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# Origin and composition of a lithalsa in the Great Slave Lowland, Northwest Territories

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ABSTRACT
Recognition of lithalsas in the Great Slave Lowland, NT, prompted an investigation to determine the geomorphic origin and composition of one lithalsa. Ice-poor conditions occur within the upper 4 m of substrate, with substantial increases in ice content at greater depths within clays. The lithalsa core is composed of layered ice lenses over 0.1 m thick, formed of isotopically-modern meteoric waters. The stratigraphy of clays, silts, and sands is sub-parallel, but domed in accordance with surficial relief of the lithalsa. The estimated differential heave between the lithalsa and an adjacent peatland is approximately 2.8 m, of which 2.17 m is directly accounted for by excess ice lenses within the upper 8.4 m of material. $^{14}C$ dating indicates permafrost aggradation within the lithalsa occurred between 700 and 400 cal yr BP.

RÉSUMÉ
Suite à l'identification de lithalses dans la région des basses terres du Grand lac des Esclaves, T. N.-O., une étude a été mise en œuvre afin de déterminer l'origine géomorphologique et la composition d'une de ces lithalses. Les premiers 4 m du substrat sont pauvres en glace, par contre la teneur en glace dans les sédiments argileux plus profonds présente une augmentation substantielle. Le centre de la lithalse est constitué de lentilles de glace de plus de 0.1 m d'épaisseur, disposées en couches et formées d'eaux météoriques de composition isotopique moderne. La stratigraphie d'argiles, de silts et de sables, est quasi-parallèle mais bombée de façon à se conformer au relief à la surface de la lithalse. La différence entre le soulèvement dû au gel entre la lithalse et la tourbière adjacente est estimée à approximativement 2.8 m, avec 2.17 m directement attribué à la présence de glace en excès dans les premier 8.4 m de sédiment. Une datation $^{14}C$ indique que l'alluvionnement de pergélisol dans la lithalse est survenu entre 700 et 400 années cal. BP.

## 1 INTRODUCTION

Lithalsas are perennial frost mounds found within the sporadic and extensive discontinuous permafrost zones (Harris 1993; Pissart 2003, 2010; Calmels and Allard 2008; Calmels et al. 2008; Pissart et al. 2011). They contain an ice-rich core and possess a thin organic surface cover. They form as permafrost aggrades into unconsolidated sediments in an environment with sufficient water and frost-susceptible soil to enable ice segregation during permafrost aggradation. They require a specific set of thermal, sedimentological, and hydrological site conditions, including a relatively "warm" ground thermal regime in discontinuous permafrost, fine-grained sediments, and an abundant groundwater supply (Calmels et al. 2008; Wolfe et al. 2014).

Lithalsas occur in modern stream valleys and near lakeshores, as well as adjacent to ponds or within former lake basins (Wolfe et al. 2014). Circular lithalsas may appear on uniform and flat surfaces such as in lake basins, valleys or marine lowlands where a uniform water supply exists, whereas lithalsas with linear and crescentic forms occur near ponds and streams, indicative of an asymmetrical water supply (Wolfe et al. 2014). Within Canada, circular lithalsas occur in the Hudson Bay region of northern Quebec with mean annual air temperatures ($T_a$) of -4.6°C to -7.0°C and mean annual ground surface temperatures ($T_s$) of -0.5°C to -0.8°C (Vallée and Payette 2007; Calmels et al. 2008; Fortier and Aubé-Maurice 2008). Circular lithalsas occur in Yukon at sites with $T_a$ of about -2°C and $T_s$ of -0.2°C to -0.5°C (Harris 1993). Outside Canada, Wünnemann et al. (2008) noted circular lithalsas in the Himalayas with $T_a$ from -4°C to -6°C, and Iwahana et al. (2012) reported linear lithalsas from the Akkol Valley of southern Siberia, with a $T_a$ of -4°C.

The purpose of this paper is to present the origin, composition, and development of a lithalsa representing one of potentially over 1700 within the Great Slave Lowland (GSL) (Stevens et al. 2012). This is achieved by describing the cryostratigraphy of the lithalsa and the surrounding landscape, and by analyzing the stable isotopic composition of ground ice and radiocarbon ages of organic material recovered from the feature.

## 2 STUDY REGION

### 2.1 Regional context

The Great Slave Lowland is part of the Taiga Shield High Boreal (HB) ecoregion, lying between 156 (present Great Slave Lake level) and 200 m a.s.l. It forms a plain along the north shore of Great Slave Lake (ECG 2008).

