Using Ground-penetrating Radar and Seismic Shothole Drillers’ Logs to Identify Massive Ice and Taliks in the Lower Mackenzie Corridor and the Colville Hills, Northwest Territories

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Using Ground-penetrating Radar and Seismic Shothole Drillers’ Logs to Identify Massive Ice and Taliks in the Lower Mackenzie Corridor and the Colville Hills, Northwest Territories

by

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Abstract

Understanding of the distribution of massive ice and near surface taliks on a regional scale can offer important insights into the geomorphology, hydrology and quaternary geology in regions underlain by permafrost. These features are poorly constrained within the lower Mackenzie Valley and in the Colville Hills, two areas with the potential for hydrocarbon extraction.

This thesis used ground-penetrating radar to identify massive ice and taliks at two sites in the lower Arctic of the Northwest Territories. Lithostratigraphic data taken from shothole drillers’ logs at Little Chicago, in the lower Mackenzie Corridor, and Lac des Bois, in the Colville Hills, act as a complement to shallow geophysical surveying undertaken in March of 2009. Three occurrences of massive ice and one talik were identified at the two study sites. The combined effectiveness, and the limitations, of ground-penetrating and seismic shothole drillers’ logs were examined in this study.
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CHAPTER ONE: INTRODUCTION

In recent years ground ice and permafrost thaw have received increased scientific scrutiny as a result of environmental and societal concerns (IPCC, 2007). In Arctic and sub-Arctic environments, such as those found in northern Canada, the presence of permafrost significantly alters the near-surface environment. The Intergovernmental Panel on Climate Change (IPCC) has advocated that research should be directed towards better understanding the interaction of permafrost and certain local environmental factors, including snow cover and surficial sediments (IPCC, 2007). Taliks are important hydrological features in permafrost areas. Unfrozen areas in permafrost terrain could release methane into the atmosphere (IPCC, 2007), contributing to greenhouse gas quantities in the atmosphere. This research tests the usefulness of non-invasive geophysics and existing lithostratigraphic logs in the detection of near-surface massive ice and taliks in the lower Mackenzie Valley and in the Colville Hills. Ground-Penetrating Radar (GPR) and seismic shothole drillers’ logs are used to identify massive ice and near-surface taliks at the Little Chicago and Lac des Bois study areas in the Northwest Territories.

1.1 SCIENTIFIC BACKGROUND

The delineation and characterization of massive ground ice and near-surface taliks requires a basic understanding of the permafrost setting. Knowledge of permafrost extent, distribution and structure are conceptually integral to this study.

1.1.1 Permafrost

Muller (1943) initially defined permafrost as perennially frozen ground. This definition has since been revised to describe thermal conditions rather than the physical state of earth materials; permafrost is now considered to be sediment or bedrock that remains below 0 °C, or cryotic, for at least two years (Permafrost-Subcommittee, 1988). Permafrost regions are deemed
to cover more than half of Canada’s land mass (Smith and Riseborough, 2002) and more than 20% of the Northern Hemisphere (Zhang et al., 2008).

Permafrost is often classified by its extent across a given area. In a particular region permafrost can be continuous (underlying 90-100% of the surface), discontinuous (50-90%), sporadic (10-50%), or isolated (0-10%) (Permafrost-Subcommittee; 1988 French, 2007). Typically these classifications of permafrost have been made on latitude and are predicated on climate (Smith and Riseborough, 2002). Mean Annual Air Temperature (MAAT) is the most important environmental factor in the development and preservation of permafrost. French and Slaymaker (1993) conclude that the southern extent of continuous permafrost corresponds with MAATs between -6°C and -8°C and that the southern limit of discontinuous permafrost occurs with MAATs of approximately -1°C.

While the occurrence of permafrost is primarily a function of MAAT, the effect of air temperature on the ground thermal regime can be mitigated by local environmental factors. Increased snow cover has been shown through empirical and numerical modelling to have a warming effect on the ground thermal regime (Goodrich, 1982; Smith and Riseborough, 2002). Smith and Riseborough (1996) concluded that the thermal conductivity of the ground, both when frozen and unfrozen, at a given site could alter the relationship between air temperature and ground temperature, thus affecting local permafrost conditions. Shur and Jorgensen (2007) demonstrated that different types, and/or a lack, of vegetation can be a causal factor in the development, preservation or degradation of permafrost. In some cases, particularly in mountainous terrain, slope and aspect can influence permafrost distributions (Lewkowicz and Ednie, 2004).
In areas underlain by permafrost there is a seasonal active layer at the ground surface that is subject to annual thawing and freezing (Permafrost-Subcommittee, 1988). In cases where there is high salinity or clay-rich sediment, the active layer may extend into the top of the permafrost, as these types of sediment profiles may become unfrozen yet remain cryotic (i.e., maintain temperatures below zero). Because thaw depth is variable on a year to year basis a three layer system has been proposed. Shur et al. (2005) suggest that a transient layer, penetrating beyond the top of permafrost, represents years of exceptionally deep thaw that occur at sub-decadal to multi-centennial intervals. Summers of extreme warmth cause thawing of the upper, ice-rich, part of permafrost and can result in slope instability, rapid mass movements and increased solifluction activity (Mackay, 1980; Shur et al., 2005; French, 2007; Morse et al., 2009). Lantz and Kokelj (2008) suggests that the frequency of these melting events has increased during recent climate warming.

At the bottom of the active layer there is the upper boundary of permafrost, referred to as the permafrost table (Permafrost-Subcommittee, 1988). The depth of the permafrost table below the ground surface depends on topography, exposure to insolation, vegetation cover, snow cover, drainage and the thermal properties of the ground (Washburn, 1979). Generally, active layer thickness varies inversely with latitude; in the High Arctic active layer thicknesses of less than 15 cm are typical (Permafrost-Subcommittee, 1988); in the discontinuous permafrost of the sub-Arctic the active layer is often more than a metre (Smith and Burgess, 2002; Tarnocai et al., 2004). The lower boundary of permafrost is called the permafrost base and corresponds to the zero degree isotherm. This is the depth at which the ground temperature is below 0°C; beyond this depth ground temperatures are above 0°C (Permafrost-Subcommittee, 1988). The distance between the permafrost table and the permafrost base is the thickness of permafrost.
1.1.2 Massive ice

A primary focus of this study is on massive ice. Massive ice refers to pure, or nearly pure, ice bodies whose volumetric ice content is at least 250% (Permafrost-Subcommittee, 1988; French, 2007). This is differentiated from excess ice which is soil having ice volume that exceeds the pore space in natural, unfrozen conditions (Permafrost-Subcommittee, 1988). Massive ice is found in a variety of forms, generally distinguished by the process that resulted in its formation, or by the source of unfrozen water immediately before freezing (Dallimore and Davis, 1992; Mackay, 1971; Mackay, 1972; Moorman et al., 1998).

For the purposes of this study there are two broad categories of massive ground ice that are of interest. One is ice that has formed \textit{in situ} within existing sediments or bedrock, and the other is surface ice that has been buried (Mackay, 1972; Mackay and Dallimore, 1992). Types of buried surface ice include sea ice, lake ice, river ice, icing ice (\textit{aufeis}), and glacier ice. The Western Canadian Arctic contains massive ground ice of different origins. Mackay and Dallimore (1992) concluded that most of the ground ice in the Tuktoyaktuk Peninsula is intra-sedimental ice. Similarly occurrences of massive ice in the Klondike district of the Yukon Territory and in northern Alaska are the product of segregation or segregation-injection processes (French, 1990). In the Slave geologic province in the Northwest Territories buried ice has been identified in coarse glaciofluvial sediments (Wolfe et al., 1997). Buried glacier ice is believed to be present on Banks Island and near Eskimo Lake in the Western Canadian Arctic (French, 1990).

Estimations on the extent and distribution of ground ice in the northern hemisphere have been made by Zhang et al. (2008). On a continental scale ground ice quantities within Canada are described by Heginbottom et al. (1995). In the Western Canadian Arctic ground ice mapping
has been done on a regional scale (French, 1998; Smith and Lesk-Winfield, 2012). Localized mapping of ground ice extent and distribution has been done in parts of the Western Canadian Arctic. Pollard (1989) identified and described massive ice on Herschel Island, in the Yukon Territory. On the Tuktoyaktuk Peninsula massive ground ice and icy sediments have been identified and characterized by Rampton et al. (1971) and by Mackay and Dallimore (1992). More recently Smith and Duong (2012) have quantified the distribution of massive ice on the Tuktoyaktuk Peninsula. On the Pleistocene Delta just east of Tuktayaktuk massive tabular ice at Peninsula Point was identified and characterized by Moorman et al. (1998). French and Harry (1988) outlined ground ice distribution and origins at a specific site on Banks Island.

The presence of massive ice can be a precursor to important, dynamic geomorphic processes in permafrost environments. The development of thermokarst is poorly understood in magnitude and extent. Thermokarst activity in northern Siberia has been described as occurring on a regional scale and taking place over a millennial time-scale in variable climates (Romanovskii et al., 2000). In the Western Canadian Arctic widespread thermokarst activity is thought to have occurred in the early-to-middle Holocene (Burn, 1997; French, 1999). Modern morphologies of melting ground ice include active layer detachments (Lewkowicz, 2007), retrogressive thaw slumps (Lewkowicz, 1987), and thermokarst, or thaw, lakes (Hinkel et al., 2005). The understanding of ground ice distribution, extent and origin is important in a scientific context as it offers insights into climate change, permafrost geomorphology, landscape evolution and paleoclimatology (De Pascale et al., 2008). Delineation of massive ground ice can therefore be regarded as an important characteristic for predicting landscape change in high latitude environments. Ground ice distribution has not been mapped on a regional scale within the lower Mackenzie Corridor and the Colville Hills.
High ice content in the ground, and the associated potential for landscape instability, present a significant hazard to northern development (Mackay, 1972). Thaw settlement associated with the melting of ground ice, or the thawing of ice-rich permafrost, has been implicated in infrastructure failures across a variety of permafrost terrains (French, 2007). Moorman et al. (2003) suggests that the melting of excess ground ice is one of the greatest geotechnical hazards found in permafrost regions. The detection of massive ice is therefore important in the context of future infrastructure development.

1.1.3 Taliks

A talik is a sub-surface unfrozen layer, or body, situated within a permafrost area (Permafrost-Subcommittee, 1988). There are eight, not necessarily exclusive, types of taliks: closed taliks, hydrochemical taliks, hydrothermal taliks, isolated taliks, lateral taliks, open taliks, thermal taliks and transient taliks (van Everdingen, 1990). For the purpose of this research only closed taliks, isolated taliks, lateral taliks and open taliks are considered relevant. These four types of talik can be either cryotic (having a temperature of less than 0°C) or non-cryotic (kept unfrozen by high ionic concentrations) and are further distinguished by their location within the permafrost system. Closed taliks are non-cryotic layers that contribute to a dip in the permafrost table (Permafrost-Subcommittee, 1988). They are most commonly associated with thermal heat transfer from a lake or river into underlying sediments or bedrock. An isolated talik is surrounded by frozen ground on all sides, and is typically cryotic, but may also be non-cryotic. A lateral talik is underlain and overlain by permafrost. Open taliks completely penetrate the permafrost layer and often act as a conduit between supra- and sub-permafrost groundwater.

Talik development and maintenance can have a significant influence on physical, chemical, biological and geomorphologic processes within the sub-surface environment (Johnston and
Brown, 1964). The development of certain periglacial landforms and processes such as proglacial springs and icings, lake drainage and groundwater flow are often reliant on the presence of taliks. Moorman (2003) noted the importance of groundwater flow through a talik in feeding a proglacial spring. The preservation and re-generation of a proglacial icing on Bylot Island depends on the existence of a talik as its source of water (Wainstein et al., 2008). Often the thermal nature of taliks can cause changes in the surrounding permafrost. Thaw settlement and permafrost degradation have been associated with taliks (Johnston and Brown, 1964). Knowledge regarding the distribution and causes of taliks in permafrost terrain is an important component of periglacial science.

Within permafrost terrains taliks represent a significant risk to geotechnical endeavours. Thaw settlement as a result of talik formation has been shown to decrease load bearing capacities and thus have had adverse effects on the performance of man-made structures (Johnston and Brown, 1964; Lunardini, 1996). Near-surface taliks can also be of concern in permafrost engineering for reasons other than thaw settlement. Frost heaving resulting from the freezing, or re-freezing, of a talik can lead to the failure of pipelines, roads and other structures. Experiments conducted under field conditions demonstrate the problematic nature of pipeline construction in permafrost areas which have taliks (Khrenov, 2010). A chilled pipeline running through a talik in Alaska experienced frost heaving of 197 mm within 200 days; this was observed within 3-5 m of the lateral extent of the talik. The pipeline was displaced by 400 mm in total at the frozen-unfrozen interface (Huang et al., 2004). Khrenov (2010) concludes that chilled pipelines which cross taliks need to be constructed above ground. Talik distribution is poorly understood within the lower Mackenzie Valley and the Colville Hills.
1.2 RESEARCH OBJECTIVES

The following specific objectives are addressed in this study:

- To test the viability of GPR in the detection of massive ice.

- Identify GPR facies that are consistent with massive ground ice.

- Assess the viability of using seismic shothole drillers’ logs in the identification and delineation of near surface taliks when combined with GPR facies analysis.

Ground-penetrating radar data gathered in the field is interpreted in the context of surficial geology, hydrology and topography. It is through the combination and analysis of these data that this study intends to meet its stated objectives.

1.3 SCIENTIFIC APPROACH

To accomplish the objectives of this study a multi-method approach, using shallow geophysics, drillers’ log data and surficial mapping was applied.

- Shallow geophysical surveys, using GPR, were used to map near-surface sedimentary and thermal structures and delineate massive ice.

- Seismic shothole drillers’ logs, collected during geophysical exploration surveys, were used to correlate lithostratigraphic data with relevant GPR profiles.

- Air photographs were used to map permafrost features, contextualizing GPR profiles and aiding in the interpretation of massive ice or icy sediments.

- Existing surficial geology mapping data was used to understand the nature of unconsolidated sediments and aid in the interpretation of near surface morphologies.
1.3.1 The use of ground-penetrating radar in the delineation of massive ice and taliks

Ground-penetrating radar (GPR) functions by emitting a pulse of electromagnetic (EM) energy into the subsurface. At or, in some cases, above the ground surface a transmitter sends out a series of EM pulses; a receiver records the energy that is returned. A control unit, in this case a Digital Video Logger (DVL), records the time at which each pulse is returned. The signal that is returned to the receiver is dictated by the propagation and reflection of the EM wave through the medium being studied. This propagation is directly affected by three physical properties: (i) electrical permittivity, (ii) electrical conductivity and (iii) magnetic permeability (Davis and Annan, 1989). When an EM wave encounters a discontinuity in any or all of these properties a portion of the energy is reflected with varying levels of amplitude (Neal, 2004). Through the interpretation of the signal returned to the receiver it is possible to resolve subsurface structures.

The nature of data gathering used by GPR makes it an effective and nonintrusive tool for studying near-surface features. A variety of disciplines have made use of GPR as a research method for studying a variety of subjects, including sedimentology (Tronicke et al., 2002), limnology (Moorman and Michel, 1997) and geomorphology (Gilbert, 2000).

The capabilities and limitations of GPR within geomorphological research is summarized in Neal (2004). Moorman et al. (2003) describes the usefulness of GPR in detecting massive ice and at identifying thermal interfaces. The physical properties of ice are such that it is subject to relatively low levels of attenuation as compared to other sedimentary media. Electromagnetic waves are attenuated at a rate of between 1-300 dB/m when propagating in clay, 26 dB/m in silt and between 0.03-3 in sand as opposed to 0.01 dB/m when the medium is pure ice (Davis and Annan, 1989). Previous studies provide examples of the effectiveness of GPR in the delineation of massive ice. Massive ice has been successfully studied using GPR in the Canadian Arctic.
Archipelago (Dallimore and Wolfe, 1988; Robinson, 1994), Alaska (Yoshikawa et al., 2006), Antarctica (Fukui et al., 2007) and the Mackenzie Delta (DePascale et al., 2008). The literature validates the use of GPR in the detection of massive ice across diverse sedimentary environments.

In the Western Canadian Arctic studies with objectives similar to this study provide a sound scientific background for the use of GPR in the delineation of massive ground ice. Wolfe (1998) used a combination of borehole data and GPR to identify massive ice in a glaciolacustrine delta in the district of Mackenzie, NWT. Massive ice in excess of 100 m in lateral extent, as far as 16 m below the surface, was observed at three locations. In a separate case study massive ice was detected in glaciofluvial deposits in the Slave geological province in the northern Northwest Territories using 50 MHz frequency GPR (Wolfe et al., 1997). Massive ice in this case presented in the GPR returns as strong semi-continuous reflectors, representing the top and bottom of massive ice. Massive ice ranging from 4 to 16 m in depth, covering a lateral extent of 125 m and with a maximum thickness of 7 m was identified. A good example of a GPR signature indicative of massive ice is seen in Figure 5 of Wolfe et al. (1997).

The literature illustrates examples of the effective application of GPR in process-based studies in permafrost terrain. These successes, however, highlight the agreement that correlation between GPR profiles and ground control data is essential in order to make meaningful interpretations in permafrost environments (Dallimore and Davis, 1992; Moorman et al., 2003). The physical properties of moisture-rich sediments changes significantly when they are frozen. Typically, frozen sediment has a dielectric constant of 6 as opposed to 25 when it is thawed and wet (Davis and Annan, 1989). This causes the reflection of GPR waves at the interface between frozen and unfrozen materials. The understanding of this principle has led to the use of GPR in
the detection of near surface taliks. Yoshikawa and Hinzman (2003) used GPR to map talik formation near thermokarst ponds in discontinuous permafrost in western Alaska. The structure of taliks underneath streams on the North Slope of Alaska was also effectively mapped using GPR (Arcone et al., 1998).

1.3.2 Seismic shothole drillers’ logs

Geotechnical and exploration drilling has been a useful source of information in the study of permafrost geology. On a localized scale this type of data has also been employed in the detection and characterization of massive ice. Rampton and Mackay (1971) used geotechnical boreholes to describe massive ground ice bodies and their surrounding sediments on Richards Island, NWT and on the Tuktoyaktuk Peninsula. This allowed for conclusions to be made regarding the morphology and genesis of the massive ice.

The first published study of drillers’ log data was by Mackay (1971) and Rampton and Mackay (1971) who analyzed approximately 5000 drillers’ logs from Richards Island, Tuktoyaktuk Peninsula, and adjacent regions in an attempt to reconstruct regional massive ice and ground ice (“icy sediments”) characteristics. Mackay (1973) expanded upon the previous study to include a reported 15 000 drillers’ log records. Subsequently, Côté et al. (2003) digitally compiled 13 574 shothole drillers’ log records (inclusive of Rampton and Mackay’s (1971) 5000 records, and Mackay’s (1973) 15 000 records), expanding the interpretation of regional massive ice and ground ice occurrences. More recently Smith and Lesk-Winfield (2010a) and Smith (2011) iteratively compiled and published, in database and GIS formats, all available seismic shothole drillers’ log records in northern Yukon and continental Northwest Territories that were held in Geological Survey of Canada and corporate archives. These 343 989 records (in addition
to the 13 574 records of Côté et al. (2003)) span the years 1952-2008 and represent the most
detailed lithostratigraphic record of surficial geology, massive ice, and ground ice in the region.

Studies using GPR as the primary methodology generally require ground control data in
order to give context to facies analysis. In the absence of geotechnical drilling or dedicated
ground-truthing, this study uses seismic shothole drillers’ records as its ground control data. On a
regional scale Smith and Lesk-Winfield (2010b) used seismic shothole drillers’ logs to compile
information regarding a variety of periglacial features including the presence and thickness of
massive ice and the distribution of relic taliks across the Northwest Territories. Logs taken at the
Little Chicago and Lac des Bois study areas between 1972 and 2008 have been compiled and
prepared as both a database and as a GIS dataset. They are used here to aid in the identification
of massive ground ice and near surface taliks.
CHAPTER TWO: STUDY AREAS

Research was conducted in two separate study areas, Little Chicago and Lac des Bois, both of which are located in the northern, continental Northwest Territories, Western Canadian Arctic (Figure 1). The geographic areas of interest for this study were chosen because of recent seismic exploration at both sites. Seismic surveying required that lines be cut though the forest and undergrowth; these recent cut-lines permitted relatively easy passage by skidoo through an otherwise largely impenetrable boreal forest, thereby permitting GPR transects to be undertaken.

