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G. Bellefleur

Authors
M. Riedel (mriedel@geomar.de)
A.E. Taylor (alan.taylor@telus.net)
S.R. Dallimore (Scott.Dallimore@canada.ca)
Geological Survey of Canada
9860 West Saanich Road
Vancouver, British Columbia
V8L 4B2

M. Riedel (mriedel@geomar.de)
Present address:
GEOMAR Helmholtz
Centre for Ocean Research
Kiel, Wischhofstrasse 1-3, 24148 Kiel, Germany

G. Taylor (ggtaylo@gmail.com)
Imperial Oil Resources
505 Quarry Park Boulevard SE, W1C.113
Calgary, Alberta
T2P 3M9

Present address:
6712 Legare Drive SW
Calgary, Alberta
T3E 6H2

Correction date:

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Evidence for a deep gas-hydrate stability zone associated with submerged permafrost on the Canadian Arctic Beaufort Shelf, Northwest Territories

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Abstract: The presence of offshore permafrost in the Canadian Beaufort Sea region has previously been identified from seismic and borehole data. The consequence of such permafrost is the possibility of an underlying gas-hydrate stability zone. In this study the authors present the first evidence for the widespread occurrence of gas hydrate in the offshore portion of the Beaufort Shelf using 3-D seismic data. A reflector of opposite polarity relative to the seafloor was identified at a depth of about 1000 m below seafloor that mimics some of the behaviour of the traditionally seen bottom-simulating reflectors in marine gas-hydrate regimes; however, the reflection identified is not truly bottom simulating, as its depth is rather controlled by the rapidly thinning wedge of submerged permafrost. The depth of the reflector decreases with increasing water depth, as predicted from thermal modelling. The reflection crosscuts strata and marks a zone of enhanced reflectivity underneath, possibly originating from free gas that accumulated at this phase boundary over time as the permafrost and associated gas-hydrate stability zones were thinning in response to the transgression. The presence of a clear and widespread gas-hydrate stability field beneath the permafrost has widespread implications on the region, including deep-drilling hazards associated with the presence of free gas, possible overpressure, and lateral migration of fluids and associated expulsion at the seafloor.

Résumé : La présence de pergélisol en milieu extracôtier dans la région canadienne de la mer de Beaufort a été relevée dans le passé grâce aux données de levés sismiques et de sondages. L'existence de ce pergélisol soulève la possibilité qu'une zone de stabilité des hydrates de gaz soit présente sous celui-ci. Dans la présente étude, nous offrons les premières preuves de la présence largement répandue d'hydrates de gaz dans la section extracôtière de la plate-forme continentale de Beaufort grâce à des données sismiques 3D. Un réflecteur de polarité inverse par rapport à celui du fond marin a été identifié à une profondeur d'environ 1 000 m sous le fond marin. Ce réflecteur imite certaines des caractéristiques des réflecteurs épousant la forme du fond marin traditionnellement observés dans les contextes d'accumulations d'hydrates de gaz en milieu marin. Toutefois, le réflecteur identifié n'est pas un réel réflecteur de ce type, puisque sa profondeur est régie par la présence du prisme de pergélisol submergé qui s'amincit rapidement. La profondeur du réflecteur diminue avec l'augmentation de l'épaisseur de la colonne d'eau, comme le prévoit la modélisation thermique. La réflexion est discordante par rapport aux contacts des strates et marque la limite supérieure d'une zone de réflectivité accrue, résultant probablement de l'accumulation au fil du temps de gaz libre le long de cette limite de phase, pendant que le pergélisol et les zones de stabilité des hydrates de gaz qui y sont associées s'amincissaient en réponse à la transgression marine. La présence d'un champ de stabilité des hydrates de gaz bien défini et étendu sous le pergélisol a des répercussions de grande portée dans la région, dont celles relevant des dangers associés au forage profond en raison de la présence de gaz libre, de la possibilité de surpression ainsi que de la migration latérale des fluides et de leur expulsion consécutive sur le fond marin.

INTRODUCTION

Gas-hydrate deposits 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-hydrate deposits 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 hydrate 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 hydrate 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 (~20 times more potent than carbon dioxide, CO_2, e.g. Shindell et al. (2009)), understanding 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. Modelling 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 at the present time significant amounts of methane are being released globally from the seabed and that about 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. Shakhova and Semiletov (2007) suggested that at the Siberian shelf, elevated methane concentrations in seawater are due to degradation of shelf permafrost and gas hydrate. In the Beaufort Sea, Hughes-Clarke et al. (2009) identified extensive free gas release at the seabed of the Beaufort Shelf. Paull et al. (2007) also documented shelf-edge methane releases near a variety of distinct geomorphic features at that shelf-edge transition including pingo-like features 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 about 250 m.

The presence of gas hydrate onshore of the Mackenzie Delta region 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 hydrate in other industry well sites onshore and offshore in the Mackenzie Delta–Beaufort Sea 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 of sea-level and transgression over the past 150 ka was conducted by Taylor et al. (2013) using present-day borehole temperature data from industry wells as calibration. The widespread and long-lasting occurrence of permafrost creates favourable conditions for gas-hydrate stability.

In this study the authors show the first seismic evidence for the presence of a gas-hydrate system occurring beneath submerged 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-hydrate deposits and resulted in a southward 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 3-D seismic volumes provided by Imperial Oil Ltd. and BP Canada. This new observation confirms the previous thermal model and hypothesis of the existence of a widespread region of gas hydrate across the shelf of the Mackenzie Delta–Beaufort Sea region up to the critical shelf-edge zone. The presence of such a gas-hydrate zone has critical implications for the region from a general geohazards point of view, but also from a climate-change point of view as outlined in this study.

GEOLOGICAL SETTING, WELL-LOG DATA, PERMAFROST DISTRIBUTION, AND GEOTHERMAL MODEL

The 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 1980s and 1990s (*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 Shelf is generally characterized by greater than 10 km of upper Cretaceous

