Surficial Geology, Pockmarks, and Associated Neotectonic Features of Passamaquoddy Bay, New Brunswick, Canada

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INTRODUCTION

Passamaquoddy Bay is a large estuary located in southwestern New Brunswick, covering an area of approximately 575 km^2 (Fig. 1). In 1988, the Atlantic Geoscience Centre and the Geophysics Division of the Geological Survey of Canada, conducted a marine geological-geophysical survey aboard the M.V. Navicula (Fader, 1989) in Passamaquoddy Bay and the adjacent St. Croix River. This survey was undertaken with high-resolution seismic reflection profilers, together with a 100 kHz sidescan sonar system and seabed samplers.

The objectives of the cruise were: 1) to map the distribution of surficial sediments, and seabed and subsurface features; 2) to determine the thickness of surficial sediments; 3) to deduce the Quaternary geological history, including the late Pleistocene-Holocene sea level history of the area; 4) to determine if the seismic reflection data show movement on adjacent faults mapped on land; and 5) to further study previously interpreted slumps (Kelley et al., in press) in the St. Croix River.

During the survey, an unexpected discovery of pockmarks and plumose structures (Fig. 2), covering a large area of the seabed of Passamaquoddy Bay was made.

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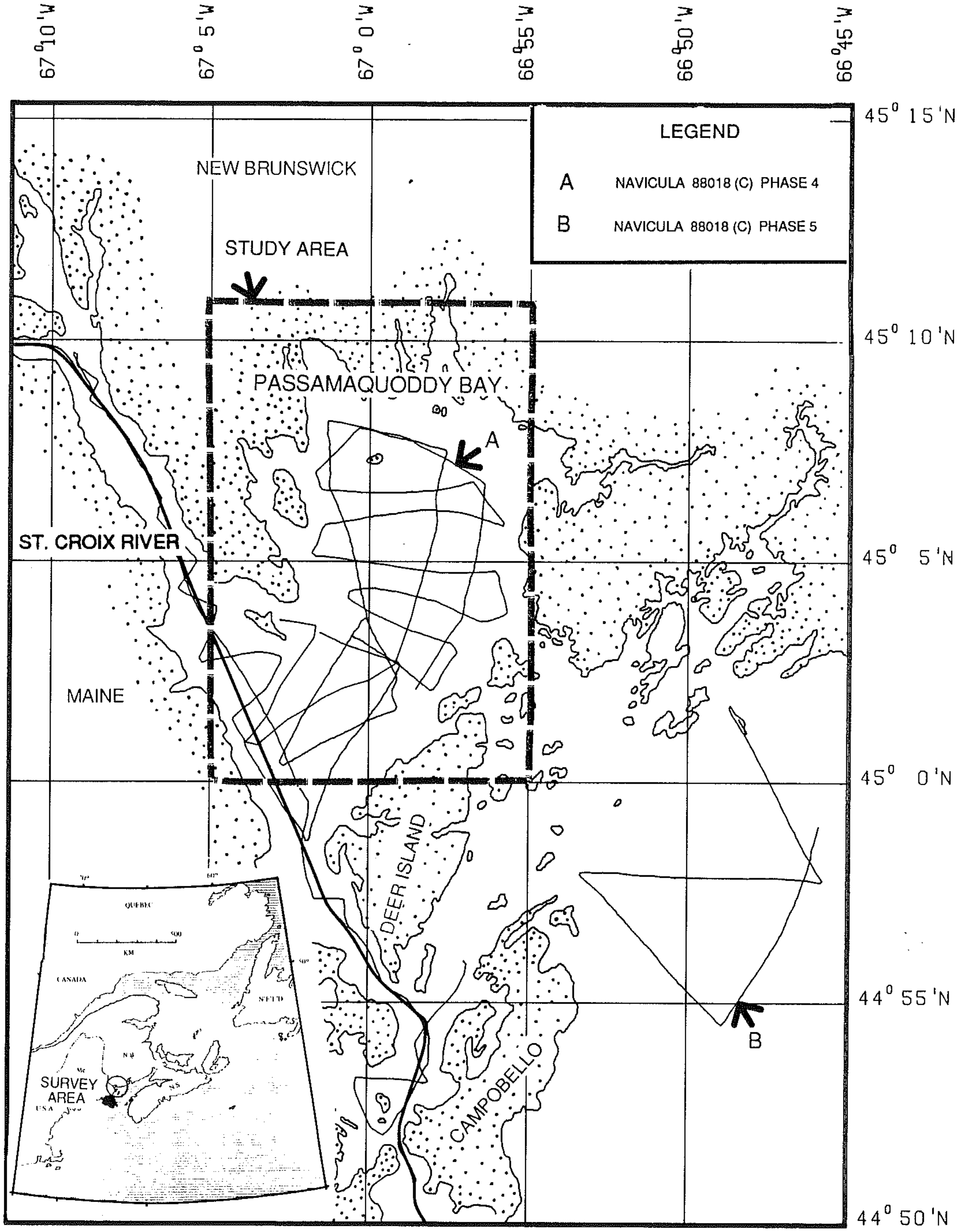

Fig. 1 Index map showing the location of Passamaquoddy Bay.

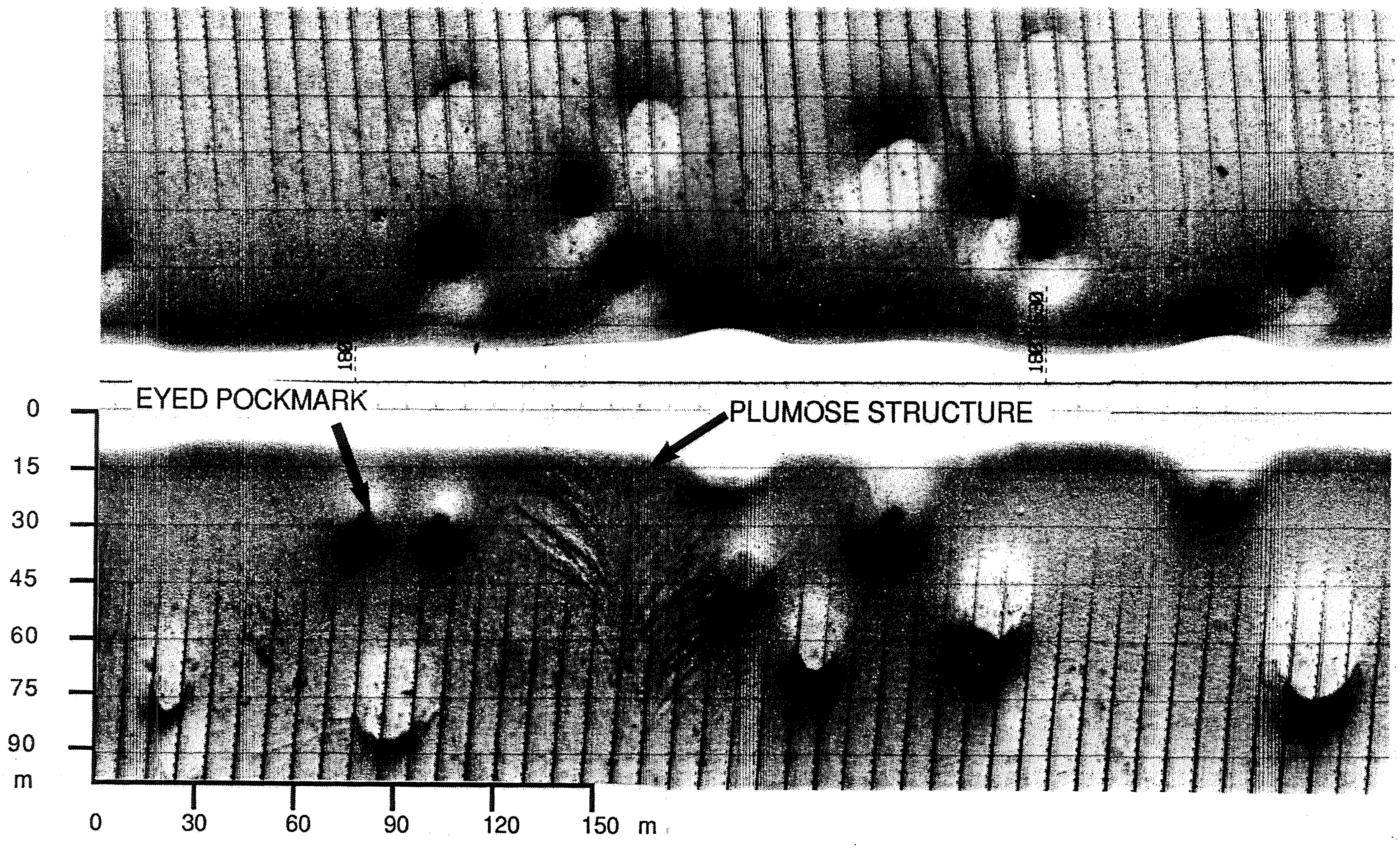

Fig. 2 A sidesacn sonogram of pockmarks and a plumose structure from the seabed of Passamaquoddy Bay. Eyed pockmarks have highly reflective dark centre spots interpretated as carbonate deposits or dense distributions of benthic invertebrates.

This report comprises a geological and geophysical interpretation of the data collected during the Navicula survey. The interpretation includes: 1) the stratigraphy and geological history of Passamaquoddy Bay; 2) the distribution and characteristics of pockmarks and other seabed features; and 3) a discussion of the possible origin of pockmarks in Passamaquoddy Bay and their relationship to local neotectonics.

PREVIOUS WORK

Previous marine geological work undertaken in the Passamaquoddy Bay area consisted of: 1) nearshore boreholes drilled by the International Passamaquoddy Engineering Board (1959) for a proposed tidal-electric generating station; 2) a New Brunswick Department of Fisheries subtidal benthic survey in areas within 100 m of the shoreline to record depth, sediment type, and marine species (MacKay et al. 1983); and 3) seismic reflection surveys in Cobscook Bay and the St. Croix River for evaluating bottom and sub-bottom characteristics (F.R. Harris Consulting, 1972), and investigating neotectonic activities (Kelley et al., in press). Bathymetric echograms were collected by the Canadian Hydrographic Service in 1986 and 1987. A new hydrographic chart will be published from data collected from these surveys, and will replace the present 1848 British Admiralty Sources hydrographic chart of Passamaquoddy Bay and St. Croix River.

REGIONAL SETTING

Topography

Previous studies suggested that Passamaquoddy Bay has developed as a result of a drowned shoreline and its shape has been controlled by the bedrock and structural geology (Cumming, 1967). The complex shoreline of the coast and islands of the Bay indicates that the Bay has been influenced by: 1) a northwest structural bedrock trend, 2) resistant Paleozoic rocks, 3) glaciation, and 4) a postglacial rise in sea level (Logan et al., 1983).

The bathymetry of the bay floor is very irregular due to the presence of pockmarks. Figure 3 shows that the bathymetry of the main bay floor ranges from 20 to 40 m water depth. Large isolated depressions near Letete and Western passages range to over 60 m water depth. North of Hardwood Island, the water depth is less than 20 m.

Bedrock Geology

Outcrops of Devonian and Silurian volcanic and sedimentary bedrock (Cumming, 1967) are exposed along the shoreline of the coast and islands of the Bay (Fig. 4).

The Silurian age Mascarene Group (Bailey and Matthew, 1872) consists of: 1) acidic and basic volcanic rocks; and 2) clastic sedimentary rocks, conglomerate, limestone, and shale (Cumming, 1967).

The Late Devonian age Perry Formation is the youngest bedrock unit in the area, and occurs unconformably or in fault contact with underlying rocks (Cumming, 1967 and Schluger, 1973). The Perry Formation was deposited in two separate basins, the St. Andrews Basin and Blacks Harbour Basin, located near the towns of St. Andrews and Blacks Harbour, New Brunswick, respectively (Schluger, 1973). Cumming (1967) proposed that the Perry Formation underlies most of the Bay. The Perry Formation outcrops at: 1) St. Andrews Peninsula and the Maine Coast; 2) the mouth of the Maqaquadavic and Bocabec rivers; and 3) Pendleton, McMaster, and Hardwoood islands (Fig. 4); and has been intersected by boreholes in the Bay undertaken by the International Passamaquoddy Engineering Board (1959).

The Perry Formation of the St. Andrews Basin consists of five members, in which three members consist of red conglomerate, sandstone, and shale; and two members consist of basalt flows. Each sedimentary rock member of the Perry Formation contains plant debris: 1) Lamb Cove Member - bioherm or lithoid tufa-like mounds, 2) Brandy Cove Member - plant fossils, and 3) St. Andrews

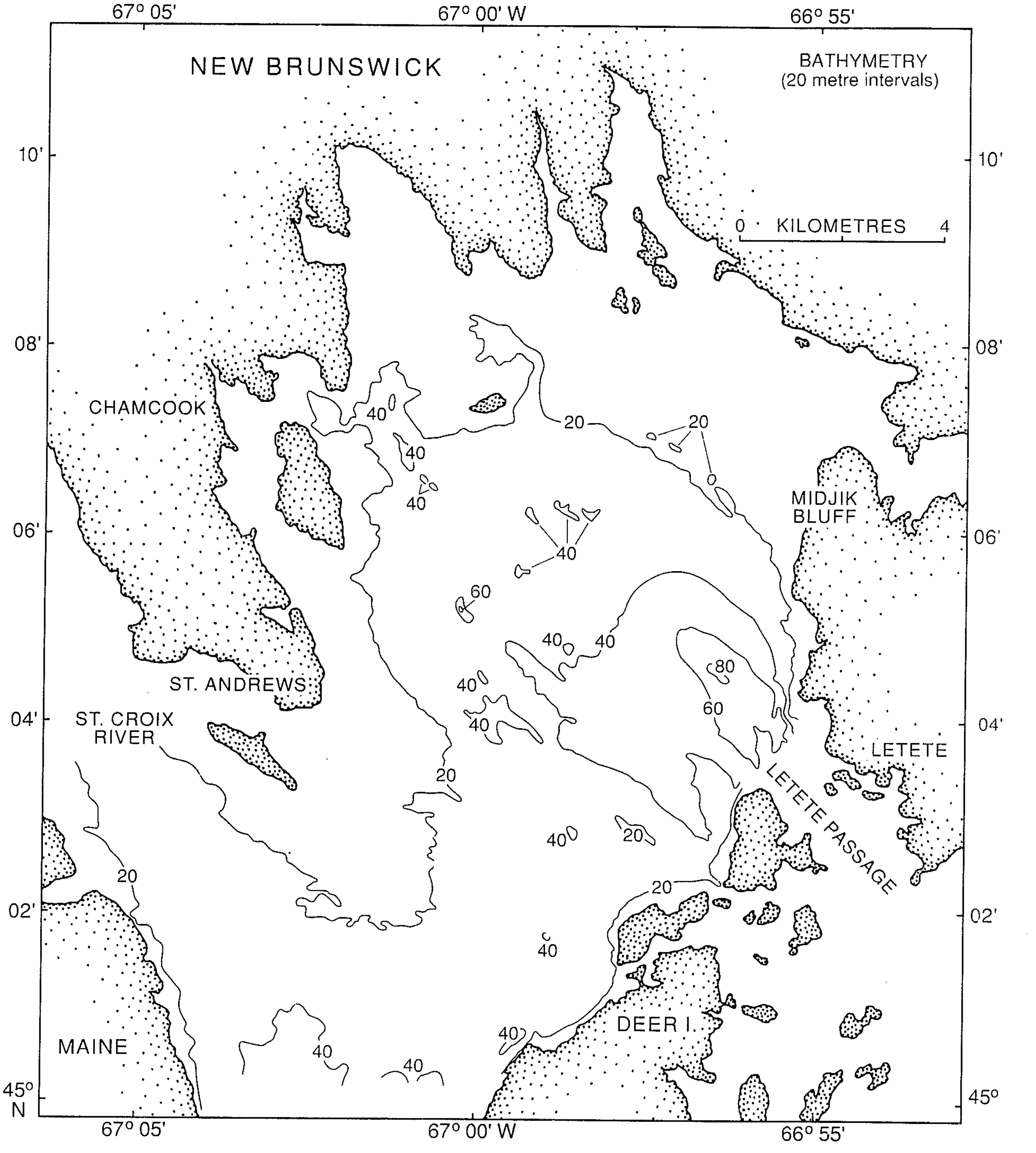

Fig. 3 Bathymetry from Canadian Hydrographic Service Field Sheets No.'s 9181, 9181b, and 9176. Note: the 60 m contour in the western centre of the Bay represents the deepest pockmark found in the Bay.

