Integration geoConvention 2013 geoscience engineering partnership

# Seismic and well-log inference of gas hydrate accumulations above the Umiak and Ya Ya gas fields, Northwest Territories

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## Summary

The Mackenzie Delta in Canada's Northwest Territories hosts many permafrost-related gas hydrate accumulations that were indirectly discovered or inferred from conventional hydrocarbon exploration programs. In particular, gas hydrate intervals characterized with high saturation show high resistivity and high P- and S-wave velocity on well-log data, and are typically found in sand-rich horizons. As demonstrated at the Mallik site, the velocity contrast between highly saturated gas hydrate-bearing sediments and unconsolidated water-bearing sediments is significant and allows their detection on seismic data. Here, we use 2D and 3D seismic reflection data acquired by industry on Richards Island to map and characterize gas hydrate accumulations beneath a thick permafrost area of the Mackenzie Delta. Specifically, we show new seismic evidences of gas hydrate accumulations near the Ya Ya and Umiak significant discovery licenses. The presence of gas hydrate was previously inferred from well-log data in several boreholes located in those areas. All seismic data were re-processed following an AVO-compliant flow that preserved relative amplitude relationships. On such data, the strong acoustic impedance of gas hydrate produces strong amplitude seismic reflections. The seismic signature of gas hydrates is confirmed by seismic-to-well correlation in areas where borehole logs are available. Results indicate that gas hydrate accumulations occur in structurally-controlled plays typical of conventional oil and gas traps found in this area, and further demonstrate that gas hydrates are part of the regional petroleum system.

## Introduction

Most gas hydrate occurrences in the Mackenzie Delta and submarine permafrost areas of the Beaufort Sea were discovered or inferred indirectly in wells drilled for conventional hydrocarbon exploration. Well-log data intersecting gas hydrates show the typical high resistivity and high P-wave velocity signature associated with relatively porous hydrate-bearing sandstone. Although essential to determine in situ properties of gas hydrates, borehole investigations alone are not capable of establishing reliable lateral continuity of a gas hydrate zone more than a few meters away from the well. Still, this information remains critical for providing reliable estimates of the resource present at reservoir, field, and basin scales. Despite recent technical progress made at Mallik, our understanding of the distribution of gas hydrates in the Mackenzie-Beaufort basin has not evolved significantly in the last decade. Particular challenges include seismic data designed, acquired, and processed for deeper conventional resources, and highly heterogeneous permafrost that locally distorts seismic images at shallow depths. In this paper, we present seismic data analyses that provide new insights on two gas hydrate occurrences located on Richards Island, Mackenzie Delta. Two-dimensional seismic data are used to characterize the Ya Ya gas hydrate accumulation whereas 3D seismic data is used to infer the presence of hydrates in the Umiak area (Figure 1). Seismic inferences of gas hydrates in the two areas is constrained and supported with well-logging data.