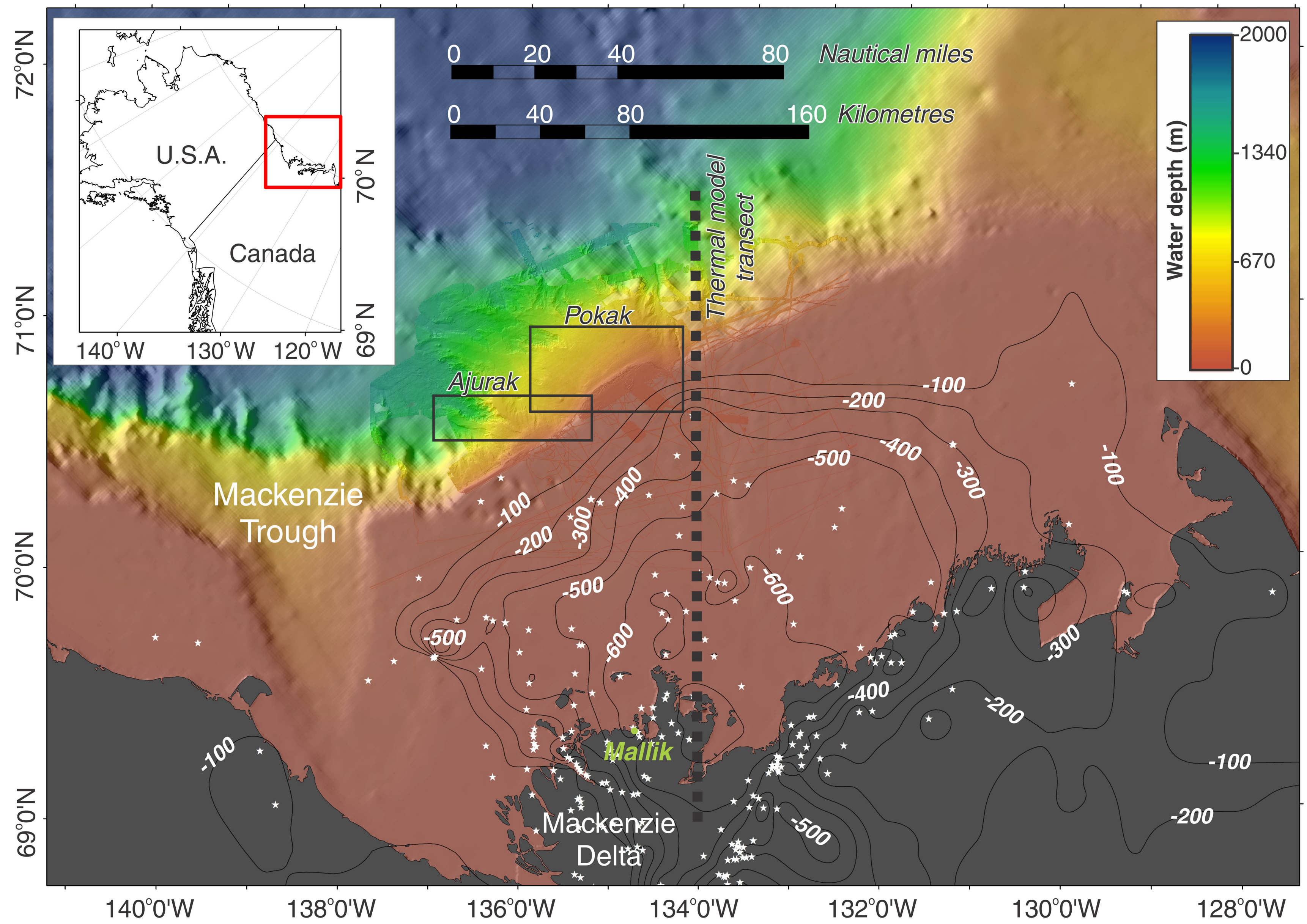

Figure 1. Study region, showing extent and thickness of permafrost (onshore and offshore), industry well locations, thermal modelling transect (*after* Taylor et al., 2013), and extent of 3-D seismic surveys used in this study.

to Cenozoic sediments, primarily comprising folded and faulted deltaic sediment complexes. The geological and geotechnical properties of shallow shelf sediments are heavily influenced by the glacial and interglacial 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; Blasco et al., 1990, 1998, 2010; Hill et al., 1991, 1993). Permafrost, or sediment that is 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 at less than about 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 northernmost extent (deep-water edge) of seismically detectable permafrost. The current offshore permafrost distribution is a result of the temporal aspect of its response to the ongoing marine transgression that started ca. 25 ka ago (Fig. 2). 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 more than 7000 a, the submerged offshore permafrost is still responding to this change because of slow rates of heat diffusion and latent heat associated with thawing (Taylor et al., 2005, 2013; Paull et al., 2007, 2011). 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).

ESTIMATING THE GAS-HYDRATE STABILITY ZONE BENEATH SUBMERGED PERMAFROST

Whereas 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-hydrate deposits (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 not only controlled 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 does not necessarily define the vertical extent of the gas-hydrate stability zone. To define the vertical extent

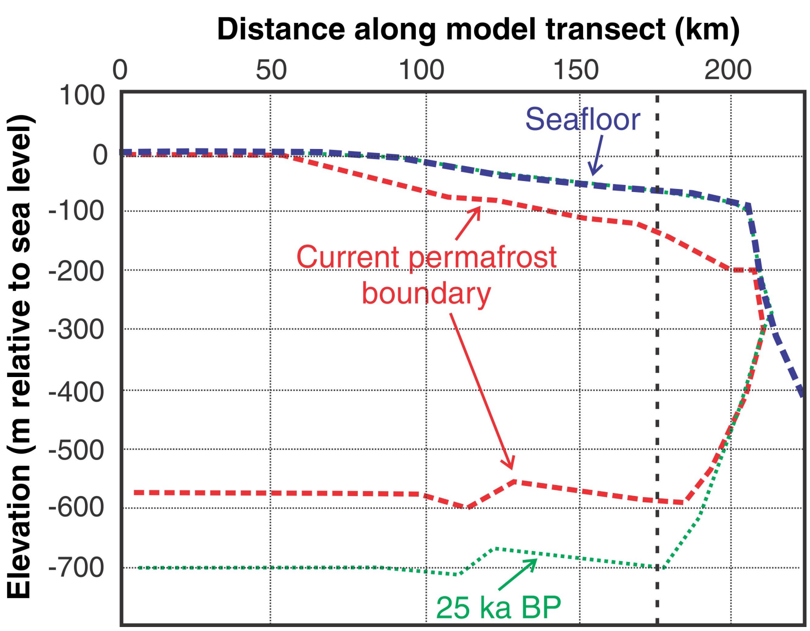

Figure 2. Simplified distribution of permafrost distribution along the thermal modelling transect shown in Figure 1 (*modified from* Taylor et al., 2013). Shown in blue is seafloor depth and red dashed line shows current extent of the permafrost boundary. Also shown is the maximum extent of offshore permafrost about 25 ka ago during the last glacial maximum (green dotted line). Vertical dashed line is the projected southernmost limit of available 3-D seismic data used in this study.

along the transect chosen by Taylor et al. (2013) requires some form of phase-boundary modelling. Using the depth of permafrost (0°C isotherm) as the starting point and defining the temperature field below permafrost by using known geothermal gradients from well-log data (e.g. Hu et al., 2010) the base of the gas-hydrate stability field can be calculated under the assumption of a simple hydrostatic regime, average pore-fluid salinity (20 ppt as defined at the Mallik site; e.g. Dallimore and Collett, (2005)), and a pure methane-gas system (representative of gas-hydrate structure-I). Figure 3 shows the extent of the gas-hydrate regime associated with the modelled permafrost distribution (shown in Fig. 2) as well as the corresponding extent of a classic marine gas-hydrate regime (Paull et al., 2012). The top of the gas-hydrate stability field associated with the offshore permafrost is within the ice-bonded permafrost regime itself. The top approximately at about 240 m below sea level is not changing across the profile as it is purely pressure controlled and temperature is below 0°C. The internal structure of the 0°C isotherm (base of permafrost) defines the undulating character of the base of gas-hydrate stability as a uniform geothermal gradient is used across the entire profile in this simple model. Between 80 km and 100 km distance from shore (shoreline is defined as the 0 km distance in Fig. 3) the permafrost rapidly thins and pinches out in a water depth of about 100 m. The associated boundary of the gas-hydrate stability zone also becomes rapidly shallower and becomes an almost vertical boundary. The 3-D seismic data extend from water depth of about 70 m to about 850 m (equivalently 90–140 km distance from shore) as indicated in Figure 3.

GAS-HYDRATE STABILITY ZONE BENEATH SUBMERGED PERMAFROST

Two adjacent 3-D seismic volumes are available to study the extent of the permafrost-associated and classic-marine gas-hydrate stability field. The two 3-D 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 3-D volume, the seismic reflector interpreted to be from the base of gas-hydrate stability zone occurs within the southeastern corner and spreads over an area of about 70 km^2 (Fig. 4). Two seismic sections were extracted from the Ajurak block to show the reflector of the base of the gas-hydrate stability zone. Crossline 7128 (north-south oriented, Fig. 5) shows the reflection from the base of the gas-hydrate stability zone at a depth of about 1.25 s at the southern end of the crossline (inline 1405 to 1620), and this reflection becomes gradually shallower toward the

