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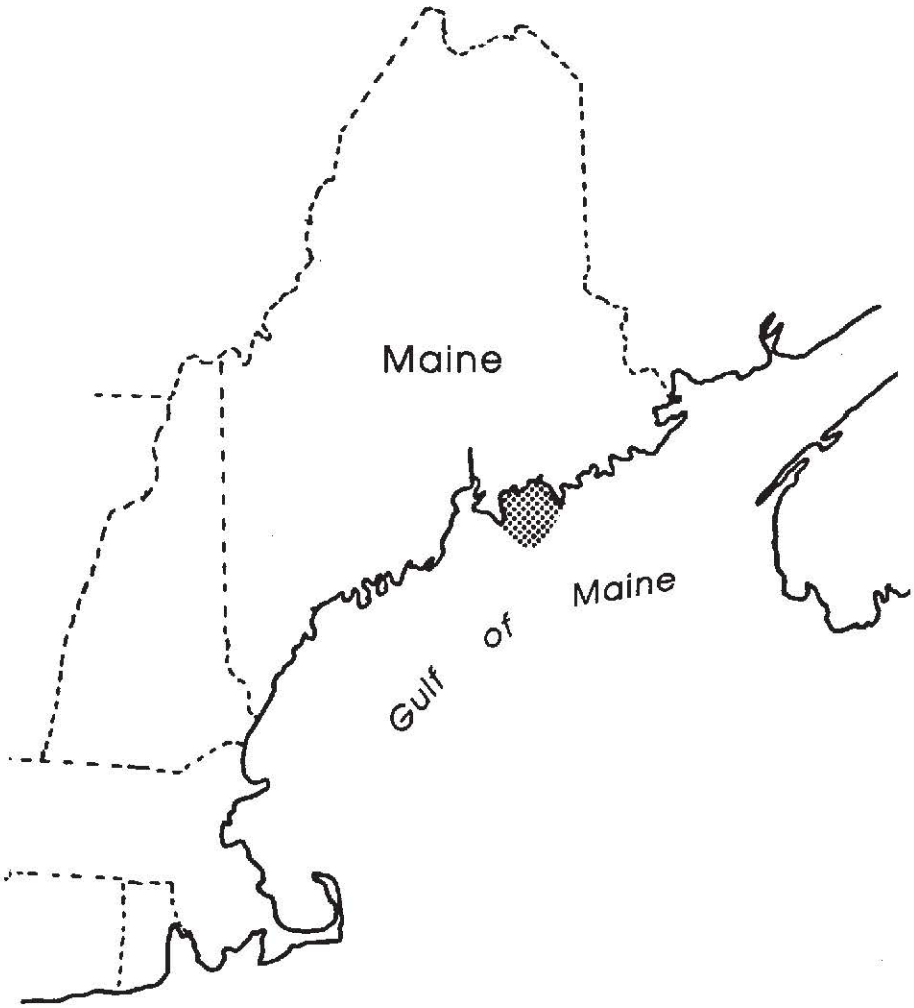
Geomorphology and Sedimentary Framework of Blue Hill and Frenchman Bays and Adjacent Inner Continental Shelf

by

Walter Barnhardt
Joseph T. Kelley



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DEPARTMENT OF CONSERVATION

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INTRODUCTION

This report describes the submarine geomorphology, surficial sediments, and Quaternary stratigraphic framework of the western Gulf of Maine within Frenchman and Blue Hill Bays, and along the adjacent inner continental shelf (Figures 1, 2). Although reference is made to many important terrestrial observations, the research is focused on the nearshore region out to the 100 meter isobath. Special emphasis is placed on the seafloor southeast of Mount Desert Island.

Within the study area, complexly-deformed bedrock ranges in age from Precambrian to Devonian, with mostly Precambrian to Ordovician metamorphic rocks (Ellsworth Formation) along the mainland of the bays, and Devonian granites forming islands in the bays (Osberg et al., 1985). Bedrock is widely exposed along the shoreline and exercises the primary control on the shape of the coast (Kelley, 1987). The Frenchman and Blue Hill Bays area is an important element of the Island-Bay Complex coastal compartment of Maine (Kelley, 1987). This area is characterized by broad embayments protected by numerous islands. The bays are generally carved out of metamorphic rocks, with granitic islands throughout the area. There are no large sand beaches in the bay, although small sand and gravel pocket beaches abound (Duffy, 1989). The intertidal zone of Frenchman and Blue Hill Bays is dominated by tidal flat deposits with mixed gravel and mud textures, derived from erosion of glacial sediments (Kelley, 1987).

Like other shelf areas of New England and the Canadian Maritimes, Frenchman and Blue Hill Bays have probably experienced numerous Quaternary glaciations, and relatively thin glacigenic sediment only partly mantles submerged bedrock exposures (Needell et al., 1983; Piper et al., 1983). Unlike the outer regions of the Gulf of Maine and beyond, however, local relative sea level has fluctuated profoundly in 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; Belknap et al., 1987; Kelley et al., in press). 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 the 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

Many people have studied the Pleistocene geology of Mount Desert Island, but little work has occurred in the adjacent bays. In the late 19th century Shaler (1889) (Table 1) mapped the surficial geology of the island and noted the overwhelming evidence for late Pleistocene sea-level changes. His map (Shaler, 1889) includes “blue clay” as a unit in most of the valleys of the island, and he recognized its glacial and marine affinities. He did not recognize the prominent moraines at the southern ends of

TABLE 1. PREVIOUS WORK IN THE MOUNT DESERT ISLAND REGION.

Study	Location	Data
Shaler, 1889	Mount Desert Island	Terrestrial surficial mapping
Bloom, 1960	Southwestern Maine	Regional terrestrial mapping
Bloom, 1963	Southwestern Maine	Study of sea level changes
Ostericher, 1965	Penobscot Bay	Seismic Stratigraphy, coring
Folger et al., 1972	Somes Sound	Bottom sediment mapping
Stuiver and Borns, 1975	Coastal Maine	Study of sea level changes
Smith, 1982	Coastal Maine	Terrestrial mapping of moraines
Thompson and Borns, 1985	Maine	State surficial map
Knebel, 1986	Penobscot Bay	Seismic stratigraphy
Kelley et al., 1987a	Southwestern Maine inner shelf	Seismic stratigraphy, bottom samples
Kelley et al., 1987b	Southwestern Maine inner shelf	Seismic stratigraphy, bottom samples
Kelley and Belknap, 1988	Muscongus Bay	Seismic stratigraphy, bottom samples
Lowell and Borns, 1988	Mount Desert Island	Terrestrial surficial mapping
Scanlon and Knebel, 1989	Penobscot Bay	Side-scan sonar
Kelley et al., 1990	Southwestern Maine, inner shelf	Cores

Jordan Pond and Echo Lake, however, and could not establish an exact chronology for the deposition of the mapped units.

Although Bloom did not work in central Maine, his description (1960, 1963) of southwestern Maine's glaciomarine sediment (Shaler's blue clay), which he elevated to formation status as the Presumpscot Formation, fits the muddy, late Quaternary deposits of the area very well. Thompson and Borns (1985) compiled large-scale surficial maps from around the region into a state surficial map. More recently, Lowell and Borns (1988) remapped Mount Desert Island on a large scale and depicted an association of moraines blocking the major valleys and lakes of the island, with glaciomarine sediment or deltas extending seaward from the moraines. The current model for deglaciation of this area invokes a floating ice shelf during the early stages of deglaciation. When the ice shelf became grounded upon topographic high places, such as Mount Desert Island, small moraines were deposited in close association with glaciomarine mud.

Ostericher (1965) was the first to employ coring and seismic reflection methods to examine submarine stratigraphy over the central Maine continental shelf. In Penobscot Bay, to the south of the study area, he described acoustic reflectors which correlated with bedrock, till, and the Presumpscot Formation, and described the acoustic properties of the surficial sediments, which he sampled. He recognized the complex transgressive/regressive unconformity on the surface of the Presumpscot Formation and dated wood fragments from cores of its surface at 7,390 years before present (yr B.P.). 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. On the basis of data collected for previous reports to the Minerals Management Service (Kelley et al., 1987a,b; Kelley and Belknap, 1988, 1989; Kelley et al., 1990) we have established that the lowstand is marked by shoreline deposits closer to the 60 meter isobath (Shipp et al., 1991). We have also inferred that the lowstand was reached around 10,500 yr B.P. (Kelley et al., in press).

In the nearshore environments of the Mount Desert Island area, Raymond and Stetson (1932) and Leonard et al. (1981) noted high concentrations of calcium carbonate (shells) on Cranberry Island Beach and Sand Beach, respectively. These anomalous high latitude shell beaches were interpreted to result from concentration of shells by waves in an environment depleted of clastic sediment. In Somes Sound, a fjord-like estuary on Mount Desert Island, Folger et al. (1972) also noted high carbonate concentrations associated with gravel deposits near the entrance to the bay. They mapped a generally muddy seafloor over much of the remainder of Somes Sound on the basis of bottom sampling. In 1985 the U.S. Geological Survey collected seismic reflection data across much of the study area, but did not otherwise interpret the records (Robert Oldale, Woods Hole, MA, personal communication).

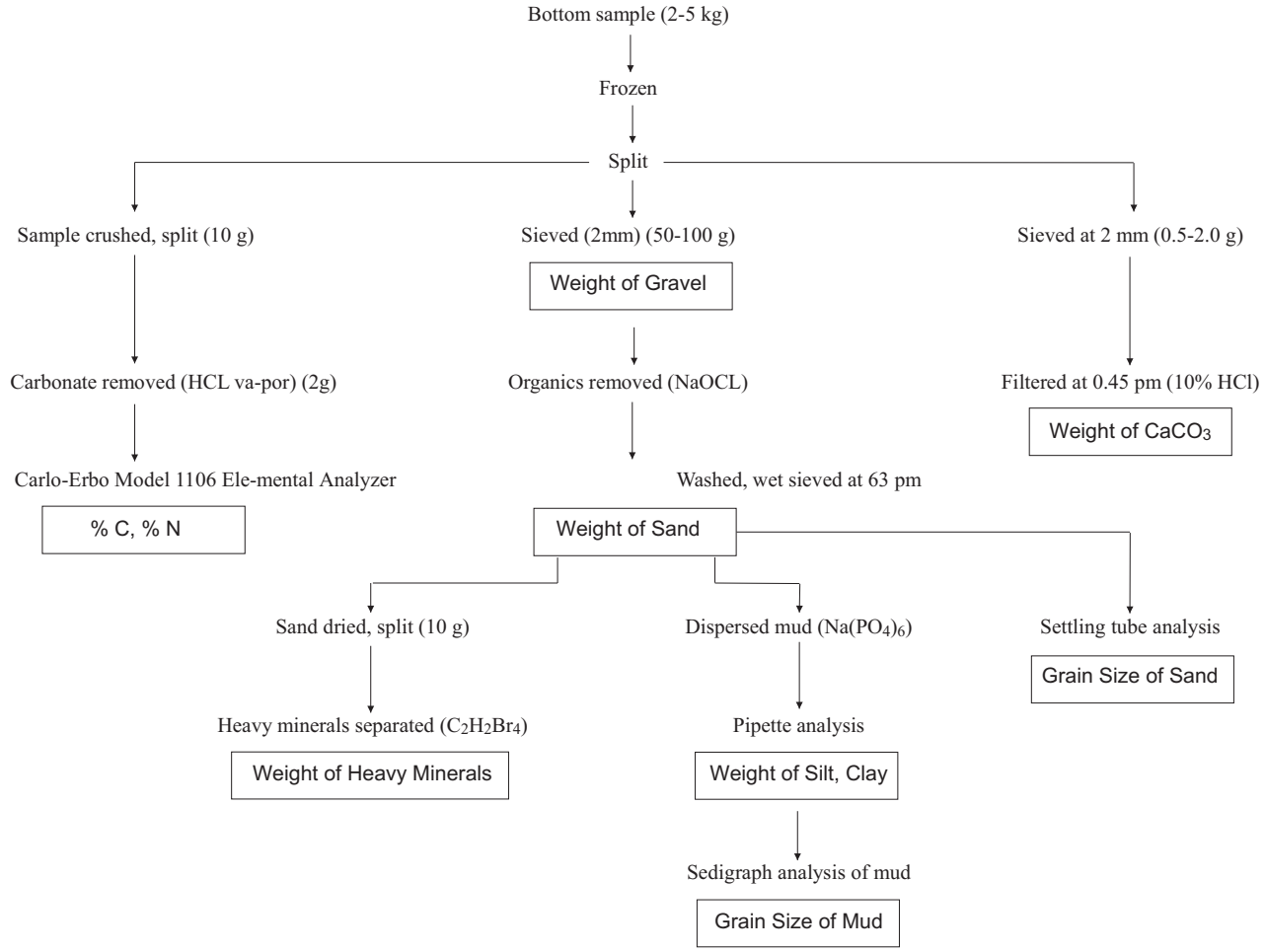
METHODS

Bottom Samples

During the summers of 1989 and 1990, 188 bottom samples were collected from the Blue Hill and Frenchman Bay region by means of a Smith-MacIntyre grab sampler (Figure 3). The device reliably gathers 0.25 cubic meters of sediment with minimal loss of material. Sample stations were generally located on LORAN-C time delay intersections, although special attention was focused on the region south of Mount Desert Island and north of the Cranberry Islands. This area is between sandy shell beaches previously reported (Raymond and Stetson, 1932; Leonard et al., 1981) and, thus, held the potential for significant accumulations of aggregate. All depths were evaluated by a Raytheon fathometer.

All samples were frozen immediately after collection and field description (Table 2). After sample splitting, gravel was screened out of a subsample which was refrozen for later carbon analysis. Gravel was also screened out of subsamples for car-

TABLE 2. DIAGRAM FOR THE ANALYSIS OF THE BOTTOM SEDIMENT.



bonate analyses, although the weight of gravel was determined. Carbon analyses were made by weight loss following ignition in a muffle furnace, while carbonate analyses were made by the acid digestion method of Molnia (1974). The textural analyses followed the outline of Folk (1974). A Micromeritics Sedigraph was employed to perform the mud fraction size analyses, and a rapid sediment analyzer (a settling tube) for the sand fraction.

Seismic Reflection Profiles

Seismic reflection profiles were made within the study area where no information had previously been gathered (Figures 4, 5). Navigation was by LORAN-C and position fixes were made every 4-5 minutes. Two types of seismic equipment were employed during the study: an ORE Geopulse "boomer", and an EG&G "boomer" system. The seismic systems 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 and overall geometry of the surface acoustic return. The seismic lines were, thus, useful for interpolating between the relatively widely-spaced bottom samples. In all, 490 kilometers of seismic reflection records were interpreted for this study.

Interpretation of the subbottom geology was based on inferences drawn from observations on land and from nearby studies where core samples were available (Kelley et al., 1990). 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. A seismic unit with chaotic internal reflectors and an irregular surface occasionally rested on bedrock. This has been interpreted as till, and small moraines, discussed below, may exist exist within the study area. 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 sur-

TABLE 3. BOTTOM SEDIMENT DATA.

Station	Description	% $CaCO_3$	% C	% Clay	% Silt	% Sand	% Gravel	Mean (phi)	Std. Dev. (phi)
1	mG	0.5	6.9	36	22	27	15	5.7	5.2
2	M		9.1	50	50	0	0	9.1	2.6
3	mG	0.8	7.9	45	27	12	16	6.1	5.7
4	sG	9.9	1.0	4	1	16	79	-1.8	2.0
5	sG	16.3	1.3	3	1	33	63	-1.3	1.9
6	sG	13.0	1.7	8	2	36	54	-1.5	2.2
7	HB								
8	HB								
9	sG	0.3	1.5	8	5	46	41	-0.1	3.3
10	sG	1.2	4.1	TR	TR	51	47	0.3	2.6
11	mG	0.9	3.5	34	20	35	11	5.6	5.0
12	gS	1.3	1.8	10	7	59	24	1.7	4.0
13	gS	1.5	3.3	20	14	58	8	4.4	4.1
14	M	0.8	4.0	34	20	46	0	6.7	3.8
15	gS	0.7	2.2	17	10	66	7	4.6	3.8
16	mS	0.6	2.2	14	8	78	TR	4.0	2.8
17	HB								
18	mS	1.4	1.5	14	3	81	2	3.9	3.0
19	HB								
20	gS	6.9	4.1	7	1	74	18	1.2	3.0
21	sG	2.1	4.2	11	3	57	29	0.7	3.5
22	gS	44.9	1.9	TR	TR	66	33	-0.6	1.6
23	sG	7.1	2.2	5	2	38	55	-1.3	2.7
24	HB								
25	gS	4.8	3.8	13	3	73	11	2.8	2.6
26	HB								
27	gS	1.4	2.2	13	5	75	7	3.7	3.0
28	gS	2.6	0.6	8	2	65	25	1.3	3.5
29	gS	11.1	1.8	15	7	58	20	2.5	4.6
30	mS	1.3	1.4	14	6	79	1	4.0	2.6
31	mG	22.5	4.8	21	10	30	39	2.3	5.4
32	M	0.7	1.9	56	30	12	2	9.9	3.6
33	mS	1.8	1.8	22	10	63	5	5.5	3.4
34	mS	0.1	2.0	20	9	69	2	5.3	3.2
35	mS	1.6	5.0	17	6	77	0	4.7	2.9
36	mS	4.9	3.0	16	6	74	4	4.5	3.0
37	gS	63.9	2.2	10	5	65	20	0.6	3.0
38	gS	47.4	3.2	TR	TR	86	12	1.8	1.2
39	gS	39.6		TR	TR	88	10	1.4	1.1
40	HB								
41	mS	53.3	2.2	9	4	84	3	1.3	1.5
42	gS	19.5	1.0	15	3	71	11	3.3	3.8
43	gS	2.0	1.0	19	5	68	8	4.4	4.5
44	gS	8.9	2.2	16	5	53	26	2.9	4.9
45	gS	14.2		11	5	61	23	2.5	4.3
46	mS	0.3	3.8	29	8	62	1	6.1	3.9
47	mS	0.6	2.7	30	18	51	1	6.1	3.9
48	HB								
49	mS	0.6	3.0	31	13	56	TR	6.0	3.8
50	HB								
51	gS	3.4	0.7	19	8	44	29	3.2	5.3
52	sG	6.2	0.7	4	1	28	67	-1.2	3.3
53	HB								
54	HB								
55	sG	8.9	1.3	13	5	27	55	0.8	4.9
56	gS	0.5	1.2	15	8	60	17	3.0	4.5
57	gS	0.1	0.7	15	7	62	16	2.6	4.3
58	mG	0.0	1.1	11	5	11	73	-0.5	4.2
59	sG	4.7	0.9	16	1	42	41	2.3	5.1

Textural Designation:

HB = Hard Bottom, no sample
G = Gravel
S = Sand
M = Mud

mG = muddy Gravel
gS = gravelly sand
sG = sandy Gravel
mS = muddy Sand

TR = Trace Amount

TABLE 3. CONTINUED.