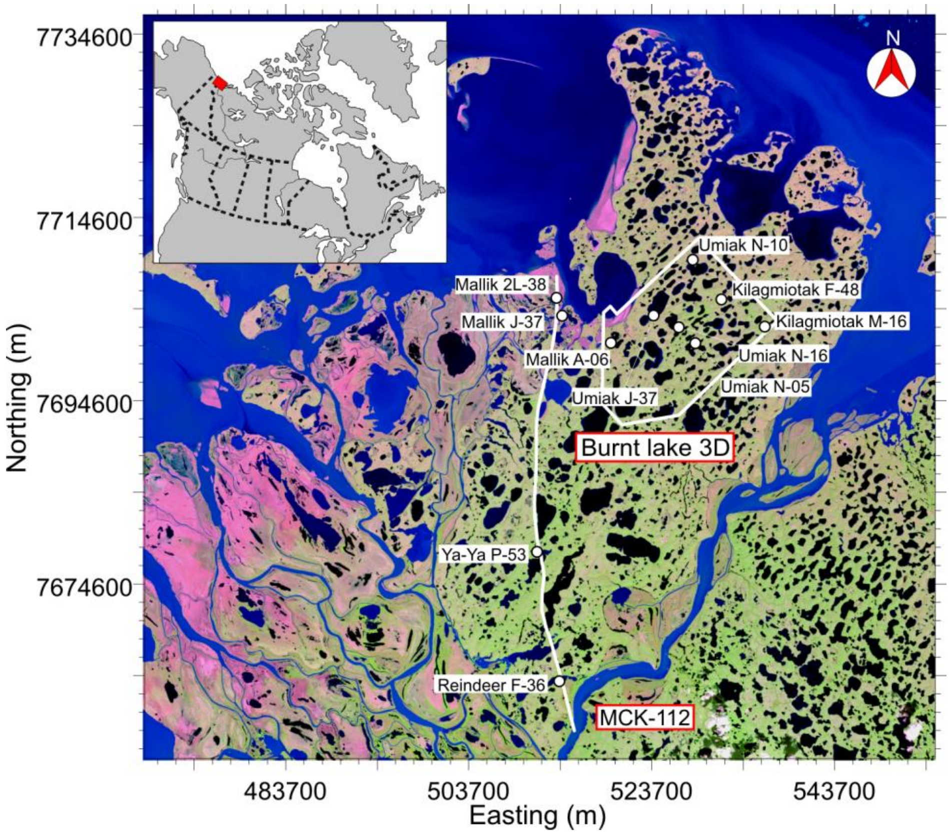


**Figure 1 Location of the 2D and 3D seismic data and wells on Richards Island, Mackenzie Delta.**

## Gas hydrate stability field

Subsurface temperature data and their implication on the gas hydrate stability field (GHSF) have been studied by Majorowicz and Smith (1999). Their results show a great variability in permafrost thickness on Richards Island. Maximum permafrost thickness is approximately 740 m near the Kilagmiotak F-48 well (Figure 1). Permafrost is significantly thinner in the southern part of Richards Island (402 m at Ya Ya P-53). The gas hydrate stability field (structure I hydrate) was estimated previously at several wells located in the Mackenzie-Beaufort Sea area (Majorowicz and Hannigan, 2000). The GHSF is laterally continuous on Richards Island but its base exhibits variability, which generally mimics the regional trend of the base of the ice-bearing permafrost. The base of the gas hydrate stability field reaches approximately 1300 m in the Umiak area. The GHSF is generally thinner near the Ya Ya lake wells and extends to a depth of approximately 800 m at Ya Ya P-53.

## Seismic Data

The seismic data used in this study comprises a 2D seismic profile located in the Ya Ya area, as well as a 220 $km^2$ 3D seismic data set in the Umiak area (Figure 1). The 3D survey covers the Umiak conventional gas field located significantly below the gas hydrate stability field. Access to the shallow part of the seismic data for gas hydrate characterization purposes has been made available to Natural Resources Canada Gas Hydrate Program by ConocoPhillips Canada, MGM Energy, BP Canada, and Chevron Canada. Both 2D and 3D data were acquired for deeper conventional targets. However, the shot and receiver intervals used for the 2D data were tight enough to allow proper seismic imaging of hydrate-bearing sediments in the deeper part of the thin gas hydrate stability field near Ya Ya. The 3D data is located in a thick gas hydrate stability field area and is suitable for imaging gas hydrate