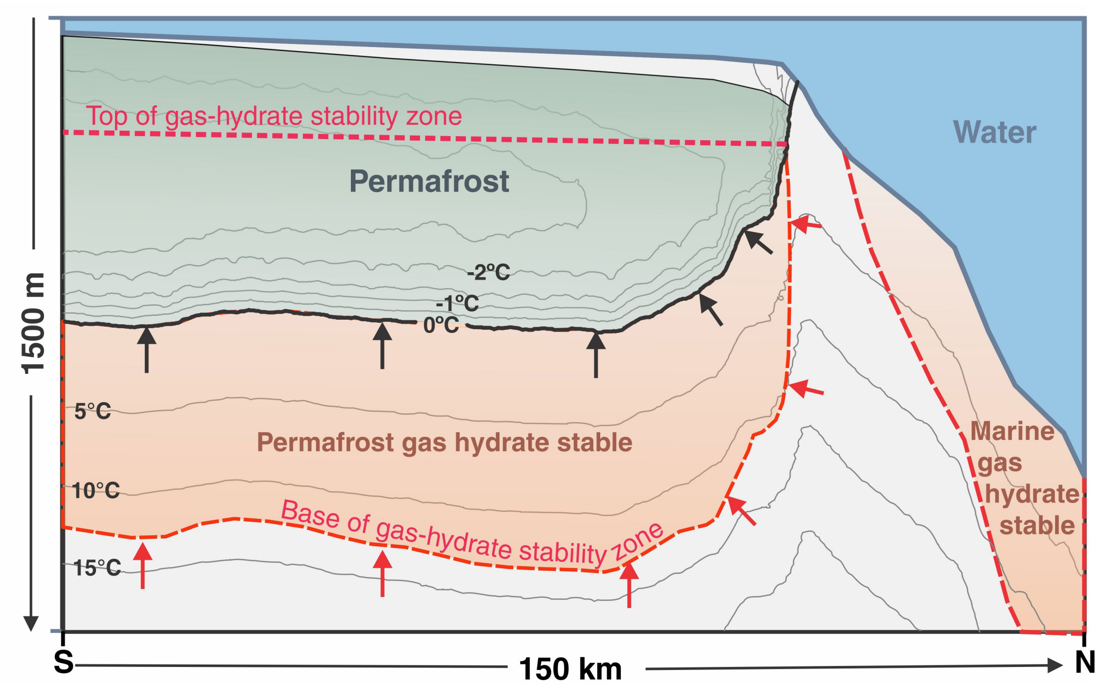

Figure 3. Model depiction of the extent of a permafrost-associated gas-hydrate zone on the shelf, and a classic deep-water marine gas-hydrate zone. The base of the gas-hydrate zone is defined based on the model of current permafrost distribution (*see* Fig. 2), a uniform geothermal gradient, hydrostatic pressure, pore-water salinity of 20 ppt, and a pure methane-gas composition. The distance used in the model are identical to that used by Taylor et al. (2013) and Figure 2, but only show the marine component of the model and not the terrestrial portion of the transect.

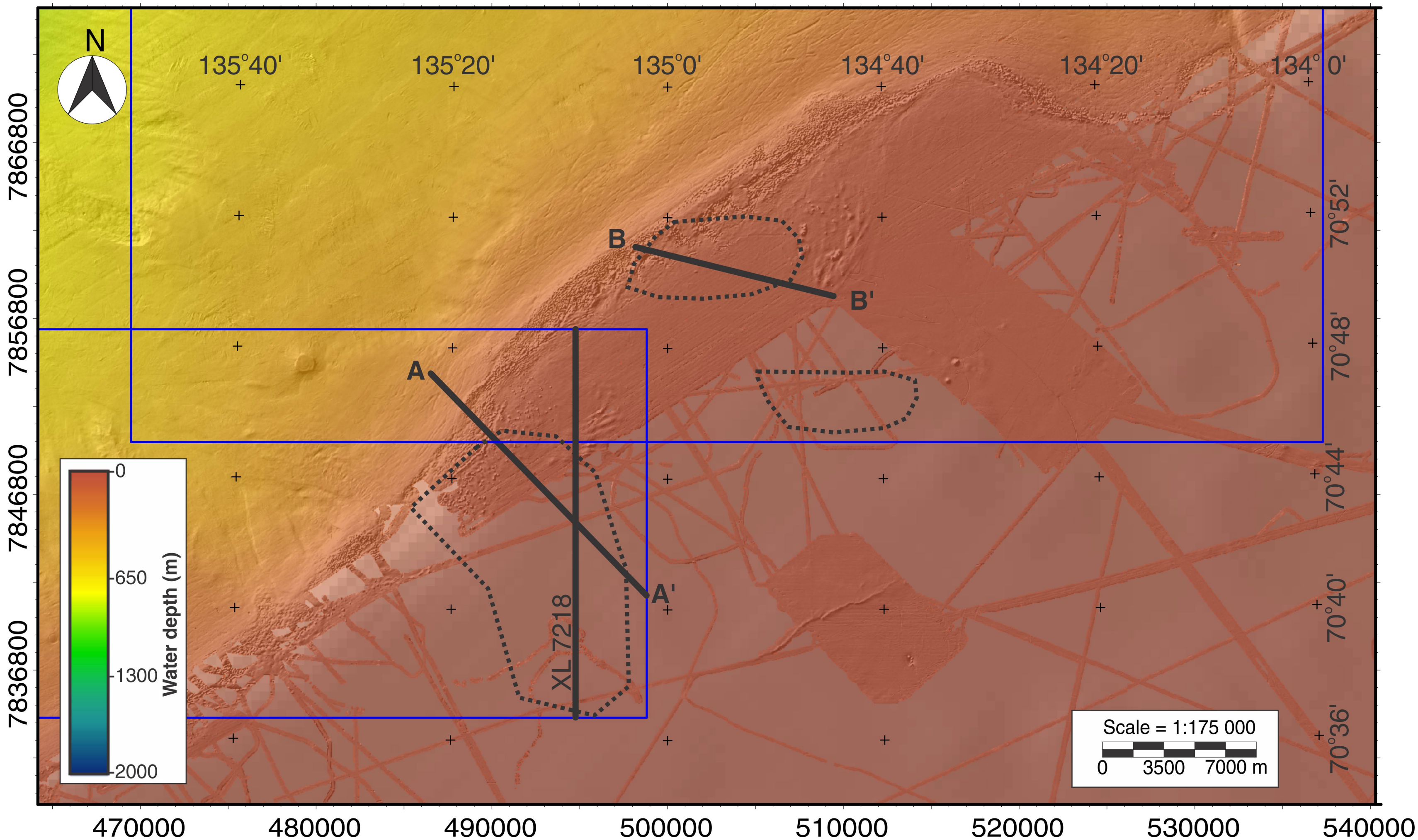

Figure 4. Map showing distribution of mapped base of gas-hydrate stability zone (polygons with dashed lines) within the 3-D volume as well as three seismic lines extracted from the 3-D volume showing the bottom-simulating–like reflection.

