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Research paper

Evidence for gas hydrate occurrences in the Canadian Arctic Beaufort Sea within permafrost-associated shelf and deep-water marine environments

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ABSTRACT

The presence of a wedge of offshore permafrost on the shelf of the Canadian Beaufort Sea has been previously recognized and the consequence of a prolonged occurrence of such permafrost is the possibility of an underlying gas hydrate regime. We present the first evidence for wide-spread occurrences of gas hydrates across the shelf in water depths of 60–100 m using 3D and 2D multichannel seismic (MCS) data. A reflection with a polarity opposite to the seafloor was identified ~1000 m below the seafloor that mimics some of the bottom-simulating reflections (BSRs) in marine gas hydrate regimes. However, the reflection is not truly bottom-simulating, as its depth is controlled by offshore permafrost. The depth of the reflection decreases with increasing water depth, as predicted from thermal modeling of the late Wisconsin transgression. The reflection crosscuts strata and defines a zone of enhanced reflectivity beneath it, which originates from free gas accumulated at the phase boundary over time as permafrost and associated gas hydrate stability zones thin in response to the transgression. The wide-spread gas hydrate occurrence beneath permafrost has implications on the region including drilling hazards associated with the presence of free gas, possible overpressure, lateral migration of fluids and expulsion at the seafloor. In contrast to the permafrost-associated gas hydrates, a deep-water marine BSR was also identified on MCS profiles. The MCS data show a polarity-reversed seismic reflection associated with a low-velocity zone beneath it. The seismic data coverage in the southern Beaufort Sea shows that the deep-water marine BSR is not uniformly present across the entire region. The regional discrepancy of the BSR occurrence between the US Alaska portion and the Mackenzie Delta region may be a result of high sedimentation rates expected for the central Mackenzie delta and high abundance of mass-transport deposits that prohibit gas to accumulate within and beneath the gas hydrate stability zone.

1. Introduction

Gas hydrates are naturally occurring ice-like crystalline compounds in which gases such as methane are trapped within a lattice of water molecules. In marine and Arctic permafrost regions gas hydrates comprise a large methane reservoir and are considered a future source of energy (e.g. Boswell and Collett, 2011). Global estimates of methane in gas hydrates vary by orders of magnitude (e.g. 10,000 Gt by Kvenvolden, 2002; 3000 Gt by Buffett and Archer (2004); and 74,400 Gt by Klauda and Sandler, 2005) but even the smaller estimates are larger in size than all conventional fossil fuels combined. The presence of gas hydrates in sediments is controlled by several factors, among which, temperature and pressure are key parameters (e.g. Sloan and Koh, 2008). In the pressure/temperature (P/T) field, the phase boundary is further determined by the gas composition and also by the salinity of the pore-water. As methane is an effective greenhouse gas (at least ~20 times more potent than

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carbon dioxide, CO_2, e.g. Shindell et al., 2009), understanding of the dynamics and potential mobilization of methane from gas hydrate and permafrost deposits is of fundamental importance in predicting future global climate scenarios.

The cycle of permafrost and gas hydrate formation during times of terrestrial exposure, followed by periods of warming and associated marine transgression, has had substantial impacts on the Arctic shelf regions. Ongoing warming due to the latest transgression in the Holocene is disturbing these deposits, creating the potential for gas migration and release. Modeling of methane release through global ocean warming predicted that a change in ocean temperature by 3 °C would release about 4000 Gt of carbon into the ocean and possibly into the atmosphere (Archer and Buffett, 2005). The shallow water depths in these Arctic shelf regions increase the efficiency by which gas released from the sediments could reach the atmosphere. Recent scientific studies showed that significant amounts of methane are presently being released from the seabed on a global scale and that ~20% of this methane may reach the atmosphere (Dimitrov, 2002; Judd et al., 2002; Kastner et al., 2005). A number of recent studies documented these processes in Arctic shelf settings: at the Siberian shelf, Shakhova and Semiletov (2007) suggest that elevated methane concentrations in seawater are due to degradation of shelf permafrost and gas hydrate. In the Beaufort Sea, Hughes-Clarke et al. (2009) have identified extensive free gas release at the seabed of the Beaufort shelf. Paull et al. (2007) have also documented shelf edge methane releases near a variety of distinct geomorphic features at that shelf edge transition including pingo-like features (PLF) and mud volcanoes. Similar observations have been made at the Svalbard margin (e.g. Westbrook et al., 2009; Hustoft et al., 2009) with extensive pockmarks and methane gas-release features on the seabed in water depths of ~250 m.

The presence of gas hydrate in the Mackenzie Delta region (on land) has been well documented through numerous drilling and coring at the Mallik research site (e.g. Dallimore et al., 1999; Dallimore and Collett, 2005). Possible evidence for the presence of gas hydrates in other industry well sites onshore and offshore in the Mackenzie Delta – Beaufort region have been proposed (e.g. Judge and Majorowicz, 1992; Smith and Judge, 1993; Majorowicz and Hannigan, 2000; Majorowicz and Osadetz, 2001; Osadetz and Chen, 2010) but most offshore wells are in relatively shallow water (<40 m). Thermal modelling of the permafrost distribution across the shelf and shelf edge extending into deeper water (~500 m) based on the climate history and sea-level low-stands and transgression over the past 150 ka was conducted using present temperature data from industry wells as calibration (Taylor et al., 2013). The wide-spread and long-lasting persistence of permafrost resulting from the latent heat of phase change creates favourable conditions for gas hydrate stability.

In this study we show the first seismic evidence for the presence of a gas hydrate system occurring beneath buried permafrost on the Canadian Beaufort shelf at the critical shelf edge zone (Fig. 1), where the last transgression (starting ~ 25 ka years ago) has had significant impact on the phase boundary for permafrost and gas hydrates and resulted in a south-ward retreat and thinning of the permafrost wedge and thus the underlying gas hydrate stability zone. The seismic reflections from the base of the gas hydrate stability zone can be traced through two adjacent 3D seismic volumes provided by industry as well as from regional 2D multichannel seismic (MCS) profiles, courtesy GX Technology, and other MCS profiles (Jin et al., 2015; Jin and Dallimore, 2016). This new observation confirms the previous thermal model and predicted existence of a wide-spread region of gas hydrate across the shelf of the Mackenzie Delta - Beaufort region up to the critical shelf edge zone.

In addition to the presence of the permafrost-associated gas hydrate occurrence, we present the first evidence for the presence of a deep-water marine gas hydrate zone in the Canadian Beaufort Sea from 2D MCS data acquired in the outer Mackenzie Trough region. Data from this region, in combination with vintage (analog) 2D data on the western shelf/slope setting towards the Alaska border, and in comparison to 2D MCS data on the Alaska Beaufort Sea slope showing wider-spread BSRs (e.g. Phrampus et al., 2014; Andreassen et al., 1995; Grantz et al., 1976) suggest that marine gas hydrates are also possibly occurring in the Canadian Beaufort Sea.

