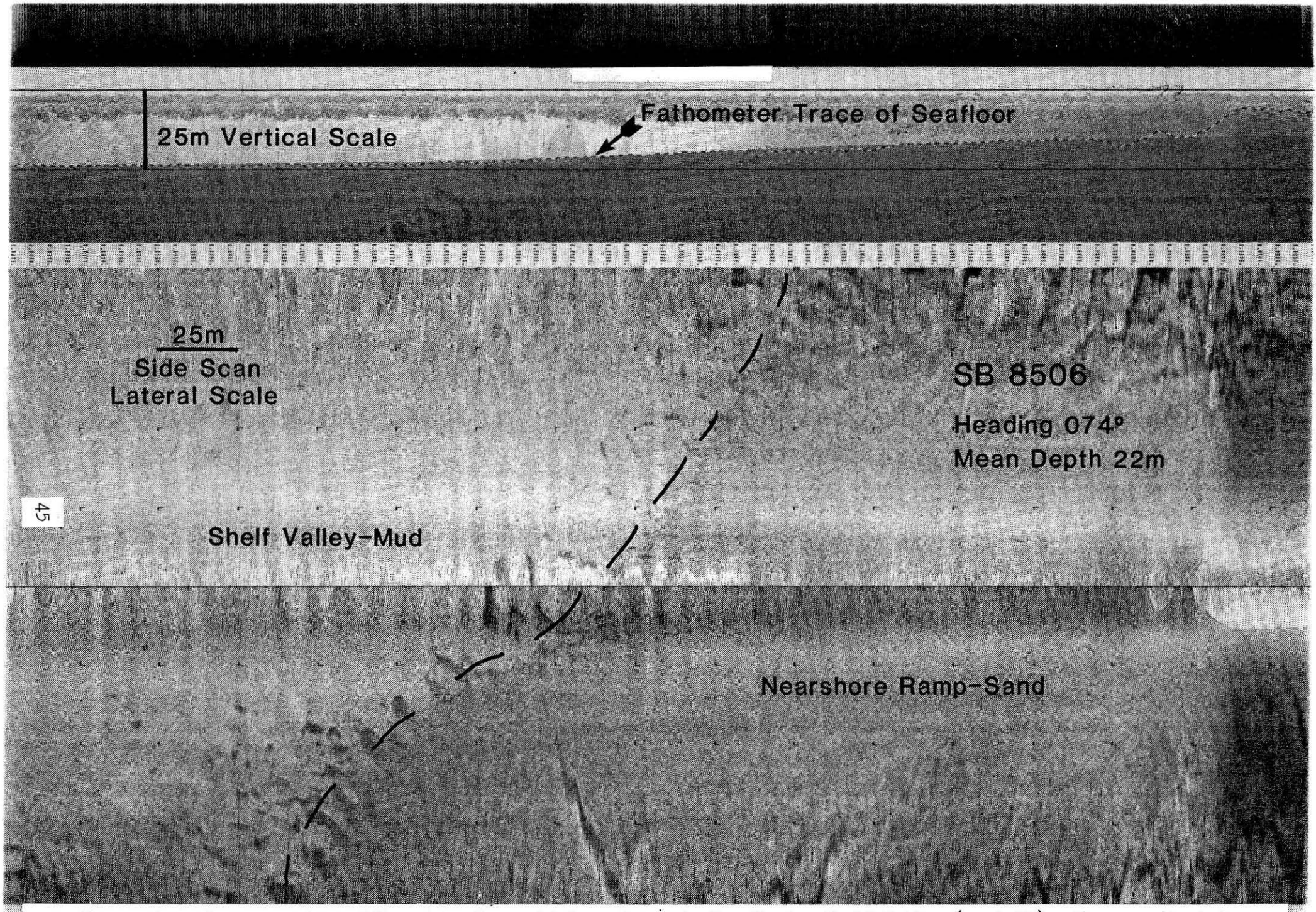


Figure 29. Outer portion of Nearshore Ramp which grades into New Meadow Shelf Valley (on left). Coarse material (dark) is partly covered by muddier sediment (light) along the contact with the valley (dashed line).

exhumed Pleistocene sediment.

Shelf Valleys

The Shelf Valleys are prominent bathymetric depressions which extend seaward of the estuaries and neutral embayments of the Indented Shoreline compartment (Figure 14). As in southwestern Maine, there are more bedrock-framed Shelf Valleys than there are major rivers. Kelley and others (1986) attributed this to repeated derangement of the regional drainage by Quaternary glaciations, and noted that Maine's second largest embayment, Casco Bay, is today fed only by local streams which drain areas entirely within the marine limit (Thompson and Borns, 1985). As sea level rises and the Nearshore Basins become more exposed, they will likely become Shelf Valleys similar to their more seaward counterparts.

The Shelf Valleys may be divided into two areas of distinctly different sediment composition: muddy thalweg regions and rocky marginal fringes (Table 3). The thalwegs are covered with muddy sand (Figure 16) which is intensely bioturbated by a variety of burrowing fauna (Kelley, unpublished submersible notes). On side-scan sonar imagery the floor of the thalwegs appears very smooth and light (Figures 30, 31, 34). This is in striking contrast to the darker, coarser grained sediment which forms a fringe along the bedrock walls of the valleys (Figure 31). Submersible observations show the fringe to be gravel and carbonate debris partly derived from the rock walls, and locally originating by exposure of glaciomarine sediment by erosion. Truncated reflectors of glaciomarine sediment are common on the edges of some Shelf Valleys (Figure 33), but not all (Figure 32). The axes of some rivers entering the study area (Sheepscot, Damariscotta, Royal) are floored by the glaciomarine sediment which is eroding to produce today's sediment. Thus the half-filled Shelf Valleys act as a repository for modern sediment in some areas, and a source of new material elsewhere.

The paleo-drainage of the region is complex, and has not yet been worked out. In some areas it is clear how tributaries joined to form master streams (Figure 31), but several of the Shelf Valleys appear to end in cul-de-sacs (Figure 12). Another unresolved problem is the occurrence of dark spots in the deeper valleys (Figure 34 arrows). These are not mussels or rocks, and may be gas escape structures or burrows (Kelley, unpublished submersible notes).

Rocky Zone

The most extensive physiographic zone on the south central Maine inner shelf is the Rocky Zone (Figure 14). As in southwestern Maine (Kelley and others, 1986b) this is a region of predominantly exposed rock, with very many small occurrences of sediment ponds and gravel plains facies. It is not yet known, but as much as half of the Rocky Zone may be exposed bedrock (Figure 14). A side-scan sonar mosaic would permit measurement of the exposed rock which is readily discerned from unconsolidated material (Figure 35). Unlike the southwestern shelf, the south central bedrock usually outcrops as linear ridges between chains of islands and peninsulas (Figure 36). As the spacing between the more erosion-resistant ridges increases, small Shelf Valleys exist (Figure 37) but most were not mappable

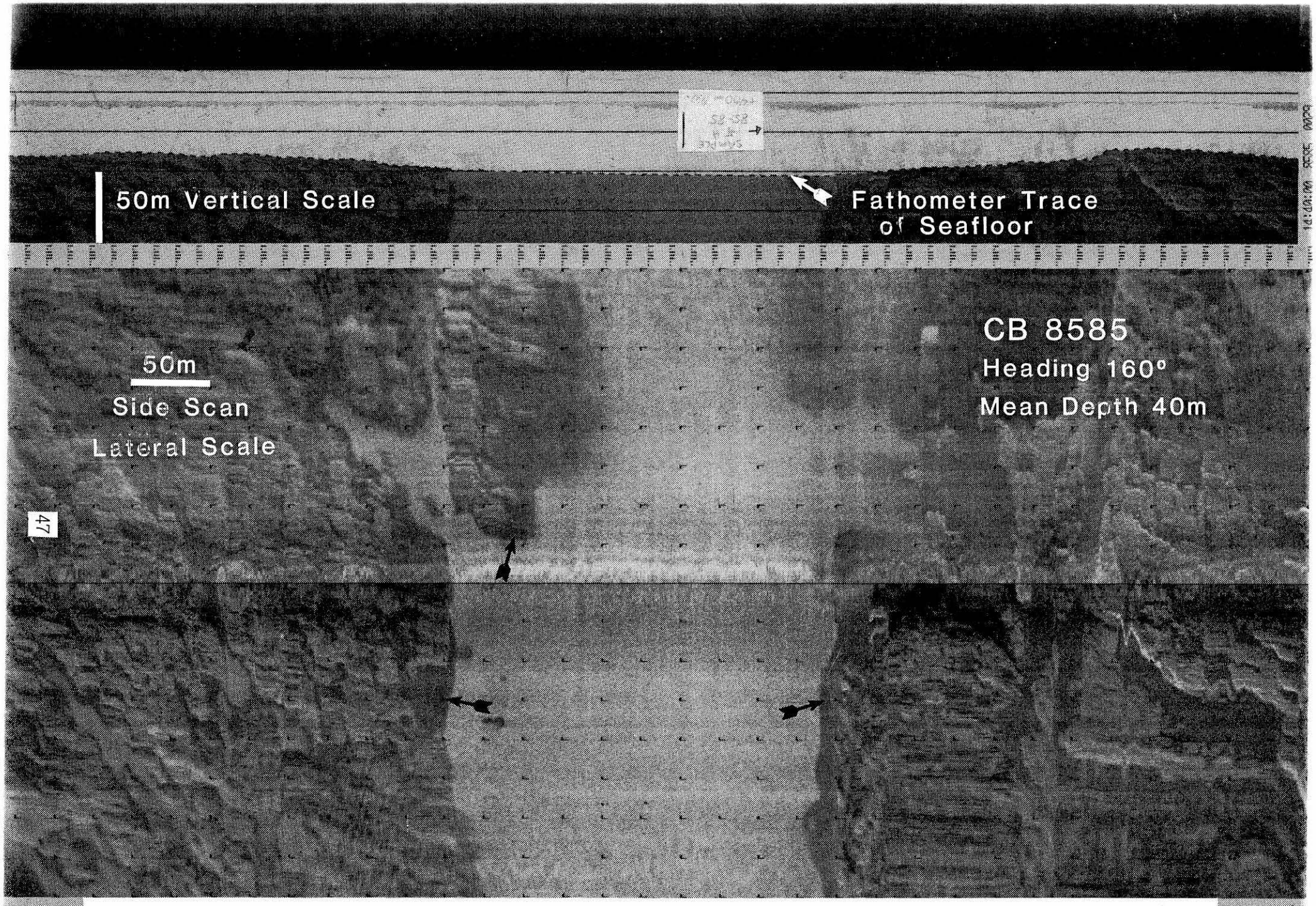


Figure 30. Side scan sonar image of a prominent Shelf Valley with about 15 meters of relief (see upper fathometer trace). The dark, coarse-grained marginal facies is indicated by arrows.

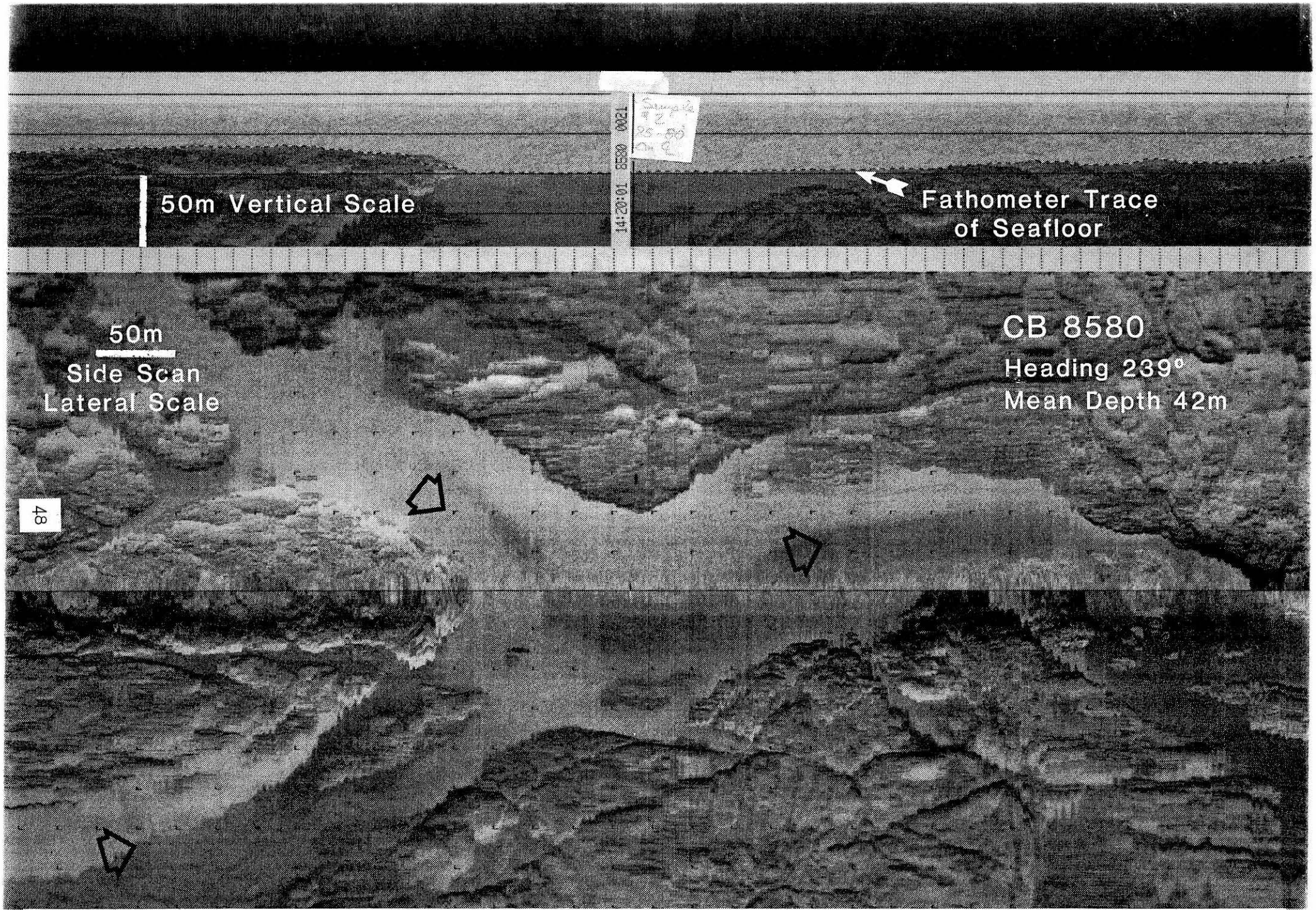


Figure 31. Side-scan sonar image depicting the convergence of two tributary valleys. Only a complete side-scan sonar mosaic would permit tracing of the paleo drainage. Arrows indicate inferred direction of flow.