Station	Description	% $CaCO_3$	% C	% Clay	% Silt	% Sand	% Gravel	Mean (phi)	Std. Dev. (phi)
60	gS	6.8		12	5	66	17	1.4	3.1
61	gS	65.2	0.5	TR	TR	71	28	-0.3	1.5
62	S	49.1	0.8	4	2	90	4	1.2	1.1
63	S	38.0	0.6	TR	TR	98	1	1.5	0.3
64	S	6.3	1.2	4	1	92	3	1.9	0.9
65	HB								
66	sG	2.0	1.9	8	2	50	40	0.8	3.8
67	sG	0.1	3.4	16	8	33	43	2.5	5.1
68	mS	4.5	3.3	TR	TR	78	1	3.9	3.3
69	sG	1.9	2.3	10	4	39	47	0.2	3.9
70	mS	0.9	3.8	25	11	64	TR	5.1	3.5
71	M	1.1	3.3	36	14	48	2	6.4	4.1
72	sG	0.7	1.1	12	5	53	30	1.2	4.2
73	HB								
74	HB								
75	M	2.3	5.4	59	34	7	TR	8.9	3.8
76	mG	1.8	2.7	23	18	25	34	2.9	5.8
77	M	1.4	4.6	59	39	TR	TR		
78	M	1.3	5.3	58	41	1	0	9.8	3.7
79	M	0.9	5.2	48	51	1	TR	8.6	3.0
80	M	2.1	4.9	58	29	9	4	9.3	3.3
81	M	0.7	3.7	61	31	7	1	9.2	3.6
82	M	1.6	5.1	64	35	1	TR	9.5	2.4
83	M	0.8		66	30	4	TR	10.0	3.4
84	M	2.7	7.4	73	24	3	TR	10.1	3.0
85	sG	2.4	0.7	17	16	34	33	2.4	5.1
86	mG	1.5	2.0	18	14	28	40	1.9	5.3
87	mG	1.9	1.8	26	14	22	38	1.8	4.9
88	sG	2.1	0.9	9	6	42	43	4.2	7.6
89	gS	0.4	2.8	16	14	43	27	2.9	4.9
90	mS	0.6	1.9	26	10	64	0	5.8	3.8
91	mS	0.5	1.4	18	4	77	1	4.7	3.2
92	gS	67.3	0.8	16	4	52	28	2.4	5.0
93	sG	90.2	0.8	12	2	27	59	-0.9	3.8
94	gS	60.2	0.7	2	1	76	21	0.1	1.5
95	S	64.9	0.9	4	2	90	4	1.5	1.4
96	S	43.7	0.7	7	2	90	1	1.6	1.4
97	S	36.4	0.8	2	2	96	TR	1.8	0.5
98	S	50.4	1.0	TR	TR	97	TR	1.6	0.4
99	S	43.3	0.9	4	1	95	TR	1.9	0.7
100	S	35.0	1.0	4	2	93	1	1.8	1.3
101	S	36.1	0.6	TR	TR	97	1	1.9	0.5
102	S	44.9	0.6	TR	TR	97	TR	2.0	0.5
103	gS	48.9	1.2	2	2	89	7	0.8	0.9
104	HB								
105	HB								
106	HB								
107	sG	0.8	1.2	12	5	46	37	0.9	4.4
108	HB								
109	mG	3.3	0.8	30	11	33	26	3.9	5.9
110	G	14.0	0.9	3	1	17	79	-1.9	1.5
111	sG	95.1	0.3	12	3	34	51	-0.6	3.5
112	sG	27.1	0.9	4	1	23	72	-1.7	1.9
113	HB								
114	HB								
115	HB								
116	gS	33.3	0.4	2	1	71	26	-0.1	1.9
117	S	51.2	0.7	TR	TR	97	1	2.0	0.5
118	S	61.2	0.6	TR	TR	96	1	2.4	0.6

Textural Designation:

HB = Hard Bottom, no sample
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S = Sand
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mG = muddy Gravel
gS = gravelly sand
sG = sandy Gravel
mS = muddy Sand
TR = Trace Amount

TABLE 3. CONTINUED.

Station	Description	% $CaCO_3$	% C	% Clay	% Silt	% Sand	% Gravel	Mean (phi)	Std. Dev. (phi)
119	gS	39.0	0.8	TR	TR	85	12	1.8	1.2
120	mS	13.0	2.3	28	15	56	1	5.6	3.4
121	mS	0.9	3.6	19	6	71	4	4.7	3.4
122	S	0.5	2.4	5	1	92	2	3.0	1.4
123	SampleLost								
124	gS	3.3	1.6	11	6	62	21	2.0	4.0
125	sG	9.4	1.1	TR	TR	34	63	-1.1	2.1
126	mS	0.1	3.7	21	5	72	2	5.0	3.7
127	sG	22.4	0.4	TR	TR	23	77	-1.9	1.4
128	S	1.1	1.2	6	1	92	1	2.4	1.4
129	mS	35.7	4.1	30	7	62	1	5.9	4.2
130	sG	42.8	1.2	TR	TR	36	62	-1.3	2.0
131	G	53.9	0.3	0	0	14	86	-2.3	1.3
132	HB								
133	gS	66.3	2.2	3	2	89	6	1.5	1.1
134	HB								
135	S	12.8	1.0	TR	TR	97	1	2.8	0.3
136	S	19.3	1.0	3	2	95	TR	2.9	0.4
137	HB								
138	sG	93.6	2.3	TR	TR	23	76	-1.5	1.9
139	sG	53.5	1.5	TR	TR	62	35	-0.6	1.5
140	HB								
141	HB								
142	HB								
143	HB								
144	mS	1.6	0.7	21	4	70	5	4.7	3.5
145	HB								
146	HB								
147	S	0.9	1.2	5	1	93	1	3.3	0.9
148	mS	4.8	2.5	18	4	73	5	4.3	3.3
149	sG	10.2	1.7	TR	TR	30	69	-1.3	2.0
150	HB								
151	sG	21.7		TR	TR	27	72	-1.4	1.9
152	gS	58.2	2.9	4	2	78	16	0.6	2.2
153	sG	3.1		5	4	22	69	-1.0	2.0
154	M	2.3	4.3	74	20	6	TR	10.3	2.7
155	mG	1.6	1.8	32	22	20	26	4.8	5.7
156	gS	1.7	1.3	18	9	58	15	3.4	4.6
157	M	0.4	6.1	77	22	1	0	10.4	2.6
158	M	0.7	4.4	69	30	1	0	9.9	2.7
159	M	0.9	3.6	73	23	4	0	10.4	2.8
160	M	1.6	3.3	53	33	14	0	8.6	3.5
161	M	0.9	3.3	67	32	1	0	9.7	2.7
162	M	2.0	3.4	73	25	2	TR	10.0	2.6
163	M	2.3	2.3	50	14	35	1	7.7	4.1
164	M	1.1	1.6	43	19	37	1	7.3	4.1
165	HB								
166	sG	1.0	2.0	13	5	42	40	1.9	4.8
167	sG	8.5	1.1	4	3	25	68	-1.1	3.0
168	HB								
169	gS	73.2	2.2	17	6	54	23	2.5	4.9
170	HB								
171	HB								
172	mS	2.7	1.2	23	9	65	3	4.7	4.0
173	mS	0.3	2.6	38	11	50	1	6.1	4.2
174	HB								
175	HB								
176	HB								
177	HB								

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TR = Trace Amount

TABLE 3. CONTINUED.

Station	Description	% $CaCO_3$	% C	% Clay	% Silt	% Sand	%Gravel	Mean (phi)	Std. Dev. (phi)
178	HB								
179	mG	0.9	2.7	19	8	25	48	2.0	5.5
180	M	0.6	4.2	43	21	36	TR	7.2	3.8
181	sG	2.2	2.6	12	6	47	35	1.9	4.4
182	M	0.5	5.4	71	23	6	0	10.7	2.8
183	M	4.2	6.0	85	12	3	TR	11.6	2.2
184	M	1.4	6.6	58	19	23	0	8.5	4.0
185	gS	1.9	2.5	21	12	56	11	4.8	4.4
186	M	0.8	4.2	35	19	46	TR	6.8	4.0
187	mS	0.6	2.6	26	10	64	TR	5.6	3.7
188	sG	23.2		7	4	35	54	1.7	3.9

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mS = muddy Sand
TR = Trace Amount

face this unit was identified as the glaciomarine Presumpscot Formation. Where it outcrops on land and its upper surface is eroding, the regressive unconformity is presently forming; while the offshore surface of the glaciomarine sediment is probably capped by the transgressive unconformity. Overlying the Presumpscot Formation, an acoustically transparent unit of modern mud was recognized in many places. Locally, a relatively thin, acoustically hard unit existed over the glacigenic material or bedrock. Side-scan sonar and bottom samples suggest this is a sand and gravel deposit. As in nearby areas (Kelley et al., 1987a,b; Kelley and Belknap, 1988; 1989) natural gas occurences were recognized throughout the study area.

Seafloor Observations

Observations of the seafloor were made by side-scan sonar profiling. The side-scan system used was the EG&G model 260 Seafloor Mapper. This system automatically provides slant-range corrections to the analogue output. It was usually run at a 100 or 200 meter range (to either side of the vessel). Many of the side-scan lines coincided with seismic reflection profiles, and 330 kilometers of side-scan records were collected in the study area (Figures 5, 6).

BATHYMETRY

The seafloor of the Blue Hill and Frenchman Bays region is as bathymetrically complex as is the topography of the adjacent islands and mainland (Figure 7). As in areas to the south (Kelley et al., 1989; Kelley and Belknap, 1991), the bathymetry is best understood when simplified to five physiographic compartments (Figure 8).

The Nearshore Basins are generally shallow, low relief regions adjacent to the mainland, and separated from other areas by islands and/or shoals. The contact between the basins and the mainland is gradational, and mud and gravel flats are the most common intertidal environments bordering the basins. In most Nearshore Basins in Maine, the seafloor is smooth except near bedrock outcrops (Kelley et al., 1987a,b, Kelley and Belknap, 1988). In upper Blue Hill Bay, however, an extensive area of pockmarks has disturbed the formerly flat seafloor as in nearby Penobscot Bay (Scanlon and Knebel, 1989; Kelley and Belknap, 1989).

Shelf Valleys are long, narrow depressions which usually extend from the Nearshore Basins to gradual terminations in deep water. The Shelf Valleys south of outer Blue Hill and Frenchman Bays typically range in depth from 30-60 meters. These valleys are usually bordered by bedrock walls, and may possess numerous outcrops of rock or depressions along their axes.

The Rocky Zones exhibit extreme relief ranging from 10 meter vertical cliffs to extensive areas of large boulders. In Blue Hill and Frenchman Bays, the local rock is commonly granite, and so there are few of the sediment ponds which are often associated with elongate cracks and cleavage in foliated rocks (Kelley et al., 1987b). Surrounding most of the large islands of the bays are shoals which may be littered with boulders, but rarely contain large sediment pockets.

The seaward portion of the study area is the Outer Basin, which generally forms the border of the study area. This is the least known of the physiographic regions because of the lack of detailed bathymetric data. In Blue Hill and Frenchman Bays the seafloor appears rocky for a considerable distance seaward of the limits of this study to the Jeffrey's Bank area (U.S. Geological Survey, 1975).

In general, the bathymetry of the study area is shallow and smooth in the the Nearshore Basins of the upper reaches of the bays except where it is broken up by islands (Long Island, and small islands near Bar Harbor, Figures 2, 7, 8). Water deeper

than 60 meters begins abruptly south of the islands and continues as Shelf Valleys to the south (Figures 7, 8). An extensive rocky platform less than 40 meters deep extends directly south of Mount Desert and the Cranberry Islands and separates the Shelf Valleys. While this platform appears smooth when depicted by a 20 meter contour interval (Figure 7), at a 5 meter contour interval it is extremely complex. The Outer Basin was not well surveyed during this study, but appears more irregular than similar physiographic regions to the south.

BOTTOM SEDIMENT TEXTURE AND COMPOSITION

Bottom sediment texture on glaciated shelves is notoriously heterogeneous (Trumbull, 1972). All components of the particle size spectrum were encountered in bottom samples from the Blue Hill and Frenchman Bay inner shelf (Figures 9, 10; Table 3). Gravel was one of the most common bottom sediments, unlike other shelf areas to the south (Kelley et al., 1987a, b; Kelley and Belknap, 1988, 1989). A very large occurrence of gravel exists in the Rocky Zone (Figure 8) directly south of the Cranberry Islands and Mount Desert Island. Smaller patches crop out on the margins of islands in northern Frenchman Bay and central Blue Hill Bay (Figure 9). One nearshore ramp directly south of Bass Harbor (Figure 8) is floored by gravel. At a scale not mappable, gravel surrounds most of the submerged bedrock in the area.

Sandy gravels and gravelly sands are also more common in this region than in areas to the south. While these occurrences are often associated with gravel outcrops, sandier constituents are most abundant in the relatively shallow water directly south of Mount Desert Island. Clean sands are exclusively located in this area as well, and all samples with greater than 90% sand are found in water depths less than 20 meters (Figure 11). Although they are small, the beaches on the south shore of Mount Desert Island extend seaward as a nearshore ramp (Figure 8) whose surface is largely comprised of sand and gravel.

Muddy gravels were rarely sampled and probably exist only adjacent to rock outcrops. Muddy sands are uncommon also, and are concentrated along the margin of the Outer Basin (Figures 8, 9). Along with gravels, muds are among the most common of seafloor materials (Figure 9; Table 3). Muddy bottoms are located in the relatively shallow water of the Nearshore Basins or deeper water of the Outer Basins. As a result, while mud concentration generally increases with depth, the correlation is weak.

As expected from previous work (Kelley et al., 1987a), the proportion of organic matter increases with increasing mud content. Although no samples exceeded 10% carbon (Table 3) many relatively high values were recorded from the finest sediment. Since fine-grained sediment was generally more abundant in deeper water (Figure 11), the higher carbon values were also from deep water.

Carbonate material was mostly associated with coarse-grained sediment, and thus, was most abundant in shallower water (Figure 11). All of the carbonate values greater than 30% were from water depths less than 40 meters (Figure 11).

GEOPHYSICAL OBSERVATIONS

Bottom sediment properties correlate well with environmental settings defined by bathymetry (Figures 7, 8, 9). Considerable variation exists, however, within the various regions. This variation is best depicted by the more detailed examination of surface sediments permitted by side scan sonar and the subbottom information generated by seismic reflection data. The seismic reflection profiles also provide insight into the geological history of the region, which further abets understanding of the overall sedimentary framework.

Nearshore Basins

As in other parts of the Maine inner shelf, Nearshore Basins are major environments of sediment accumulation in the Blue Hill and Frenchman Bay region. These basins are oriented northwest-southeast and separate Mount Desert Island from the mainland to the east and west (Figure 8). The seafloor of the Nearshore Basins is uniformly muddy except adjacent to rock outcrops. Seismic profiles indicate that the seafloor mud is dynamic, with alternating regions of sediment erosion and accumulation. To the northwest of Mount Desert Island the seafloor descends toward the center of the basin where an elevated region exists. Across the sloping surface, the closely-spaced reflectors of the glaciomarine sediment are truncated at the seafloor (Figure 12), suggesting on-going erosion of that muddy material. The raised area at the center of the basin is floored by what we interpret as modern mud. The mound of modern mud appears supported by natural gas at a shallow depth. To the east of the mound, the seafloor ascends the other wall of the basin across what we again interpret as eroding glaciomarine material at a depth of 70 meters. At about 50 meters we believe modern mud lies unconformably over the glaciomarine sediment.

Most of the central axis of the basin (Figure 13) is also floored by a relatively thin (averaging 10 meters) wedge of what we interpret as modern mud overlying natural gas, with glaciomarine reflectors occasionally cropping out on the seafloor. Similarly, the central axis of the Nearshore Basin on the western side of Mount Desert Island possesses thin and patchy deposits of modern mud over an eroded or eroding substrate of glaciomarine sediment 10-15 meters thick. At the northwest end of this basin, near Long Island (Figures 2, 5), a widespread and apparently thick occurrence of what we interpret as natural gas appears (Figure 14). This feature is associated with depressions that are v-shaped in cross section and circular in plan view (Figures 15, 16), and up to 30 meters deep. We (Kelley and Belknap, 1989) and others (Scanlon and Knebel, 1989) have called these depressions pockmarks in Penobscot

TABLE 4. RADIOCARBON DATES ON INDIVIDUAL CONSTITUENT ORGANISMS FROM SAMPLE NO. 61.

Organism	Size Fraction	% of Sample	Description	^{14}C Age (yrs B. P.)
Barnacle	Gravel	24.4	Light tan, shiny luster, angular plates	104.3% modern
Barnacle	Sand	9.9	Brown to dark gray, dull luster, mod. rounded	770 40
Echinoderm	Gravel	1.7	Green spines and sugary white plates (whole), mod. rounded	320 55
Echinoderm	Sand	0.8	Small spines and plates (whole)	No date

Bay because of their similarity to gas-escape structures elsewhere in the world.

Rocky Zones

The Rocky Zones are the most widespread physiographic areas on this part of the inner shelf, and their geology is varied. In the area between Mount Desert Island and the Cranberry Islands (Figures 2, 8) much of the seafloor is relatively flat and veneered with coarse gravel that is difficult to sample. Over large areas it has been dragged by commercial fisherman (Figure 17). At the entrance to Somes Sound prominent glacial moraines with up to 5 meters of relief provide the hard surface of the Rocky Zone (Figure 18). Samples from this area are generally gravelly, but complex as was noted by Folger et al. (1972). Exposed bedrock crops out commonly seaward of the high cliffs of Mount Desert Island and defines the Rocky Zone there (Figures 19, 20). Between the rock exposures coarse gravel composed of clastic sediment shapes a flat or sloped seafloor, while carbonate sand and gravel commonly exists in extensive fields of rippled bedforms (Figures 19, 20). Radiocarbon dates on the shells are all modern, and become younger with decreasing grain size (Table 4). This suggests that the shells, which are primarily hard-substrate-dwelling mussels, echinoderms and barnacles, are formed on the rock exposures and transported toward the nearby sandy, shell beaches (Barnhardt, 1991; Leonard et al., 1981).

Nearshore Ramps

Unlike the extensive Nearshore Ramps along the southern Maine inner shelf (Kelley et al., 1987a, b), there are only 2 such areas in the study region, and they are small (Figure 8). The Nearshore Ramp near Northeast Harbor extends from 40 meters depth to the shoreline, and is mantled by ripples of shelly sand and gravel like the nearby Rocky Zone (Figures 19, 20). Seismic data across the ramp suggest that the shelly surficial sediment is a thin (2 meters) veneer over glaciomarine sediment (Figure 21). A larger area with a regular, gentle seaward slope occurs between Bass Harbor and some islands to the south. This area is less than 20 meters deep and floored by gravel of various sizes (Figure 22). All previously mapped Nearshore Ramps (Kelley et al., 1987a, b) are sandy and abut sand beaches. It is notable that this gravel ramp connects with several small gravel beaches on the nearby islands (Duffy et al., 1989).

Shelf Valleys

Two Shelf Valleys continue seaward from the two Nearshore Basins (Figure 8) between about 40 and 70 meters depth. Like the basins, the Shelf Valleys are floored by muddy modern sediment, or fine-grained glaciomarine material (Figures 23, 24) that appears to be eroding. The textural transition from rock to gravel to mud from the neighboring Rocky Zones is usually abrupt, and often occurs over less than 25 meters.

Outer Basins

Owing to budgetary constraints, little data were gathered from the Outer Basins. While the deep water basins occupy a great deal of area (Figure 8), bedrock may occupy much of the seafloor (Figure 25). Large areas of mud were mapped or inferred on the basis of the side-scan sonar imagery (Figure 9), but less than 1% of the Outer Basins were surveyed. As in other Outer Basins along Maine's inner shelf, gravel appeared to surround the bedrock outcrops, regardless of depth.