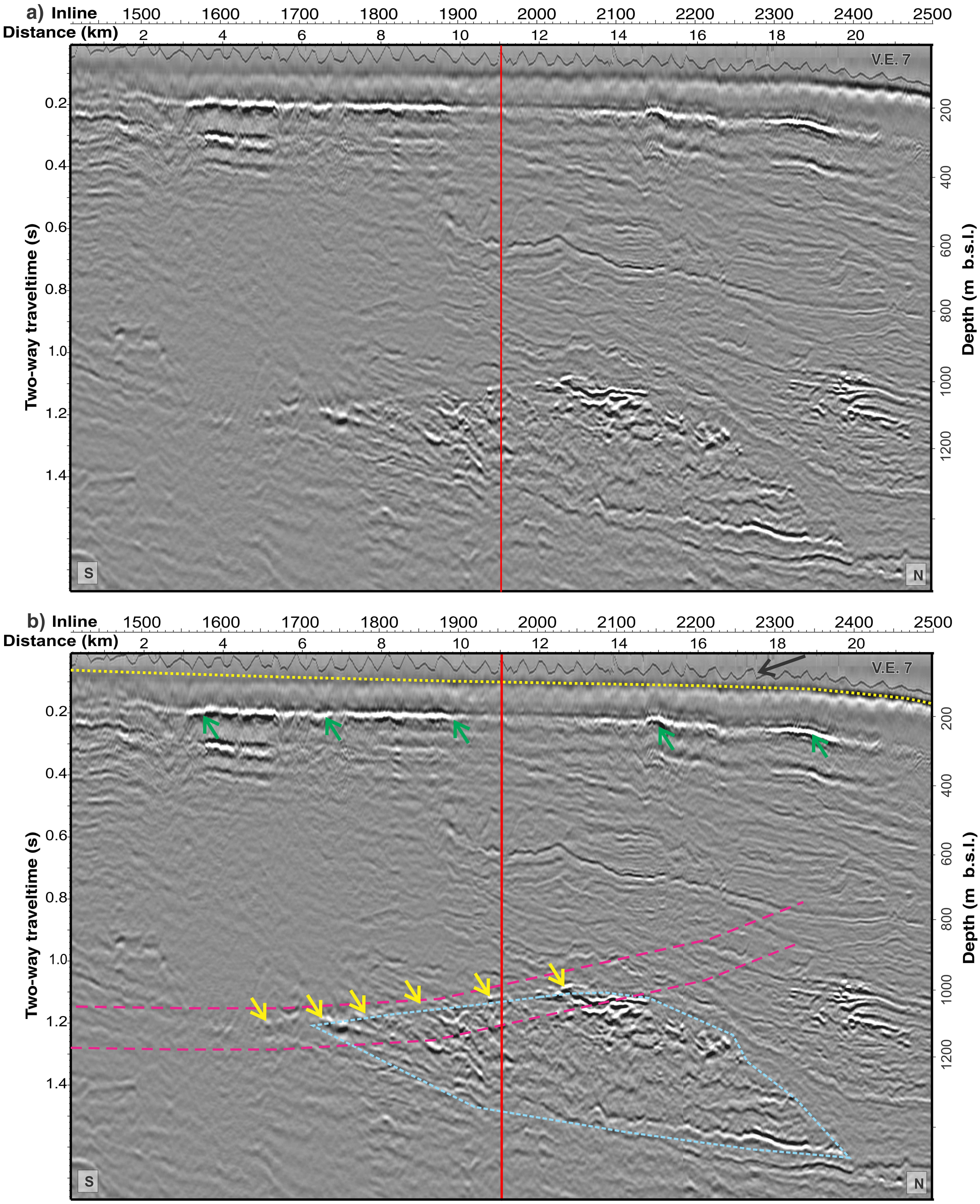

Figure 5. Seismic crossline 7128 from Ajurak 3-D volume with **a)** time-migrated data, and **b)** interpreted section showing the base of the gas-hydrate stability zone in yellow arrows, zone of free gas underneath (blue dashed outline), seafloor reflection as dotted yellow line, and the first seafloor-multiple in green arrows. A seafloor pick from echo-sounder data was inserted as positive peak (top solid line, black arrow), but is heavily compromised by swell. The projected base of gas-hydrate stability zone from Figure 3 is shown as thin magenta dashed line with some vertical uncertainty due to the ill-defined seafloor. The vertical red line is the intersection of this line with arbitrary line A-A′ shown in Figure 6. V.E. = vertical exaggeration

north into deeper water. The reflector is characterized by a polarity opposite to that of the seafloor and is seen to crosscut 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 base of the gas-hydrate stability zone.

The base of the gas-hydrate stability zone is controlled mostly by the depth change in the overlying permafrost and as that boundary deepens toward the shelf edge, the authors selected an arbitrary seismic line (A-A′) from the Ajurak volume crossing the shelf edge almost perpendicular (Fig. 6). Seismic line A-A′ shows a reflection from the base of the gas-hydrate stability zone that becomes rapidly shallower toward the northwest and toward deeper water, as predicted by the thermal model. Along this line, two segments of enhanced seismic reflectivity beneath the base of the gas-hydrate stability zone are identified that could possibly be the result of some free gas within the sediments.

Within the Pokak volume, reflections from the base of the gas-hydrate stability zone are much less pronounced and occur only over two smaller patches as outlined in Figure 4. The authors extracted one line near the edge of the shelf break (line B-B′) to illustrate the features of the base of the gas-hydrate stability zone reflection in this area (Fig. 7). Along this line the sediments show overall much less dip relative to the seafloor and as such the base of the gas-hydrate stability zone crosscuts only at a small angle relative to the dominant dip of sediment layers; however, the base

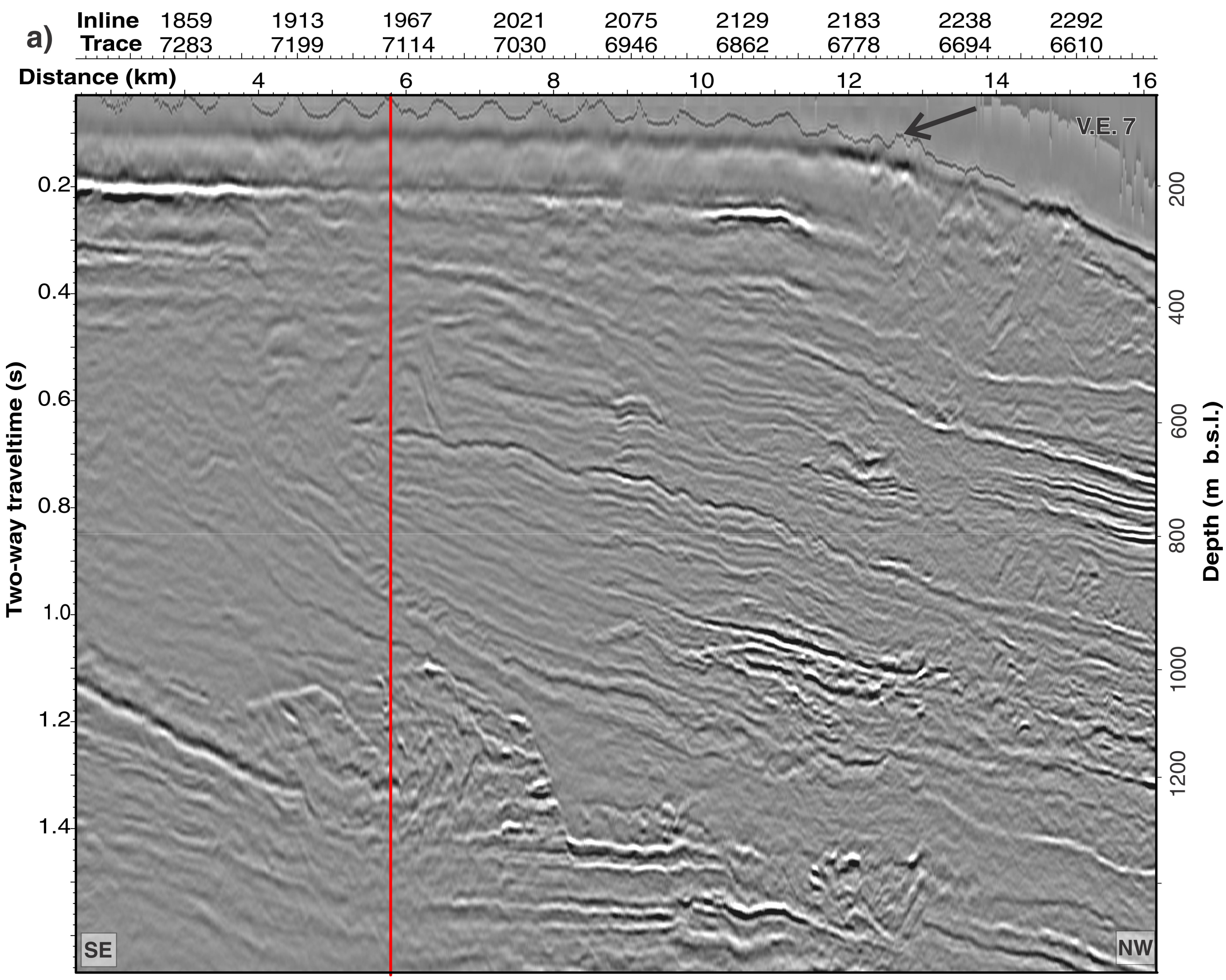

Figure 6. Arbitrary line A-A′ extracted from Ajurak 3-D volume perpendicular to shelf break; **a)** original data, **b)** interpreted section. The base of the gas-hydrate stability zone is shown in yellow arrows. The seafloor is indicated by yellow dotted line, and the first multiple is indicated by green arrows. Two zones of increased reflectivity from possible free gas are outlined by blue dashed lines. A seafloor pick from echo sounder data was inserted (top solid line, black arrow). The vertical red line is intersection with crossline 7128 shown in Figure 5. The projected base of gas-hydrate stability zone from Figure 3 is shown as thin magenta dashed line with some vertical uncertainty due to the ill-defined seafloor. V.E. = vertical exaggeration

of the gas-hydrate stability zone becomes shallower toward the shelf break (toward the northwest) and can be identified also by the up-dip truncation of high-amplitude reflections (e.g. at trace 10798 in Fig. 7) and by the sporadic occurrence of high-amplitude anomalies farther to the southeast along the same line. The example shown in line B-B′ is from the edge of a small channel-levée complex (Fig. 8) and the high-amplitude anomalies are small ponds (or small lakes) occurring on the eastern side of the levée complex and are possibly part of a flooding plain. Within the small ponds, finer sediments may have accumulated and free gas can be trapped at the base of the ponds with the current base of the gas-hydrate stability zone being a cap prohibiting further migration of the gas.

