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Shallow stratigraphic control on pockmark distribution in north temperate estuaries

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ABSTRACT

Pockmark fields occur throughout northern North American temperate estuaries despite the absence of extensive thermogenic hydrocarbon deposits typically associated with pockmarks. In such settings, the origins of the gas and triggering mechanism(s) responsible for pockmark formation are not obvious. Nor is it known why pockmarks proliferate in this region but do not occur south of the glacial terminus in eastern North America. This paper tests two hypotheses addressing these knowledge gaps: 1) the region's unique sea-level history provided a terrestrial deposit that sourced the gas responsible for pockmark formation; and 2) the region's physiography controls pockmarks distribution. This study integrates over 2500 km of high-resolution swath bathymetry, Chirp seismic reflection profiles and vibracore data acquired in three estuarine pockmark fields in the Gulf of Maine and Bay of Fundy. Vibracores sampled a hydric paleosol lacking the organic-rich upper horizons, indicating that an organic-rich terrestrial deposit was eroded prior to pockmark formation. This observation suggests that the gas, which is presumably responsible for the formation of the pockmarks, originated in Holocene estuarine sediments (loss on ignition 3.5–10%), not terrestrial deposits that were subsequently drowned and buried by mud. The 7470 pockmarks identified in this study are non-randomly clustered. Pockmark size and distribution relate to Holocene sediment thickness ($r^2 = 0.60$), basin morphology and glacial deposits. The irregular underlying topography that dictates Holocene sediment thickness may ultimately play a more important role in temperate estuarine pockmark distribution than drowned terrestrial deposits. These results give insight into the conditions necessary for pockmark formation in nearshore coastal environments.

1. Introduction

Most often interpreted as fluid-escape features, pockmarks, or seafloor depressions, are well studied in areas with gas hydrates, abundant tectonic activity, deltas and petroleum resources (Judd and Hovland, 2007). However, large pockmarks also persist in environments lacking those characteristics (e.g., Kelley et al., 1994; Webb et al., 2009), and that presently exhibit minimal fluid venting (Ussler et al., 2003). Constrained to fine-grained substrates and typically associated with subsurface gas (Judd and Hovland, 2007), the factors that determine why pockmarks scar some gassy seafloors while other muddy embayments remain relatively flat are unknown. In eastern North America pockmark fields are not reported south of Long Island Sound (Fleisher et al., 2001; Poppe et al., 2006), despite the abundance of well-studied, gassy, muddy estuaries (e.g., Reeburgh, 1969; Schubel, 1974; Hagen and Vogt, 1998; Martens et al., 1998). The absence of pockmarks south of the glacial terminus suggests that local and regional heterogeneities, possibly related to glacial or sea-level history or bedrock geology, influence pockmark field distribution (e.g., Rogers et al., 2006). This paper focuses on three estuarine pockmark fields in the Gulf of Maine and Bay of Fundy (Figs. 1–3; Table 1). Using densely gridded, high-resolution geophysical data combined with vibracore results we test the hypotheses that deposits formed during lower-than-present sea level source the gas responsible for pockmarks, and that regional physiography contributes to pockmark distribution in northern temperate estuaries. These results provide insights into origins of regional shallow gas, shallow fluid migration pathways, and the set up conditions necessary for pockmark formation.

2. Regional setting

Metamorphic and igneous bedrock, ranging from Precambrian to Paleozoic age, frame Maine's coast (Osberg et al., 1985), while igneous, metamorphic and sedimentary bedrock typify the Bay of Fundy (Cumming, 1967). Differential erosion of bedrock associated with

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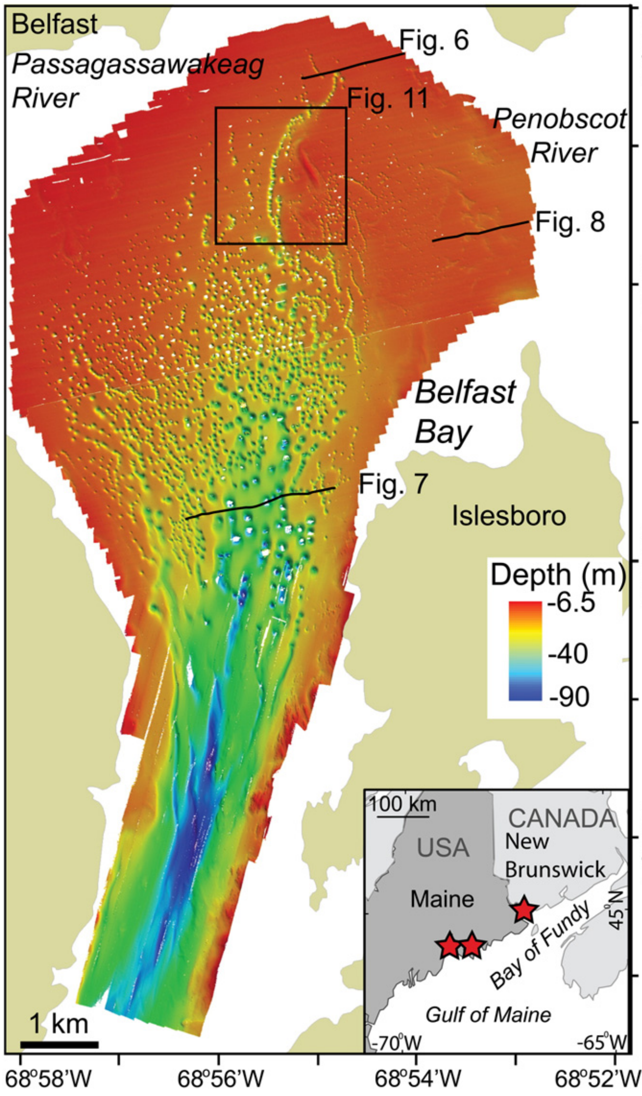

Fig. 1. Bathymetry of Belfast Bay, Maine, USA, the southern most pockmark field examined. Inset map shows locations of Figs. 1–3. Boxes and lines denote other figure locations.

glaciations, coupled with Holocene sea-level rise, formed an irregular coastal and inner shelf region characterized by numerous estuaries and bays (Kelley, 1987; Kelley et al., 1989), and littered by pockmarks (Rogers et al., 2006). In cross section, the coastal embayments are 10–60 m deep bedrock-framed depressions filled with sediment termed 'nearshore basins' (Kelley and Belknap, 1991). As these topographic lows extend seaward they become scoured, seaward sloping troughs, termed 'shelf valleys' (Kelley and Belknap, 1991; Barnhardt et al., 1996, 2009). The origin of underlying depressions is unknown, though they may reflect faulting (Osberg et al., 1985), fluvial erosion (Johnson, 1925), glacial scour (Shepard, 1931), some combination of the three mechanisms (Uchupi, 1968), or even subglacial meltwater pathways as inferred elsewhere (Boyd et al., 1988).

During deglaciation, approximately 15 ka (Dorion et al., 2001), sea level was ~75 m above the present coastline of Maine (Belknap et al., 1987). By 12.5 ka it had fallen to a lowstand position 60 m below present sea level (Kelley et al., 2010). Sea level then rose quickly from the lowstand until ~11 ka when the rate of rise slowed significantly until 7.5 ka. During that 'slowstand' period widespread erosion of glaciogenic deposits occurred and was accompanied by concurrent deposition of reworked sediment into beaches and coastal wetlands. These deposits were subsequently drowned during the rapid sea-level rise after 7.5 ka (Kelley et al., 2010).