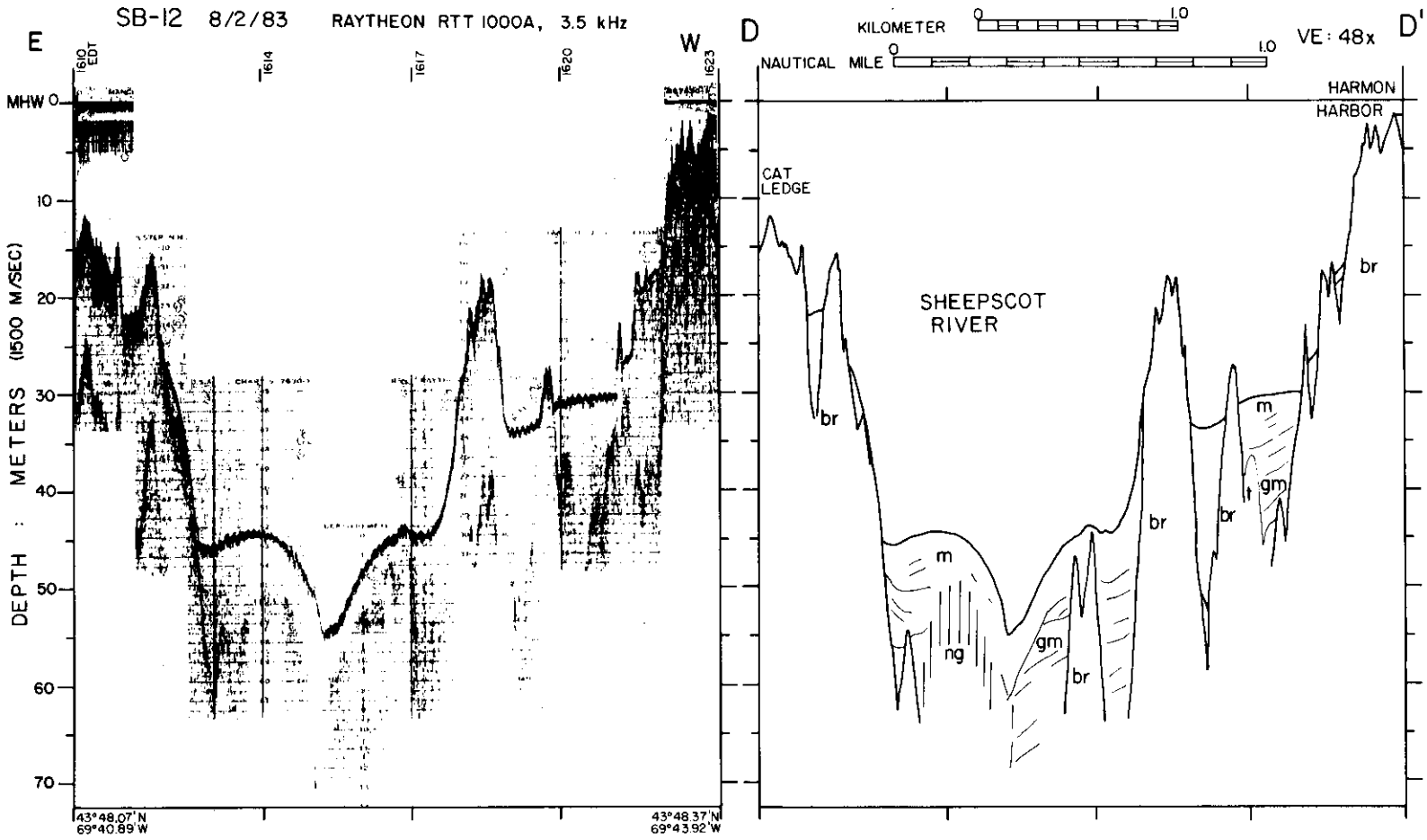
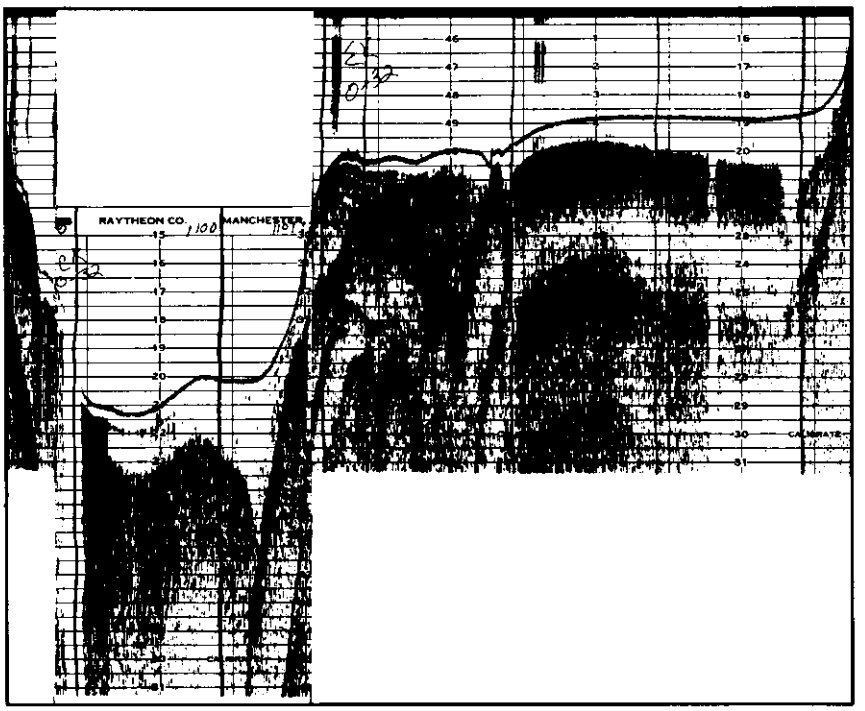


Figure 32. Seismic reflection profile across the upper Sheepscot Shelf Valley (from Belknap et al., 1986). The valley here is less than half filled with sediment and is covered with modern mud (m). Gas (ng) and glaciomarine (gm) sediment fill the remainder of the valley.



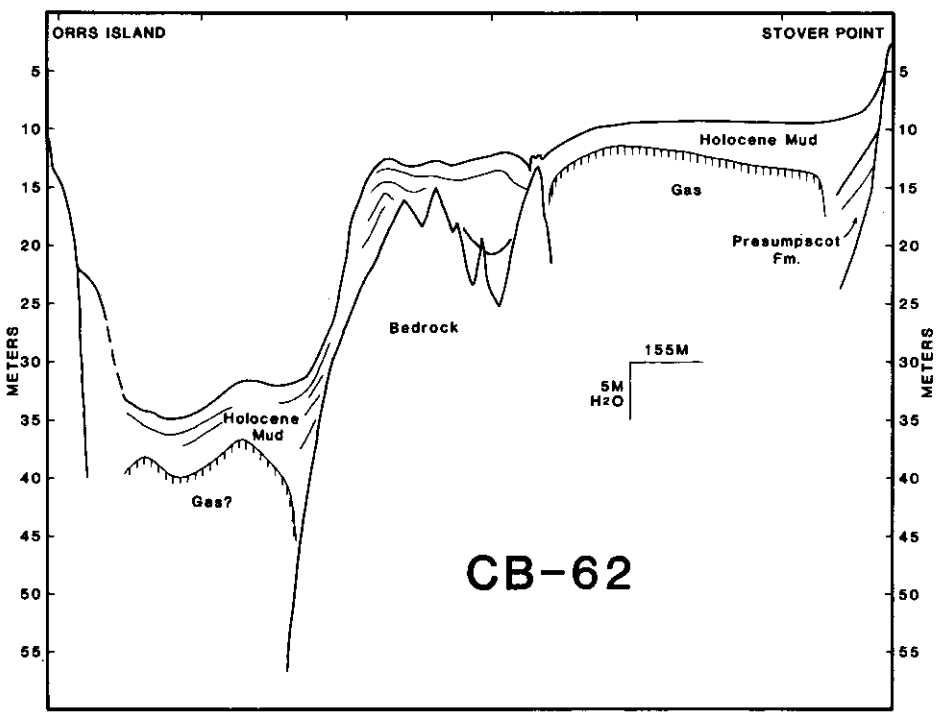


Figure 33. Seismic reflection profile across the Harpswell Sound Shelf Valley. Truncated reflectors of Presumpscot Formation sediment are seen above the deep axis of the valley. No modern stream presently enters this valley.

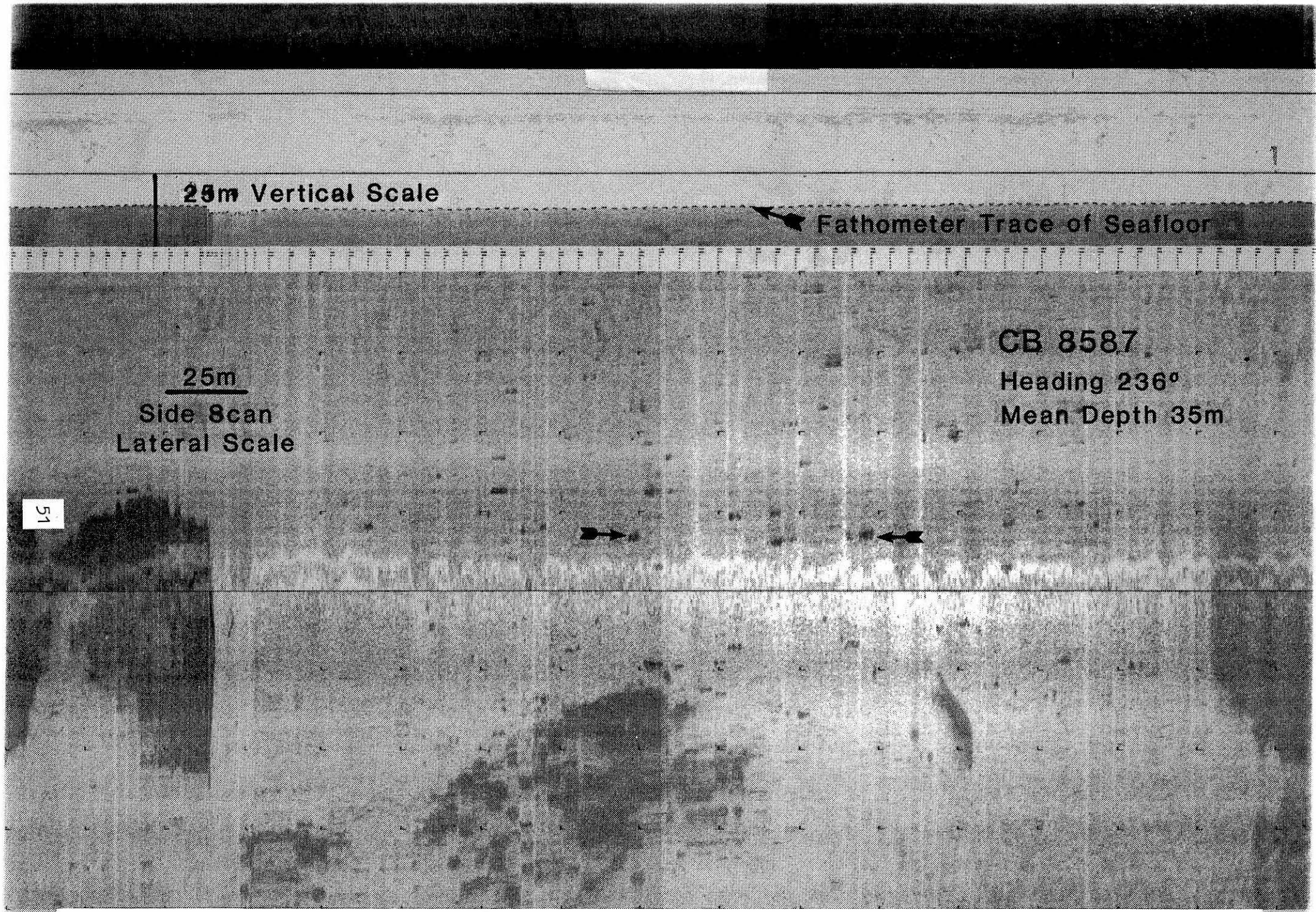


Figure 34. Side-scan sonar image of large Shelf Valley in outer Casco Bay. Dark spots (arrows) may be gas escape craters or burrows.