EVOLUTION AND SEDIMENTARY FRAMEWORK OF THE INNER CONTINENTAL SHELF NEAR FRENCHMAN AND BLUE HILL BAYS

The Quaternary sedimentary framework of the Mount Desert Island region has been most strongly influenced by deglaciation, and the sea-level changes which accompanied it (Stuiver and Borns, 1975; Belknap et al., 1987). Melting ice, possibly in the form of an ice shelf, reached the present Maine coast between 13,800 and 13,200 yr B.P.. Many washboard moraines, representing brief grounding-line positions of the ice, were observed in Muscongus Bay (Kelley and Belknap, 1988), to the south of the study area, although none were recognized from Frenchman or Blue Hill Bays. Large glacial moraines are mapped at the southern ends of many of Mount Desert Island's lakes and valleys (Lowell and Borns, 1988), and Folger et al. (1972) speculated that the surficial gravels at the entrance to Somes Sound marked a moraine. Side-scan sonar records confirm this interpretation and reveal prominent, gravel-strewn ridges across the entrance to the Sound (Figure 18). These correlate with eroding bluffs of gravel observed on the land adjacent to the sound. No outwash deltas still exist seaward of these moraines as on land, presumably due to subsequent erosion. The

coarse-grained outwash was likely reworked during the current transgression into the homogeneous sheet of terrigenous sand and gravel found between Mt. Desert Island and the Cranberry Islands (Figures 9, 17).

Accompanying retreat of the ice, glaciomarine sediment, the Presumpscot Formation, was deposited. In some locations the lower portion of this acoustic unit displays closely-spaced seismic reflectors indicative of rapid deposition of beds of coarse and fine grained sediment (Figure 21). It appears that most of the depressions of Frenchman or Blue Hill Bays were rapidly filled with this glaciomarine sediment during deglaciation. Fossils from the emergent glaciomarine sediment throughout Maine typically yield radiocarbon dates around 12,500 yr B.P. (Stuiver and Borns, 1975; Smith, 1982). On the west side of Mount Desert Island (Goose Cove), fossil shells have been dated at 12,250 yr B.P. (Gilman et al., 1988). By 11,000-12,000 yr B.P. it is felt that sea level had withdrawn to the elevation of the present coast (Belknap et al., 1987; Kelley et al., in press) as a consequence of isostatic uplift due to unloading of the ice. The Presumpscot Formation was then exposed to subaerial erosion sometime between about 11,000 yr B.P. and 9,500 yr B.P. By 9,500 yr B.P. it is inferred that sea level was at its lowstand around 60 meters below present sea level. No information on the depth of the lowstand has yet been uncovered from Blue Hill or Frenchman Bays.

The upper part of the glaciomarine sediment is marked by a strong reflector which has been recognized from cores as an unconformity (Ostericher, 1965; Knebel, 1986; Kelley et al., 1990 and in press). The regressive unconformity on the surface of the glaciomarine sediment is only interpreted from one location in Maine where a thick deposit of river sediment covers it in Penobscot Bay (Kelley and Belknap, 1989). We infer that the strong reflector, which truncates lower reflectors from what is interpreted as the glaciomarine sediment throughout the study area, is the transgressive unconformity (Figures 12, 13, 14, 15, 21, 23, 26, and 27).

Much of the sediment which had existed in the bays was reworked during either the late Pleistocene regression or the Holocene transgression. The extensive, shallow Rocky Zones represent what remains following that reworking. Only in the more-protected Nearshore Basins and Shelf Valleys were important thicknesses of sediment preserved (Figures 26, 27). Even here, however, currents have apparently begun to remove glaciomarine mud where it is well exposed (Figure 21). "Moating" or scouring around rock outcrops (Figures 21, 22) and slumping (Figure 12) appear to be as important in Blue Hill and Frenchman Bays as in other Maine embayments (Kelley et al., 1987a, b; Kelley and Belknap, 1988, 1989). Earlier, Ostericher (1965) commented often on the number of slump deposits he interpreted from Penobscot Bay, as did Kelley et al. (1989), from other regions of the state.

At some point after a considerable thickness of Holocene sediment had accumulated in upper Blue Hill Bay, natural gas was generated and began to accumulate in the fine grained sediment. For reasons that are not yet clear, the gas apparently began to escape from the sediment, possibly in conjunction with pore waters as suggested in adjacent Penobscot Bay (Scanlon and Knebel, 1989; Kelley and Belknap, 1989). Once a small pockmark was begun, it is simple enough to envision additional gas and water migrating from nearby sediment and enlarging the depression. Scouring of a hole apparently ceased when the bottom reached the surface of the Presumpscot Formation, and the end of the natural gas. What caused the gas to be released in the first place (if indeed this is the cause of the pockmarks), we do not know. When they began to form, and whether they are still forming, we do not yet know either.

We have recognized other features like the Blue Hill pockmarks in Penobscot Bay and Fader (1988) has recently described similar features from the U.S.-Canadian boundary. They invoked seismicity as the mechanism for initiation of the pockmarks. While this idea is plausible in Penobscot Bay where faulting has been recognized (Rand and Gerber, 1976), no seismic activity is known from Blue Hill Bay. Much more remains to be learned about the pockmarks before all aspects of their occurrence are explained.

A considerable effort was made to better document the occurrence and abundance of carbonate sediments in Frenchman Bay. Although observations on carbonate abundance were made from throughout the area, shell-rich bottom sediment was only common in the area southeast of Mount Desert Island. The recent age of the shells and the increasing age with decreasing grain size support the suggestion that the carbonate is presently forming in the Rocky Zone south of Mount Desert Island. Waves and currents (Figures 19, 20) then transport the shells toward the coast where they accumulate on a few local beaches. The rate of production and destruction of the shells is not known, and so no assessment of the value of the material as aggregate can be made.

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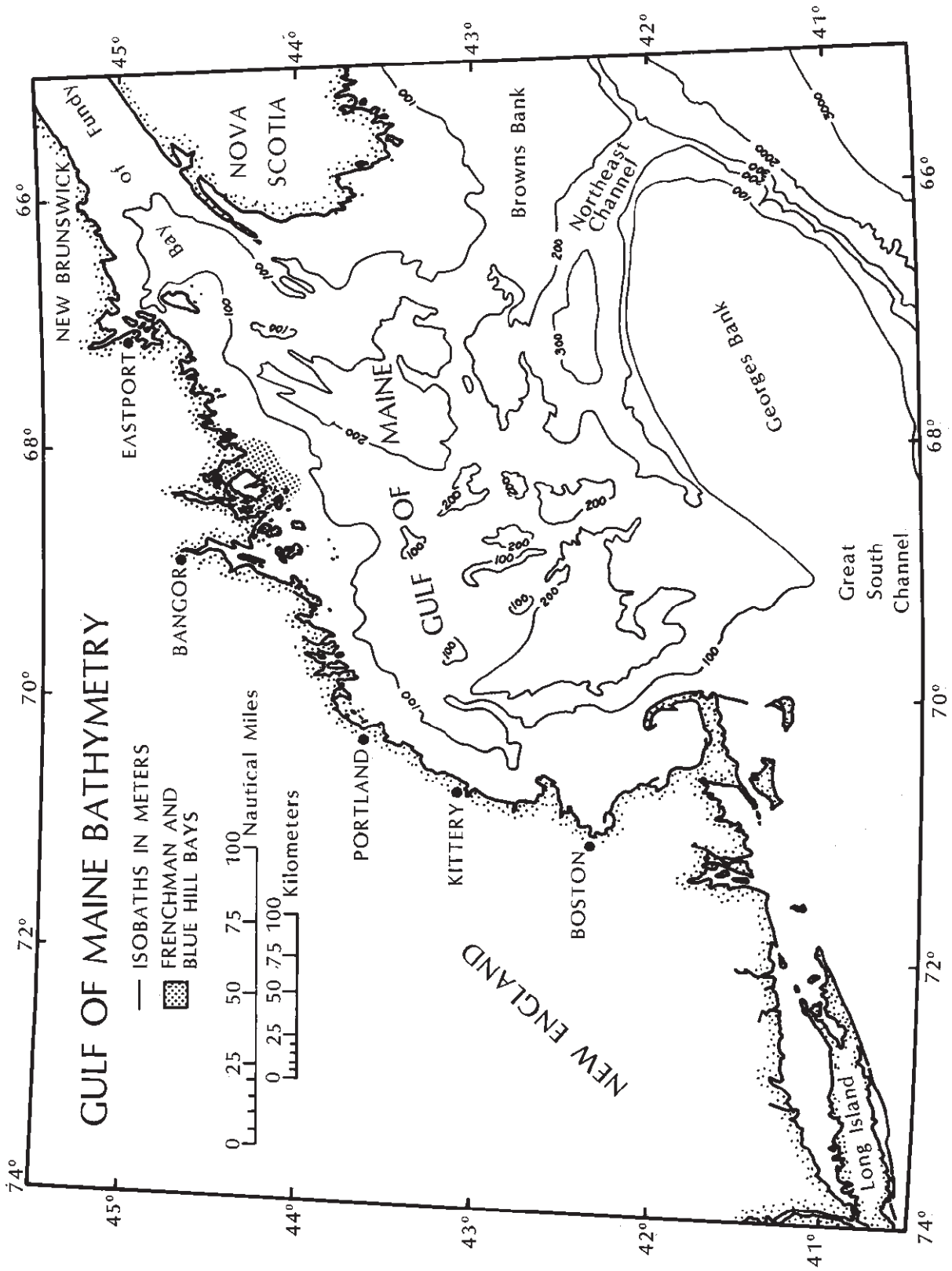


Figure 1. Location of Frenchman and Blue Hill Bays in relation to the Gulf of Maine.

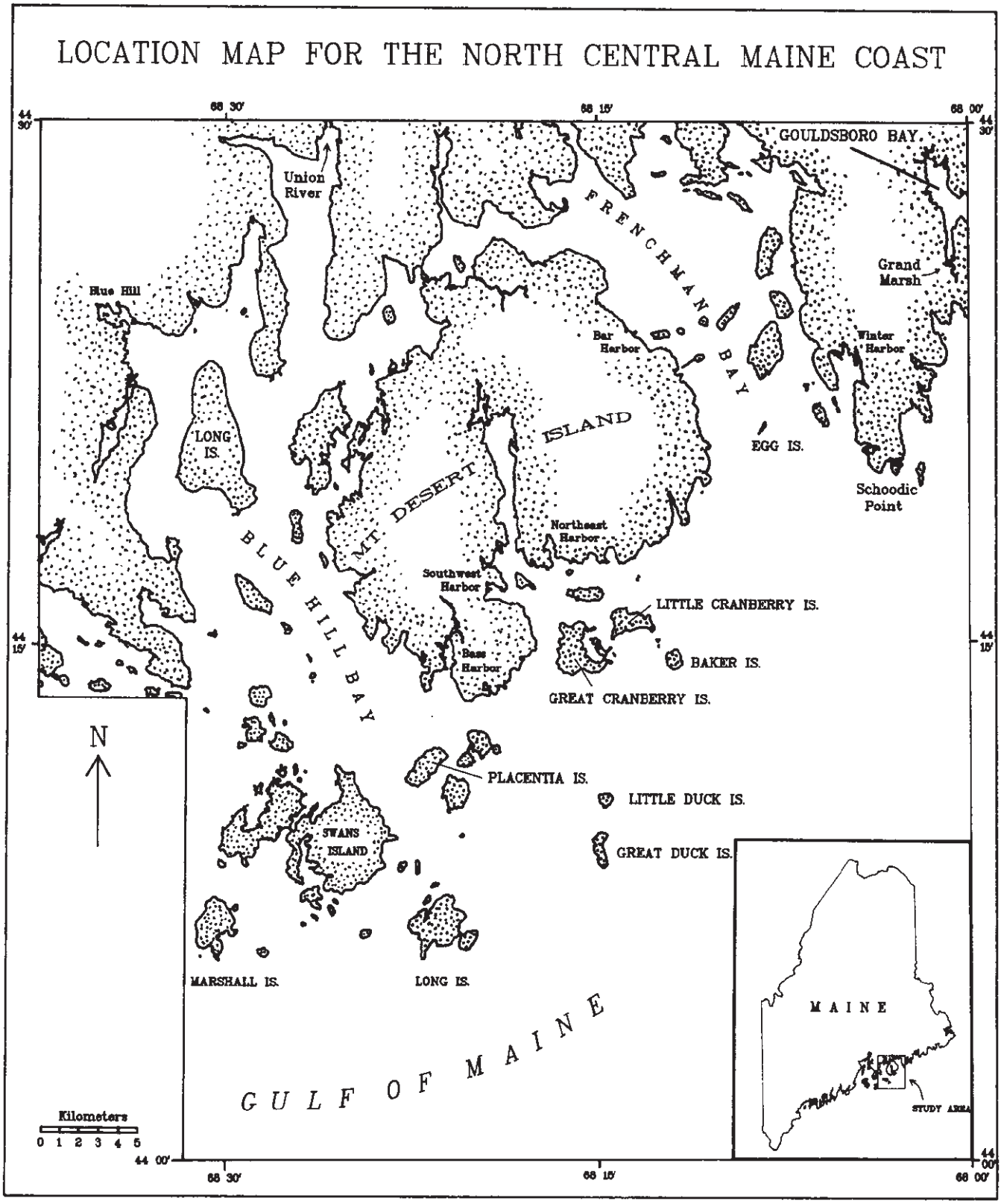


Figure 2. Location map of the study area.

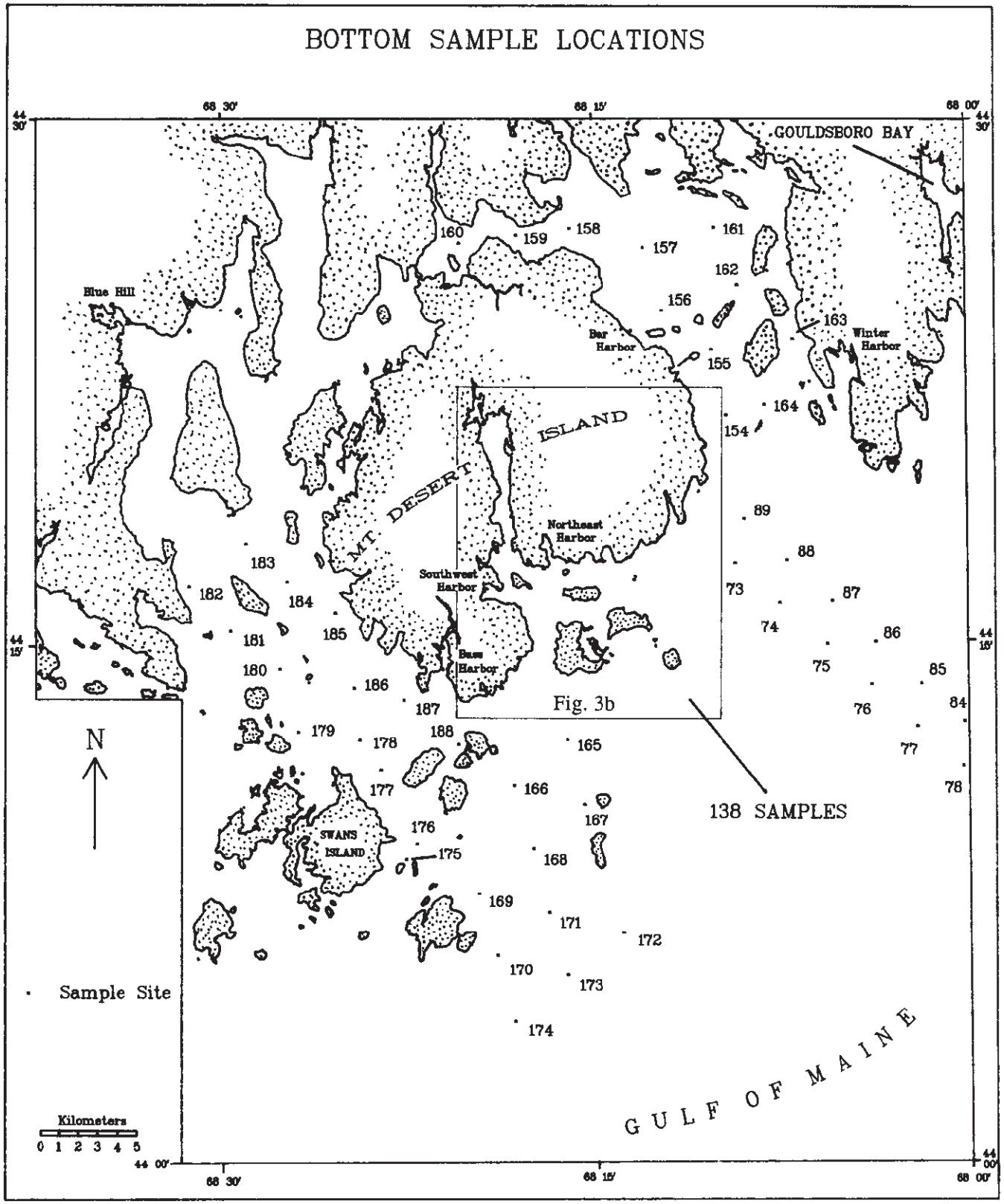


Figure 3a. Location of the bottom sample stations.

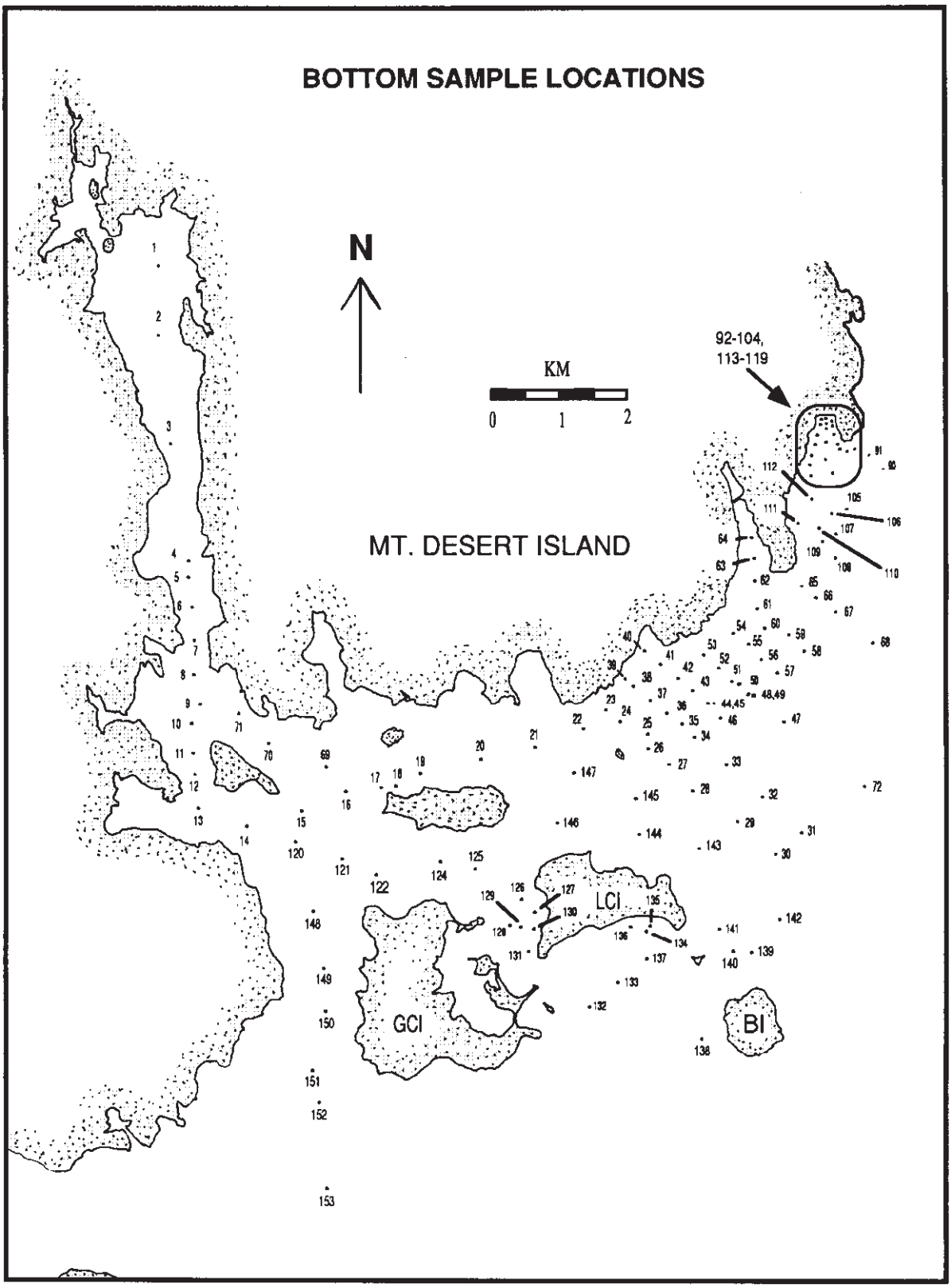


Figure 3b. Detailed map of bottom sample stations between the Cranberry Islands and Mount Desert Island.