2. Geological setting, well-log data, permafrost distribution and geothermal model

The Canadian southern Beaufort Sea shelf and slope region is one of the best documented Arctic coastal/shelf areas in the world as it has benefited from more than forty years of scientific research and substantive engineering experience during intensive offshore hydrocarbon exploration in the 1980's and 1990's (see e.g. Dixon, 1996). Also, a comprehensive gas hydrate research program conducted at the Mallik site (Dallimore et al., 1999; Dallimore and Collett, 2005) provided among the best-documented gas hydrate occurrences and serves as a terrestrial analogue to compare with the shelf and shelf-edge environment. The Beaufort basin is generally characterized by greater than 10 km of upper Cretaceous to Cenozoic aged sediments, comprised primarily of folded and faulted deltaic sediment complexes. The geological and geotechnical properties of shallow shelf sediments are heavily influenced by the glacial and inter-glacial history and permafrost formation. The margin has been studied by scientists of the Geological Survey of Canada since the 1970s and resulted in a wealth of information available for this study (e.g. Pelletier, 1987; Hill et al., 1992, 1993; Blasco et al., 1990, 1998, 2010). Permafrost, or sediments that are below 0 °C, is ubiquitous beneath much of the Beaufort Shelf (e.g. Pelletier, 1987; Pullan et al., 1987; Hu et al., 2013) having formed during periods of lower sea level when portions of the shelf less than ~100 m water depth were an emergent coastal plain exposed to very cold surface temperatures. The regional occurrence of permafrost across much of the Beaufort shelf region was studied using industry seismic refraction data by Pullan et al. (1987) and from industry well log data (Hu et al., 2013). The extensive seismic data were used by Pullan et al. (1987) to define three distinct zones of permafrost occurrence (continuous ice-bonded sediments where velocity is consistently higher than 2500 m/s, discontinuous permafrost distribution where velocity varies and can be below the 2500 m/s threshold, and a zone of low ice content with velocities lower than 1800 m/s). In a recent study, Riedel et al. (2014) used newly acquired multichannel seismic data to delineate the occurrence of permafrost with the same refraction velocity technique, but focused on the region near and across the shelf edge zone. The onset of high-velocity material with velocity over 2500 m/s marks the northern-most extent (deep-water edge) of seismically detectable permafrost. A slightly different threshold of 2300 m/s to define high-velocity ice-bearing sediments was used in the study by Brothers et al. (2012) along the US/Alaska Beaufort margin.

The current offshore permafrost distribution is a result of the temporal aspect of its response to the ongoing marine transgression that started ~25 ka ago. Taylor et al. (2013) did include this transgression in an extensive thermal model along a main onshore-offshore transect (see map in Fig. 1 for location). The flooding of the shelf with relatively warm waters has imposed a change from mean annual temperatures as low as −20 °C during terrestrial exposure, to present bottom water temperatures that are near -1 °C. Despite the fact that deeper parts of the shelf have been submerged for

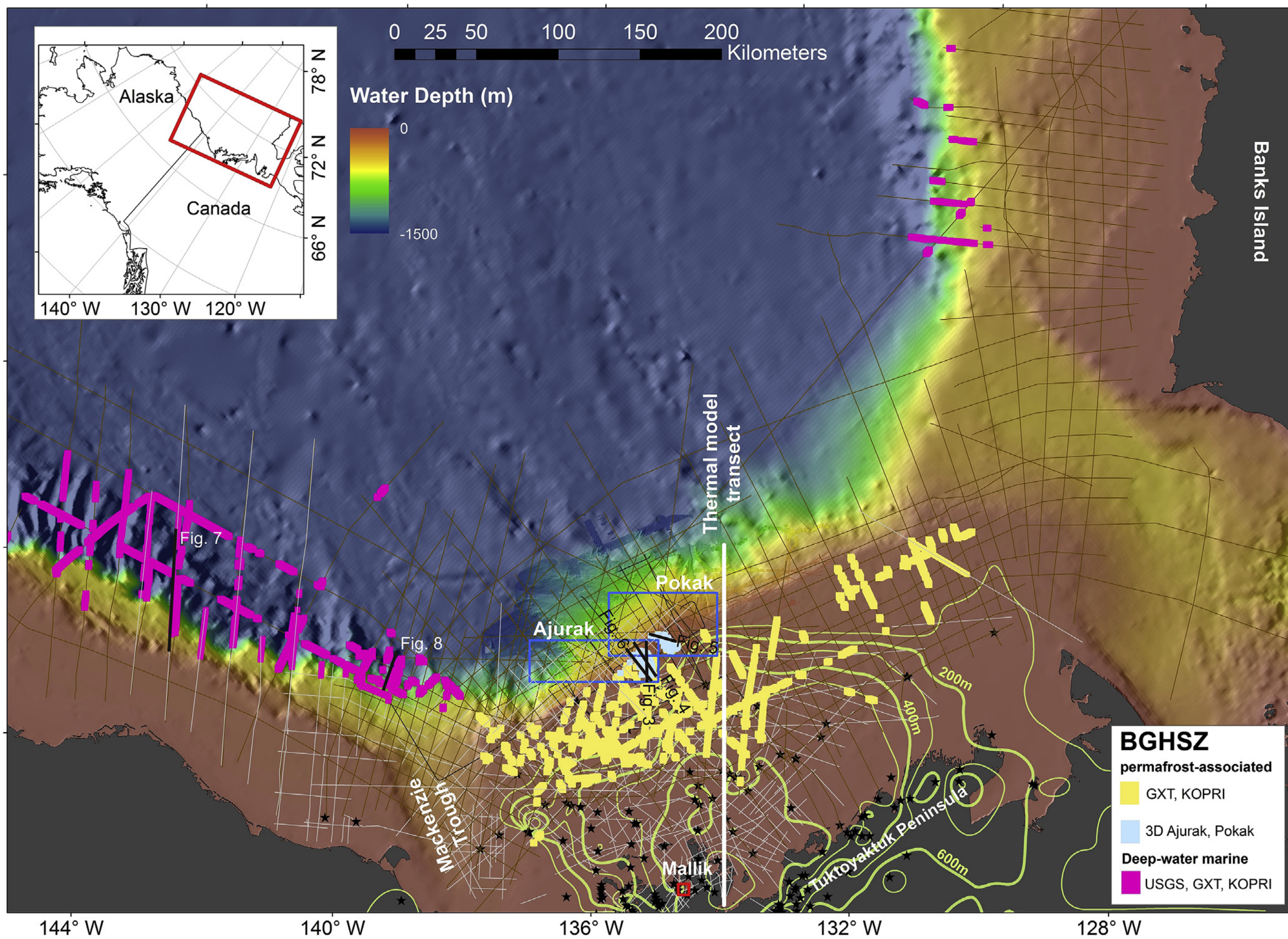

Fig. 1. Map of the extent of gas hydrate occurrences from seismic data available in the southern Beaufort Sea. Reflections from the BGHSZ associated with permafrost are shown as pale blue and yellow colors. Reflections from the BGHSZ representing a deep-water marine gas hydrate environment as shown as bold pink lines, and occur mostly in the western portion of the study region in transition to the Alaska margin. Thin grey lines are seismic data available as re-digitized paper copies. Blue rectangles are outlines of 3D data coverage. Black thin lines are 2D lines acquired in 2013/14 with the IBRV Araon. Brown thin lines are location of BasinSPAN™ profiles, courtesy GX Technology Corporation. The multibeam bathymetry in this region of the slope is courtesy of industry, GSC, and the Canadian university consortium ArcticNet. The extent of offshore permafrost is shown by beige-green isopach lines. The thermal modeling-transect by Taylor et al. (2013) is shown as white line, and offshore well-locations are indicated by black stars. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

more than 7000 years, the buried offshore permafrost is still responding to this change because of latent heat effects and slow rates of heat diffusion associated with thawing (Paull et al., 2007, 2012; Taylor et al., 2005, 2013). Where permafrost pinches out at the edge of the shelf there may be conditions where pressured fluids migrate vertically and horizontally. Such conditions could substantially influence pore pressures in shelf edge and slope sediments, making them particularly susceptible to liquefaction and slope failure (Blasco et al., 2013). Though not the focus of this study, it should be noted that substantial work has been completed on the offshore permafrost distribution and BSRs along the US/Alaska portion of the Beaufort shelf/slope region. Results show that subsea permafrost is less common along the Alaska margin (e.g. Brothers et al., 2016; Brothers et al., 2012; Ruppel et al., 2016), while the deep-water marine BSR covers up to 80% of the slope region (e.g. Andreassen et al., 1995; Grantz et al., 1976).