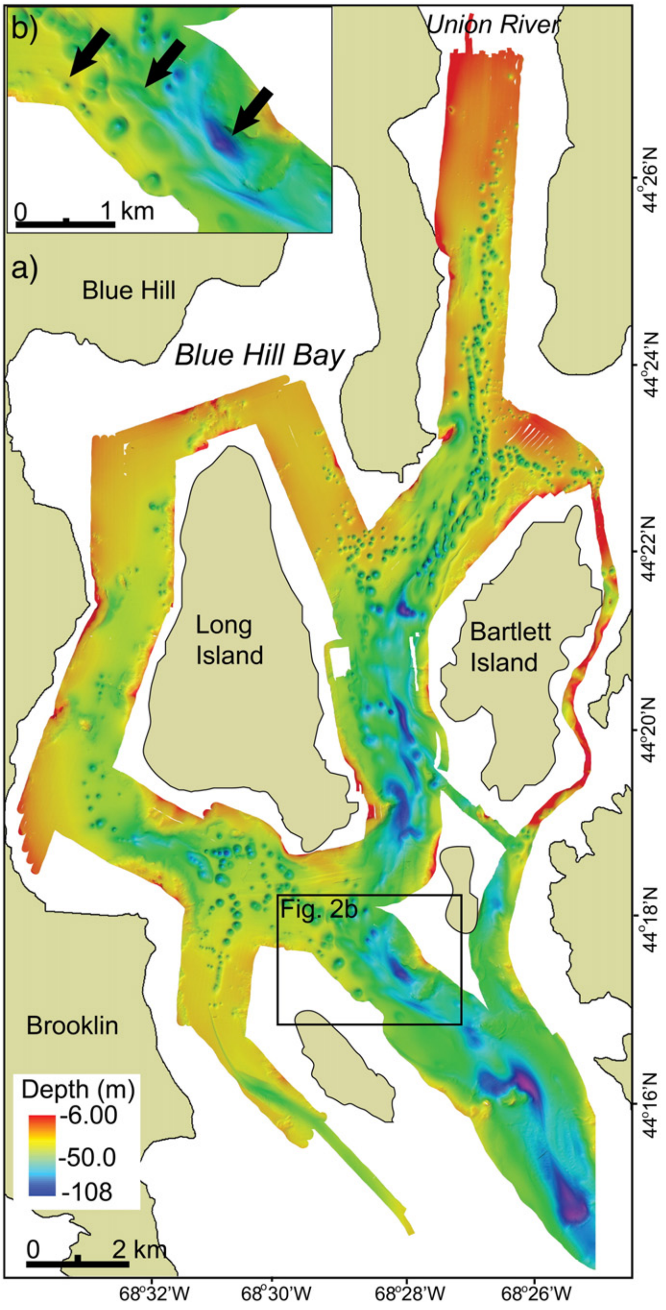

Fig. 2. a) Bathymetry of Blue Hill Bay, Maine, USA. Map location is shown in Fig. 1 inset. b) Southern Blue Hill Bay morphology changes from circular pockmarks in the periphery and eroded flute-like pockmarks in the thalweg.

Extensive geophysical surveys indicate that methane and pockmarks occur in Holocene sediments throughout Maine and New Brunswick's muddy estuaries (Scanlon and Knebel, 1989; Shipp, 1989; Fader, 1991; Barnhardt et al., 1996; Gontz, 2005; Rogers et al., 2006). Inconsistent evidence for venting (Kelley et al., 1994; Ussler et al., 2003), a dearth of methanotropes (Wildish et al., 2008), and nominal seafloor change (Brothers et al., 2011a) suggests these pockmark fields currently experience minimal fluid-escape activity. Geochemical sampling (Ussler et al., 2003) suggest that the region's methane is microbial in origin, although the stratigraphic source of the gas remains undetermined. Barnhardt et al. (1997), Gontz (2005) and Kelley et al. (2010) found micro-and macro-fossil evidence for drowned coastal wetlands in core sampling, and Rogers et al. (2006) proposed that such deposits provided a concentrated source of organic material that evolved into methane, and, by inference, formed regional pockmarks. They suggested such organic

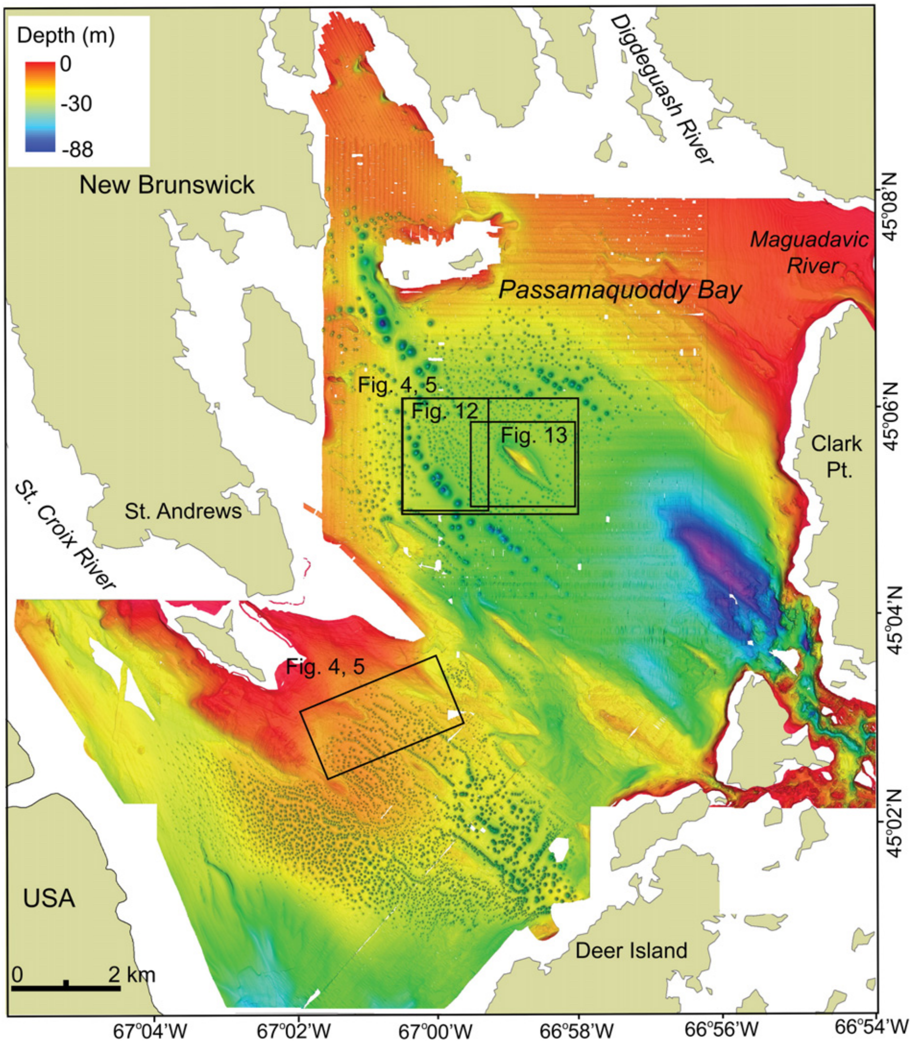

Fig. 3. Bathymetry of Passamaquoddy Bay, New Brunswick, Canada. Boxes and lines denote other figure locations. Location of map is shown in Fig. 1 inset.

layers would occur at the base of the Holocene in topographic lows where it was protected from the erosive effects of the last transgression.

3. Methods

3.1. Geophysical data

Over the last two decades four organizations collected swath bathymetry and dense grids of high-resolution seismic reflection data in the Belfast Bay, Blue Hill Bay, Maine, and Passamaquoddy Bay, New Brunswick (Table 2). Survey tracklines were spaced 100–200 m apart. Bathymetry data were collected and processed using techniques described in Andrews et al. (2010) and by the Ocean Mapping Group (2012a). Pockmark locations and size were extracted from the bathymetry data as point features, and the fields spatially examined, using methods presented by Andrews et al. (2010). Where seismic data were available, we generated isopach maps of the Holocene sediment by subtracting interpreted surfaces from each other (Fig. 4). Different seismic data were collected using different systems and frequencies that are described in Table 2. Sediment thickness in Blue Hill Bay could not be mapped due to the prevalence of acoustic turbidity in the upper sediment column that obscures lower units.

Table 1
Physical characteristics of examined estuarine pockmark fields (tide data from Brooks, 2006; NOAA, 2012).

Field	Mean tidal range (m)	Associated rivers	Max. water depths (m)	Total Bay area (km^2)	Area examined (km^2)
Belfast Bay, ME, USA	3.1	Passagassawamkeg River, Penobscot River	92	76	50
Blue Hill Bay, ME, USA	3.1	Union River	108	159	93
Passamaquoddy Bay, NB, CANADA	5.7	St. Croix River Digdeguash River Maguadavic River	88	269	143

3.2. Vibracore samples

Since 2007, 37 Rossfelder vibracore samples (1–7 m in length) have been collected in the Belfast Bay pockmark field (Supplemental material for latitudes, and longitudes) (Fig. 5). Cores were collected with the methods described by Barnhardt et al. (1997), and were evaluated for sediment texture, color, water content, loss on ignition (LOI) by weight and the presence of macrofossils. Three logs of vibracore samples collected by Barnhardt (1994) are also used in this study.