The surficial sediments of the region were deposited in Glacial Lake McConnell (Figure 1), a large Wisconsinan pro-glacial lake that formed along the retreating western margin of the Laurentide Ice Sheet between approximately 12.7 and 9.3 cal yr BP (Smith 1994). The lake originated in Great Bear basin, and expanded southwards to fill Great Slave and Athabasca lake basins. As Glacial Lake McConnell rose, GSL was flooded to depths of over 100 m. Glaciolacustrine clays were deposited and subsequently washed into topographic lows (Stevens et al. 2012). Ancestral Great Slave Lake levels receded rapidly prior to 9000 cal yr BP, but are now declining at about 2 mm $yr^{-1}$ (Vanderburgh and Smith 1988).

GSL experiences a continental climate. Mean annual air temperature is -4.1°C, and mean total precipitation is 291 mm, of which 41 % falls as snow (Environment Canada http://climate.weather.gc.ca). The mean annual air temperature has increased by 0.3°C per decade between 1940-1970, and by 0.6°C per decade since 1970 (Hoeve et al. 2004; Wolfe et al. 2014).

The study area is in the widespread discontinuous permafrost zone (Heginbottom 1995). The distribution and condition of the permafrost is variable and sensitive to topography, vegetation, snow accumulation, and subsurface geology. Mean annual ground temperatures ($T_g$) at depths to 15 m vary by up to 2°C among different terrain types, and are lowest in open black spruce peatlands, and highest in bedrock (Brown 1973). Brown (1973) reported $T_g$ in frozen clayey silts at 3-m depth between -0.2°C to -0.3°C. Permafrost occurs in peatlands near Yellowknife. Karunaratne et al. (2008) reported mean annual permafrost temperatures ranging between -0.2°C and -1.9°C at 1-m depth in this ecotype.

Permafrost aggradation in GSL postdates the withdrawal of Glacial Lake McConnell and subsequent lowering of ancestral Great Slave Lake. Permafrost likely formed as isolated pockets confined to peatlands during the Hypsithermal interval, or in the following cold period, perhaps as recently as 4 ka BP (Aspler 1978).

Active-layer depths typically range between 0.4 and 2.3 m in association with variations in peat or organic layer thickness (Aspler 1978; Karunaratne et al. 2008; Wolfe et al. 2011). Excess ice, common in silts and clays, ranges between 5 and 20 % by volume, and in places exceeds 80 % (Aspler 1978). Reticulate ice veins up to 70 mm and stratified ice lenses from 1 mm to 0.1 m thick are common in fine-grained mineral sediments (Aspler 1978).

## 2.2 Boundary Creek Study Area

The study area (62° 32'N; 114° 58'W) is located on the south side of NWT Highway 3, at 166 m a.s.l. and 30 km west of Yellowknife, within GSL (Figure 1). Nearby, Boundary Creek flows south-eastward into Great Slave Lake. Permafrost occurs at temperatures between 0°C and -1°C under the road embankment, and contains excess ice (Hoeve et al. 2004). Subsidence has occurred locally on the highway due to permafrost thaw. Boundary Creek Study Area (BCSA) is representative of the local terrain and includes a bedrock outcrop, pond, spruce forest peatland and mixed deciduous-coniferous forest.

The BCSA lithalsa is approximately 4 m higher than the surrounding topography, over 700 m in length, and up to 135 m wide. The dominant vegetation species on the lithalsa are paper birch (*Betula papyrifera*), black spruce