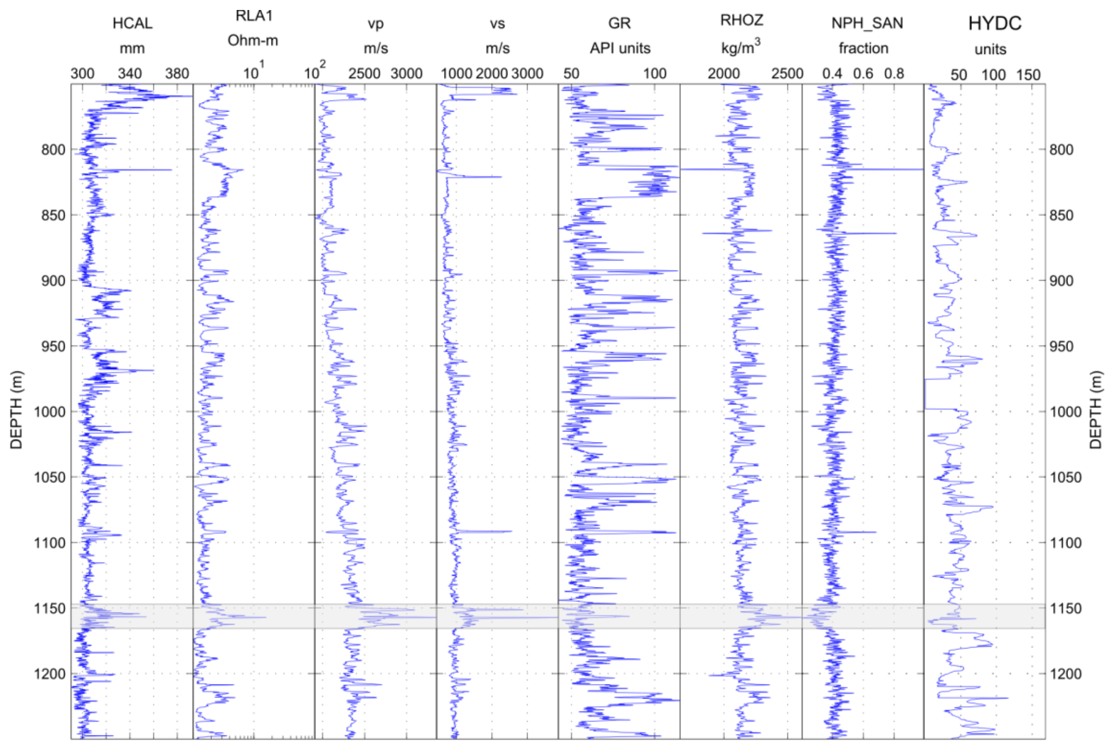


**Figure 2 Well-logging data in Umiak N-16. Tracks are (from left to right) caliper, resistivity, P-wave velocity, S-wave velocity, gamma-ray, density, thermal neutron porosity, and hydrocarbon counts. The gas hydrate interval is between 1150 m and 1160 m.**

accumulations close to the base of the stability field. Both 2D and 3D data were re-reprocessed following an AVO-compliant processing flow to preserve the relative true-amplitude character of the data.

Gas hydrate intervals were first assessed based on well-log data following a series of criteria defined in Collett et al. (1999) that enabled the identification of three gas hydrate intervals at the Mallik site (Mallik 2L-38 on Figure 1). Most of the well-log data on Richards Island date from the 1970's to 1980's with variable quality that sometimes prevented a clear and unique diagnostic of the presence of in-situ gas hydrates. In addition, the suite of logs available varied from well-to-well, occasionally preventing a firm identification of gas hydrates. The Umiak N-05 and N-16 wells (Figure 1) were logged with modern tools and provided a comprehensive suite of logs. However, NMR data that are useful for determining gas hydrate saturation were not acquired during the logging program that aimed at characterizing deeper conventional reservoirs. Once gas hydrate intervals were defined, sonic and density logs were used to assess seismic ties at well locations, and synthetic traces were compared to traces from the 2D and 3D data set. Synthetic seismic traces for vertical incidence were calculated by convolving the reflection coefficients obtained from the sonic and density logs with a wavelet extracted from the seismic traces near the well using a frequency matching approach. Time-to-depth conversion was established using checkshot surveys available in each of the wellbore. In this study, we will focus on areas near the Ya Ya P-53, and Umiak N-16 wells.