Figure 2.1. Location of Little Chicago and Lac des Bois study areas within the Northwest Territories
The Little Chicago site is in the lower Mackenzie corridor. The field base for this site was Wilfred Jackson’s cabin, situated at 67°6’7’’N, 130°15’17’’W on the western bank of the Mackenzie River. This site is approximately 110 km northwest of Fort Good Hope and 270 km from Norman Wells.

The Lac des Bois study area is in the Colville Hills, 250 km to the east of Little Chicago, 65 km south of the hamlet of Colville Lake, and 180 km to the northeast of Norman Wells. The field base of operations was Robert Kochon’s cabin situated at 66°30’06’’N, 125°10’11’’W, on the western shore of Lac Des Bois, ~40 km north of Great Bear Lake’s Smith Arm.

The two sites have been the focus of recent hydrocarbon exploration projects. In the winters of 2007 and 2008, a seismic survey was carried out at the Little Chicago area by Kodiak Energy. In February and March of 2008 a seismic exploration was carried out at Lac des Bois by Explor. These two projects cut 2 to 5 m swaths in the forest to facilitate the movement of drilling, recording, related equipment and temporary housing.

2.1 GEOLOGY

The two study areas are situated in the Interior Plains physiographic region. Bedrock in the Little Chicago area is comprised of Paleozoic sedimentary rocks, typically shale and sandstone (Ecosystem Classification Group, 2007; Wheeler et al., 1997). The area was inundated during the late Wisconsinan glaciation, and is characterized by a fine textured till blanket, often mantled by peat plateaux (Tarnocai et al., 2003). A large glacio-fluvial terrace network of coarse-grained sands and gravels is found in the area, and silty-sand glaciolacustrine deposits blanket the low-lying regions along the Mackenzie River Valley (Duk-Rodkin, 1992; Duk-Rodkin and Hughes, 1992). Deglaciation of the region occurred between 13 and 14 ka (Dyke, 2004).
The Lac des Bois site is predominately underlain by Ordovician and Silurian dolomites of the Mount Kindle Formation (Cook and Aitken, 1971). Devonian limestone is interspersed with these more resistant materials; notable karst features, including sinkholes, have been mapped in the area (Cook and Aitken, 1971; Ecosystem Classification Group, 2007). Bedrock outcrops, such as those on the Belot and Manoir ridges, define the Colville Hills region. Typically bedrock in the area is overlain with gently undulating, coarser-grained till veneers and blankets. Glaciofluvial features, such as anastomosing esker systems, were observed during field work by Dr. Rod Smith. Deglaciation of the Lac des Bois area occurred between 11 and 12 ka (Dyke, 2004).

2.2 VEGETATION

Vegetation distribution and structure in the lower arctic and subarctic is primarily dictated by climate (Timoney et al., 1993). The two study areas contain similar, yet not identical, plant communities. The Little Chicago and Lac des Bois study areas are in the Taiga Plains ecozone of Canada’s northwest (Marshall, 1999). More specifically, the Lac des Bois and Little Chicago sites are found within the sub-region known as the Northern Great Bear Plains High Subarctic Ecoregion (NGBPHSE) (Ecosystem Classification Group, 2007). Locally constrained within the NGBPHSE, Little Chicago and Lac des Bois are found within two smaller ecoregions: the Arctic Red Plain High Subarctic Ecoregion (ARPHSE) and the Colville Hills High Subarctic Ecoregion (CHHSE), respectively.

The ARPHSE, in which the Little Chicago site is located, is characterized by a forest dominated by black spruce with an understory that is comprised of willow, red bearberry, dwarf birch and lichens (Ecosystem Classification Group, 2007). Field observation recorded an open
canopy forest in which there were several areas that had burned within the last 20 years, and are now regenerating.

The CHHSE region (containing the Lac des Bois site) has a slightly different forest structure than that of the TUHSE. Here the forest is more mature and is dominated by white spruce; willow, larch and black spruce are also found here (Ecosystem Classification Group, 2007). The ground vegetation in this area is typically composed of northern and common Labrador tea, cloudberry, sedges, cotton-grass, lichens and mosses. Field observations show a less open canopy than at Little Chicago. Recent (<20 year) forest fires appear to have affected only a small percentage of the area surveyed.

2.3 CLIMATE

Located in the lower Western Canadian Arctic, both study areas are subject to long cold winters and short cool summers. Long-term, detailed climatological data is not available for the two sites. What limited regional climate data that exists for the region is derived from Environment Canada records (Canada, 2009). The nearest long term weather station is at Norman Wells where the mean annual air temperature (MAAT) was -6.3°C for the period from 1951-1980. The Little Chicago site has an adjacent Environment Canada weather station that recorded temperature for the year 2006. This showed a MAAT of -5.4°C (Canada, 2009). At Fort Good Hope the MAAT for the eight year period from 1999-2006 was -5.7°C (Canada, 2009). No precipitation data is available for the Little Chicago government weather site. At Fort Good Hope the average annual precipitation was 229.7 mm from 2003 through 2006. During this time 63% of the precipitation was in the form of snow; eliminating one rain-heavy year (2006) raises this average to 70.8% of the annual water equivalent budget.
Local data for the Lac des Bois site is less robust. Natural Resources Canada weather data from Colville Lake shows a MAAT of -7.7°C between 2004 and 2006 (Canada, 2009). Actual precipitation data is not available for this area, however Derksen and Mackay (2006) describes a perennial band of low pressure that exists at the northern extent of the boreal forest in the Great Bear Lake region. This band typically deposits roughly 100 mm water equivalent of snow in the late fall to early winter. The temperature data for both study areas is commensurate with the southern extent of continuous permafrost according to recent ground temperature modelling (Smith and Riseborough, 2002).

2.4 REGIONAL PERMAFROST

The Little Chicago and Lac des Bois study sites are situated within the continuous permafrost zone (Heginbottom et al., 1995). Local data regarding permafrost thickness is unavailable for both study areas. Nearby sites have, however, been studied with regards to permafrost thickness. Approximately 110 km to the southwest of Little Chicago, at Fort Good Hope, permafrost thicknesses range from 33-48 m. At Tsiigehtchic ~150 km to the northwest of Little Chicago, permafrost is 107 m thick. (Smith and Burgess, 2002). Roughly 70 km to the southeast of the Lac des Bois site, at the El Dorado Uranium mine, permafrost was recorded as being 104 m thick. In and around Norman Wells permafrost, where present, is between 15-67 m thick (Smith and Burgess, 2002).

Active layer thickness in the Mackenzie Valley varies from 50 cm to 140 cm. At Norman Wells active layer thicknesses between 50 cm and 130 cm were recorded (Smith and Burgess, 2002; Tarnocai et al., 2004). Roughly 130 km to the northwest active layer thicknesses at Fort Good Hope range between 90 cm and 140 cm (Smith and Burgess, 2002). Further down the Mackenzie River, 35 km south of Little Chicago, active layer thickness at the Grand View
site has fluctuated between 75 cm and 91 cm between 1992 and 2005 (Smith et al., 2009). At Tsiigehtchic, ~ 150 km northwest of Little Chicago, active layer thickness varied between 80 and 98 cm between 1992 and 2006 (Smith et al., 2009). Recent monitoring has shown that active layer thickness values in the Mackenzie Valley are poorly correlated with latitude (Smith et al., 2009) (Figure 2.2). Primary controls on active layer thickness in the region are, therefore, likely local environmental conditions and not broad-scale temperature gradients. Active layer thickness in the Colville Hills has not been measured.

![Figure 2.2 Active layer thicknesses (cm) vs. latitude (decimal degrees), Mackenzie Valley, NWT. Data from Smith et al. (2009).](image)

Ground ice mapping of Canada shows a regional discrepancy between Little Chicago and Lac des Bois in regards to ground ice quantities (Heginbottom et al., 1995; Smith and Lesk-
Winfield, 2010b). The lower Mackenzie corridor, including the Little Chicago site, is regarded as having moderate-to-high ground ice content. The Colville Hills region, encompassing the Lac des Bois site, has been classified as having low to moderate amounts of ground ice. Ground ice occurrence and distribution for both sites is poorly constrained. Regional records indicate that ground ice (of unknown origin and morphology) is found in, or around, both Little Chicago and Lac des Bois (Smith and Lesk-Winfield, 2010a). Thermokarst lakes and drunken forest (see figure 2.3), indicative of melting of excess ground ice, were observed at the Lac des Bois site.

Figure 2.3 Drunken forest seen in Lac des Bois area, March 16, 2009.

2.5 RELIEF AND DRAINAGE

The topography of the Little Chicago and Lac des Bois sites are typical of the northern Interior Plains. Both areas are relatively low-lying and are flat to moderately undulating. At Little Chicago the elevation ranges between 25 and 200 m above sea level (asl). East of the
Mackenzie River the ground rises and at Lac des Bois the elevation is 300 m asl. Maximum elevation for the Lac des Bois study area is approximately 340 m asl. Topography and hydrology for the two study sites can be seen in figures 2.4 and 2.5.

Figure 2.4 The relative topography as indicated by shaded relief around the Little Chicago study area. An azimuth of 345 degrees and a vertical exaggeration of 3x was used. *Elevation data derived from NASA Aster DEM data (2010).*
Figure 2.5 The relative topography as indicated by shaded relief around the Lac des Bois study area. An azimuth of 345 degrees and a vertical exaggeration of 3x was used. *Elevation data derived from NASA Aster DEM data (2010).*

Drainage in the little Chicago area is into the Mackenzie River. The Lac des Bois site drains into Liverpool Bay via Lac des Bois and the Anderson River. Locally the surface hydrology of both study areas is dominated by series of poorly-draining lakes, bogs and small streams.
CHAPTER THREE: METHODS AND DATA ACQUISITION

3.1 GROUND-PENETRATING RADAR DATA ACQUISITION

Because a thawed active layer with high water content is highly attenuating to GPR pulses, and because winter snow cover provided access for snowmobile transportation, fieldwork was conducted March 2-17, 2009. Temperatures during work days were between -16°C and -48°C. The cold temperatures encountered in the field dictated that special measures needed to be taken to ensure the operability of the radar unit. The Digital Video Logger (DVL), 12V batteries and multiplexer were placed in a hard, insulated plastic cargo container during data collection. A clear plastic top to this container allowed the operator to monitor the progress of the GPR lines being collected. In order to keep the instruments warm the container was packed with four hot water bottles that had been filled with boiling water at the beginning of each day. The top of the box was lined with an insulating blanket when the system was not collecting data. Batteries were charged at night with the use of a gasoline powered generator.

Subsurface stratigraphy was imaged using a PulseEKKO Pro GPR unit. Two frequencies were used during data collection at both sites. Simultaneous 100 and 250 MHz surveys were conducted with the use of a multiplexer. The system was pulled between 4-7 km/hr by snowmobile with transmitters and receivers lying parallel to the direction of travel. The unshielded 100 MHz antennae were arranged with an antenna separation of 1 m; the 250 MHz had a separation of 40 cm. A time window of 280 ns was used. The profiles were acquired in continuous or free run, mode with either 4 or 8 stacks. A handheld Garmin E-trex10 Global Positioning System (GPS) receiver was connected to the radar unit and collected positional data every five GPR traces. Upon return from the field, the GPR data were filtered for low frequency signal saturation and (enhanced with an Automatic Gain Control (AGC). Wave propagation
velocity was set at 0.13 m/ns based on previous research in similar sedimentary environments and ground thermal regimes (Wolfe et al, 1997; Wolfe, 1998).

While attempts were made to simultaneously record multiple frequencies (100, 250, 500, 1000 MHz), only the 100 MHz antennae provided data with sufficient depth of penetration to be of use in this study. A deep snow pack and other near surface conditions meant that higher frequencies were subject to too much attenuation of the radar signal and therefore could not provide sufficient depth of penetration to be effective within the parameters of this study. Extreme cold temperatures and difficult field conditions also inhibited their operability.

Selection of the two study areas was based on the presence of seismic cutlines. These 2-5 m wide cutlines, made during the winters of 2007 and 2008, provided avenues of travel for snowmobiles, free of trees and shrubs, along which data could be collected. The operator, the control unit (DVL, batteries and multiplexer) and shielded antennae were towed directly behind the snowmobile in a 2 m long toboggan. Because the 100 MHz receiver and transmitter are unshielded, and thus receptive to outside sources of EM energy (eg. EM waves produced by the engine of a snowmobile), they require sufficient separation from the snowmobile. They were pulled ~10 m behind the toboggan connected by a fibre optic communication cable protected within a thick plastic hose. The 100 MHz antennae were mounted to wooden sleds with a plastic shield beneath. This enabled the antenna assembly to slide smoothly across the snow and not get caught up by small protrusions. The 100 MHz setup is shown in Figure 3.1.
3.2 GROUND-PENETRATING RADAR DATA PROCESSING

The profiles used in this study were processed through the EKKO pro software package from Sensors and Software, Inc. The data has been filtered, dewowed, repositioned according to GPS readings and processed with digital gain. Typically a constant gain was applied to enhance later surface returns during facies analysis.
3.3 SEISMIC SHOTHOLE DRILLERS’ LOGS

In this study, seismic shothole drillers’ records were used as a source of lithostratigraphic information (Smith, 2011). These data were collected during seismic surveys conducted between 1972 and 2008. At Little Chicago former exploration company Western Decalta provided 324 drillers’ logs from a 1972 seismic survey. A further 339 records are the product of a 2007 seismic program conducted by Kodiak Energy Limited. The logs recorded lithostratigraphic data from as deep as 18.2 metres. Explor, a Calgary-based seismic exploration company, conducted a seismic survey in and around the Lac des Bois study area. Subsequently 2732 logs, recording unconsolidated materials, bedrock and other stratigraphic features up to a depth of 9 metres, were collected in the area. The drillers’ records taken in and around the Little Chicago and Lac des Bois study areas have been compiled and prepared as both a database and a GIS (Smith, 2011). They are used in this study as complementary data during interpretation of the radar facies.

3.4 SNOW DEPTH MEASUREMENT

Snow depth measurements were made only at Lac des Bois. Measurements were made, on and off the snowmobile trail, with a graduated frost probe. This was done at 29 locations along the GPR transects.
CHAPTER FOUR: RESULTS

Field work in March 2009 yielded 83 GPR profiles along 58.4 km of seismic cutlines at the Little Chicago and Lac des Bois study sites.

4.1 GROUND-PENETRATING RADAR FACIES DESCRIPTIONS

Radar facies observations and interpretations follow the principles employed by Jol and Smith (1991). Observation and analysis of individual profiles and sections of profiles, allowed for the interpretation of the morphology, strength and depth of returns. Depth of signal penetration, and occurrence of signal attenuation, has also been noted where applicable. Average theoretical velocity has been set at 0.13 m/ns. Arrival at this number is based on the assumption of frozen sediments, results from other work in permafrost regions (Wolfe, 1998; Wolfe et al., 1997), and based on the materials commonly found in the areas. At certain locales, where hyperbolic reflections exist, inverse modelling has been used to adjust the velocity of the EM wave. These values can used to make deductions as the type of material through which the EM wave has passed. Reflections were most commonly categorized into the following architectural groups: 1) Laterally continuous (>30m), horizontal to sub-horizontal parallel reflections; 2) Discontinuous (<30m), or disrupted reflections; 3) Parallel and sub-parallel, dipping, reflections; 4) Concave, or bowl-shaped reflections; and 5) Chaotic reflections or diffractions. Examples of commonly observed architectures are shown in Table 4.1.
<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
<th>Example / Schematic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laterally continuous, horizontal to sub-horizontal reflections</td>
<td>More than 30 m across with little, or no, change in slope angle</td>
<td>![Image of continuous reflections]</td>
</tr>
<tr>
<td>Discontinuous, or disrupted, reflections</td>
<td>Less than 30 m across; ranging from horizontal to hummocky</td>
<td>![Image of discontinuous reflections]</td>
</tr>
</tbody>
</table>
Dipping reflections

<p>| Short, inclined (&gt;10°) reflections that may be parallel or sub-parallel | <img src="image" alt="Diagram" /> | <img src="image" alt="Diagram" /> | <img src="image" alt="Diagram" /> |</p>
<table>
<thead>
<tr>
<th>Concave reflections</th>
<th>Reflection, or a series of reflections, that forms a bowl-shaped or saucer-shaped feature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chaotic returns or diffractions</td>
<td>Abundant individual reflections or intermingled hyperbolae</td>
</tr>
</tbody>
</table>
Table 4.1 Examples and schematics of commonly observed GPR facies

All profiles are described below with Universal Transverse Mercator (UTM) co-ordinates (eastings and northings) at the beginning and end of the profile and length of the profile along with any pertinent observations that were made in the field. Data that were corrupted due to equipment malfunctions are noted but not described. Subsections of interest are shown as figures. Digital Appendix A contains all of the GPR profiles as bitmap images.

4.1.1 Little Chicago

During six days of data collection 39 GPR profiles were collected at Little Chicago. These data were collected sequentially, beginning with profile LC-11 and ending with profile LC-49. The survey transect of GPR profiles LC-11 to LC-24, goes westward from the Mackenzie River for 14 km climbing from an area characterized by glaciolacustrine deposits and alluvial sediments onto a flat to gently sloping, morainal plain (Duk-Rodkin and Hughes, 1992); Figure 4.2). Data collection continues on a morainal plain with scattered fens. Figure 4.3 shows the location of radar profiles LC-25 to LC-49. This series of GPR data goes from till veneer onto outwash sands and gravels, and other ice contact glaciofluvial deposits, before turning north. As the transect moves north the terrain is again characterized by till deposits, typically presenting in gently sloping, fluted or drumlinoid morphologies (Duk-Rodkin and Hughes, 1992). Surficial
geology descriptions for individual GPR profiles at Little Chicago are derived exclusively from Duk-Rodkin and Hughes (1992).

The order of the GPR lines is sequential and moves clockwise in Figure 4.2 and Figure 4.3. Because of equipment failure, radar profiles LC-29 and LC-33 could not be positioned and are not depicted in Figure 4.2. Figure 4.1 shows the entire Little Chicago study area and Figure 4.1 and Figure 4.2 in a regional context; the markings on the map border denote the UTM co-

![Figure 4.1. Satellite image of the Little Chicago study area and the relative location of Figure 4.2 and Figure 4.3. Co-ordinates are in UTM. Source: http://www.geobase.ca/geobase/en/data/imagery/imr/index.html](http://www.geobase.ca/geobase/en/data/imagery/imr/index.html)
Figure 4.2. Satellite image of the eastern portion of Little Chicago with GPR lines LC-11 to LC-24. Source: http://www.geobase.ca/geobase/en/data/imagery/imr/index.html
Figure 4.3. Satellite image of the western portion of Little Chicago with GPR lines LC-25 to LC-49. Source: [http://www.geobase.ca/geobase/en/data/imagery/imr/index.html](http://www.geobase.ca/geobase/en/data/imagery/imr/index.html)
Figure 4.4. Surficial geology at Little Chicago. Modified from Duk-Rodkin and Hughes (1992).
The first profile from Little Chicago, LC-11, begins approximately 70 m from the western bank of the Mackenzie River. The line travels perpendicular to the river, heading west and climbs a small rise. Surficial geology across LC-11 consists of thick lacustrine deposits.

The first 50 m of LC-11 contains discontinuous, parallel, sub-horizontal reflections in the near surface. Ringing returns do not allow for the determination of maximum depth of penetration. The subsection from 50-95 m contains short (~10m), inclined reflections to a depth of between 3.5 m and 3.8 m. Between 95 m and 430 m there are discontinuous, sub-horizontal to weakly hummocky reflections observed to a maximum depth of 3.5 m. This architecture is disrupted by several inclined parallel reflections between 430 m and 455 m (Figure 4.5). There is an increase in signal penetration between 455 m and 560 m, as discontinuous returns are observed as deep as 4.7 m. Between 560 m and 590 m there is a bowl-shaped reflection that reaches a maximum depth of 5.0 m. It is onlapped by abundant disrupted reflections. From 590 m to 685 m there are discontinuous, sub-horizontal reflections and a maximum depth of penetration of 3.5 m. At 685 m penetration is reduced to less than 3.5 m and discontinuous sub-horizontal reflections persist to the end of the profile at 830 m with the exception of a 50 m section beginning at between 685 and 735 m where there is a wide bowl-shaped increase in signal penetration to 4.7 m.
Figure 4.5. Subsection of GPR profile LC-11 with short, inclined parallel reflections. Vertical exaggeration =7.5x.