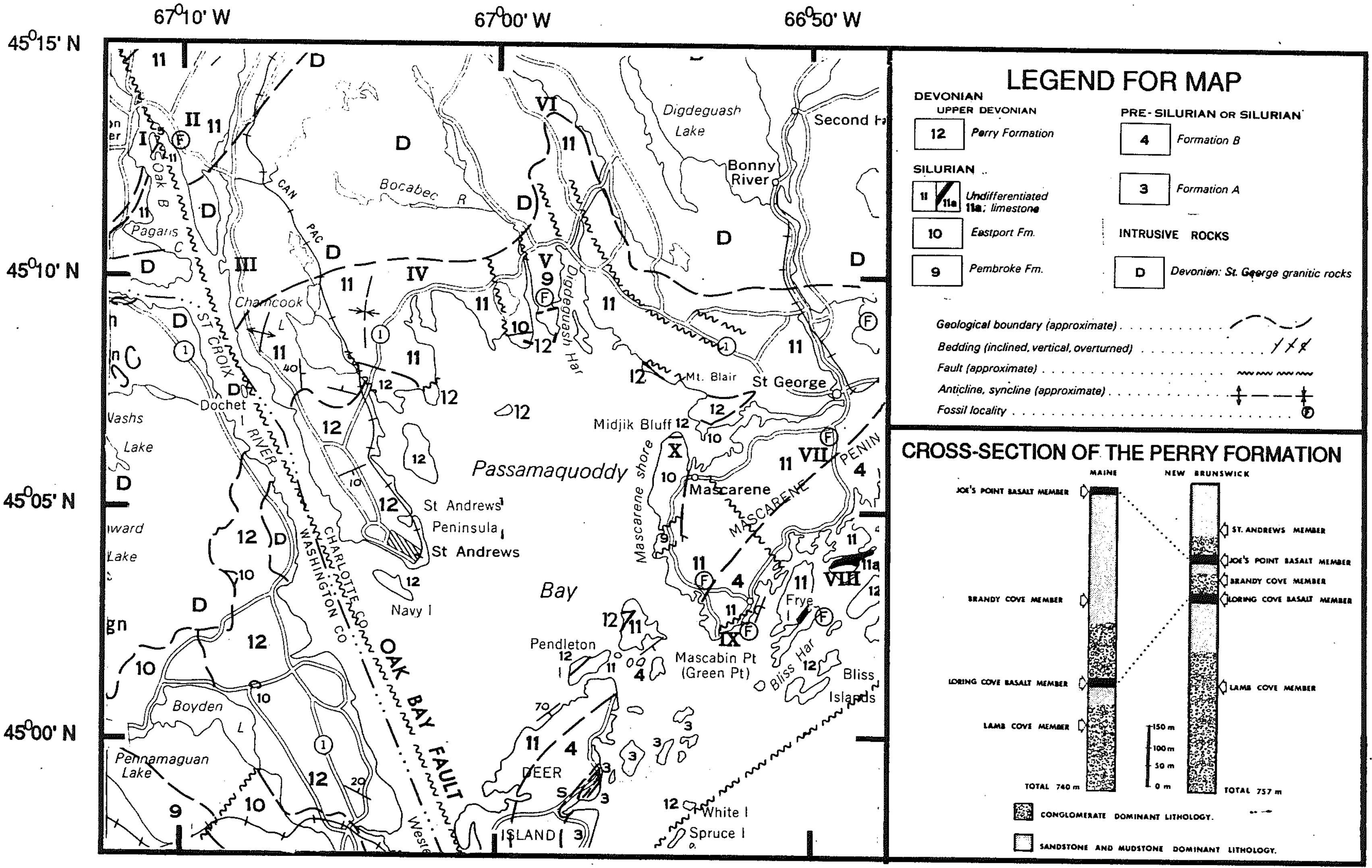

Fig. 4 Bedrock geology of the Passamaquoddy Bay area (Cumming, 1967). Stratigraphic columns are from the Perry Formation of the St. Andrews Basin (Schulger, 1973) - the length of the lithologic symbol represents the approximate percentage of rock type in each member.

Member plant fragments. The amount of plant debris increases in abundance up through the stratigraphic column (Smith and White, 1905; Rhoades, 1963; Schluger, 1973).

Quaternary Geology

Grounded glacial ice advanced through southwestern New Brunswick and eastern Maine during the Late Pleistocene. During this time, bedrock was eroded and basal tills were deposited. Rapid glaciomarine sedimentation followed as the ice retreated. At 13,500 yrs. BP, a marine limit of 73 m above present sea level was formed along the south coast of New Brunswick and eastern Maine (Fader et al., 1977; Belknap et al., 1986). Relative sea level then fell as the rate of isostatic rebound exceeded the rate of eustatic sea level rise, resulting in a regression. Equilibrium between the two rates occurred approximately 9,500 yrs. BP at a low sea level stand of 40 to 65 m below present sea level in eastern Maine (Belknap et al., 1986; Knebel, 1986). Following this time sea level continued to rise, depositing Holocene muds from reworked and eroded Pleistocene sediments and bedrock.

Surficial geology units mapped by Fader et al. (1977) in the Bay of Fundy and Gulf of Maine, and named by King (1970) are: 1) Scotian Shelf Drift (Pleistocene till), 2) Emerald Silt (Pleistocene glaciomarine sediments), 3) LaHave Clay (Holocene clay), and 4) Sambro Sand (reworked sublittoral sediments).

Sheepscot Estuary and Penobscot Bay are located southwest of Passamaquoddy Bay in eastern Maine. The Quaternary stratigraphy of these areas consists of: 1) a coarse-grained Pleistocene drift, 2) a well-stratified, fine-grained Pleistocene glaciomarine deposit, 3) a muddy, marine sediment, rich in organic matter, and 4) glaciofluvial deposits (Belknap et al., 1986; Knebel and Scanlon, 1985; Knebel, 1986).

Pockmarks

Pockmarks are found in Passamaquoddy Bay and are interpreted to form from fluid (liquid or gas) seepages at the seabed. Pockmarks were first recognized on the Scotian Shelf off Nova Scotia and described by King and MacLean (1970) as gas or water escape craters occurring in large numbers. Since then, pockmarks have been discovered in many areas around the world (Table 1). The most widely accepted theory on pockmark formation is associated with fluid escape through the seabed lifting fine grained sediments into suspension. This sediment is then redistributed by near-bottom currents. Local slumping within the pockmark may modify and expand the depression to a more complex form (Fig. 5). This process is called "gasturbation" (Josenhans et al., 1978).

Faults

The two dominant faults in the Passamaquoddy Bay region are the Oak Bay (Matthew, 1878) and Lubec (Gates, 1961) faults. Other smaller local faults in the western and central part of the Bay, trend NNW, parallel to the Oak Bay Fault. Faults in the eastern part of the Bay trend NE (Fig. 6) (Cumming, 1967; Stringer and Burke, 1985).

The Passamaquoddy Bay region is seismically active, and this activity appears to be related to the faults in the region. In the last 170 years, there have been at least three >M5 earthquakes (LeBlanc and Burke, 1985), including a series of six M3 earthquakes in the Bay region during 1983-84 (Ebel, 1985; Adams and Basham, 1989).

Physical Oceanography

The maximum tidal range in Passamaquoddy Bay is 8.3 m (Anon, 1970). General surface circulation (Fig. 7a) in Passamaquoddy Bay is usually counterclockwise, with outflows at the St. Croix River, Western Passage, and Letete Passage (Chevrier and Trites, 1960). Average tidal currents (Fig. 7b) range from 0.2 to 2.0 m/s, in which the strongest currents are restricted to the Letete and Western passages. Currents in the area do not vary much with depth, except within a metre or two of the seafloor (Forrester, 1959). Whirlpools were observed in Western Passage by Fader (1989).

	Water depth (m)	Size: Average (m)	Size: Range (m)	Depth: Average (m)	Depth: Range (m)	Density	Seabed sediment type
Witch Ground Basin, North Sea*	100–150		<50 100–150		 1–3	$<40\,km^2$ $10–15\,km^2$	soft to very soft sandy muds very soft mud
Norwegian Trench, North Sea	200–>350		<250		<15	$<60\ km^2$	soft, plastic silty clay
Lygenfjord, Norway		80	<300	<3	<5	150–400 m spacing	acoustically transparent–?muddy
Barents Sea northern region	~200		10–20		<1	<25% of seabed	clayey till with thin cover of mud
Eckernförder Bay, Baltic Sea	20–30		<several hundred				soft muds
Adriatic Sea	80–90		60–350		1–6	$10\ km^2$	soft silty clays and clays
Aegean Sea	6–25	15	1–25		<3		stiff clays
Arabian Gulf	~30 ~30	 12	<80	 4.5	1.5	$20\,km^2$ $240\ km^2$	soft silts silty to sandy
Poverty Bay, New Zealand	>15	<20	<50		0.3–0.5	$<30/100\,m^2$	firm, muddy or silty very fine sand
Norton Sound, Alaska	<20	2	1–10		<0.5	$200–1000\,km^2$ (max. 1340)	fine grained sandy silts
Shelikof Strait, Alaska	170–200	50			<5		very soft muddy sands to sandy mud
Gulf of Mexico			<46		1.5–3.0		soft sediments
Bahama Outer Ridge	4400–4800		30–40		~5	40 in $100\ km^2$	fine grained cohesive sediments
Penobscot Bay, Maine	20–50	20–60	10–200	5–10	1–30		acoustically transparent muds (average 35% silt, 59% clay)
Scotian Shelf		50		4	5	6% of seabed $30\,km^2$	LaHave Clay A
		150		10	15	18% of seabed $10\ km^2$	LaHave Clay B
		55		4	6	7% of seabed $28\,km^2$	Emerald Silt
Verrill Canyon, Nova Scotia	500–1100				<4	5–10% of seabed	
Labrador Shelf			<100		<7		sandy silt

Table 1 Summary of world wide pockmark features - dimensions and sediment type (Hovland and Judd, 1989).

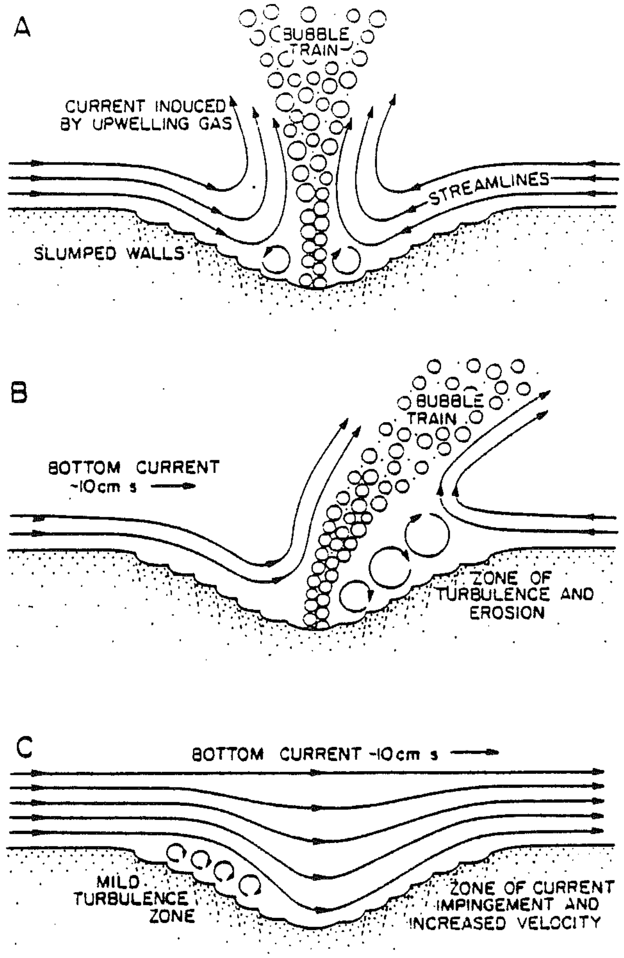

Fig. 5 A proposed mechanism by Josenhans, King, and Fader (1978) for pockmark formation by gas venting from the seafloor.

(A) Streamlines indicate current direction over a gas seepage in a muddy sediment. Shearing and slumping of bottom sediment around the seepage results in the removal of the sediment at the site causing a pockmark to form.

(B) Same mechanism as (A) and but with the introduction of residual and tidal currents. This would cause the pockmark to become elongated.

(C) Hyrodynamic regime over an inactive pockmark. Some erosion may continue over the inactive pockmark on the upstream edge, if current velocities are sufficient to induce turbulence. This could cause the pockmark to become irregular.

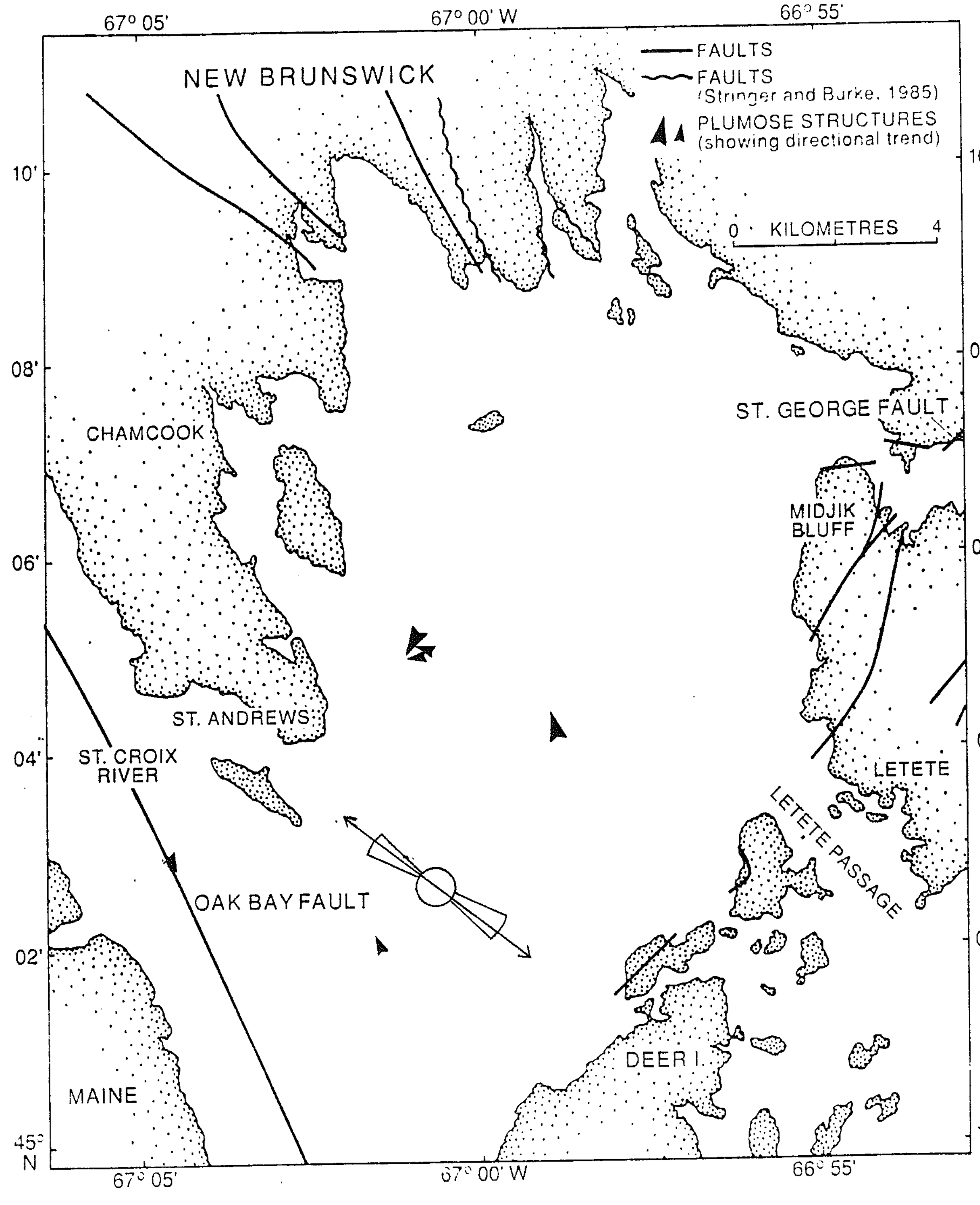

Fig. 6 Faults described by Cumming (1967), and Stringer and Burke (1985) with associated neotectonic features interpreted by sidescan sonograms: 1) plumose structures and 2) preferred alginment of eyed pockmarks shown by the rose diagram.