3. Estimating the gas hydrate stability zone beneath buried permafrost

While the distribution of permafrost is well constrained from various sources (seismic refraction data (e.g. Pullan et al., 1987; Riedel et al., 2014), well log picks of physical properties (e.g. Hu et al., 2013), and temperature measurements (e.g. Hu et al., 2010), the depth of the gas hydrate stability zone is not as well established. Although numerous studies have been undertaken to define the occurrence of gas hydrates (Judge and Majorowicz, 1992; Smith and Judge, 1993; Majorowicz and Hannigan, 2000; Majorowicz and Osadetz, 2001; Osadetz and Chen, 2010), the occurrence of gas hydrate is controlled not only by the pressure and temperature regime, but also by pore-water salinity, gas composition, and sedimentology, i.e. occurrence of coarse-grained material (silt, sand, gravel). Thus, the occurrence of individual gas hydrate shows identified in well logs or interpreted from seismic surveys does not necessarily define the vertical extent of the gas hydrate stability zone. The intersections of the modeled temperature-depth profiles (Taylor et al., 2013) with the methane hydrate phase curve (e.g., Holder and Hand, 1982) were used to estimate the depth of the gas hydrate stability zone at 5 km intervals along the model-transect shown in Fig. 2. The calculation assumed a simple hydrostatic regime, average pore-fluid salinity (20 ppt as determined at the Mallik site; e.g. Dallimore and Collett, 2005), and a pure methane

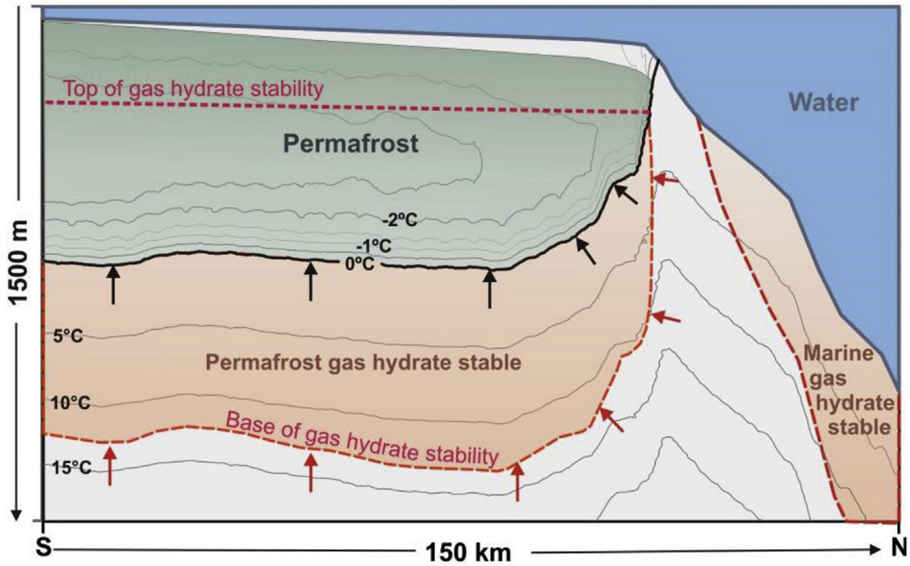

Fig. 2. Model-prediction of the extent of a permafrost-associated gas hydrate zone on the shelf, and beyond, a classic deep-water marine gas hydrate zone. The base of the gas hydrate zone is determined from the intersection of modeled temperatures below the permafrost and the methane hydrate phase curve, assuming hydrostatic pressure, pore-water salinity of 20 ppt, and a pure methane composition. The image shows only the marine component of the model by Taylor et al. (2013) and not the terrestrial portion of the transect.

gas system (representative of gas hydrate structure-I). Any presence of higher hydrocarbons (other than methane) shifts the sI gas hydrate stability field accordingly, or may allow even the potential occurrence of sII gas hydrate.

While such a geothermal model is sensitive to these various controlling parameters and local fluctuations may exist, it provides a realistic first-order prediction of the geothermal regime for the central Beaufort Shelf (see discussion in Taylor et al., 2013). Fig. 2 shows the extent of the gas hydrate regime associated with the modeled permafrost distribution as well as the corresponding extent of a classic marine gas hydrate regime (i.e., in a non-permafrost setting, Paull et al., 2012). The top of the gas hydrate stability field associated with the offshore permafrost is within the permafrost regime, and at ~240 m below sea level is at constant depth across the profile as it is purely pressure-controlled and temperature is near isothermal <0 °C. The base of modeled permafrost is reflected also in the undulating character of the base of gas hydrate stability as a uniform sand lithology is used across the entire profile in this simple model. The permafrost rapidly thins and pinches out in a water depth of ~100 m. The associated boundary of the gas hydrate stability zone base also becomes rapidly shallower and becomes steeply inclined boundary.

4. Gas hydrate stability zone beneath submarine permafrost

Two adjacent 3D seismic volumes, made available by industry, allow study of the extent of the permafrost-associated and classic marine gas hydrate stability field. The two 3D volumes cover a portion of the shelf and shelf edge and extend into deeper water covering a region of 1700 km^2 (Ajurak volume) and 2250 km^2 (Pokak volume) with a small overlapping region (Fig. 1). Within the Ajurak 3D volume, the reflection interpreted to be from the base of gas hydrate stability zone (BGHSZ) occurs within the south-eastern corner and spreads over an area of ~70 km^2. Two seismic sections were extracted from the Ajurak block to show the reflection of the BGHSZ. Cross-line 7128 (N-S oriented, Fig. 3) shows the reflection from the BGHSZ at a depth of ~1.25 s at the southern end of the cross-line (inline 1405 to 1620), and this reflection becomes gradually shallower towards the north into deeper water. The reflection is characterized by a polarity opposite to that of the seafloor and is seen to cross-cut regular strata that typically dip to the north. Underneath this reflection, a zone of enhanced seismic reflectivity can be seen (inline 1720–2200), where individual reflectors are truncated at the BGHSZ.

The BGHSZ is controlled mostly by the depth-change in the overlying permafrost (Fig. 2). As this boundary deepens towards the shelf edge, we selected an arbitrary seismic line (A-A′) from the Ajurak volume crossing the shelf edge almost perpendicular (Fig. 4). Seismic line A-A′ shows a reflection from the BGHSZ that becomes rapidly shallower towards the NW and towards deeper water, as predicted by the thermal model. Along this line, two segments of enhanced seismic reflectivity beneath the BGHSZ are identified that could possibly be the result of some free gas within the sediments.

Within the Pokak volume, reflections from the BGHSZ are much less pronounced and occur only over two smaller patches. We extracted one line near the edge of the shelf break (Line B-B′) to illustrate the features of the BGHSZ reflection in this area (Fig. 5). Along this line the sediments show overall much less dip relative to the seafloor meaning that the BGHSZ cross-cuts only at a small angle relative to the dominant dip of sediment layers. However, the BGHSZ becomes shallower towards the shelf break (towards the NW) and can be identified also by the up-dip truncation of high amplitude reflections (e.g. at trace 10798 in Fig. 5) and by the sporadic occurrence of high amplitude anomalies further to the SE along the same line.

