Detection and characterization of massive ground ice using Ground Penetrating Radar and seismic shothole records

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ABSTRACT
This study utilized Ground Penetrating Radar and seismic shothole drillers' log records to examine the occurrence, distribution and origin of massive ground ice at two locations in Northwest Territories. Through traverses along recent seismic cut-lines, discreet bodies of massive ice were identified in differing sedimentary facies within the Colville Hills, and Little Chicago – lower Mackenzie corridor study areas. Ice bodies are between 40-110 m in lateral extent and up to 3.6 m thick. Application of these complimentary methodologies demonstrates their utility to regional ground ice mapping as may be required for future regional infrastructure development activities.

RESUME
Cette etude utilise la georadar et les donnees des trous de forage sismique pour examiner la presence, la repartition et l'origine de la glace massive du sol a deux endroits dans les Territoires du Nord-Ouest. Par les transects sismiques recent, deux incidences de la glace massive sont identifies dans les facies sedimentaire variables dans les regions d'etudes de les Colville Hills at a Little Chicago-la couloirs-bas Mackenzie. Les masses de glace sont entre 40-110 m d'etendue lateral et jus'qua 3.6 m d'epaisseur. L'application de cettes methods complimentaires demontrents sons efficacite dans la delimitation de la glace de sol dans les deux regions pour la development de l'infrastructure dans la future.

1 INTRODUCTION

Massive ground ice, defined as subsurface ice containing gravimetric water content in excess of 250% (Permafrost Subcommittee, 1988), is a prominent feature of periglacial environments. Massive ice is typically considered to be either buried ice or intra-sedimentary ice. Buried ice may include glacier ice, snowbank ice, and river icings (Wolfe et al., 1997). Intra-sedimentary ice is formed in-situ within unconsolidated sediment or bedrock by a variety of processes including segregation and intrusion (Mackay, 1972). Notable forms of intra-sedimentary ice include pingo ice, ice lenses and ice-wedge ice.

Occurrences of massive ice in the western Canadian Arctic are well-documented (Rampton and Mackay, 1971; Dallimore and Wolfe, 1988; Mackay and Dallimore, 1992). The understanding of ground ice distribution, extent and origin is important for two main reasons: 1) from a scientific perspective, knowledge regarding the origins of ground ice can offer insights into permafrost geology, landscape evolution and paleoclimate, 2) engineers and geotechnical planners need to know the distribution of ground ice in order to avoid subsidence due to its melting. The melting of excess ice has been identified as one the greatest geotechnical hazards in permafrost environments (Moorman et al., 2003). This latter point is of particular importance to this study as the two areas of interest are regions of active hydrocarbon exploration and potential development.

The Colville Hills, in which the Lac des Bois study site is located, contains one of mainland Canada's largest known undeveloped conventional natural gas reserves outside of the Mackenzie Delta (Hannigan et al. 2009). The other study area, the Little Chicago site, lies in the Mackenzie corridor, and could be included in planning of the proposed Mackenzie Valley gas pipeline.

Presently, the origin, extent and distribution of massive ground ice for much of the lower Mackenzie corridor and the Colville Hills is unknown. This study uses Ground Penetrating Radar (GPR) and drill records from seismic shotholes to improve the understanding of ground ice distribution and origin within these two regions.

2 STUDY SITES

The two study sites for this project are the Little Chicago area in the lower Mackenzie Valley and the Lac des Bois area in the Colville Hills. Both sites are located in the western Canadian Arctic, just south of the southerly limit of continuous permafrost (Heginbottom et al. 1995). The two locations have been categorized as having moderate to low amounts of ground ice (Heginbottom et al. 1995). Norman Wells is the closest weather station to Little Chicago and Lac des Bois (270 and 180 km, respectively) and has a mean annual air temperature of -5.5 °C for the 30 year period ending in 2000 (Environment Canada, 2009). Average annual snowfall for this period was 153 cm.

The Little Chicago site (Figure 1) is at 67°6'7"N; 130°15'17"W, and lies on the western bank of the Mackenzie River. Permafrost depths at nearby Fort Good Hope (110 km to the south) range between 33-48 m

(Smith and Burgess, 2002). Active layer depths measured from monitoring stations north of Norman Wells range from 60-68 cm (Tornacai et al. 2004). In 2007, Kodiak Energy conducted seismic surveys as part of petroleum exploration in the region. The 2-5 m wide cutlines made during this program provide the spatial access network utilized by this research.