## Umiak gas hydrate prospect

The Burnt Lake area comprises seven wells. Five wells were drilled in the 1970's (Mallik A-06, Umiak N-10, Umiak J-37, Kilagmiotak F-48, Kilagmiotak M-16) whereas two drilled more recently in 2004-05 (Umiak N-05 and Umiak N-16) lead to the discovery of the Umiak conventional gas field. Recent wells

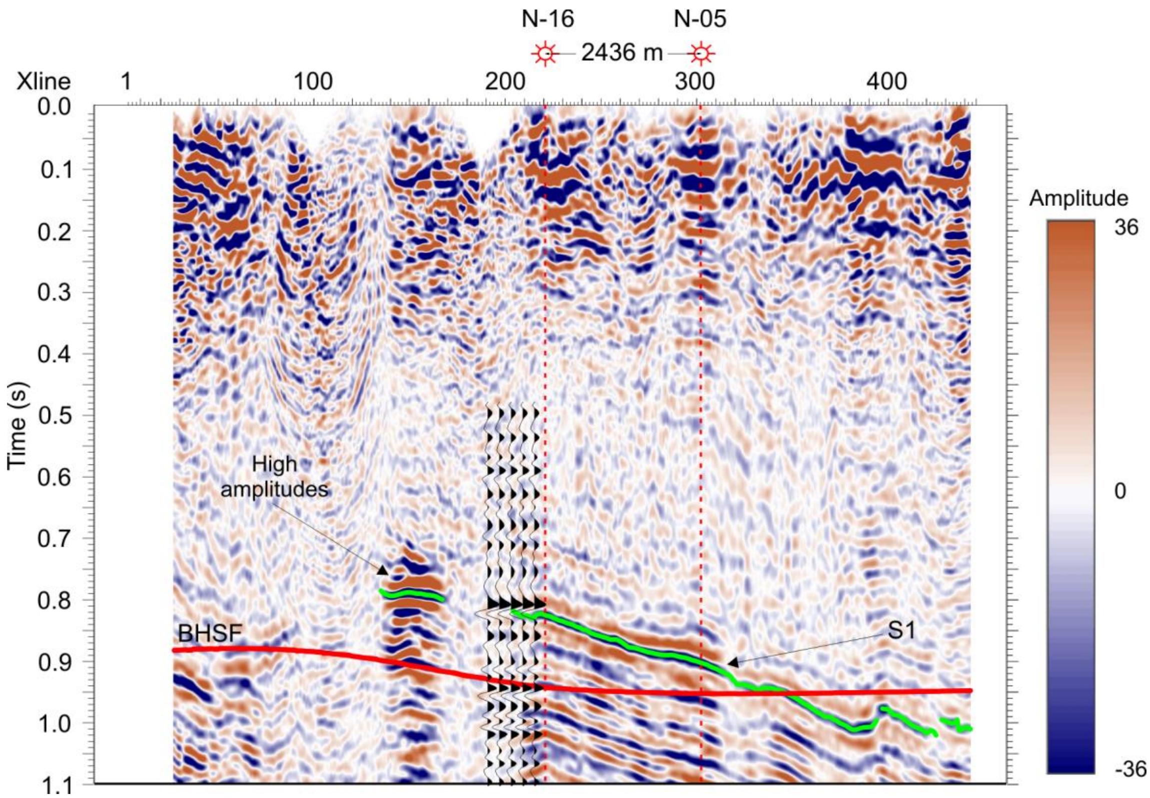


**Figure 3 Inline from the Burnt Lake 3D seismic data showing the S1 reflection, the base of the gas hydrate stability field, and near-vertical incidence synthetic seismic trace at Umiak N-16. Strongest amplitudes for S1 are at the top of a dome structure that appears as an anticline on this section. BHSF is the base of the gas hydrate stability field.**

comprised modern well-logging program, including mud-gas analysis. Figure 2 shows the well-log data in Umiak N-16. The resistivity, compressional- and shear-wave velocities show increased values relative to background values between 1150 m and 1160 m that we interpret as gas hydrates. The resistivity and sonic velocities in this interval, although higher than background values, suggest relatively low saturation (approximately 20-40% based on saturation-velocity relationships established at Mallik). The gamma-ray log in this interval indicates relatively clean sand. The density and neutron porosity have higher and lower values than those observed in sediments above and below the gas hydrate interval. In this well, the geological samples show the presence of a conglomerate unit that likely explain the higher density (2300 $kg/m^3$) and lower porosity values (near 25%). Following the stratigraphy, similar log characteristics are also found in Umiak N-05 but between 1200 m and 1207 m (not shown). Density and porosity logs indicate finer sediments for this interval in Umiak N-05. In Umiak N-16, the total hydrocarbon counts from mud log (last track on Figure 2) shows a broad occurrence of gas (mostly methane) in the Kugmallit Formation, possibly resulting from the dissociation of gas hydrates during drilling of the well. The hydrocarbon counts are low to moderate and again suggest sediments with relatively low gas hydrate saturation. No other log anomalies suggest the presence of gas hydrates in Umiak N-05 and N-16.