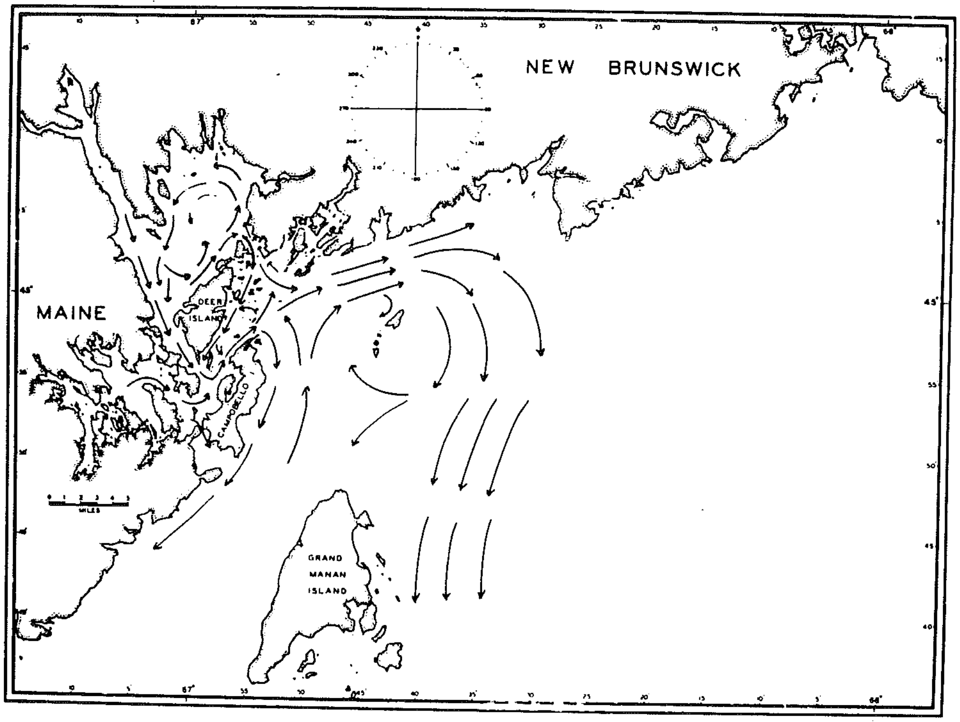

Fig. 7a General surface circulation in the Quoddy Region for 1957-58 as indicated by drift bottles (Chevrier and Trites, 1960).

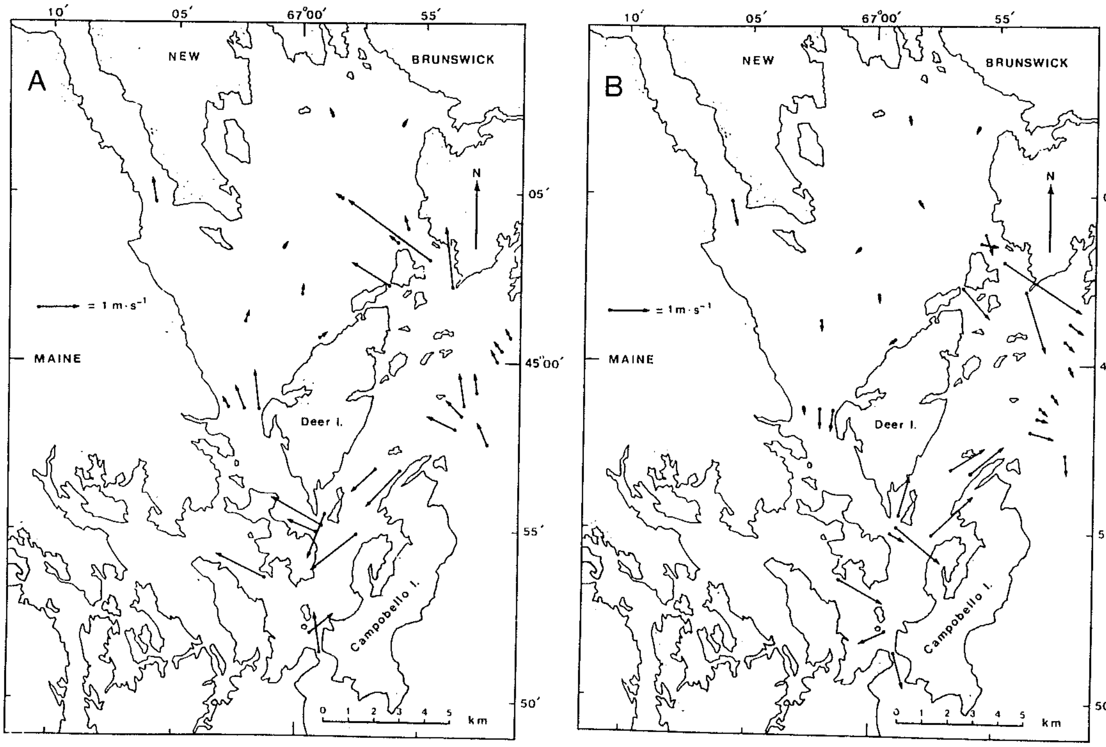

Fig. 7b Average surface tidal currents 3 hours before high water (A), and 3 hours after high water (B) (Forrester, 1959).

COLLECTION AND INTERPRETATION OF DATA

Navigation

Navigational control was provided by Loran C (Fig. 8) and ship's radar. Bathymetry was recorded using a 30 kHz Elac type LAZ72 echosounder.

Sidescan Sonar System

A 100 kHz Klein sidescan sonar system was used to provide sonograms of the seabed. Sidescan sonar is capable of resolving small topographic irregularities and objects on the seafloor, as well as textural changes between sediment types. The aspect ratio of sonograms varied from 1:1 to 1:1.5, depending on ships speed. The Klein sidescan was generally operated at the 100 m range (200 m total swath) to provide optimum assessment of pockmark distribution. The system was occasionally operated at 50 m or 150 m ranges. Thermocline interference degraded sonogram quality in the northern part of Passamaquoddy Bay. Interference from the thermocline and the sparker reflection seismic system, made it difficult at times to calculate the density of small pockmarks (<10 m in diameter).

Huntec Sea Lion Shallow Tow Boomer

The Huntec Sea Lion is a 350 joule high-resolution seismic reflection system which is designed for use in shallow water, and has a resolution of $\approx$ 1 m. For part of the survey, the system was towed at the manufacturers recommended depth of 5 m below the water surface, but resulted in water surface reflections on the profiles, and thus, degraded the profiles. For the remainder of the survey, the system was towed at the surface, resulting in more easily interpreted profiles with no acoustic artifacts. A firing rate of 0.75 seconds was used throughout the survey.

Sparker Seismic Reflection Systems

A 280 joule sparker seismic reflection system was deployed during the cruise. The sparker and Huntec Sea Lion systems could not be deployed simultaneously due to the availability of one power

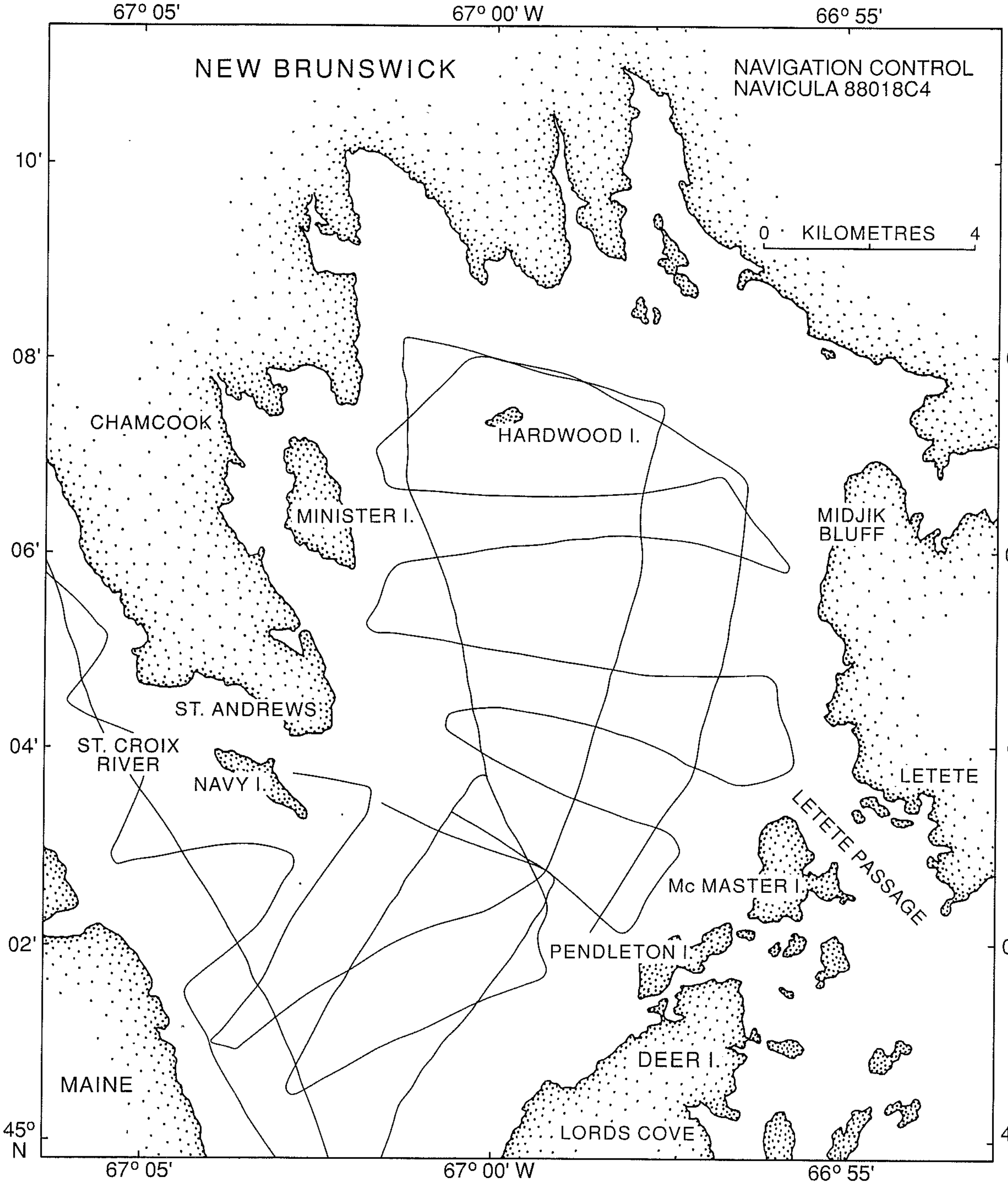

Fig. 8 Navicula 88018C4 Survey Tracks in Passamaquoddy Bay.

unit on the Navicula. Because the resolution of the sparker was only ≈ 5 m, the Huntec Sea Lion was deployed for most of the survey.

Datasonics Bubble Pulser

A 20 joule Datasonics Bubble Pulser was deployed for the entire survey and provided continuous penetration to the bedrock surface with a resolution of ≈ 10 m, much less than the Huntec Sea Lion system. The system was towed at the surface and a firing rate of 0.75 seconds was used throughout the survey.

Van Veen Grab Samples

Fourteen van Veen grab samples were collected to provide groundtruth for the interpretation of sidescan sonar and seismic reflection data. All sample sites were selected in Passamaquoddy Bay, and are shown in Figure 9. Field descriptions of the samples were made at the time of collection and are summarized in Table 2.

Data Interpretation

The stratigraphic framework of Passamaquoddy Bay was established through the interpretation of echograms and seismic reflection profiles. An isopach map of Holocene clay was constructed using the seismic reflection data together with Canadian Hydrographic Service echograms, which defined the lateral extent and thickness of the acoustically transparent Holocene Clay. The echogram interpretation was corroborated with the seismic reflection profiles, which also enabled the recognition of other surficial and deeper subsurface sedimentary units.

Databases were created to record the interpretation of pockmarks from sidescan sonograms, echograms, and seismic reflection profiles. The Canadian Hydrographic Service echograms were also used in defining the lateral extent of pockmarks, and noting any special characteristics of the seabed morphology associated with the pockmarks.