Newly acquired 2D MCS data across the shelf-edge region with the icebreaker ARAON in 2013 and 2014 (Jin et al., 2015; Jin and Dallimore, 2016) provide further evidence for the existence of a reflection from the BGHSZ (Fig. 6). Data processing and imaging is, however, challenged by the presence of strong seafloor-multiples that could not be completely removed as described by Riedel et al. (2016). Yet, the 2D MCS data generally confirm observations made across the 3D seismic data volumes.

5. Deep-water marine gas hydrate stability zone in the outer Mackenzie Trough

Marine deep-water gas hydrate occurrences are, in contrast to permafrost-associated gas hydrates, controlled by a simpler temperature field (water-temperatures and geothermal gradients) as well as a hydrostatic pressure regime. Additional constraints are pore-fluid salinity and gas-composition. In the deep-water Beaufort Sea little is known about most of these parameters; hence predictability of the base of the gas hydrate stability zone in the offshore region is restricted and its depth can vary considerably without these constraints. Accordingly, exploration for BSRs is difficult, especially given the dominance of (mostly fine-grained, thus less porous and less permeable) turbidity current and mass-transport depositional environments of the Canadian Beaufort Sea and Canada Basin, because of the inherent bottom-simulating geometry of such deposits (e.g. Mosher et al., 2011, 2012). Despite this, the thermal field is assumed to generally parallel to the seafloor so any seismic reflection from the base of gas hydrate stability zone should likewise simulate the bottom such that detection of any BSR is most likely where it cross-cuts slope stratigraphy. The only previously known BSR in the Beaufort Sea occurs along the slopes off Alaska (e.g. Andreassen et al., 1995; Grantz et al., 1976, Fig. 7). The BSR appears at a depth of 300–400 ms two-way time below the seafloor. Using a simplified assumption of pore fluid salinity (34 ppt) and a pure methane gas composition, the depth of the Alaska BSR translates to thermal gradients between 25 and 45 °C/km with values generally increasing northward into deep water (Phrampus et al., 2014). These estimates are based on an average value of 1600 m/s as P-wave sediment velocity (conversion from two-way time to meters) and a constant thermal conductivity of 1.0 mK/m^2 for the upper few hundred meters of sediment. Topographic effects due to canyons in the region (Fig. 1) may further complicate this estimate of thermal gradients.

The data coverage of the deep-water portion of the Canadian Beaufort Sea is relatively sparse (Fig. 1) and many lines are available only as digitized paper copies. However, during expedition ARA05C conducted in 2014 (Jin and Dallimore, 2016) a seismic transect was conducted along the outer Mackenzie Trough into water depths up to 1550 m. Along this transect, a seismic reflection with bottom-simulating characteristics and opposite-to-seafloor polarity (Fig. 8) was imaged, manifesting very similar character as the BSR off Alaska (compare to Fig. 6a in Phrampus et al., 2014). Seismic velocity analyses conducted along this seismic line (Riedel et al., 2016) show a clear decrease in the rms-velocity beneath this reflection, indicating the presence of free gas. Both, this and the Alaska-BSR, display gas-brightening of stratigraphic horizons underneath the BSR which cross-cut the phase boundary (CDPs 1500–1800, Fig. 8). Using the same assumption as for the Alaska-BSR example, the thermal gradients along the seismic line shown in Fig. 8 of the outer Mackenzie Trough range from 25 to 38 °C/km, with higher values seen further offshore. Again, topographic complexities exist especially from CDP 1500–1700 and CDP 3050–3250, where proximity to canyons and neighboring ridges degrade imaging of the seafloor and deeper structures.

With this BSR as control, similar reflections were identified along the 2D MCS lines in this region, especially on those to the west, toward the Alaska margin. These additional picks demonstrate a continuity of the well-established deep-water marine gas hydrate occurrence of Alaska (as shown by Andreassen et al., 1995) into Canadian waters, extending at least to the central portion of the outermost Mackenzie Trough (Fig. 1, pink squares). No additional reflections that may be associated to the base of the marine gas hydrate stability zone have been identified further to the east off the Tuktoyaktuk peninsula on any of the 2D MCSD data, the 3D volumes. However, evidence for a BSR is again seen off Banks Island (Fig. 1); however, no permafrost-associated BSR has been identified there.

6. Discussion

The occurrence of a marine permafrost-associated gas hydrate stability zone has long been postulated and some evidence has been previously presented from well-log interpretations (e.g. Majorowicz and Hannigan, 2000) and thermal modeling (Taylor et al., 2013). However, near the shelf edge zone and in waters exceeding ~75 m, lack of deep industry drilling along the Canadian margin precludes direct evidence for gas hydrates. Vintage seismic data acquired across the Beaufort outer shelf and slope region did not reveal any seismic indication of the existence of a BSR. A partial explanation is that the expected depth of such a BSR event is partly masked by prominent unconformities in the region, coupled with an overall near-seafloor-parallel nature of the upper 1000–1500 m of sediment below seafloor. Thus the seismic signature of the BGHSZ cannot be easily distinguished from regular seismic horizons. However, shelf-edge perpendicular lines are sparse and of overall low quality (often available only as re-digitized paper records).

Surrounding the Mallik gas hydrate research site on Richards Island, an extensive field with gas hydrate beneath 600 m thick permafrost was described (e.g. Dallimore et al., 1999). However, regional 2D as well as 3D seismic data collected across the onshore Mackenzie Delta did not show a regional reflection from the BGHSZ. Instead, individual gas hydrate-rich horizons were mapped (e.g. Riedel et al., 2009; Bellefleur et al., 2012) though well above the BGHSZ. Significant variations in grain-size and pore-fluid salinity are expected to occur in the thick sediment package of the dominantly deltaic-style pro-grading sediment sequences. Such variations can result in a seismic reflection from the BGHSZ that may not always be perfectly flat or bottom-simulating over large distances, as typically seen in a “classic” marine environment. Local taliks (unfrozen) in zones of discontinuous permafrost can further create “holes” in the geothermal structure (e.g. Ramachandran et al., 2011), locally uplifting the BGHSZ and thus disrupting the reflection from it.

The reflection interpreted to be from the BGHSZ shows several typical characteristics usually associated with BSRs in the classic deep-water marine environment: (a) polarity reversed relative to seafloor, (b) cross-cutting of sedimentary stratigraphy, (c) enhanced reflectivity underneath, indicative of the presence of free gas, (d) high-amplitude up-dip truncation of layers at the BGHSZ.

Polarity-reversed reflections are common in the available 3D seismic data, but are usually associated with either free gas bright-spots or mass-transport deposits (MTDs). Shallow gas-related reflections (bright-spots) show polarity-reversed reflection-phase relative to the seafloor but are typically strata-bound, not cross-cutting existing stratigraphy. MTDs are usually deposited in a downslope fashion and therefore they can occur as bottom-simulating events. However, their only cross-cutting relationships are erosional truncations at their origin, base, and/or the distal end of the deposit.

