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Recent Advances in Mapping Deep Permafrost and Gas Hydrate Occurrences using Industry Seismic Data, Richards Island Area, Northwest Territories, Canada

Gilles Bellefleur
Geological Survey of Canada - Ottawa
615 Booth Street
Ottawa, ON, K1A 0E9, CANADA
gbellefleur@nrcan.gc.ca

Michael Riedel
McGill University, Earth and Planetary Sciences
3450 University Street.
Montreal, Quebec, H3A 2A7, CANADA

Kumar Ramachandran
University of Tulsa, Department of Geosciences
600, South College Avenue
Tulsa, Oklahoma
USA- 74104-3189

Tom Brent*
Geological Survey of Canada - Calgary
3303-33 Street North West,
Calgary, AB, T2L 2A7, CANADA

Scott Dallimore
Geological Survey of Canada - Pacific
9860 West Saanich Road
Sidney, B.C., V8L 4B2, CANADA

Summary

An industry-acquired (2002) 3D seismic survey over the Mallik area in is used to map heterogeneities in permafrost and to determine the extent of gas hydrate occurrences. Seismic amplitude anomalies associated with lakes and drainage systems are observed in the data. Beneath lakes, the seismic indicate weaker amplitudes, locally degrading images of the geology within, and below the permafrost. On Richards Island, lakes may not become ice-fast in winter promoting talik development that vertically penetrate permafrost. Amplitude effects on the seismic data arise from velocity and attenuation associated

with this frozen / un-frozen variability of the permafrost zone. A 3D travel-time tomography algorithm produced a map of the permafrost velocity structure. The 3D velocity map clearly reveals a heterogeneous velocity distribution, primarily related to thermal variations within the permafrost. Results from acoustic impedance inversion at hydrate reservoir interfaces indicate that sediments with high gas hydrate saturation near the Mallik well site extend over an area of 0.25 km^2.

Introduction

The Mackenzie Delta area is characterized by a remarkable variability in permafrost conditions. From the central Mackenzie Delta to northern Richards Island, permafrost may increase from 80 m to 700 m thick (Judge et al. 1987). This variability in part reflects a complex Quaternary history of surface temperatures and geologic processes (Taylor et al. 1996). As elaborated in more detail by Wright et al. (2008), lakes which cover between 20 and 50% of the landscape of the Mackenzie Delta area have played an important role in conditioning ground temperatures. Warmer ground temperatures beneath lakes affects the proportion of liquid water versus ice within the sediment matrix. Both conditions can modify the physical properties of sediments, affecting the propagation of seismic waves. Sediments with ice in the pore space are stiffer and characterized by higher seismic velocities whereas unfrozen sediments have lower velocities (Zimmermann and King 1986). Seismic amplitude and frequency degradation effects on data under deep taliks, are evident on 3D seismic data over the Mallik area on Richards Island (3D seismic outline location on Fig. 1). Data show weaker amplitudes under lakes which locally compromise seismic quality (Figure 2).

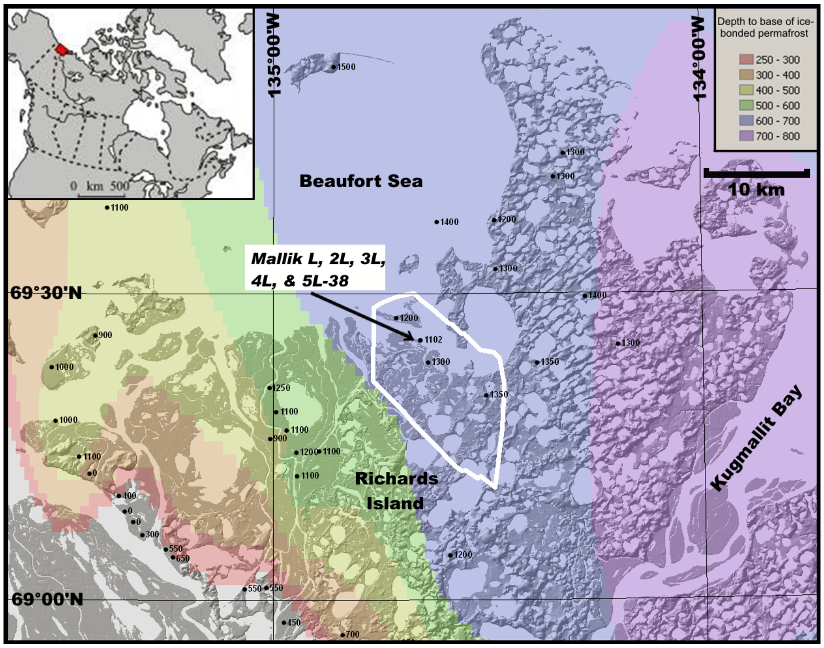

Figure 1: Location of the JAPEX/JNOC/GSC et al. Mallik gas hydrate research wells in the Mackenzie Delta. White outlined polygon is area covered by 3D seismic data used in this study. Topography DEM (Gov. of N.W.T., 2006) is shown with colors overlain representing the depths to the base of ice-bonded permafrost (K.Hu, pers. comm.2008). Numbers posted at black dots (wells) are depths (m) to base hydrate stability field as estimated by Majorowicz and Hannigan (2000).