Table 2
A summary of geophysical and coring observations used in this study.

Pockmark Field	Observation Type	Acquisition			
		Organization	Equipment	Dates	Vessels
Belfast Bay, ME, USA	bathymetry	U.S. Geological Survey, University of Maine	Submetrix interferometric sidescan sonar 234 khz	2006, 2008	26' R/V Raphael
	subbottom	U.S. Geological Survey, University of Maine	4–24 kHz Edgetech Chirp	2006, 2009	26' R/V Raphael
	sediment cores	University of Maine	Rossfelder (10 cm) vibracores	1993, 2007, 2008	R/V ARGO
Blue Hill Bay, ME, USA	bathymetry	University of New Brunswick's Ocean Mapping Group, University of Maine	EM3000S 300 kHz	2009	34' CSL Heron
	subbottom	University of New Brunswick's Ocean Mapping Group, University of Maine	3.5–210 kHz Knudsen 320 M system	2009	34' CSL Heron
Passamaquoddy Bay, NB, CANADA	bathymetry	Canadian Hydrographic Service, University of New Brunswick's Ocean Mapping Group	EM1000 100 kHz, EM3000S 300 kHz	1992, 2002, 2008, 2009	CSS Frederick G.Creed, 34' CSL Heron
	subbottom	University of New Brunswick's Ocean Mapping Group	3.5–210 kHz Knudsen 320 M system	2002, 2008, 2009	34' CSL Heron

4. Results

4.1. Pockmark field stratigraphy

Seismic reflection profiles and core samples were used to define the stratigraphy of pockmark fields in all three estuaries. Interpretations of units follow those of Belknap and Shipp (1991), Barnhardt et al. (1997) and Belknap et al. (2002).

4.1.1. Unit BR -Bedrock

The basal reflector identified in seismic profiles has a high-intensity return, and a highly irregular surface with relief up to tens of meters over short horizontal distances (Fig. 6). The surface of this unit is shaped into basins that, generally, trend from northerly to southerly quadrants. Interpreted as bedrock, this facies is identified throughout all three study areas, but acoustic turbidity related to gas in the upper sediment column can obscure it (Fig. 7). The unit was not sampled by vibracores.

4.1.2. Unit T

Unit T has a strong surface reflector that overlies bedrock and is sometimes difficult to distinguish from bedrock where the unit is thin. Irregularly distributed in ridge-like deposits throughout the study areas, Unit T is interpreted as till. These deposits trend north–south in Belfast and Blue Hill Bay, and northwest–southeast in Passamaquoddy Bay. Large pebbles and cobbles (6-cm diameter) typify this unit in core samples.

4.1.3. Unit GM

With a moderate-intensity, continuous surface return, this unit is either acoustically massive or highly stratified. Filling bedrock basins,

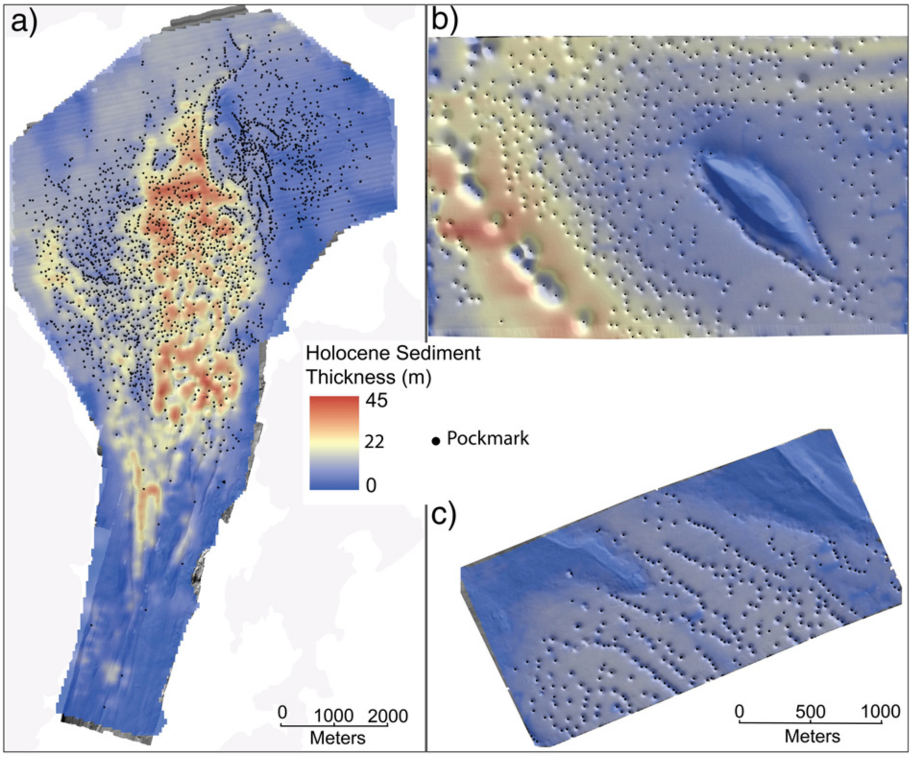

Fig. 4. Holocene sediment isopach maps overlaying hillshaded bathymetry of Belfast Bay (a) and portions of Passamaquoddy Bay (b, c). Black dots represent individual pockmarks.

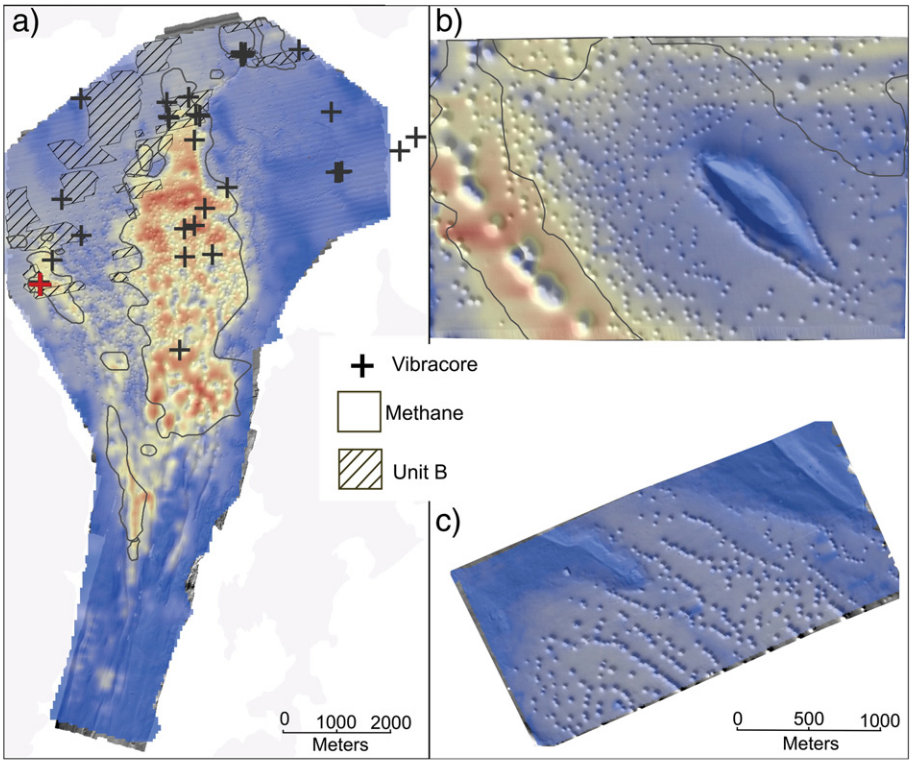

Fig. 5. Isopach maps of Belfast Bay (a) and portions of Passamaquoddy Bay (b, c) overlain by examined vibracore locations (crosses), methane (outlined in gray) and Unit B (hatched) distribution. A red cross denotes the location of core PBVC-08-11. Fig. 4 shows isopach scale.