*LC-12*

Start (UTM): 443968 E  7443341 N  
End (UTM): 443216 E  7443311 N  
Length: 753 m  

This line continues westward and crests the small rise described in LC-11. Approximately halfway through LC-12 an area of recent (~15 yr) forest fire is entered. The surficial geology of LC-12 is comprised of flat glaciolacustrine deposits overlain by colluvial slope deposits.

This profile is characterized by near surface attenuation which allows for no returns from deeper than 3.6 m. Continuous to discontinuous, horizontal to sub-horizontal reflections with no strong returns comprise the architecture of radar profile LC-12.
Continuing west, all of radar profile LC-13 is in the burned area described in LC-12 and shown in Figure 4.6. The line initially descends into a small boggy area before beginning a gradual climb. A stream is crossed ~225 m into the profile. At 680 m a pond of roughly 900 m$^2$, with a raised rim, is located to ~40 m to the right of the path of radar profile LC-13. The beginning of LC-13 consists of glaciolacustrine deposits. Roughly halfway through the profile the surficial geology transitions onto a drumlinoid plain.

Figure 4.6 Area of ~ 15 year old forest fire described in LC-12 and LC-13
The first 75 m of LC-13 contains discontinuous hummocky reflections with a signal penetration of less than 4 m. These discontinuous returns persist over the next 25 m. Between 75 and 100 m they are underlain by two strong reflections; a dome-shaped reflection between 2.6 and 4 m, and an inclined reflection that rises from 6.5 to 5.2 m (Figure 4.7). Between 100 and 230 m there are discontinuous, weakly hummocky reflections, with a maximum signal penetration of no more than 3.5 m. From 230 to 265 m a series of disrupted hummocky reflections comprise a wedge-shaped zone of increased propagation, with a maximum penetration of 4.9 m observed at the 250 m mark. Between 265 m and 365 m there is a maximum penetration of 3.9 m with discontinuous to disrupted, sub-horizontal reflections close to the surface. From 365 m to the end of LDB-13 at 1035 m there is a series of discontinuous, sub-horizontal reflections observed to depths between 2.7 and 4.1 m.

![Figure 4.7. Subsection of radar profile LC-13 showing discontinuous returns underlain by dome-shaped, and inclined, reflections between 75 and 100 m.](image)
Data collection continued to move west for 550 m in LC-14 before veering slightly to the north for 335 m. The profile was collected over flat ground and culminates close to the western extent of the burned area discussed in the preceding profiles. Surficial geology in this profile consists of till deposits occurring as a drumlinoid plain.

For the first 185 m of LC-14 disrupted hummocky reflections are observed to a depth of 3.6 m. Underlying these returns from 75 to 125 m is a strong, laterally continuous reflection between 3.6 and 3.9 m. Between 185 and 225 m there are continuous, non-parallel, sub-horizontal reflections to a depth of 3.3 m. From 225 m until the end of LDB-14 at 885 m discontinuous reflections predominate. In the subsection between 350 and 480 m these are underlain by a strong, continuous reflection between 1.6 and 3.9 m.

Radar profile LC-15 continues in the same north-west direction as the end of LC-14 for its first 720 m before turning south to skirt a medium-sized (1300 x 650 m) lake. In the latter segment of this profile data collection within seismic cutline KOD-07-05 begins. There is minimal relief within LC-15. Till, in the form of a drumlinoid plain comprises the surficial geology for most of LC-15. At the end of the profile the surficial geology changes from till to glaciofluvial deposits in the form of outwash deposits.

The first 150 m of LDB-15 has discontinuous, or disrupted, sub-horizontal reflections observed over the first 150 m. Short, parallel dipping reflections are then seen between 150 and
180 m. From 180 to 380 m there are discontinuous, hummocky reflections to depths of less than 3.6 m. Between 380 and 425 m disrupted returns overlay a single continuous reflection that rises from a depth of 4.1 to 2.6 m. In the subsection between 425 and 575 m there are discontinuous returns with a maximum depth of penetration of 3.6 m. From 575 to 650 m there is a continuous reflection underlying these discontinuous reflections. The underlying reflection rises from 4.0 to 2.7 m. Between 650 and 695 m there are disrupted returns to a depth of 3.6 m. From 695 m until the end of LDB-15 at 920 m there is an increase in signal penetration; discontinuous returns are observed to maximum depth of between 4.2 and 4.9 m.

**LC-16**

Start (UTM): 440515 E 7443639 N
End (UTM): 440018 E 7443395 N
Length: 580 m

This line begins approximately 125 m from the southern tip of the lake described in the previous profile. It travels southwesterly, continuing along the seismic cutline. There is no significant topography other than a small, incised creek that forced a slight deviation in the path of this profile. GPR profile LC-16 is located on the southwestern corner of an area of glaciofluvial outwash deposits.

Radar propagation over the first 60 m of LC-16 was good with hummocky discontinuous reflections observed as deep as 4.9 m. From 60 to 70 m there are short, parallel, inclined reflections with no change in signal penetration. Between 70 and 135 m there is a continuous near surface reflection. Disrupted to chaotic returns are observed beneath this to a maximum depth of 3.6 m. Two concave-up, or bowl-shaped, reflections, onlapped with disrupted returns, are observed in the subsection between 135 and 175 m. There are disrupted returns to a depth of 3.6 m between 175 and 200 m. From 200 to 250 m continuous, undulating, non-parallel reflections are observed to a depth of 4.5 m. Between 250 and 345 m the depth of penetration is
reduced to 3.9 m, with continuous, sub-horizontal reflections being the only returns. From 345 m to 385 m continuous, undulating, non-parallel reflections are once again observed as deep as 4.5 m. Between 385 and 395 m there are several short, parallel, inclined reflections. From 395 to the end of LDB-16 at 580 m there is good propagation of the EM wave; the architecture consists of strong, continuous, parallel reflections. These returns become discontinuous between 485 and 525 m before resuming to the end of the profile at 580 m.

**LC-17**

Start (UTM): 440018 E 7443395 N  
End (UTM): 439241 E 7443012 N  
Length: 865 m

This line begins in a low lying area on the western side of a small creek. The path of travel continues in a southwesterly direction along the cutline as it climbs roughly 10-20 m out of the flat, low lying area. This profile begins at the margins of an area of outwash deposits and moves immediately onto a wide till veneer for its remainder.

The first 10 m of LC-17 are a continuation of the architecture found at the end of LC-16. The subsection between 10 and 60 m is characterized by strong attenuation of the signal with a thick, continuous reflection at 2.6 m. Between 60 and 110 m there is a discontinuous attenuating layer over a strong, continuous, slightly domed reflection at 3.2 m. Disrupted returns to a depth of 3.2 m make up the subsection between 110 and 160 m. Between 160 and 250 m undulating, discontinuous reflections are observed as deep as 5.5 m. Penetration decreases to roughly 3.3 m between 250 and 315 m with disrupted reflections being the only observed returns. From 315 to 350 m there is a U-shaped increase in penetration, reaching 5.6 m at its deepest, formed by discontinuous returns. From 350 to 565 m there are disrupted returns to a maximum depth of 3.3 m. Across a 50 m stretch, beginning at 435 m, these disrupted reflections are underlain by a strong continuous reflection that undulates between 4.3 and 5.0 m. From 565 to 655 m two
continuous, parallel sub-horizontal reflections are observed to a depth of 3.6 m. From 655 to 710 m the architecture is comprised of disrupted to discontinuous reflections with little variation in signal penetration. From 710 m to the end of LC-17 at 865 m the profile has discontinuous reflections over a strong, continuous reflection that varies in depth between 3.3 and 4.7 m.

**LC-18**

Start (UTM): 439241 E 7443012 N
End (UTM): 438467 E 7442646 N
Length: 855 m

The direction of travel in LC-18 remains southwesterly within the cutline. The terrain is mildly undulating with an approximately 10 m increase in elevation between the beginning and end of the profile. The surficial geology is that of a till veneer over streamlined bedrock ridges. Fens are common in the area.

The first 65 m of LC-18 is characterized by poor propagation of the EM wave with disrupted reflections observed to a depth of less than 3.5 m. From 65 to 110 m discontinuous reflections are seen above a strong, continuous reflection between 3.6 and 4.2 m. The bottom reflection is interrupted by hyperbolic reflections (see Figure 4.8). Velocity testing on these hyperbolae indicates that the material above them allows for a wave velocity of between 0.09-0.11 m/ns. Between 110 m and 280 m discontinuous reflections are observed; a faint reflection can be seen underlying these returns at ~4.0 m. The subsection from 280 m to 305 m contains parallel, sub-horizontal reflections. Irregular velocity of the snowmobile during data collection makes the following 10 m unusable. Between 315 and 360 m continuous reflections are observed over an underlying reflection that is interrupted by hyperbolae. Velocity testing was not possible in this case due to the weakness of the return and the overlapping of the hyperbolic features. Poor propagation characterizes the subsection between 360 and 510 m with discontinuous reflections
observed to a depth of less than 3.4 m. A series of continuous and discontinuous returns over a lower bounding reflection are observed from 510 m until the end of LC-18 at 855 m.

Figure 4.8. Subsection of radar profile LC-18 showing three continuous reflections with the deepest reflection including hyperbolas between 75 and 95 m

**LC-19**
Start (UTM): 438467 E  7442646 N
End (UTM): 437637 E  7442229 N
Length: 935 m

The beginning of GPR profile LC-19 is 250 m east of the western shore of a crescent shaped lake that is roughly 2000 x 600 m. The direction of travel for this profile is southwest, continuing along KOD-07-05. Approximately 450 m into the profile the lake is reached and data collection continues across the lake ice for roughly 400 m. The final ~100 m ascend the western bank of the lake and return to flat ground. With the exception of the lake depression, this profile has no significant relief. Thin till with scattered fens comprise the local surficial geology.

The first 175 m of LC-19 has low signal penetration as discontinuous reflections can be observed no deeper than 3.6 m. An underlying reflection, interrupted by several hyperbolae is
seen at various points across this segment. Velocity testing on these features indicates that the radar wave travelled at a velocity of ~0.10 m/ns in the sediment overlying the hyperbolic features. The signal is further attenuated between 175 and 240 m as no reflections are seen beyond a single, horizontal reflection that never appears deeper than 2.7 m (Figure 4.9). Between 240 and 270 m a single, strong reflection inclines from 4.1 to 2.4 m. From 270 to 285 m there is strong attenuation of the radar signal with a single reflection and no signal penetration beyond 2.7 m. Between 285 and 455 m there are discontinuous returns observed to maximum depths between 3.0 and 4.0 m. In the subsection from 455 to 520 m there are two strong, thick, parallel bands; the first at the surface and the second undulating, dipping as deep as 4.4 m. These reflections are interrupted between 520 and 625 m by a series of disrupted, highly attenuating returns. From 625 to 835 m there are two thick, continuous reflections, the deepest of which disappears when it dips below 5.4 m. Discontinuous, horizontal reflections, observed to a maximum depth of 3.5 m, comprise the last portion of LC-19 between 835 and 935 m.
Figure 4.9. Subsection of radar profile LC-19 showing decrease in signal penetration associated with a single continuous reflection between 175 and 240 m

**LC-20**
Start (UTM): 437637 E 7442229 N
End (UTM): 437065 E 7441965 N
Length: 660 m

Radar profile LC-20 begins 85 m from the lake that was crossed in LC-19. After 230 m of heading southwest the direction of travel is diverted to the north, away from the southwestern direction followed by the cutline, by heavy brush and deep snow associated with the shore of another lake. After a 140 m diversion LC-20 resumes its south-western direction, crossing the northern tip of the oval shaped lake for approximately 210 m. The final 90 m of the profile climbs out of the lake basin and rejoins the cutline. Surficial geology for the profile is till veneer.

The first 215 m of LC-20 is characterized by poor signal penetration with discontinuous, sub-horizontal reflections resolved only as deep as 3.0 m. Between 215 and 370 m continuous, parallel, horizontal reflections replace the discontinuous returns while signal penetration remains constant. From 370 to 430 m there is a thick reflection at 1.3 m. Underlying this is a strong,
continuous reflection that inclines from 4.1 to 2.0 m. The architecture of the subsection between 430 and 590 m is comprised of two strong, thick horizontal reflections between 0.7 and 2.4 m. Beneath this is an undulating reflection that joins the upper reflections at each end of the segment. For 20 m, between 520 and 540 m, the upper two reflections are briefly interrupted as the lower reflection rises close to the surface. From 590 m to the end of LC-20 at 660 m hummocky, discontinuous reflections are observed to a depth of 5.4 m.

**LC-21**

Start (UTM): 437065 E 7441965 N  
End (UTM): 436743 E 7441801 N  
Length: 355 m  

Radar profile LC-21 begins roughly 70 m from the northwest corner of a lake. It heads southwest passing over the edge of a small lake for approximately 80 m beginning at the 185 m mark. Its path passes within 50 m to the north of a larger lake. Till veneer over streamlined bedrock makes up the surficial geology of LC-21.

Good propagation continues from the end of LC-20 into the first 35 m of LC-21 as hummocky, discontinuous reflections are seen as deep as 4.5 m. Signal penetration is reduced between 35 and 115 m as near surface attenuation associated with two parallel, continuous, horizontal reflections reduces maximum depth of penetration to less than 3.5 m. Depth of penetration remains constant between 115 and 185 m as a single, continuous reflection overlays poorly defined, disrupted reflections. From 185 to 260 m there are two strong, thick horizontal reflections between 0.7 and 2.3 m, underlain by an undulating reflection that varies in depth between 2.4 and 6.7 m. The subsection between 260 and 280 m contains hummocky, disrupted reflections to a maximum depth of 3.4 m. Between 280 and 330 m signal penetration increases to maximum depths between 4.7 and 5.3 m while the architecture remains the same as the previous
Between 330 m and the end of LC-21 at 355 m the profile is characterized by near surface attenuation as a single reflection overlays unstructured returns that can be resolved to a depth of only 3.5 m.

**LC-22**

Start (UTM): 436743 E  7441801 N  
End (UTM): 436743 E  7441801 N  
Length: 960 m

Beginning at the end of LC-21, this profile traverses gently undulating terrain while experiencing a ~10 m gain in elevation from beginning to end. Starting roughly 70 m northwest of a small lake/pond, LC-22 heads southwest along the cutline. Approximately 300 m from its beginning the profile descends onto a lake measuring 1600 m in length (north-south) and 500 m at its widest point. The radar profile crosses near the southern end of the lake for 340 m. Data collection continues up the steep western shore of the lake before reaching level ground and culminating approximately 300 m from the lake’s edge. The surficial geology is made up of till veneer over streamlined bedrock.

The first 40 m of LC-22 has significant attenuation associated with a continuous, horizontal reflection close to the surface; beneath this reflection are poorly defined, disrupted reflections (Figure 4.10). From 40 to 95 m there is an increase in signal penetration from 3.1 to 5.7 m. This increase in penetration forms a U-shaped feature comprised of abundant, discontinuous returns. From 95 to 225 m a series of discontinuous, hummocky reflections are observed to a maximum depth of 4.3 m. Between 225 and 270 m attenuation of the radar signal in the near surface is prominent and two parallel, sub-horizontal reflections are observed to a depth of only 3.0 m. These reflections are pinched out between 270 and 300 m by a deeper reflection that rises to 1.6 m. From 300 to 325 m two strong, continuous reflections, overlay weak chaotic returns. At 325 m the lower of these two reflections begins to dip while the upper
reflection remains horizontal. The lower reflection declines below 9.3 m, and then is no longer visible before rising again to rejoin the upper reflection at 630 m. From 630 to 665 m there are disrupted reflections and strong attenuation of the radar signal, allowing no returns from more than 3.1 m in depth. Signal penetration increases to 3.4 m between 665 and 750 m as a continuous, weakly hummocky reflection overlays disrupted returns. From 750 to 845 m a dome-shaped, continuous reflection rises from 4.1 to 1.6 m and pinches out the previously described upper reflections at 820 m before receding to 3.7 m at 845 m. The last subsection of LC-22, from 845 to 960 m, contains disrupted, hummocky reflections to a depth of 3.4 m.

Figure 4.10. Subsection of radar profile LC-22 showing an increase in signal penetration between 45 and 95 m with the highlighted area marking the maximum depth of penetration (note the ringing returns on the hyperbola at 100m).

**LC-23**
Start (UTM): 436743 E 7441801 N
End (UTM): 435750 E 7441320 N
Length: 135 m
Radar profile LC-23 continues on the same southwest path as the previous profile. The profile enters a large flat area with scattered bogs and fens. The surficial geology consists of till veneer over streamlined bedrock.

The first 85 m of LC-23 is characterized by high attenuation and poor signal penetration with disrupted reflections to a maximum depth of 3.1 m. Between 85 m and the end of LC-23 at 135 m discontinuous, hummocky reflections are seen as deep as 4.1 m.

**LC-24**

Start (UTM): 435750 E  7441320 N
End (UTM): 435088 E  7440978 N
Length: 790 m

Flat, boggy conditions persist from the beginning to the end of LC-24. The general direction of travel remains southwesterly as data collection continues along KOD-07-05. Because of difficult snow conditions and a diversion around a small pond starting at 460 m, LC-24 is less straight than previous profiles. A stream is crossed at 610 m. Thin till deposits over bedrock makes up the surficial geology of LC-24.

Disrupted, hummocky reflections to a maximum depth of 3.4 m comprise the architecture of the first 290 m of LC-24. Between 40 and 140 m these returns are sporadically underlain by a reflection that ranges in depth between 3.1 and 4.7 m. This architecture is interrupted by three short, inclined reflections between 290 and 320 m before resuming for a further 30 m until 350 m. From 350 to 410 m the signal becomes increasingly attenuated near the surface as returns cannot be resolved below 2.7 m. Between 410 and 575 m the architecture is comprised of disrupted, hummocky reflections to a depth of 3.1 m; these returns are sporadically underlain by a reflection observed between 3.7 and 4.0 m. The subsection from 575 to 680 m has a series of discontinuous reflections forming a wide, U-shaped increase in propagation. Signal penetration
through this portion of the profile is between 4.7 and 5.0 m. From 690 m to the end of LC-24 at 790 m signal penetration is reduced to less than 3.6 m and discontinuous, hummocky reflections comprise the architecture.

**LC-25**

Start (UTM): 435088 E 7440978 N
End (UTM): 434547 E 7440731 N
Length: 595 m

Boggy conditions persist as LC-25 continues towards the southwest through a low-lying area. The profile ends on the eastern end of a lake measuring ~800 x ~200 m lake, with the last ~30 m of data collected on the lake ice. The surficial geology of LC-25 is comprised of thin till over streamlined bedrock.

The first 50 m of LC-25 is characterized by attenuation of the radar signal near the surface, with disrupted reflections observed to a depth of 3.5 m (Figure 4.11). Signal penetration is abruptly increased at 55 m as two strong, continuous, non-parallel reflections are seen to a depth of 5.4 m. These two reflections form a wide, flat wedge-shaped increase in propagation between 50 and 100 m. The lower reflection is twice interrupted by hyperbolae; once at 50 m and once at 60 m. Velocity testing on these hyperbolas indicates that the EM wave was travelling at a velocity of 0.16m/ns. From 100 to 200 m the profile is again characterized by poor signal penetration as disrupted hummocky reflections are observed to a maximum depth of 3.6 m. Between 200 and 285 m there are chaotic returns before electromagnetic noise in the data makes the following 15 m, until 300 m, unusable. The signal between 300 and 500 m is subject to near surface attenuation with no resolvable architectures below 3.0 m. From 500 to 560 m there are discontinuous reflections to a depth of 3.6 m. The final subsection of LC-25, between 565 and 595 m, contains a continuous, horizontal reflection over a dipping, continuous reflection.
Figure 4.11. Subsection of radar profile LC-25 showing wedge-shaped increase in signal penetration formed by two non-parallel continuous reflections with the highlighted area denoting the depth of signal penetration.