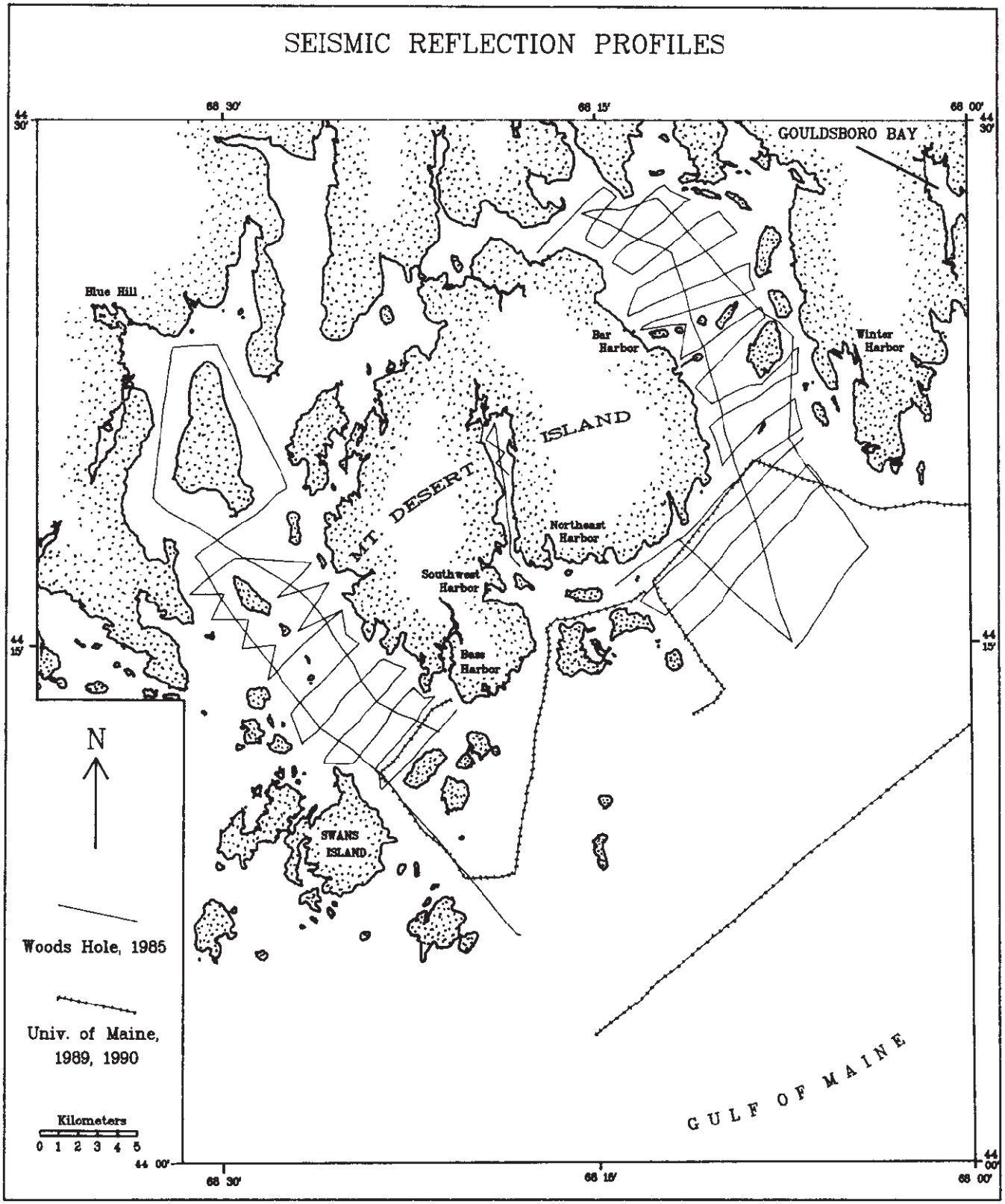


Figure 4. Location of seismic reflection profile lines.

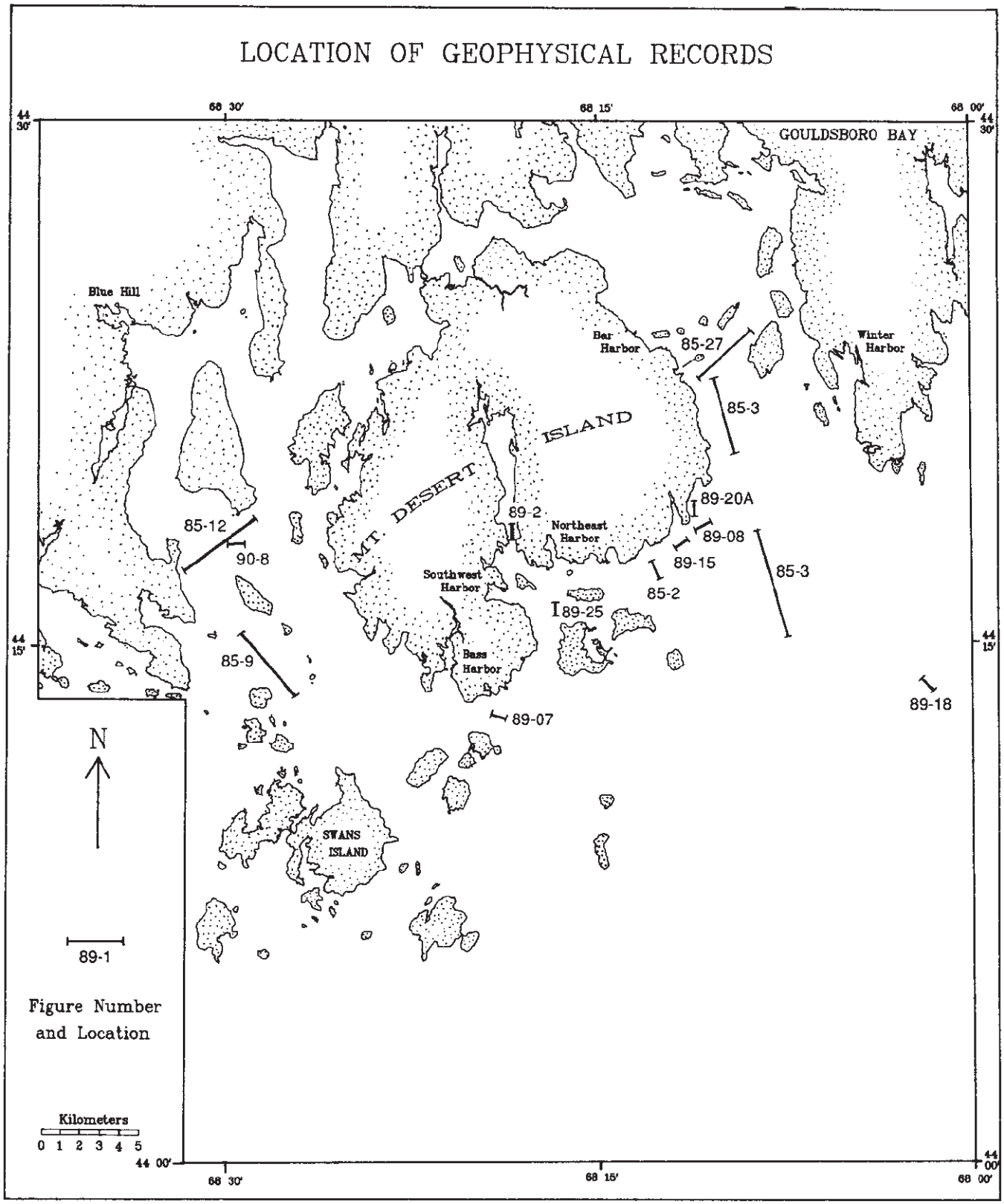


Figure 5. Location of geophysical tracklines used in text.

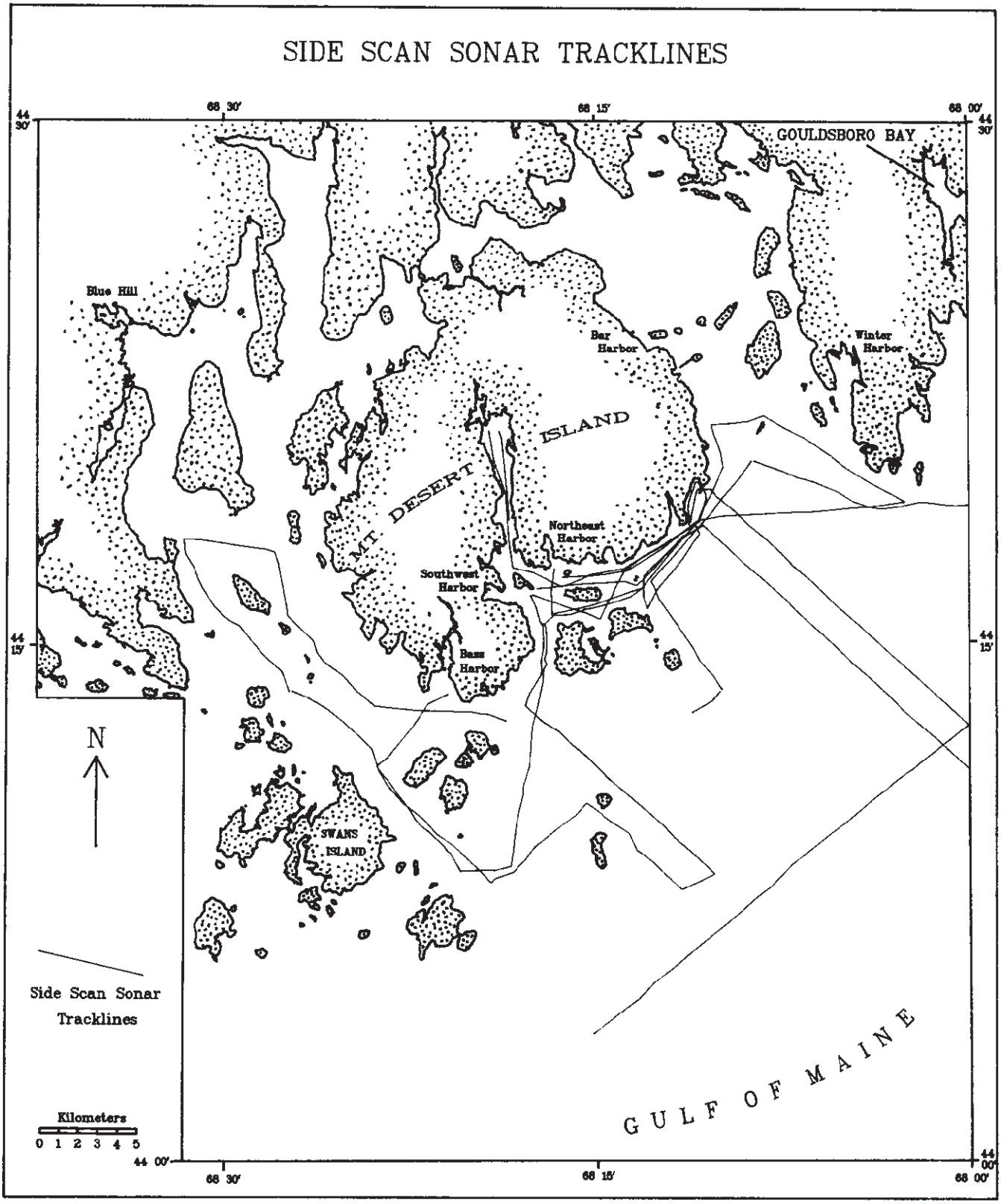


Figure 6. Location of side-scan sonar tracklines.

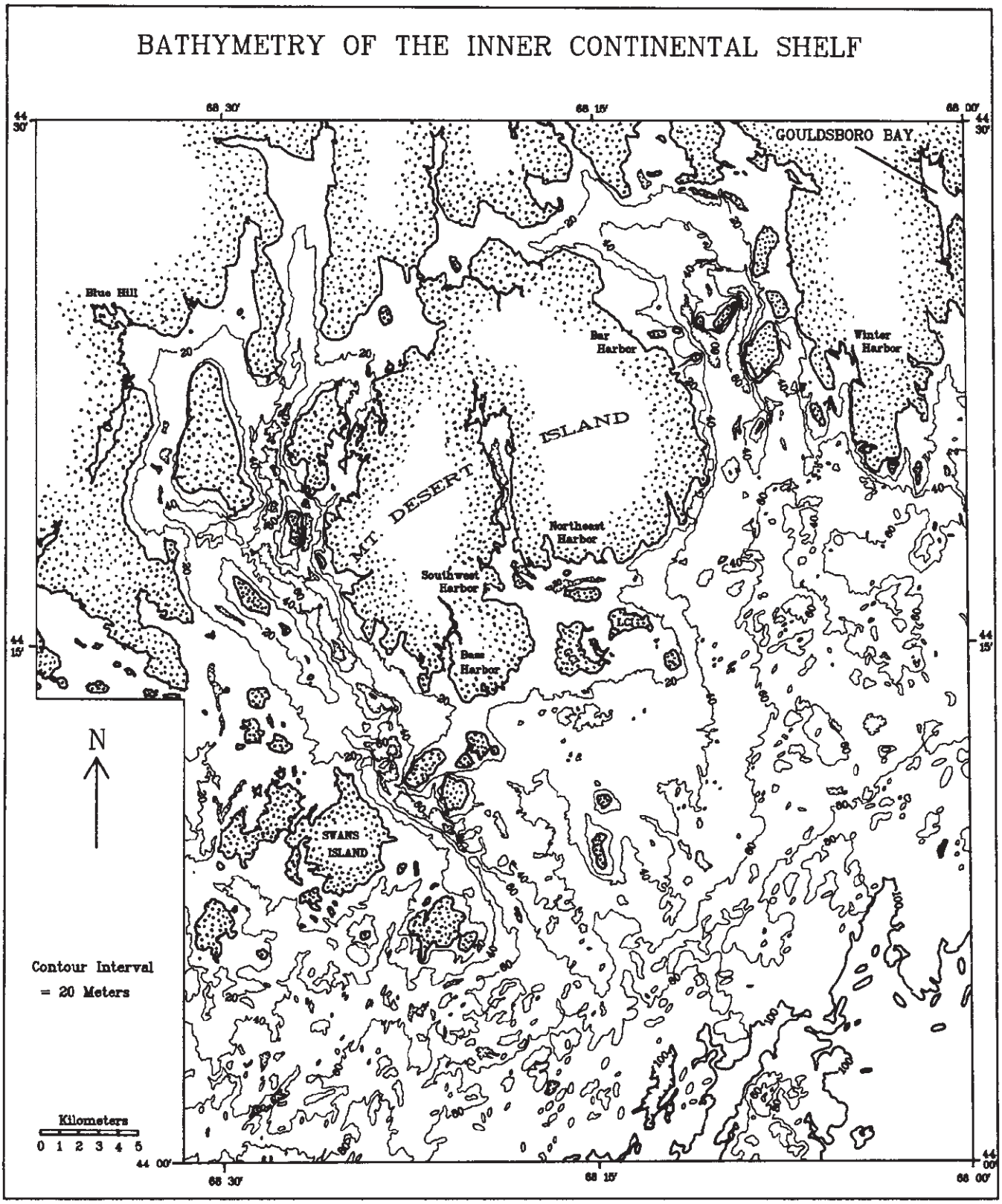


Figure 7. Bathymetry of the study area.

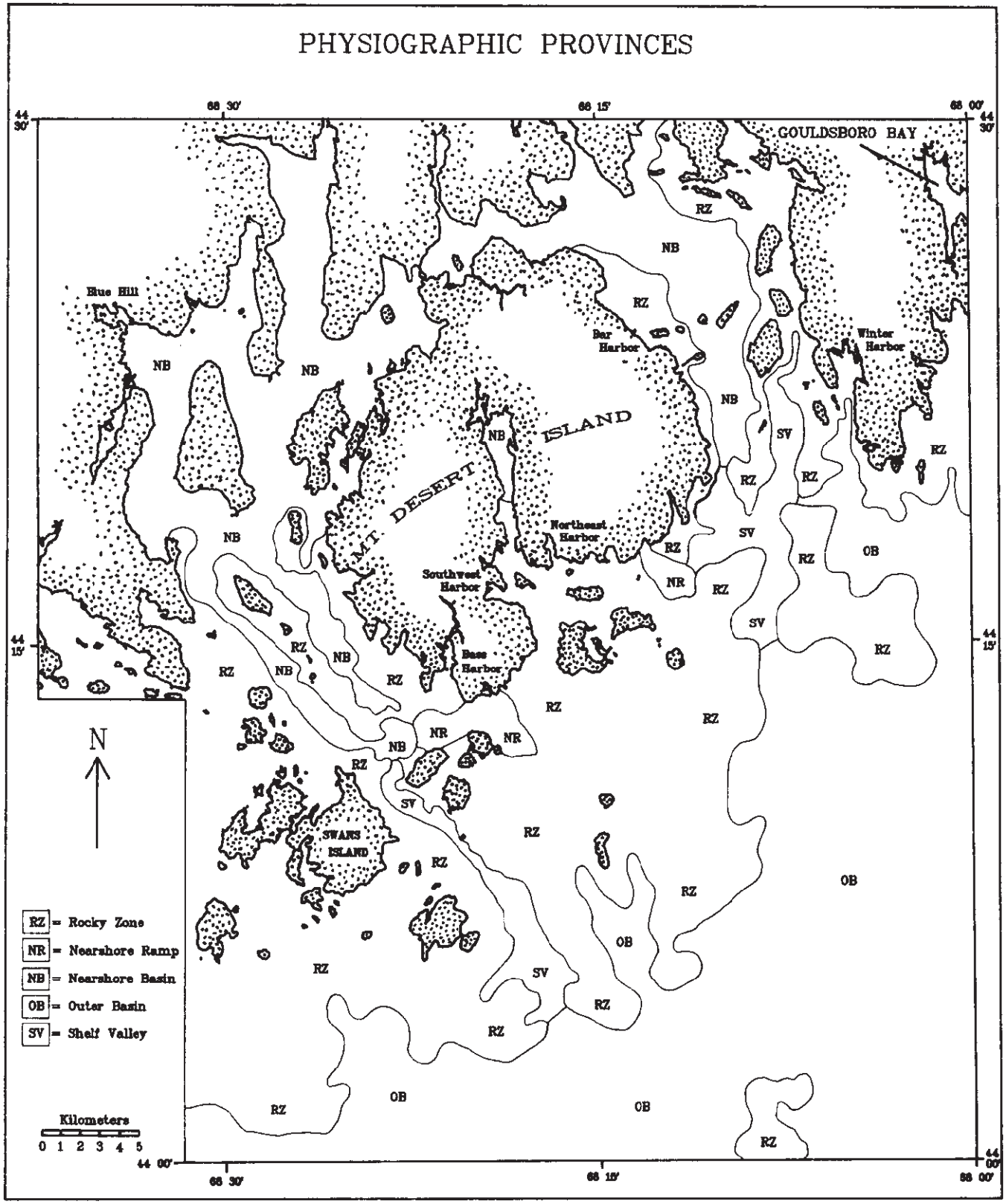


Figure 8. Physiographic provinces within Frenchman and Blue Hill Bays.