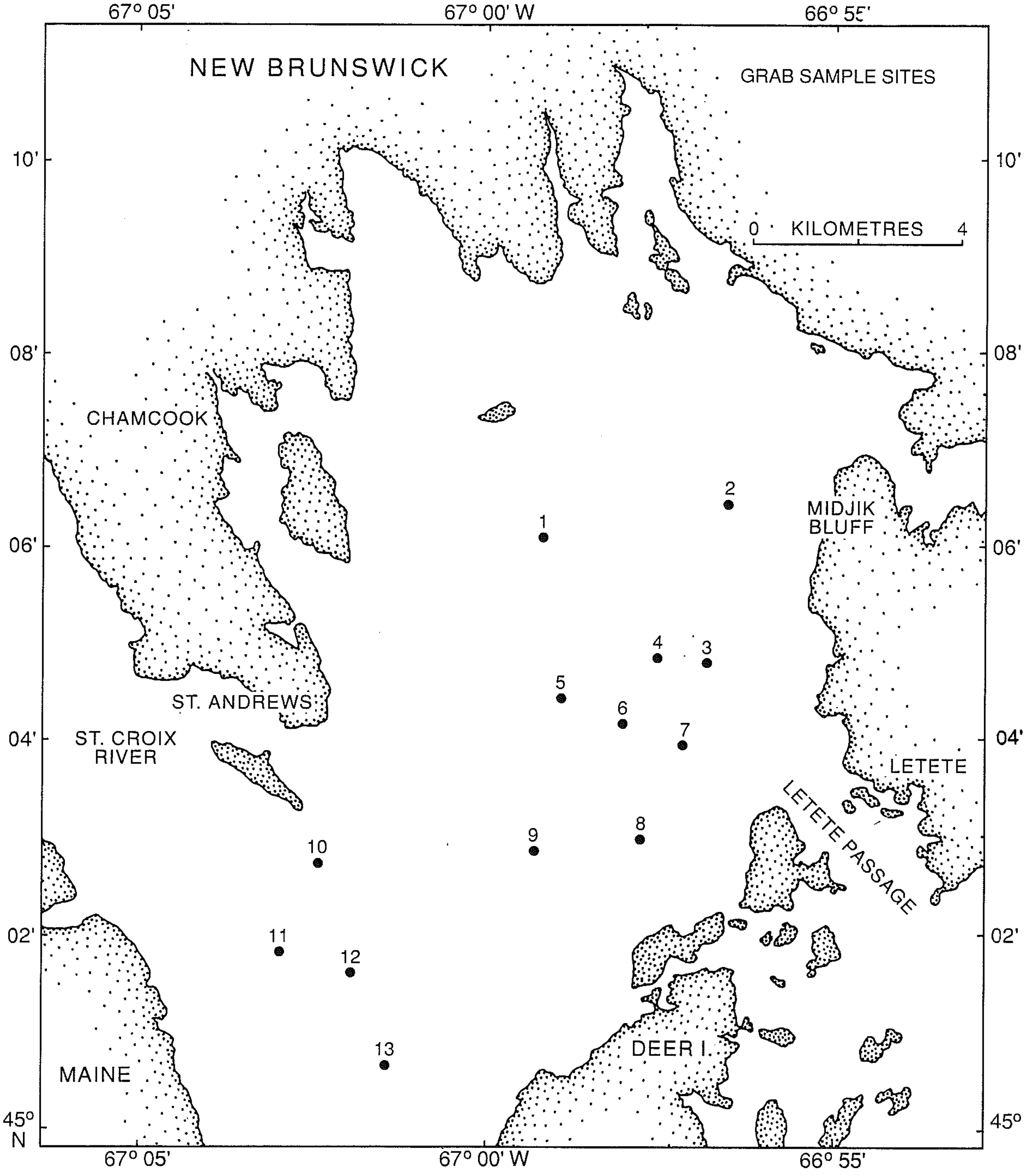

Fig. 9 Van Veen grab sample sites during the survey in Passamaquoddy Bay.

Samp. #	Sample Type	Jul. Day/ Time	Latitude	Longitude	Depth (m)	# of Attempts	# of Sub-samples	Geographic Location	Notes
001FAA	van Veen	1831145	45°06.10'N	66°59.19'W	32	1	2	Passamaquoddy Bay	Over gas, 5 m pockmarks, middle of bay. Dark greyish brown mud, 2 sea cucumbers. Few shells, articulated.
002FAA	van Veen	1831206	45°06.47'N	66°56.54'W	21	1	2	Passamaquoddy Bay	Mud patch over till and bedrock, brown mud, 1 pebble.
003FAA	van Veen	1831223	45°04.81'N	66°56.80'W	71	1	2	Passamaquoddy Bay	Sand waves off Letete Passage. Thin sand over Presumptscot. Muddy sand and gravel, 1 large clast.
004FAA	van Veen	1831248	45°04.86'N	66°57.50'W	50	1	2	Passamaquoddy Bay	Flank of channel, possible Presumptscot. Sandy mud, large disk-shaped gravel clasts, well rounded fragments.
005FAA	van Veen	1831254	45°04.38'N	66°58.89'W	42	1	2	Passamaquoddy Bay	Over gas, Centre Bay, few pocks nearby. Brown-grey, marine mud, no shells or gravel.
006FAA	van Veen	1831308	45°04.18'N	66°57.99'W	45	1	2	Passamaquoddy Bay	Centre of bay, numerous trawl marks. Silty clay, note lots of clam shells dead & alive, marks on seabed are clam gear tows.
007FAA	van Veen	1831319	45°03.90'N	66°57.12'W	48	3	2	Passamaquoddy Bay	Mottled seabed. Sand, gravel, large rock 20 cm., small grits, scallop shells, small and broken. Large rock split for bucket. Perry Formation sandstone large rock, flat.
008FAA	van Veen	1831336	45°02.96'N	66°57.72'W	24	2	2	Passamaquoddy Bay	Gravel on top of bedrock. Sill area between basins, off little Letete Passage. Gravel, sand, <10% mud. Hard bottom, lots of shells, scallop shells etc., growth.
009FAA	van Veen	1831350	45°02.85'N	66°59.32'W	26	1	2	Passamaquoddy Bay	Thin mud overlying glacial outwash, unconformity on surface, small pocks or mud volcanoes, see sidescan for further details. Mud, few clasts, no sand. 2 unique gastropods in bags.
010FAA	van Veen	1831406	45°02.68'N	67°02.38'W	14	2	2	Passamaquoddy Bay	Scallop grounds, lots of scallop drag marks on sidescan. Gravel, boulders, sand, some mud, shells scallop-clams, sea cucumber, split large rock, local granite, saved only small split piece.
011FAA	van Veen	1831419	45°01.79'N	67°02.88'W	30	1	2	Passamaquoddy Bay	Small pocks, mud
012FAA	van Veen	1831429	45°01.59'N	67°01.91'W	31	1	2	Passamaquoddy Bay	Large gassy pockmarks. Okive brown mud, few clams, no sand or gravel. Note: near bottom of pockmark. See echosounder for more info.
013FAA	van Veen	1831447	45°00.60'N	67°01.36'W	45	1	2	Passamaquoddy Bay	Heavy trawl area. Sandy mud, few clam shells, 1 sea cucumber, sandy feel to mud.
014FAA	van Veen	1831502	44°58.97'N	67°02.25'W	70	1	2	Passamaquoddy Bay	Mottled seabed on sidescan. Sand, slightly muddy, gravel, shells.

Table 2 Navicula 88018C4 van Veen grab samples (Fader, 1989).

One database was used to record the following data from sidescan sonograms and track plots at four minute time intervals: 1) day and time; 2) speed of the vessel over the seabed; 3) area covered by the sidescan swath; and 4) number of pockmarks within a specific diameter range. A four minute time interval was chosen over a fixed distance interval (eg. 500 m or 1000 m) because the records were annotated with day and time at these intervals. Due to fluctuations in the ship speed, the distance between a four minute time interval ranges from 400 to 550 m, with an average interval of 465 m. Average ship speed in the pockmark area was 3.8 knots. Pockmarks were classified into specific diameter ranges: 1) <10 m, 2) 10-30 m, 3) 30-50 m, and 4) >50 m. A statistical analysis was then undertaken for: 1) density, average diameter, and area covered by pockmarks; 2) total area covered by sidescan; and 3) total number of pockmarks observed.

A second database was established to record the diameter and depth of pockmarks on echograms and seismic reflection profiles, and enabled the calculation of the average slope of a pockmark wall. The slopes agreed to within 1° on both echograms and seismic reflection profiles. Average depth was computed using average slope and average diameter. These data were used to calculate total sediment dispersement.

RESULTS

Stratigraphy

The interpretation of seismic reflection profiles and sidescan sonograms resulted in the definition of four Quaternary sedimentary units overlying the bedrock surface: 1) glacial till, 2) glaciomarine sediments, 3) clay, and 4) sublittoral sand (Figs. 10 to 12). Bedrock outcrops at the flanks of the Bay (Fig. 10) as cliff edges or ridges. Thick accumulations of sediment (up to 53 m) generally occur in bedrock depressions.

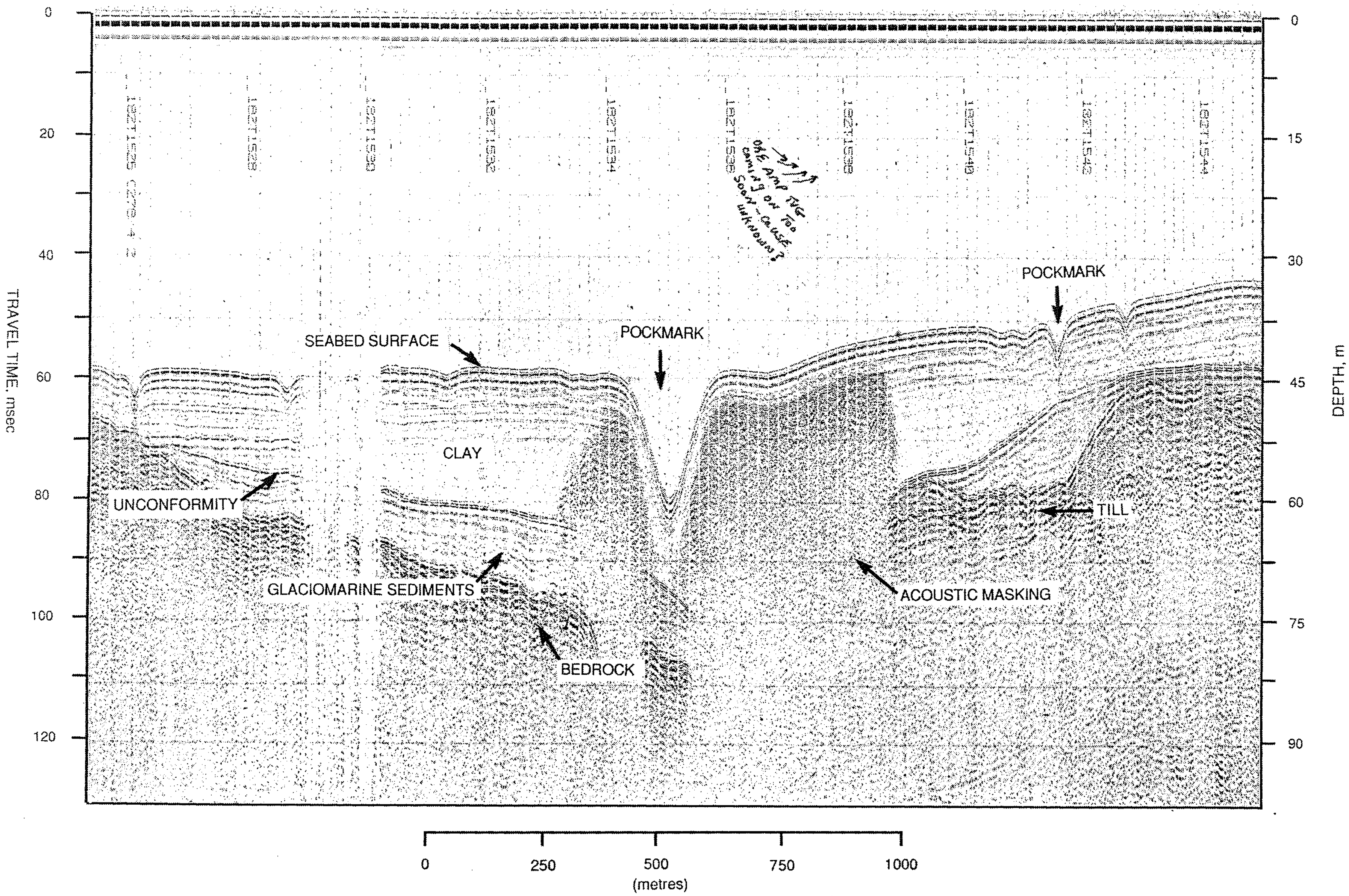

Fig. 11 A typical Huntec Sea Lion seismic reflection profile, showing the stratigraphy of Passamaquoddy Bay, with associated seabed features. Pockmarks and acoustic masking are restricted to the Holocene clay.

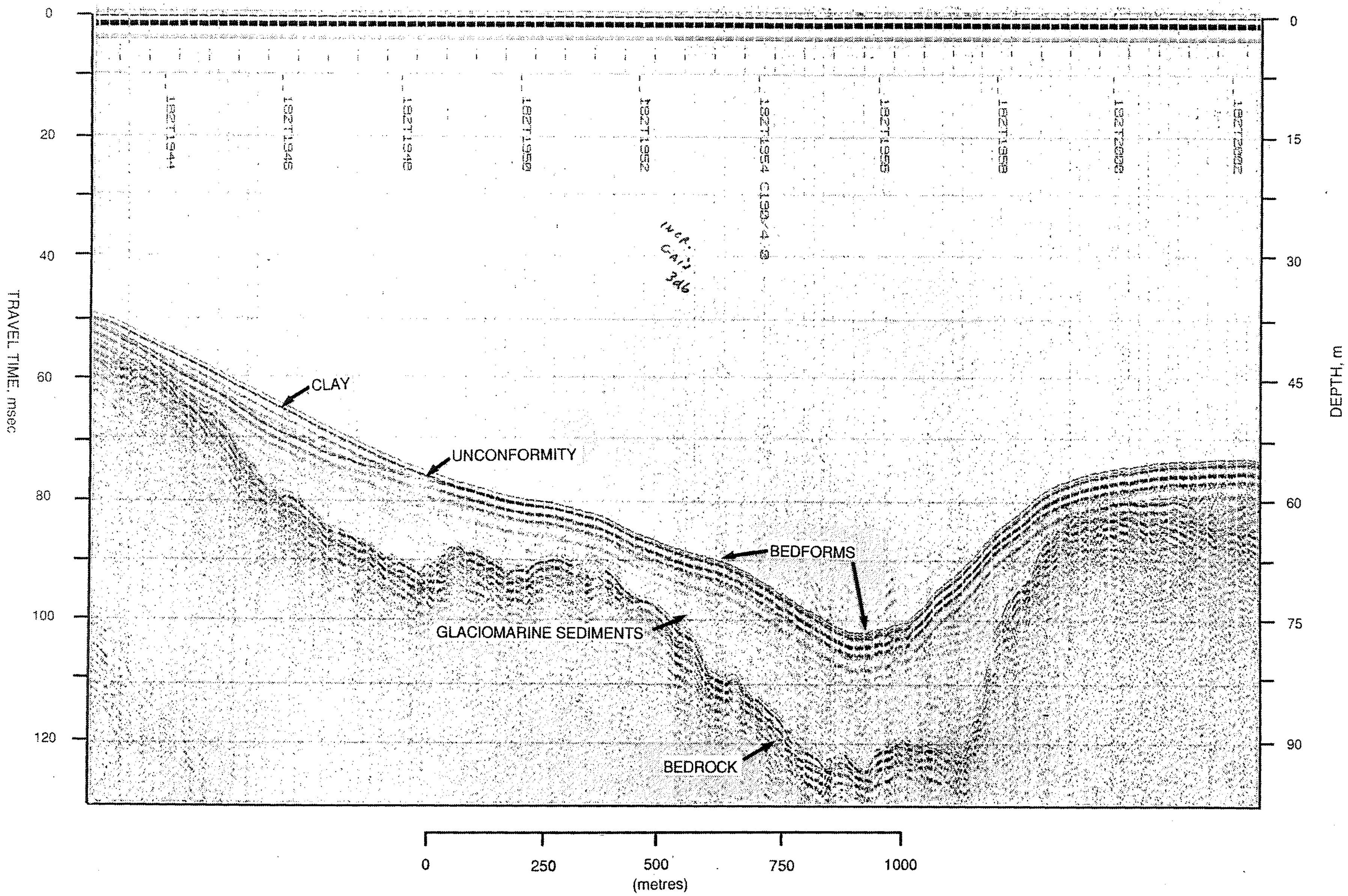

Fig. 12 A Huntec Sea Lion seismic reflection profile showing the stratigraphy of the isolated basin west of the Letete Passage. It is difficult to see the bedforms on this profile because of their low relief, but they are noticable on sidescan sonar and represent a veneer layer of sublittoral sand.