The Lac des Bois study area is 40 km north of Smith Arm, Great Bear Lake at 66°30'06"N; 125°10'11"W. Depth of permafrost at the Eldorado Mine, 70 km to the south was measured at 104 m (Smith and Burgess, 2002). In 2008 Explor Resources Inc. conducted seismic exploration research in the Lac des Bois area. Once again seismic cutlines provided access for the field component of this study.

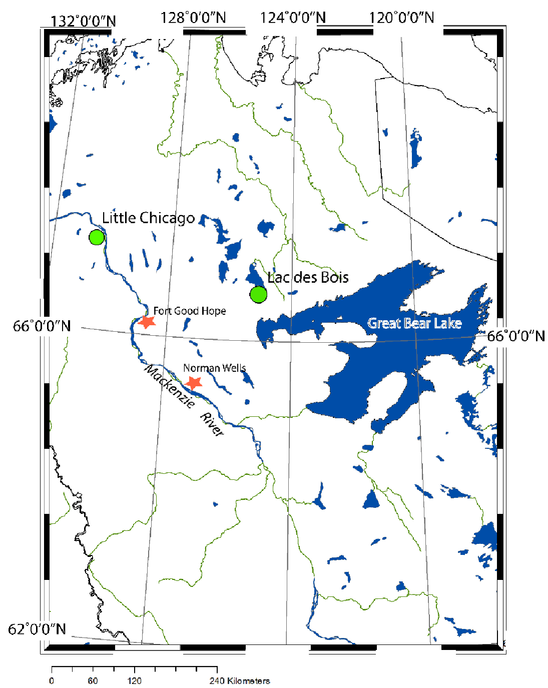

Figure 1. Little Chicago and Lac des Bois study areas, NWT, Canada

3 METHODS AND DATA

The contrast between the electromagnetic properties of ice, unfrozen water and sediment makes GPR an effective tool in the delineation of massive ice (Moorman et al. 2003). Massive ice bodies have been successfully studied using GPR in the Canadian Arctic Archipelago (Robinson, 1994; Dallimore and Wolfe, 1988), Alaska (Yoshikawa et al., 2006), Antarctica (Fukui et al., 2007) and the Mackenzie Delta (DePascale et al., 2008; Robinson et al. 1993). This study uses GPR interpretations and lithostratigraphic records from seismic shothole drillers' logs to identify and characterize ice bodies. Subsurface ice is first delineated by GPR. The origin of these ice bodies is then inferred based on the sedimentary data retrieved from seismic shotholes and observations made in the field.

3.1 GPR surveys

Subsurface features, including massive ice, were detected using a pulseEKKO Pro GPR unit. Surveys conducted in the field employed a 100 MHz transmitter/receiver, with an antennae separation of 1 m. Time window settings ranged between 285-320 ns for all data collected. Between the two study areas more than 70 km of GPR line data was collected between March 2 and March 17, 2009.

Editing and post-processing of the GPR data was minimal. Positional data acquired with a global positioning system was applied to all GPR profiles to correct for distance. Where necessary, GPR profiles were also corrected for topography. To enhance weaker reflections that result from increasing loss of energy with depth, an automatic gain control was applied. All GPR profiles have been plotted in a grey-scale format.

3.2 Borehole data

In addition to the aforementioned seismic boreholes drilled in 2007 and 2008, data from a 1972 drilling program were also used (Smith and Lesk-Winfield, 2010). All boreholes for the three projects were drilled to 5-19 m depth. Records for each of the drill sites use a combination of 22 descriptors to identify surficial and bedrock geology encountered during drilling. An example of drill records used in this study is illustrated in Table 1.