**LC-26**

Start (UTM): 434547 E 7440731 N

End (UTM): 433799 E 7440364 N

Length: 840 m

GPR profile LC-26 begins with ~130 m of data being collected on lake ice before the rest of the profile crosses flat ground. Thin till deposits comprise the majority of the surficial geology within LC-26. The end of the profile lies at the margins of a glaciofluvial complex comprised of ice contact deposits.

The first 130 m of LC-26 contains a continuous, horizontal reflection over an undulating, continuous reflection. Between 130 and 310 m there are discontinuous, sub-horizontal reflections to a maximum depth of less than 3.6 m. Between 310 and 720 m the architecture consists of a series of discontinuous, hummocky returns. These are overlaying a faint, continuous reflection
that undulates between 3.0 and 3.7 m. From 720 m until the end of LC-26 at 840 m the signal is strongly attenuated as discontinuous returns are observed to a maximum depth of 2.5 m.

**LC-27**
Start (UTM): 433799 E 7440364 N  
End (UTM): 433439 E 7440719 N  
Length: 950 m

The first 130 m of LC-27 continues southwest along a cutline. After 130 m the profile’s path was diverted by a long thin lake with steep banks. The route of travel turns sharply to the north and slightly east, skirting the lake’s eastern edge by ~75 m. At the northern end of the lake, LC-27 curves back to the west and finally to the southwest, stopping approximately 60 m from the western edge of the lake. The surficial geology of LC-27 is comprised of ice-contact glaciofluvial deposits.

The first 160 m of LC-27 contains discontinuous, hummocky reflections to a maximum depth of 3.3 m. From 160 to 230 m the returns are chaotic while signal penetration is unchanged. The subsection from 230 to 495 m is characterized by improved propagation of the EM wave, with disrupted reflections observed as deep as 4.1 m. Three short, parallel, inclined reflections are the only returns between 395 and 405 m. Two parallel, sub-horizontal reflections are observed between 405 and 475 m before being replaced by disrupted returns from 475 to 525 m. Inclined, parallel reflections comprise the architecture between 525 and 560 m. From 560 to 590 m signal penetration increases to 4 m with only discontinuous returns. Between 590 and 770 m discontinuous, poorly structured reflections are the only returns with no resolvable returns below 3.0 m. Between 770 and 870 m propagation improves as a series of lower-bound ing, concave-up, reflections are onlapped by abundant disrupted returns; maximum signal penetration though this wide, bowl-shaped feature ranges between 4 and 6.5 m. The abrupt increase in signal penetration
can be seen in Figure 4.12. From 870 to 950, at the end of LC-27, there are disrupted, hummocky reflections to maximum depths between 3.3 and 4.0 m.

Figure 4.12. Subsection of radar profile LC-27 shows an abrupt increase in signal penetration at 770 m with the highlighted area denoting the maximum signal penetration. Note the possible ice wedges 788, 800 and 814 m.

**LC-28**

Start (UTM): 433439 E 7440719 N
End (UTM): 433321 E 7440622 N
Length: 175 m

Radar profile LC-28 runs along the northwest shore of a long, thin lake. It heads southwest keeping the lake roughly 65 m to its left throughout the profile. Hummocky, ice contact, glaciofluvial deposits comprise the surficial geology of LC-28.

The first 110 m of LC-28 is characterized by strong attenuation in the near surface with discontinuous, hummocky reflections seen to depths of no more than 3.2 m. The last 65 m, from 110 to 175 m, has similar architecture with maximum signal penetration increased to depths between 4.1 and 4.4 m.
Radar profile LC-29 was unusable due to equipment failure. The data collected is not of use for this study as the loss of the GPS signal means that GPR traces cannot be properly positioned.

LC-30
Start (UTM): 432932 E 7439974 N
End (UTM): 432781 E 7440151 N
Length: 320 m

The southwesterly direction of the cutline is often diverted by lakes and ponds in this portion of the study area. The path of LC-30 follows one of these diversions as it heads north before turning back west and finally to the southwest as it rounds the northern tip of an oval shaped lake measuring ~300 x ~100 m. The surficial geology of LC-30 is comprised of ice contact glaciofluvial deposits.

The first 55 m of LC-30 is characterized by good propagation of the EM wave as continuous and discontinuous reflections are observed to depths up to 5.4 m (Figure 4.13). The remaining 265 m, from 55 to 320 m, is characterized by shallow signal penetration. Disrupted returns are seen to depths of no deeper than 3.3 m throughout this portion of LC-30.
Figure 4.13. Subsection of radar profile LC-30 showing a rapid decrease in signal penetration at 55 m with the highlighted area denoting the maximum depth of signal penetration.

**LC-31**
Start (UTM): 432781 E 7440151 N
End (UTM): 432159 E 7439529 N
Length: 1020 m
No data: this profile was corrupted by battery failure in the transmitter antennae.

**LC-32**
Start (UTM): 432159 E 7439529 N
End (UTM): 431544 E 7439256 N
Length: 875 m
The beginning of LC-32 resumes a southwesterly direction along a cutline for 225 m before being diverted to the north by a steep-banked stream. The course of the profile follows the stream’s path for roughly 210 m before gradually turning to the south to rejoin the cutline for its last 95 m. Glaciofluvial deposits comprise the surficial geology for most of LC-32. The profile starts on ice-contact sands and gravels and moves onto outwash deposits underlying a terrace. The profile ends on alluvial sediments.
Across the first 120 m of LC-32 continuous hummocky reflections are observed to a maximum depth of 5.5 m. This architecture persists between 120 and 290 m, reduced to less than 3.3 m depth. Between 290 and 400 m signal penetration again reaches 5.5 m within a series of discontinuous, mildly undulating reflections. From 400 to 480 m there are abundant, disrupted reflections to a depth of 4.4 m. In the subsection between 480 and 600 m continuous, sub-horizontal reflections are observed as deep as 4.7 m. For the final 275 m of LC-32, between 600 and 875 m, the signal is attenuated in the near surface and discontinuous, hummocky returns are observed no deeper than 3.3 m.

**LC-33**
Start (UTM): 431544 E 7439256 N  
End: N/A  
Length: N/A  
No Data: radar profile LC-33 was unusable due to battery failure in the receiver antenna.

**LC-34**
Start (UTM): 431399 E 7439190 N  
End (UTM): 430568 E 7438812 N  
Length: 912 m  
Radar profile LC-34 runs in a south-westerly direction. There are no bodies of water along this stretch and no significant change in elevation. The end of LC-34 is at the intersectional of two cutlines. The surficial sediments in LC-34 are alluvial, comprised mainly of silt and sand.

This profile is characterized by attenuation of the EM wave close to the surface. Signal penetration for LC-34 never exceeds 4 m within a variety of architectures. The first 205 m of LC-34 contains discontinuous, horizontal reflections. Between 205 and 315 m there are disrupted, hummocky returns. From 315 to 385 m there are continuous reflections. The remaining 527 m, from 385 to 912 m, is comprised of disrupted, hummocky returns.
Profile LC-35 heads north and slightly east. The path of the profile remains follows a cutline, has no bodies of water and sees little change in elevation. The beginning of LC-35 is on alluvial material, primarily silts and sands. As the profile moves north, surficial deposits become a mixture of alluvial sediments and till, with the till being less than 20 m thick, and forming low hills or broad hummocks.

Signal penetration remains relatively constant within this profile, with returns coming from no deeper than 3.9 m. The first 450 m of LC-35 shows mildly undulating, discontinuous reflections. These give way to a series of inclined, parallel reflections between 450 and 480 m (Figure 4.14) before returning from 480 to 620 m. Between 620 and 645 m the returns are chaotic. Discontinuous, hummocky reflections are the only returns for the final portion of LC-35, from 645 to 740 m.

Figure 4.14. Subsection of radar profile LC-35 showing short, parallel, inclined reflections between 450 and 480 m. Vertical exaggeration = 7.3x
Data collection continues to follow a cutline in radar profile LC-36. A northern and slightly eastern direction is taken. The course of the profile was not influenced by bodies of water or by topography. Surficial geology in LC-36 is comprised of low hills of till with some alluvial deposits.

Signal penetration is relatively shallow across all of LC-36 and never exceeds 3.7 m. Discontinuous and disrupted reflections, weakly hummocky in nature, comprise the architecture of the profile.

Radar profile LC-37 continues north along cutline KOD-07-07. Its path is relatively straight, running perpendicular to the dip of a slope of ~10-15 °. No lakes or streams intersect with LC-37. Till and alluvial deposits comprise the surficial geology.

This profile is characterized by relatively shallow signal penetration as returns are observed no deeper than 4.0 m. The first 270 m of LC-37 has disrupted reflections to a depth of 3.9 m. An underlying reflection is seen sporadically across this subsection. From 270 to 560 m the returns are disrupted, or poorly structured, with near surface attenuation causing a reduction in signal penetration to less than 3.2 m. Between 560 and 585 m a single domed reflection is seen. The remainder of LC-37, from 585 to 660 m, has disrupted returns and a maximum signal penetration of less than 3.2 m.
**LC-38**
Start (UTM): 431005 E  7441076 N
End (UTM): 431067 E  7441457 N
Length: 385 m

This profile continues to the northeast along the side of a slope. Descending slightly, LC-38 is uninterrupted by any body of water. Surficial geology for LC-38 consists of till, forming low hills and broad hummocks, and alluvial deposits.

Poor propagation persists in radar profile LC-38 as returns come from no deeper than 3.2 m across the entire profile. The architecture of LC-38 is comprised of disrupted, weakly hummocky returns.

**LC-39**
Start (UTM): 431067 E  7441457 N
End (UTM): 431068 E  7441483 N
Length: 30 m

This profile was aborted after 30 m due to battery failure. The surficial geology and facies architecture described in LC-38 continues through all of LC-39.

**LC-40**
Start (UTM): 431092 E  7441560 N
End (UTM): 431236 E  7442329 N
Length: 785 m

Continuing along a cutline LC-40 heads north and slightly east. There is no significant elevation change and the terrain is mildly hummocky. Surficial geology is comprised of till and alluvial deposits.

The first 355 m of LC-40 contains a series of discontinuous, horizontal reflections and is characterized by strong attenuation of the EM wave in the near surface. Signal penetration is less than 3 m over this subsection. Between 355 and 400 m there is a near surface, continuous reflection that is underlain by a strong reflection that dips from a depth of 2 m to a depth of 3.7 m. From 400 to 550 m discontinuous, undulating reflections are observed to a maximum depth of 3.2 m. Signal penetration increases to 4 m between 550 and 565 m and a strong, thick reflection
is present. The remaining 220 m of LC-40, from 565 to 785 m, is characterized by strong attenuation in the near surface with continuous, horizontal reflections observed no deeper than 3.1 m.

**LC-41**
Start (UTM): 431236 E 7442329 N
End (UTM): 431392 E 7443009 N
Length: 720 m

Radar profile LC-41 begins on flat, hummocky ground. For its last ~200 m a prominent hill is ascended (view from top of the hill is shown in Figure 4.15). The line ends near the crest of the hill, at the junction of two cutlines. The surficial geology of LC-41 is comprised of till and alluvial deposits.
Figure 4.15. View looking south back down cutline KOD-07-07 from the end of GPR profile LC-41.

The first 120 m of LC-41 is characterized by attenuation of the EM wave in the near surface with disrupted, hummocky reflections observed no deeper than 3.3 m. From 120 to 170 m there are discontinuous reflections to a maximum depth of 3.5 m. Between 170 and 210 m the
architecture is comprised of two laterally continuous, mildly undulating reflections that are observed as deep as 3.8 m. The lower of these two reflections is onlapping onto a dipping reflection that inclines from 3.8 m in depth at 210 m to 1.9 m at 250 m. The subsection from 250 to 340 m is comprised of hummocky, continuous reflections to a maximum depth of 3.7 m. The lower reflection rises to 1.7 m and pinches out the upper reflection for 10 m from 340 to 350 m.

A strong concave (up) reflection, overlain by random reflections, is present between 350 and 390 m. The final portion of LC-41, from 390 to 720 m, is made up of a series of disrupted returns.

**LC-42**

Start (UTM): 431392 E 7443009 N
End (UTM): 431440 E 7443357 N
Length: 210 m

Continuing north and slightly east LC-42 begins at the crest of a ~50 m rise and traverses slightly hummocky terrain. Till and alluvial sediments make up the surficial geology of LC-42.

This profile is characterized by high attenuation in the near surface. Discontinuous, sub-horizontal reflections can be seen no deeper than 3 m across all of LC-42.

**LC-43**

Start (UTM): 431439 E 7443351 N
End (UTM): 431602 E 7444155 N
Length: 820 m

Radar profile LC-43 travels north and slightly east within a cutline across relatively flat ground. The path of this profile crosses two streams; the first at 325 m and the second at 550 m. Surficial geology in this area is comprised of till.

Discontinuous reflections make up the architecture over the first 240 m of LC-43. Signal penetration across this subsection does not exceed 3.7 m. Beginning at 240 m the propagation improves gradually and signal penetration reaches a maximum depth of 5.8 m at 355 m. At 355 m signal penetration is gradually reduced until it reaches 3.6 m at 475 m. The subsection from 240 to 475 m forms a wide, saucer-shaped feature comprised of discontinuous, hummocky
returns. The final portion of LC-43, from 475 to 820 m, contains disrupted reflections that can be observed no deeper than 3.7 m.

**LC-44**
Start (UTM): 431602 E 7444155 N  
End (UTM): 431751 E 7444924 N  
Length: 785 m

Radar profile LC-44 heads north and slightly east. The terrain covered in this profile was weakly hummocky. The surficial geology consists of till, occurring as a drumlinoid plain or extensively fluted. Drift materials are deemed to be between 2 and 30 m thick.

The first 240 m of LC-44 is comprised of disrupted reflections. This subsection is characterized by attenuation in the near surface as returns are observed no deeper than 3.5 m. From 240 to 285 m there are disrupted returns underlain by a faintly seen, continuous reflection between 3.1 and 3.3 m. From 285 to 360 m the architecture consists of disrupted returns. Signal penetration within this subsection is less than 4 m. Beginning at 360 m a faint, continuous reflection, observed at depths between 3 and 3.3 m, underlies discontinuous reflections for 35 m before disappearing at 395 m. The remainder of LC-44, from 395 to 785 m, is comprised of hummocky, discontinuous reflections. Signal penetration is less than 3.7 m.

**LC-45**
Start (UTM): 431751 E 7444924 N  
End (UTM): 431874 E 7445577 N  
Length: 660m

The terrain in LC-45 is flat with small hummocks. The direction of travel continues to be north and slightly to the east. Surficial geology is comprised of till, occurring as a drumlinoid plain or extensively fluted. Fenlands flank the left side of radar profile LC-45.

The first 55 m of LC-45 contains laterally continuous, thick, banded reflections. Propagation of the EM wave is good, relative to the rest of LC-45, with returns observed as deep
as 4.2 m. Between 55 and 330 m the signal becomes attenuated in the near surface and signal penetration is reduced to less than 3.3 m. Horizontal discontinuous reflections predominate within this subsection with one exception; a dome-shaped reflection between 175 and 200 m protrudes through the aforementioned horizontal reflections. Between 330 and 380 m signal penetration increases to 4.0 m and parallel undulating reflections are observed. In the final portion of LC-45, from 380 to 660 m, signal penetration is reduced to less than 3.5 m and sub-horizontal, discontinuous reflections are the only returns.

**LC-46**

Start (UTM): 431874 E 7445577 N  
End (UTM): 431972 E 7446014 N  
Length: 445 m

Radar profile LC-46 heads north and slightly east, culminating at the junction of two cutlines. The terrain has little relief with the exception of a forked stream that is crossed at ~225 m. Surficial geology is comprised of till, occurring as either a drumlinoid plain or extensively fluted. Fenlands flank the western side of LC-46.

Laterally continuous, mildly undulating reflections, observed to depths between 3.1 and 4.0 m comprise the architecture of LC-46’s first 95 m. Abundant disrupted returns are seen between 95 and 110 m. From 110 and 190 m there are disrupted, hummocky returns to a maximum depth of 3.8 m. Between 190 and 225 m continuous, parallel reflections are observed to a depth of 3.4 m. The subsection between 225 and 275 m is comprised of disrupted returns to maximum depths between 3.3 and 4.0 m. Short, parallel, dipping reflections are seen between 275 and 300 m. Disrupted reflections make up the portion of LC-46 between 300 and 340 m with returns being seen as deep as 3.5 m. From 340 to 380 m there are two gently inclined (~10°), parallel reflections. The final segment of LC-46, from 380 to 445 m, is made up of sub-
horizontal, continuous reflections. This subsection has poor propagation of the EM wave as returns cannot be resolved any deeper than 3.1 m.

**LC-47**

Start (UTM): 431972 E 7446014 N  
End (UTM): 432829 E 7446250 N  
Length: 830 m

Radar profile LC-47 begins at the junction of cutlines and heads east and slightly north along an east-west running cutline. The terrain is gently sloping from west to east. The path of LC-47 skirts the western and northern edges of a ~200 x ~250 m lake for its last 280 m. Surficial geology in the area is comprised of till occurring as a drumlinoid plain or extensively fluted.

The first 190 m of LC-47 is characterized by poor propagation of the EM wave. Discontinuous reflections can be seen only as deep as 3.1 m. Between 190 and 235 m signal penetration is increased as there are two inclined reflections rising from 4.5 to 1.5 m. From 235 to 245 there are two parallel, sharply dipping, reflections. The subsection between 245 and 750 m contains disrupted, hummocky reflections to maximum depths between 3.0 and 4.0 m. From 750 m to the end of LC-47 at 830 m signal penetration is increased as non-parallel, laterally continuous reflections can be observed as deep as 5 m.

**LC-48**

Start (UTM): 432811 E 7446248 N  
End (UTM): 433142 E 7446488 N  
Length: 435 m

This profile begins approximately 25 m east of a lake measuring roughly 250 x 200 m. It heads east for 160 m, along cutline KOD-08-03, towards a larger lake (approximately 800 x 450 m). As radar profile LC-48 approaches the lake’s edge the path of the profile turns north, skirting the lake for its next 190 m, keeping the lakeshore ~50 m to the east. At the northern tip of the
lake the line was disrupted; it resumes heading east again for its final 85 m. Till makes up the surficial geology of LC-48, generally occurring as a drumlinoid plain or extensively fluted.

The first 150 m of LC-48 contains laterally continuous, mildly undulating reflections. Propagation during this segment is good with returns from as deep as 5.5 m. The subsection from 150 to 300 m is characterized by strong attenuation of the radar signal in the near surface and subsequently a drop in penetration to less than 3.6 m. Between 300 and 400 m discontinuous, hummocky reflections, overlaying a strong continuous reflection at 4.1 m, are observed; below this reflection the signal is attenuated. From 400 m to the end of LC-48 at 435 m signal penetration is improved with abundant, disrupted returns observed as deep as 7.1 m (Figure 4.16).

Figure 4.16. Subsection of radar profile LC-48 showing discontinuous reflections to a depth of 7.3 m at 425 m with the highlighted area denoting the maximum depth of signal penetration.
Radar profile LC-49 begins at the northern tip of the lake described in LC-48. The profile travels south for 150 m skirting the eastern shore of the lake. Roughly 175 m into LC-49 the profile turns east along a cutline. The profile crosses a shallow valley, with a small fen at the bottom, before culminating approximately 90 m from a small lake/pond. The surficial geology in the area is till occurring as extensively fluted or as a drumlinoid plain.