Interpretations of geophysical well logs from exploration wells in the area of the Mallik 3D suggest the base of ice-bonded permafrost is 600 to 650 m from surface and that gas hydrates can occur to depths of 1150 m (Judge et al. 1987). Two major gas hydrate research well programs have been conducted at the Mallik site (Dallimore and Collett 2005). Core studies and geophysical interpretations document that gas hydrate occurs in coarse-grained sandy sediments of the Mackenzie Bay and Kugmalit Tertiary sequences from 870 to 1100 m depth. The gas hydrate-bearing sediments are separated by silty sediments with little or no gas hydrate.

3-D seismic data. The upper 2 s of a 3D seismic survey was supplied by industry for this study. It was acquired with a combination of vibroseis and dynamite and covers approximately 130 km2 that include four gas hydrate research wells (1998; 2002) and four industry wells drilled in the 1970s. The 3D acquisition geometry was optimized to image conventional hydrocarbon accumulations located well beneath the depth of gas-hydrate zones (900 - 1100 m.). The initial data processing also emphasized the deeper imaging and the resulting 3D volume provides poor reflection images of the permafrost (above 600 m) and low fold in common-depth-point gathers in the gas-hydrate depth range. We used 3D data reprocessed to relative true-amplitude (Riedel et al. 2006).

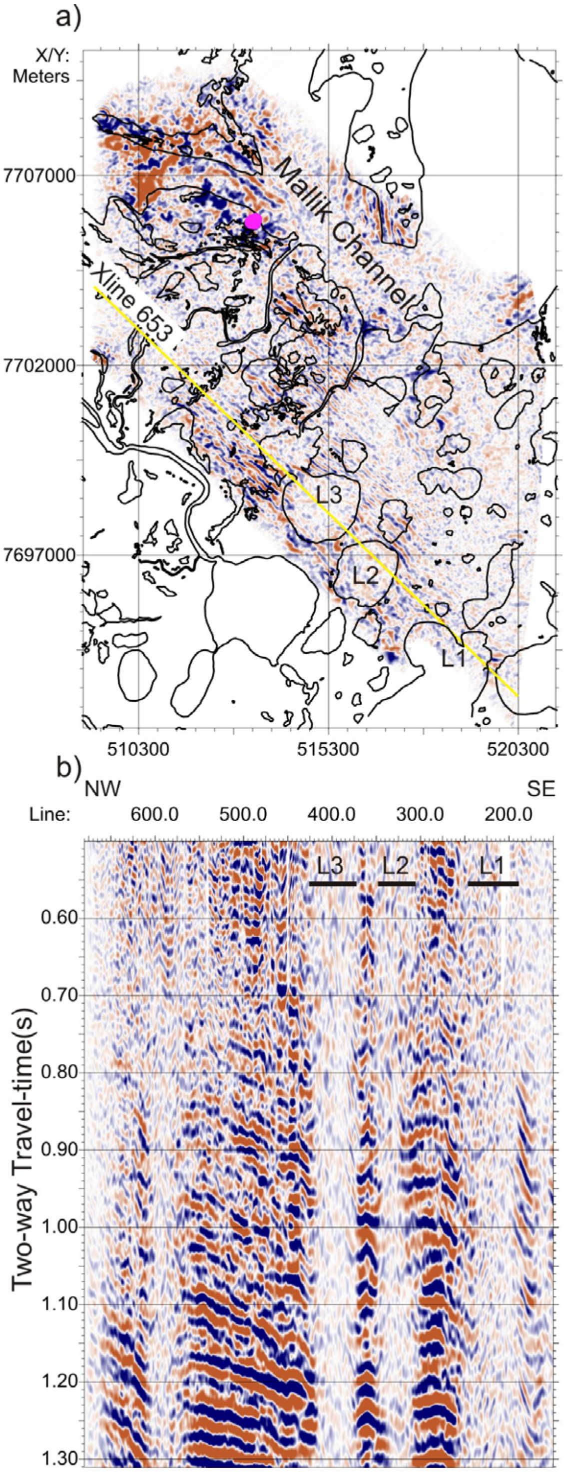

Figure 1 (a): Time slice from the true-amplitude 3D seismic data at 800 ms (approximately 1100 m). The purple dot shows the location of the Mallik wells. (b): Cross-line 653 showing reduction of amplitude beneath the lakes. The location of cross-line 653 is shown in (a) (yellow line). Colors represent seismic amplitudes (blue: negative amplitude; red: positive amplitude)