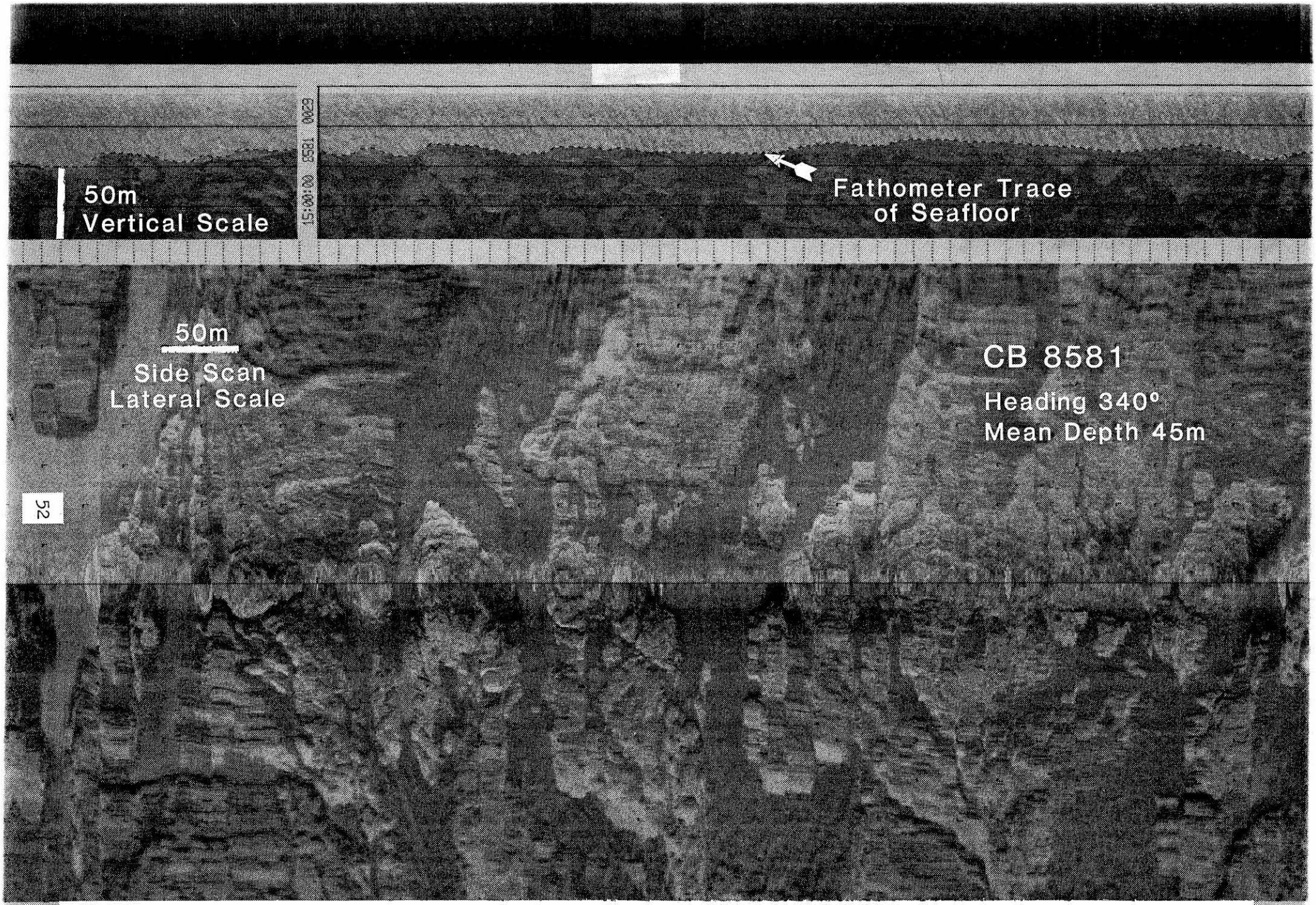


Figure 35. Side-scan sonar image of Rocky Zone typical of outer Casco Bay. Gravel and muddy gravel exist between bedrock outcrops.

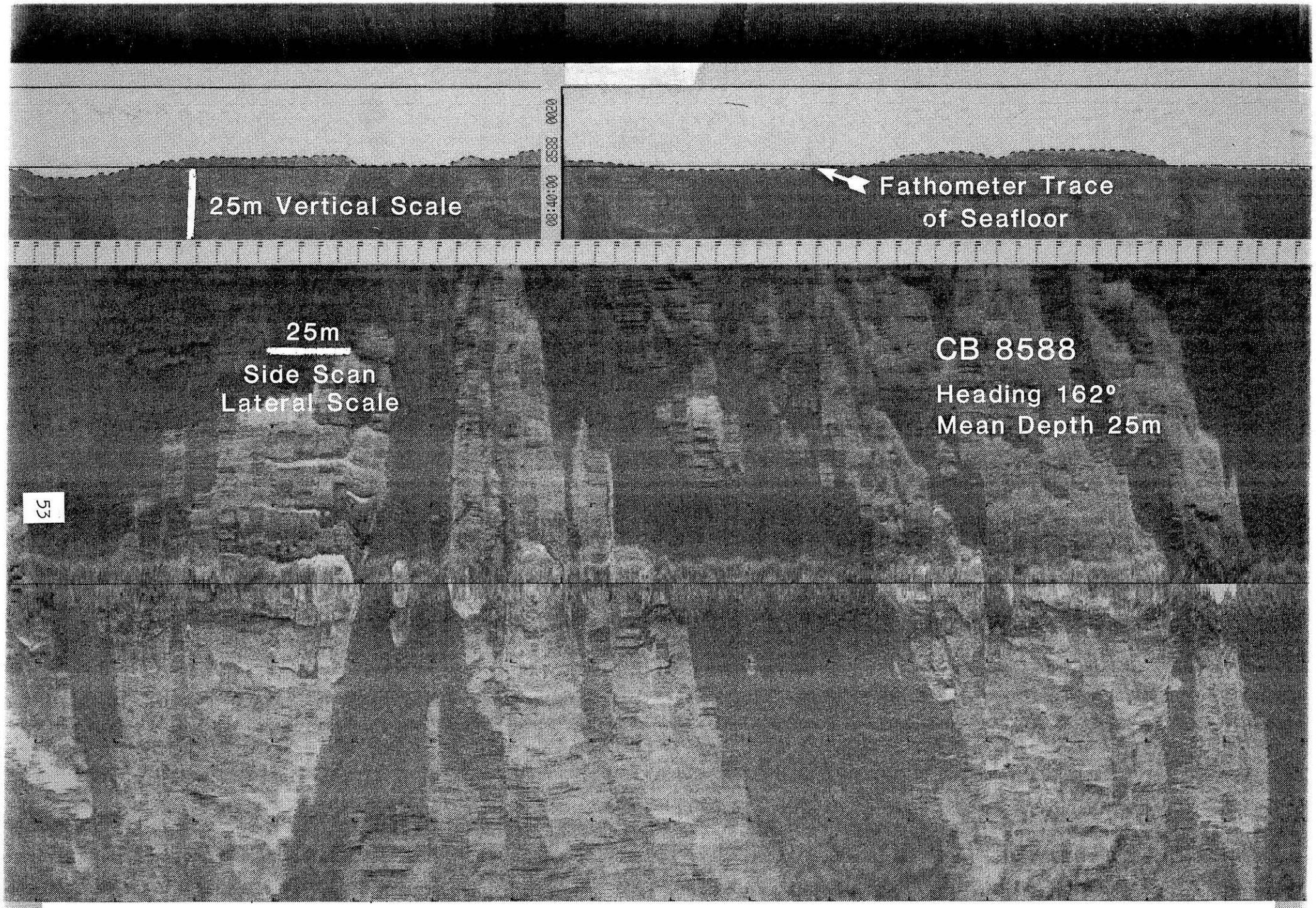


Figure 36. Side-scan sonar image of ridges of bedrock with pronounced foliation. The rock in this area has a pronounced northeast strike.

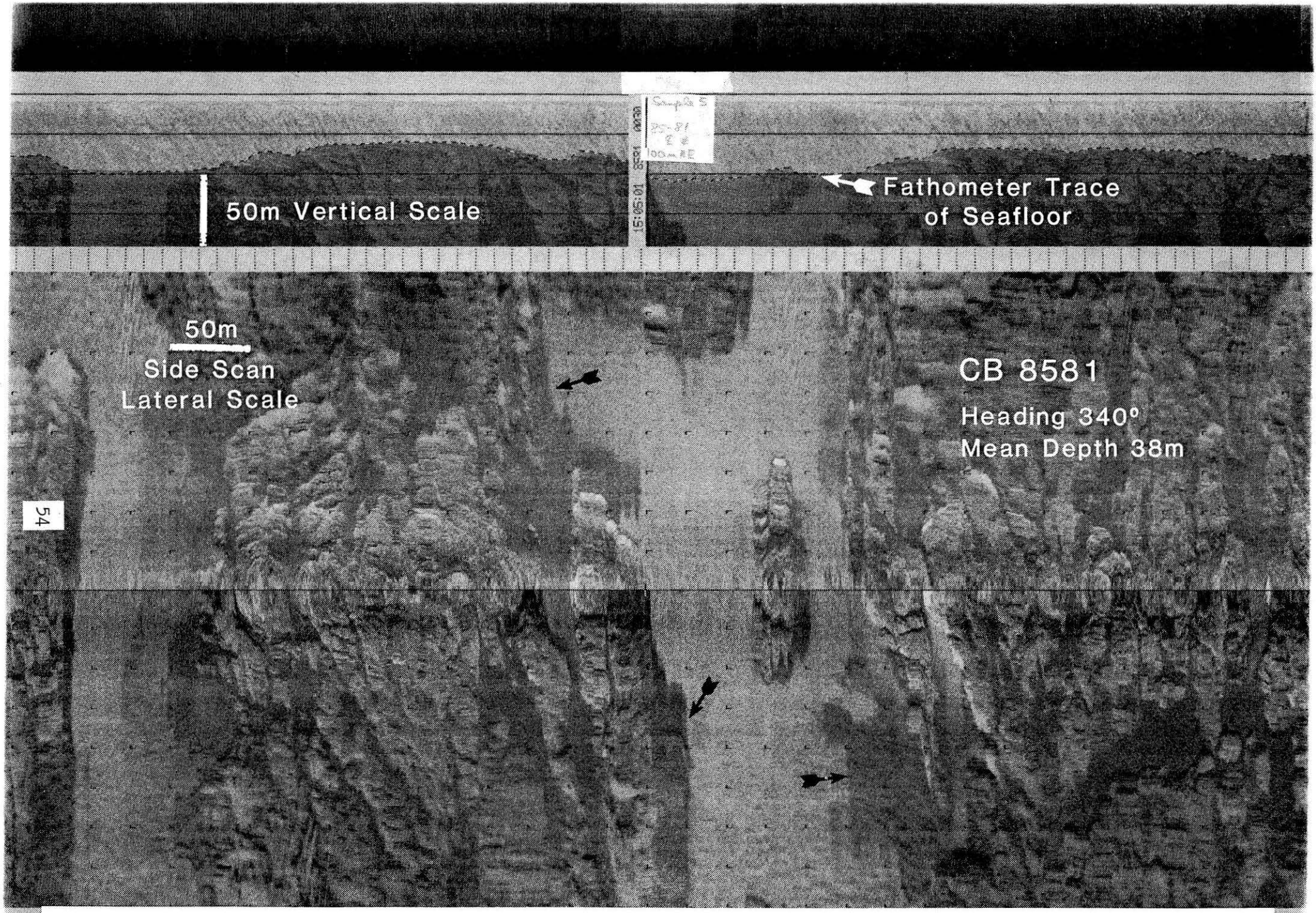


Figure 37. Side-scan sonar image of bedrock ridges with large intervening sediment ponds. Gravel is apparent where adjacent to the rock (arrows).

and often disappear over short distances. Locally, especially in the outer Casco Bay area, bedrock of more complex structure was encountered (Figures 38, 39). This may be a region of folding and faulting, or possibly the site of igneous intrusions.

Direct observations of the bedrock reveal it to be an area intensely encrusted by organisms (Kelley, unpublished submersible notes). The large surface area of the rock permits numerous carbonate-bearing fauna to live here. Thus, much of the sediment found in the many ponds between rock ridges contain abundant carbonate fragments. The rippled bedforms in many of the sediment ponds indicate on-going winnowing of the sediment, and possible transport of the locally-produced carbonate (Figure 38).

While no extensive gravel plains were mapped in this study similar to those recognized to the southwest (Kelley and others, 1986b), many smaller gravel areas are included within the Rocky Zone (Figures 40-45). On side-scan sonar imagery these are often areas littered with boulders (Figures 40-45) and appear to be "washed tills". Frequently, the gravel deposits exist as a dark halo surrounding a mound interpreted as a moraine (Figures 40-42). The moraines may possess up to 10 meters of local relief (Figures 40-42), and boulders are conspicuous only on the surfaces of the mounds. The surrounding dark gravel areas on the side-scan sonar imagery are presumably areas where sand and gravel were washed from the till. Seismic reflection profiles show that the moraines are up to 20 meters thick (Figure 10) although moraines have only been mapped across small parts of the study area (Kelley and Hay, 1986).