Table 1. Sample of shothole drillers' log data (from Smith and Lesk-Winfield, 2010)

Shotpoint	Total depth (m)	Depth of first interval (m)	Logged material - first interval	Depth of second interval (m)	Logged material - second interval
WD-1506	12.0	6	clay, rocks	12	shale
WD-1507	18.3	18.3	gravel	N/A	
WD-1508	18.3	18.3	sand, gravel	N/A	
WD-1509	12.0	6	clay, rocks	12	rock

4 RESULTS AND DISCUSSION

A total of 97 GPR profiles were collected. Radar facies analysis has been done on the profiles and interpretations have been made with the aid of field observations. An average wave velocity of 0.13 m/ns was determined from hyperbolic reflections. This translated to a signal penetration of 10-17 m for all profiles.

At both study areas interpretation of massive ice bodies in excess of 40 m in lateral extent have been made. Examples of what are interpreted to be two subsurface ice bodies are presented here. Discussion as to their characteristics and origin is offered.

4.1 Buried ice at Little Chicago

At the Little Chicago site, GPR line LC-28 showed two strong, continuous reflectors at depths between 8 m and 12 m (Figure 2). They are found towards the western end of an east-west transect that runs along one of a series of ridges between 10-20 m high. These two returns represent the top and bottom of what is interpreted to be massive ice. The upper ice/sediment contact ranges from a depth of 8.2 to 11.6 m. Returns interpreted as the bottom of the ice range from 10.6 to 12 m in depth. Maximum ice thickness, accounting for a velocity of 0.16 m/ns through the ice body, is 3.6 m. The east-west lateral extent of the massive ice within the profile is 110m.

This profile is a subsurface pseudo-section taken from the top of a low ridge that runs parallel to a long thin lake of approximately 3.7 km in length. The ridge is one of several in the area. It is sharply crested and has a prominent slope running down to the lake's edge. The area is situated within what is interpreted to be a former glaciofluvial channel. This observation is supported by the GPR facies analysis, which indicates near-surface fluvial sediment structures. Good, constant propagation indicated a stratigraphy consisting primarily of coarse sediments. A relative dearth of large, hyperbolic reflectors indicates that this sub-surface section is relatively free of large boulders.

The GPR line LC-28 did not have any shothole records within it. There were, however, two nearby shotholes on the ridge. One, WD-1508, was located 60 m to the north of the body of ice, and records a mix of sand and gravel down to a depth of just over 18 m. Shothole WD-1507 is 75 m to the south of the massive ice body, and records gravel within the first 18 m of the subsurface. These data are consistent with the sedimentology that is typical of glaciofluvial landforms.

This body of ice is interpreted to be relatively pure. A lack of reflectors within the body of ice leads to the inference that the ice is free of sediment bands. It is deemed to be buried ice because of the morphology of the feature as well as the nearby sedimentology. The geometry of this massive ice compares well to buried ice detected in an ice-cored esker at Carat Lake (Wolfe et al. 1997).. Further, the coarse sediments found in this locale are not conducive to the growth of intra-sedimentary ice. Large grain and pore sizes inferred from both the shothole data and the GPR analysis are not compatible with accepted models of in-situ ice growth for an ice structure of this size.