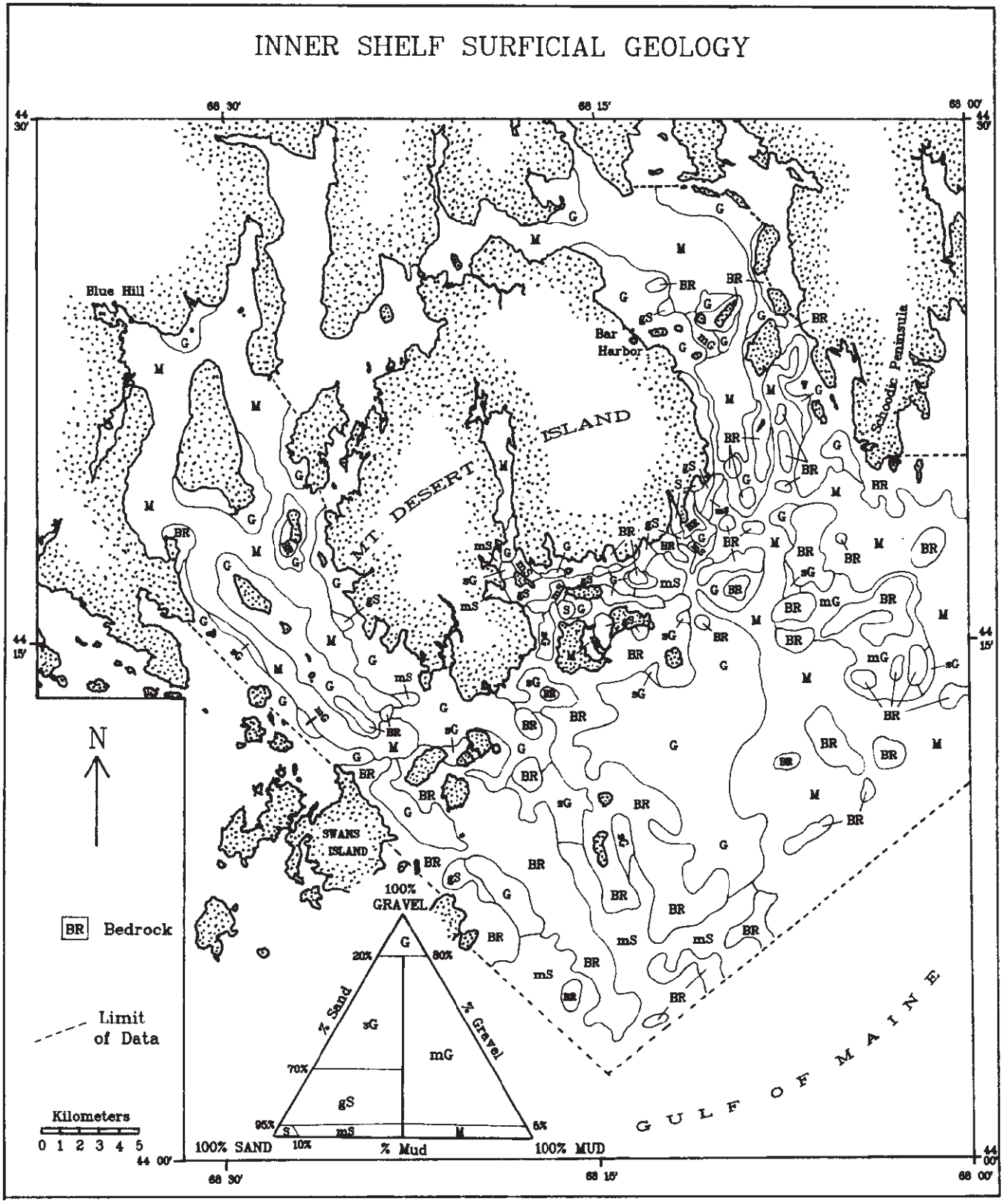


Figure 9. Surficial sediments of Frenchman and Blue Hill Bays.

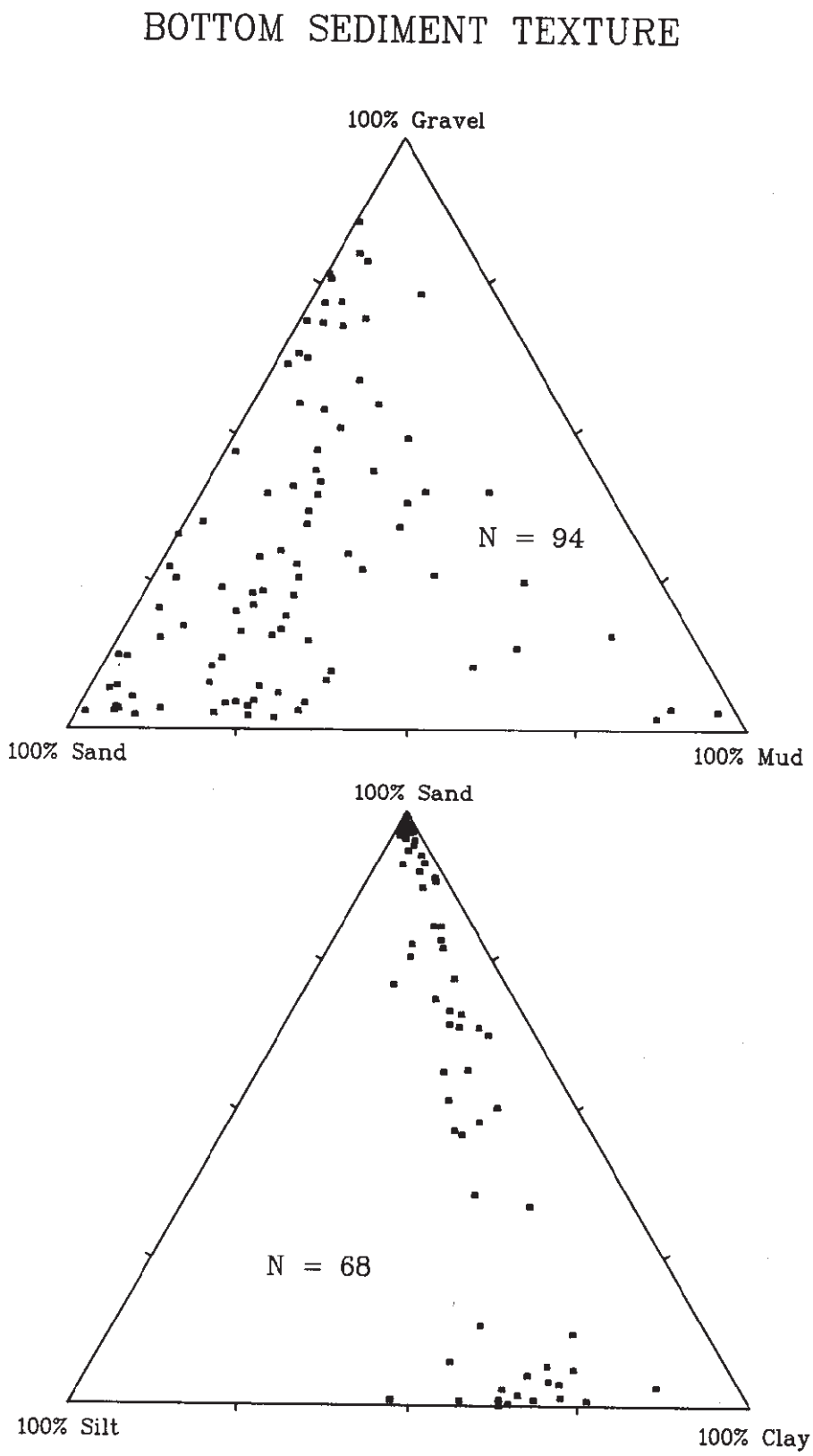


Figure 10. Texture of bottom samples from the study area.

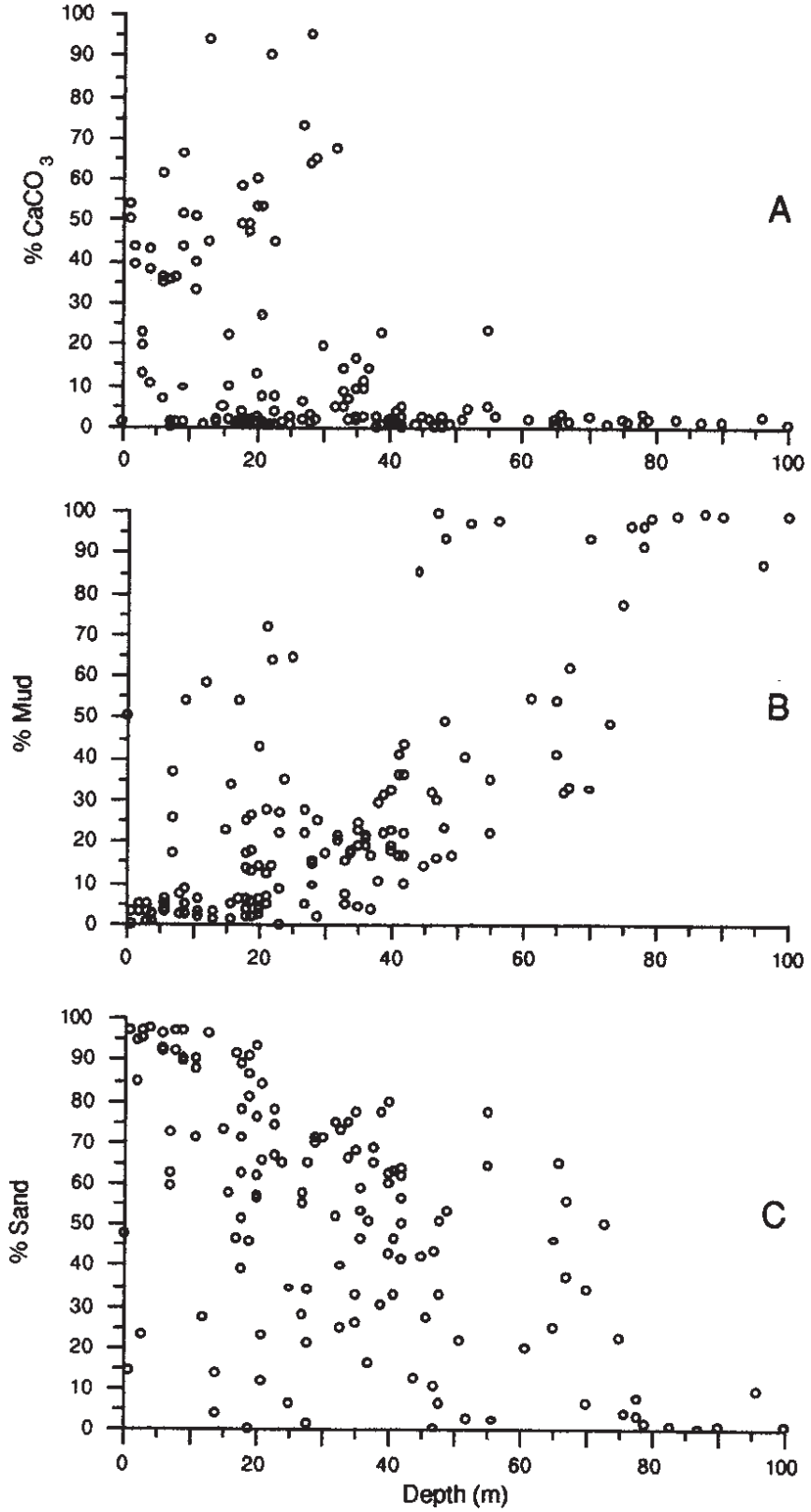
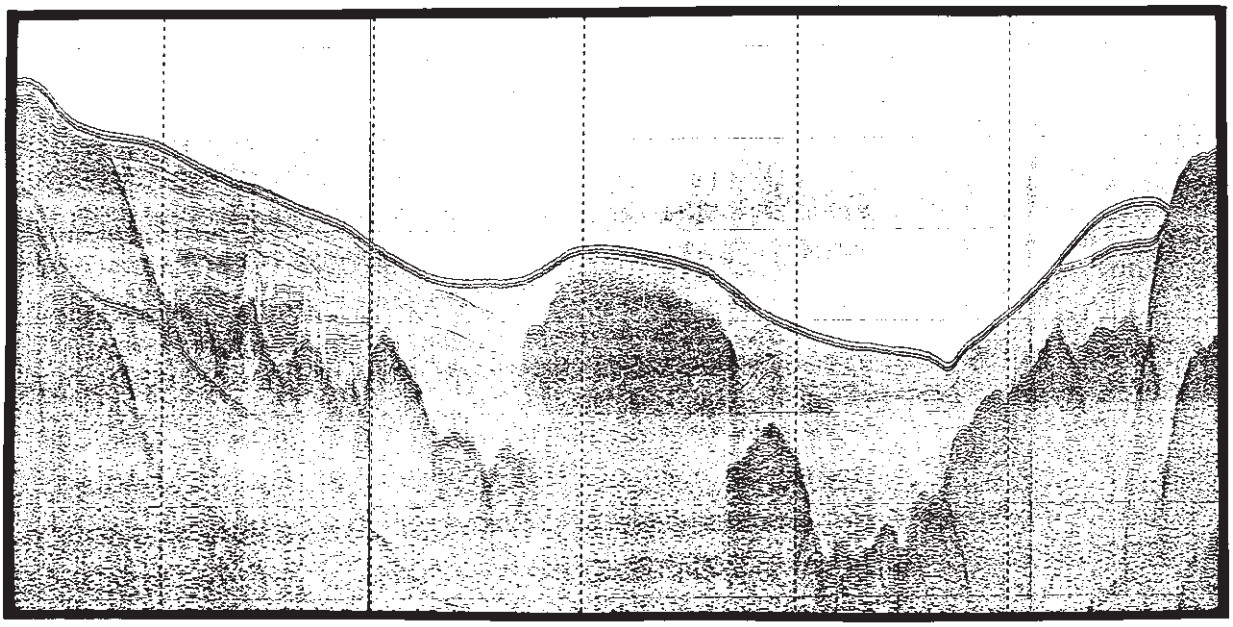


Figure 11. (a) Percent carbonate versus depth of sample. (b) Percent mud versus depth of sample. (c) Percent sand versus depth of sample.

Figure 12. Seismic reflection profile MD85-27 across eastern Nearshore Basin; this is also shown as profile "D" in Figure 26. In this and all other seismic profiles, "br" represent bedrock; "ng" represents natural gas; "t" represents till; "gm" represents glaciomarine sediment; "m" represents modern mud; and "sg" represents sand and gravel. Note channel cut below transgressive unconformity on surface of glaciomarine sediment with mud on top, and that gas occurs beneath thick bulge of modern sediment.



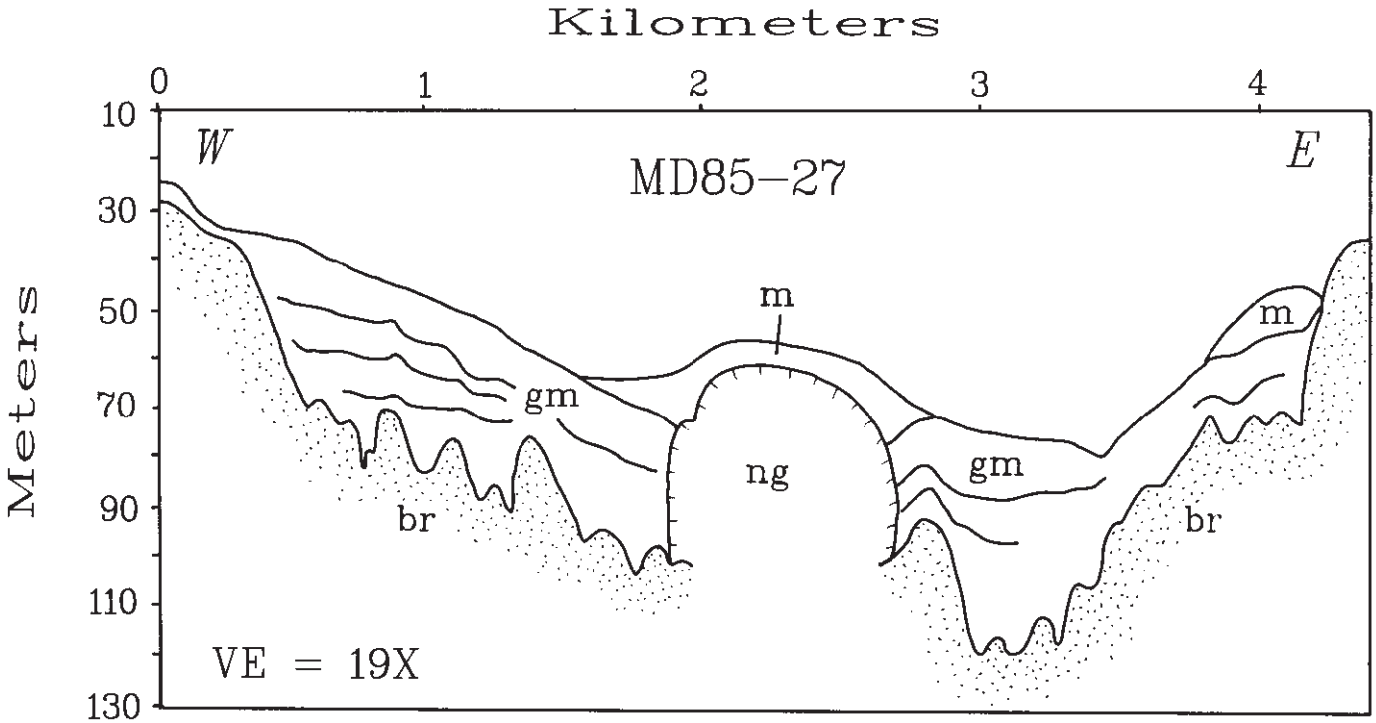
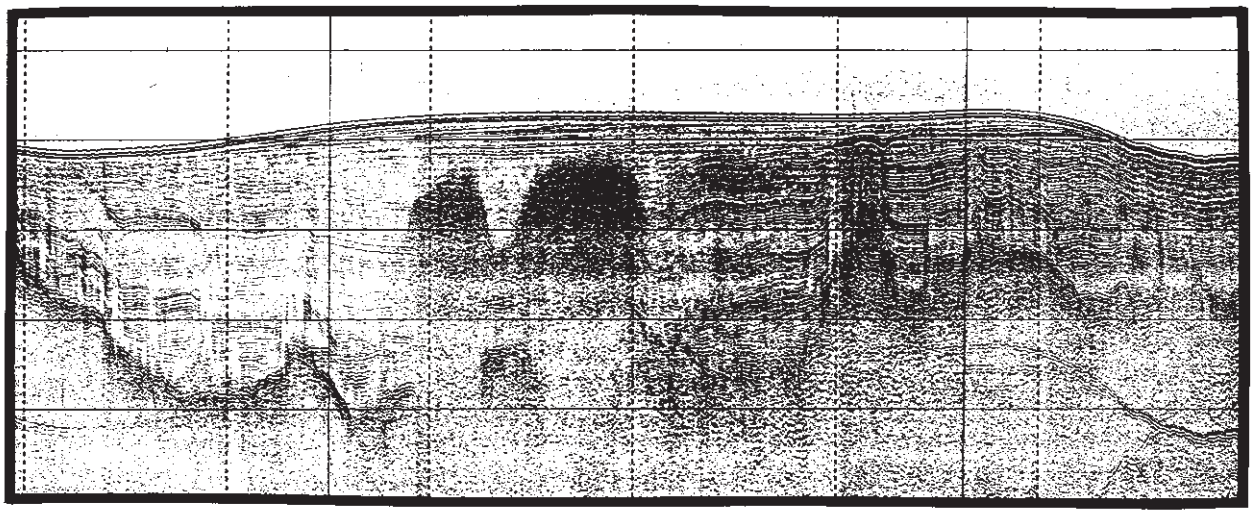


Figure 13. Seismic reflection profile MD85-3 along axis of eastern Nearshore Basin. This is also shown as a boxed area in profile "G" in Figure 26. In this and all other seismic profiles, "br" represent bedrock; "ng" represents natural gas; "t" represents till; "gm" represents glaciomarine sediment; "m" represents modern mud; and "sg" represents sand and gravel. Note gas over thickest location of sediment.