Several areas of reduced seismic amplitude are observed in the true-amplitude 3D seismic data set at depths exceeding 1 km (Fig. 2). Understanding these low-amplitude anomalies (also referred to as washout zones) is important for any attribute-related interpretation. In the marine environment, wide-spread amplitude blanking has often been attributed to the presence of gas hydrate (Holbrook et al. 2001). At Mallik, the low seismic amplitude areas in the gas hydrate stability field (200 to 1100 m) may not indicate the presence of gas hydrates but instead likely result from variations of physical properties in permafrost, and more specifically to property changes associated with deep taliks.

A time slice from the 3D true-amplitude data set, with an overlay of the hydrology, is shown in Figure 2. The time slice is located beneath the permafrost near the base of the gas hydrate stability field at 800 ms (approximately 1100 m depth). Areas of seismic blanking or reduced seismic amplitude are coincident with the location of some larger lakes. A seismic cross-section (Fig. 2b) shows that the reduced amplitudes beneath the lakes extend down to 1.3 seconds. The effect of ice bonding on seismic velocity is well documented. In water-saturated and unconsolidated sediments, velocity of P-waves varies significantly as a function of the fraction of pore water that is unfrozen (Zimmermann and King, 1986). Sediments with only ice in the pore space can have P-wave velocity as high as 4200 m/s whereas as sediments mostly filled with water have velocities near 1800 m/s. Other factors such as composition, density, porosity and pressure also affect P-wave velocity of sediments. Large lakes in the Richards Island area can have a significant talik beneath them (Wright et al., 2008). The unfrozen or partially unfrozen areas attenuate propagating seismic waves more severely than fully frozen sediments, producing low amplitude areas in Figure 2. Areas with lower velocity delay seismic waves propagating down to and up from deeper reflective geological structures. These delays, because they occur at shallow depths, must be taken into account during data processing to produce the most accurate images of deeper geological structures and quantitative information about the velocity distribution of the permafrost is required to estimate proper static corrections. The velocity distribution can also provide information about the internal structure of the permafrost.

In general, synthetic traces from the 3D survey show positive amplitude peaks at the top and troughs at the base of gas hydrate zones A, B and C (Figure 2). The synthetic traces also predict a reflection in the middle of zone B corresponding to higher velocities in this interval. The seismic traces extracted from the 3D data set close to 5L-38 reveal strong and continuous troughs at the base of horizons B and C (Figure 2). These two reflections represent excellent markers to determine the spatial extent of the gas hydrate zones. These traces also show a second peak within zone B that could correspond to the middle reflection on the synthetic traces; however, correlation with the synthetic traces for that reflection is less convincing. The 3D and synthetic traces do not correlate well in the time range corresponding to zone A, likely due to inadequate imaging of this zone on the real data.

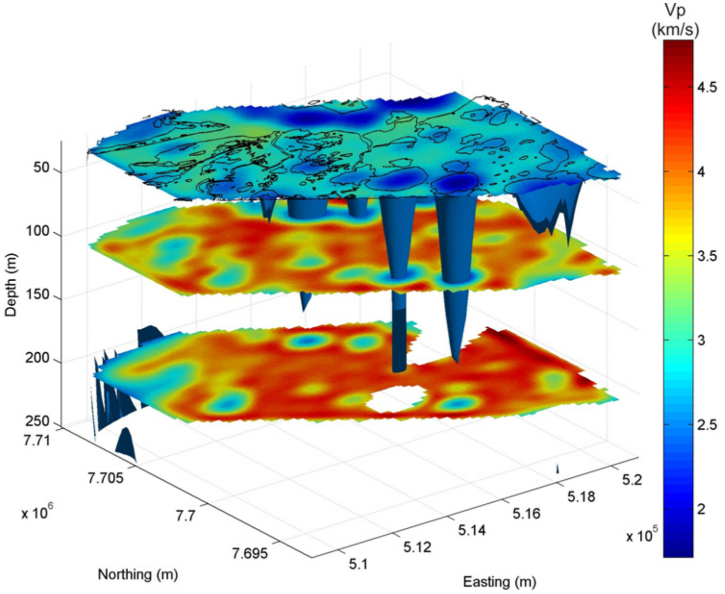

Figure 3 (LEFT): Plunge view to the NE showing three velocity slices (at 25m, 100m and 200m), natural drainage system and iso-surfaces set at 2.4 km/s.