Overall, the reflection interpreted to be from the BGHSZ mimics the behaviour predicted from the thermal modeling and follows the shape of the associated wedge of permafrost (Taylor et al., 2013). Therefore, we believe that this reflection is associated with gas hydrates in the overlying sediments and some accumulation of free gas underneath. The distribution of the high amplitude zone underneath the BGHSZ shows some fault control and often layers are truncated at the phase boundary, forming mini-bright-spots. These spots align, describing a discontinuous horizon along the

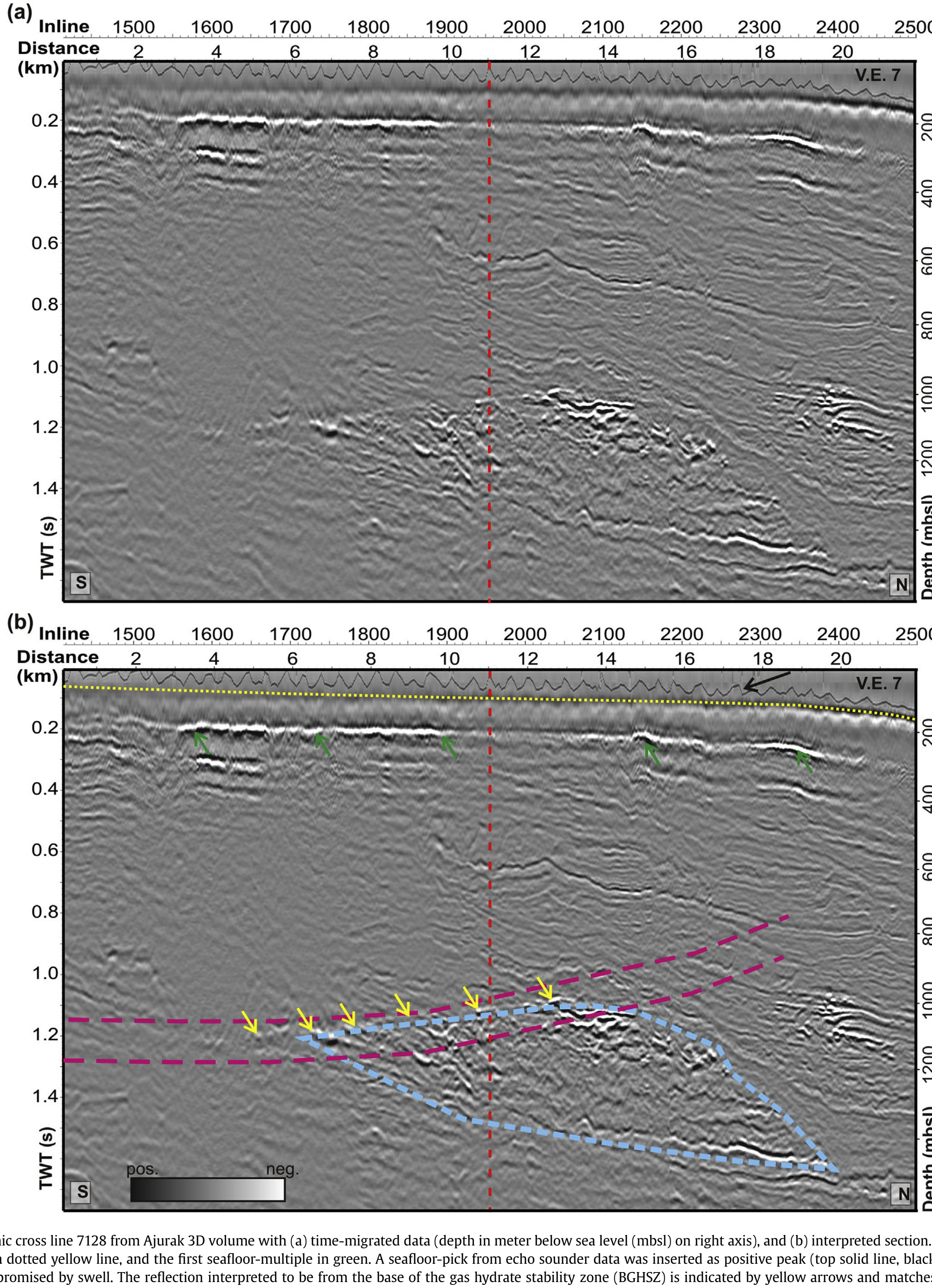

Fig. 3. Seismic cross line 7128 from Ajurak 3D volume with (a) time-migrated data (depth in meter below sea level (mbsl) on right axis), and (b) interpreted section. The seafloor is depicted as a dotted yellow line, and the first seafloor-multiple in green. A seafloor-pick from echo sounder data was inserted as positive peak (top solid line, black arrow), but is heavily compromised by swell. The reflection interpreted to be from the base of the gas hydrate stability zone (BGHSZ) is indicated by yellow arrows and matches the projected position of the modelled BGHSZ from Fig. 2 (shown as magenta-colored dashed lines with some vertical uncertainty due to the ill-defined seafloor). A zone interpreted as free gas underneath the BGHSZ is outlined by the blue dashed polygons. The vertical red line is the intersection of this line with arbitrary line A-A′ shown in Fig. 4. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

BGHSZ, which helps guide it's tracking between adjacent seismic lines. The history of the last warming following the last transgression as modelled by Taylor et al. (2013) resulted in an upward shift of ~100 m of the base of permafrost and associated