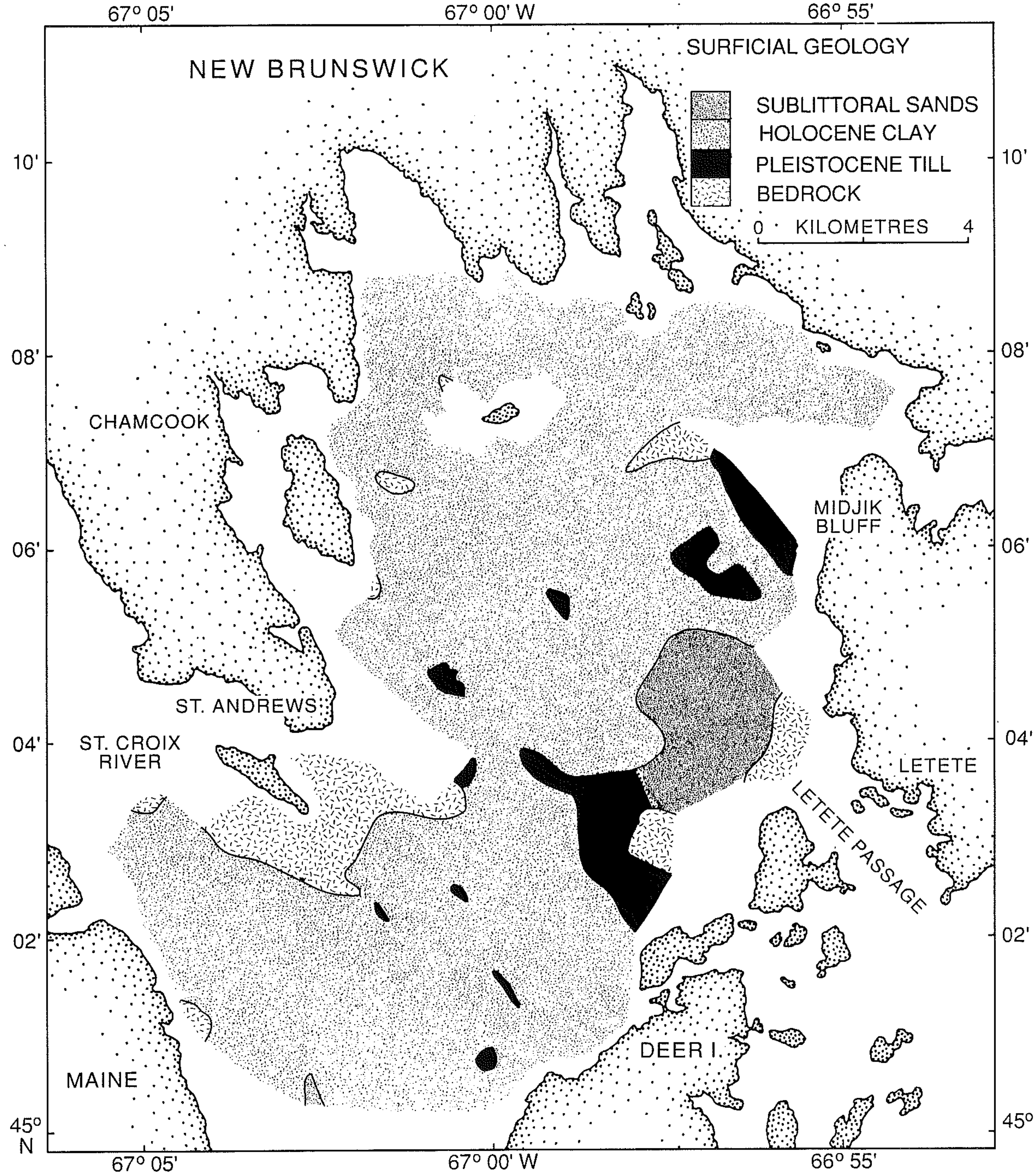

Fig. 10 Surficial Geology of Passamaquoddy Bay based on sidescan sonograms, seismic reflection profiles, and Canadian Hydrographic Service echograms.

Glacial Till

Glacial till in Passamaquoddy Bay is characterized on seismic reflection profiles as a zone of incoherent reflections and parabolic reflections, which suggest large boulders within the till. Till commonly infills bedrock depressions, and is normally less than 15 m thick. It is also deposited: 1) as ground moraine on flat bedrock surfaces, in areas southeast of St. Andrews and west of Midjik Bluff; and 2) as a series of ridges less than 20 m high, east of Minister Island.

Till outcrops as ridges and mounds (Fig. 10) in several local areas in the southern part of the Bay. Near Letete Passage and Midjik Bluff, large areas of till outcrop at the seafloor, possibly overlain by a thin layer of winnowed sand and gravel. These till outcrops also flank bedrock highs and overlie flat bedrock surfaces. West of Midjik Bluff the till is thin (<10 m) and may be very muddy because it appears to be more acoustically transparent on echograms. It also appears to have a rough hummocky surface based on the sidescan data.

Glaciomarine Sediments

Glaciomarine sediments overlie bedrock and till in Passamaquoddy Bay and are characterized on seismic reflection profiles by their moderate to strong continuous coherent, internal reflections. The greatest accumulations of glaciomarine sediments occur in deep bedrock depressions and the internal stratification is highly conformable to the subsurface bedrock and till morphology. The thickest accumulations of glaciomarine sediments are up to 35 m in a bedrock channel northeast of Hardwood Island, which continues to the centre of the Bay. Glaciomarine sediments are generally less than 5 m thick overlying bedrock highs and the glaciomarine sediments do not usually outcrop at the seafloor.

Holocene Clay

The uppermost unit in Passamaquoddy Bay is clay and this sediment dominates the seabed of the Bay (Fig. 10). The clay overlies bedrock, till, and glaciomarine sediments, and is characterized on seismic reflection profiles by its homogeneous structure, and on echograms by its acoustic transparency and its smooth featureless surface (with the exception of pockmarked areas). The thickest accumulation is 32 m in a bedrock depression southeast of Minister Island (Fig. 13). Thick clay accumulations (>10 m) generally occur in bedrock depressions which also contain glaciomarine sediments. Thin layers normally occur where bedrock or till is found near or at the seafloor, and also in areas where strong tidal currents are present.

Sublittoral Sands

A thin veneer of sublittoral sand and/or gravel with little mud overlies bedrock, till, and glaciomarine sediments in areas of strong tidal currents (Fig. 10). Sidescan sonar and echograms, show the presence of bedforms less than 0.5 m high in these areas. These deposits may be equivalent to the Sambro Sand formation in the Bay of Fundy (Fader et al., 1977), and are indicators of recent erosion and sediment transport.

Seabed Features

Pockmarks: Distributions and Characteristics

Pockmarks cover a total area of 87 km^2, which comprises 15 percent of the seafloor of Passamaquoddy Bay. Pockmarks occur in two large areas: 1) the central to northern part of the Bay, and 2) southeast of Navy Island (Fig. 14). Approximately 1320 pockmarks, covering an area of 13 km^2 in Passamaquoddy Bay, were recorded during the survey by sidescan sonar. Calculations show that there are approximately 11,000 pockmarks in the Bay.

Average pockmark density is 126 per km^2. A maximum of 418 pockmarks per km^2 was recorded in the southern part of the Bay (Fig. 15). Figures 16 to 18 show the densities of selected diameter ranges of pockmarks. The maximum density of large pockmarks, >50 m in diameter, is 73 per km^2. Pockmarks in the northern area of the Bay occur in low density, generally <100 per km^2, and high density, 100-400 per km^2 in the southern area of the Bay.

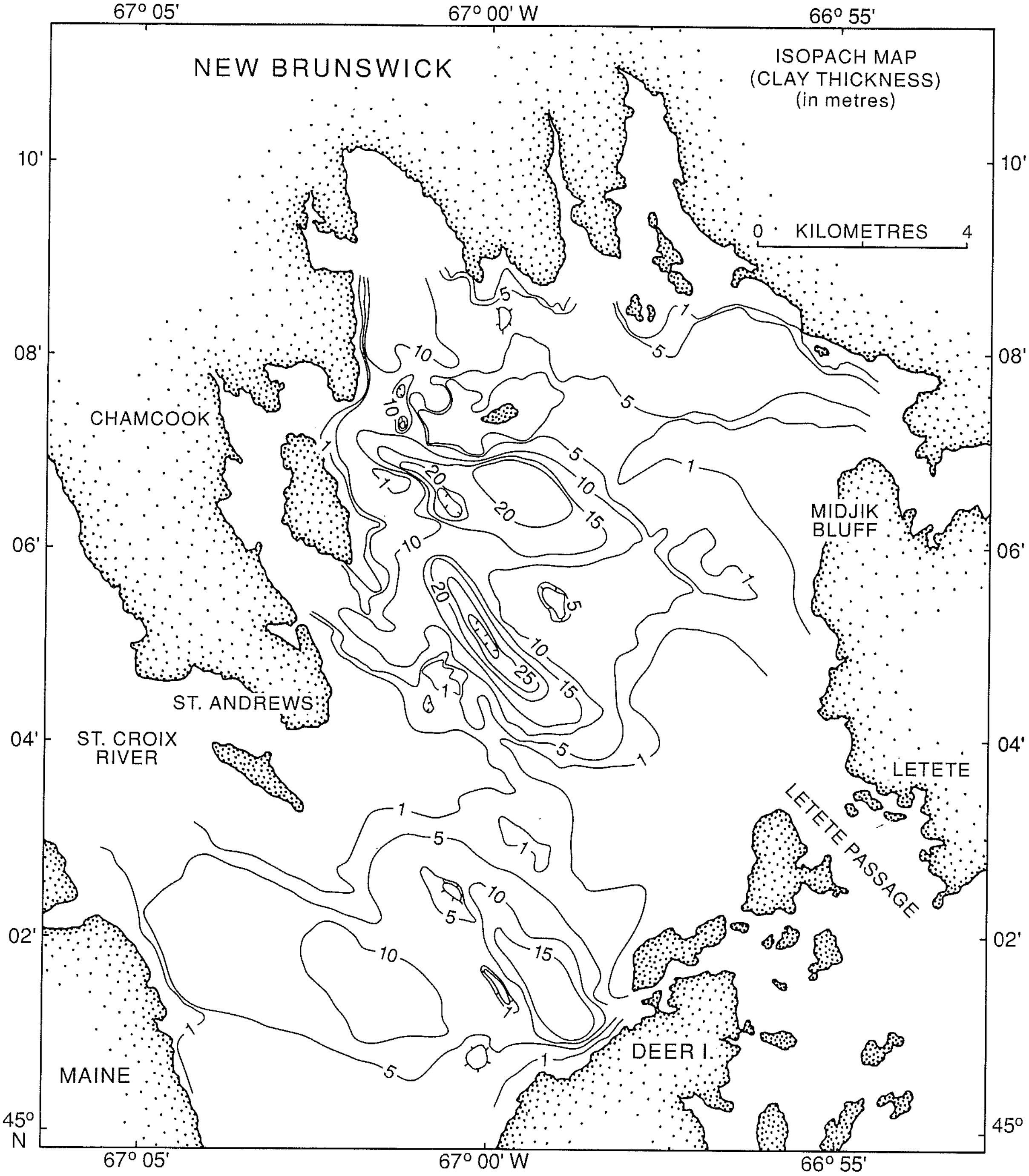

Fig. 13 Isopach map of Holocene clay constructed through the extensive use of Canadian Hydrographic Service echograms with correlation checks with Huntec Sea Lion seismic profiles.

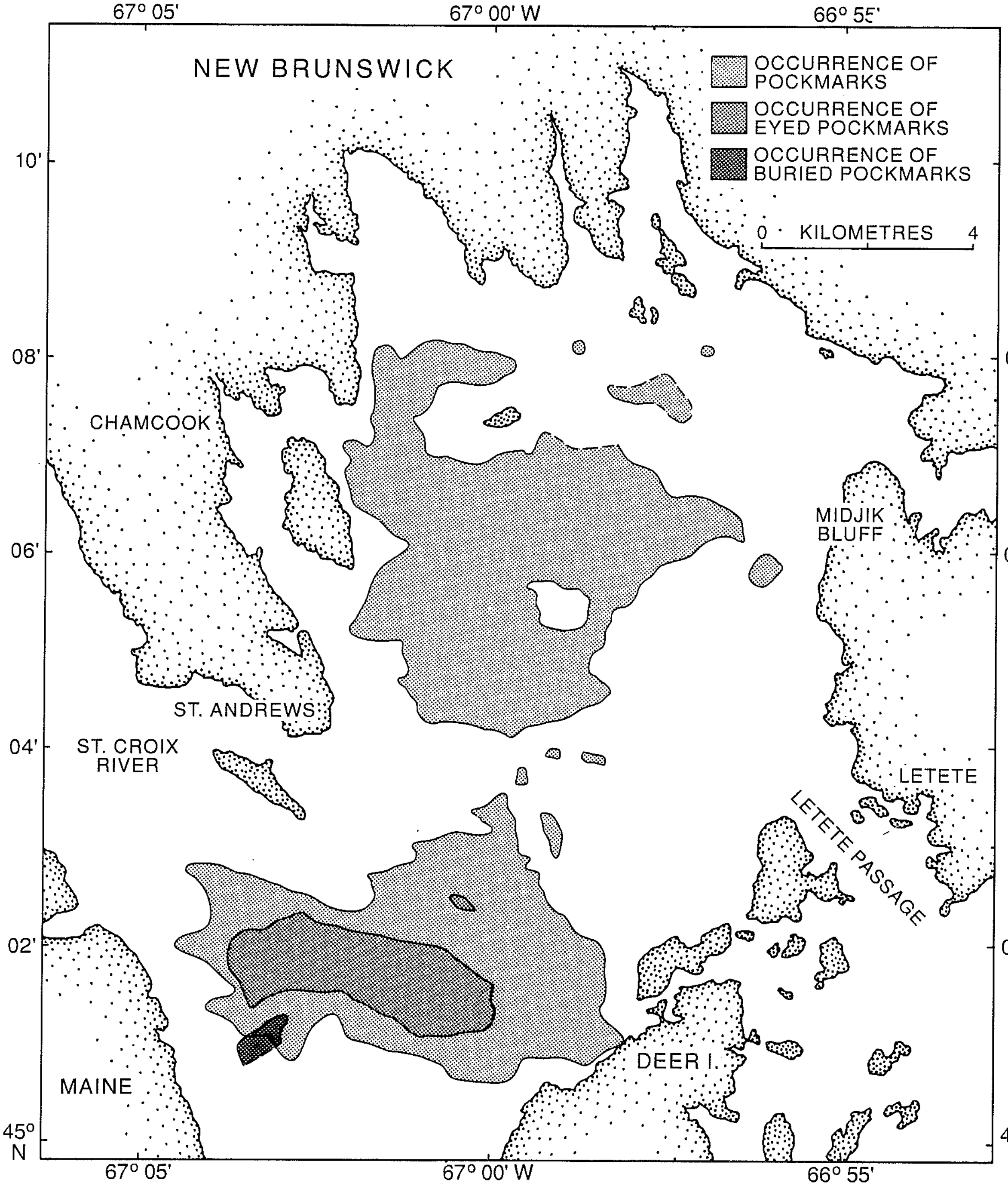

Fig. 14 The occurrence of pockmarks, eyed pockmarks, and buried pockmarks interpretated from sidescan sonograms, echograms, and seismic reflection profiles.