In many parts of the Rocky Zone, moraines and till are not prominent yet, but are emerging as younger sediment is stripped away (Figures 43, 44). In these areas closely spaced bottom samples could recover mud, sand, gravel, or rock (Figure 43). Locations of this sort are especially common in inner Casco, New Meadows, and Boothbay regions. The first occurrence of gravel and boulders is usually along the crest of a bedrock ridge connecting islands (Figure 44). A similar, though less readily-mapped area of gravel surrounds all islands in the study area (Figure 45). Here currents apparently scour away modern sediment and leave a lag of gravel which rests on rock. Some large boulders in these narrow, unmappable areas (Figure 45) may have actually been derived from the island and rocky shoals themselves.

Outer Basins

The deep Outer Basins are an extensive physiographic region of the south central Maine inner shelf, but a relatively poorly understood area (Figures 14, 16). Bathymetric control is largely lacking here due to an absence of bathymetric charts, and so its true complexity is only hinted at in this report.

The transition from the Rocky Zone to Outer Basin is frequently an abrupt one seaward of Casco Bay (Figure 46). The change in character of the seafloor is similarly profound as exposed rock is replaced by the soft mud covering the Outer Basins. The transition from the Nearshore Ramp, and possibly the Shelf Valleys near Sheepscot Bay is also abrupt as one crosses a "berm" or shoreline incised into the unconsolidated sediments at 65

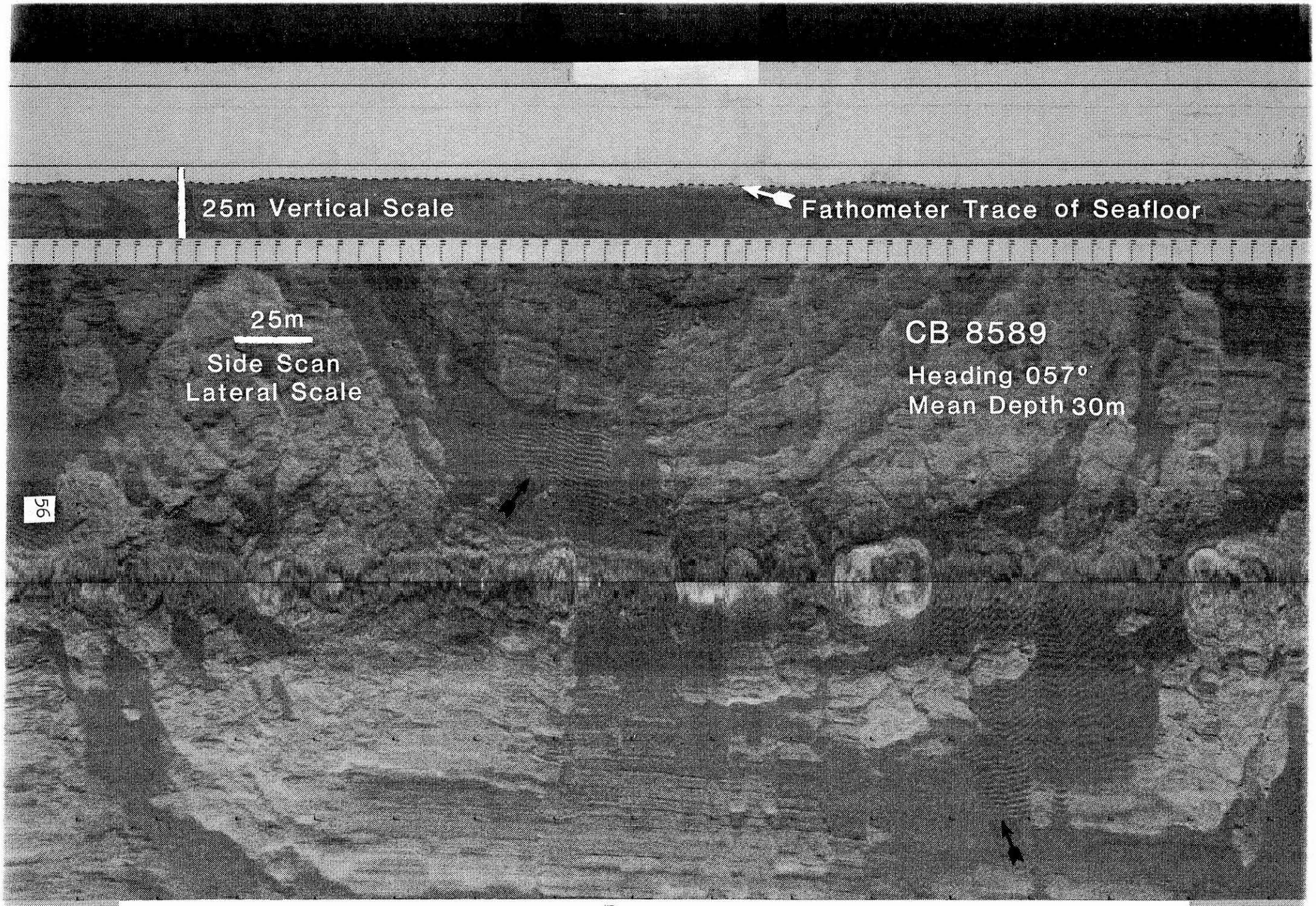


Figure 38. Complex bedrock structure with rippled, gravel patches in sediment ponds (arrows).

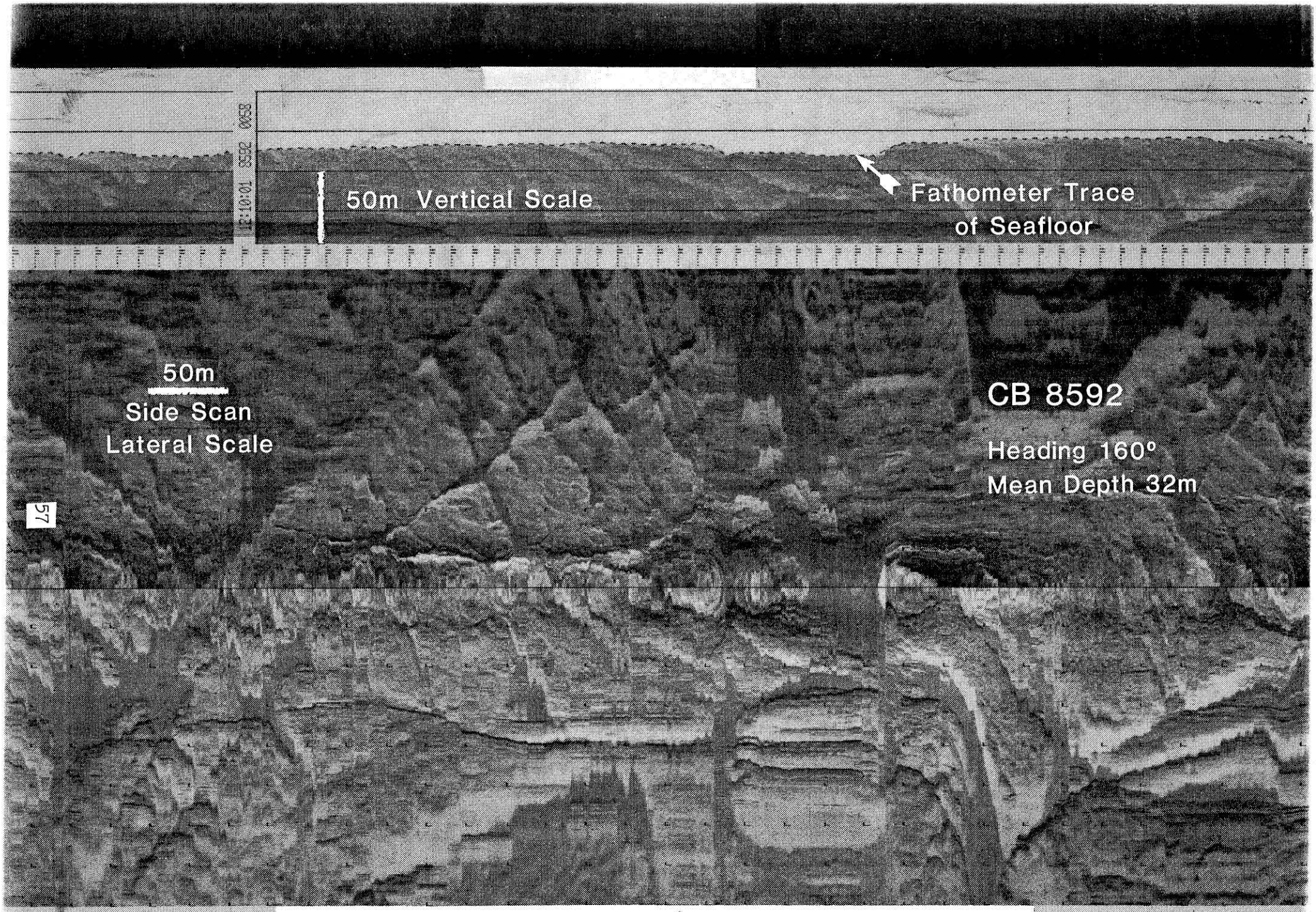


Figure 39. Side-scan sonar image of complex bedrock structure.

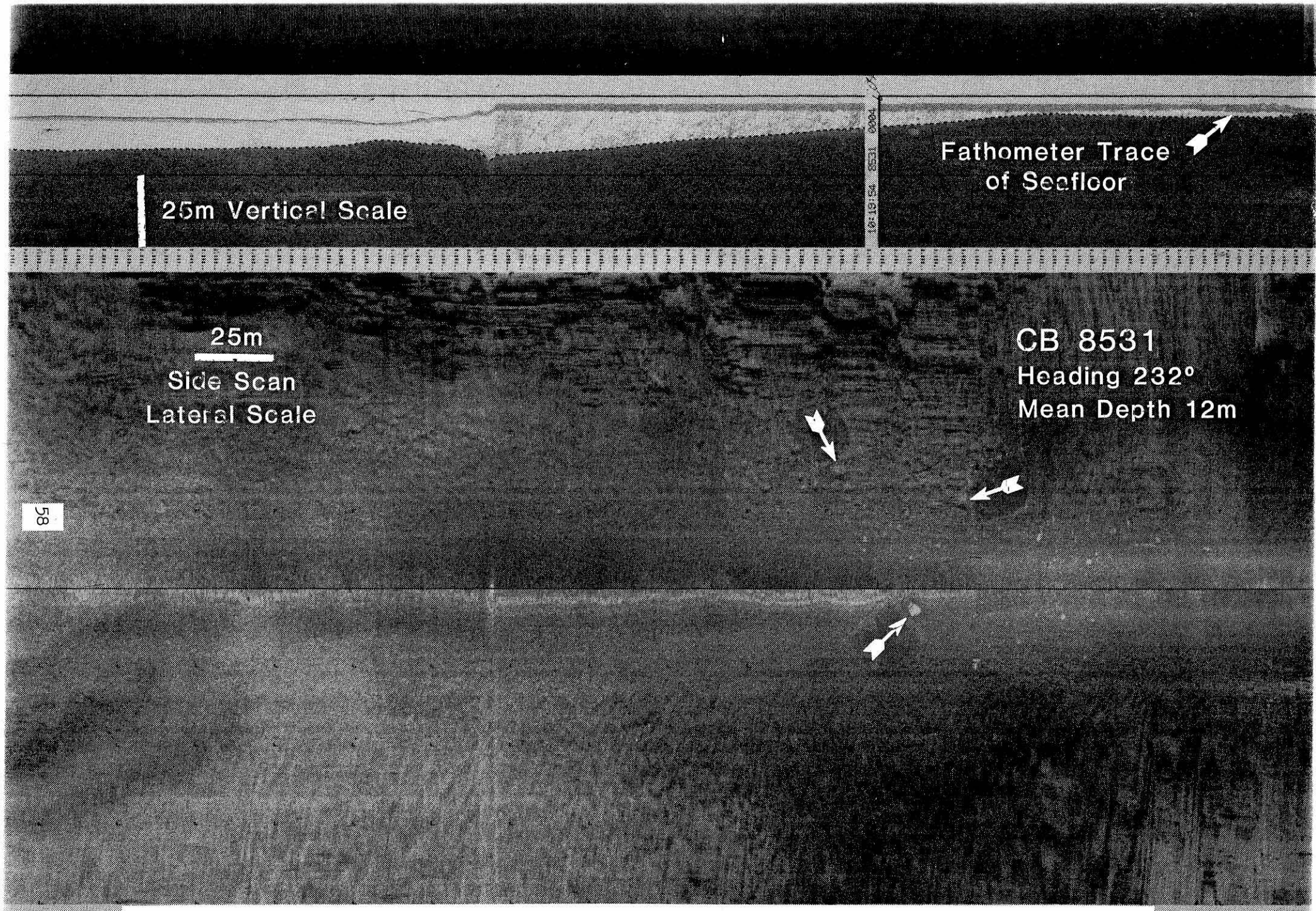


Figure 40. Side scan sonar image of inferred till deposit with numerous boulders (arrows).