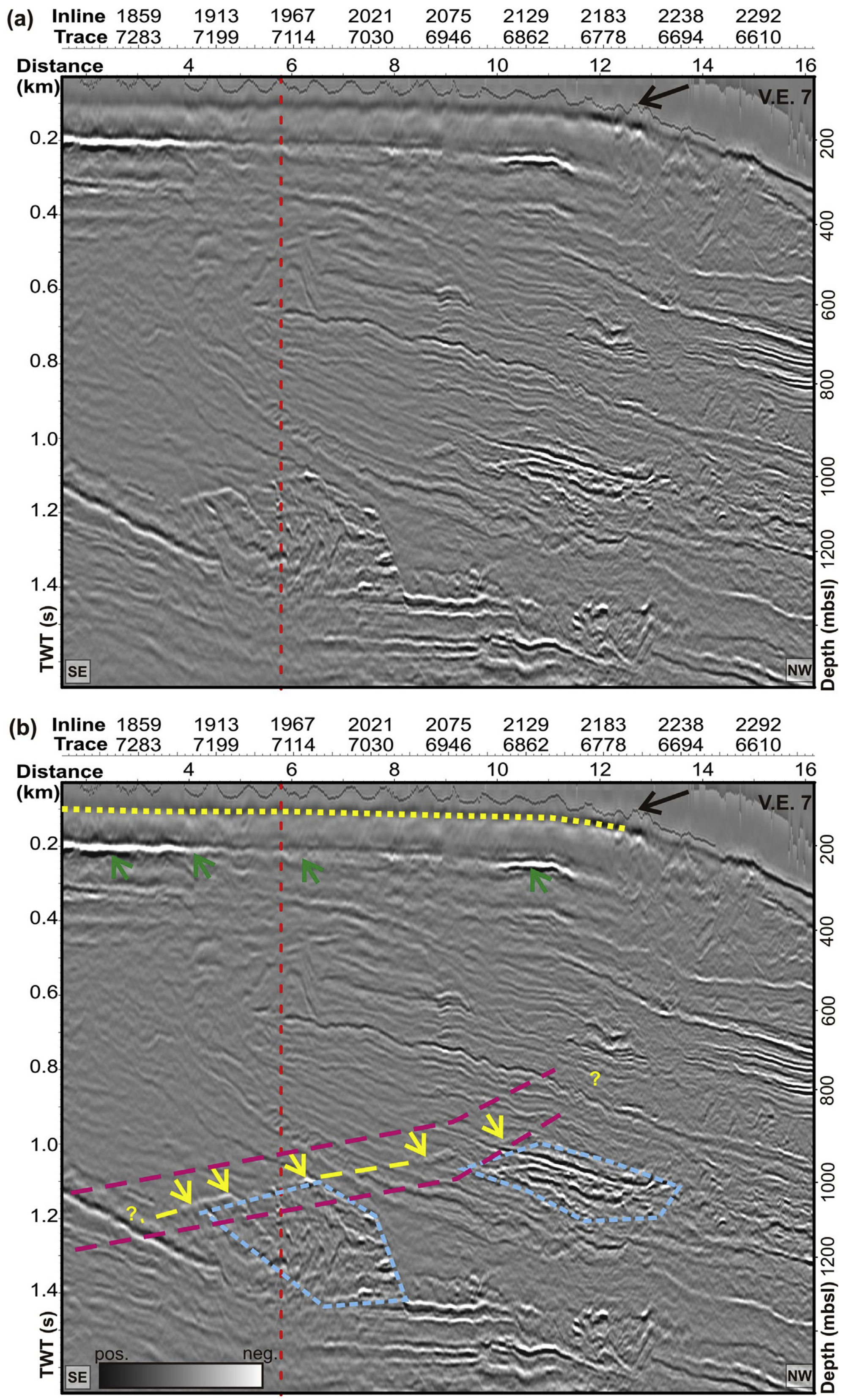

Fig. 4. Arbitrary line A-A′ extracted from Ajurak 3D volume perpendicular to shelf-break: (a) Original data, (b) interpreted section. Arrow, line, and zone designations as per previous figure. Two zones of increased reflectivity from possible free gas are outlined by blue dashed polygons. The vertical red line is the intersection with crossline 7128 shown in Fig. 3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

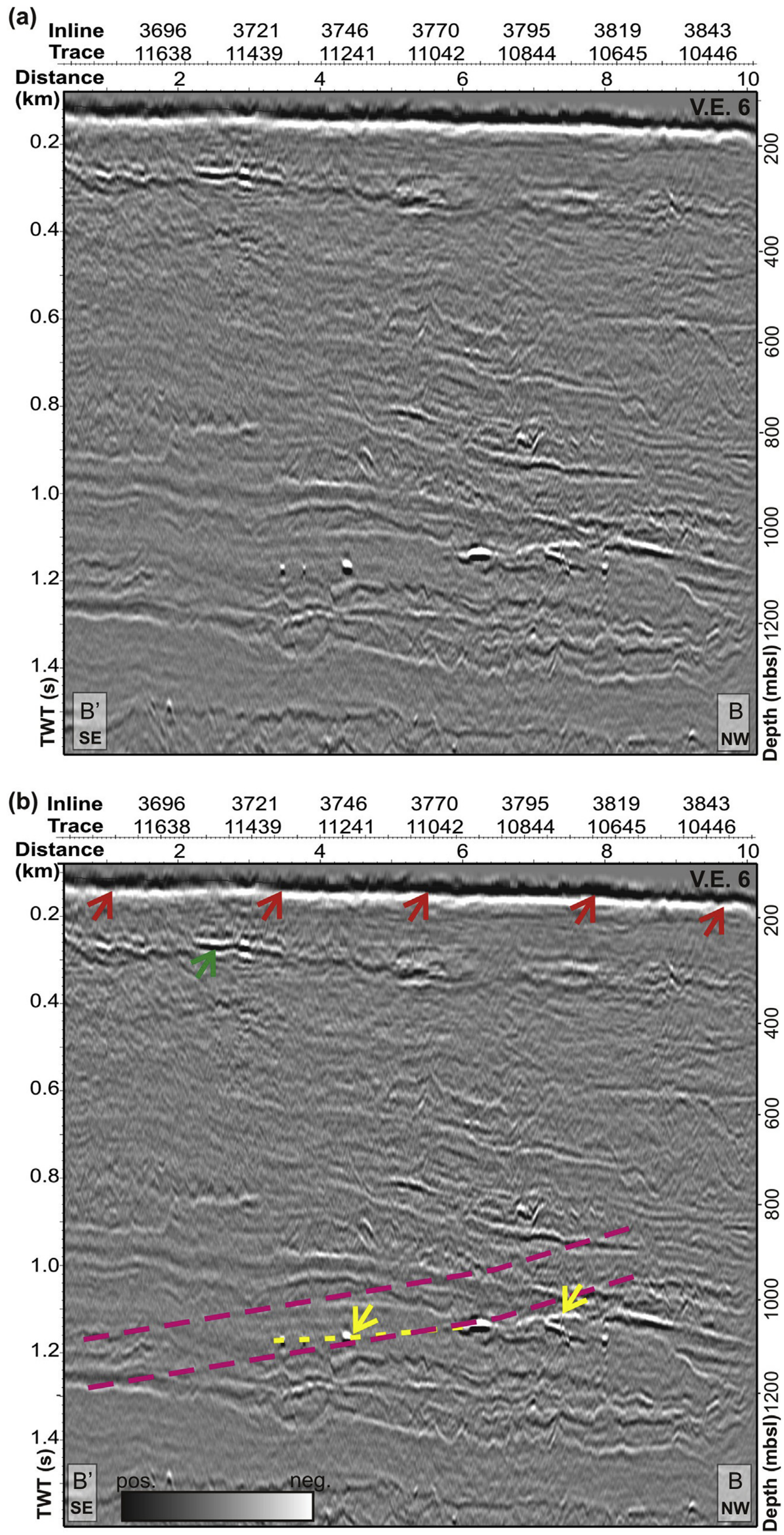

Fig. 5. Image showing arbitrary seismic line B-B′ (NW-SE oriented) extracted from the Pokak 3D volume: (a) Original data and (b) interpreted section. As per previous illustrations, the base of gas hydrate stability zone (BGHSZ) is shown in yellow and the modelled as magenta. The seafloor is indicated by red arrows, and the first multiple (incompletely suppressed) is indicated by green arrows. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