Unit GM occurs throughout all three estuaries. Where imaged, deeper deposits drape over bedrock, while shallower deposits exhibit ponded geometry (Fig. 6). GM deposits range from 0 m to >25 m in thickness. The surface of GM is often an unconformity and overlain by Holocene gravel, sand, or mud. Lithologically the unit consists of bluish-gray (5B 4/1, 5BG 4/1) stiff sediments with low organic contents (<5% LOI). Based on these acoustic and lithologic characteristics, we interpret Unit GM as Pleistocene-age glacial-marine sediments, which are well documented in the region (e.g., Belknap and Shipp, 1991; Fader, 1991).

In seven core samples the upper 0.1–0.7 m of Unit GM transitioned from blue-grey (5BG 4/1) to mottled red (10 YR 3/6) sandy mud, and contained indurated mud clasts and soft mud masses (Fig. 8). Mud

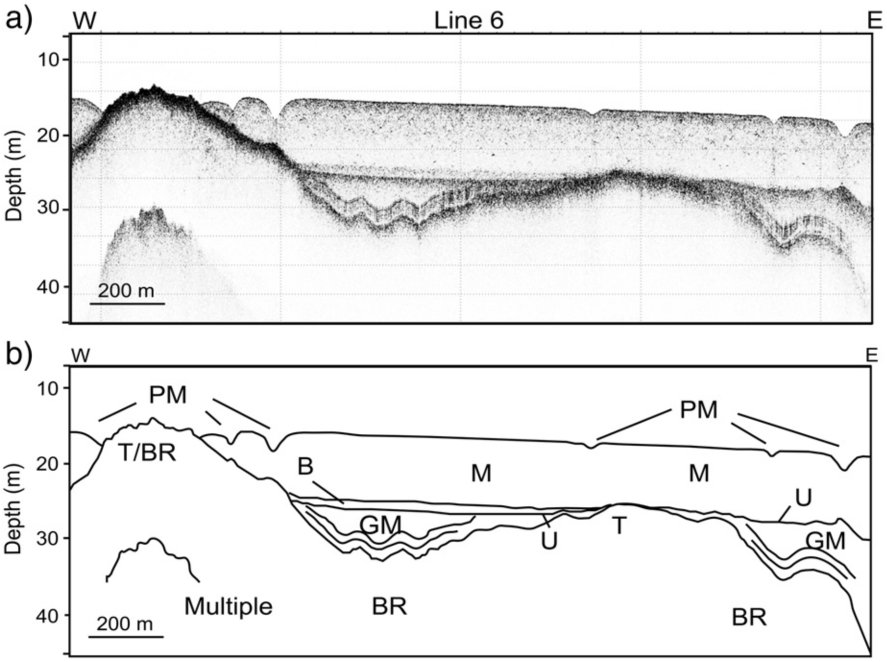

Fig. 6. Seismic profile (upper panel) and interpretation (lower panel) from Belfast Bay containing the principle acoustic units of regional pockmark fields: *BR* bedrock, *T* till, *GM* glacial-marine sediment, *U* Pleistocene/Holocene unconformity, *B* unit B (only in Belfast Bay), *M* Holocene estuarine mud. *PM* denotes pockmarks. In this record T and BR cannot be separated. See Fig. 1 for location. Depth conversions are based on sound velocity of 1500 m/s in both water and sediment.

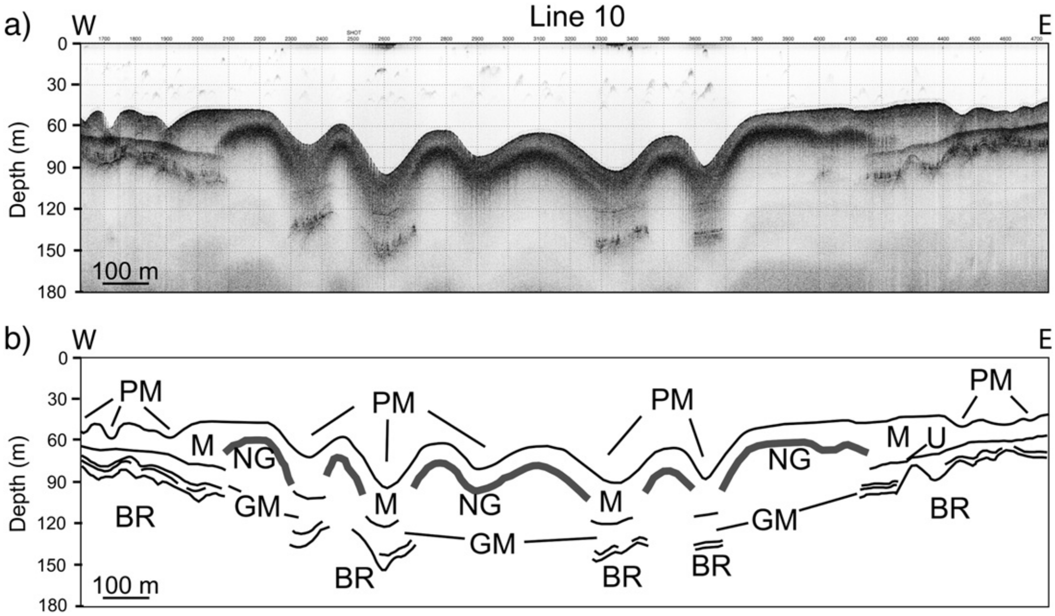

Fig. 7. Seismic reflection profile (a) and interpretation (b) are from Belfast Bay. Methane, or natural gas, *NG* interpreted from acoustic turbidity and, intensified reflectors are ubiquitous in all three pockmark fields. See Fig. 1 for location.