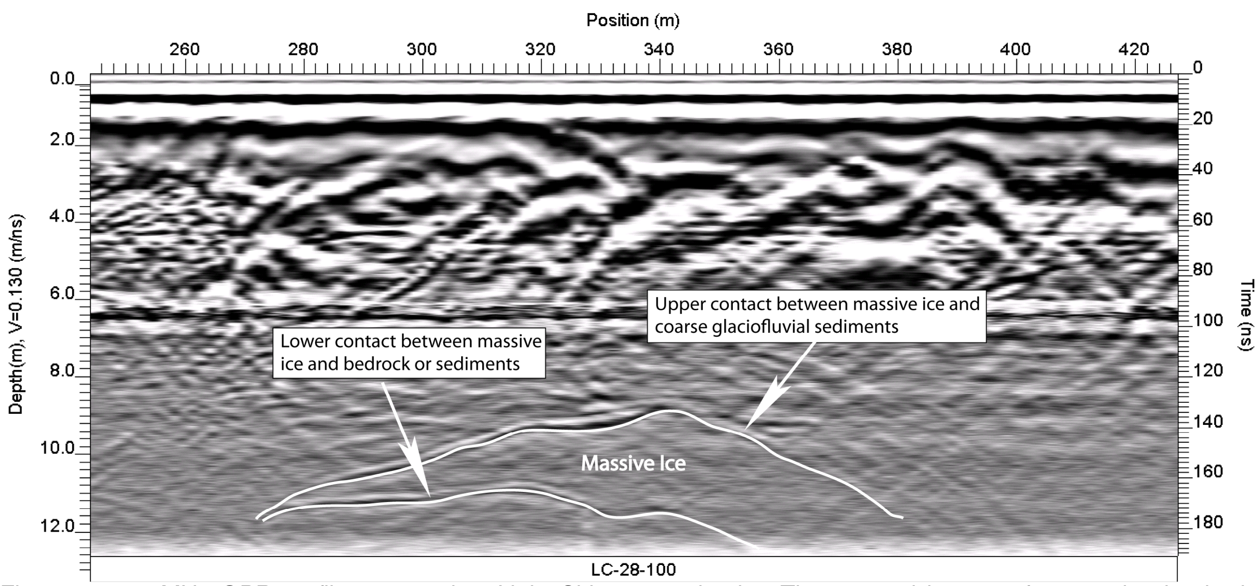

Figure 2. 100 MHz GPR profile surveyed at Little Chicago study site. The top and bottom of a massive ice body is delineated with a solid white line.

4.2 Segregated massive ice in the Colville Hills

At the Lac des Bois study site in the Colville Hills, massive ice is interpreted in GPR line LDB-37. A strong, continuous reflector is observed across the first 40 m of the east-west transect at a depth between 10-12.5 m (Figure 3). The linear reflection noted with a solid white line in Figure 3 represents the upper interface between massive ice and the overlying sediment, thus indicating the upper extent of the ice body. The reflection seen between 10 ns and 20 ns later is interpreted as a lateral off-center reflector and not as the bottom of the ice body. Thickness of this ice body is, therefore, not resolved.

This part of the study area is in a low-lying region with almost no relief. The ice body discussed herein is situated 300 m from a small lake. Three shotholes were drilled within 45 m of the ice shown at the beginning of GPR line LDB-37. Two of the records, CVL03-1709.5 and CVL02-2015.5, describe a subsurface composed of clay, sand, gravel and rocks; no specific stratigraphy is described. This sedimentological composition, combined with the apparent lack of stratification, is consistent with a poorly sorted glacial diamicton. The third record, CVL02-2021.5, lists the shothole log materials as sand and sandstone, suggesting that the diamicton is underlain by sandstone bedrock.

Near-surface hyperbolic reflections within the GPR profile indicate the presence of rocks or boulders, while reduced wave propagation at depths over 8 m indicates a matrix of fine-grained materials. This is supported by the recorded surficial geology. The continuous nature of the strong reflector shown in Figure 3 is inconsistent with sandstone bedrock. The lack of hyperbolae associated with this interface indicate a lack of fracturing, thus presenting a profile that is atypical of sandstone. This feature within the GPR profile is interpreted as massive ice due to the size and strength of the reflection at a depth in excess of 10 m, as well as the exclusion of bedrock as an alternative reflector.

The genesis of this ice body is likely that of intrasedimental ice formation processes. The localized surficial geology offers a profile typical of this type of ice growth. An unsorted, structureless diamicton with a fine-grained matrix has been shown to be the most common sedimentary profile overlying massive ice in both the western Canadian Arctic and in Russia (Mackay and Dallimore, 1992). The massive ice is usually underlain by coarse materials, typically sand. Mackay and Dallimore (1992) report that the massive ice was found to be intrasedimental ice resulting from segregation and/or intrusion processes. The shothole records used here, in conjunction with GPR facies analysis, describe near-surface deposits that are conducive to similar ice growth processes. The inclusion of sand in all of the sedimentary data, as well as the documentation of sandstone bedrock, suggests a porous layer of either sand or sandstone that likely lies beneath the body of massive ice. Ice segregation has been found to require grain sizes of less than 0.01 mm in diameter (Taber, 1929). The presence of clay within the localized sedimentology provides such conditions and is consistent with the material typically found to be overlying massive intrasedimental ice (Mackay and Dallimore, 1992). It is likely that this body of ice formed via segregation with the local, downward aggradation of permafrost during and following deglaciation.