Velocity Structure of Permafrost

Direct P-wave travel-time tomography is used to produce a 3D velocity map of the permafrost (Figure 3). Tomographic inversion of first arrival travel-time data is a non-linear problem since both the velocity of the medium and the ray paths in the medium are unknown. The final solution is typically obtained by repeated applications of linearized inversion until model parameters (velocities) explain the observations (travel-times) within satisfactory criteria (Ramachandran et al. 2005).

The tomographic inversion of direct seismic arrivals resulted in a velocity model extending to a depth of 500 m, about 100 m above the base of permafrost. Figure 3 displays three depth slices from the model. As expected, lower velocities are found underneath lakes and drainage. Some of the low velocity areas beneath the lakes extend down to approximately 300 m and have an inverted-cone shape (Figure. 3).

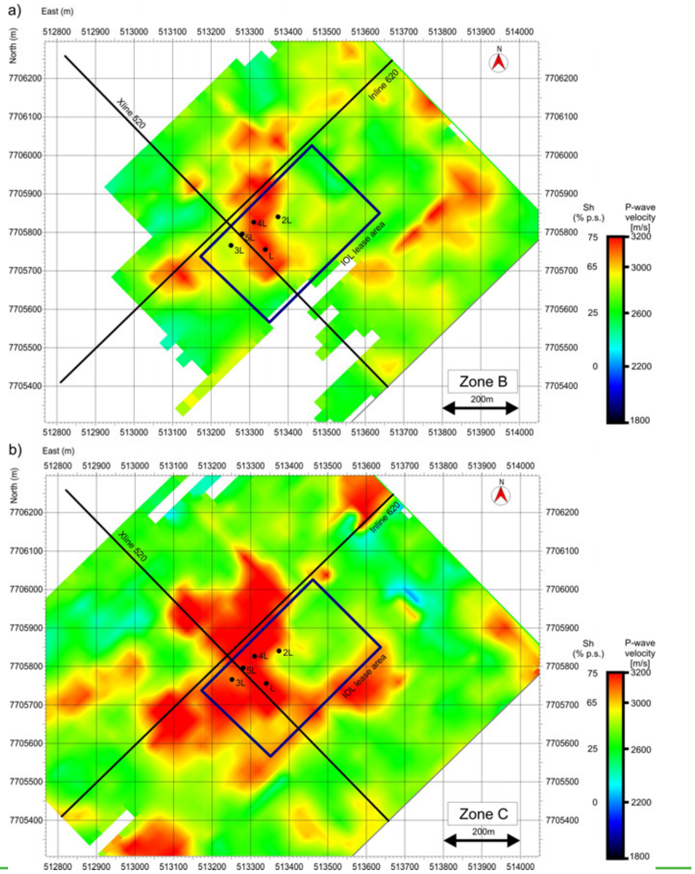

Figure 4 (RIGHT): Velocity map inferring extent of gas hydrate zones B (top) and C (bottom). Color code shows P-wave velocity in m/s and gas hydrate concentration in % of pore space (% p.s.).

Gas Hydrates

Two internationally-partnered research well programs successfully determined in-situ physical properties of Mallik gas hydrate intervals (Dallimore and Collett, 2005). The intervals are up to 40 m thick hydrate saturation to 80% of pore volume with porosities from 25% to 40%. Zones are named A, B and C, wher base zone C is bottom of stability zone. Sonic P-wave velocity of sediments increase with concentration of gas hydrates (Guerin & Goldberg 2005). P-wave velocities are 2400 m/s and up to 3200 m/s in strata with 80% hydrate saturation. To map hydrate extent we used seismic-to-well correlation and acoustic impedance inversion. We extracted P-wave velocities from impedances assuming no lateral variability in the density. We converted P-wave velocity to gas hydrate concentration (result in Fig. 4) by using the effective medium theory by Helgerud et al. (1999).

Conclusions

Lower seismic amplitudes are observed on the 3D Mallik data beneath some lakes and water channels. Amplitudes effects on the seismic data arise from velocity and attenuation variations associated with frozen and un-frozen parts of the permafrost. A 3D velocity map of the permafrost obtained with direct arrival travel-time tomography indicates that some of the low-velocity areas beneath the lakes have an inverted-cone shape and extend down to approximately 300 m. Beneath the permafrost, results from acoustic impedance inversion indicate that sediments with high gas hydrate saturation near the Mallik well site extends over an area of 0.25 km^2 and suggest that lateral and depth-dependent geology variations play a significant role in the distribution of gas hydrates.

Acknowledgments

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