The Burnt Lake 3D data is located over the Umiak conventional gas field, the fourth largest gas discovery located onshore the Mackenzie Delta (Hogg et al., 2009). The 3D program was conducted on Richards Island in the winter of 2002. The AVO-compliant reprocessed seismic data, similarly to the original data, displays almost no reflections in the shallow part of the 3D volume (see Figure 3 for the re-processed data).

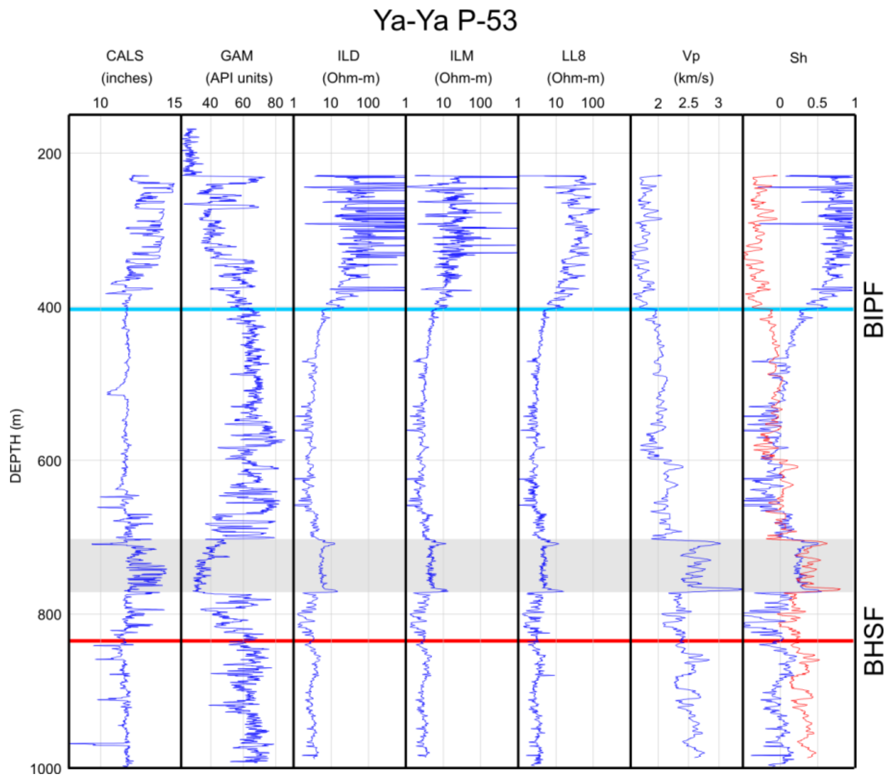


**Figure 4 Well-log data in YaYa P-53. Tracks are (from left to right) caliper, gamma-ray, three resistivity curves, P-wave velocity, and gas hydrate saturation estimates. The gas hydrate interval is highlighted in gray. BIPF is the base of ice-bonding permafrost. BHSF is the base of the gas hydrate stability field.**