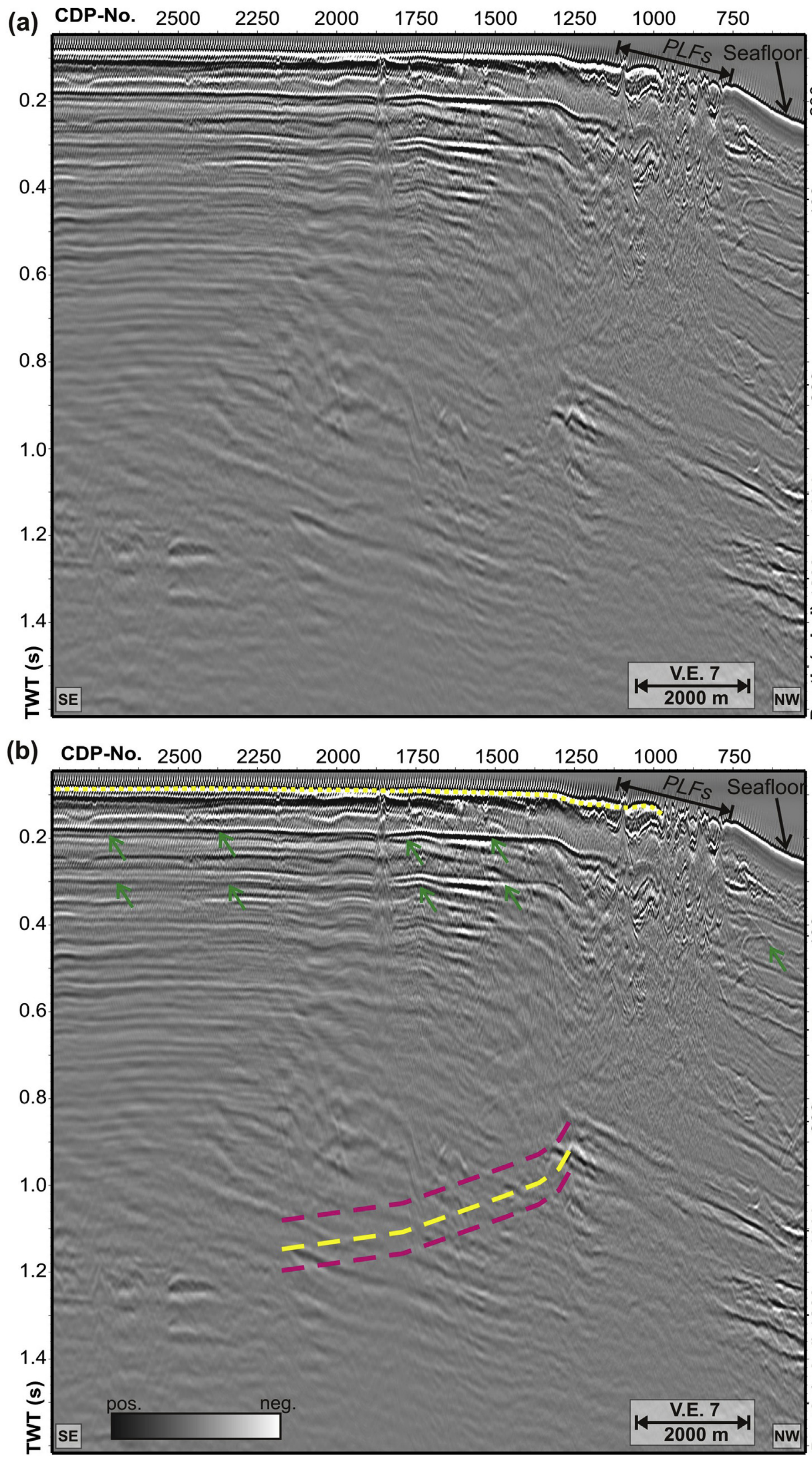

Fig. 6. Portion of 2D MCS line acquired in 2014 (Jin and Dallimore, 2016) across the shelf-slope transition where 3D data suggest the presence of a seismic reflection from the BGHSZ: (a) original data and (b) interpreted section. The phase boundary is seen only as a faint reflection. Image quality is degraded by the presence of seafloor multiples (green arrows), which could not be successfully suppressed. Also, imaging across the shelf edge, where numerous pingo-like features (PLFs) occur, is difficult due to scattering of seismic energy from the complex seafloor morphology. The projected BGHSZ from Fig. 2 model is, again, shown as in magenta, with similar vertical uncertainty as previously used in Fig. 3–5. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

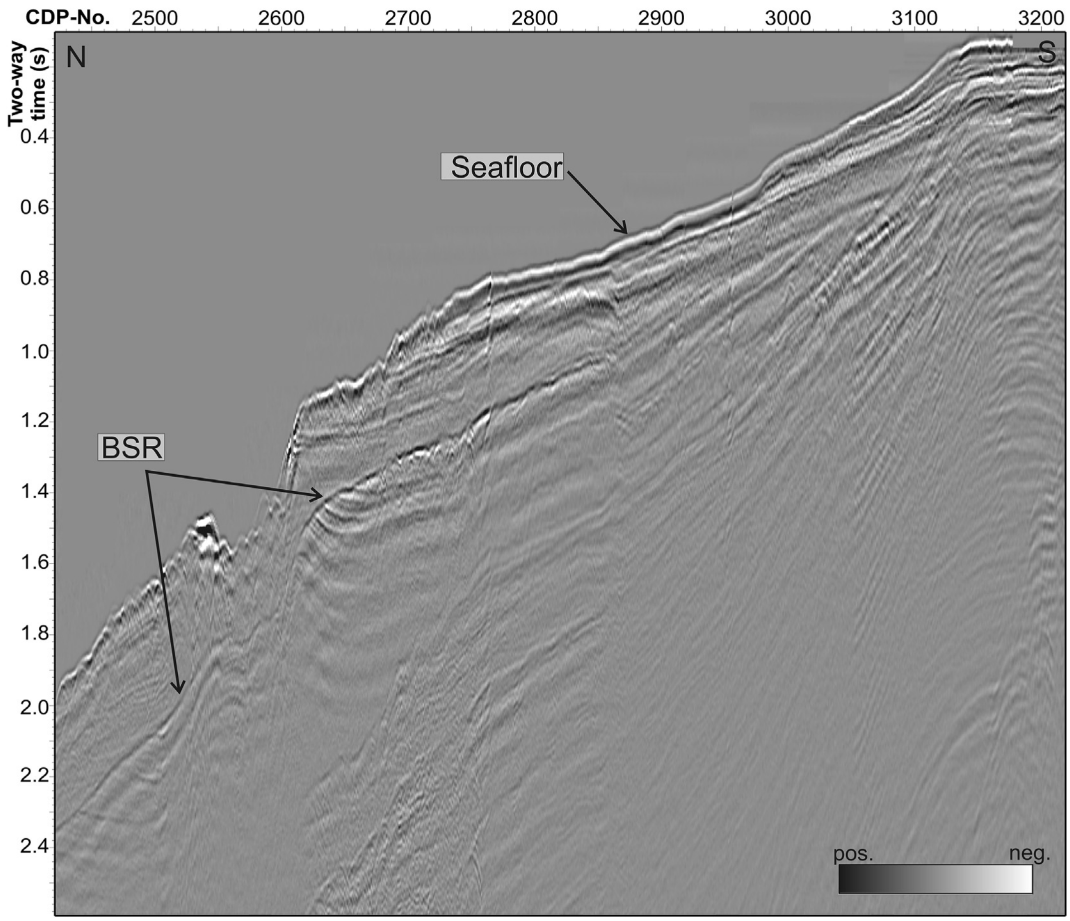

Fig. 7. Example of a seismic line from the Alaska margin (Line 18) showing clear BSR between CDPs 2400 and 2850. The BSR was previously identified by Andreassen et al. (1995) and Grantz et al. (1976) and also shown by Phrampus et al. (2014) [data credit: USGS; Triezenberg et al., 2016].