DISCUSSION

The occurrence of a deep, 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 modelling (Taylor et al., 2013); however, near the shelf-edge zone and in waters exceeding about 75 m, no deep industry drilling has occurred to date and therefore no direct evidence for gas hydrate exists. Vintage seismic data acquired in the far offshore region of the offshore Beaufort Shelf and Beaufort Slope region did not reveal any indication of the existence of a bottom-simulating reflector, which in part may be hampered by the fact that the expected depth of such a reflector is in part masked by prominent unconformities in the region and an overall near-seafloor-parallel nature of the upper 1000–1500 m of sediment below seafloor.

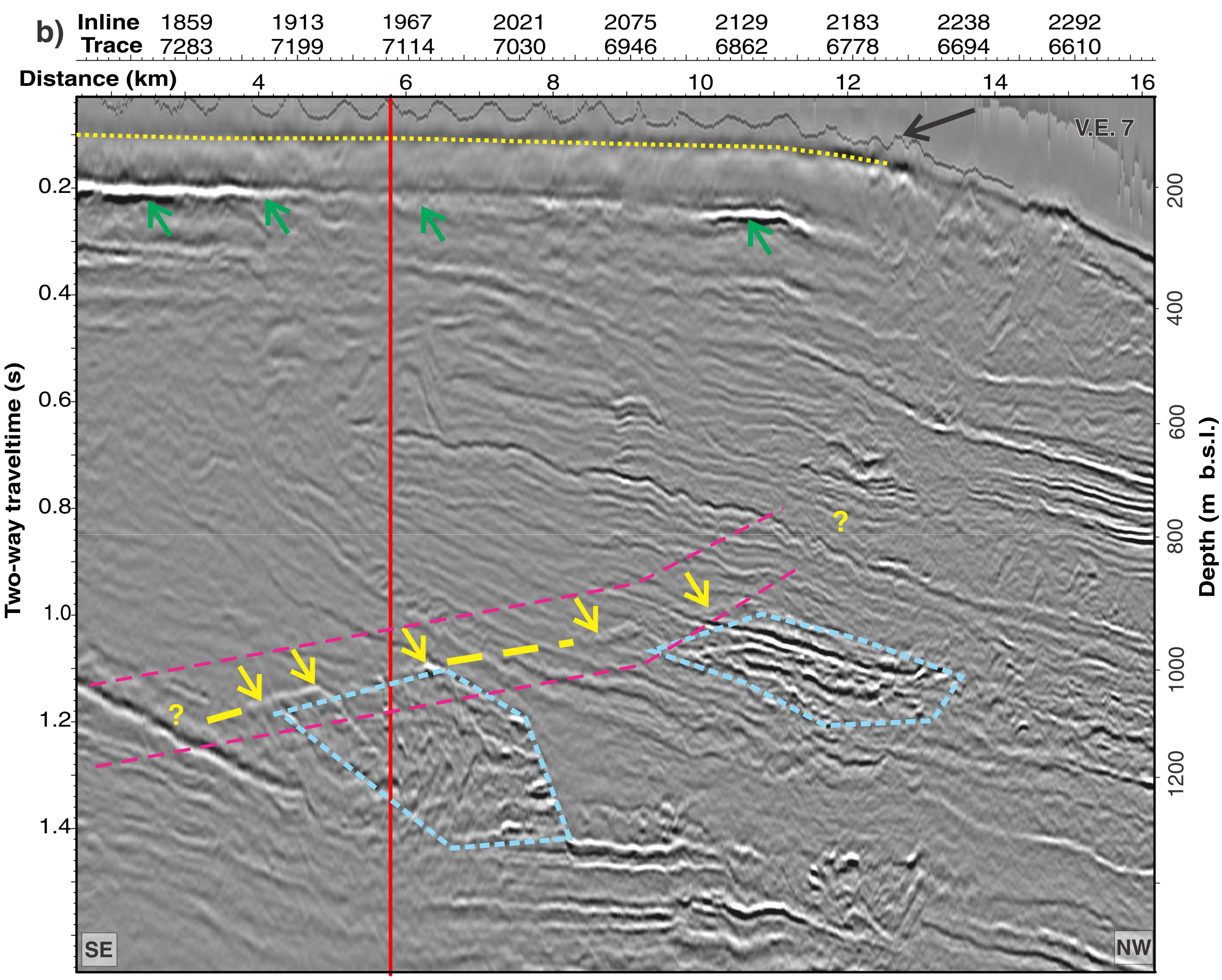

Figure 6. (Cont.)