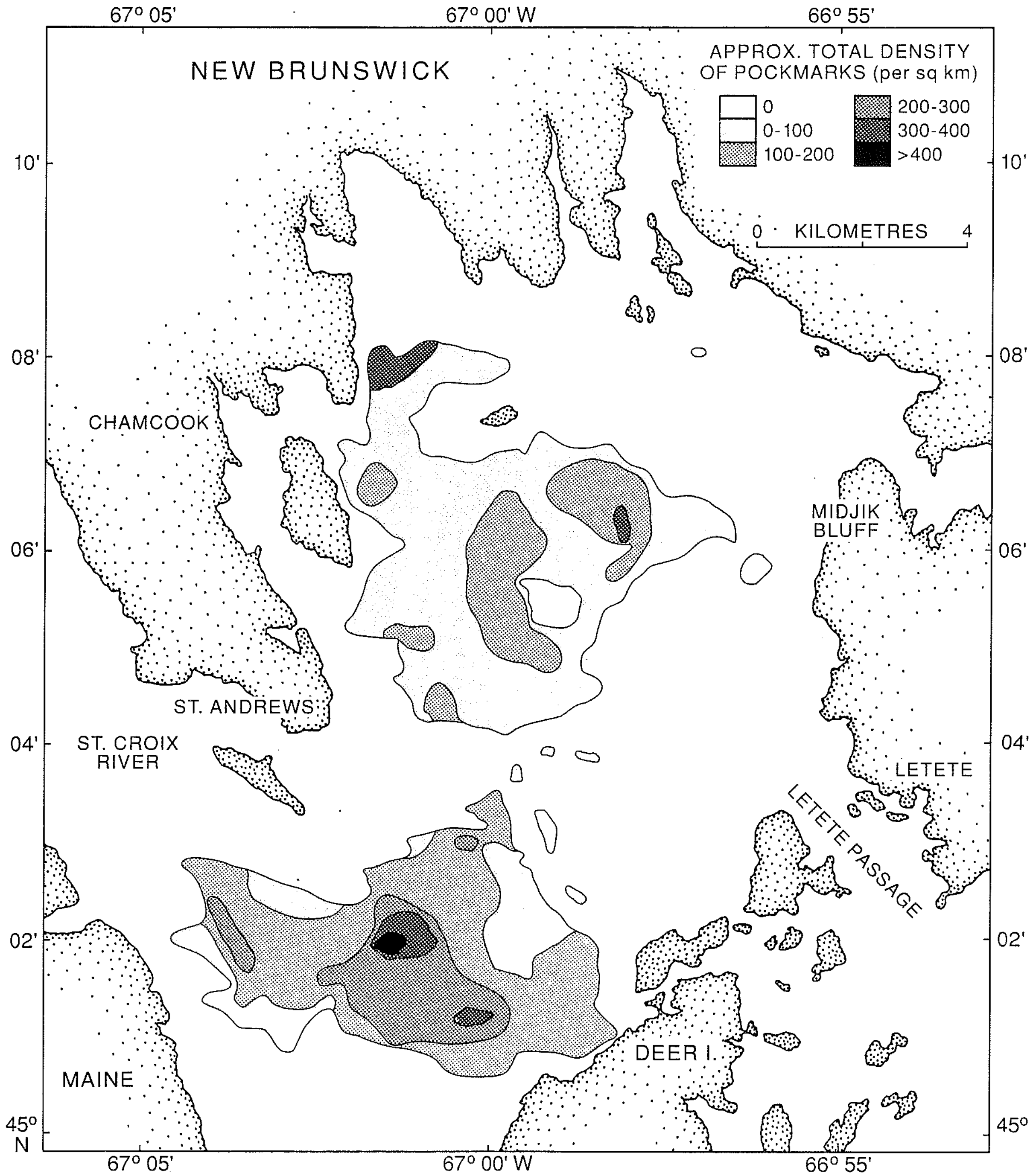

Fig. 15 Approximate total density of pockmarks (per sq. km) derived from sidescan sonogram interpretations.

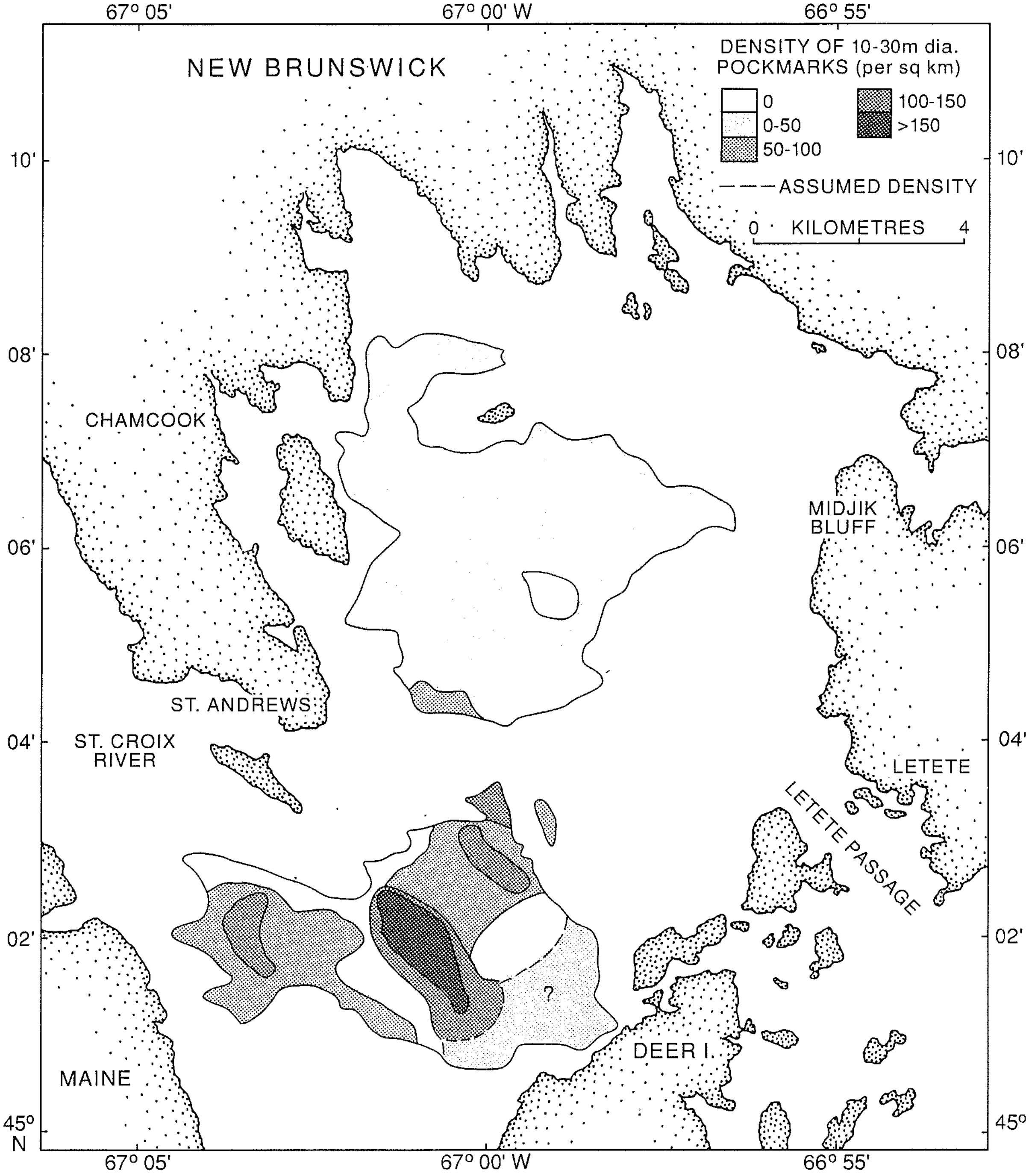

Fig. 16 Density of 10-30 m diameter pockmarks (per sq. km) derived from sidescan sonogram interpretions. Assumed densities were based on the study of Canadian Hydrographic Service echograms.

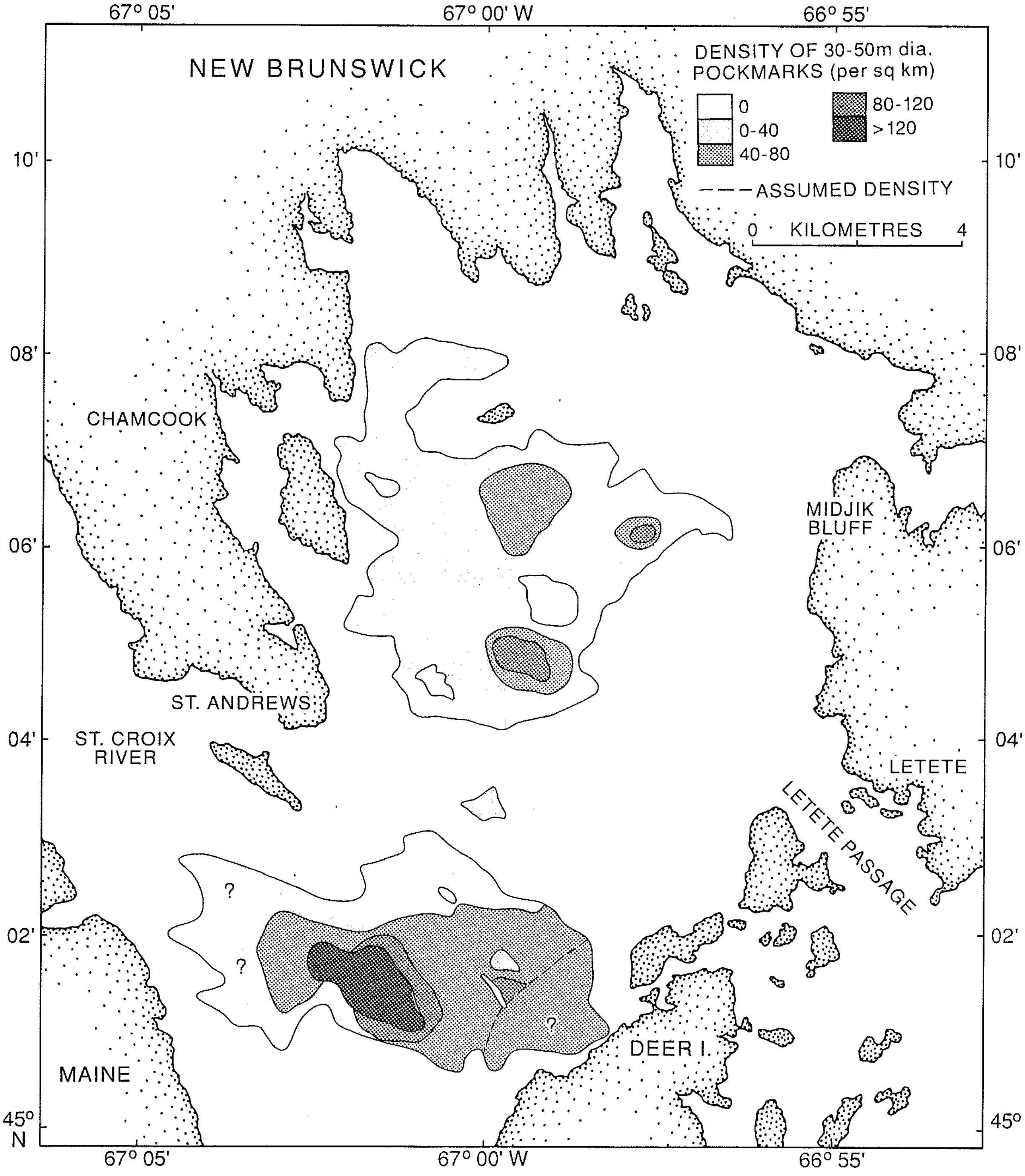

Fig. 17 Density of 30-50 m diameter pockmarks (per sq. km) derived from sidescan sonogram interpretions. Assumed densities were based on the study of Canadian Hydrographic Service echograms.

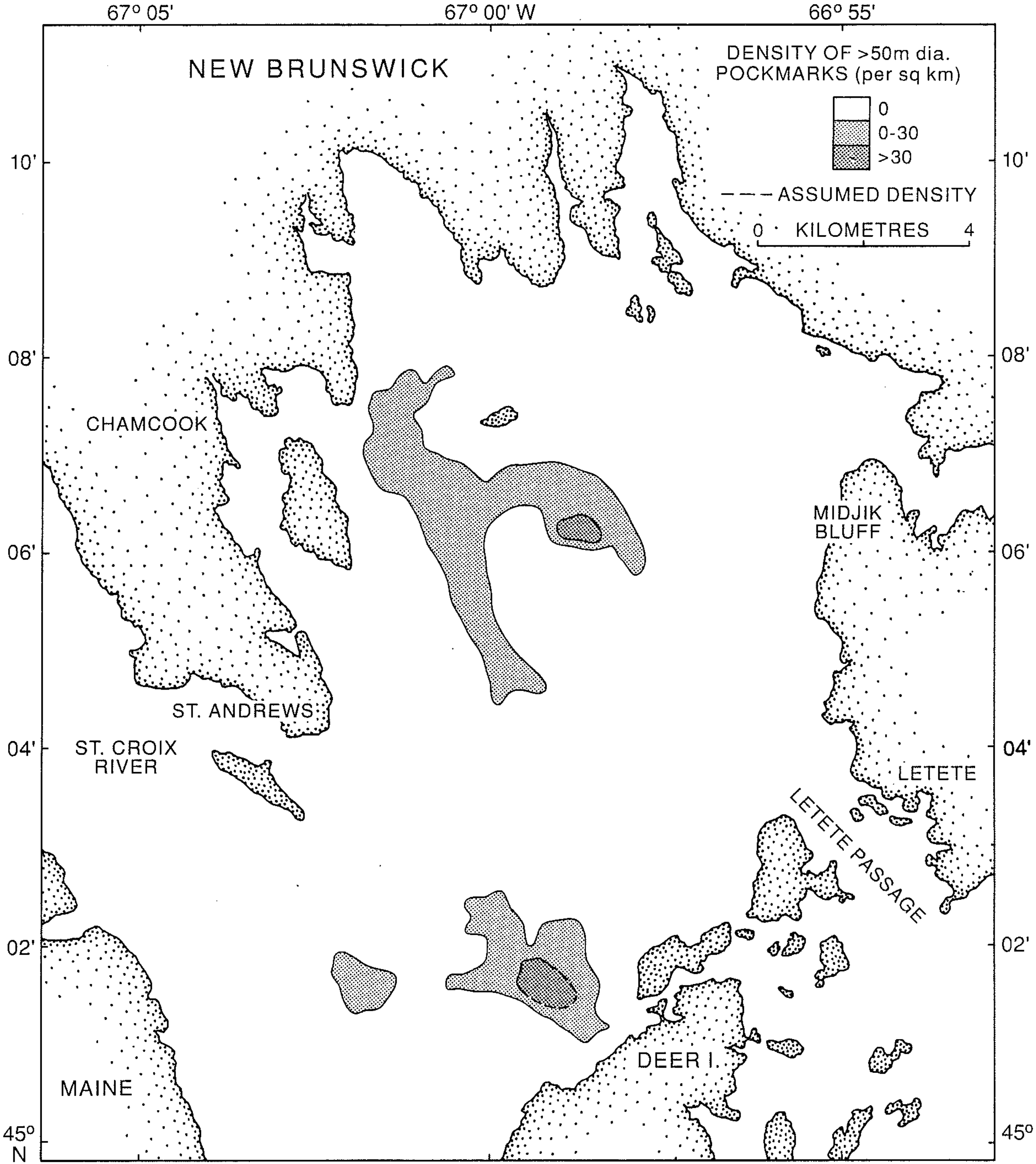

Fig. 18 Density of >50 m diameter pockmarks (per sq. km) derived from sidescan sonogram interpretions. Assumed densities were based on the study of Canadian Hydrographic Service echograms.