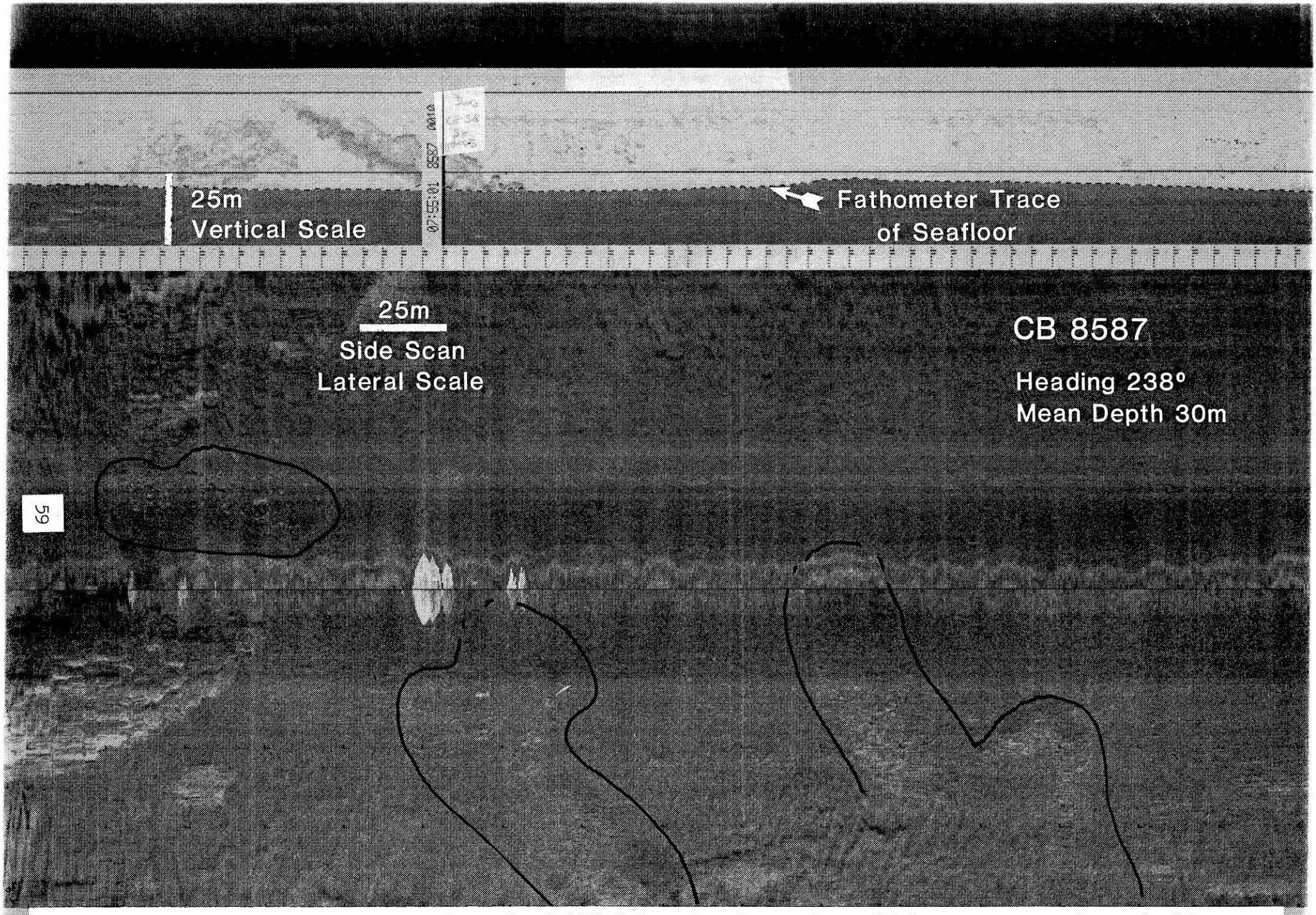


Figure 41. Side-scan sonar image of mounds of till inferred to be moraines. Light areas on mounds are boulders and the dark background of the image is indicative of gravel.

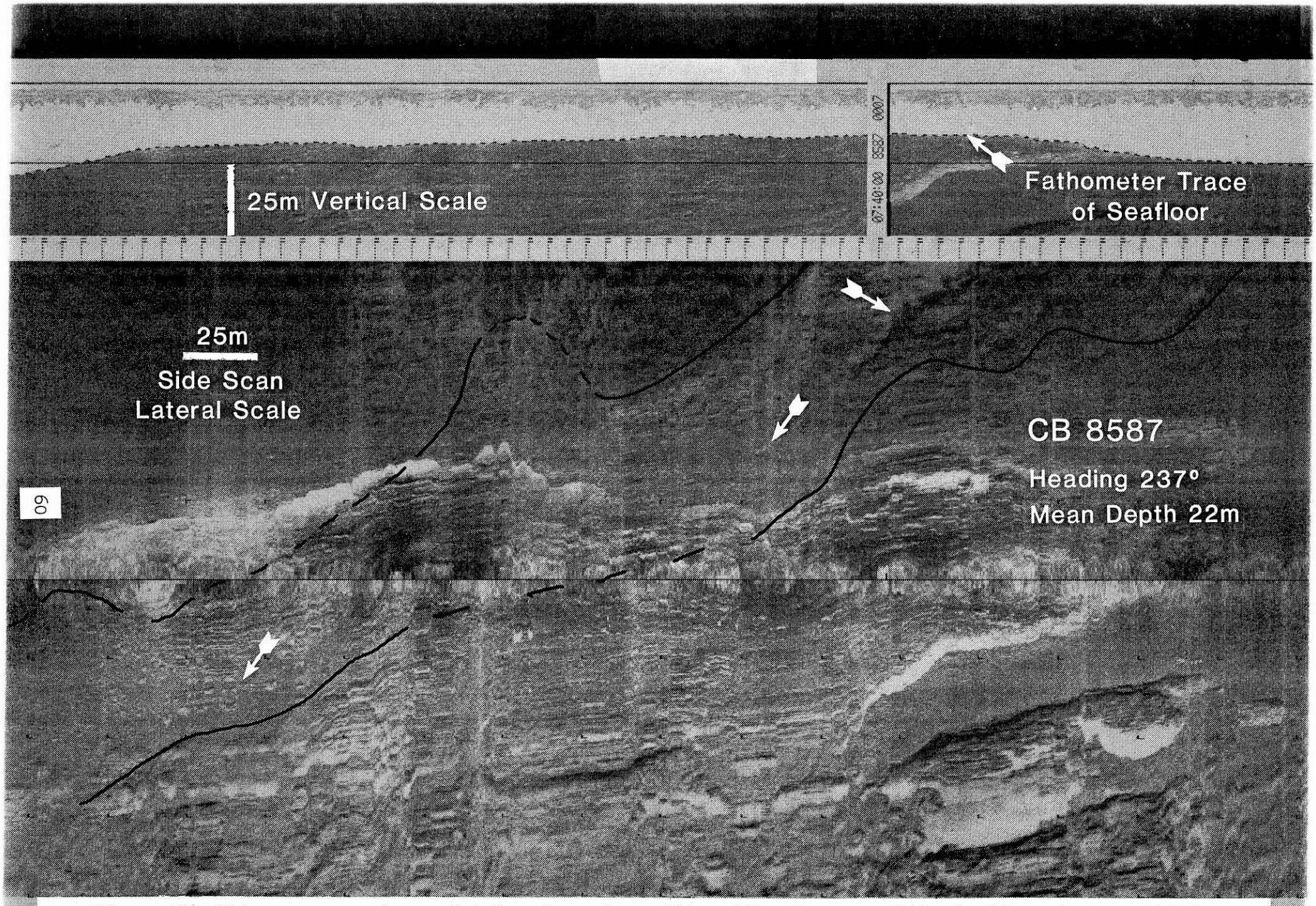


Figure 42. Side-scan sonar image of inferred moraine cutting obliquely across bedrock ridge. Arrows point to scarp in morainal ridge.

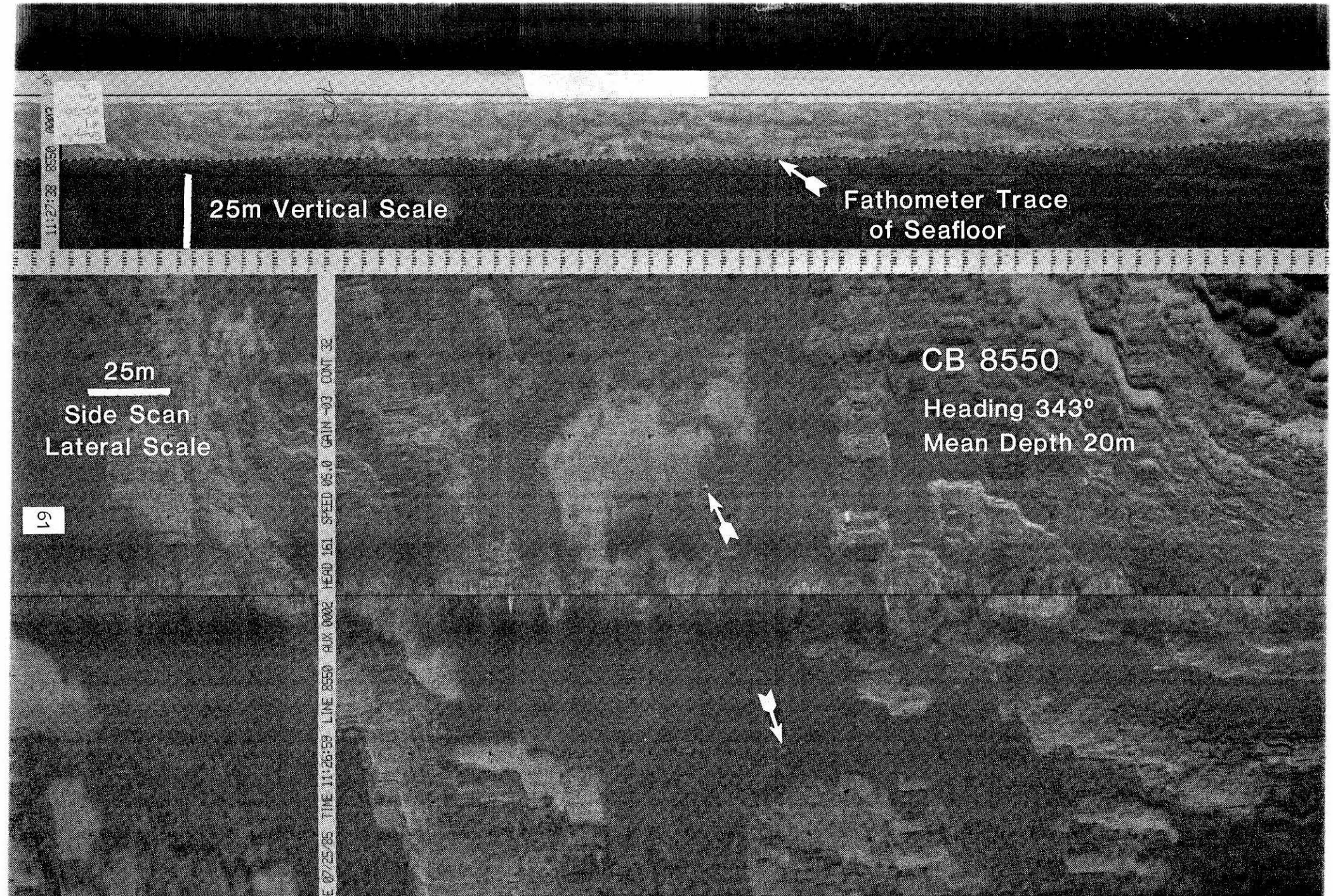


Figure 43. Side-scan sonar image of inner Casco Bay Rocky Zone which is inferred to be losing its younger sediment as the older, rockier glacial material emerges (arrows). Nearby megaripples are indicative of the wave/current scours.

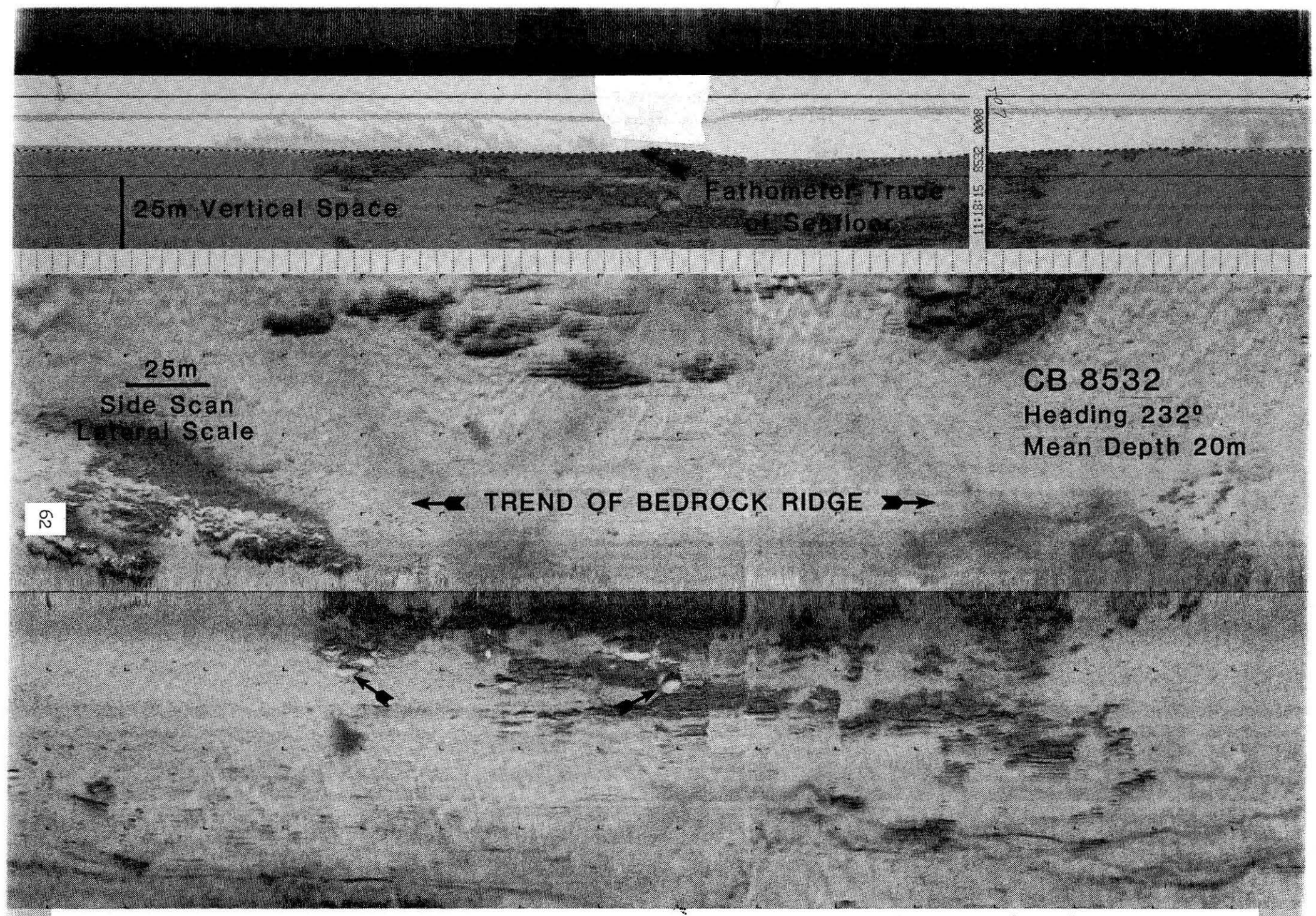


Figure 44. Side-scan sonar image of rock ridge and bouldery, overlying glacial sediment (arrow) emerging as younger sediment is stripped away.