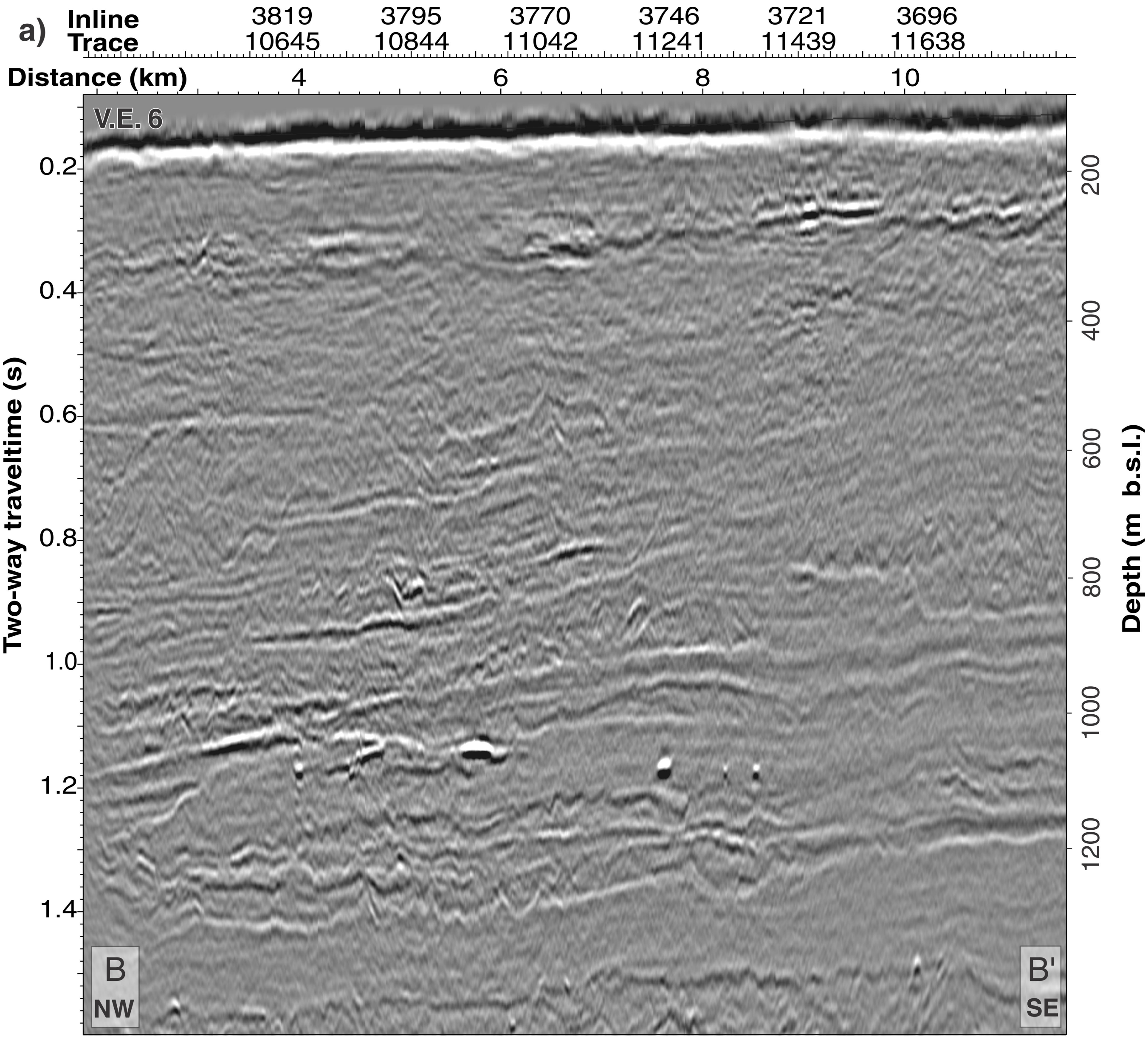

Figure 7. Arbitrary seismic line B-B′ (northwest-southeast oriented) extracted from the Pokak 3-D volume; **a)** original data and **b)** interpreted section. The base of gas-hydrate stability zone is shown in yellow. The seafloor is indicated by red arrows, and the first multiple (incompletely suppressed) is indicated by a green arrow. The projected base of gas-hydrate stability zone from Figure 3 is shown as thin magenta dashed line with some vertical uncertainty due to the ill-defined seafloor. V.E. = vertical exaggeration

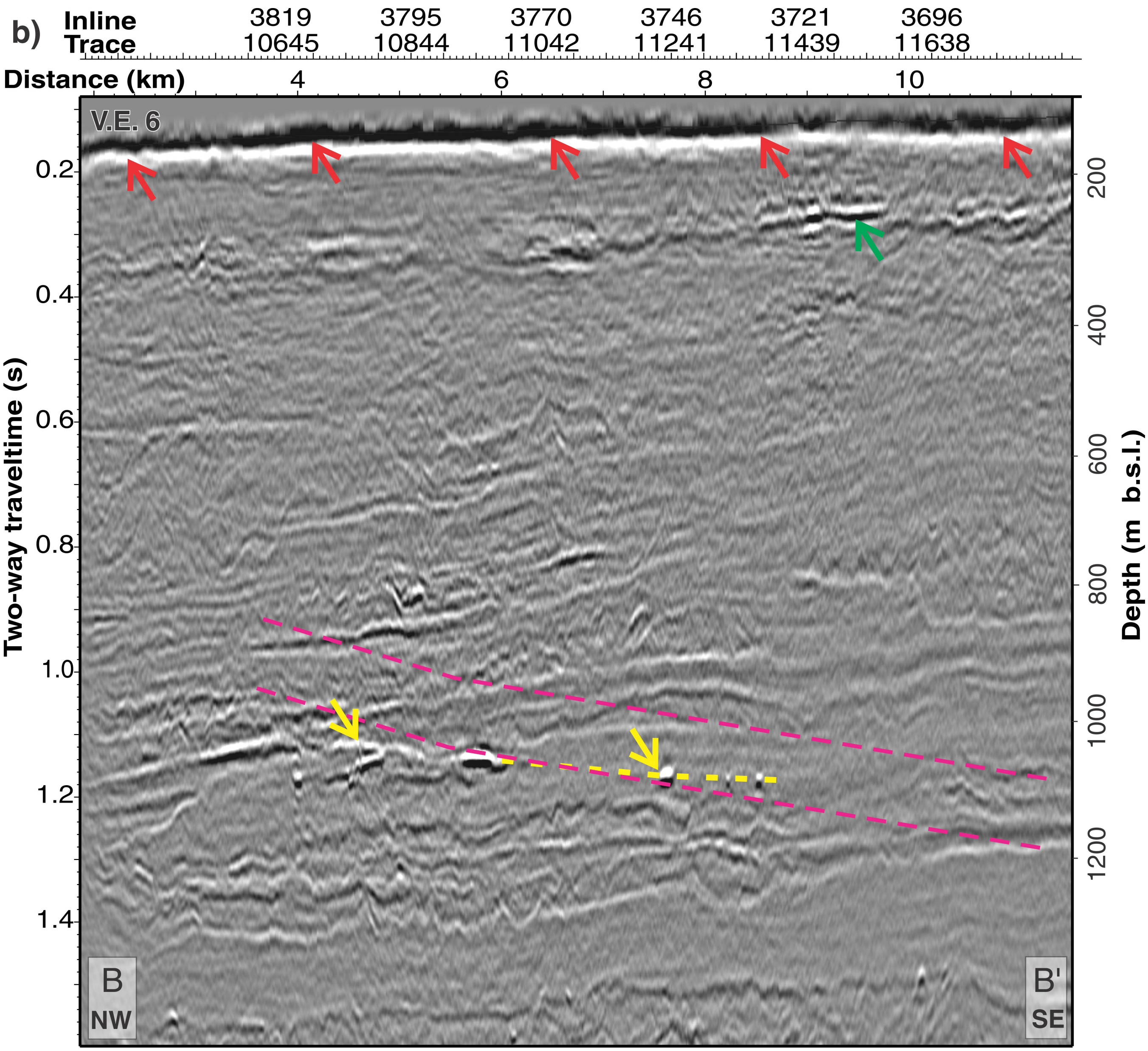

Figure 7. (Cont.)