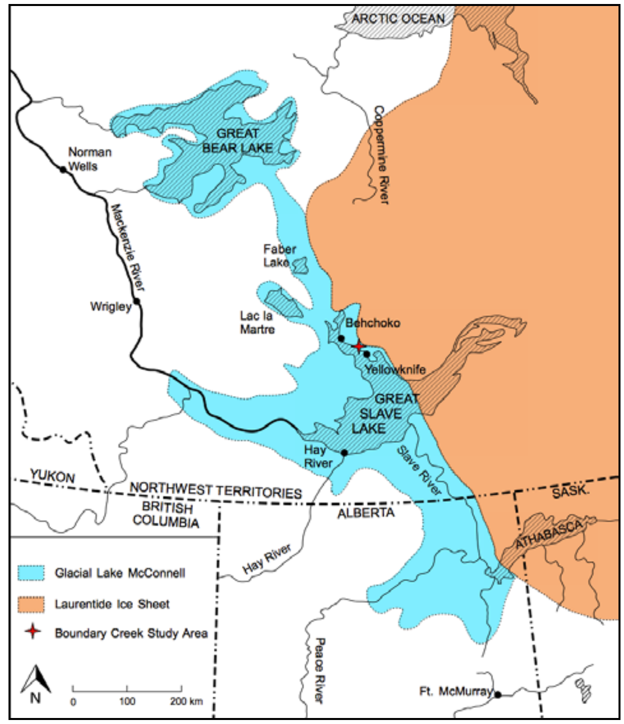


Figure 1. Extent of Glacial Lake McConnell at ca. 10 ka BP and the adjacent Laurentide Ice Sheet. The study site (BCSA) is indicated with a star.

(*Picea mariana*) and white spruce (*Picea glauca*) trees. The vegetative ground cover is composed of deadfall and grasses.

Permafrost is present below both the peatland and the lithalsa, but is absent under a pond near the road (Oldenborger 2012). Thermal conditions within the lithalsa over one year (1 September, 2012 to 31 August, 2013) indicate $T_g$ range from -1.1°C at 3.3-m depth to -0.7°C at 10.3 m, with the zero degree annual amplitude occurring at 7.3-m depth. The shallow depth of zero annual amplitude is related to high latent heat effects in "warm" ice-rich permafrost within fine-grained sediments, producing low apparent thermal diffusivities.

# 3 METHODS

## 3.1 Field methods at BCSA

A straight-line transect was established perpendicular to the long axis of the lithalsa, on which most field investigations were conducted. A cross-sectional profile of the transect was established from LiDAR soundings. A water-jet-drilled hole determined the depth to bedrock in the peatland.

Fifteen boreholes were drilled with a CRREL drill, and core samples were retained to describe cryostratigraphy (Murton and French 1994). Visible ice content (VI) in each core sample was estimated to ±2.5 % for samples containing <10 % VI, and to ±5 % for samples containing >10 % VI. Boreholes extended to between 4.7 and 8.4-m depths at five sites (BH01 to BH05) and down to no more than 3.5 m at ten shallow sites. Most shallow boreholes (BH06 to BH13) helped to establish near-surface stratigraphy between deep boreholes. Two additional boreholes up to 0.85-m depth were drilled in small pockets of peat on top of the feature (DP1 and DP5) to obtain samples for $^{14}$C dating.

### 3.2 Laboratory analyses

Bulk density, $\rho$, was determined on drill core samples in a frozen state. At saturation, clays at BCSA have a frozen bulk density >1.8 g cm$^{-3}$. Therefore, lower $\rho$ values generally indicate a greater proportion of water or ice.

Grain-size analysis was conducted at the Geological Survey of Canada's sediment laboratory using a Retch Technology Camsizer to analyze sand-sized particles (0.063 mm to 2 mm), and a Leotrac LT100 LD for silt and clay sediments (<0.063 mm). Some samples were processed with a Beckman Coulter LS 13 320 LD at Carleton University.

Sample excess ice contents were estimated from a combination of field notes (VI estimates) and frozen bulk densities. The Kokelj and Burn (2003, 2005) method of determining excess ice content (allowing a sample to thaw and syphoning off the supernatant water) was not feasible due to the excessive settling time required for very fine clays to fall out of suspension. Frozen bulk densities helped mitigate the error in excess ice estimation.

Water samples from sediment pore water and ice lenses, as well as samples from the adjacent pond, nearby borrow pits, and rainwater, were submitted to the University of Ottawa G.G. Hatch Isotope Laboratory for oxygen ($\delta^{18}$O) and hydrogen ($\delta$D) analyses. Radiocarbon ages from basal peat samples and detrital organics indicated values for interpretation of sedimentation rates and terrestrial exposure. The samples were processed by Beta Analytic Inc. in Miami, Florida, and interpreted using the INTCAL09 database.

## 4 RESULTS

### 4.1 Vegetation and site characteristics

The peatland at BCSA is an undisturbed black spruce – Labrador tea peatland located 20 m from a bedrock outcrop. Black spruce trees 4 m high account for 20 % of the ground cover. The vegetation on the lithalsa is an open birch – white spruce woodland and birch forest, comprising trees 8-10 m tall representing 20 % surface cover, whereas bare ground and deadfall represent dry, well-drained surfaces.