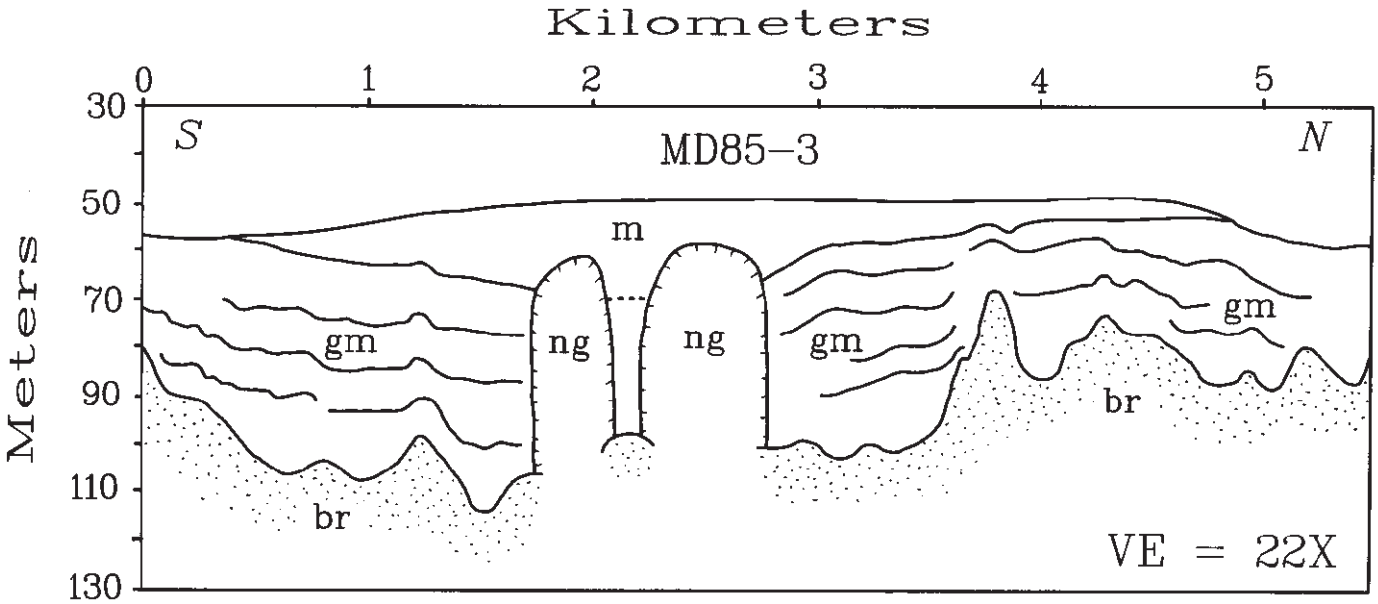
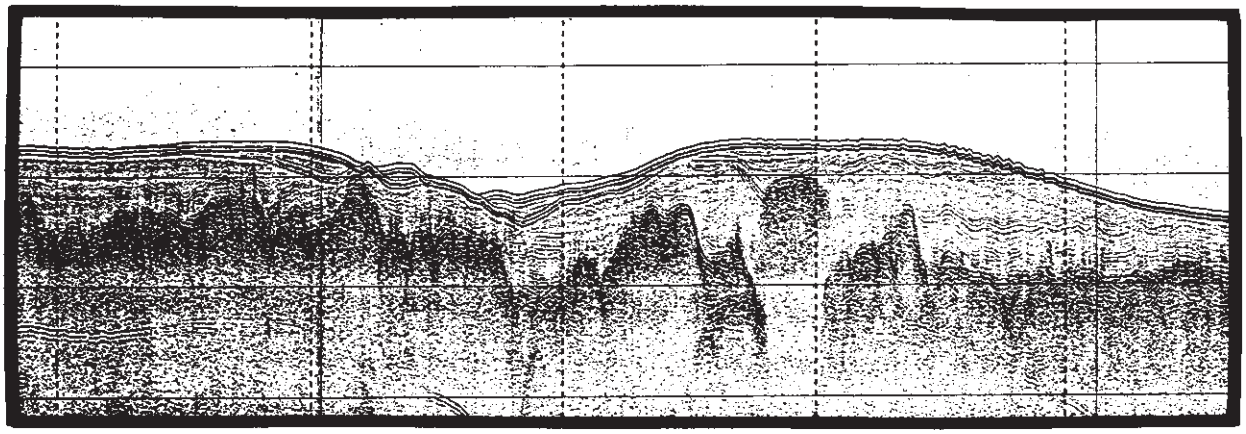


Figure 14. Seismic reflection profile MD85-9 along axis of western Nearshore Basin. This is also shown as a boxed area in profile "C" in Figure 27. In this and all other seismic profiles, "br" represent bedrock; "ng" represents natural gas; "t" represents till; "gm" represents glaciomarine sediment; "m" represents modern mud; and "sg" represents sand and gravel. Note patchiness of modern mud deposits and that gas exists only over thickest accumulation of sediment.



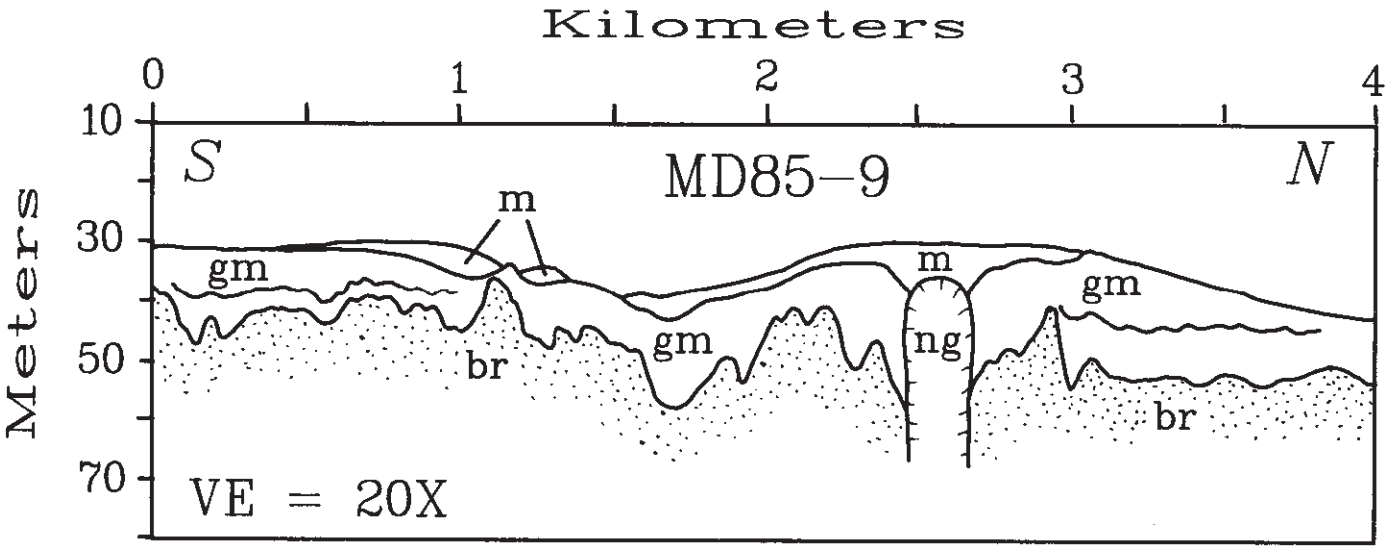
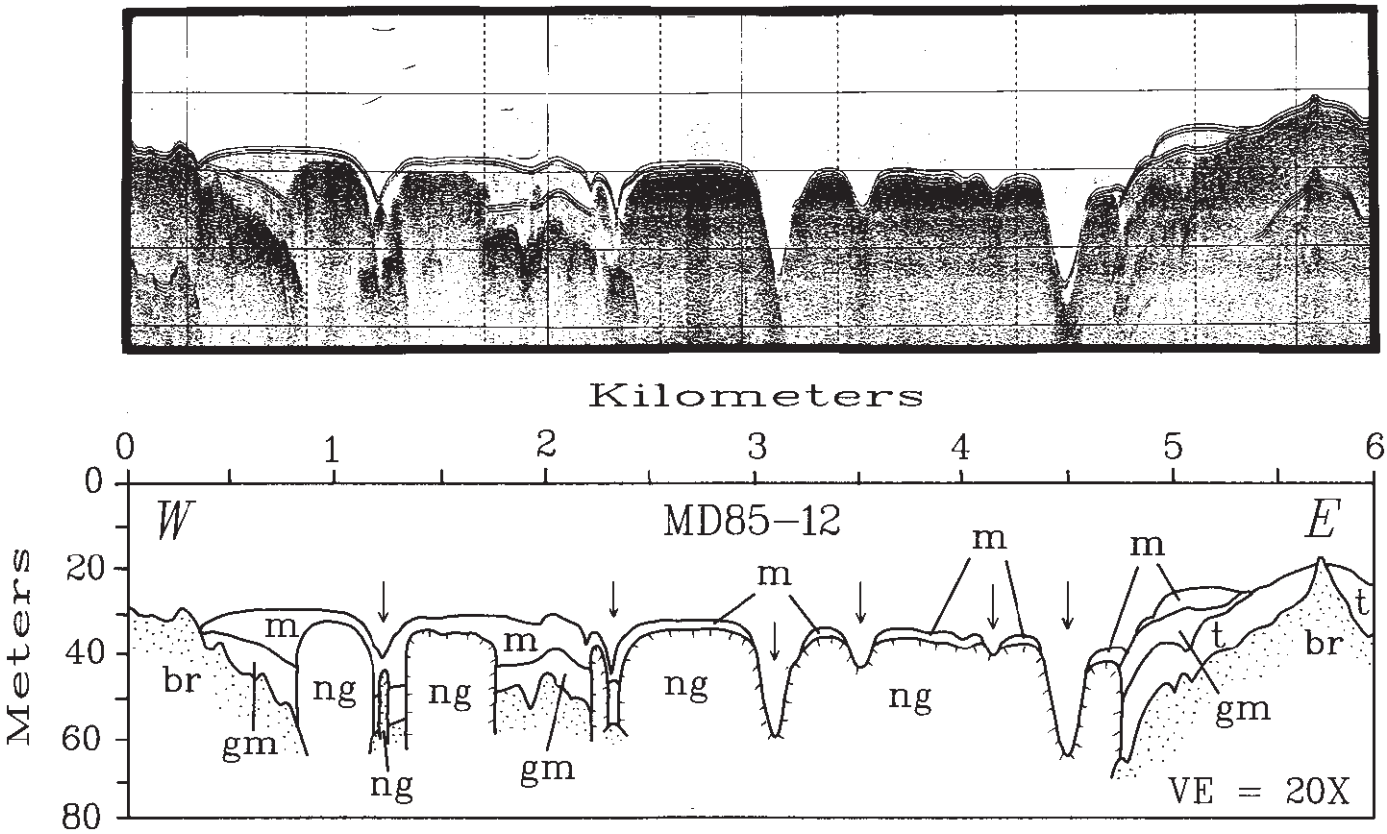


Figure 15. Seismic reflection profile MD85-12 across upper western Nearshore Basin. This is also shown as profile "A" in Figure 27. In this and all other seismic profiles, "br" represent bedrock; "ng" represents natural gas; "t" represents till; "gm" represents glaciomarine sediment; "m" represents modern mud; and "sg" represents sand and gravel. Arrows point to pockmarks. Note pockmarks throughout natural gas field, and that no gas appears beneath pockmark.



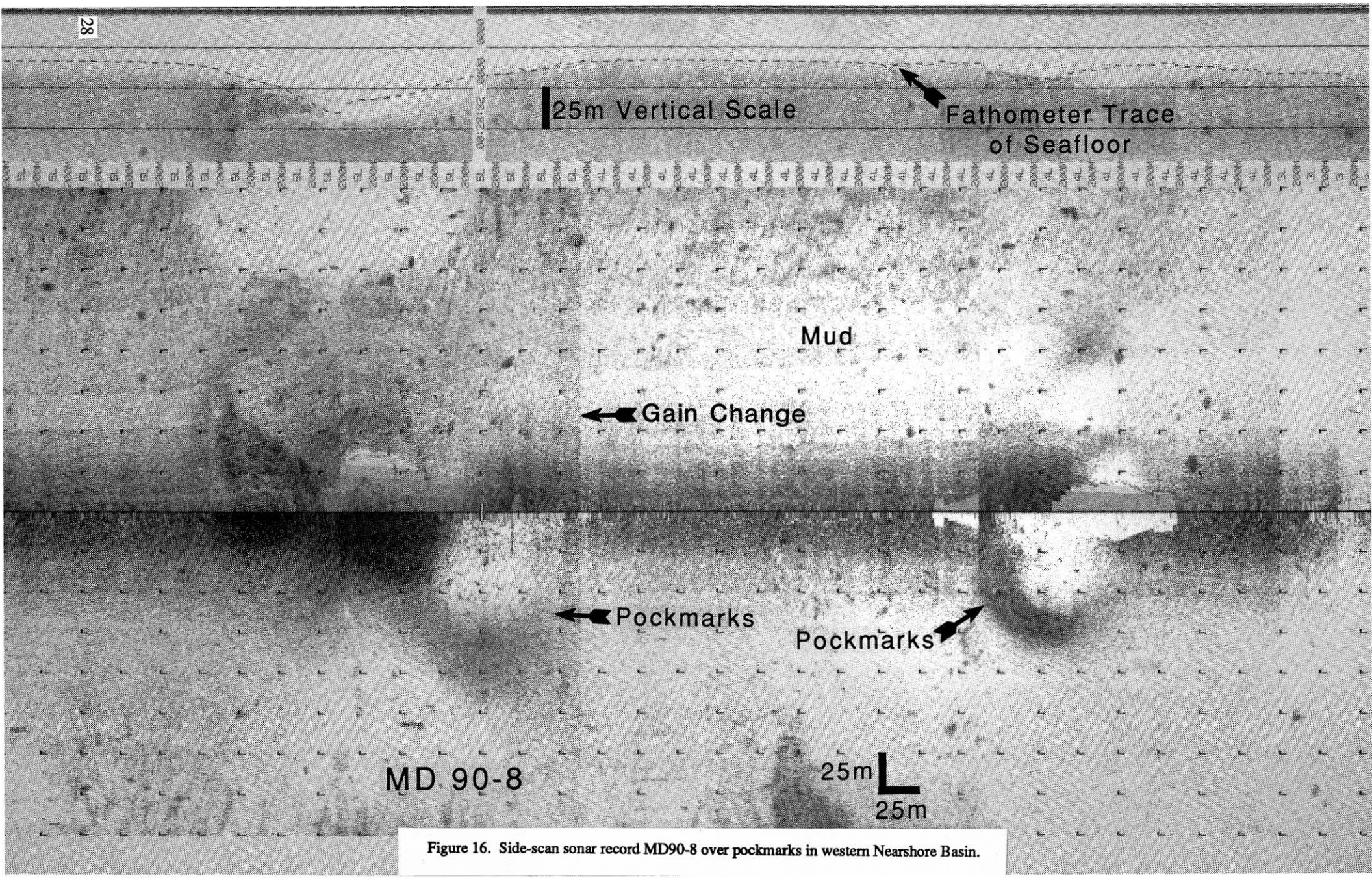


Figure 16. Side-scan sonar record MD90-8 over pockmarks in western Nearshore Basin.

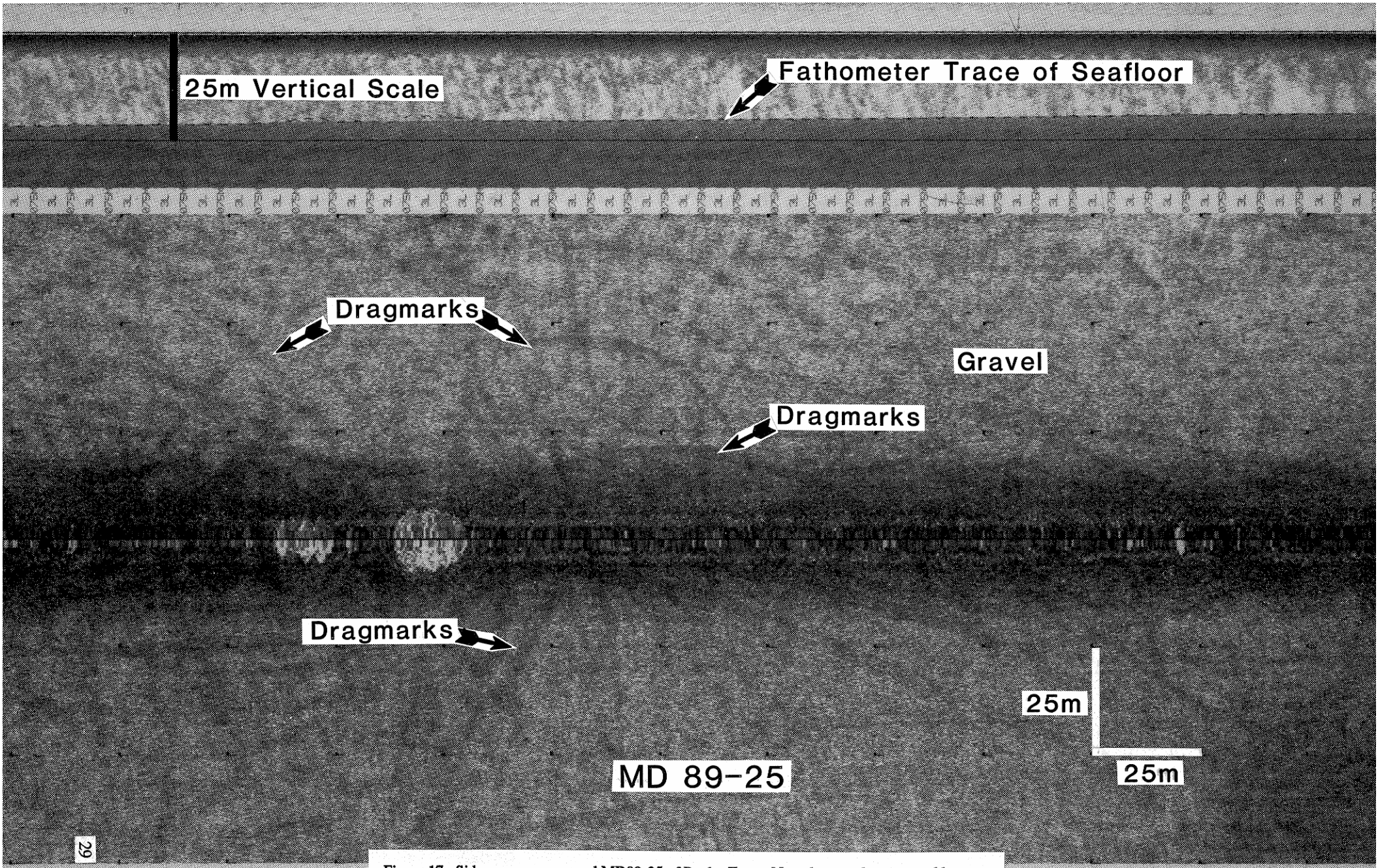


Figure 17. Side-scan sonar record MD89-25 of Rocky Zone. Note drag marks on gravel bottom.