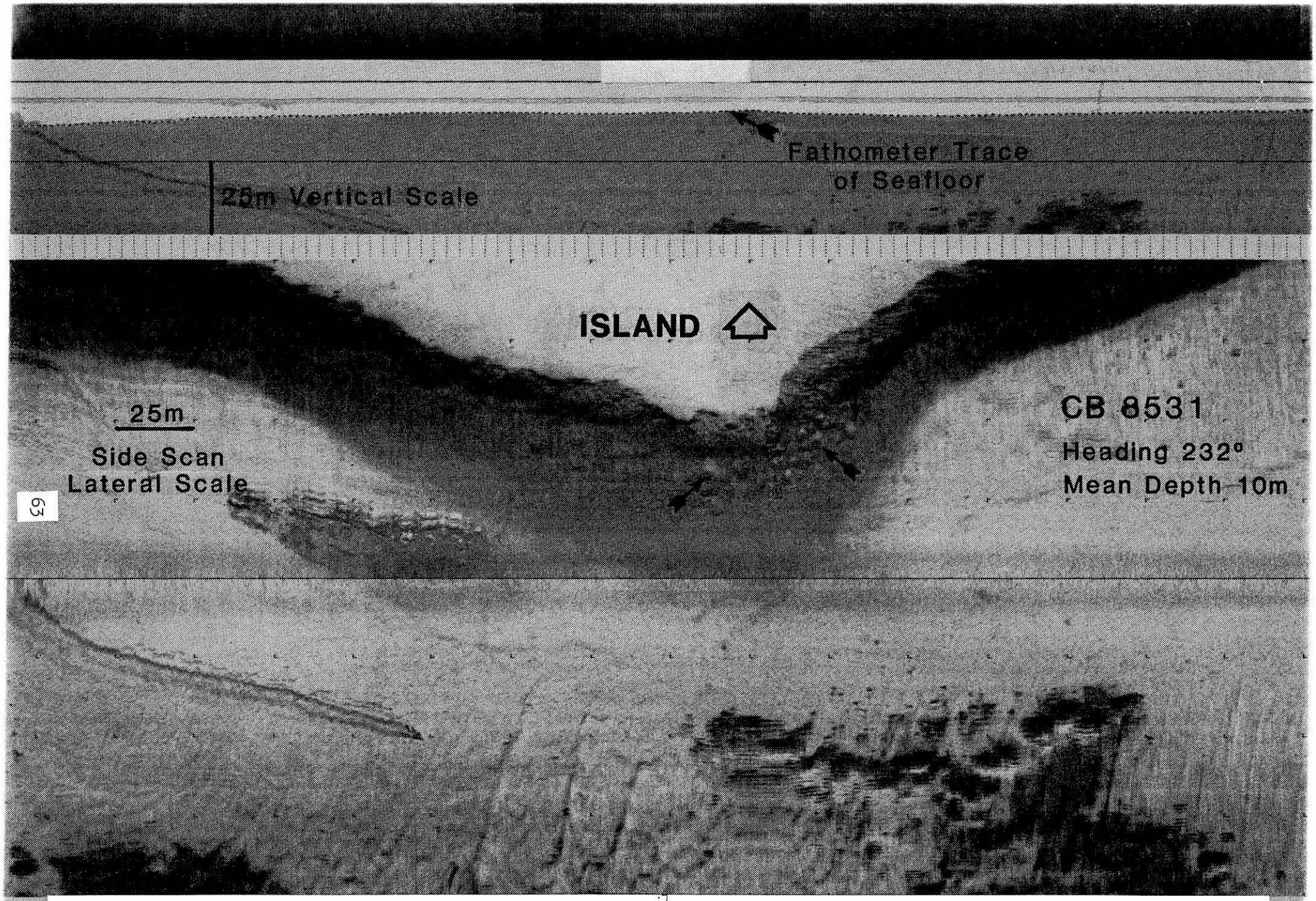


Figure 45. Gravel fringe (dark) adjacent to island and Nearshore Basin. Boulders may be derived from nearby island, or till deposit on edge of rock ridge.

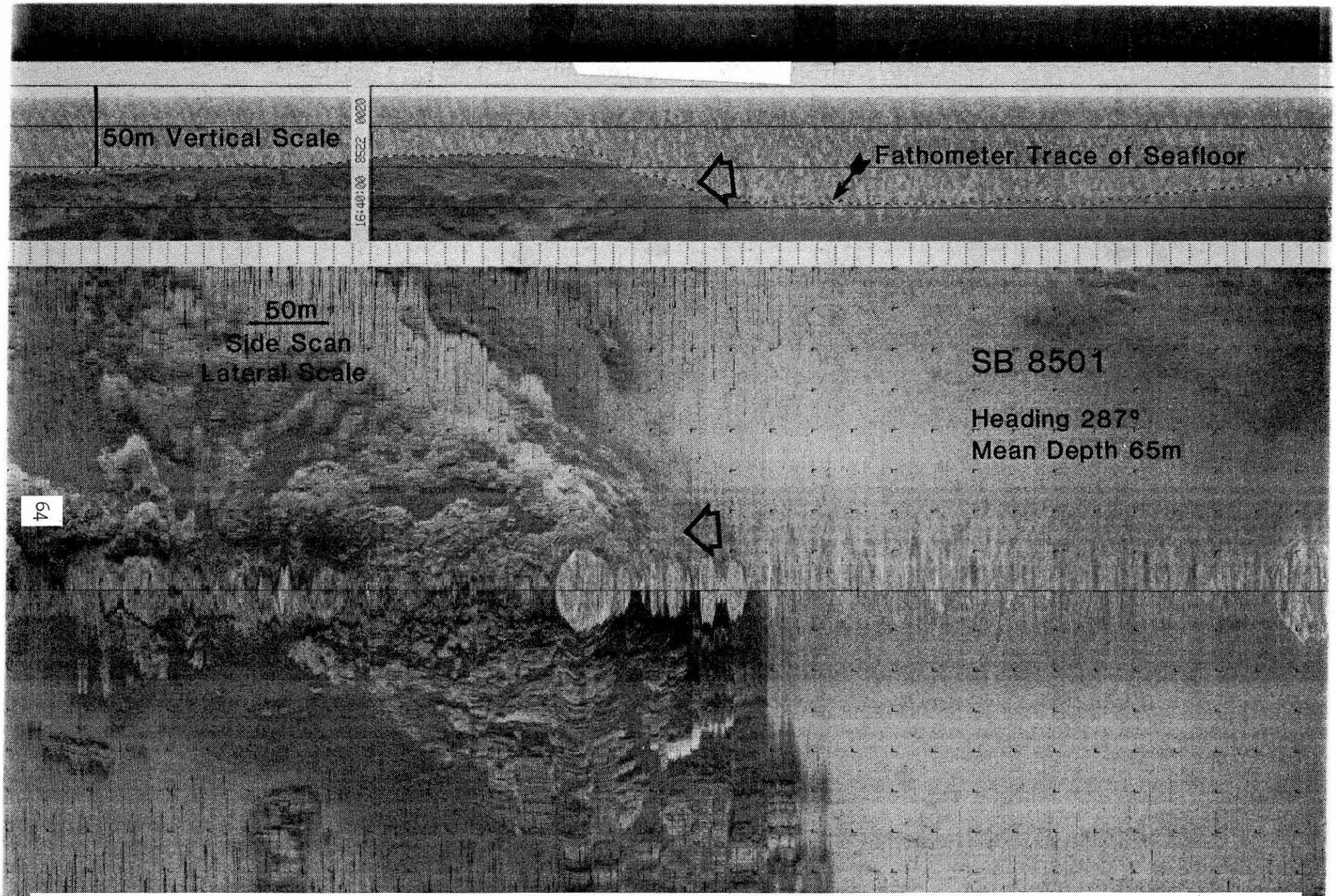


Figure 46. Side-scan sonar image of the transition (arrow) from the Rocky Zone to an Outer Basin between 50 and 75 meters depth. The muddy character of the Outer Basin (light) contrasts strongly with the bedrock (dark).

meters (Schnitker, 1974; Belknap and others, in press, b).

While most of the bottom sample stations from the Outer Basins contained mud, rock outcrops are apparent on the side-scan sonar imagery (Figure 47). The relief of the rock is subdued compared to nearshore exposures, however, and in many places the rock is covered with a thin layer of mud (Kelley, unpublished submersible notes). Gravel may be seen as a dark halo around the rock outcrops, but it is smaller in areal extent than that seen in the shallower Shelf Valleys (Figure 47).

GEOLOGICAL HISTORY AND ORIGIN OF SHELF SURFICIAL SEDIMENT

The south central Maine inner shelf is an area of unusually complex geology. Its physiography is controlled by numerous bedrock ridges which divide the area into a series of linear peninsulas, islands, and shoals with intervening depressions. One exception to this may be in the Outer Basin whose bathymetry remains unclear. The bedrock surface was probably incised by rivers at various times during the Quaternary (Denny, 1982) as well as during still earlier periods. This complex surface experienced a deglaciation ending around 13,000 years ago and accompanied by a marine inundation (Stuiver and Borns, 1975). Those topographically low areas, not already filled with till, were choked with the glaciomarine Presumpscot Formation between 13,000 and 11,000 years before present. Shortly after deposition of this muddy material, relative sea level fell and a new drainage was incised into the former seafloor at a depth of 65 meters (Schnitker, 1974). At this time Casco Bay apparently received sediment only from small, muddy streams originating locally, while the Sheepscot Bay area was inundated with sand from the combined drainages of the Androscoggin and Kennebec Rivers (Belknap and others, 1986). The sandy regressive, fluvial deposits of the upper Kennebec River valley have been called the Embden Formation (Borns and Hagar, 1965), although that name has not been used in this report. Since about 9,500 years ago (Belknap and others, in press, b) sea level has transgressed the predominantly sandy sediments of the Cape Small area, and the muddier material of Casco Bay, and reworked the older, unconsolidated sediments into today's shelf surficial cover (Figures 14, 16). There is, thus, a change in the nature of the shelf surficial sediments between Casco and Sheepscot Bays owing to their differing geological history, and a change in the inner and outer areas of each bay resulting from differing lengths of time exposed to marine action.