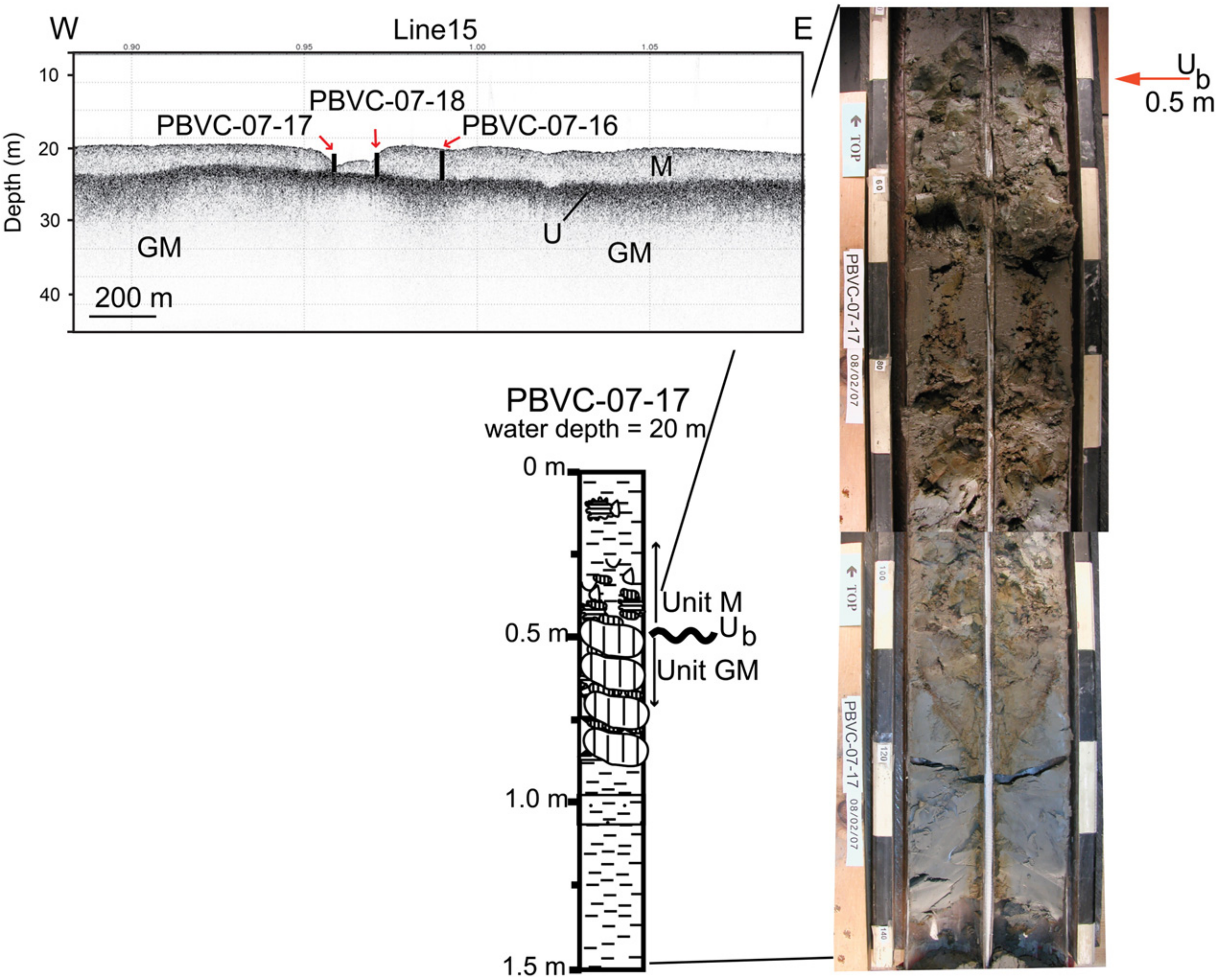

Fig. 8. CHIRP seismic line with core locations from Belfast Bay, see Fig. 1 for locations. The photograph and log of Core PBVC-07-17 show irregular, indurated mud clasts within a mud matrix, grading downward into a mottled blue mud. The deepest portion of PBBVC-07-17 has a strong mottled appearance, and an oxidation horizon at 111–122 cm. Because indurated mud clasts originate in Pleistocene age parent material, we place the basal unconformity, at 50 cm (red arrow), above where indurated mud exceeds 50% of the cores' content, and thus are most likely in place.

clasts ranged from 1 to 7 cm in diameter and were rounded, angular pebbles or highly irregular, contorted, pipe-like fragments (Fig. 9). The hardest clasts were generally greenish brown (5G4/2, 5G 5/2, 5GY 6/1) and contained holes ranging from <0.1 cm to 1 cm in diameter. Other clasts had a soft blue-gray surface coating (5BG 5/1), but internally had yellow-red (10YR 3/6) bandings and iron nodules. Soft masses shared the same color patterns as clasts, but were amorphous and easily manipulated by hand. All features tested negative for calcium carbonate when treated with 10% hydrochloric acid, and x-ray diffraction analyses revealed no carbonates. These clasts and masses had LOI values of <5%.

4.1.4. Basal unconformity (U)

A high amplitude acoustic reflection on seismic profiles separates Pleistocene and Holocene deposits. This surface commonly truncates the internal reflections in the glacial-marine unit indicating that it is an erosional surface (Fig. 6). In core samples this surface is coarse-grained (Fig. 8).

4.1.5. Unit B

Unit B overlies the basal unconformity and has a maximum thickness of 6 m. Of the three estuaries examined, it was only imaged in Belfast Bay. The unit occurs in patches in the western and northern portion of Belfast Bay, with its most continuous expression as a wedge that thins from 6-m thickness closest to the present shoreline and diminishes in the field's interior (Figs. 5 and 6). The unit also occurs as isolated pools between bedrock, or till, subcrops. The unit lacks internal bedding, and was not sampled by vibracores.

4.1.6. Unit M

The uppermost acoustic unit is transparent. Unit M occurs in all the examined fields, and locally may exceed 40 m in thickness (Fig. 4). Pockmarks occur solely within this unit. The bottoms of some pockmarks extend to the base of this unit and terminate at the basal unconformity. Unit M is interpreted as estuarine mud of Holocene age. In Belfast Bay the thickest deposits occur in the center of the embayment while Holocene sediment thins in shallow portions of the bay, and in the southern thalweg. In Passamaquoddy Bay, where seismic data were available, the thickest sediments occur along the strike of bedrock. In both fields, zones of minimal Holocene sediment thickness correspond to moraines, drumlins, and bedrock outcrops (Fig. 4).

Of the 37 cores collected, 28 were entirely within Unit M, while the remaining 9 also sampled an older, deeper facies. Unit M generally has Munsell colors of reddish brown (2.5 Y 4/2 and 10YR 5/2) in the first 0.1 to 0.2 m, transitioning to dull olive gray (5Y 5/1 and 5Y 4/1) downcore. Texturally the unit consists of structureless mud to sandy mud, with minimal bedding. Thirteen cores contained clasts (Fig. 9) within the reddish brown mud matrix indicating proximity to Unit M's base. We found virtually no macrofossils and did not find any articulated fossils in life positions and therefore did not date any samples. Pore water content generally ranged from 60% to 25% from the surface to the bottom of the cores. LOI values ranged from 3.5% to 10%.

4.1.7. Natural gas (NG)

Acoustically opaque wipe-out curtains occur throughout Holocene sediments in all three estuaries. This unit obscures deeper reflections and is interpreted to be due to gas in the sediments. Although gas-charged sediments challenge resolution of deeper units, in Belfast Bay and Passamaquoddy Bay such acoustically opaque curtains are interspersed with unblanked reflections (Fig. 7). These windows of transmission, on the order of tens of meters, typically coincide with pockmarks, and allowed us to map sediment thickness in these two estuaries. Within Belfast and Passamaquoddy Bays gas typically coincides with Holocene sediments >16 m in thickness (Fig. 5). Other indications of gas in sediments, such as acoustically disrupted columns, or “chimneys” (*sensu* Cathles et al., 2010), were not observed in any of the estuaries.

While collecting core PBVC-08-11 we witnessed bubbling at the sea surface. This core sampled the center of a pockmark underlain by gas (Fig. 5 for location). The deepest segment of the core shows extensive cracking. We interpret the cracks as evidence of gas expansion following Barnhardt et al. (1997, their Figure 10), who describe similar habit in cores from Belfast Bay.

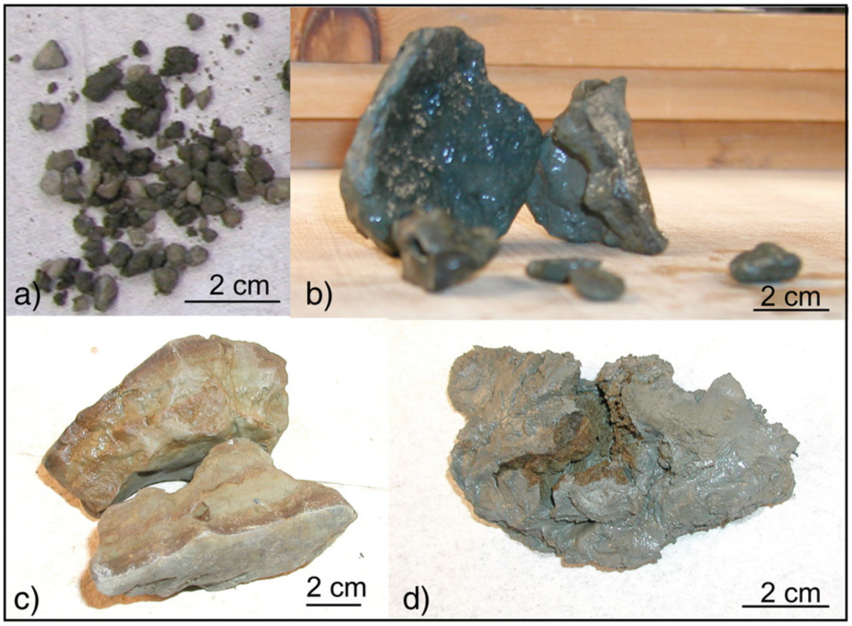

Fig. 9. Indurated mud clasts occur higher in the cores (a, b). These clasts had Munsell coloring generally of 5G 5/2 (dark green). The clast-dominated section graded down core into larger, more cohesive, oxidized soft mud masses. Close examination of the clasts (c) and soft masses (d) reveal oxidation gradients (c) and mottling (d). Samples pictured are from cores PBVC-07-18 (a), PBVC-07-17 (b) and PBVC-07-16(c, d). Coring locations are shown in Fig. 5.