Within the area where pockmarks occur, approximately 7.5 percent of the seabed is covered by pockmarks. In two areas of the southern part of the Bay, pockmarks occupy up to 24 percent (southwest) and 29 percent (southeast) of the seafloor (Fig. 19). This is due to the extremely high densities of 10 to 45 m diameter pockmarks and a density of 73 per km^2 of 60 m diameter pockmarks. The southeast area is characterized by a frequent occurrence of 15 to 20 m deep pockmarks, which were observed on the Canadian Hydrographic Service echograms. It is assumed that the area covered by pockmarks in this area is greater than 20 percent because of their large size.

Pockmarks in the Bay range from 1 to 300 m in diameter. The maximum size shown on the sidescan sonograms was 120 m in diameter, but a Canadian Hydrographic Service echogram showed one pockmark with a minimum diameter of 300 m and a depth of 29 m. The same pockmark was also observed on a perpendicular pass by the Canadian Hydrographic Service, and appears to be 180 m in diameter and 26 m deep. This would suggest that the pockmark is oval in plan view. Average pockmark diameter for the study area is 24 m, with an average depth of 3.5 m. The average interior slope of a pockmark wall is 9°, with a range of 6 to 18°.

Sidescan sonograms show that many pockmarks are also aligned with an average orientation of 309°, and that this orientation ranges from 294 to 315° (Fig. 6).

Approximately 5.8 million m^3 of sediment has been eroded and redistributed in Passamaquoddy Bay as a result of pockmark formation.

Buried and Active Pockmarks

A few buried or ancient pockmarks (Fig. 20) have been interpreted on both the Huntec Sea Lion and sparker seismic profiles. These pockmarks occur in a small area in the southern part of the Bay, near the mouth of the St. Croix River (Fig. 14).

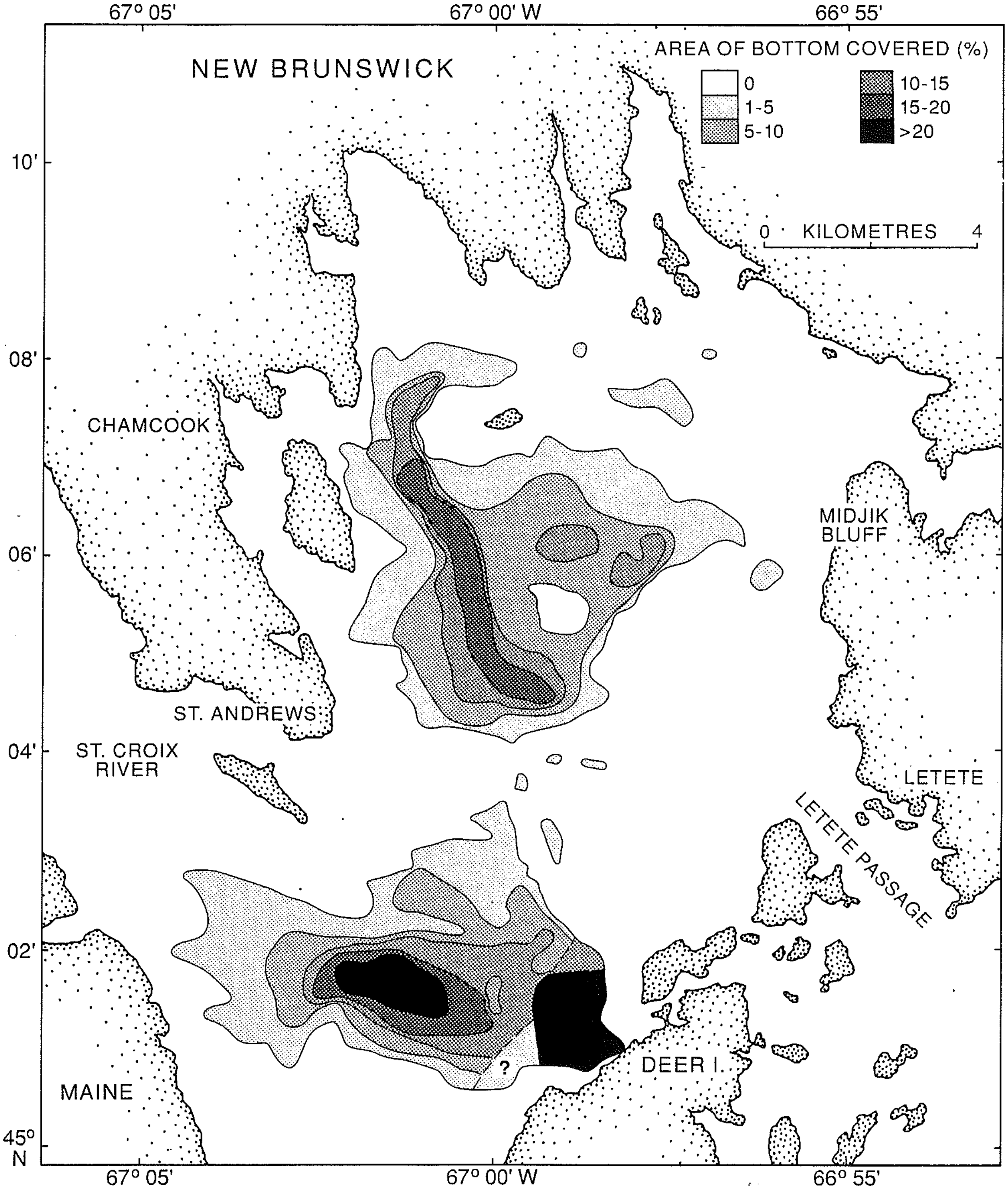

Fig. 19 Percentage per sq. km area covered by pockmarks in Passamaquoddy Bay.

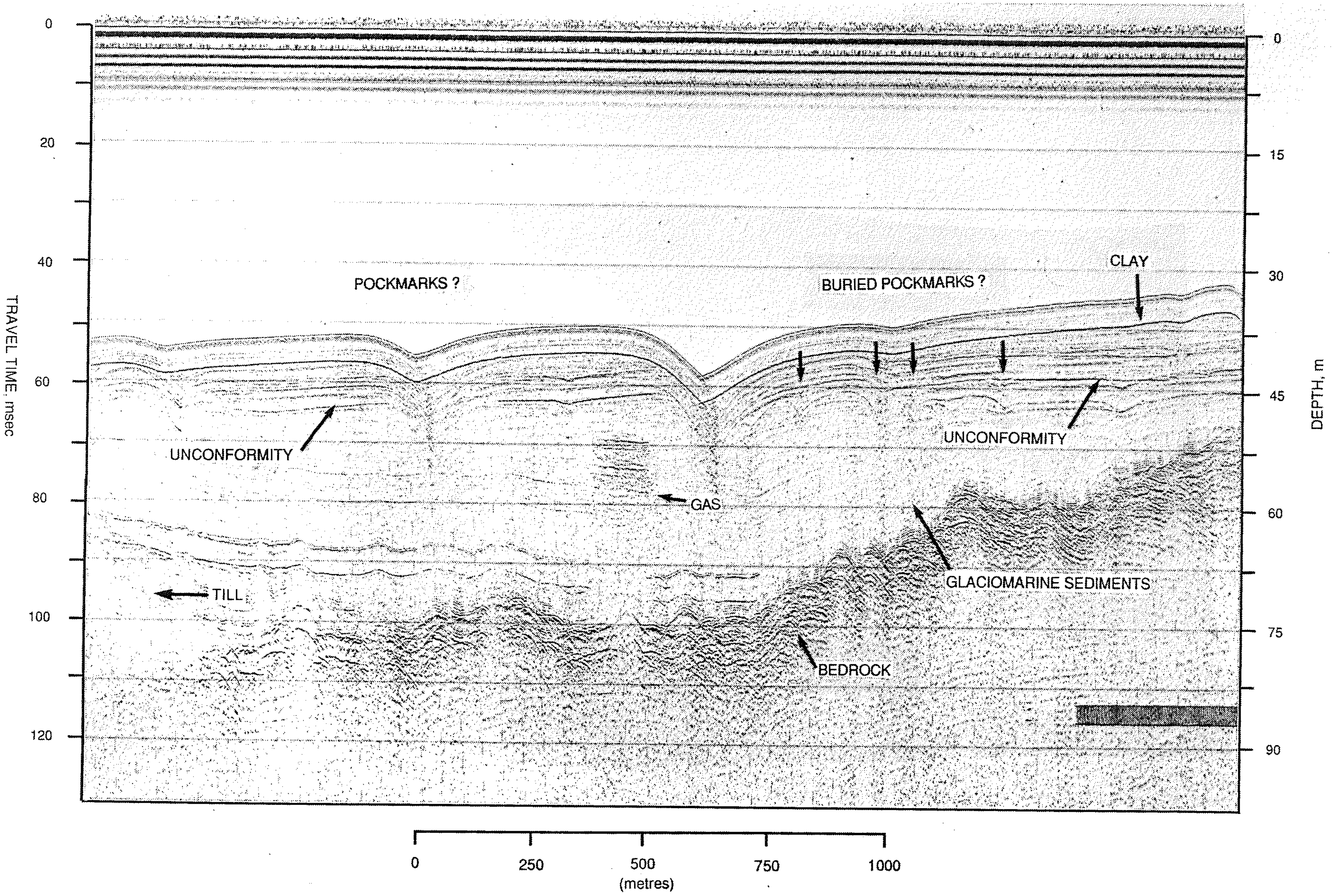

Fig. 20 A Huntec Sea Lion seismic reflection profile showing buried pockmarks near the mouth of the St. Croix River. It is not known if the sediment filled features to the left are pockmarks or old channels.

The absence of sediment clouds in the water column over pockmarks on seismic profiles suggests that pockmarks were not active at the time of the survey. Similar features to sediment clouds were recorded on echograms and sonograms in the Bay, but are more likely interpreted as schools of fish.

Irregular-shaped Pockmarks

Several irregular-shaped pockmarks were detected with the Huntec Sea Lion and echosounders. The irregularity in most is probably caused by slumping, but in two cases, the pockmarks have formed against subsurface bedrock highs. This has resulted in exposure of bedrock in the side of the pockmark.

Eyed Pockmarks

Eyed pockmarks exhibit bottom areas of high acoustic backscatter resulting from the presence of carbonate deposits (Figs. 2 and 21) or dense benthic communities. They occur in an area covering 11.5 km^2, in the southern part of the Bay (Fig. 14). Similar pockmarks have been observed in the Laurentian Channel (Fader et al., 1982), North Sea (Hovland et al., 1987), and Scott Inlet (Grant et al., 1986).

Acoustic Masking

Acoustic masking results from the presence of shallow gas within sediments. The acoustic energy of the seismic reflection system is either scattered or attenuated (Fig. 11), and prevents the sediment layers below the gas from being resolved. There are six areas of acoustic masking in Passamaquoddy Bay, occurring in clays >10 m thick (Figure 22).

Plumose Structures

Plumose structures are neotectonic features recently found in the Canadian Great Lakes, which have been interpreted to occur in muds over active bedrock faults, Ken McMillan, pers. communication. They occur as linear depressions (10-15 cm deep) (MAGNEC, 1989) at the seabed, with arcuate radiating arms giving them a feather shape on sidescan sonograms (Figs. 2 and 23).

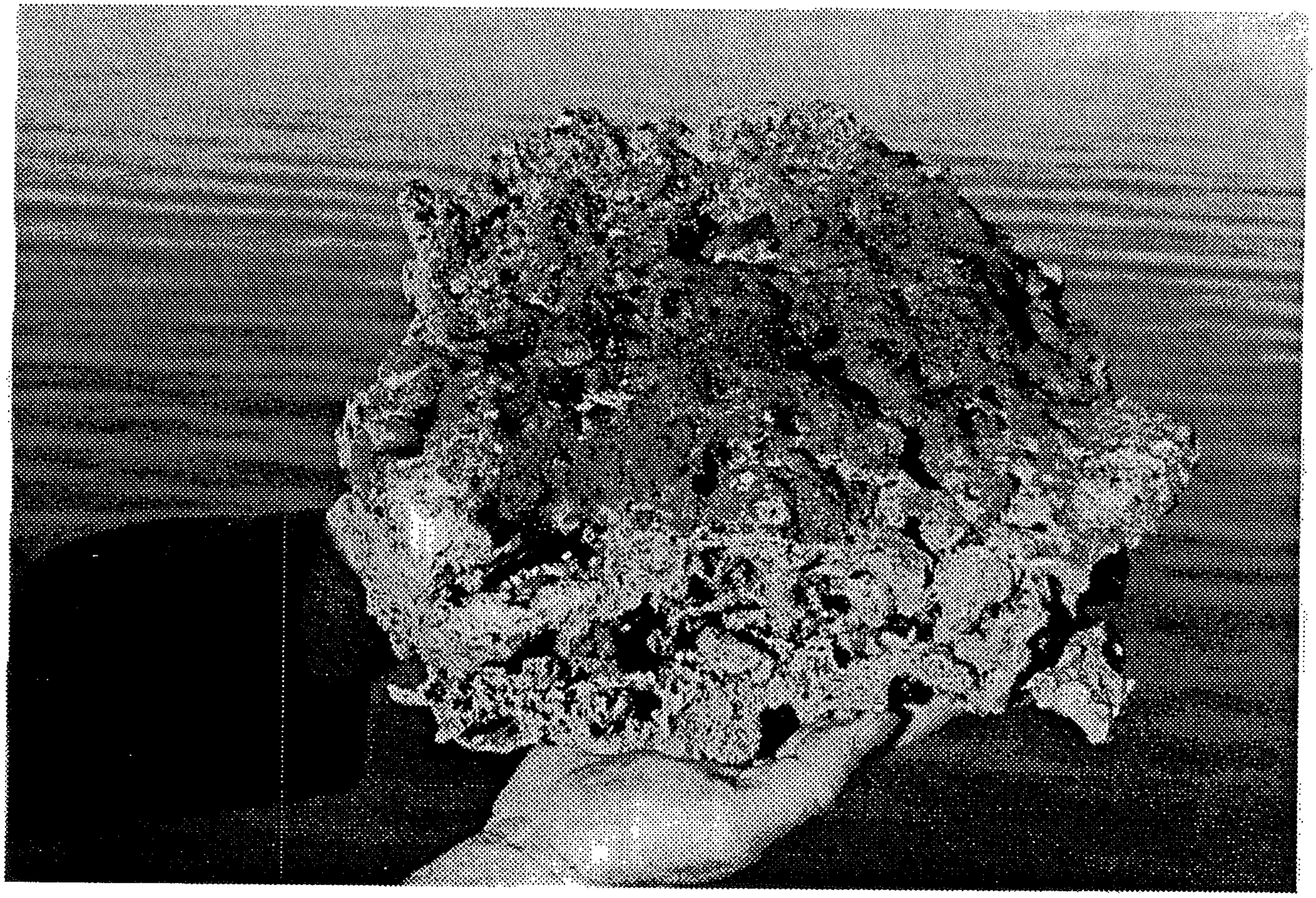

Fig. 21 A carbonate-cemented rock sample retrieved from a pockmark in Scott Inlet (Courtesy of A.C. Grant, AGC).