The inner portion of Casco Bay, the largest Nearshore Basin, is a bedrock depression almost entirely filled with sediment (Figure 48a). Since most of the modern material is introduced from eroding bluffs of the Presumpscot Formation, the Holocene sediment is muddy. Near the Royal River, where sandy, regressive sediment caps the Presumpscot Formation, the seafloor is muddy sand, and in many nearby places exposed beds of the Presumpscot Formation are eroding at the seafloor (Figure 48d). The seafloor of the inner Casco Bay area, however, is generally smooth except near outcrops of rock and adjacent to channels. Near islands and shoals, gravel deposits outcrop due to exhumation of Pleistocene sediments (Figure 43) or as a result of coarse-grained material introduced from a subaerial source (Figure 45). Near channels, tidal currents or waves are apparently

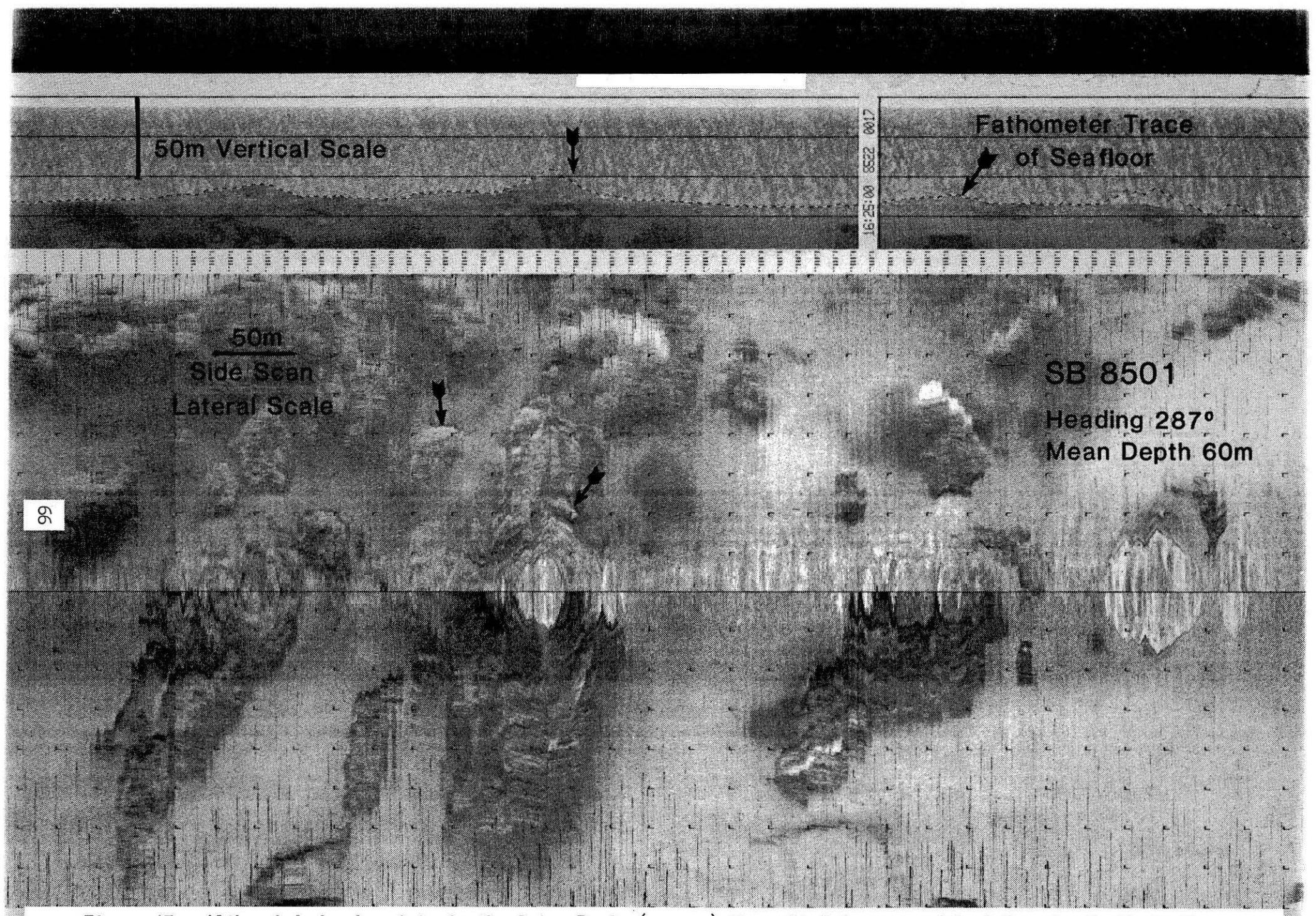


Figure 47. Although bedrock exists in the Outer Basin (arrows) the relief is more subdued than in the Rocky Zone and mud (light) covers most of the seafloor.

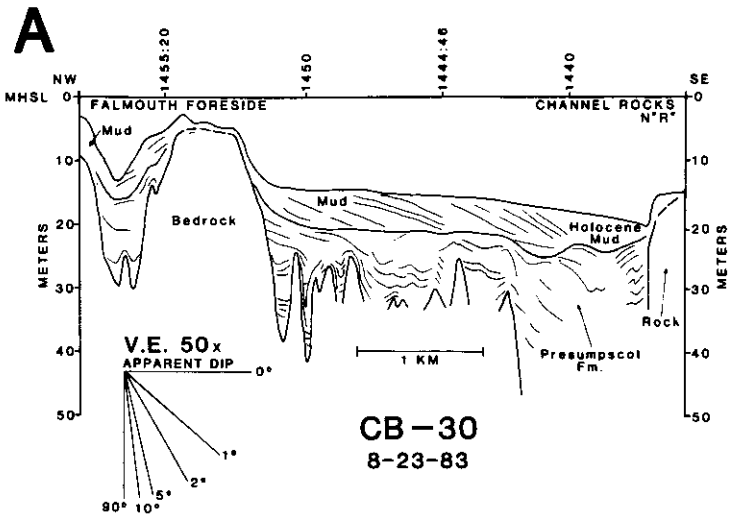


Figure 48a. Interpreted seismic profile normal to the strike of bedrock in the inner bay. CB-30: in areas protected from waves and currents the complete Quaternary stratigraphic section is preserved.

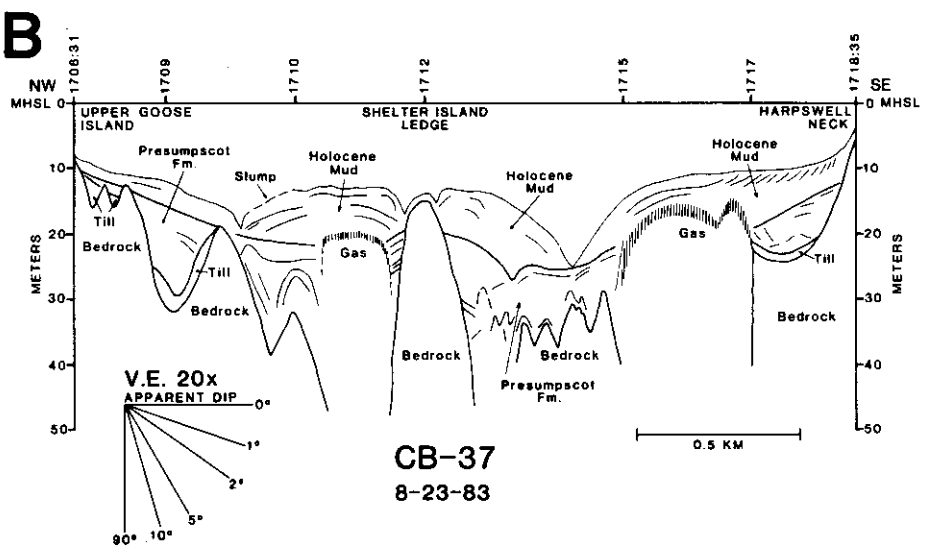


Figure 48b. Interpreted seismic profile normal to the strike of bedrock in the inner bay. CB 37: though these areas are sheltered from wave action, tidal currents are scouring Holocene muds, resulting in channels with slumping margins.

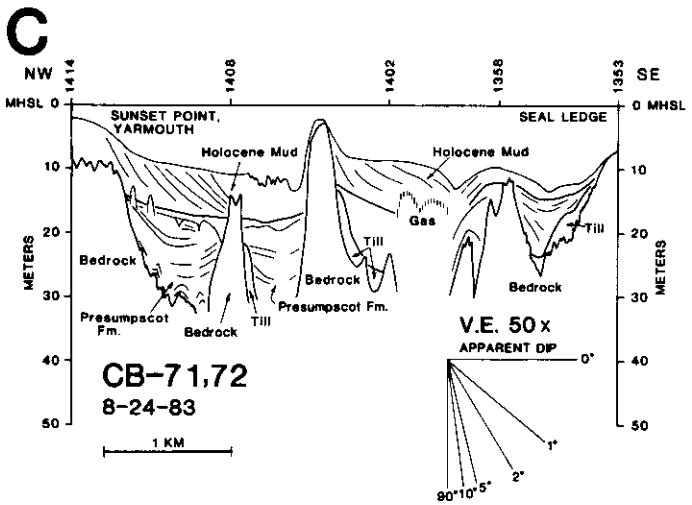


Figure 48c. Interpreted seismic profile normal to the strike of bedrock in the inner bay. CB 71 and 72: though these areas are sheltered from wave action, tidal currents are scouring Holocene muds, resulting in channels with slumping margins.

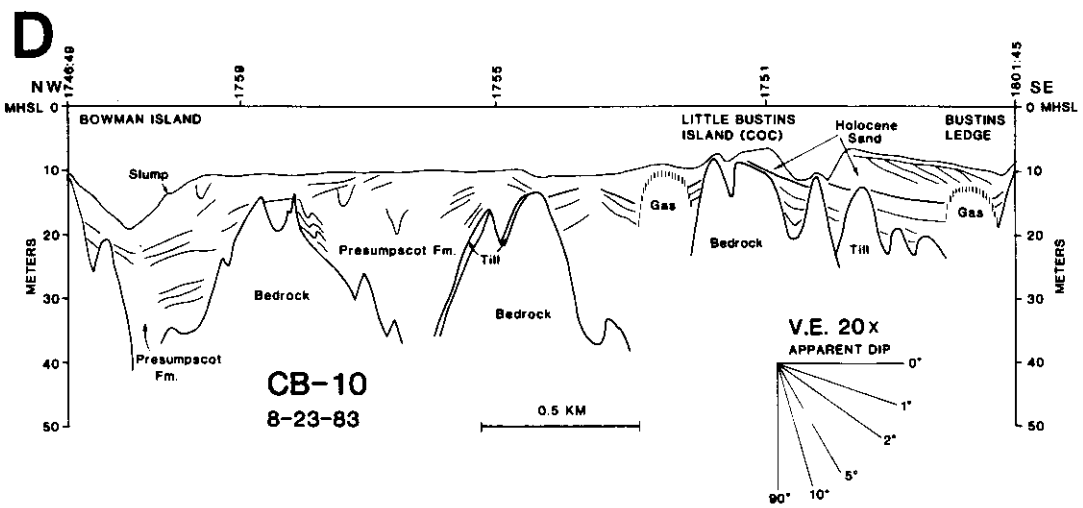


Figure 48d. Interpreted seismic profile normal to the strike of bedrock in the inner bay. CB-10: this exposed area has eroding Presumpscot Formation mud and Holocene sand at the surface. The sand appears to connect two islands and may represent a drowned tombolo. Natural gas may be seen in locations where a gully appears to have been cut into the Presumpscot Formation.

causing scouring and slumping of seafloor sediments (Figures 22, 24, 48b, 48c, 48d).

As one moves into central and outer Casco Bay, where the seafloor has been exposed to open ocean conditions for a long time, more extensive areas of exposed rock and gravel are found (Figures 16, 40, 41, 49). This is well observed in a seismic line normal to the bedrock strike (Figure 49c) which reveals increasing occurrences of exposed rock in a seaward direction. Most of the sediment in the outer bay exists in sediment ponds and is labeled "Presumpscot Formation" although palimpsest is possibly a better word. The seaward tilt of the sediment ponds is indicative of the rise of sea level across the area, just as the fluvial-terrace-like deposits banked against Luckse Sound and Halfway Rock probably reflect deposition during the sea-level lowstand (Figure 49c). The only apparently thick deposits of sediment in the outer bay area are till deposits whose coarse-grained surface has resisted erosion (Figure 10).

In the Kennebec-Sheepscot River region there is a similar transition from a region of sediment accumulation in the upper estuary (Figure 7) to one of slumping and sediment removal in the central area (Belknap and others, 1986) to a thoroughly reworked outer zone (Figure 50). The Sheepscot Bay and Boothbay regions are more like Casco Bay and its muddy substrate, however, than the sandy nearby Kennebec River mouth (Figure 16). The great volume of sand which covers most of the rock outcrops of the area could not even be penetrated by the seismic systems employed in the study (Figure 50b), and certainly is the source of sand for the Popham Beach and Reid State Parks. Although not yet removed by erosion, the great sand mass near Cape Small (Figure 11) is actively undergoing reworking by waves and currents today and is covered by megaripples indicative of that activity (Figures 25-27).

In summary, the inner shelf of south central Maine possesses Quaternary sedimentary deposits whose geometry is dictated by the shape of pre-glacial bedrock basins. The texture of the shelf surficial sediment is controlled by the nature of the eroding substrate and the degree of exposure to marine processes. Only in the inner Nearshore Basins, and estuaries which feed into them is modern sediment, generally mud, presently accumulating.

ACKNOWLEDGMENTS

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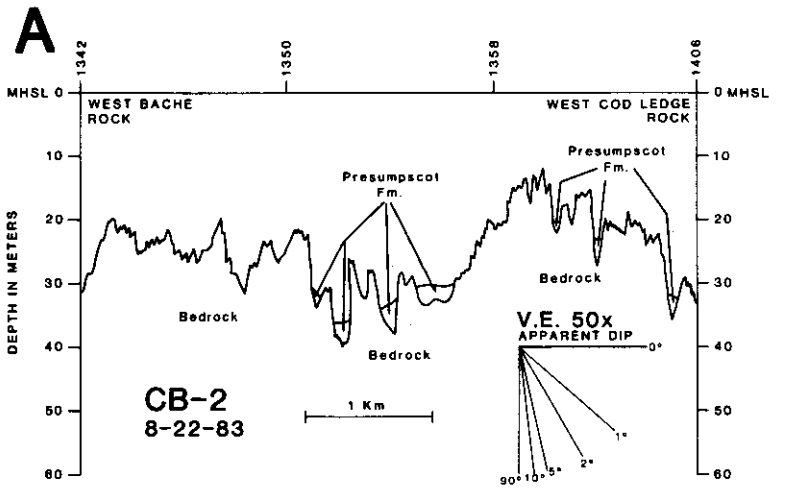

Figure 49a. Interpreted seismic profile from the outer bay. CB-2: much of the outer bay possesses no sediment cover, as seen in this digitized seismic reflection profile.