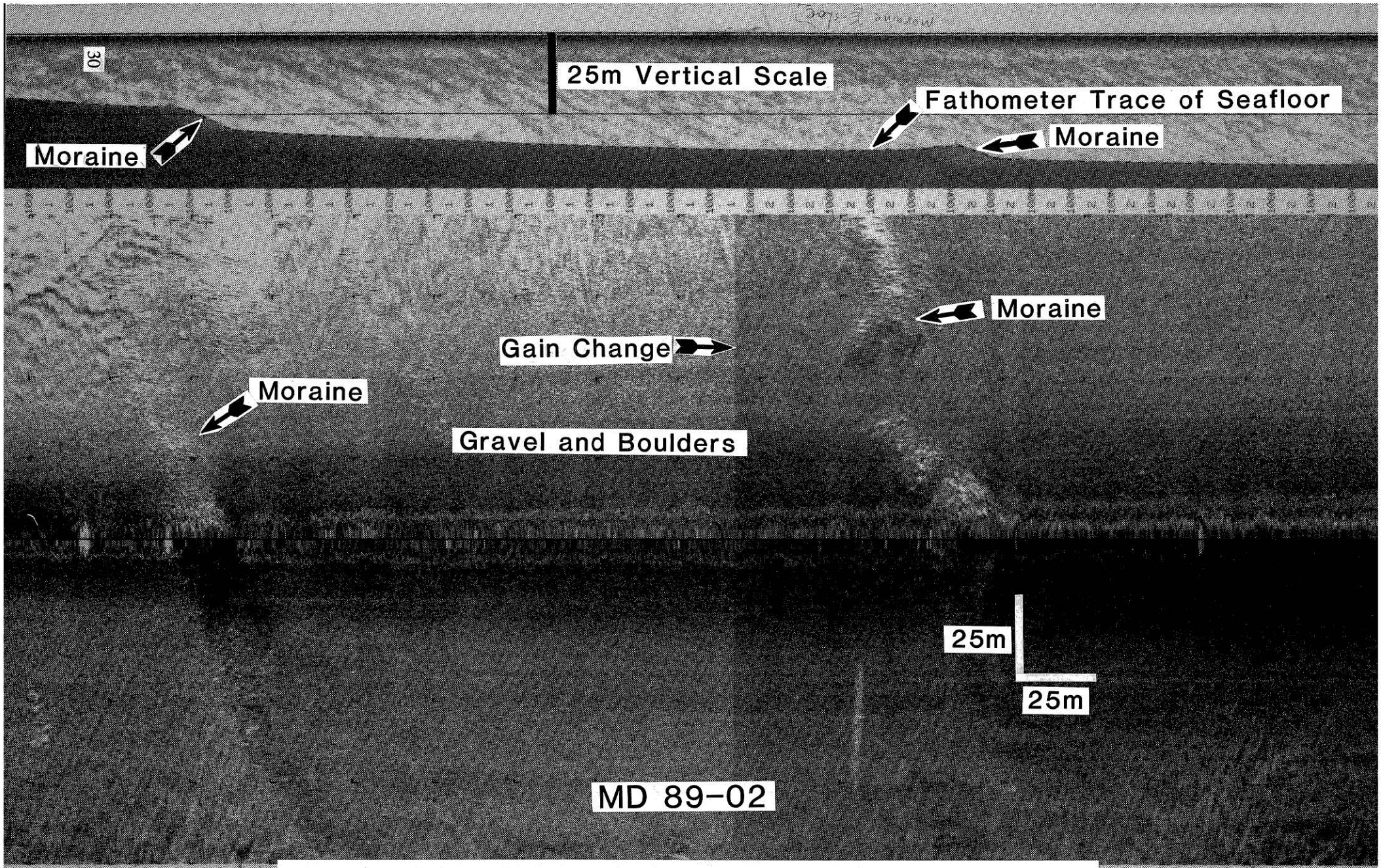


Figure 18. Side-scan sonar record MD89-02 over entrance to Somes Sound. Note 5 meter high moraine ridges and generally gravel-covered bottom.

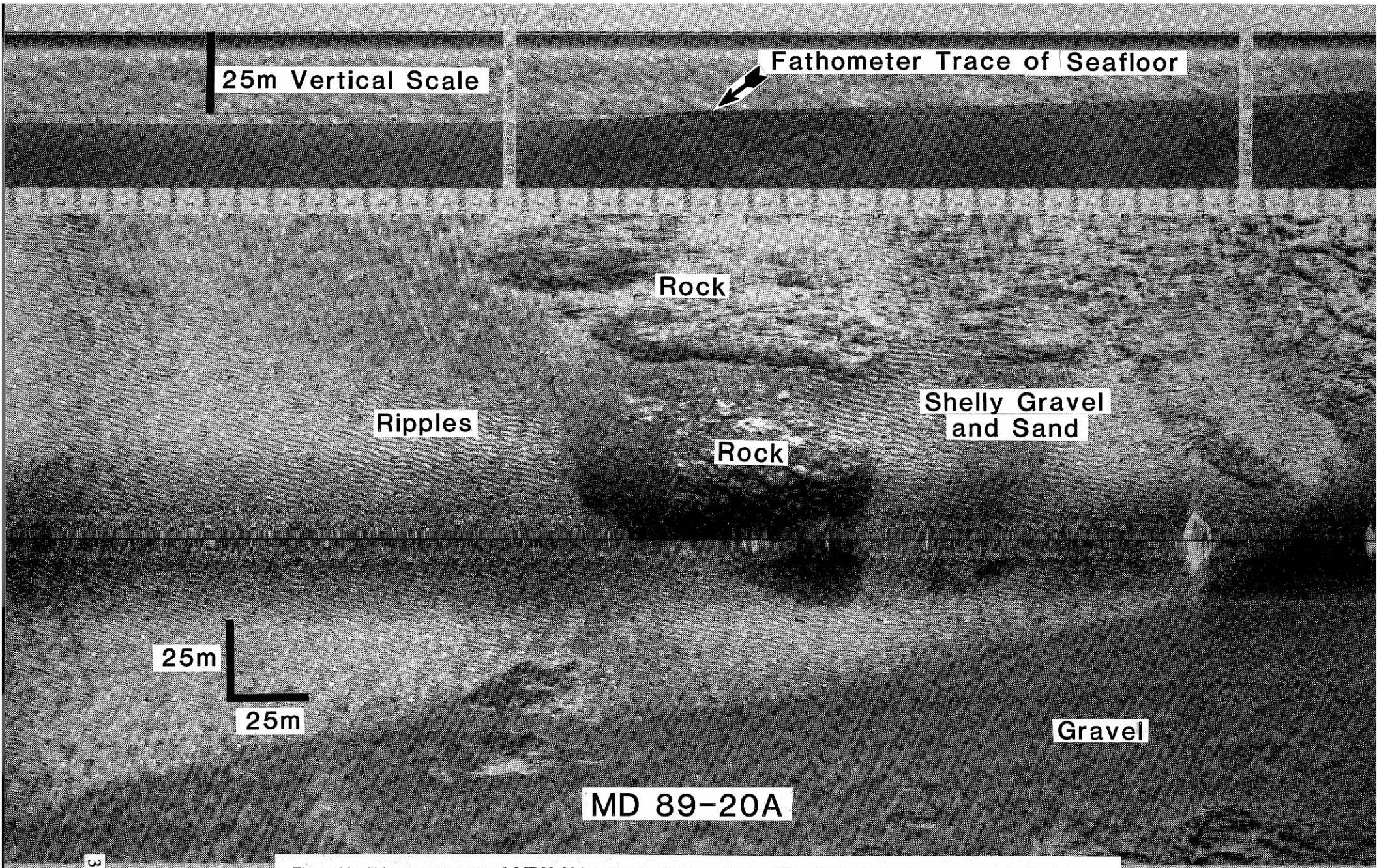


Figure 19. Side-scan sonar record MD89-20A across Rocky Zone off Mount Desert Island. Ripples are composed of carbonate-rich sand and gravel.

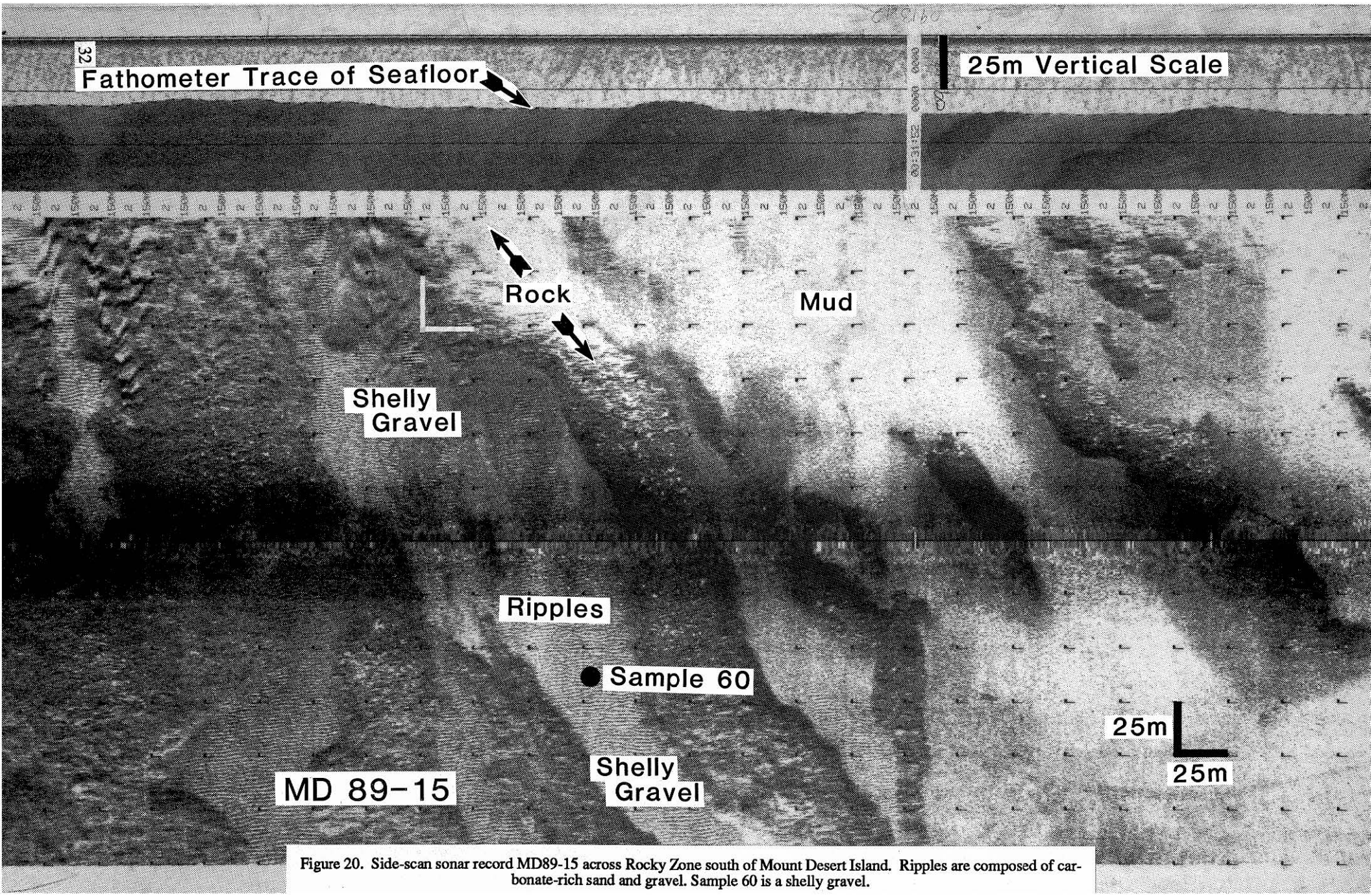
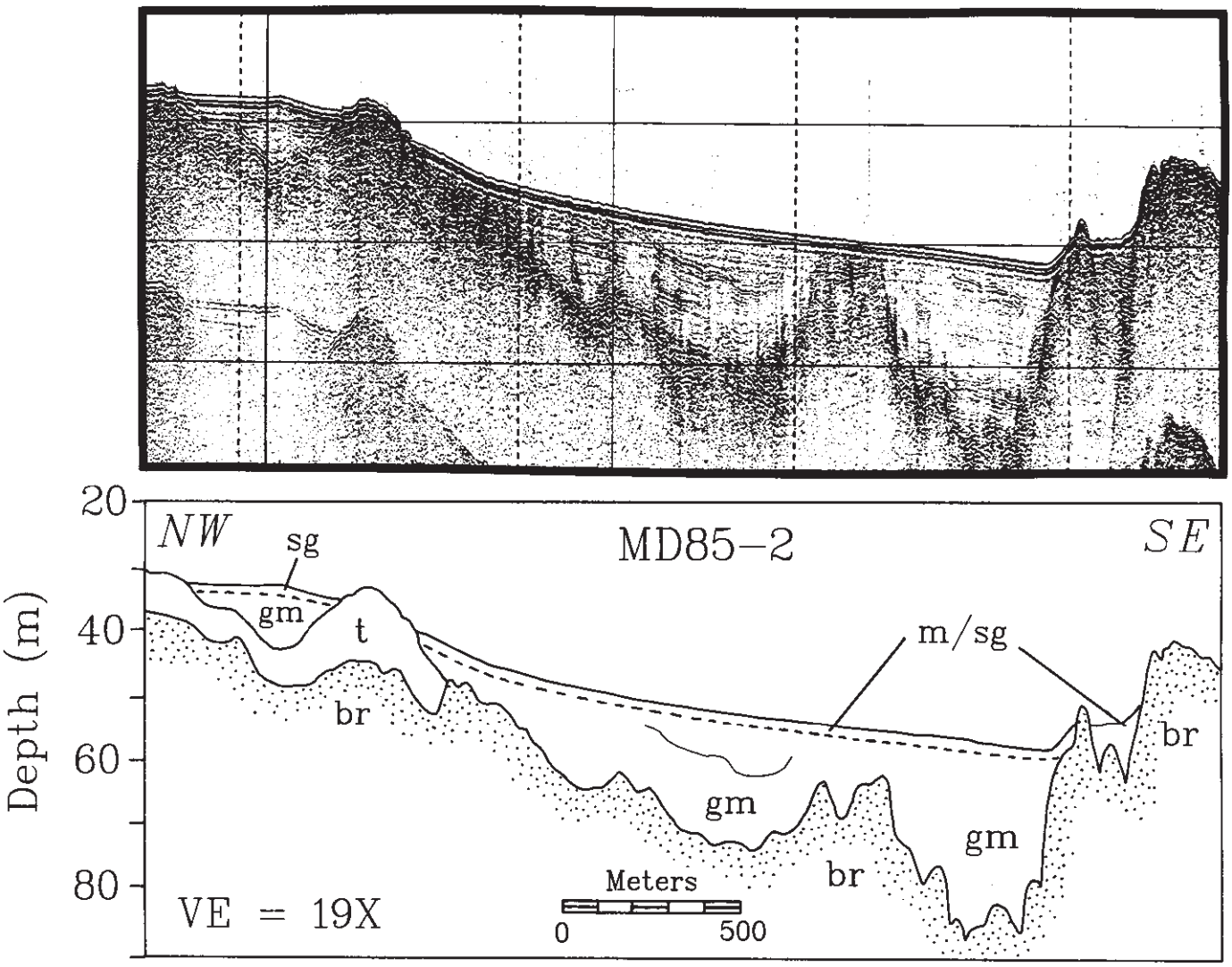


Figure 20. Side-scan sonar record MD89-15 across Rocky Zone south of Mount Desert Island. Ripples are composed of carbonate-rich sand and gravel. Sample 60 is a shelly gravel.

Figure 21. Seismic reflection profile MD85-2 across Nearshore Ramp and Rocky Zone on south Mount Desert Island. In this and all other seismic profiles, "br" represent bedrock; "ng" represents natural gas; "t" represents till; "gm" represents glaciomarine sediment; "m" represents modern mud; and "sg" represents sand and gravel. Note that the sand and gravel is a thin veneer over the glaciomarine sediment.



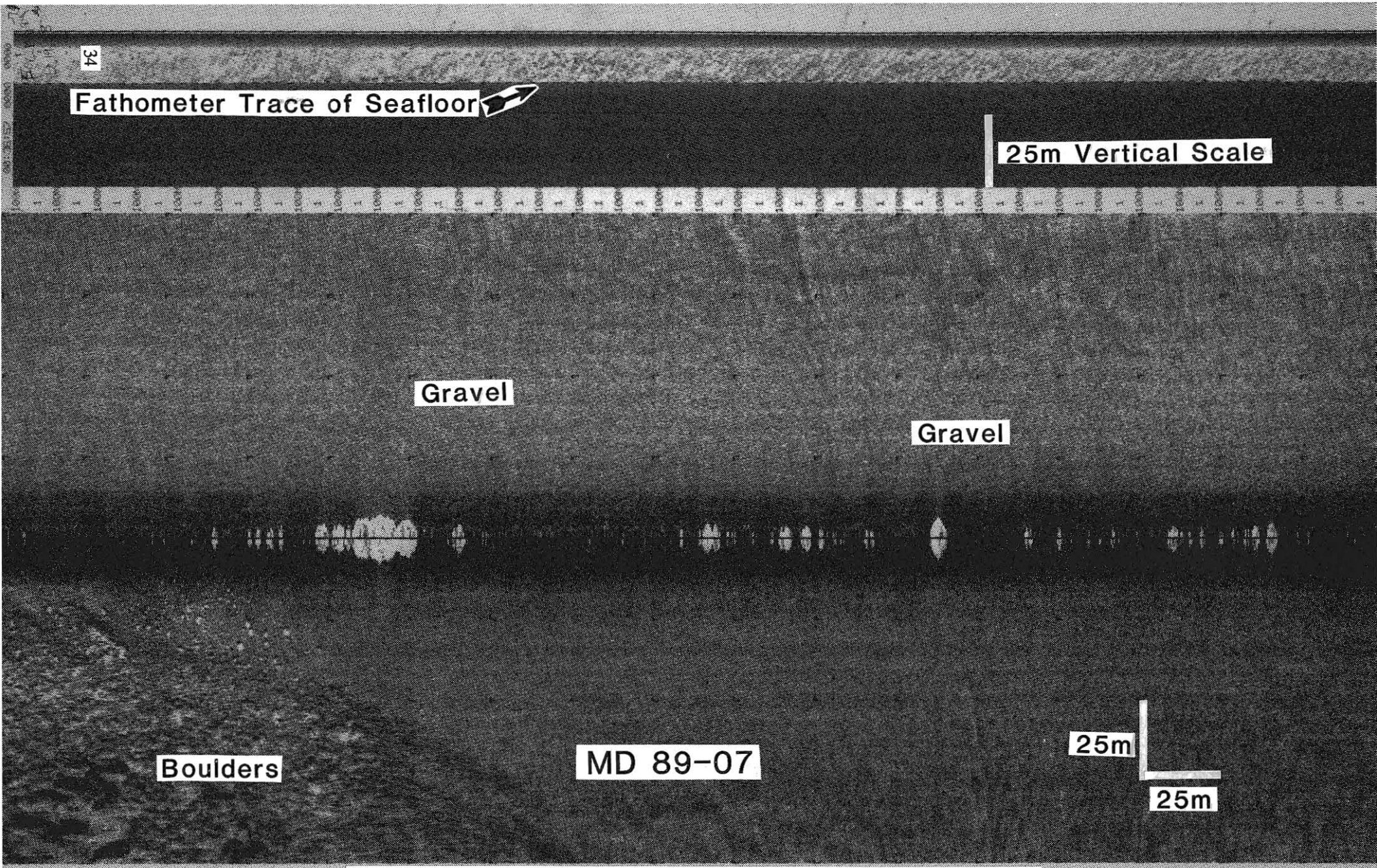
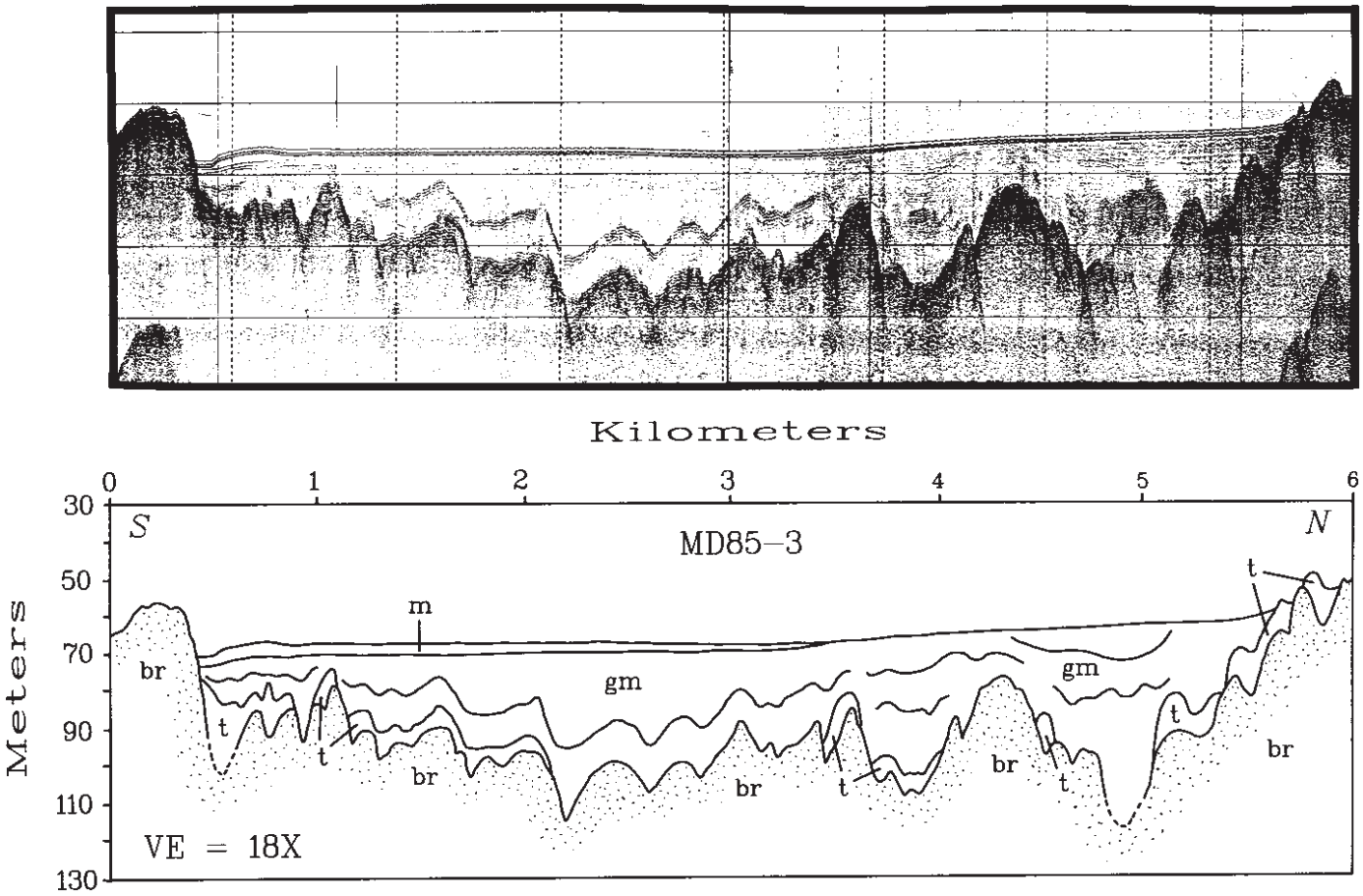