### 4.2 Stratigraphy

Organic thickness on the lithalsa was typically less than 0.2 m. Depth to bedrock below the peatland was approximately 9 m. Sediments recovered at BCSA were divided into clay, clayey silt, and silty sand. Clay (<0.004 mm) was found below 4 to 8.4-m depths (Figure 2), and was the lowest stratigraphic unit in all deep boreholes. The clay was dense, stiff, and homogenous. Sampled $\rho$ were highly variable, as the clays were frequently layered with ice lenses, and ranged from <0.9 to more than 2.0 g cm$^{-3}$ depending on ice content (Figure 3).

Clayey silt appeared as upper and lower layers in the stratigraphic profile (Figures 2 and 3). Grain-size analysis indicated negligible differences in texture between these layers. In BH04, clayey silt appeared as 4 layers due to a thin near surface sandy layer and a thin secondary clayey silt layer within clay at depth. Lower clayey silt was observed above basal clay in all boreholes, and commonly contained excess ice that increased with depth.

Each deep borehole contained a prominent layer of silty sand between the upper and lower clayey silt (Figure 2). The silty-sand layers were 0.5 to 1.2 m thick. Sandy layers were encountered at similar depths in each borehole in the lithalsa, between 2 and 4 m below the surface (Figure 2).

Average ground temperatures from 4.3 to 9.3-m depth were 0.93°C (Gaanderse 2015). As unfrozen water contents of silt and clay at -1°C are 3 and 12 % by volume (Osterkamp and Burn, 2003), clay below 4-m depth may contain up to 12% unfrozen water.

### 4.3 Cryostructures and ice content

Cryostructures and ice contents of visible ice samples collected from the boreholes are shown in Figure 3.

Within the lithalsa, only a small amount of visible ice occurred above 4-m depth. Reticulate cryostructures 1-10 mm thick and lenticular lenses 1-20 mm thick were common. The ice content increased significantly below 4-m depth. At BH02, VI remained low to 5.5-m depth, but VI of 90-95% was noted to near 6 m. At BH03, layered lenses 40-140 mm thick were noted. At BH04, the deepest borehole, lenses 20-50 mm thick were recorded between 4 to 5 m. Below this, lenses 15 to 150 mm thick and layered ice up to 240 mm thick, were present to 8.4 m (Figure 3). At BH05, lenticular lenses 4 to 30 mm thick were noted to 6 m, and ice content increased to over 80% VI with layered lenses appearing up to 210 mm thick. As in BH04 (Figure 3), frozen bulk density was inversely proportional to ice content at all boreholes.

The cumulative thickness of ice at all deep boreholes is plotted against the total height of the feature as measured from the top of the first sediment layer in Figure 4. The overlying organic layers at each borehole were not included so as to compare a constant stratigraphic surface. The top of the mineral layer beneath the peat at BH01 is used as the 'sediment reference height' (Figures 2 and 4). Observed ground ice accounts for 54 % of lithalsa height variation at its peak (BH04).

### 4.4 $\delta^{18}$O values at BCSA

Values of $\delta^{18}$O were most negative in the peatland (BH01) at the near surface (-22.7 ‰ at 0.45-m depth) and were less negative in frozen peat (-16.8 ‰ at 0.81 m-depth). In the lithalsa, $\delta^{18}$O values ranged from -18.8 ‰ to -15.1 ‰. The largest range was 3.4 ‰ at BH02. $\delta^{18}$O values were more negative with depth (Figure 3). $\delta^{18}$O values of local water sources, collected in summer 2012, include Boundary Creek (-12.1 ‰), Yellowknife River (-14.5 ‰), local rainwater (-14.8 ‰), and BCSA pond (-15.6 ‰).