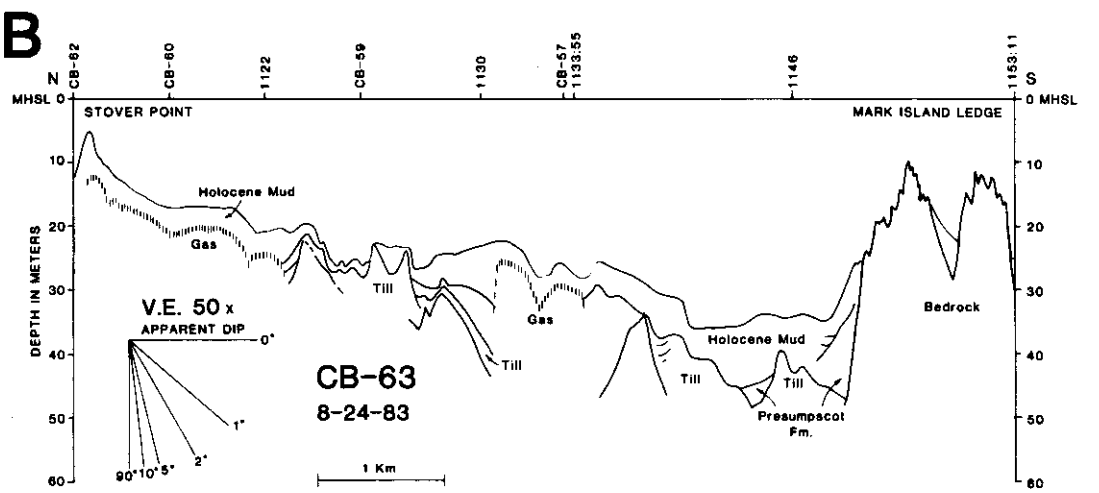

Figure 49b. Interpreted seismic profile from the outer bay. CB-63: this line shows the rapid transition from a protected embayment with abundant sediment to the exposed rock of the outer bay.

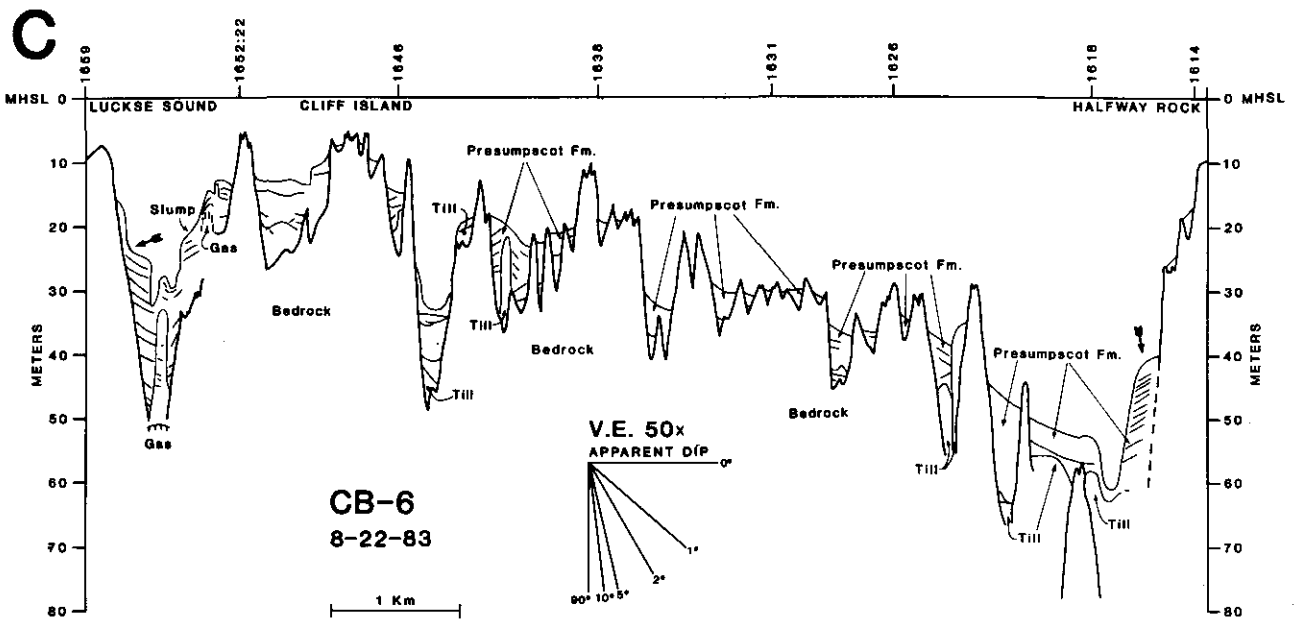

Figure 49c. Interpreted seismic profile from the outer bay. CB-6: along profiles normal to bedrock strike in the outer bay, sediment exists only in the ponds between rock ridges. Terrace-like landforms are visible adjacent to Halfway Rock and Luckse Sound, and may be fluvial in origin (arrows).

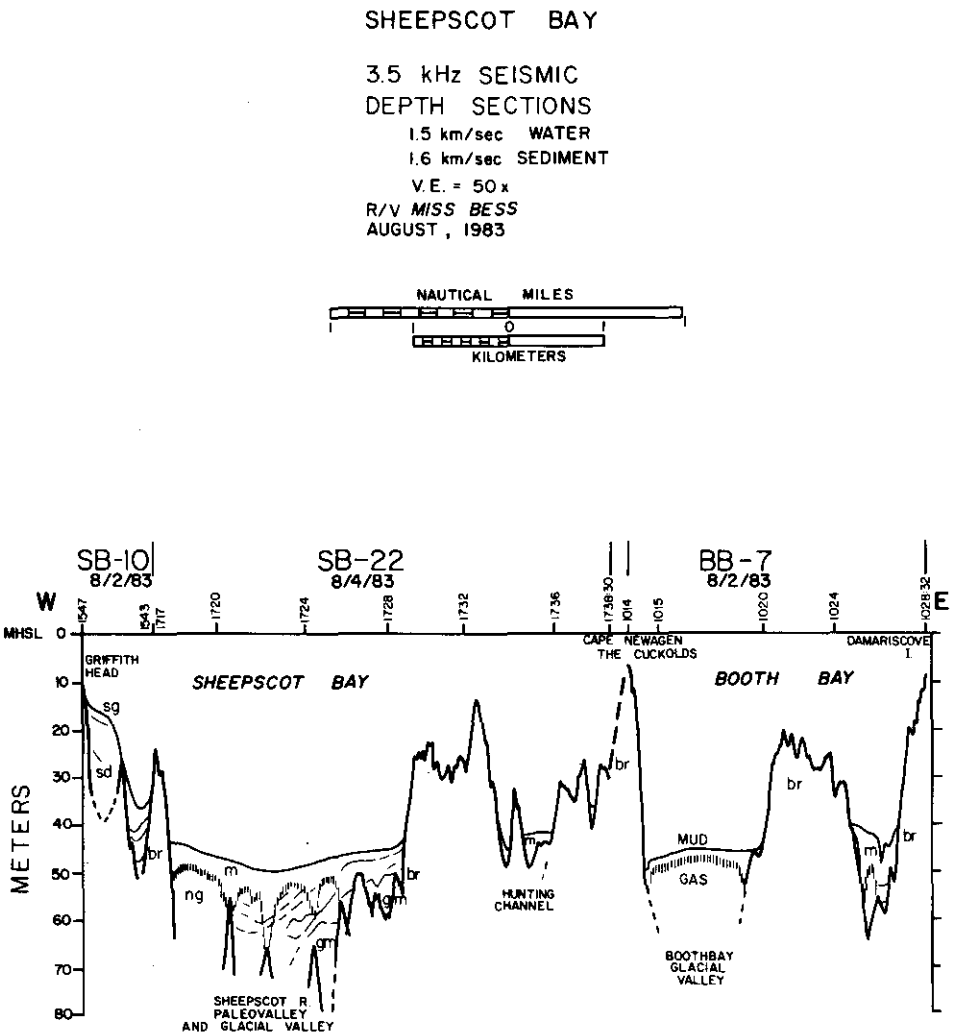

Figure 50a. Interpreted seismic reflection profile from Sheepscot Bay and Boothbay (from Belknap et al., in press, a). A cross section of the upper two Shelf Valleys is seen. Gas obscures most of the record.

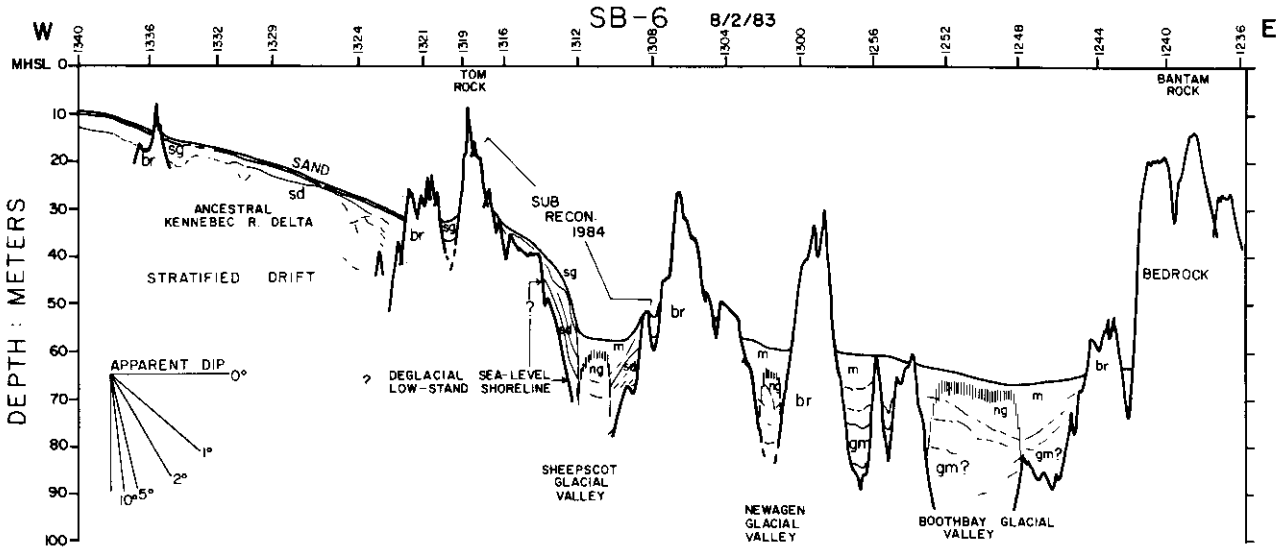

Figure 50b. Interpreted seismic reflection profile from Sheepscot Bay and Boothbay (from Belknap et al., in press, a). A cross section of the Sheepscot Bay and Boothbay Shelf Valleys as well as the "paleodelta" at the mouth of the Kennebec River.

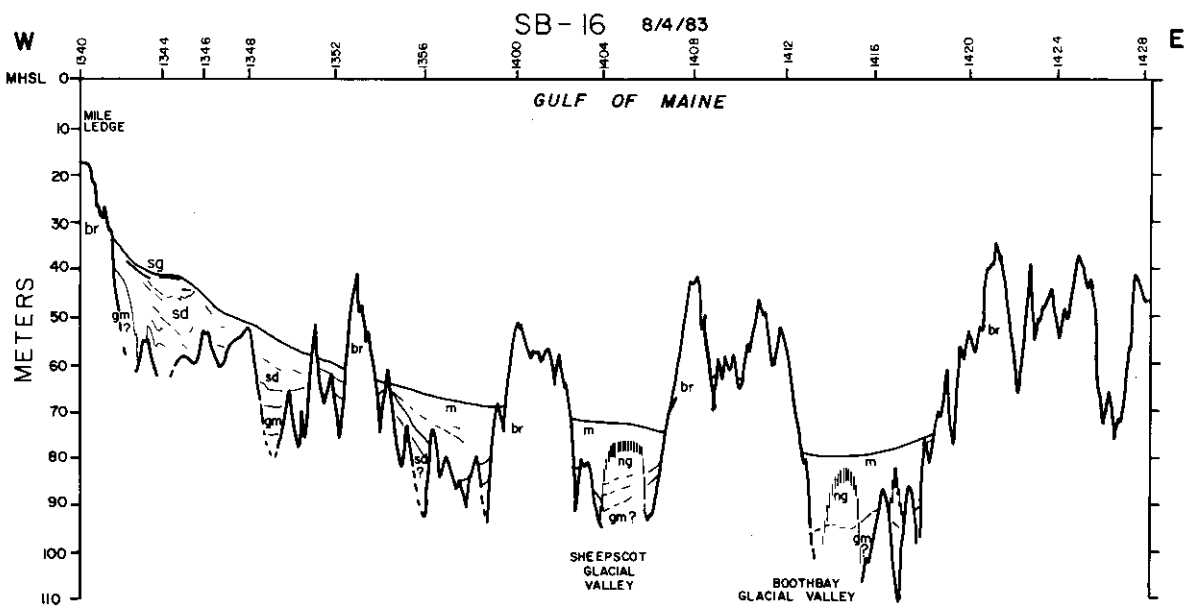

Figure 50c. Interpreted seismic reflection profile from Sheepscot Bay and Boothbay (from Belknap et al., in press, a). Cross sections of the outer Shelf Valleys showing the paucity of sediment filling the bedrock valleys seaward of 65 meters depth, which is the early Holocene lowstand depth.

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