This is in part explained by relatively homogeneous character of the clean sand of the upper Kugmallit Formation and by the relatively low fold in the shallow part of data. Figure 3 presents a seismic section with the projection of the Umiak N-05 and N-16 wells, and the estimated base of the gas hydrate stability field. The first continuous reflection is found at approximately 0.8 s (S1 on Figure 3). Seismic-to-well correlation using near-vertical incidence synthetic seismograms shows a good correlation between the S1 reflection and the log-inferred gas hydrate anomaly described in Umiak N-16 well (Figure 3). The combination of high P-wave velocity but also higher densities explains the strong amplitudes on the synthetic trace at the depth of the S1 reflection (near 0.8 s at Umiak N-16). In the central part of the Burnt Lake 3D, the S1 reflection clearly defines a continuous lithological marker within the Kugmallit Formation. Amplitude variations along S1 may indicate the presence of gas hydrates. Part of the S1 reflection is located within the gas hydrate stability field, in particular in the upper part of a dome structure located in the center of the survey area. The amplitude of the S1 reflection is generally low at the location of the Umiak wells, consistent with the possible presence of low-saturation gas hydrates. The amplitude is further reduced at depth below the base of the gas hydrate stability field south of Umiak N-05. This response is consistent with sediments containing no gas hydrates or no free gas directly beneath the base of the gas hydrate stability field. The strongest amplitudes for reflection S1 are observed near the top of the dome structure. At that location, the prominent reflection has the character and signature of gas hydrate reflections observed in the Mallik area (Collett et al., 1999; Riedel et al., 2009). The northwest end of this structure terminates on a NE-SW fault. No well data are available at the top of the dome structure to confirm that the high amplitude reflections are caused by the presence of gas hydrates. However, the presence of low-saturation hydrate-bearing sediments in the stratigraphy downdip direction, and the broad distribution of hydrocarbons observed in mud logs suggest that they could be. If so, then the gas hydrates would be located at the top of a 4-way closure structure, similar to many conventional gas fields in the area.

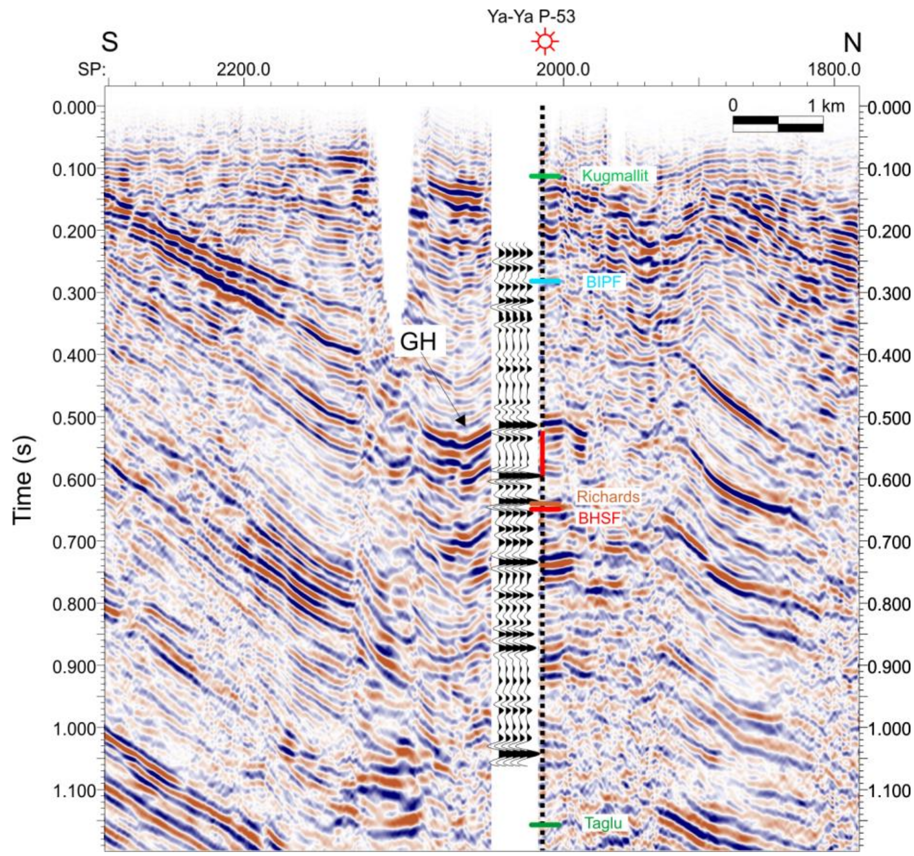


**Figure 5 Subset of the MCK-01-112 seismic profile near YaYa P-53. Synthetic seismic trace (repeated 5 times) is inserted at YaYa P-53. The synthetic trace shows reflection for the top and the bottom of the thick hydrate-bearing sand layer. The top is clear on both sides of the well whereas the bottom reflection shows up only south of the well.**