4.2. Pockmarks spatial distribution and subsurface characteristics

Pockmarks in this study occur between −10 and −108 m water depths. Their frequency and size varied among embayments (Table 3). Because pockmarks in Belfast Bay have a consistent depth-to-diameter ratio (Andrews et al., 2010) we use the depth of a pockmark's base below the background seafloor as an indication of its size. In Passamaquoddy Bay pockmarks are the most numerous (4515), smallest (mean depth below seafloor = 3.6 m), and vary the least in size (standard deviation ±2.6 m). Blue Hill Bay hosted the largest pockmarks (mean depth below seafloor = 12 m) with the greatest standard deviation (±8 m). Belfast Bay has the greatest concentration of pockmarks per area (46.5 pm/km^2), and has size characteristics in between the other two bays. In all three embayments pockmarks are circular close to shore, but become elongated farther offshore, or in thalwegs (Fig. 2b). In one example, the seafloor in southern Belfast Bay terminates in flute-like structures, 50–150 m wide, 2–4 km long and 15–60 m deep (Fig. 1). Nearest neighbor analysis, the ratio of where features are expected to occur relative to where they actually occur, indicates that pockmarks are non-randomly distributed in all three fields (Table 4). This means that the pockmark's spatial distribution departs significantly from complete spatial randomness, implying that pockmark occurrence depends upon some factor(s).

Where sediment thickness could be mapped, pockmarks were identified only in areas with Holocene sediment thickness >2 m. Holocene sediment thickness strongly relates to pockmark size (Fig. 10). Larger pockmarks occur in thicker deposits while smaller pockmarks are in thinner deposits. Point-density analysis reveals that in Belfast and Passamaquoddy Bays the densest clustering of pockmarks occurs in Holocene sediments <15 m thick. Pockmark chains in Belfast and Passamaquoddy Bays consisting of large pockmarks (>100 m diameter) coincide with abrupt changes in depth of the unconformity (Figs. 11 and 12). Chains of small pockmarks outline glacial deposits (Fig. 13).

5. Discussion

5.1. Depositional and Erosional History

The study area's nearshore stratigraphy reflects the regional glacial and local sea-level history (Barnhardt et al., 1997; Belknap et al., 2002; Kelley et al., 2010). Late Wisconsinan glacial retreat from the Maine coast, between 15 and 13 ka (Dorion et al., 2001), was accompanied by marine incursion. During retreat, glaciers left heterogeneous deposits of till and glacial outwash (Unit T) across the seafloor (Belknap and Shipp, 1991; Kelley and Belknap, 1991). Glacial-marine muddy sediments (Unit GM) then blanketed these coarse-grained deposits. By 12.5 cal. ka further ice retreat and associated isostatic uplift caused relative sea-level fall to the lowstand of approximately 60 m below present-day level (Barnhardt et al., 1995). After the lowstand, sea level rose at varying rates (Kelley et al., 2010) leaving an eroded surface (U) along most of the region (Shipp et al., 1991). Since submergence, estuarine mud has accumulated over the transgressive surface (Unit M).

Table 3
Pockmarks frequency and size statistics.

Field	Number of Pockmarks	Pockmarks per km^2	Pockmark depth below seafloor (m)			
			Min	Max	Mean	Standard Deviation
Belfast Bay	2280	46.5	1.0	28	8.1	4.9
Blue Hill Bay	671	6.68	1.0	40	12	8.0
Passamaquoddy Bay	4515	31.7	1.1	29	3.6	2.6

Table 4
Nearest neighbor analysis of pockmark distribution.

Field	Ratio of observed/ expected average distance of pockmarks within a field	*p*-Value	Pattern	Likelihood the pattern is random (%)
Belfast Bay	0.72	0.01	clustered	<1
Blue Hill Bay	0.51	0.01	clustered	<1
Passamaquoddy Bay	0.71	0.01	clustered	<1

Within this study we identified acoustic Unit B only in Belfast Bay. Further, the unit has not been identified elsewhere in regional seismic surveys. This could reflect the unit's origins, or, less likely, could relate to the different seismic sources used (Table 2). Unit B's placement above the unconformity indicates that the unit was deposited during the Holocene. The unit's occurrence in the periphery of Belfast Bay suggests that Unit B formed around the estuary during lower sea level, perhaps as a marsh or eroded bluff toe deposit (e.g., Belknap et al., 2002). Due to the unit's depth within the sediment column we were unable to sample it using vibracores. Unit B's patchy distribution along the edge of Belfast Bay and absence in Blue Hill and Passamaquoddy Bays suggest that it is not related to pockmarks.

5.2. Pockmark Field Paleogeography since the Late Pleistocene and Shallow gas origins

Though mottled glacial-marine sediments were logged previously in the region (e.g., Ostericher, 1965; Shipp, 1989; Barnhardt, 1994; Gontz, 2005), their significance was uncertain because of the paucity of samples. We consistently recovered mottled features at the basal unconformity in Belfast Bay's periphery (Fig. 8). Based on color, composition and texture, we identify these indurated mud clasts and soft masses as redoximorphic features. Diagnostic of hydric (wetland) soils, the development of redoximorphic features requires saturation, respiring bacteria, and an adequate supply of decomposable organic carbon (Vepraskas, 2001). Redoximorphic features form by reduction, translocation, and oxidation of Fe and Mn oxides (Vepraskas, 1994; New England Hydric Soils Technical Committee (NEHSTC), 1998). Within a soil profile, redoximorphic features occur directly under the uppermost soil horizons, O or A, richest in organic material (NEHSTC, 1998) (Fig. 14). Our cores did not sample any organic-rich (>10% LOI) horizons.

The distribution of redoximorphic features confirms that wetlands occurred throughout Belfast Bay at a period of lower relative sea level. The features' coincidence with the Holocene/Pleistocene unconformity and the absence of the upper organic horizons in core samples strongly suggest that the upper organic horizons of the paleosol eroded during transgression (Fig. 14). The consequent unconformity was then buried with Holocene-age nearshore detrital sediments (Unit M).

Rogers et al. (2006) suggested that a buried, terrestrial, organic-rich layer, such as a peat (LOI ~60%), evolved into methane, and, by

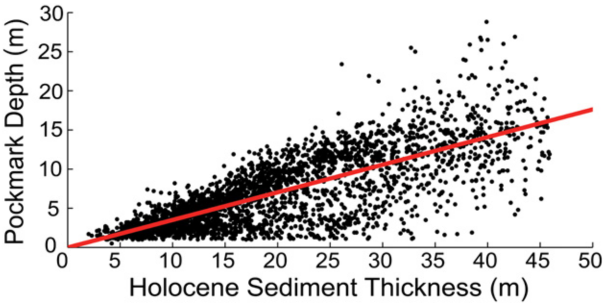

Fig. 10. For pockmarks in Belfast Bay and Passamaquoddy Bay, where underlying sediment thickness could be measured ($n = 3066$), Holocene sediment thickness strongly relates to pockmark depth, $r^2 = 0.60$.