The first 65 m of LC-49 is characterized by poor propagation of the radar signal and contains mildly hummocky reflections to a maximum depth of 3.4 m. At 65 m signal propagation abruptly increases to 4.3 m. The subsection between 65 and 155 m has two, strong, continuous reflectors that are sub-parallel. Both reflections undulate, the first varying in depth between 2 and 3.4 m and the second between 3.6 and 4.8 m. The two reflections join at 155 m at a depth of 3.6 m. The next 130 m, between 155 and 285 m, is comprised of discontinuous, or disrupted, reflections that can be observed as deep as 3.5 m. At 285 m a single, continuous, sub-horizontal reflection between 2.2 and 3.0 m is present until 355 m, ending with a steeply dipping edge at 355 m. Between 315 and 330 m, a single, faintly seen reflection is present at 4.4 m. The subsection between 355 and 635 m is comprised of a series of discontinuous returns; signal penetration here is between 3.3 and 3.8 m. Between 635 and 675 m a slightly inclined, lens-shaped feature, made up of an upper and a lower reflection, is present between 1.9 and 4 m. From 675 to 740 m a series of inclined, parallel reflections are seen to a maximum depth of 4.0 m. The segment between 740 and 760 m has chaotic returns to a depth of 4.4 m. The subsection between 760 and 810 m contains continuous, parallel, undulating reflections to a depth of 4.7 m.
This architecture is interrupted by a series of disrupted reflections between 810 and 880 m before resuming from 880 m to the end of LC-49 at 940 m.

Data collection at Little Chicago yielded 39 GPR profiles. These were gathered in areas of till, glaciofluvial deposits, glaciolacustrine sediments, alluvial sediments and colluvium. In certain instances data was collected on lake ice and over frozen streams. Fens and bogs were commonly traversed as well. The quantity of data that could be collected was limited by hydrological features, topography and the operability of the radar equipment. The GPR survey provided a maximum depth of penetration ranging from 2.0 to 7.1 m.

4.1.2 Lac des Bois

During three days of data collection 47 GPR profiles were collected at Lac des Bois. These data were collected sequentially, beginning with profile LDB-01 and ending with profile LDB-47. The Lac des Bois study area is shown in Figure 4.17. Profiles LDB-01 to LDB-19 are located in the northeast portion of the Lac des Bois study area. These are shown in Figure 4.18. Figure 4.19 shows the center of the area, which includes GPR profiles LDB-20 to LDB-36. The northwest part of the study area, shown in Figure 4.20, contains GPR profiles LDB-37 to LDB-47.
Figure 4.17. Satellite image of Lac des Bois and the relative location of Figure 4.18, Figure 4.19 and Figure 4.20. Co-ordinates are in UTM. Source: http://www.geobase.ca/geobase/en/data/imagery/imr/index.html
Figure 4.18. Satellite image of the northeastern portion of the Lac des Bois area with GPR lines LDB-01 to LDB-19. Source: http://www.geobase.ca/geobase/en/data/imagery/imr/index.html
Figure 4.19. Satellite image of the southeastern portion of the Lac des Bois area with GPR lines LDB-20 to LDB-36. Source: http://www.geobase.ca/geobase/en/data/imagery/imr/index.html
Data collection at the Lac des Bois site began approximately 8 km to the southeast of the southern tip of Lac des Bois. The first GPR profile, LDB-01, begins on the western edge of a cluster of lakes that extends roughly 16 km south from the tip of Lac des Bois. Radar profiles LDB-01 to LDB-15 travel from east to west, and slightly south, roughly following a seismic cutline. The direction of travel during data collection then turns to the northwest for profiles LDB-16 to LDB-19. Profiles LDB-20 to LDB-33 begin at the same point as LDB-16 and heads southeast along a cutline. Radar profiles LDB-34, LDB-35 and LDB-36 branch off this cutline onto with LDB-34 heading east and LDB-35 and LDB-36 heading west. Data collection then resumes at the spot of the beginning of profiles LDB-16 and LDB-20. The remaining 11 profiles, LDB-37 to LDB-47, run west from there. Specific directions of travel are provided for each GPR
profile along with descriptions of any relevant topography, changes in vegetation and contact with, or proximity to, bodies of water. Comprehensive mapping of the surficial geology has not been undertaken in the region; any descriptions of surficial features or processes are derived from observations made in the field. The UTM co-ordinates for all starting and ending points of individual profiles are provided with their description.

**LDB-01**

Start (UTM): 426870 E 7390938 N  
End(UTM): 426371 E 7390692 N  
Length: 550 m

The beginning of LDB-01 starts on the southwestern shore of a crescent-shaped lake measuring ~ 900 x ~450 m. To the south there is a pond ~250 x ~100 m. The profile travels southwest away from the lake out onto flat, sparsely wooded terrain. After approximately 180 m LDB-01 turns to the west and joins an east-west running cutline.

The first 40 m of GPR profile LDB-01 is characterized by poor propagation of the EM wave with disrupted, hummocky reflections observed to a maximum depth of 3.3 m. Between 40 and 105 m signal penetration increases to 5.8 m; from 50 to 105 m the architecture consists of weakly hummocky, continuous reflections. Velocity testing on a hyperbola at 65 m revealed that the EM wave was travelling at 0.136 m/ns. Near surface attenuation characterizes the subsection between 105 and 200 m with disrupted, sub-horizontal reflections observed to a maximum depth of 3.5 m. From 200 to 305 m there are discontinuous, hummocky reflections to maximum depths between 4.1 and 5.2 m. Between 305 and 390 m the architecture consists of continuous, sub-parallel, hummocky reflections. From 390 m to the end of LDB-01 at 550 m the returns are characterized by attenuation in the near surface as signal penetration is reduced to less than 3.4 m with disrupted, hummocky reflections being the only observed architecture.
Radar profile continues west along the cutline. The cutline is diverted to the south briefly by a stream before resuming its westerly direction. The terrain is flat and is among a sparsely forested black spruce stand.

The near surface attenuation observed at the end of LDB-01 persists through the first 50 m of LDB-02 with continuous parallel reflections observed to a depth of 3.2 m. Between 50 and 80 m concave, upward facing, reflections are observed. The base of these reflections range from 3.9 to 6.5 m and are overlain by disrupted, hummocky returns. From 80 to 165 m good propagation of the EM allowed for the observation of continuous, hummocky reflections as deep as 5.2 m. Signal penetration is reduced from 165 m to the end of LDB-02 at 235 m as disrupted, hummocky returns are seen no deeper than 4.0 m.

LDB-03 continues across flat ground. The beginning of the profile is sparsely forested. The second half of LDB-03 enters mature boreal forest (Figure 4.21).
Figure 4.21. Looking westward down seismic cutline CVL-03 from the end of GPR profile LDB-03.

Propagation of the radar pulse at the beginning of LDB-03 is poor, with disrupted, hummocky reflections seen no deeper than 3.4 m for the first 40 m. Between 40 and 80 m there are continuous, mildly undulating, reflections with maximum signal penetration of between 3.5 and 4.9 m. There are short, parallel, inclined reflections between 80 and 90 m. The subsection between 90 and 340 m is comprised of a series of continuous, mildly undulating reflections, observed to maximum depths between 4 and 4.5 m. From 340 to 525 m there are disrupted returns and strong attenuation in the near surface with maximum signal penetration being less
than 3.2 m. Propagation improves from 525 m to the end of LDB-02 at 620 m as continuous, non-parallel reflections that are seen as deep as 4.6 m.

**LDB-04**

Start (UTM): 425558 E 7390555 N
End (UTM): 424794 E 7390401 N
Length: 795 m

Radar profile LDB-04 continues along flat terrain while following the cutline. It crosses an open, boggy area with stunted trees and bushes before ending in a small stand of spruce trees.

Radar profile LDB-04 contains continuous, sub-parallel reflections for its first 110 m. Good propagation of the radar pulse is found across this subsection as reflections are observed as deep as 6 m, with the maximum depth of penetration never being less than 4.5 m. The subsection between 110 and 200 m is characterized by attenuation of the signal in the near surface as discontinuous, hummocky reflections are seen no deeper than 3.2 m. From 200 to 355 m a single, continuous reflection is observed in the near surface. Strong attenuation of the signal is associated with this reflection, restricting depth of penetration to a maximum of 2.4 m. From 355 to 440 m the architecture is comprised solely of discontinuous reflections that were observed as deep as 3.3 m. Between 440 and 550 m propagation improves as depth of penetration increases to between 3.4 and 4.6 m. The architecture is made up of discontinuous, undulating reflections. Between 550 m and the end of LDB-04 at 795 m signal penetration is once again reduced to less than 3.3 m with discontinuous reflections persisting from the previous subsection.

**LDB-05**

Start (UTM): 424794 E 7390401 N
End (UTM): 424473 E 7390341 N
Length: 335 m

This profile begins just before crossing a raised boggy area approximately 2 m high. There is no other topography of note. The line culminates by re-entering the forest.
The first 50 m of LDB-05 is comprised of discontinuous, hummocky reflections observed to a maximum depth of 3.4 m. Propagation improves between 50 and 170 m as discontinuous, hummocky reflections are seen to maximum depths of between 3.4 and 5.5 m. Between 170 m and the end of LDB-05 at 335 m there is a reduction in signal penetration with discontinuous reflections observed no deeper than 3.4 m.

**LDB-06**

Start (UTM): 424473 E  7390341 N  
End (UTM): 423882 E  7390215 N  
Length: 605 m

Entirely within mature forest, LDB-06 continues within the east-west cutline as the ground rises slightly and the direction of data collection remained westward.

Radar profile LDB-06 is characterized by poor propagation of the EM wave across all 605 m. Abundant, disrupted returns are seen throughout. For the first 95 m, and between 165 and 205 m, a single continuous reflection, ranging from 2.1 to 3.4 m in depth, is seen underlying the aforementioned disrupted returns.

**LDB-07**

Start (UTM): 423882 E  7390215 N  
End (UTM): 423486 E  7389862 N  
Length: 705 m

LDB-07 travels along the cutline for its first 300 m. The profile is then diverted to the south, off the cutline. A small lake/pond of ~80 x ~40 m is roughly 50 m to the west of the profile as it heads south. After travelling south for 200 m LDB-07 heads west for 70 m. The profile moves south for another 70 m before curving around the south end of a single ridged esker. The esker is undulating, ~ 4 m in height at its southern end and roughly 8 m high further north. LDB-07 culminates by turning to the northwest before finishing running parallel along the western side of the esker (Figure 4.22).
The disrupted, hummocky reflections described at the end of LDB-06 persist for the first 100 m of radar profile LDB-07. Signal penetration for this subsection does not exceed 3.4 m. Propagation improves from 100 to 155 m as disrupted returns are observed as deep as 4.0 m. From 155 to 330 m the architecture consists of disrupted, hummocky returns with a maximum depth of penetration of 3.4 m. Between 330 and 380 m weak, disrupted returns overlay two strong, continuous, sub-horizontal reflections that are seen at ~2.6 and ~4.0 m (Figure 4.23). From 380 to 480 m discontinuous, hummocky reflections comprise the architecture, with maximum signal penetration ranging from 3.2 to 5.2 m. Between 480 m and the end of LDB-07

Figure 4.22 Western side of a single ridged esker that was bypassed at the end of GPR profile LDB-07.
at 705 m there is good propagation of the EM wave as discontinuous, undulating reflections are observed to maximum depths between 4.5 and 6.8 m.

![Figure 4.23. Subsection of GPR profile LDB-07 showing two parallel reflections between 330 and 380 m.](image)

**LDB-08**

Start (UTM): 423486 E 7389862 N
End (UTM): 422928 E 7390016 N
Length: 675 m

LDB-08 heads northwest for 120 m before briefly turning temporarily to the west. It then continues to the northwest for another 170 m before again turning west as it rejoins cutline CVL-03. This profile ends within an anastomosing esker complex with individual esker ridges measuring 2-4 m in height (Figure 4.24).
Figure 4.24. The end of GPR profile LDB-08 moving perpendicularly across a series of anastomosing esker ridges.

The first 50 m of LDB-08 has a single concave (up), or bowl-shaped, reflection that begins at 4.1 m, dips to 5.4 m at its deepest point, then rises to 2.9 m at 50 m. This reflection is overlain by a series of discontinuous returns. From 50 to 100 m there are discontinuous, hummocky returns observed as deep as 4.6 m. Propagation is good between 100 and 145 m as non-parallel, continuous reflections are returned from as deep as 6.5 m. From 145 to 180 m good propagation of the EM wave persists as thick, abundant, disrupted reflections are seen as deep as 6.2 m. Between 180 and 200 m there are short, inclined, parallel reflections. From 200 to 260 m
continuous, hummocky reflections, between 1.9 and 2.8 m are underlain by a series of discontinuous reflections. The subsection from 260 to 330 m contains well-defined, continuous, parallel reflections. Between 330 and 385 m disrupted reflections are observed to a depth of 5.2 m. From 385 to 440 m the architecture is comprised of two continuous, dipping reflections. These two reflections bracket a lens-shaped series of diffractions that are seen within a dipping reflection. The deepest point of this feature is observed at 5.8 m. Signal penetration is then reduced to 3.9 m between 440 and 505 m with a single continuous reflection overlying disrupted returns. Propagation is improved through the rest of LDB-08 with maximum signal penetration always exceeding 6.5 m and reaching a maximum depth of 8.1 m. Between 505 and 595 m the architecture consists of disrupted to chaotic returns. From 595 m to the end of LDB-08 at 675 m is of a series of bowl-shaped reflections that are overlain with disrupted returns.

**LDB-09**
Start (UTM): 422928 E 7390016 N
End (UTM): 422340 E 7389895 N
Length: 605 m

Radar profile LDB-09 begins within a braided esker complex and heads west along cutline CVL-03. The end of LDB-09 is at the beginning of a slow climb from east to west.

The first 105 m of LDB-09 consists of a series of bowl-shaped reflections that are overlain with abundant disrupted returns. From 105 to 285 m there are discontinuous, hummocky reflections. Maximum signal penetration across this subsection varies between 3.9 and 7.1 m. From 285 m to the end of LDB-09 at 605 m the architecture is comprised of disrupted to chaotic returns. This subsection is characterized by reduced signal penetration as returns come from no deeper than 3.9 m.
There is a slight gain in elevation (~10 m) as LDB-10 climbs a gentle slope heading west. A stream was crossed roughly 100 m into LDB-10.

The first 70 m of LDB-10 is characterized by strong attenuation of the signal in the near surface; disrupted, hummocky reflections are observed no deeper than 3.2 m. Between 70 and 130 m signal penetration increases to as much as 5.2 m. The architecture in this subsection consists of a series of discontinuous reflections that form a bowl-shaped feature. From 130 to 245 m disrupted returns are observed to maximum depths between 3.3 and 4.6 m. From 245 m to the end of LDB-10 at 690 m the profile is dominated by near surface attenuation as unstructured, or disrupted, returns are seen no deeper than 3.2 m.

Profile LDB-11 follows the cutline as it heads west. The cutline is diverted slightly to the north at 205 m. At narrow stream was crossed at ~350 m. The slow climb from east to west continues in LDB-11.

Strong attenuation of the radar signal persists through the first 250 m of LDB-11, with disrupted returns observed no deeper than 3.2 m. From 250 to 325 m there are two continuous, undulating, parallel reflections that are observed as deep as 3.4 m. From 325 m to the end of LDB-11 at 595 m there are disrupted returns and a signal penetration of less than 3.2 m. The lone exception is between 395 and 425 m; this 30 m stretch has discontinuous reflections that form a wedge-shaped increase in signal penetration down to 4.1 m.
**LDB-12**

Start (UTM): 421087 E 7389638 N  
End (UTM): 430445 E 7389502 N  
Length: 650 m

LDB-12 climbs slowly as it heads west. There are no bodies of water of note in this profile.

The entire 650 m of LDB-12 consists of disrupted returns and poor propagation, with maximum depth of penetration being less than 3.3 m.

**LDB-13**

Start (UTM): 430445 E 7389502 N  
End (UTM): 419775 E 7389359 N  
Length: 695 m

Profile LDB-13 continues climbing slowly as it heads west. The second half of the line crests the slope levelling out onto flat, hummocky terrain. The last ~200 m of LDB-13 passes a long, oval shaped lake that is roughly 700 m north-to-south and 200 m east-to-west.

Disrupted reflections and near surface attenuation characterize the first 90 m of LDB-13, with signal penetration never exceeding 3.2 m. From 90 to 210 m there are disrupted reflections overlaying a strong, laterally continuous reflection that rises from 3.4 to 2 m in depth. Upon reaching 2 m this reflection replaces the disrupted reflections. This reflection continues until 290 m; from 225 to 290 m there is another reflection that is seen at depths between 3.9 and 4.5 m. Strong attenuation of the radar signal characterizes the subsection between 290 and 500 m, with disrupted returns observed no deeper than 2.6 m. Between 500 and 535 m there is a single wedge-shaped reflection. From 535 to 635 m, penetration is slightly increased as disrupted hummocky reflections are observed as deep as 3.1 m. Signal penetration is reduced to ~2.5 m from 635 m to the end of LDB-13 at 695 m.
Profile LDB-14 follows the east-west cutline for its first 175 m. It is then diverted slightly to the north for 140 m before rejoining the cutline at ~315 m. At ~340 m the profile crosses a narrow stream. The terrain covered in LDB-14 is flat with little or no net change in elevation across the profile.

The first 145 m of radar profile LDB-14 has a near surface layer of disrupted hummocky reflections that attenuates the GPR signal. As a result signal penetration through this subsection is less than 2.6 m. From 145 to 170 m the depth of penetration increases to 4.2 m. Between 170 and 215 m there is a single concave (up) reflection; this bowl-shaped feature begins at a depth of 3.3 m, dips to 5.2 m at its centre and rises again to 2.9 m. From 215 to 415 m the architecture is comprised of disrupted hummocky reflections with maximum signal penetration ranging between 3.2 and 4.5 m. Between 415 m and the end of LDB-14 at 615 m attenuation of the radar signal in the near surface predominates as disrupted returns are observed no deeper than 2.6 m across this subsection.

LDB-15
Start (UTM): 419141 E 7389178 N
End (UTM): 418438 E 7388994 N
Length: 730 m

LDB-14 follows the cutline west across flat ground. A narrow stream was crossed ~290 m into the profile.

The attenuation of the signal seen at the end of LDB-14 persists across the first 165 m of LDB-15 as disrupted returns are seen no deeper than 2.6 m. Between 165 and 305 m signal penetration is increased to ~4.6 m and the architecture is comprised of hummocky, discontinuous reflections. From 305 to 335 m there are three short, inclined, sub-parallel reflections. Between
335 and 405 m there are discontinuous returns to a depth of 4.2 m. Between 405 and 505 m there is a slight reduction in the depth of penetration as discontinuous reflections are seen to a depth of 3.8 m. From 505 m to the end of LDB-15 at 730 m there is strong attenuation of the radar signal. Discontinuous reflections can be seen no deeper than 2.6 m.

**LDB-16**

Start (UTM): 418438 E 7388994 N  
End (UTM): 417918 E 7389324 N  
Length: 630 m  

Radar profile LDB-16 heads northwest along a cutline. The profile begins within mature forest then enters a series of high-centred bogs in its second half (Figure 4.25). For its last 350 m LDB-16 skirts the northeastern shore of a lake measuring approximately 400 x 250 m.

Figure 4.25. Looking south down cutline CVL-02 in the boggy area crossed in GPR line LDB-16.
The first 195 m of LDB-16 has strong attenuation of the radar signal in the near surface, with signal penetration of less than 3.2 m; the architecture is comprised of discontinuous, sub-horizontal reflections. Between 195 and 285 m there are discontinuous reflections observed to a maximum depth of 3.9 m. From 285 to 345 m there is a single continuous reflection at ~2.0 m. This is underlain by a series of discontinuous reflections to a maximum depth of 3.1 m. Disrupted hummocky reflections to a depth of 3.2 m comprise the subsection between 345 and 360 m. Between 360 and 450 m a series of continuous, near surface reflections are observed; signal penetration across this subsection ranges between 3.2 and 3.5 m. Propagation of the radar signal improves between 450 and 470 m, as discontinuous returns are observed to a maximum depth of 4.6 m. From 470 to 495 m the signal penetration is reduced to 3.5 m with discontinuous, hummocky returns being the only observed architecture. Between 495 and 615 m disrupted hummocky returns comprise the architecture while signal penetration across this subsection vacillates between 3.3 and 4.5 m. The final subsection of LDB-16, from 615 to 630 m, has a single reflection that is truncated by the end of the profile.

LDB-17
Start (UTM): 417918 E 7389324 N
End (UTM): 417411 E 7389645 N
Length: 610 m

LDB-17 begins within a series of raised boggy areas. As it heads northwest it enters mature forest. The terrain is flat with some small hummocks.