## Ya-Ya gas hydrate prospect

The MCK-01-112 seismic profile intersects three wells with previously identified gas hydrate intervals (Majorowicz and Hannigan, 2000). Gas hydrates intersected in the Mallik 2L-38 well have been described in numerous publications (see Dallimore and Collett, 2005) and are not discussed in this paper. Gas hydrates were also inferred in Reindeer F-36 from high-resistivity anomalies. However, the high-resistivities are not coupled to high P-wave velocities (not shown) and the presence of gas hydrate in this well remains uncertain. Figure 4 shows the vintage well-logging data in Ya Ya P-53. The base of the ice-bonding permafrost corresponding to a sharp decrease of very high resistivity values and the estimated base of the gas hydrate stability field are also shown on this figure. Gas hydrates are inferred in a thick sand layer between 702 and 772 m. This interval has high resistivities, high P-wave velocities and low gamma-ray values indicative of sand-saturated hydrates. Gas hydrate saturation is estimated using resistivity (blue line in the last track shown in Figure 4) and sonic velocity (red line in Figure 4). Resistivity-saturation estimates were obtained with the quick-look Archie approach using a baseline resistivity value of 3.5 ohm-m (see Dallimore and Collett, 1999). This approximate approach was used because no porosity information is available over the gas hydrate interval (no density or neutron porosity data). An empirical velocity-saturation relationship established at Mallik was used for velocity-derived saturation estimates (Riedel et al., 2009). Sonic-saturations are slightly higher than resistivity saturation and locally exceed 50%. Average saturation estimated from resistivity data is approximately 30%.

Figure 5 shows a detailed view of the MCK-01-112 seismic data near Ya Ya P-53. The base of the ice-bonding permafrost and base of the gas hydrate stability field are also shown in this figure. Strong amplitude reflections corresponding to gas hydrates are also indicated. This part of the seismic data is located within the Taglu Fault Zone, a northeast-trending zone comprising normal and reverse faults in the Tertiary sediments at the southeastern margin of the Beaufort fold belt (Lane and Dietrich, 1995). In the area of the Reindeer wells (F-36), the Tertiary section has been uplifted and folded and has been subject to erosion. As a result, recent Tertiary sediments are thinner in the Ya-Ya lake area than in the northern part of Richards Island. A strong reflection observed at the top of the thick hydrate-bearing sand interval defines a local fold structure. The bottom of the gas hydrate sand also produces a reflection but with generally weaker amplitudes. The near-vertical incidence synthetic seismic trace generated using P-wave velocity from logs and constant density of 2100 $kg/m^3$ also shows reflections at the top and bottom of the thick as hydrate interval (Figure 5). The seismic data suggest that gas hydrates in this sand layer extends over approximately 1.2 km in the north-south direction.

## Conclusions

We have shown new evidence of gas hydrate accumulations on 2D and 3D seismic reflection data acquired by industry near the Ya Ya and Umiak wells. The presence of gas hydrate was previously inferred from well-log data in the Ya Ya area, whereas well-log data shows additional gas hydrate occurrences near the Umiak N-05 and N-16 wells. All seismic data was re-processed following an AVO-compliant flow that preserved a relative amplitude relationship. On such data, the strong acoustic impedance of gas hydrate produces the characteristic strong amplitude seismic reflections. The seismic signature of gas hydrates is further supported by seismic-to-well correlations. The distribution of the strong reflections indicates that gas hydrate accumulations occur in structurally-controlled plays typical of conventional oil and gas traps found on Richards Island, and further demonstrate that gas hydrates are part of the regional petroleum system.


## Acknowledgements

We thank MGM Energy and ConocoPhillips Canada for providing access to upper part of the Burnt Lake 3D seismic data, support data, and logging data in the Umiak N-05 and N-16 wells and for permission to publish the results. We also thank BP Canada and Chevron Canada for providing access to 2D seismic data on Richards Island and permission to publish the results.


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