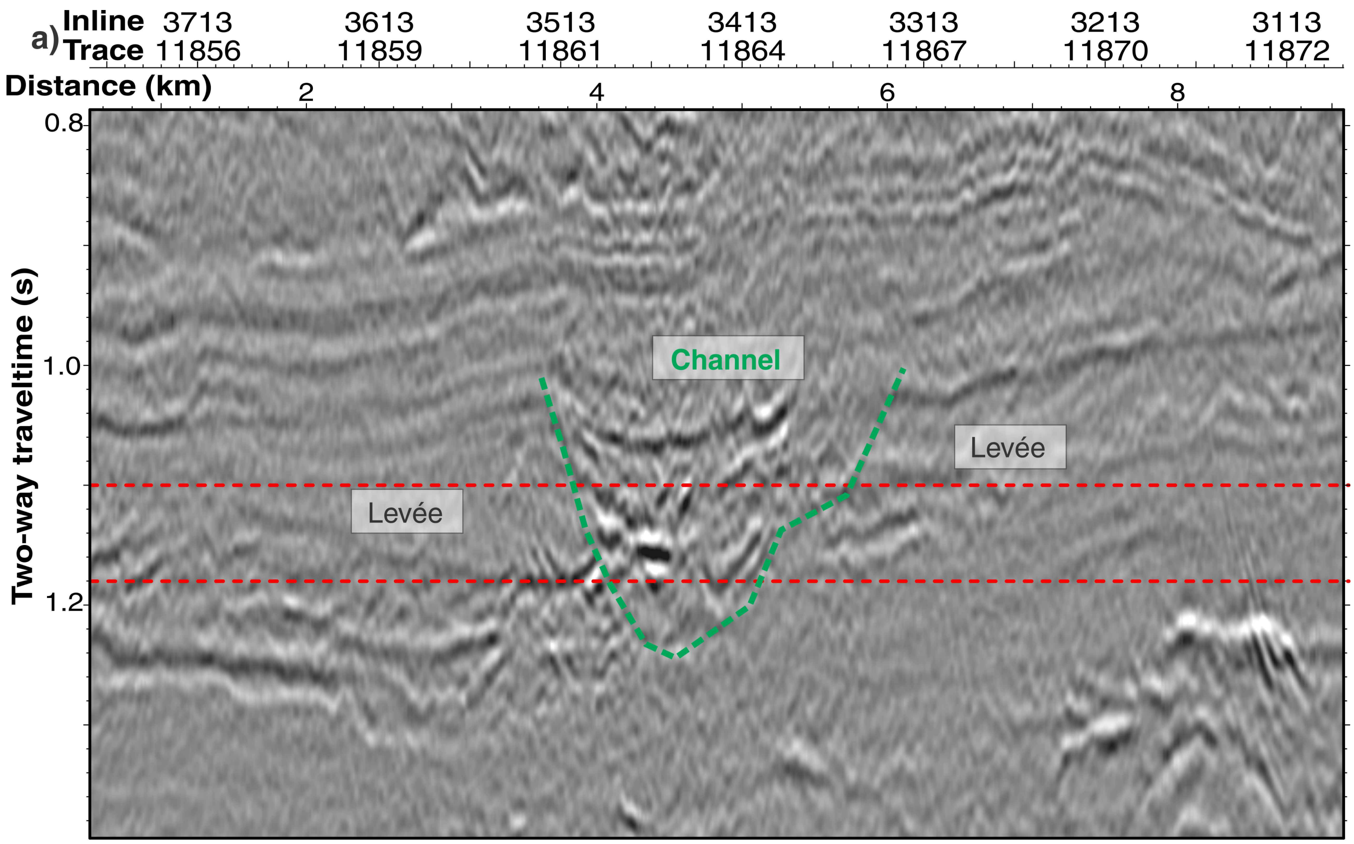

Figure 8. a) Seismic section C-C′ extracted from the Pokak 3-D volume perpendicular to the channel complex. **b)** Amplitude time slice taken at 1.1 s two-way traveltime to show the channel-levée system. **c)** Amplitude slice taken 1.18 s two-way traveltime highlighting the occurrence of small high-amplitude anomalies (highlighted by small black arrows) that likely are small ponds (traps for gas) within the levée or flood plain.

Thus the seismic signature of the base of the gas-hydrate stability zone is potentially indistinguishable from regular seismic reflectivity; however, shelf-edge perpendicular lines are sparse and of overall low quality (often available only as paper records).

Around the Mallik gas-hydrate research site on Richards Island (*see* Fig. 1 for location), an extensive field with gas hydrate beneath 600 m thick permafrost has been described (e.g. Dallimore et al., 1999) and regional 2-D as well as 3-D seismic data collected across the Mackenzie Delta did not show a regional bottom-simulating reflection from the base of the gas-hydrate stability zone. Instead, individual gas-hydrate–rich horizons were mapped (e.g. Riedel et al., 2009; Bellefleur et al., 2012) well above the base of the gas-hydrate stability zone. Significant variations in grain size and pore-fluid salinity are expected to occur in the thick sediment package of the dominantly deltaic-style prograding sediment sequences. Such variations can result in a seismic reflection from the base of the gas-hydrate stability zone that may not always be perfectly flat or bottom simulating over large distances, as typically seen in a 'classic' marine environment. Local taliks from zones of discontinuous permafrost can further create 'holes' in the thermal regime, locally uplifting the base of the gas-hydrate stability zone and thus disrupting the reflection from it.

The reflection interpreted to be from the base of the gas-hydrate stability zone shows several typical characteristics usually associated with bottom-simulating reflectors in the classic deep-water marine environment: 1) polarity is reversed relative to seafloor; 2) crosscutting regular stratigraphy; 3) occurrence of enhanced reflectivity underneath, indicative of the presence of some free gas; and 4) high-amplitude updip truncation of layers at the base of the gas-hydrate stability zone. To best delineate this bottom-simulating reflector, which shallows toward deeper water, seismic lines were extracted from the 3-D seismic volumes at orientations to maximize crosscutting geometry between the seaward-prograding sediment stratigraphy and the base of the gas-hydrate stability zone.

Polarity-reversed reflections are common in the 3-D seismic data available, but are usually associated with either free-gas bright spots or mass-transport deposits. Shallow gas-related reflections (bright spots) show polarity-reversed reflection-phase relative to the seafloor, but are typically stratabound, not crosscutting through existing stratigraphy. Mass-transport deposits are usually deposited in a downslope

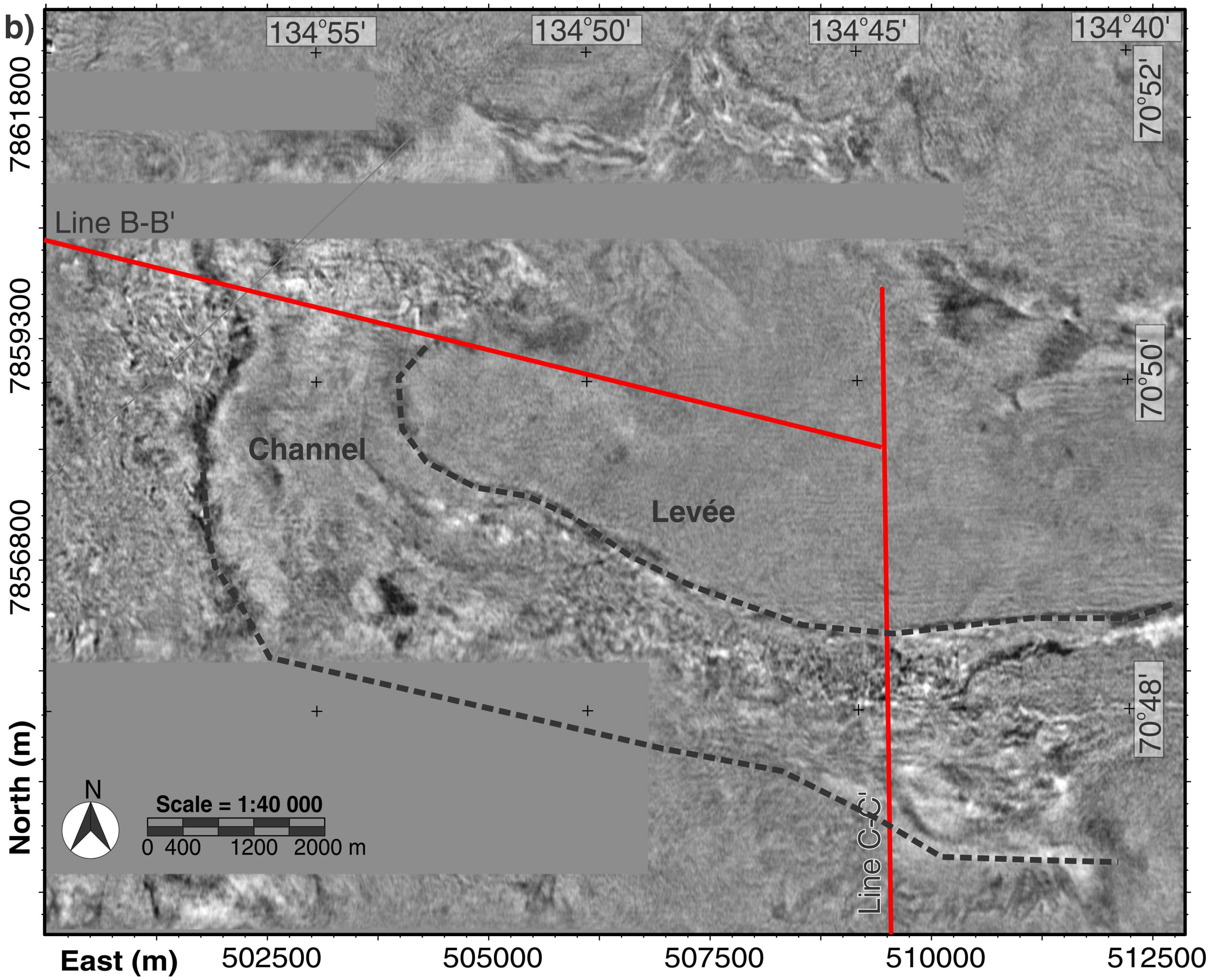

Figure 8. (Cont.)

fashion and therefore they can occur as bottom-simulating events; however, their only crosscutting relationships are erosional truncations at their origin, base, and/or the distal end of the deposit.