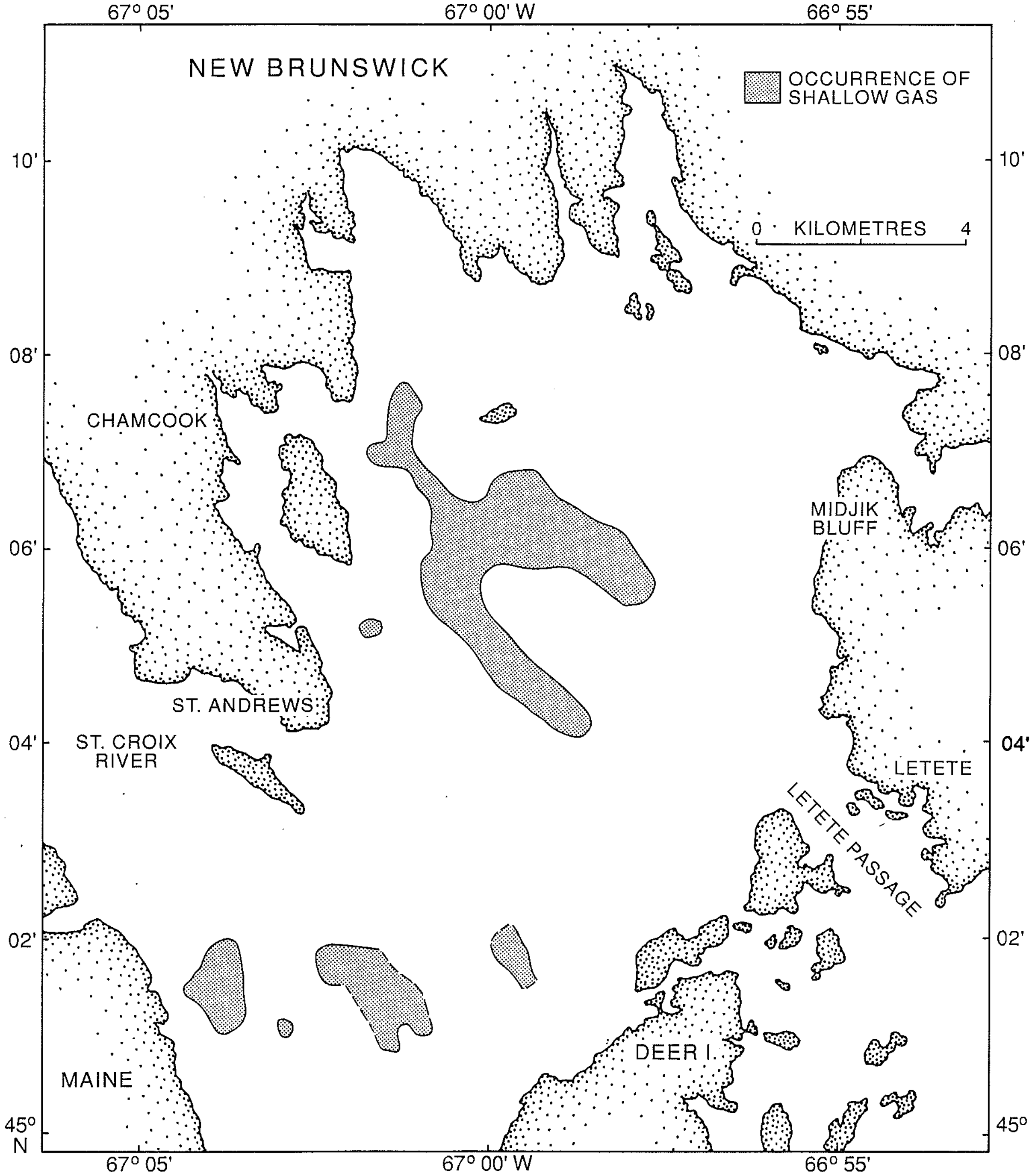

Fig. 22 Occurrence of shallow gas termed "acoustic masking" from the study of seismic reflection profiles collected during the survey in Passamaquoddy Bay.

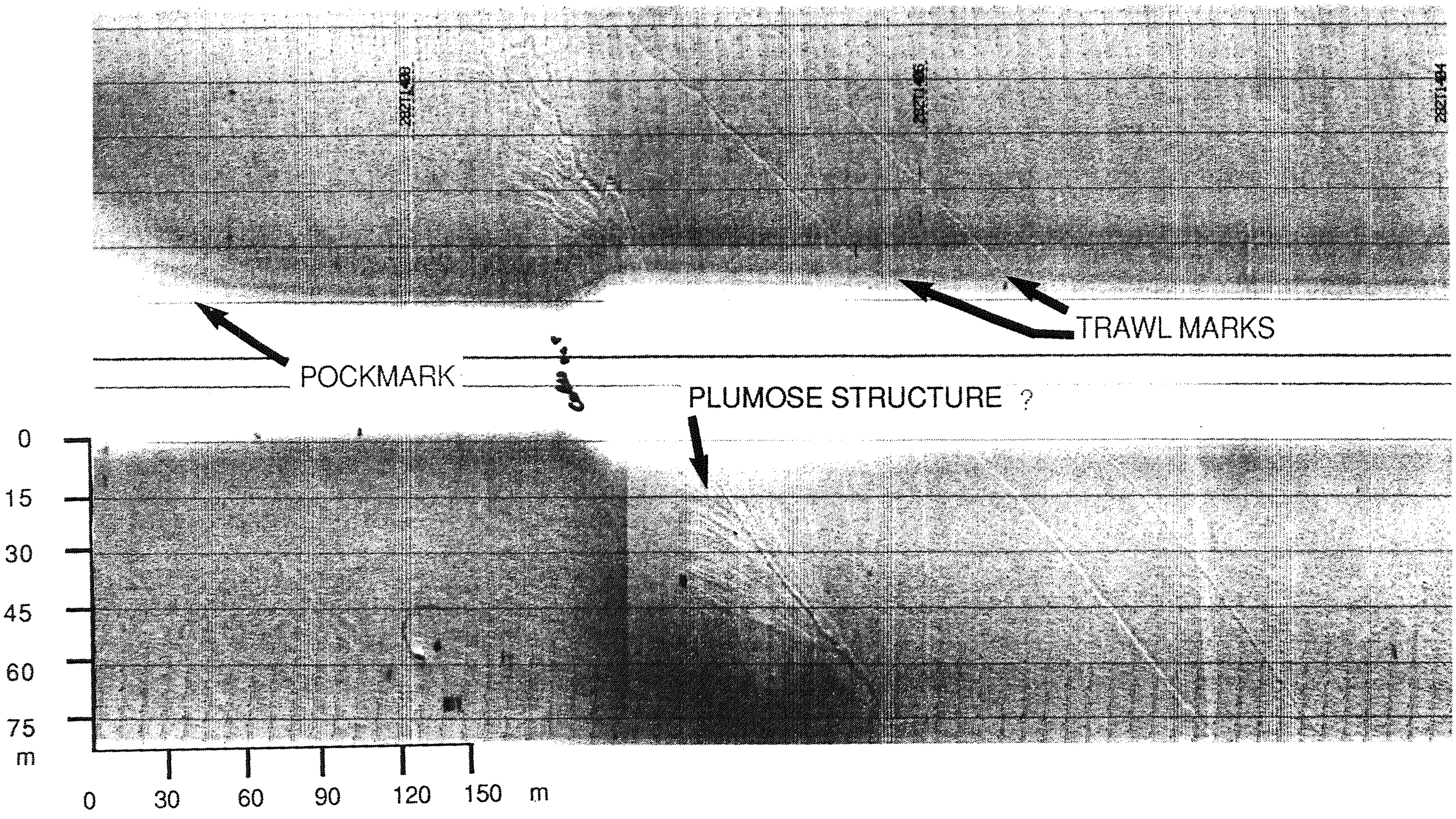

Fig. 23 A sidescan sonogram of a plumose structure from Passamquoddy Bay. Plumose structures occur in areas near known faults mapped on land, and are interpreted to result from recent activity on the faults.

Five plumose structures have been interpreted on sidescan sonograms in Passamaquoddy Bay (Fig. 6). They are 100 to 250 m long and 40 to 65 m wide, with no apparent relief on seismic profiles and echograms.

DISCUSSION

Geological Setting

Four distinct surficial seismostratigraphic units were recognized in Passamaquoddy Bay on seismic reflection profiles: 1) glacial till, 2) glaciomarine sediments, 3) marine clay, and 4) sublittoral sands and gravels. This correlates with the Quaternary stratigraphy and sediment characteristics of adjacent areas: 1) Bay of Fundy and Gulf of Maine (Fader et al., 1977), and 2) eastern Maine (Belknap et al., 1986; Knebel and Scanlon, 1985).

Grounded glacial ice advanced through Passamaquoddy Bay during the Late Pleistocene (Fader et al., 1977), eroding the bedrock and depositing thin deposits of till over the bedrock. Glaciomarine sedimentation followed as the ice retreated and the sediments conformably overlie the till. A pronounced regional unconformity on the glaciomarine sediment was developed during a regression and transgression of the sea during a period of time from 13,500 yrs. BP to present. Approximately 9,500 yrs. BP, a low sea level stand occurred in eastern Maine (Belknap et al., 1986; Knebel, 1986). A similar low sea level stand of approximately 60 m below present sea level was observed on seismic reflection profiles in Passamaquoddy Bay. Sea level continued to rise, depositing Holocene muds from reworked and eroded Pleistocene sediments and bedrock. Sublittoral sands and gravels are local and were probably formed in response to increased tidal dynamics within this macrotidal estuary.

Pockmarks and Fluid Seepage

All pockmarks observed in the study area were found in the Holocene clay and did not cut into the underlying glaciomarine sediments. Therefore, the depth of a pockmark is controlled by the thickness of clay in which it occurs, ie. 10 m of clay will allow a 10 m deep pockmark to form.

Pockmarks occurring in areas of gas-charged sediments have the following characteristic: 1) eyed pockmarks less than 10 m deep, in the southern part of the Bay, and 2) pockmarks 10 m to 29 m deep, in the northern and southeastern parts of the Bay. The variation in depths of pockmarks is probably due to the variations in clay thickness. In general, pockmarks tend to be deeper in areas of gas-charged sediments than areas without gas.

It is uncertain whether the eyed pockmarks in Passamaquoddy Bay result from the presence of carbonate deposits or dense benthic communities. If carbonate deposits are present, then carbonate slab(s) would likely consist of sediments (sand, silt, clay, and shell debris) which have been cemented by aragonite and calcite. The oxidation of methane or other alkane gases can result in the supersaturation and high concentration of CO_2, causing $CaCO_3$ to be precipitated (Jorgensen, 1976).

There are many areas in both Penobscot and Passamaquoddy bays where pockmarks occur without associated acoustic masking. This could indicate the total escape of biogenic gas, or that the pockmarks were formed by other mechanisms such as petrogenic or crustal gas, or fresh water seepages. Fader (1989) suggests that the Perry Formation, which underlies most of Passamaquoddy Bay (Fig. 5), could be a source of petrogenic gas and as such would represent the oldest sedimentary rocks in eastern Canada from which venting gas has been found to originate and produce pockmarks. Scanlon suggested that pockmarks in Penobscot Bay are caused by the seepage of groundwater from the Pleistocene-Holocene unconformity (Scanlon and Knebel, 1989). This mechanism could apply to Passamaquoddy Bay as well. It is also possible that the seepage of groundwater could be from the sandstone of the Perry Formation, which underlies the Bay. However, the thick glacial and post glacial sediment overlying the bedrock in the central part of the Bay suggests that gas is the most likely agent for the formation of pockmarks.

Acoustic Masking

Acoustic masking in Passamaquoddy Bay occurs only in the clays and would suggest that biogenic gas has formed by the decomposition of organic material at or above the unconformity on the glaciomarine sediments. Generally, the acoustic masking occurs 5 to 12 m below the seabed, at an average elevation of 30 to 45 m below present sea level.

Knebel (1986) observed that acoustic masking in Penobscot Bay occurs when there is a thickness of clay greater than 10 to 20 m. Knebel speculated that the correlation between gas charged sediments and sediment thickness could be caused by: 1) total amount of organic matter, and 2) total amount of overburden preventing degassing. Gas-charged sediments were probably charged by the decomposition of organic matter trapped when the Holocene sediments were deposited (Knebel, 1986; Fader et al., 1977). This would suggest that the gas would be biogenic in nature.

Neotectonic Features

Eyed pockmarks tend to align themselves parallel to the Oak Bay Fault in the immediate proximity of the fault, and are associated with gas-charged sediments or acoustic masking. This suggests that the release of gas may be occurring concomitant with active faulting.

Plumose structures occur close to the major faults which have been recognized on the adjacent land and appear oriented in the same direction as the faults. This also supports the idea that recent activity has occurred on the faults. However, the seismic reflection profiles do not show faulting in the overlying sediments or bedrock, suggesting that major displacement has not occurred during faulting.

It is uncertain how plumose structures form. It is suggested that they represent a tensional response in clays to an event occurring in the underlying material (MAGNEC, 1989). It was also noted that there are areas of high acoustic backscatter on the lineations of plumose structures, which may suggest the injection of coarser material into the clays, or a vibratory motion causing dewatering of clays. Fader (1989) observed the similarity between the features found in Passamaquoddy Bay, and anchor and chain marks at the seabed of Halifax Harbour (Miller and Fader, 1989). These marks are probably produced during the period when a vessel was anchored, with the chain of the anchor moving up and down, due to wave or tidal motion, striking the seabed at various positions from an apex, thus forming a feather like feature.

Three of five plumose structures in Passamaquoddy Bay occurred at the seabed in areas where there is: 1) 7 to 18 m of clay; 2) no acoustic masking; 3) < 3 m of glaciomarine sediments; 4) < 2 m of till; and 5) bedrock highs of the Perry Formation. The other two plumose structures occur in the same setting with the exception that: 1) one plumose structure occurs in clay, but is underlain by 22 m of glaciomarine sediment, and 2) another structure occurs in an area of acoustic masking and overlies a broad bedrock low.

CONCLUSIONS

1) Glaciation and sea level changes during the past 20,000 yrs. in Passamaquoddy Bay have resulted in a fining upward sequence of sediments, with the uppermost unit dominated by muds.

   Till overlies the bedrock and is generally thin. Glaciomarine sediments conformably overlie the till and have a pronounced regional unconformity on the glaciomarine sediments developed during a regression and transgression of the sea during a period of time from 13,000 yrs. BP to present. Acoustically transparent, gas-charged clay overlies the glaciomarine sediments. Sublittoral sands and gravels in the Bay represent a response to increased tidal dynamics in this macrotidal estuary.

2) In Passamaquoddy Bay, pockmarks cover an area of 87 km^2 with maximum bottom area coverage of 29 percent and a maximum total density of 418 pockmarks per km^2. It is estimated that there are 11,000 pockmarks in the Bay and they are confined to the Holocene clay layer. Approximately 5.8 million m^3 of clay has been eroded and redeposited as a result of pockmark formation.

3) Pockmarks in Passamaquoddy Bay are of high density compared to those found elsewhere in the world. They are of average diameter (24 m) and depth (3.5 m), but exhibit a high interior slope range, 6 to 17°. Passamaquoddy Bay has one of the world's deepest recorded pockmarks at 29 m.

4) The type of fluid seepage causing the formation of pockmarks in Passamaquoddy Bay is not known. Areas of acoustic masking probably suggests the release of biogenic gas. Areas of pockmarks without acoustic masking may represent petrogenic gas from the Perry Formation, crustal gas from activity along the Oak Bay Fault, or groundwater from underlying sediment unconformities or underlying sandstones of the Perry Formation.

5) Eyed pockmarks in Passamaquoddy Bay may also be indicators of neotectonic activity. Eyed pockmarks tend to be aligned parallel with the Oak Bay Fault and are found only in the immediate proximity of the fault in areas of acoustic masking. This suggests that the release of gas may be occurring concomitant with active faulting.

6) Plumose structures in Passamaquoddy Bay may provide a means of identifying recent activities along faults. They are orientated parallel to nearby known faults on land, and occur at the seabed in Holocene clay.

ACKNOWLEDGMENTS

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