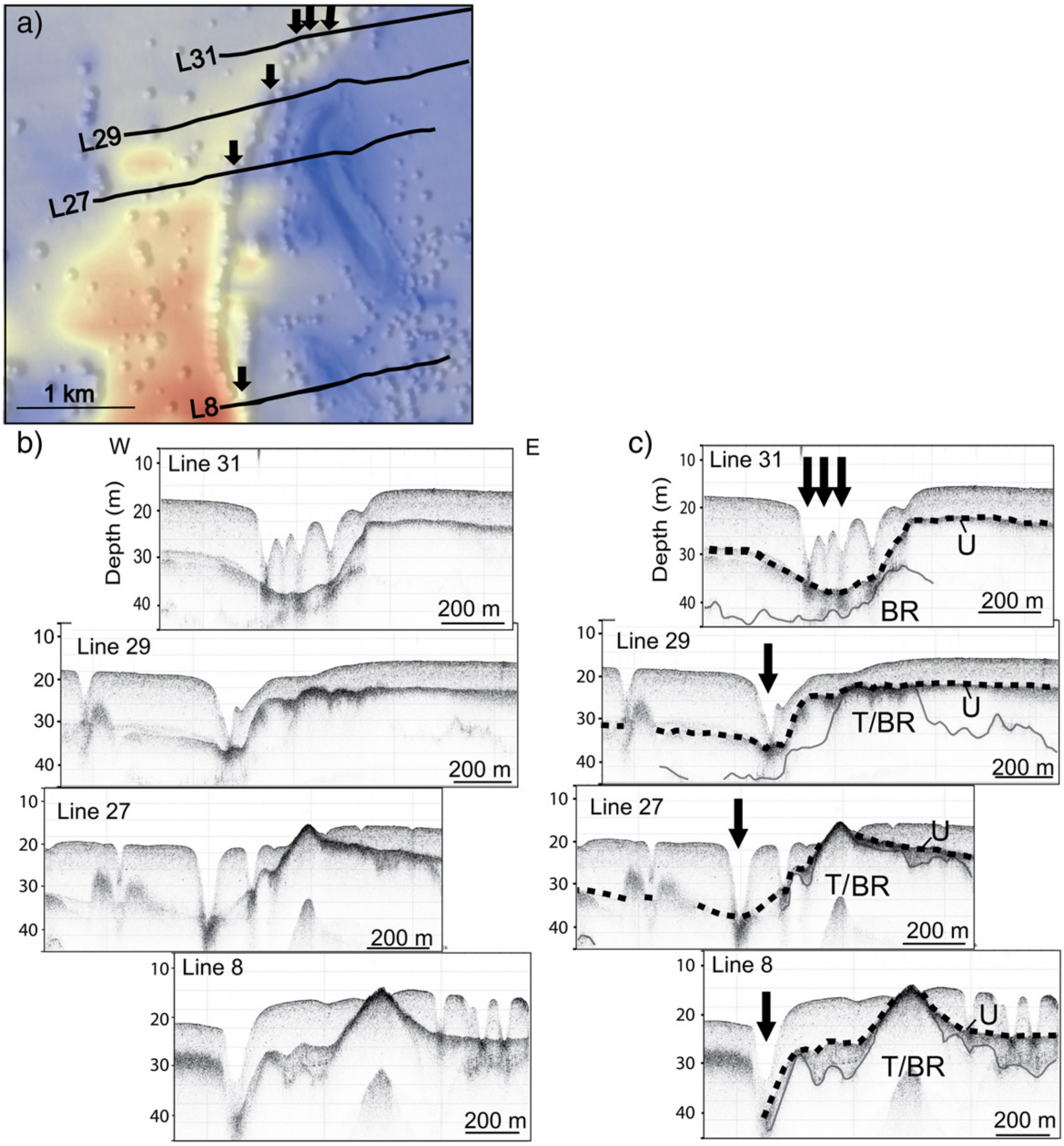

Fig. 11. Chain pockmarks coincide with an abrupt change in depth of the Holocene/Plesitocene Unconformity. An isopach map of Holocene sediment thickness overlays hill shaded bathymetry of the dominant Belfast Bay pockmark chain (a). Black lines show the locations of seismic profiles (b) and interpretations (c). Arrows point to pockmarks in plan view (a) and in profile (c). Fig. 1 shows location the chain. Fig. 4 shows isopach scale. Seismic units are defined in Fig. 6 and the text.

inference, formed regional pockmarks. We found no evidence for such a layer. Further, a concentrated organic deposit is not necessary to generate methane in this setting. According to Rice (1992), total organic content (TOC) in excess of 0.5% is sufficient to induce methanogenesis in sediments. LOI values, an estimate of TOC, measured in Unit M are at least an order of magnitude greater than that threshold. Because there is no evidence for a buried, organic-rich Pleistocene-age deposit, and the organic content of Unit M is sufficient to foster methane generation, we conclude that Holocene estuarine sediments are the stratigraphic source of shallow gas in Belfast Bay, and likely the other study sites.

5.3. Pockmarks' relation to stratigraphy

Pockmarks occur solely in the Holocene sediment package, with the bases of pockmarks not extending below the Holocene/Pleistocene unconformity. We interpret this confinement as evidence that pockmarks formed during the Holocene from the expulsion of gas generated in estuarine sediments. Our spatial analysis indicates that variation in Holocene sediment thickness, reflecting the region's irregular underlying topography, influences pockmark size and distribution (Figs. 10 and 15). Deep pockmarks coincide with areas of thick Holocene sediment, while shallow pockmarks occur in areas of minimal Holocene sediment accumulation. Based on this relationship we hypothesize that size differences between pockmarks in the three embayments (Table 3) reflect Holocene sediment thickness (i.e., Blue Hill Bay has the thickest sediments and thus the largest pockmarks, Passamaquoddy Bay has the thinnest sediments and thus the smallest pockmarks). The absence of shallow pockmarks in thicker sediments may reflect the propensity for pockmark collapse, amalgamation, or erosion in thick deposits; or alternatively, such size sorting may indicate different consequences of fluid flow in thin and thick sediment packages, such as the development of more integrated pathways of gas flow in thicker units.

Chains of pockmarks also relate to the Holocene sediment package and are quasi-normal to the steepest gradient in Holocene sediment thickness. Variation in Holocene sediment thickness likely

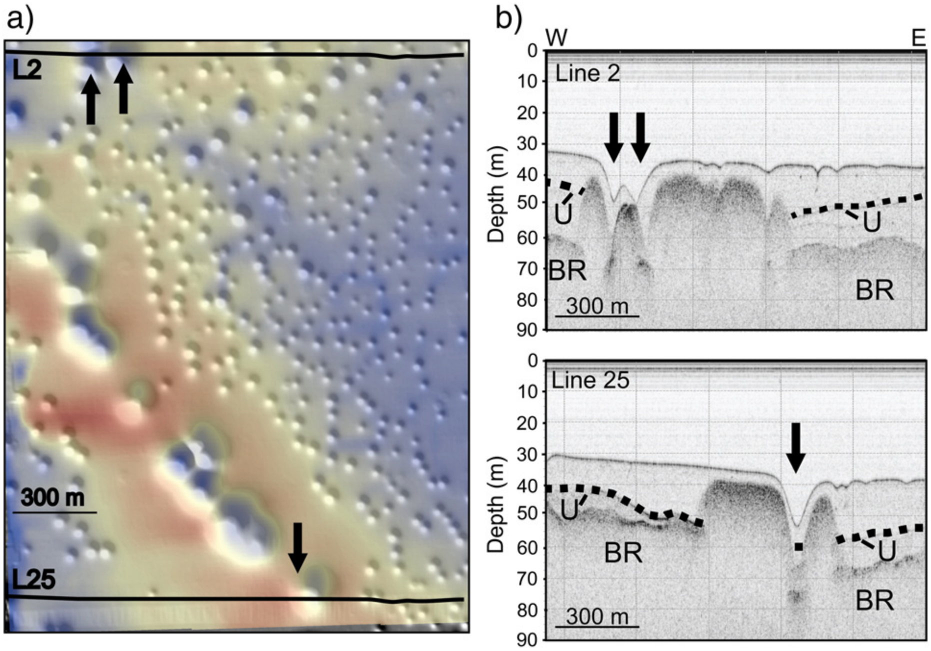

Fig. 12. Isopach overlaying hillshaded bathymetry (a). Seismic lines 2 and 25 (b) show the cross section of the dominant Passamaquoddy chain coincide with a relative low in the Holocene/Pleistocene Unconformity. Arrows point to pockmarks in plan view and in profile. By virtue of being depressions, large pockmarks are zones of thin Holocene sediment. Fig. 3 shows location of the bathymetry. Fig. 4 shows isopach scale. Units are the same as Fig. 6.

creates a pressure gradient, enabling gas migration from zones where the overburden pressure is greatest (thickest sediment) to zones of minimal overburden pressure (thin sediments). In Belfast Bay and Passamaquoddy Bay, pockmark chains occur at the abrupt thinning of Holocene sediment related to antecedent geology, glacial deposits and paleochannels. Hovland et al. (2002) noted that pockmark chains often nucleate along zones of weakness where fluid flow focuses. The tens of meters of relief over a relatively short horizontal difference (e.g., 200 m) that typifies the regions' underlying topography may set up conditions for focused fluid expulsion capable of forming pockmarks. Pinet et al. (2010), and Lavoie et al. (2010) have also noted a relationship between pockmarks and the underlying bedrock and topography of the St. Lawrence estuary.

We note that not all muddy, gassy estuaries underlain by irregular topography have pockmarks. For example, paleochannels similar in relief to the underlying topography of north temperate estuaries underlie Chesapeake Bay, yet the bay lacks pockmarks. Differences in seafloor morphology may result from the permeability of sediments that infill topographic lows. In Chesapeake Bay the lower channel-fill unit of each paleochannel is a fluvial deposit, typically made of coarse sand and fine gravel (Coleman et al., 1990). This is in stark contrast to the homogenous, cohesive fine-grained estuarine sediment that fills the nearshore basins in the north temperate pockmark fields. Coarser-grained channel fill could promote fluid migration and diffusion along the channel, rather than vertical migration of fluids that occurs in fine-grained sediment (e.g., Jain and Juanes, 2009; Scandella et al., 2011), resulting in gas spatially coincident with paleochannels and minimal seafloor disturbance (Hill et al., 1992).