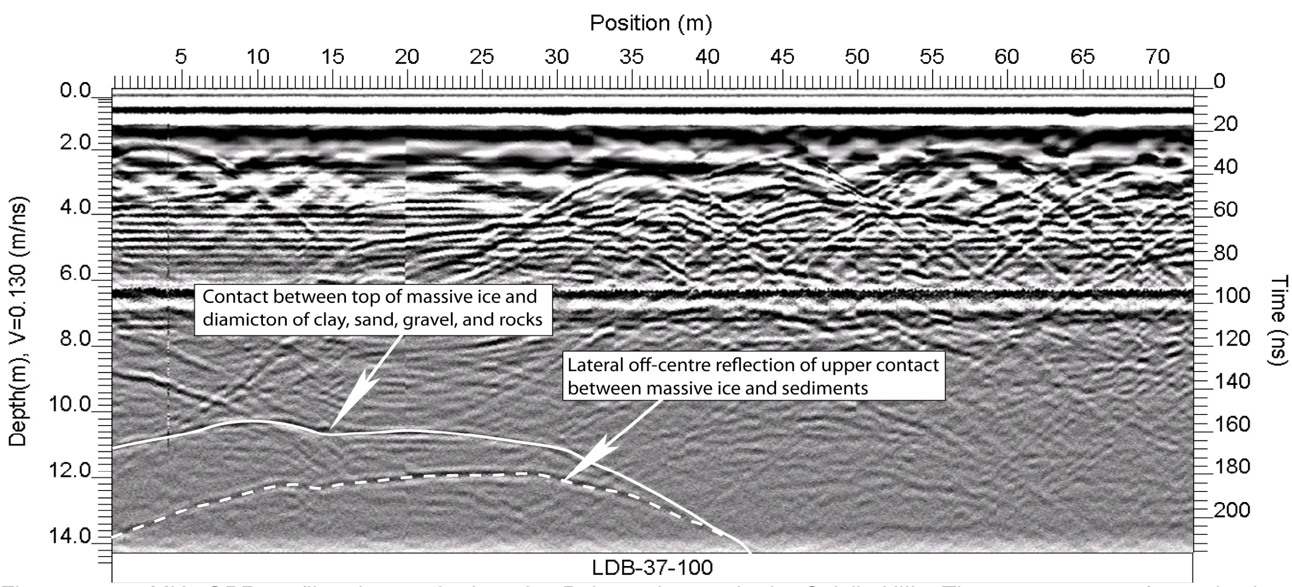

Figure 3. 100 MHz GPR profile taken at the Lac des Bois study area in the Colvile Hills. The upper extent of massive ice is delineated by a solid white line; a lateral off-centre reflection of that upper interface is indicated by a dashed line.

5 CONCLUSIONS

This study used GPR and seismic shothole drillers' logs to identify and characterize massive ice within the Little Chicago-Mackenzie corridor and the Lac des Bois-Colville Hills study areas. The following conclusions can be drawn from the results:

1. Occurrences of large bodies of massive ground ice have been confirmed in the widespread discontinuous permafrost of the two study areas. Large bodies of massive ice can be considered to be an important geomorphic feature of the subsurface and of specific interest to potential geotechnical concerns on a local and regional scale.
2. Two potential origins for large massive ice bodies are presented. It is likely that buried ice as well as intrasedimental ice is found within both study areas. Depositional history and associated near-surface sedimentary structures dictate the distributions of both types of massive ice.
3. Despite a spatially limited density of data, this study illustrates the effectiveness of the employed methodologies. Conjunctive use of GPR and seismic shothole drillers' logs can be considered to be a viable means of delineating and characterizing subsurface permafrost features, particularly massive ice.

ACKNOWLEDGEMENTS

Funding was provided by Natural Resources Canada's Environmental Geoscience Program (Northern Energy Development – Mackenzie Valley pipeline project) and the Program of Energy Research and Development (PERD) Pipelines program 1.2.5. The authors wish to thank the communities of Fort Good Hope and Colville Lake for their support of this research, and for the assistance provided by Wilfred Jackson, Robert Kochon and Shawn Tobac. Additional thanks are extended to Christopher Stevens and Pablo Wainstein for their input. This publication represents ESS contribution #20090386.

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