Overall, the reflection interpreted to be from the base of the gas-hydrate stability zone mimics the behaviour predicted from the thermal modelling and follows the shape of the associated wedge of permafrost (Taylor et al., 2013). Therefore, the present authors believe that this reflection is associated with gas-hydrate deposits in the overlying sediments and some accumulation of free gas underneath. The distribution of the high-amplitude zone underneath the base of the gas-hydrate stability zone shows some fault control and often layers are truncated at the phase boundary forming mini–bright spots. These mini–bright spots align, describing a discontinuous horizon along the base of the gas-hydrate stability zone that helps guide its tracking between adjacent seismic lines. The history of the last transgression as modelled by Taylor et al. (2013) resulted in an upward shift of about 100 m of the base of permafrost and associated base of the gas-hydrate stability zone. As the gas-hydrate phase boundary moves upward, gas hydrate is dissociated and free gas can accumulate underneath the phase boundary. The free gas cannot easily move upward, as the overlying gas-hydrate layer forms an almost impermeable barrier. Unless permeable pathways such as faults allow free gas to move up and into the gas-hydrate stability field (where it re-forms solid gas hydrate), the free gas is trapped underneath the base of the gas-hydrate stability zone. The authors believe this process is responsible for creating the observed zones of enhanced reflectivity beneath most of the shelf-edge region.

The two areas defined by the polygons shown in Figure 4 near the shelf edge are relatively small (combined <100 km^2) and thus do not reflect a significant accumulation of gas hydrate and associated free gas underneath on their own; however, it can be speculated that the occurrence of gas

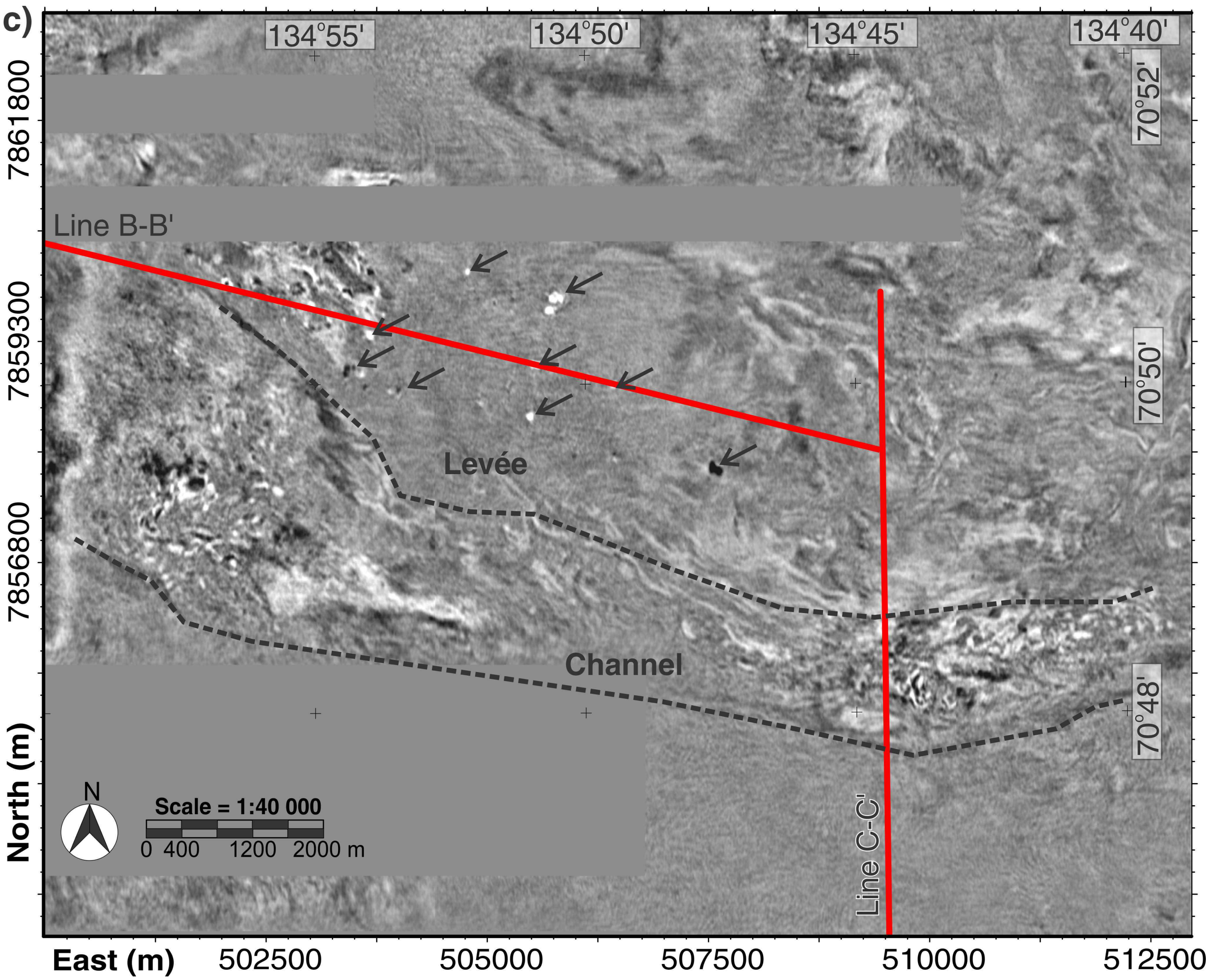

Figure 8. (Cont.)

hydrate is more widespread along the entire Beaufort Sea margin and that the seismic reflections are more prominent in regions of shallower water further landward where the warming signal from the transgression has had less impact on the base of the gas-hydrate stability zone. Although these two regions identified from the present seismic data do not reflect a significant accumulation and total carbon content that would significantly impact, for example climate-modelling scenarios, it is the first evidence of such occurrence in the Beaufort Sea and thus points toward further need of seismic-data acquisition for verification of the distribution for a more complete assessment of gas-hydrate abundance in the region.

CONCLUSIONS

The occurrence of a prominent seismic reflection from the base of the gas-hydrate stability zone underneath most of the shelf-edge region confirms previous hypothesis of the existence of a widespread regional gas-hydrate occurrence associated with the submerged permafrost layer in the offshore region of the Canadian Beaufort Sea. The dip of the reflection boundary and its overall geometry, including becoming shallower toward the shelf edge, as the thermal model would predict, is the result of a 'melting' process of the overlying permafrost since beginning of the last transgression ca. 25 ka ago. The bottom-simulating reflector–like event is further characterized by a crosscutting of the stratigraphy, and high-amplitude updip truncations of individual sediment layers.

The presence of free gas underneath the base of the gas-hydrate stability zone is suggested by the occurrence of widespread gas brightening. 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 postglacial melting moving updip as the phase boundary progressively shallows. Furthermore, high-amplitude updip truncations suggest an impermeability (cap) at the base of the gas-hydrate stability zone, preventing further migration of any free gas. This has implications for potential overpressure development at this depth.

The observation of the reflection of a regional base of the gas-hydrate stability zone has implications for a variety of scientific and engineering factors. The thermal history of the shelf since the last glacial period is compatible with modelling (e.g. Taylor et al., 2013) and provides several observations in its further support. The generation of a free-gas zone just below the base of the gas-hydrate stability zone at a relatively shallow depth of about 1000 m (and less) below seafloor presents a scenario where overpressures may develop and thus represent a potential geohazard not previously recognized with drilling safety and casing strategy implications for any new drilling in this region.

The absence of a classic marine gas-hydrate–associated bottom-simulating reflector in the seismic data available does not necessarily exclude the presence of gas hydrate in the deep-water environment. Here, the sediment column across which such a classic marine bottom-simulating reflector would form is dominated by mass-transport phenomena, erosional canyons, and rapid sedimentation rates under glacial input. All these factors tend to minimize the conditions favourable for bottom-simulating reflector formation despite the possible presence of gas hydrate and free-gas accumulation beneath it.

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