Within the three temperate embayments, pockmarks do not persist seaward of the 70 meter isobath. In seaward portions of all three embayments pockmark morphology alters from circular to comet-like features terminating in elongate scours related to increased nearbed uni-directional flow (Fig. 2b) (e.g., Brothers et al., 2011b). In Belfast and Blue Hill Bays, nearbed currents within thalwegs are likely 1.2–1.7 times faster than the velocities in the upper bay, using continuity of water volume where U_c is channel velocity, U_b is basin velocity, D_c is channel depth, D_b is basin depth, W_c is channel width, and W_b is basin width.

$$\frac{U_c}{U_b} = \frac{(D_c \times W_c)}{(D_b \times W_b)} \tag{1}$$

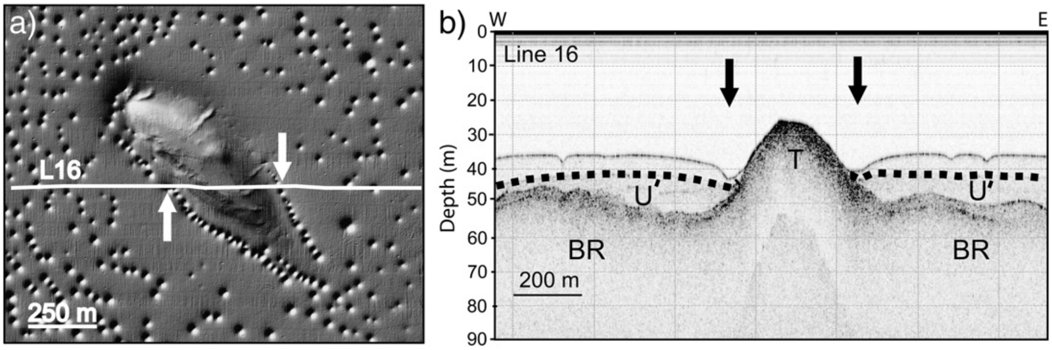

Fig. 13. Bathymetry (a) and subsurface data (b) from Passamaquoddy Bay (location shown in Fig. 3) show pockmarks abut topographic highs. Seismic reflection profile line 16 intersects a prominent drumlin. Arrows point to pockmarks in plan view and in profile outlining the boundary of a drumlin (modified from Ocean Mapping Group, 2012b). Fig. 4 shows isopach scale.

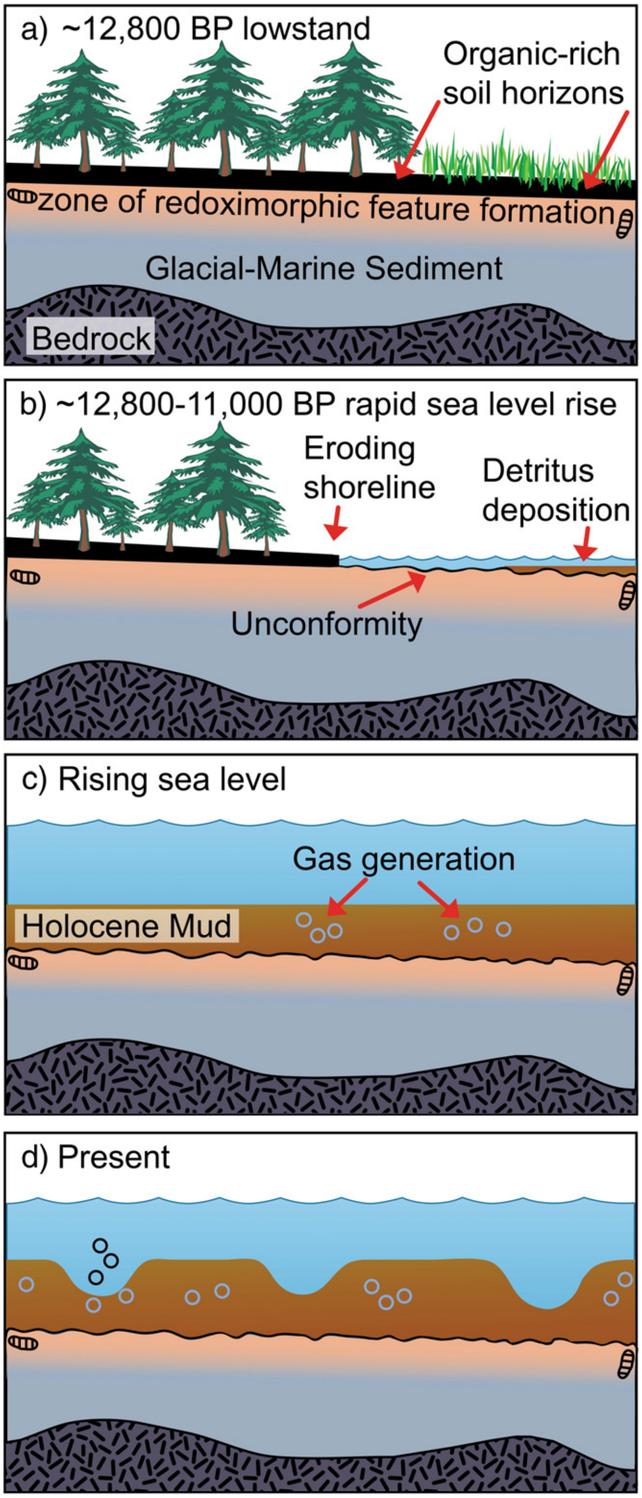

Fig. 14. Conceptual model of nearshore evolution since local sea-level lowstand. (a) During the lowstand areas presently inundated were coastal lowlands. Redoximorphic features formed underneath the peat and topsoil. The Pleistocene age glacial-marine sediment was the parent material for the hydric soil. (b) From 12,800 to 11,000 sea level rose rapidly. Wave-action eroded organic-rich horizons of the soil, leaving a ravinement unconformity. Pelagic deposition of Holocene age estuarine mud began. (c) From 11,000 to present, estuarine mud was deposited. Methanogenesis occurred within the Holocene sediments. (d) Between the transgression and the present, gas entrained sediments as it escaped the seafloor, forming pockmarks.

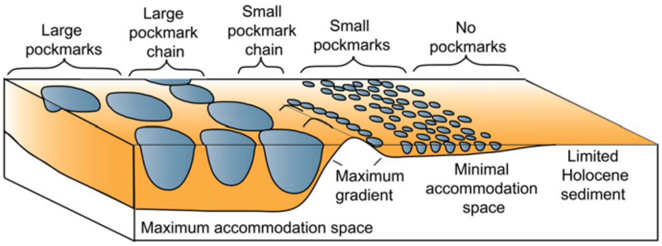

Fig. 15. Conceptual model of pockmark size and habit related to underlying topography. The largest pockmarks occur where Holocene sediment is thickest. Smaller pockmarks occur in thinner Holocene sediment packages. Chains of pockmarks occur quasi-normal to the maximum gradient in Holocene sediment thickness. Pockmarks are not found in Holocene sediment less than 2 m thick.

In semi-enclosed bodies of seawater, it is possible that the protection of bedrock, or till headlands, is required to preserve pockmark morphology. Enhanced offshore nearbed currents may limit the seaward extent of the estuarine pockmark field. In addition, the pockmarks may not continue offshore due to the diminution in Holocene sediment thickness, but more extensive seismic coverage is necessary to confirm this. The factors that appear to control pockmark distribution in the examined temperate estuaries may also explain pockmark distribution in other structurally-controlled coastal settings such as fjords, or Rias (Iglesias and Garcia-Gil, 2007; Webb et al., 2009).

6. Conclusion

We conclude that a terrestrial deposit high in organic content is not the source for gas responsible for pockmarks. Instead, our data analysis suggests that sediments deposited in the last 11,000 years fostered the gas related to the pockmarks. Holocene sediment thickness, dictated by available accommodation space, exhibits control on pockmark size and distribution. Our findings indicate that variation in Holocene sediment thickness made possible by irregular underlying topography may ultimately play a more important role in temperate estuarine pockmark distribution than drowned terrestrial deposits.

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