Figure 22. Side-scan sonar record MD89-07 across gravel-covered Nearshore Ramp south of Bass Harbor.

Figure 23. Seismic reflection profile MD85-3 across Shelf Valley east of Mount Desert Island. This is also shown as a boxed area in profile "G" in Figure 26. In this and all other seismic profiles, "br" represent bedrock; "ng" represents natural gas; "t" represents till; "gm" represents glaciomarine sediment; "m" represents modern mud; and "sg" represents sand and gravel. Note that only about about half of the seafloor is covered with modern mud.



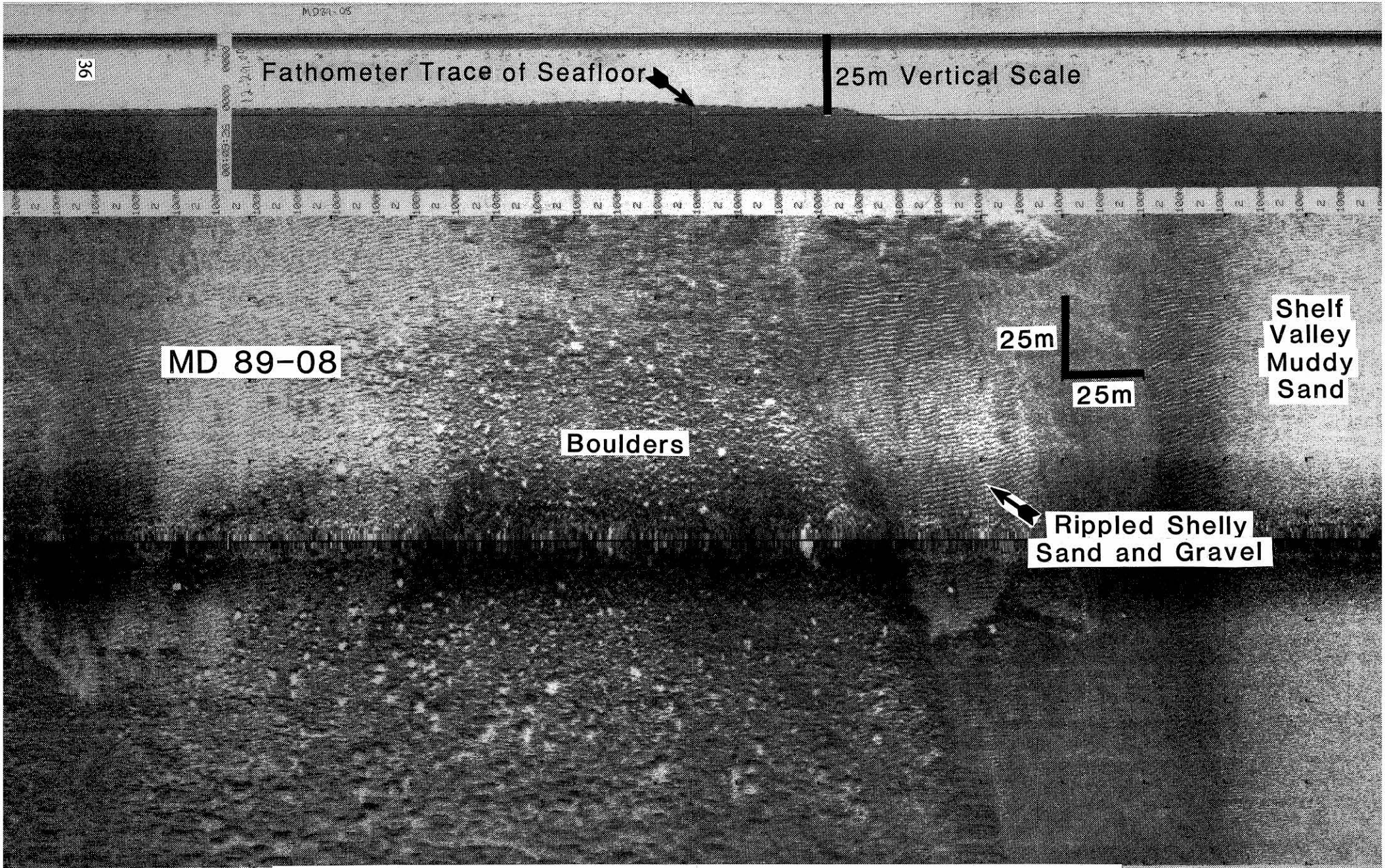


Figure 24. Side-scan sonar record MD89-08 across border between Rocky Zone and Shelf Valley. Ripples mark the border.

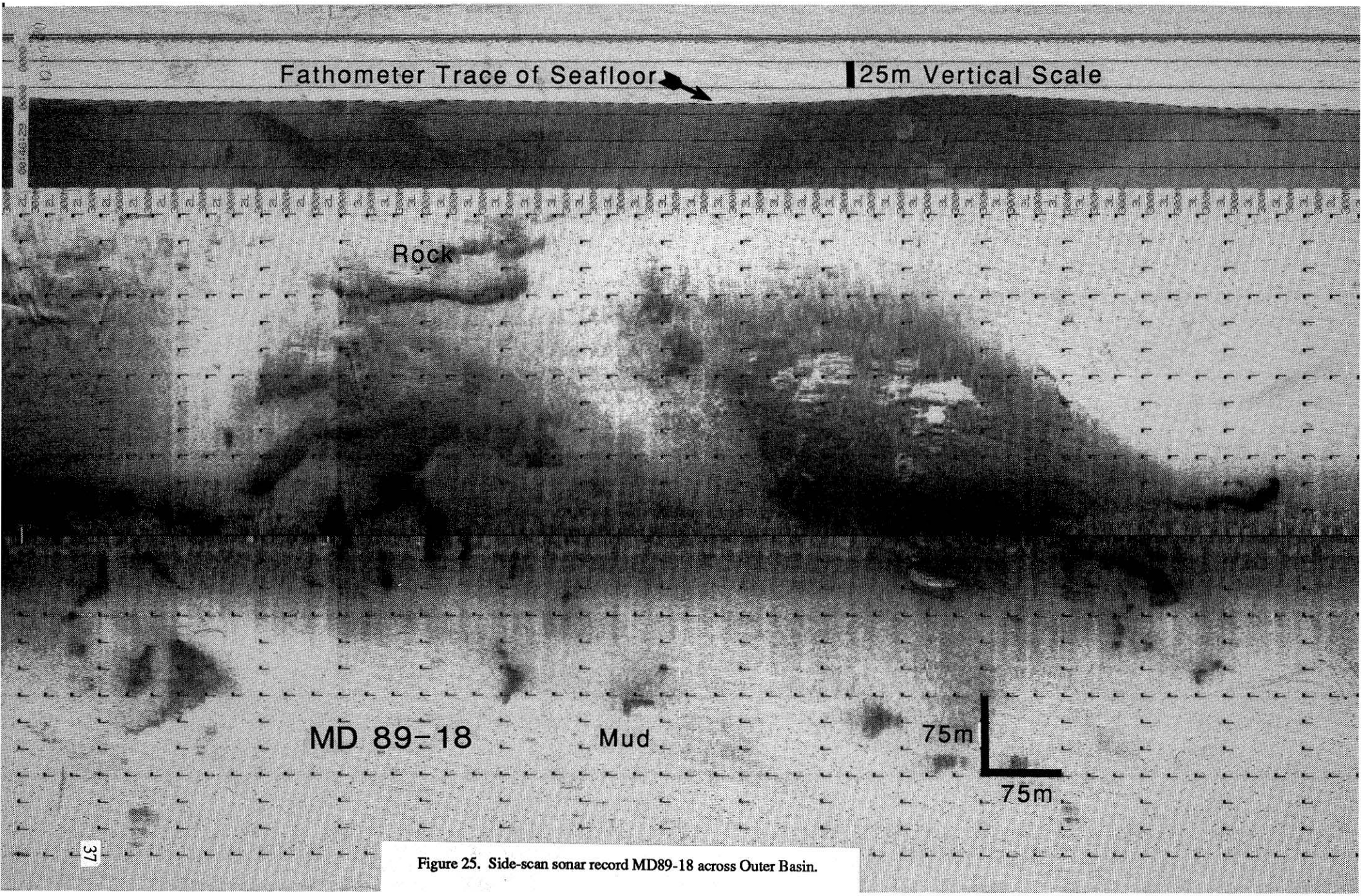


Figure 25. Side-scan sonar record MD89-18 across Outer Basin.

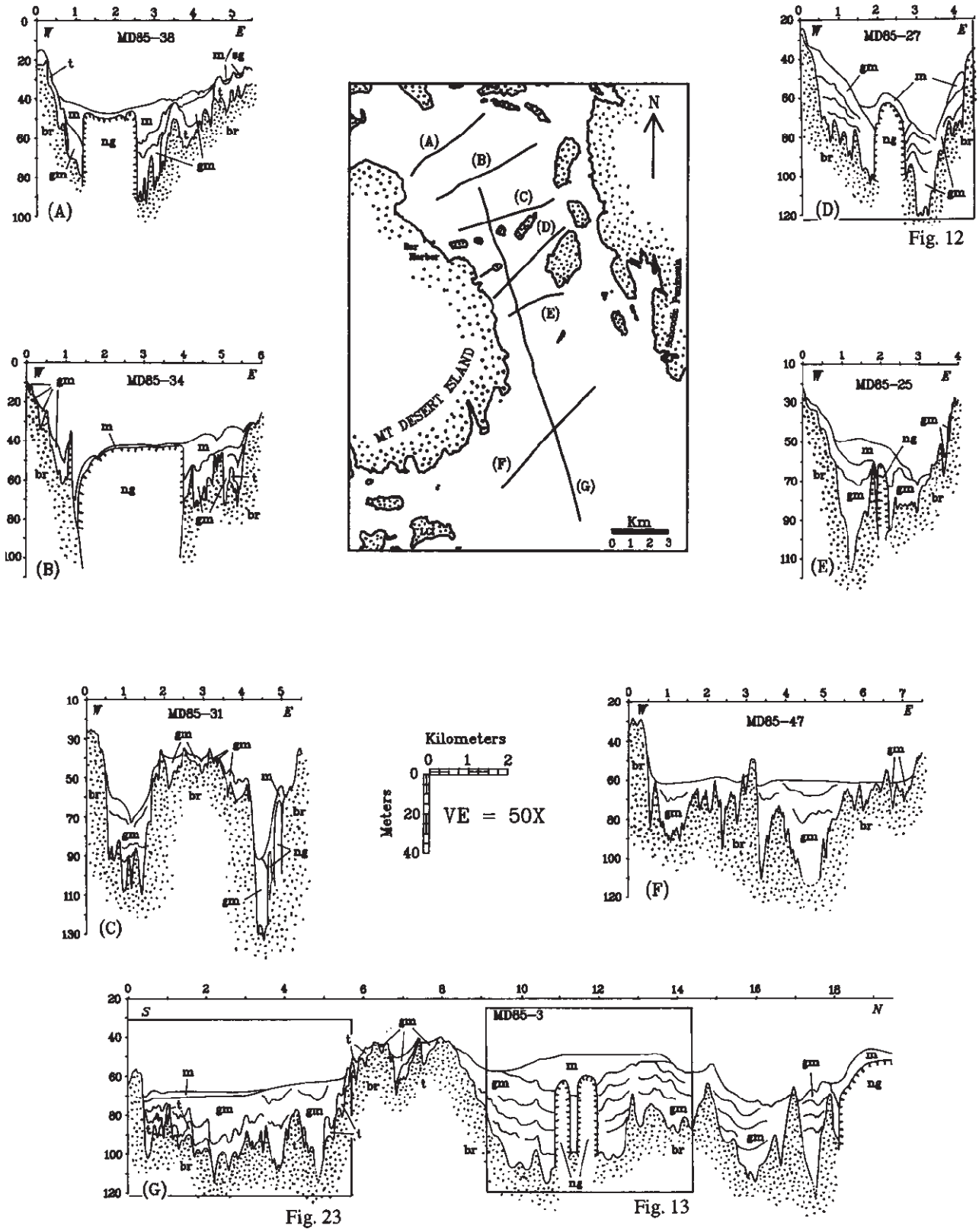


Figure 26. Digitized seismic reflection profiles from Frenchman Bay. Boxes indicate original records from other figures.

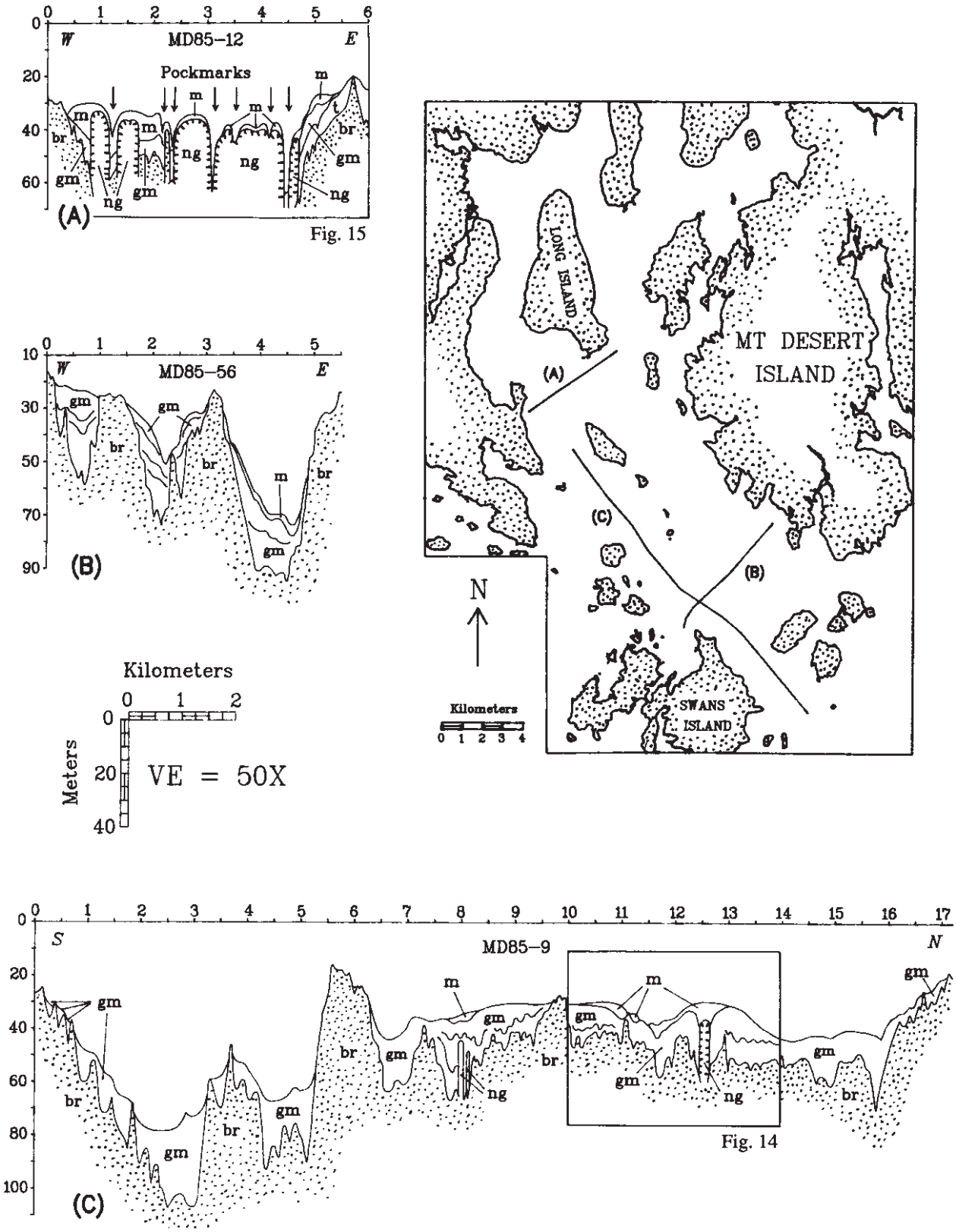


Figure 27. Digitized seismic reflection profiles from Blue Hill