The first 45 m of LDB-17 is comprised of a wedge-shaped group of hummocky, discontinuous reflections. Signal penetration across this subsection reaches a maximum of 9.0 m at 16 m. Between 45 and 110 m the architecture consists of a single, continuous reflection at ~2.0 m overlaying discontinuous returns to maximum depths between 3.6 and 4.0 m. From 110 to 155
m two parallel, continuous reflections are observed (Figure 4.26). The uppermost of these inclines from 2.9 to 1.6 m; the lower reflection rises from 4.0 to 2.6 m. The subsection between 155 and 290 m has hummocky, discontinuous reflections that can be seen as deep as 3.9 m. From 290 m to the end of LDB-17 at 610 m there are disrupted hummocky returns observed no deeper than 3.3 m.

![Figure 4.26](image)

**Figure 4.26.** Subsection of radar profile LDB-17 showing parallel, continuous reflections between 110 and 155 m.

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**LDB-18**

Start (UTM): 417411 E 7389645 N  
End (UTM): 417158 E 7389800 N  
Length: 295 m

LDB-18 continues towards the northwest through mature forest. There is no change in elevation and there are no visible hydrological features.

The entire 295 m of LDB-18 is characterized by strong attenuation of the radar signal in the near surface. Discontinuous, hummocky returns are seen to a maximum depth of 2.8 m.
**LDB-19**

Start (UTM): 417158 E 7389800 N  
End (UTM): 416897 E 7389970 N  
Length: 310 m  
LDB-19 travels along flat ground through mature forest. There is no change in elevation or visible hydrology.

Due to failure of the fibre optic cable connecting the 100 MHz receiver to the DVL the data collected in LDB-19 could not be used in this study.

**LDB-20**

Start (UTM): 418452 E 7388989 N  
End (UTM): 418847 E 7388746 N  
Length: 460 m  
LDB-20 runs southeast from the beginning of profile LDB-16 along a cutline. A narrow stream was crossed ~285 m into LDB-20. The profile runs slightly downhill through mature forest.

The first 155 m of LDB-20 is characterized by strong attenuation of the radar signal, resulting in a maximum penetration of 2.6 m. The architecture across this subsection consists of discontinuous returns. Signal penetration improves between 155 and 295 m as disrupted, hummocky returns can be seen to maximum depths ranging between 3.2 and 4.6 m. From 295 to 345 m there are a series of short, sub-parallel, inclined reflections reaching a depth of 3.5 m. The final subsection of LDB-20, from 345 to 460 m, is once again characterized by attenuation of the EM wave. Signal penetration does not exceed 3.0 m and the architecture consists of discontinuous and disrupted reflections.

**LDB-21**

Start (UTM): 418847 E 7388746 N  
End (UTM): 419205 E 7388520 N  
Length: 425 m  
The terrain is level as radar profile travels southeast. There is no significant topography or visible hydrology.
The first 150 m of LDB-21 has a series of discontinuous reflections in the near surface. These reflections are associated with strong attenuation of the radar signal, limiting maximum signal penetration across this subsection to less than 2.9 m. From 150 to 320 m there is a single reflection at ~ 4.0 m that underlies a series of discontinuous reflections seen close to the surface. From 320 to 375 m a continuous reflection that inclines from 1.9 to 3.4 m is seen underlying discontinuous returns. Between 375 and 425 m there is once again significant attenuation of the EM wave; disrupted, sub-horizontal reflections within this subsection are observed no deeper than 2.7 m.

**LDB-22**

Start (UTM): 419205 E 7388520 N  
End (UTM): 419555 E 7388299 N  
Length: 410 m  

LDB-22 runs southeast along flat ground. There is no topography or visible hydrology within the profile.

The first 145 m of LDB-22 consists of discontinuous, sub-horizontal reflections observed to a maximum depth of 2.8 m. Between 145 and 380 m the discontinuous, sub-horizontal reflections described in the first subsection can now be seen overlaying a weak continuous, undulating reflection that varies in depth between 3.6 m and 5.2 m. From 380 m until the end of LDB-22 at 410 m, the underlying reflection becomes stronger and clearer as propagation of the EM wave is improved.

**LDB-23**

Start (UTM): 419555 E 7388299 N  
End (UTM): 420124 E 7387942 N  
Length: 675 m  

Radar profile LDB-23 travels southeast along a cutline. There is no significant topography or visible hydrology within the profile.
The first 285 m of LDB-23 consists primarily of hummocky, disrupted returns. Sporadically across this subsection a weak reflection between 3.9 and 5.2 m can be seen underlying these reflections. From 285 m until the end of LDB-23 at 675 m the architecture consists of hummocky, disrupted returns which can be seen no deeper than 3.2 m.

**LDB-24**

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</thead>
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<tr>
<td>420124 E 7387942 N</td>
<td>420799 E 7387515 N</td>
<td>785 m</td>
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Radar profile LDB-24 maintains a southeasterly direction. There is no significant topography or visible hydrology.

The first 80 m of LDB-24 is comprised of hummocky, disrupted reflections to a maximum depth of 3.3 m. Between 80 and 210 m the architecture consists of discontinuous, hummocky reflections. Typically signal penetration was less than 2.8 m through this subsection. Periodically, however, isolated reflections were present between 2.9 and 4.1 m in depth. From 210 to 390 m the returns are chaotic with signal penetration of less than 3.3 m. The subsection between 390 and 475 m contains a wedge-shaped feature comprised of disrupted hummocky reflections. The last 310 m of LDB-24 is characterized by poor propagation, and weakly hummocky, discontinuous reflections can be seen no deeper than 3.2 m.

**LDB-25**

<table>
<thead>
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<th>Start (UTM):</th>
<th>End (UTM):</th>
<th>Length:</th>
</tr>
</thead>
<tbody>
<tr>
<td>420799 E 7387515 N</td>
<td>421435 E 7387113 N</td>
<td>785 m</td>
</tr>
</tbody>
</table>

LDB-25 begins by travelling to the southeast. A high-centred bog was crossed in the middle of the profile. At 500 m the profile is diverted to the east as it skirts a low-lying boggy area for 125 m before it resumes its southeastern direction.

The first 175 m of LDB-25 is comprised of discontinuous, slightly hummocky reflections that can be seen only as deep as 3.2 m. Disrupted returns are seen from 175 to 215 m, as
maximum signal penetration increases to 4.0 m. Maximum signal penetration remains unchanged between 215 and 320 m with disrupted to chaotic returns seen overlying a continuous reflection that undulates between 3.9 and 4.2 m in depth. Disrupted to chaotic returns persist from 320 to 365 m, with signal penetration reaching maximum depths between 3.5 and 4.5 m. Between 360 and 445 m a single continuous reflection, undulating between 3.2 and 3.8 m, underlies discontinuous, sub-horizontal reflections observed near the surface. From 445 to 510 m, the underlying reflection is inclined as it rises to 1.3 m (Figure 4.27). This reflection is underlain in this subsection by a strong continuous reflection that varies in depth between 4.6 and 6.5 m. Between these two reflections there is a cluster of discontinuous, inclined reflections between 475 and 510 m. Between 510 m and 635 m there is a U-shaped feature that has signal penetration as deep as 9.6 m. This U-shaped architecture is comprised of a series of disrupted reflections. From 635 m to end of LDB-25 at 785 there is a series of discontinuous reflections that are underlain by a single continuous reflection that undulates between 3.9 and 5.2 m.
Figure 4.27. Subsection of radar profile LDB-25, with schematic, showing a cluster of discontinuous reflections between two continuous reflections starting at 470 m.

**LDB-26**
- **Start (UTM):** 421435 E 7387113 N
- **End (UTM):** 422166 E 7386595 N
- **Length:** 900 m

Radar profile LDB-26 travels southeast along a cutline. The terrain is flat and there is no visible surface hydrology.

The architecture observed at the end of LDB-25 persists through the first 90 m of LDB-26. At this point in the profile the underlying reflection is no longer present as discontinuous reflections to a maximum depth of 4.7 m are the only architecture observed between 90 and 140 m. The final 760 m of LDB-26, from 140 to 900 m, is characterized by attenuation of the radar signal in the near surface. Sub-horizontal, discontinuous reflections to a maximum depth of 3.6 m constitute the only architecture across this subsection.
**LDB-27**

Start (UTM): 422166 E 7386595 N
End (UTM): 422956 E 7386018 N
Length: 960 m

Radar profile LDB-27 heads towards the southeast. There is no significant relief or visible hydrology within the profile.

The first 165 m of LDB-27 is comprised of discontinuous end of LDB-26; maximum depth of penetration for this segment is 3.3 m. From 165 to 250 m there is an increase in penetration with discontinuous reflections observed to a depth of 3.9 m. In the middle of this subsection, between 190 and 225 m there is a strong, continuous reflection underlying these returns. Between 250 and 310 m signal penetration is once again reduced to less than 3.3 m. From 310 to 360 m there are hummocky discontinuous reflections; this subsection has a marked increase in signal penetration with the deepest returns coming from 4.5 m. The final 600 m of LDB-27, from 360 to 960 m, is characterized by poor propagation of the EM wave. Discontinuous, sub-horizontal reflections can be observed to a maximum depth of 3.2 m.

**LDB-28**

Start (UTM): 422956 E 7386018 N
End (UTM): 423717 E 7385456 N
Length: 960 m

Radar profile LDB-28 maintains southeasterly direction as it follows a cutline for its first 480 m. It is diverted slightly to the south for ~170 m by a lake small round lake before rejoining the cutline for the rest of the profile.

The shallow signal penetration and discontinuous returns observed at the end of LDB-27 persist through the first 510 m of LDB-28. Between 510 and 660 m there is an increase in signal penetration to 3.9 m with the predominant architecture being disrupted hummocky reflections. There are two exceptions within this subsection. Between 550 and 560 m and 580 and 605 m
there are three wedge-shaped clusters of reflections. These architectural features exhibit an increase in signal penetration; maximum penetration in these features is 7.1 m. From 660 to 710 m maximum signal penetration is reduced to 3.3 m and discontinuous reflections are the only returns. Between 710 and 825 m short, disrupted reflections are observed as deep as 3.9 m. Between 825 and 880 m a single, undulating, continuous reflection overlays discontinuous hummocky returns that can be observed as deep as 5.0 m. This architecture is interrupted between 880 and 905 m by a U-shaped collection of disrupted returns which can be observed to a depth of 5.4 m before resuming from 905 m to the end of LDB-28 at 960 m.

**LDB-29**

Start (UTM): 423717 E 7385456 N
End (UTM): 424721 E 7384726 N
Length: 1255 m

LDB-29 continues to follow the cutline towards the southeast with the exception of a 250 m segment; the profile is diverted to the east between 150 and 400 m by a small pond. There is no significant topography within this profile.

The first 55 m of LDB-29 has a single continuous reflection overlying a series of discontinuous returns to a maximum depth of 3.8 m. Between 55 and 95 m the overlying reflection disappears and weakly hummocky reflections are the only returns. From 95 to 145 m there are disrupted to chaotic returns that can be seen as deep as 4.5 m. From 145 to 235 m the signal penetration gradually increases until it reaches 6.5 m at 235 m; the architecture of this subsection is comprised of discontinuous, hummocky reflections. Between 235 and 310 m there are layers of discontinuous reflections and a maximum depth of penetration of 6.5 m. From 310 to 370 m signal penetration is gradually reduced until maximum penetration is only 3.5 m at 370 m; discontinuous reflections comprise the architecture of this subsection. Between 370 and 550
m there are disrupted hummocky returns and a maximum signal penetration of 3.8 m. Near surface attenuation of the radar signal characterizes the subsection between 550 and 920 m, with discontinuous, sub-horizontal reflections observed no deeper than 2.8 m. This architecture persists from 920 m to the end of LDB-29 at 1255 m; propagation of the EM wave is slightly improved in this subsection as returns come from as deep as 4.0 m.

**LDB-30**
Start (UTM): 424721 E 7384726 N
End (UTM): 425630 E 7384074 N
Length: 1125 m

Radar profile LDB-26 moves towards the southeast. There is no significant change in elevation or surface hydrology within the profile.

The first 815 m of LDB-30 are characterized by attenuation of the radar signal in the near surface. Sub-horizontal, disrupted returns to a depth of 2.9 m comprise the architecture of this subsection. A wedge-shaped cluster of abundant, disrupted reflections is seen from 815 to 890 m; this subsection has a marked increase in signal penetration with the deepest returns coming from 7.2 m. Signal penetration is reduced between 890 and 1005 m as sub-horizontal, discontinuous returns are observed to a maximum depth of 3.0 m. From 1005 until the end of LDB-30 at 1125 m there are disrupted hummocky returns that are underlain by a strong continuous reflection that ranges between 3.2 and 4.2 m in depth.

**LDB-31**
Start (UTM): 425630 E 7384074 N
End (UTM): 425771 E 7383960 N
Length: 175 m

Radar profile LDB-31 runs southeast. There is no significant relief and no lakes or streams within the profile.

The first 75 m of LDB-31 is a continuation of the architecture observed at the end of LDB-30; disrupted returns underlain by a continuous reflection. Between 75 and 125 m the
disrupted returns persist but are no longer overlaying a continuous reflection. From 125 m until the end of LDB-31 at 175 m the disrupted reflections are underlain by a strong dome-shaped reflection that is seen between 5.2 and 6.8 m.

**LDB-32**

- Start (UTM): 425771 E 7383960 N
- End (UTM): 426772 E 7383232 N
- Length: 1180 m

Radar profile LDB-32 heads southeast along a cutline. It climbs a gentle rise before finishing on flat ground. There is no visible hydrology within the profile.

The first 35 m of LDB-32 has two parallel, continuous, sub-horizontal reflections; the uppermost undulates between 1.9 and 2.6 m, the second between 2.6 and 3.2 m. These reflections are underlain by disrupted returns to a maximum depth of 6.5 m. Between 35 and 75 m a wide W-shaped reflection between 3.2 and 3.8 m is overlain by abundant disrupted returns. From 75 to 95 m the architecture consists of short inclined, parallel reflections, the deepest of which is at 4.8 m. Between 95 and 130 m a gently inclined, continuous reflection is observed to a maximum depth of 6.5 m. This reflection is overlain by disrupted to chaotic returns. From 130 to 595 m there are a series of discontinuous reflections observed to depths between 3.2 and 3.9 m. These returns are sporadically underlain by a faint reflection that can be seen between 3.9 and 4.6 m. A strong, continuous reflection underlies discontinuous returns between 595 and 630 m. From 630 to 655 m there are two concave (down) reflections. Poor propagation of the GPR signal characterizes the subsection between 655 and 880 m, with discontinuous reflections observed no deeper than 2.6 m. Between 880 and 955 m there are a series of inclined, sub-parallel reflections. The architecture between 955 and 980 m is comprised of hummocky discontinuous reflections with a maximum signal penetration of 4.5 m. From 980 to 1025 m these discontinuous reflections are underlain by a strong, sub-horizontal reflection at 4.6 m.
Between 1025 and 1120 m there are three wedge-shaped increases in signal penetration that are comprised of disrupted returns. Between 1120 m and the end of LDB-32 at 1180 m there is a strong continuous reflection that begins at a depth of 2.4 m and rises to 1.9 m at 1145 m before dipping to 3.2 m at the end of the profile. At its apex this reflection represents the only reflection; on either side it is overlain by disrupted returns.

**LDB-33**

Start (UTM): 426772 E    7383232 N
End (UTM): 427950 E    7382360 N
Length: 1450 m

LDB-33 is the last, and southern-most, profile collected at this site. It heads southeast and covers terrain with no significant relief. The last 250 m of the profile run approximately 150 m from the western edge of a lake measuring ~250 x ~150 m.

The first 135 m of LDB-33 consists of discontinuous hummocky reflections to a maximum depth of 4.5 m. From 135 to 270 m there are abundant, stratified, discontinuous reflections. Signal penetration across this subsection reaches 7.0 m. At 270 m the signal penetration is abruptly reduced to 3.5 m. Between 270 to 330 m the lowest returns are in the form of a single, thick, continuous reflection which underlies discontinuous returns. The underlying reflection becomes discontinuous between 330 and 390 m. Propagation across this segment of LDB-33 remains poor with signal penetration of less than 3.5 m. The subsection between 390 to 575 m contains a continuous hummocky reflection as deep as 5.9 m. Between 410 to 450 m there are two strong reflections underlying the continuous reflection. From 450 to 490 m there is a noticeable time offset, while the continuous reflection is underlain by a series of chaotic returns to a depth of 3.4 m. Between 490 and 575 m there is a continuous, sub-horizontal reflection in the near surface. Towards the end of this subsection this reflection dips to a depth of 3.0 m and is then below a collection of disrupted returns. Disrupted, hummocky reflections are
the only returns between 555 and 600 m. From 600 to 705 m the architecture consists of continuous weakly hummocky reflections to a depth of 3.9 m. Between 705 and 805 m disrupted returns are observed no deeper than 3.2 m. A marked increase in signal penetration is observed at 805 m. The subsection between 805 and 965 m has discontinuous reflections to maximum depths between 4.6 and 6.9 m. Between 965 and 1025 m there are parallel slightly inclined reflections, the deepest of which reaches 4.5 m. From 1025 to 1075 m the architecture consists of discontinuous, hummocky returns to a depth of 4.5 m. From 1075 m to the end of LDB-33 at 1450 there are only disrupted returns; signal penetration in this subsection does not exceed 3.8 m.

*LDB-34*

Start (UTM): 426615 E 7384215 N
End (UTM): 425708 E 7383974 N
Length: 940 m

LDB-34 starts just west of the beginning of the previous profile and heads east along a cutline. A stream is crossed at ~365 m. The terrain was slightly undulating across this profile with total relief of less than 5 m. At 550 m data collection was interrupted for 100 m. Description of the radar facies resumes 100 m to the west following the break in data collection; the 100 m in which data was not collected is not reflected when the lateral position of architectures are described.

The first 105 m of LDB-34 contains discontinuous hummocky reflections to a depth of 3.9 m. Between 105 and 290 m the previous architecture persists while signal penetration across the subsection is gradually reduced to less than 3.2 m. Continuous parallel horizontal reflections close to the surface predominate between 120 and 550 m. This subsection is characterized by strong attenuation of the radar signal with penetration not exceeding 2.6 m. Data collection was
interrupted at this point in the profile. Upon resumption of the profile there are chaotic returns between 550 and 605 m. From 605 to 645 m there are two parallel, continuous layers that can be seen only as deep as 2.7 m. Discontinuous reflections are the only architecture from 645 to 800 m; signal penetration across this subsection is typically less than 3.8 m with a brief spike of good propagation between 770 and 785 m that has returns coming from as deep as 4.6 m. From 800 to 890 m there are disrupted returns to a depth of 3.2 m. A wide wedge-shaped series of discontinuous returns makes up the subsection between 890 m and the end of LDB-34 at 990 m. Propagation is improved across this subsection with returns coming from a maximum depth of 6.0 m.

**LDB-35**

Start (UTM): 425706 E 7383974 N
End (UTM): 424654 E 7383698 N
Length: 1100 m

Radar profile LDB-35 starts at the beginning of the previous profile and travels west along the same cutline. A stream is crossed at ~400 m. The terrain is slightly undulating with total relief within the profile being less than 5 m.

The first 225 m of LDB-35 are characterized by poor propagation of the EM wave, with discontinuous reflections to a depth of only 2.8 m. From 225 to 670 m discontinuous returns are observed, underlain by a recurrent reflection that ranges between 3.3 and 6.5 m in depth. Between 670 and 720 m there are a series of inclined (<10°), parallel reflections. The lowest returns from this feature come from 5.5 m. From 720 to 780 m a concave (up), or bowl-shaped, reflection between 2.3 and 3.5 m underlies disrupted returns in the near surface. The subsection between 780 and 1000 m is characterized by good propagation, with discontinuous returns coming from as deep as 7.2 m. From 1000 to 1075 m signal penetration is abruptly reduced, with
disrupted returns coming from a depth of no more than 3.9 m. Good propagation returns between 1075 m and the end of LDB-35 at 1100 m as disrupted reflections are the only returns.

**LDB-36**
Start (UTM): 424654 E 7383698 N
End (UTM): 424251 E 7383594 N
Length: 390 m

LDB-36 continues west from the end of the previous profile. The topography is slightly undulating with total relief of less than 5 m. No lakes or streams intersect this transect.