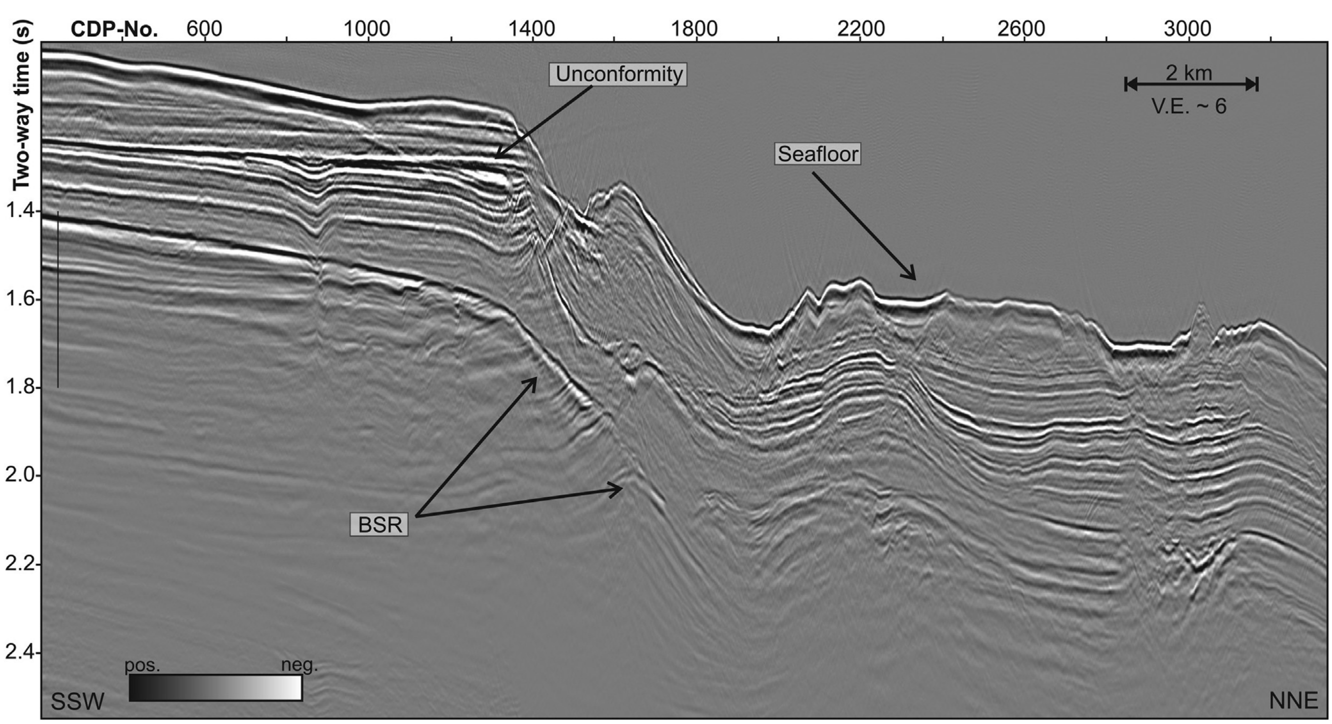

Fig. 8. Portion of 2D MCS line acquired in 2014 (Jin and Dallimore, 2016) across the outer Mackenzie Trough showing an opposite-to-seafloor reflection that is similar to the BSR seen off Alaska (Fig. 6a in Phrampus et al., 2014). Note the increase in reflection amplitude of sedimentary reflections beneath the BSR between CDPs 1500–1800.

BGHSZ. As the gas hydrate phase boundary migrates upwards, gas hydrate is dissociated allowing free gas accumulation underneath the phase boundary. The free gas cannot easily escape, as the overlying gas hydrate presents a largely impermeable barrier. Unless permeable pathways, such as faults, allow free gas migration upward and into the gas hydrate stability field (where it would refreeze to a hydrate), the free gas is trapped underneath the BGHSZ. We believe this process is responsible for creating the observed zones of enhanced reflectivity in seismic data beneath most of the Canadian shelf-edge region.

The combined observations from 3D and 2D MCS data reveal a wide-spread seismic reflection from the BGHSZ across the shelf zone (Fig. 1). This region does therefore reflect a significant accumulation of methane (and possibly higher hydrocarbons) and their eventual atmospheric release would be significant in terms of climate modeling scenarios. This occurrence represents the first such evidence in the Canadian Beaufort Sea and points towards the need of further seismic data acquisition for verification of the distribution for a more complete assessment of gas hydrate abundance in the region, especially in shallower waters, currently not part of the seismic data coverage shown in Fig. 1.

Furthermore, the new recognition of a deep-water marine gas hydrate stability zone in the outer Mackenzie Trough which likely extends westward to the BSRs off Alaska can have more regional implications in terms of slope-stability and climate-change sensitivities. The cap and free gas beneath the BGHSZ has the potential for formational overpressure development, both a concern for hydrocarbon or scientific drilling and one that might drive seabed expressions of structural and/or efflux features (c.f. Paull et al., 2015; Dallimore et al., 2015) and possibly slope stability (Kayen and Lee, 1991). Climate sensitivities were suggested for the Alaska portion of the Beaufort Sea by Phrampus et al. (2014), based on oceanographic time-series observations pointing to ongoing warming of the shallow to intermediate water depths. They reasoned that such a warming signal could lead to dissociation of gas hydrates and also potential for degassing and related slope instability. The lack of seismic indicators of BSRs further to the east in our study region is not necessarily an indicator for the absence of gas hydrate in that region. Quality of some vintage data in water depths greater than 1000 m is very poor, often with harsh seafloor mutes (unknown polarity of seafloor reflection) and further constrained by unknown amplitude gain functions. Crossings of the MCS data from the ARA04C and ARA05C expeditions as well as the Beaufort-SPAN data (Dinkelmann et al., 2008) lie in water depths exceeding 1500 m (the realm where most BSRs are found off Alaska), yet, no BSR was recognized. Morphologically, this region in the central Mackenzie Delta is very different from the rather canyon-dominated slope region off Alaska (Fig. 1). High sedimentation rates would result in fast accumulation of sediments in the slope/fan region. This may be prohibiting any accumulation of free gas at the BGHSZ, which rapidly changes in depth due to the high sedimentation rate. Any organic carbon deposited with the sediment may be passed through the gas hydrate stability zone too fast for microbial activity to produce any significant amount of gas to allow gas hydrate formation (e.g. Bhatnagar et al., 2007). The common occurrence of mass transport deposits in the outer slope region on the Canadian Beaufort margin (e.g. Mosher et al., 2012) may further prohibit gas hydrate formation as these deposits form a blanket of low permeability sediments that limit vertical methane advection and fluid migration.

7. Conclusions

A prominent seismic reflection is recognized from the base of the gas hydrate stability zone (BGHSZ) in seismic data across the Canadian Beaufort Sea shelf in good agreement with predictions based on geothermal modeling (Fig. 1). While deviating in some characteristics from "classic" deep-water marine BSRs, the seismic reflections from the BGHSZ underneath most of the outer shelf and shelf edge region confirms the existence of a wide-spread regional gas hydrate occurrence associated with submarine permafrost. The dip of the reflection-boundary and its overall geometry, including a shallowing towards the shelf edge, as the thermal model predicts, is the result of thawing of the overlying permafrost since beginning of the last marine transgression ~20 ka ago. The reflection from the BGHSZ is further characterized by a cross-cutting of the regional stratigraphy, and high-amplitude up-dip truncations of individual sediment layers.

The presence of free gas underneath the BGHSZ is suggested by the occurrence of wide-spread gas-brightening and phase reversal. The overall strata- and fault-control of the gas-brightening suggests that the entire sedimentary section is gas-rich, but that the free gas may have been liberated from the post-glacial transgression and migrated up-dip as the phase boundary progressively shallowed. Furthermore, high-amplitude up-dip truncations suggest impermeability (cap) at the BGHSZ, preventing further migration of any free gas. This has implications for potential over-pressure development at this depth.

The observation of the reflection of a regional permafrost-related BGHSZ has implications for a variety of scientific and engineering factors. The thermal history of the shelf since the last glacial period is compatible with modeling (e.g. Taylor et al., 2013) and provides several corroborative observations. The generation of a free gas zone just below the BGHSZ at a relatively shallow depth of ~1000 m (and less) below seafloor presents a scenario where over-pressures may develop and thus represent a potential geohazard. This has safety implications for any new hydrocarbon or scientific drilling as well as development of surficial soil foundation across this region.

The presence of a deep-water marine gas hydrate associated BSR in the seismic data available is suggested along the available survey lines in the outer Mackenzie Trough region. The BSR shows a similar character to known occurrences along the Alaska margin (Andreassen et al., 1995). However, a BSR is apparently absent over most of the deeper, easterly Beaufort slope region in Canadian waters. This might be a function of degraded seismic data quality with overall sparse coverage. Additionally, the dominance of seabed parallel sedimentation processes such as mass transport phenomena, erosional canyons, and rapid sedimentation rates under glacial input, could partially masked a deep-water marine BSR. All these factors tend to minimize the conditions favorable for BSR formation and possible presence of gas hydrates and free gas accumulation beneath it.

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