The first 85 m of LDB-36 is characterized by good propagation of the EM wave. Discontinuous reflections are seen to depth of 9.2 m at the beginning of the profile. These are underlain by a continuous reflection which slopes upward until it reaches 3.2 m at 85 m. This reflection persists at ~ 3.2 m until 175 m. From 175 to 200 m there is a single reflection in the near surface. Between 200 and 280 m there is a wide, bowl-shaped feature comprised of abundant discontinuous reflections. The bottom of this feature is at 7.4 m. From 280 m to the end of LDB-36 at 390 m there is a wide, dome-shaped reflection that it is overlain by disrupted returns.

**LDB-37**
Start (UTM): 418457 E 7388982 N
End (UTM): 417937 E 7388855 N
Length: 610 m

LDB-37 starts at the junction of two cutlines, at the end of radar profile LDB-15. It heads west along a cutline across relatively level ground. At 360 m the profile is diverted to the south by the southern tip of a lake of approximately 450 x 200 m. LDB-37 rejoins the cutline for its last 40 m.

The first 475 m of LDB-37 consists of discontinuous, sub-horizontal reflections to a maximum depth of 3.4 m. From 475 to 495 m there is a wedge-shaped increase in signal
penetration that reaches a depth of 5.2 m. This is comprised of disrupted returns. From 495 m to
the end of LDB-37 at 605 m there are a series of discontinuous reflections and a maximum signal
penetration of 3.9 m.

**LDB-38**

Start (UTM): 417937 E 738855 N
End (UTM): 417213 E 738866 N
Length: 745 m

LDB-38 follows a cutline to the west across level ground. The profile enters a boggy area
for the second half of the profile. There is no significant topography along the transect.

Radar profile LDB-38 is characterized by poor propagation of the EM wave. All 745 m
of the profile consist of discontinuous, sub-horizontal reflections to a maximum depth of 3.1 m.

**LDB-39**

Start (UTM): 417213 E 738866 N
End (UTM): 416378 E 7388430 N
Length: 975 m

LDB-39 re-enters mature forest from a boggy area as it travels west. Between 485 m and
850 m the profile is diverted to the north by a small, round lake before resuming a westerly
direction for its last 125 m.

Shallow penetration of the radar signal persists throughout all 975 m of LDB-39.
Discontinuous, hummocky returns to a maximum depth of 3.4 m comprise the architecture of
LDB-39.

**LDB-40**

Start (UTM): 416378 E 7388430 N
End (UTM): 415540 E 7388197 N
Length: 885 m

Radar profile LDB-40 maintains a westerly direction as it follows a cutline. There is no
significant relief and no visible hydrology within the profile.
The first 635 m of LDB-40 consist of disrupted returns to a maximum depth of 3.1 m. A bowl-shaped collection of discontinuous reflections comprises the architecture of the subsection between 635 and 690 m. Signal penetration reaches a maximum of 5.2 m at the deepest point of this feature. From 690 m to the end of LDB-40 at 885 m there are sub-horizontal, discontinuous reflections, with maximum signal penetration varying between 3.8 and 4.5 m.

**LDB-41**

Start (UTM): 415540 E 7388197 N
End (UTM): 414714 E 7387903 N
Length: 885 m

Transect LDB-41 begins by heading west along a cutline. At 290 m the direction of travel changes as the cutline turns slightly to the south. LDB-41 follows the direction of the cutline and travels in a southwesterly direction from 290 m to the end of the profile. Between 230 and 530 m the transect skirts the northern edge of lake of ~1300 x 450 m. LDB-41 ends in an old forest fire (~15 years old).

The first 35 m of LDB-41 is comprised of discontinuous reflections to a depth of 3.2 m. Between 40 and 220 m there is a wide, saucer-shaped feature which has a gradual increase in signal penetration, until it reaches a maximum of 5.5 m at 165 m, before a gradual reduction to 3.1 m at 220 m. The saucer-shaped feature is made up of abundant, layered, discontinuous reflections. A similar, smaller, feature is observed between 220 and 280 m. Maximum signal penetration in this subsection is 4.9 m. Between 280 and 395 m there are discontinuous, slightly hummocky reflections to depths between 3.2 and 3.9 m. From 395 to 545 m there are abundant disrupted returns; these form two wedge-shaped features whose deepest points are at 5.2 m. Two parallel, sub-horizontal reflections to a depth of 3.8 m form the architecture of the subsection between 545 and 630 m. Signal penetration is unchanged from 630 to 720 m while the
architecture is made up of discontinuous returns. A series of discontinuous reflections form a wedge-shaped feature between 720 and 750 m; the bottom of the V is at a depth of 4.5 m. The final subsection of LDB-41, from 750 to 885 m, is comprised of discontinuous, hummocky reflections to a depth of 3.5 m.

LDB-42
Start (UTM): 414714 E 7387903 N
End (UTM): 413927 E 7387575 N
Length: 845 m

Radar profile LDB-42 continues west across flat ground. The first 250 m of the profile runs among a cluster of small lakes. Two streams are traversed within LDB-42; the first at ~105 m and the second at ~785 m. The terrain covered within the profile is part of the forest fire described in LDB-41 (Figure 4.28).
The first 30 m of LDB-42 contains discontinuous reflections to a depth of 3.6 m. From 30 to 170 m there are disrupted, hummocky returns to a maximum depth of 5.1 m. A saucer-shaped continuous reflection is observed between 170 and 255 m. This is overlain by disrupted returns and underlain by discontinuous, concave (up) reflections to a depth of 5.2 m. A wedge-shaped feature consisting of disrupted returns to a depth of 5.4 m makes up the architecture of the subsection between 255 and 290 m. From 290 to 400 m there are discontinuous reflections to a depth of 3.8 m. Between 400 and 440 m these are replaced by continuous sub-horizontal reflections. Short, parallel, inclined reflections comprise the architecture between 440 and 470 m. From 470 to 570 m there is strong attenuation of the radar signal as continuous, horizontal
reflections can only be seen as deep as 2.8 m. Between 570 and 730 m the reflections become discontinuous and slightly hummocky; poor propagation persists as the depth of penetration remains unchanged. A wide wedge-shaped increase in signal penetration between 730 and 790 m is comprised of disrupted returns to a depth of 3.8 m. The subsection between 790 and 820 m has two sharp, concave (up) reflections that are onlapped by disrupted returns. These features are characterized by good propagation of the EM wave, with signal penetration reaching 5.8 m. The end of LDB-42, from 820 to 845 m, has discontinuous reflections to a depth of 4.6 m.

**LDB-43**

Start (UTM): 413927 E 7387575 N
End (UTM): 413126 E 7387235 N
Length: 880 m

LDB-43 travels towards the southwest. The transect crosses a wide, shallow valley and finishes by beginning to climb a gentle slope. There is no visible hydrology within the profile.

The first 95 m of LDB-43 has discontinuous returns to a depth of 4.5 m. From 95 to 125 m there are short, parallel, inclined reflections. Poor propagation of the EM wave characterizes the subsection between 125 and 620 m; continuous, horizontal reflections to maximum depth of 2.5 m comprise the only architecture. From 620 m to end of LDB-43 at 880 m there are discontinuous reflections to a depth of 2.7 m.

**LDB-44**

Start (UTM): 413126 E 7387235 N
End (UTM): 412364 E 7386919 N
Length: 835 m

LDB-44 climbs a gentle slope as it travels southwest. There is no surface hydrology within the profile.

The strong attenuation of the radar signal and discontinuous reflections to a depth of 2.7 m observed at the end of LDB-43 persist through the first 415 m of LDB-44. This architecture is
interrupted by chaotic returns between 415 and 490 m before resuming from 490 to 540 m. Between 540 and 695 m there discontinuous, weakly hummocky reflections observed to a depth of 2.6 m. These are underlain by a single, faintly-seen, continuous reflection that ranges between 2.6 and 3.9 m in depth. From 695 m the end of LDB-44 at 835 m the radar signal is highly attenuated and continuous, horizontal reflections can be seen no deeper than 2.6 m.

**LDB-45**

Start (UTM): 412364 E 7386919 N
End (UTM): 411658 E 7386619 N
Length: 845 m

LDB-45 continues to climb slightly as it heads southwest. The end of the transect ends on flat ground. From ~450 m until the end of the profile the direction of travel is diverted to the south by a small lake.

The first 400 m of LDB-45 consists of discontinuous, horizontal reflections to a depth of 2.6 m. Between 400 and 475 m depth of penetration is increased as disrupted, sub-horizontal returns overlay a strong, dome-shaped reflection seen between 3.2 and 3.9 m. Two continuous, parallel, sub-horizontal reflections to a depth of 3.3 m comprise the architecture between 475 m and 530 m. From 530 to 575 m there is a continuous saucer-shaped reflection that reaches 3.9 m at its deepest. This is overlain by abundant, disrupted returns. From 575 to 655 m there are two continuous, sub-parallel reflections to a depth of 3.7 m. Between 655 and 690 m these returns are underlain by a bowl-shaped reflection. There are three steeply inclined, parallel reflections to a maximum depth of 4.4 m between 690 and 720 m. Between 720 and 760 m there are discontinuous, weakly hummocky reflections to depth of 3.5 m. A concave (up) reflection, with onlapping discontinuous returns is seen between 760 and 800 m. Between 800 m and the end of LDB-45 at 845 m there are discontinuous reflections to a depth of 3.5 m.
**LDB-46**

Start (UTM): 411658 E 7386619 N  
End (UTM): 410895 E 7386310 N  
Length: 840 m  

LDB-46 travels towards the southwest. The profile ends on a creek bed between two lakes. Roughly 50 m to the north there is a lake of ~250 x 175 m. Fifty metres to the south is a lake measuring ~950 x 600 m.

The first 95 m of LDB-46 consists of discontinuous reflections to a depth of 3.6 m. This architecture is interrupted between 95 and 115 m by a series of short, dipping reflections before returning between 115 and 140 m. From 140 to 215 m there is a continuous reflection between 2.6 and 2.9 m. This is underlain by a strong reflection that undulates between 5.4 and 6.5 m; there are no resolvable returns between these reflections. Between 215 and 325 m the upper reflections becomes discontinuous. The lower reflection persists and rises from 6.5 to 3.4 m. From 325 to 375 m there is a bowl-shaped increase in penetration to 5.7 m that is made up of a series of discontinuous returns. Signal penetration is briefly reduced to 3.3 m between 375 and 385 m. Between 385 and 435 m there are discontinuous returns and a maximum depth of penetration varies between 4.1 and 5.2 m. Good propagation characterizes the subsection between 435 and 510 m. A wide saucer-shaped reflection underlies abundant disrupted returns and maximum depth of penetration is 6.0 m. Between 510 and 605 m propagation is reduced as discontinuous returns can be observed no deeper than 3.3 m. A single continuous reflection between 3.6 and 4.6 m, overlain by discontinuous returns, is observed between 605 and 730 m. From 730 m to end of LDB-46 at 840 m there is a wide, half-saucer-shaped reflection that is overlain by discontinuous layered, discontinuous reflections. Signal penetration across this subsection is between 5.1 and 6.0 m.
LDB-47
Start (UTM): 410895 E 7386310 N
End (UTM): 410009 E 7385894 N
Length: 980 m

LDB-47 continues along cutline CVL-03 as it travels towards the southwest. The first 185 m hug the northwestern shore of the lake. The rest of the profile covers flat ground with no bodies of water.

The first 130 m of LDB-47 has two continuous reflections between 3.9 and 5.7 m. These are overlain by disrupted returns. Between 130 and 285 m there are discontinuous reflections to a depth of 4.1 m. Signal penetration is reduced to less than 3.7 between 285 and 810 m with sub-horizontal, discontinuous reflections being the only returns. Strong attenuation of the radar signal characterizes the final subsection of LDB-47 between 810 and 980 m; continuous, horizontal reflections observed to a maximum depth of 3.1 m are the only architecture.

Forty-seven GPR profiles were collected at the Lac des Bois site. The survey was able to avoid lakes during data collection. Maximum depth of penetration at this site ranged between 1.9 and 9.6 m.

4.2 SNOW DEPTH AT LAC DES BOIS

Snow depth was recorded at 27 locations within the Lac Des Bois study area. Values were recorded both on and off the snowmobile track.

Mean snow depth in undisturbed areas (off the snowmobile track) was 60.6 cm. The maximum recorded depth was 85 cm while the minimum recorded depth was 44 cm. The standard deviation among snow depth values was 10.1 cm.
On the snowmobile track the mean snow depth was 36.1 cm. The maximum recorded depth was 60 cm and the minimum 25 cm. Median snow depth was 35 cm and the standard deviation was 8.7 cm.
CHAPTER 5: DISCUSSION

5.1 MASSIVE ICE

Analyses of GPR data taken at the Little Chicago and Lac des Bois study sites have led to three interpretations of massive ice; two at Little Chicago and one at Lac des Bois. These features range in lateral extent from 40 to 90 m. Maximum thicknesses of the individual ice bodies measure between 1.8 and 2.7 m. The massive ice was identified by morphology and combined with the identification of areas where propagation of the EM wave was markedly improved. Further evidence in support of interpretations of massive ice was gleaned from secondary data including velocity testing, shothole drillers’ logs (Smith, 2011) and geomorphic evidence of active thermokarst interpreted from air photographs.

Previous research provided this study with criteria for identifying GPR signatures consistent with massive ice. Two characteristics typical of massive ice were used as diagnostic markers for the identification of ice bodies. First, ice allows for a wave velocity of 0.16 m/ns. This value is different from any of the values that would be present in the till, glaciolacustrine and glaciofluvial materials typically found in the Mackenzie Valley and the Colville Hills. This leads to interfaces between massive ice and sediment generally producing a strong reflection within a GPR profile (Wolfe et al., 1997). Secondly, massive ice generally promotes good propagation of the radar signal (Moorman et al., 2003) which typically causes an increase in the depth of penetration.

5.1.1. LC-25: ground-penetrating radar and velocity testing

A wide wedge-shaped feature, between 45 m and 110 m into radar profile LC-25, has returns that are consistent with massive ice. The subsection in question is not in contact with, or
in close proximity to, any body of water. Surficial geology for this area has been described by Duk-Rodkin and Hughes (1992) as consisting of a thin till layer overlying streamlined bedrock. Shothole driller’s log KOD-07105-489, found within the interpreted massive ice, indicates a mixture of clay, rocks, sandstone layers and shale to a depth of 12 m. The location of the subsection discussed in this section, as well as the location of the driller’s log described above, is shown in Figure 5.1.

![Figure 5.1 Location of massive ice and shothole driller's log KOD-07105-493 within radar profile LC-25.](image)

Two continuous reflections, between 50 and 105 m along radar profile LC-25, are interpreted as the top and bottom of the massive ice feature (Figure 5.2). The upper reflection undulates between 1.7 and 2.5 m. At its closest to the surface, the bottom reflection is at 2.2 m. At its deepest, the bottom reflection is at 4.3 m. The lower reflection is interrupted at 50 m and at
60 m by two hyperbolae. The wedged shape of the reflections here represents a similar morphology to those found to be massive ice at Parsons Lake, NWT (Angelopoulos et al., 2013).

The sudden increase in signal penetration between 50 m to 105 m along radar profile LC-25 from 3 m to 5 m is consistent with a quick transition from fine-grained till to ice or ice rich sediments. This architecture is not to be expected from the unsorted, typically fine-grained, till found in this area (Duk-Rodkin and Hughes, 1992). The drillers’ log’s contents (clay, rocks, sandstone layers and shale) also include nothing that would typically produce the returns observed here. Low levels of attenuation, in contrast to the expected attenuation associated with fine-grained till found in the area, are consistent with massive ice. The physical properties of ice are such that it is subject to lower levels of attenuation than other sedimentary media. Electromagnetic waves are attenuated at a rate of between 1-260 dB/m when propagating in clay as opposed to 0.01 dB/m when the medium is pure ice (Davis and Annan, 1989). These morphologies are supportive of an interpretation of massive ice.
The hyperbola highlighted in Figure 5.2 allows for a quantitative analysis of the velocity using a computer software algorithm. Hyperbolic reflections are produced when the EM wave encounters bodies approximately the size of the wavelength of the radar pulse, (in this case ~ 1 m). These bodies act as point reflectors. The point sources of reflection are characterized within a GPR profile as hyperbolae whose roundness, or their horizontal to vertical size ratio, can be used to determine the velocity at which the EM wave travelled through the material overlying the hyperbola(e). This can be done manually but was carried out here using the EkkoView2 software platform from Sensors and Software. Testing on the hyperbola in Figure 5.2 provided a calculated velocity of 0.16 m/ns. The established velocity for pure ice is 0.16 m/ns (Table 5.1). Considering that the interpreted ice is below sediment, the calculated value is slightly high. The discrepancy between the calculated velocity of 0.16 m/ns and the combined value of sediment
and ice is likely the result of the inclusion of the snow pack in the average velocity. Including the snowpack and it’s relatively high velocity of 0.23 m/ns (Lalumiere, 2006) would likely account for a slightly higher value than would be expected. The calculated value corresponds most closely with known values for ice and is inconsistent with other materials likely to be found in the study area.

<table>
<thead>
<tr>
<th>Medium</th>
<th>Typical electromagnetic wave velocity (m/ns)</th>
<th>Rate of attenuation (dB/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>0.3</td>
<td>0</td>
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<tr>
<td>Fresh water</td>
<td>0.033</td>
<td>0.1</td>
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<td>Pure ice</td>
<td>0.16</td>
<td>0.01</td>
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<td>Saturated sand</td>
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<td>0.03-0.3</td>
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<td>Saturated clay</td>
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<td>Saturated till</td>
<td>0.1-0.12</td>
<td>n/a</td>
</tr>
<tr>
<td>Limestone</td>
<td>0.12</td>
<td>0.4-1</td>
</tr>
<tr>
<td>Frozen sand</td>
<td>0.12</td>
<td>1.5-2.0</td>
</tr>
<tr>
<td>Frozen silt</td>
<td>0.11</td>
<td>9-10</td>
</tr>
</tbody>
</table>

Table 5.1 Theoretical velocities and attenuation rates of a selection of common sedimentary materials (Davis and Annan, 1989; Neal, 2004)

Assuming the calculated velocity of 0.16 m/ns derived from the hyperbolae analysis, the thickness of the massive ice must be adjusted. The uppermost, or earliest, reflection that is interpreted as the top of the ice feature is seen at 33 ns (Figure 5.3). The lower, or later, reflection that denotes the bottom of the massive ice comes at 67 ns. To determine the thickness of the feature the difference between these reflections is multiplied by the velocity and divided by two to account for two-way travel time. The equation for calculating the thickness of the ice feature would be:

\[
(1) \quad T h = \frac{v(R_2 - R_1)}{2}
\]
Where \( v \) = velocity (m/ns), \( R2 \) = bottom reflection (ns), \( R1 \) = upper reflection (ns), and \( Th \) = ice thickness. By using equation 1 the ice thickness was calculated to be 2.7 m.

\[
\frac{0.16(67-33)}{2} = 2.7 \text{ m}
\]

At its thickest, 68 m into the profile, the ice is 2.7 m thick assuming the adjusted velocity. Massive ice at this site measures 53 m across and has a maximum thickness of 2.7 m.

**5.1.2 Massive ice within radar profile LC-49**

A 95 m long feature between 60 and 155 m along radar transect LC-49 has been interpreted as massive ice. The feature is found on the northeastern edge of a lake that is ~800 m from north to south and ~450 m east to west (Figure 5.4). The ice is approximately 50 m from the lake’s edge. The area is flat to mildly undulating. The surficial geology in the area is mapped as till occurring as a drumlinoid plain or as extensively fluted (Duk-Rodkin and Hughes, 1992).
This example of massive ice is represented within the GPR profile as two strong, undulating, sub-parallel reflections between 60 and 155 m of GPR line LC-49 (Figure 5.5). There is an increase in signal penetration across this subsection that is typical of ice or ice-rich sediments. The continuous nature of these returns is not what one would expect from the surficial geology described by Duk-Rodkin and Hughes (1992). The till that comprises the drumlinoid plain on which this feature is found is generally fine-grained and unsorted, a composition that is unlikely to produce the continuous strong reflections observed here.
Drillers’ log KOD-08101-604 is the only record within this subsection. Located ~140 m along LC-49 it describes frozen clay between 3-5 m, overlying clay and rocks to a depth of 12 m. The first 3 m are listed as unknown. The described interfaces at 3 and 5 m coincide well with the strong reflections seen within the GPR data and are supportive of an interpretation of massive ice.

Pure ice typically appears “transparent” between its upper and lower extents (Moorman and Michel, 2000). The presence of reflections in this case likely indicates the presence of a significant amount of sediment within the massive ice. This is consistent with the drillers’ log describing frozen clay. It is likely that these are ice-rich, or icy, sediments with high volumetric ice content. This feature is therefore interpreted as being similar to what was characterized by Rampton and Mackay (1971), Mackay (1973), and Côté et al.(2003) as being “icy sediments”
based on their interpretation of shothole drillers’ log data from the Tuktoyaktuk Peninsula region.

5.1.3 Massive ice within radar profile LDB-07

A 50 m feature within radar profile LDB-07 has been interpreted as massive ice. The interpreted ice is 40 m to the east of a lake measuring 80 m north-south by 40 m east-west. The location of the massive ice and radar profile LDB-07 is shown in Figure 5.5. The lake lies just east of a glaciofluvial complex containing a series of braided and single-channel eskers (Figure 4.22). The ground in the immediate area is flat to mildly undulating.

Figure 5.5. Location of massive ice within GPR profile LDB-07. Dots represent the location of shothole records

Between 330 and 380 m of GPR profile LDB-07 there are two strong, continuous, sub-parallel reflections underlying disrupted returns (shown in figure 5.7). The upper most of these reflections varies in depth between 2.7 and 3.2 m, while the lower reflection ranges between 3.3
and 4.2 m depth. The lower reflection represents an increase in signal penetration relative to the surrounding area. The subsection before 330 m had signal penetration up to 3.4 m, while immediately after 380 m there is a maximum depth of penetration of 3.2 m. The strength and definition of the continuous reflections and the good propagation between the reflections supports the interpretation of massive ice at this site.

Figure 5.6. Subsection of radar profile LDB-07 showing massive ice between 330 and 380 m. Vertical exaggeration = 6.7x.

Air photographs were used to identify thermokarst terrain in the immediate area of the interpreted ice body (Figure 5.8). The lake located 40 m to the west of the massive ice has morphologies that are characteristic of a thermokarst basin. Smooth curving lake margins and sharply raised edges are typical of lake basins formed by the melting of ground ice or ice-rich sediments. To the east (~500 m) of the massive ice there is a collection of depressions that form a honeycomb pattern. This morphology is usually characteristic of active thermokarst processes. Thermokarst basins, generally between 0.8 and 3.0 km in diameter, are common Arctic lowland areas (French, 2007) and represent localities that contain, or once contained, large quantities of
ground ice. The presence of a variety of thermokarst features in this area is consistent with the characteristics of a thermokarst basin and supportive of the interpretation of massive ice or icy sediments.

Figure 5.7. Air photograph showing location of interpreted massive ice relative to thermokarst features in the area. Source: Government of Canada, Department of Energy, Mines and Resources.

5.1.4. Overview of massive ice interpretations and related study limitations

This study has identified three occurrences of massive ice. In two out of the three instances, the massive ice is considered to have formed within or below till. The location of the third occurrence (LDB-07) has not been mapped for surficial geology. The occurrences at LC-25 and at LDB-07 occurred close to the margins of an anastomosing esker complex that was observed in the field.
The interpretations of massive ice presence were made based on GPR returns of a similar morphology. Continuous reflections representing both the top and bottom of the ice bodies are found at all three sites, as is a noticeable increase in signal penetration. These observations and the subsequent interpretations were made through qualitative analysis and, in the complex sedimentary environment found in the study areas, could not be done by automated interpretation software. These qualitative analyses are best complemented by other data in order for reasonable conclusions to be made. Seismic shothole drillers’ lithostratigraphic logs, inverse modelling and aerial photographs were used, in lieu of traditional ground-truthing, to support the interpretation of the GPR profiles.

From the 58.4 km of GPR profiles collected, 190 m were interpreted as containing massive ice. It is likely that massive ice within the two study sites is underrepresented by this study. The absence of dedicated and consistent ground-control data has imposed constraints on this group of methodologies’ ability to make more comprehensive conclusions regarding the amount of massive ice in these two areas.

The most often used complementary data for this study were seismic shothole drillers’ logs (Smith, 2011). Typically these point source data were separated by 60 m. This spatial density of data does not provide the ability to map massive ice. The linear nature of the drillers’ data also makes mapping of features difficult. Furthermore, land use policies prohibiting seismic testing within 50 m of water bodies. This creates a spatial restriction on these data as there will be no records from areas that are within 50 m of bodies of water. Some of these shortcomings could be mitigated by the implementation of a dedicated ground-truthing program. In one case (GPR profile LC-25) there is an area that based on the GPR data is interpreted to contain massive ice measuring 65 m in lateral extent and 2.7 m thick, however a drillers’ log located within this
section failed to mention the presence of ice. It is possible that certain periglacial features, including massive ice, were not recorded at some locales. The presence of a permafrost/Quaternary geologist on future seismic programs who could better assess and record the nature of materials drilled through could greatly improve the accuracy of the records. The seismic shothole drillers’ logs did, however, provide one positive identification of massive ice. However, due to spatial limitations and a lack of quality control it is likely that these records have under-reported massive ice at these two sites.

5.2 TALIKS AND UNFROZEN WATER AND SEDIMENTS IN SEISMIC DRILLERS’ LOGS AT LAC DES BOIS

Four case studies at the Lac des Bois study area are used to examine the effectiveness of seismic shothole drillers’ logs at identifying taliks. Qualitative facies analysis of the GPR data is compared with the lithostratigraphic data provided by the drillers’ logs. Examples from the literature were used to aid in the interpretation of thermal interfaces (Stevens, 2008).

There are two aspects of unfrozen ground within permafrost areas that produce diagnostic characteristics on GPR profiles. First, the presence of unfrozen water causes attenuation of the radar signal (Stevens et al., 2008). This typically results in a significant reduction in signal penetration. Second, the large contrast in dielectric contrast between frozen and unfrozen sediments leads to a reflection coefficient of 0.34 (Moorman et al., 2003) which produces a highly reflective surface. By comparison the reflection coefficient at an interface between frozen sediment and ice is notably lower (0.16). Typically the thermal interface at the top of a talik will therefore present on a GPR profile as a strong continuous reflection (Arcone et al., 1998;
Moorman et al., 2003). The facies analysis undertaken in this section used these criteria to identify profiles consistent with the presence of unfrozen water or unfrozen sediments.

Seismic shothole drilling carried out in March 2008 yielded nine instances, at four locations within the Lac des Bois study area, of unfrozen water or unfrozen sediments recorded within the subsurface along cutline CVL-02. These records are compared with interpretations derived from the GPR data.

5.2.1 Seismic shothole drillers’ log CVL02-1967.5

Drillers’ log CVL02-1967.5 recorded sand, sandstone and water over a depth of 9 m. Traversed during collection of radar profile LDB-21, the terrain surrounding this shothole is flat. The location of drillers’ log CVL02-1967.5 and GPR profile LDB-21 is shown in Figure 5.9. The nearest body of water is a lake measuring 275 x 150 m, 345 m to the southwest.

Figure 5.8. Location of shothole drillers’ log CVL02-1967.5 within radar profile LDB-21
The identification of unfrozen water within the subsurface prompted the comparison of the drillers’ data with GPR facies analysis. The characteristics typical of GPR profiles representing unfrozen zones within permafrost regions are not present in the subsection of LDB-21 which contains drillers’ log CVL02-1967.5.

There is no significant change in the signal penetration around the proposed area of unfrozen water as compared to the adjacent area in which water was not noted (Figure 5.10). Drillers’ log CVL02-1961.5, 60 m to the southeast of CVL02-1967.5, describes sand and sandstone to a depth of 9 m. Despite the recorded absence of liquid water, attenuation of the radar signal is not visibly reduced around CVL02-1961.5; signal penetration is static across this subsection of GPR profile LDB-21. The depth of penetration within this subsection is similar to that of other nearby areas. The strong reflections expected within a GPR profile representing a frozen to unfrozen interface are not visible within this subsection of LDB-21.

The GPR data is unable to confirm the presence of water at this site. This could be accounted for by the relatively shallow penetration (as compared to the 9 m depth in the drillers’ log) achieved by the radar. If the water were encountered at a depth of greater than 3 m the GPR data would not detect it.
Facies analysis of GPR profile LDB-21 cannot successfully confirm the presence of unfrozen water. The lack of typical morphologies within the GPR profile makes it unlikely that this is the site of either an open talik, penetrating completely through the permafrost, or a supra-permafrost talik. A lateral talik, unfrozen sediment overlain and underlain by permafrost (van Everdingen, 1990), may be present. Because of the relatively shallow penetration of the radar signal a talik located at a depth of more than 3 m in this area would likely not be detected by the GPR equipment used in this study. Similarly, because of the relatively shallow nature of the GPR survey, a sub-permafrost talik would not appear in the GPR data.

5.2.2 Seismic drillers’ logs CVL02-1073.5 and CVL02-1067.5

Two seismic drillers’ logs located within GPR profile LDB-32, CVL02-1073.5 and CVL02-1067.5, report unfrozen water. Gravel and water, to depths of 5 m and 3 m, are reported in CVL02-1073.5 and CVL02-1067.5, respectively. There are no significant bodies of water in
close proximity to these shotholes. The terrain climbs gently as the profile moves southeast. The location of the two shotholes within GPR profile LDB-32 is shown in Figure 5.11.

![Figure 5.10. Location of shothole drillers' logs CVL02-1073.5 and CVL02-1067.5 and radar profile LDB-32](image)

There is no visible decrease in signal penetration in the vicinity of the two recorded incidences of unfrozen water. There is a continuous reflection between 595 and 630 m (Figure 5.12), between the two shotholes. This reflection is between 2.5 and 2.9 m below the surface. The strength of the reflection is not noticeably stronger than other nearby returns.
The GPR facies interpretations do not correspond well with the drillers’ logs in profile LDB-32. The absence of a strong continuous reflection near shothole CVL02-1073.5 and no significant change in signal penetration is not consistent with the presence of water as noted in the record. Signal penetration is static at CVL02-1067.5 and in surrounding areas. The continuous reflection seen in the radar profile is similar in strength to other nearby reflections and is unlikely to represent a thermal interface.

The presence of unfrozen water within the subsurface (<5 m) at shothole CVL02-1073.5 is not supported by the GPR facies analysis. An open talik or a supra-permafrost talik is unlikely here as the radar architecture immediately below the depth of the active layer/seasonal frost is atypical of a thermal interface. The depth of drilling (5 m) exceeds that of the radar signal (~4 m). Unfrozen water as part of a lateral talik would therefore not be resolved within the radar data and could be the source of the drillers’ records of water. The depth of penetration of the drilling
at CVL02-1067.5 (3 m) does not exceed that of the GPR signal (~4 m). The absence of characteristics typical of thermal interfaces in this subsection of LDB-32 makes it unlikely that there is unfrozen water within the first 3 m as noted in the drillers’ records. As taliks are often maintained by the presence of relatively warm surface water (Woo, 1986), the absence of lakes and streams in the immediate area is also not suggestive of the presence of a talik in the vicinity of seismic shotholes CVL02-1073.5 and CVL02-1067.5.

5.2.3 Seismic drillers’ logs CVL02-956.5 and CVL02-953.5

Wet sand was recorded in two seismic drillers’ logs, CVL02-956.5 and CVL02-953.5, found within the first half of GPR profile LDB-33; the depths of the shotholes are 5 m and 3 m respectively. The terrain here is flat and there is no lake, stream or pond within 300 m of the two shotholes. The location of CVL02-956.5 and CVL02-953.5, as well as CVL02-893.5, CVL02-887.5, CVL02-881.5 and CVL02-877.5, within GPR profile LDB-33 is shown in Figure 5.13.
Figure 5.12. Location of shothole drillers' logs CVL02-956.5, CVL02-953.5, CVL02-893.5, CVL02-887.5, CVL02-881.5 and CVL02-877.5 along GPR profile LDB-33.

The GPR facies observed in the area of drillers’ logs CVL02-956.5 and CVL02-953.5 has characteristics consistent with a thermal interface. A strong, continuous reflection is observed from 390 to 575 m (Figure 5.14), where it is seen as deep as 3.5 m and as shallow as 1.4 m. Multiples at 5.0 and 6.7 m are seen between 410 and 450 m. The reflection interpreted to be a thermal interface intersects with both shotholes. There is also attenuation of the GPR signal below the reflection that is consistent with saturated, unfrozen sediment.
The uppermost extent of the reflection at 1.4 m, between 460 and 490 m is consistent with the base of seasonal frost. The talik interpreted here is either a supra-permafrost talik or an open talik. In the absence of marine sediments or thermal springs it is likely that this talik is non-cryotic. Without the influence of significant amounts of surface water in the form of lakes or streams, it is likely that this talik is a thermal talik, a product of the general thermal regime of the subsurface in the area (van Everdingen, 1990). Snow depth at the beginning of GPR profile LDB-33 was 84 cm. This is the deepest snow depth recorded and 23.4 cm higher than the mean in the area. It is possible that increased snow depth is responsible for insulating the near surface thereby contributing to the maintenance of the talik.

5.2.4 Seismic drillers’ logs CVL02-893.5, CVL02-887.5, CVL02-881.5 and CVL02-877.5

Four drillers’ logs recorded unfrozen water across a 160 m segment of GPR profile LDB-33. Drillers’ log CVL02-893.5, CVL02-887.5, CVL02-881.5 and CVL02-877.5 recorded sand,
gravel and water to depths of 5 m, 4 m, 7 m and 7 m, respectively; they are, respectively, 200 m, 170 m, 125 m and 125 m to the west of a lake measuring roughly 250 x 150 m. There are no streams and no significant topography in the area. The location of the shotholes and GPR profile LDB-33 are shown in Figure 5.14.

The characteristics typical of GPR profiles of unfrozen sediments within permafrost areas are not seen in the subsection of LDB-33 in which shotholes CVL02-893.5, CVL02-887.5, CVL02-881.5 and CVL02-877.5 are located. The architecture consists of disrupted, or discontinuous, returns with no noticeably strong reflections (Figure 5.15). Signal penetration is not significantly changed across the subsection. The absence of notable increases in signal attenuation and the absence of strong, continuous reflections is inconsistent with the presence of water in the near surface. Depth of penetration of the radar signal across the subsection is ~4 m. In the case of shotholes CVL02-893.5, CVL02-881.5 and CVL02-877.5 the depth of drilling exceeds that of the GPR signal penetration. A lateral talik deeper than 4 m would not be detected within the radar data and could be the source of the recorded unfrozen water. In all four cases the GPR data is inconsistent with the presence of either an open talik or a supra-permafrost talik.
5.2.5 Overview of taliks described in seismic shothole drillers’ logs

Four areas at the Lac des Bois site denoted by the shothole drillers’ logs as containing unfrozen sediments or water were examined. In one of these cases the GPR returns were supportive of the presence of a thermal interface. The typical morphologies of a thermal interface were not present at any of the other sites. A relatively shallow depth of GPR penetration at these sites may have caused this lack of consistency between the drillers’ logs and the GPR facies.

The low spatial density of data likely means that taliks are underrepresented by the drillers’ log. Also, the absence of data within 50 m of bodies of water is particularly pertinent in detecting lateral taliks extending beyond larger water bodies. This imposes an important limitation on the drillers’ log as a comprehensive source for mapping taliks as the thermal mass of bodies of water are often responsible for the formation and maintenance of taliks (Woo, 1986).
CHAPTER SIX: SUMMARY AND CONCLUSIONS

6.1 SUMMARY

The aim of this thesis was to provide a greater understanding of specific periglacial features in the lower Mackenzie Valley and in the Colville Hills, Northwest Territories while assessing the usefulness of GPR as a surficial geology mapping tool in areas underlain by permafrost. The effectiveness of seismic shothole drillers’ logs as a means for the identification of buried massive ice, and the detection of taliks was also examined in this study.

The results of this study emphasize the importance of integrating different forms of data while mapping massive ice and taliks. The abilities and limitations of GPR are highlighted by this research. The ability of GPR to detect interfaces between ice and sediment allows for the tentative identification of massive ice and taliks. However, because of the complex sedimentary structures often found in previously glaciated terrain these identifications cannot be conclusive without ground-truthing or other forms of corroboration. Depth of penetration, particularly in fine-grained sediments, also constitutes a significant limitation on the effectiveness of GPR in detection of massive ice; massive ice has been found at depth of greater than 10 m (Rampton and Mackay, 1971).

The seismic shothole drillers’ logs used in this study acted as a form of corroboration for the GPR data. This was effective in identifying icy sediments at the Little Chicago site. These data also acted as support for the interpretation of a talik at the Lac des Bois site. These examples illustrate that while spatial restrictions and the linear nature of seismic drillers’ log provide limitations on this dataset as a mapping tool, these data can provide useful context to geophysical surveys.
There were two primary foci of this study. This thesis attempted to use GPR facies analysis and seismic shothole driller’s logs to identify massive ice in the lower Mackenzie Valley and in the Colville Hills. By using these data, along with aerial photograph analysis and inverse modelling, the study derived three interpretations of massive ice.

The effectiveness of seismic shothole drillers’ logs as a tool for mapping near-surface taliks was examined using GPR facies analysis. At four locations in the Colville Hills drillers’ logs describing unfrozen sediments, or water, were compared to GPR profiles for the same locales. At one site the GPR returns were supportive of the drillers’ logs, while at the other three locations the returns were not supportive of the presence of unfrozen sediments or water.

6.2 CONCLUSIONS

The primary conclusions, relating to the stated objectives, that were reached are:

- Massive ice, or icy sediments, was interpreted at three locations; two incidences at Little Chicago and one incidence at Lac des Bois. The features were all within 3 m of the surface and would likely be responsive to alteration of the ground thermal regime. These areas are susceptible to instability and subsidence of the ground surface due to melting of excess ice under scenarios of climate change and/or human disturbance.

- Ground-penetrating radar produced interpretations of massive ice at both study sites. In the absence of a comprehensive ground-truthing program the importance of complementary data was highlighted by this research. The use of seismic
drillers’ logs, air photographs and inverse velocity modelling was integral in the interpretation of massive ice. However, without dedicated ground-truthing it was not possible to conclusively identify massive ice at either site. Further research is required to attain a comprehensive understanding of the extent and distribution of massive ice at the Little Chicago and Lac des Bois sites.

- The effectiveness of seismic shothole drillers’ logs in the mapping of taliks could not be corroborated by GPR facies analysis. The presence of open taliks or supra-permafrost taliks at the locations recorded in the drillers’ logs is not supported by typical GPR signatures in three out of the four instances. The relatively shallow depth of penetration of the radar signal provided limitations on this research’s ability to assess the accuracy of the drillers’ data.

**6.3 SUGGESTIONS FOR FUTURE RESEARCH**

While the research conducted over the course of this thesis has provided improvements on the understanding of periglacial features in the lower Mackenzie Valley and the Colville Hills, there are opportunities for significant improvements in the understanding of the thermal regime and ground ice conditions at these two sites. Specifically, the extent and origins of massive ice in these areas is poorly understood. Similarly, the presence of unfrozen sediments as outlined by the drillers’ logs remains unverified.

A better understanding of these components of the near surface environment could be gained through the following research endeavours:

- Alternative geophysical methods should be explored in these study areas. For example, Capacity Coupled Resistivity Imaging (CCRI) surveys would provide a significant
complement to the information contained within this thesis. The effectiveness of CCRI in highly conductive sediments, where GPR is largely ineffective, would allow for an improved understanding of subsurface conditions in areas underlain by till, glaciolacustrine deposits or other fine-grained sediments. Further delineation of massive ice by this method would constitute a significant contribution to the quantification of ground ice within the region.

- A targeted ground-truthing program would provide better understanding of ground ice extent and distribution while providing a more thorough assessment of the accuracy of the seismic shothole drillers’ logs.
REFERENCES