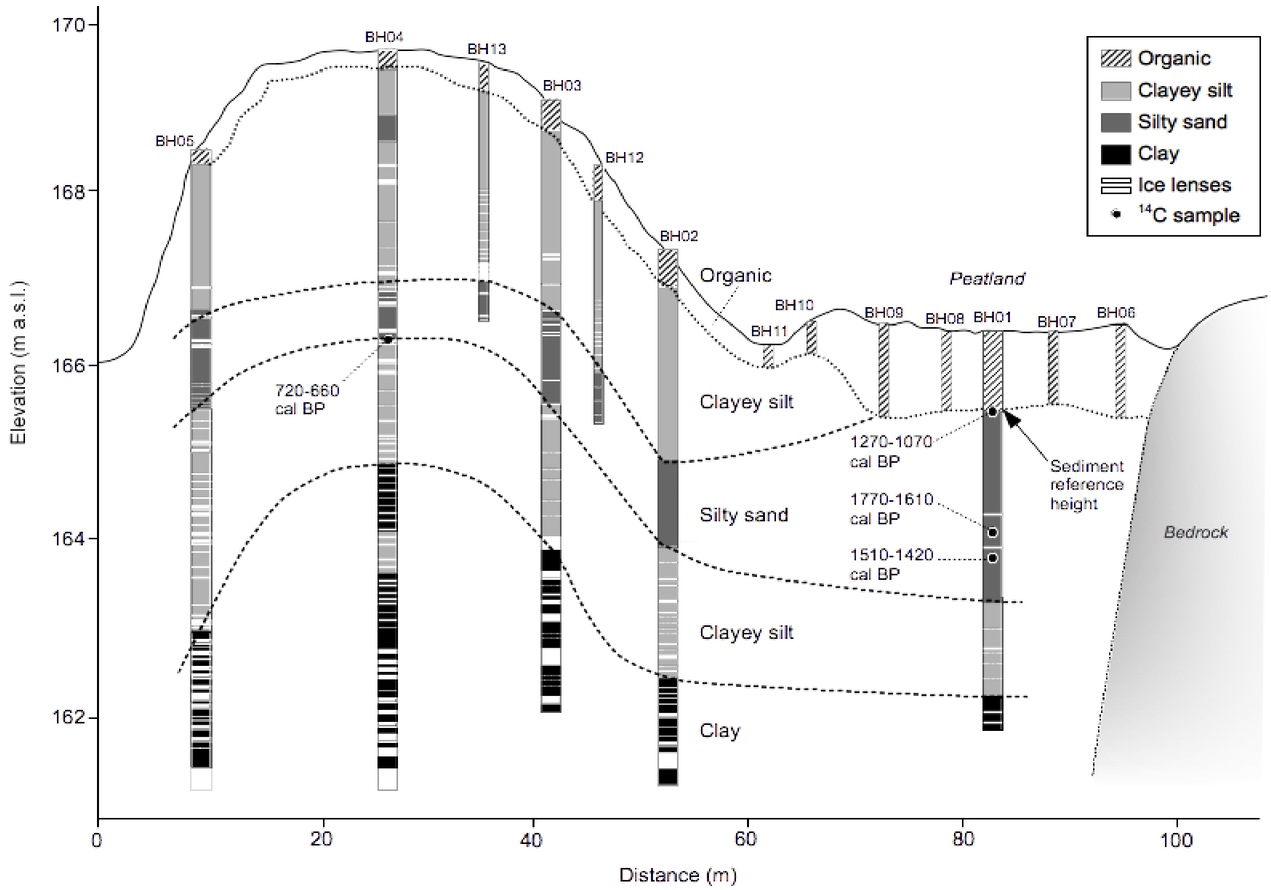


Figure 2. Cross-section of lithalsa at BCSA, displaying all boreholes, ground ice thicknesses, and interpolated stratigraphy.

### 4.5 AMS Radiocarbon dates

Several $^{14}$C dates were obtained from organic samples collected at BCSA (Table 1, Figure 3), including basal organic dates from BH01, DP1 and DP5, as well as a detrital organic sample from the lithalsa (BH04).

Table 1. AMS radiocarbon dates (conventional and calibrated to a standard deviation of 2σ) for all organic samples at BCSA.

| Borehole | Depth (m) | Sample type | Date (conventional) | Date (cal BP) |
|---|---|---|---|---|
| BH01 | 0.93 | Basal peat | 1240 +/- 30 | 1270-1070 |
| BH01 | 2.20 | Burned wood | 1770 +/- 30 | 1770-1610 |
| BH01 | 2.55 | Burned wood | 1570 +/- 30 | 1510-1420 |
| BH04 | 3.50 | Detrital organic | 740 +/- 30 | 720-660 |
| DP1 | 0.33 | Wood in basal peat | 210 +/- 30 | 280-post 1950 |
| DP5 | 0.55 | Wood in basal peat | 150 +/- 30 | 280-post 1950 |
| DP5 | 0.80 | Plant material in sediment | 300 +/- 30 | 460-300 |

## 5 DISCUSSION

### 5.1 Stratigraphy

The underlying clay at BCSA (Figure 2) exhibits a fine-grained texture indicative of a low-energy deep-water environment associated with Glacial Lake McConnell (Smith 1994). The presence of isolated drop stones (Aden 2014) also indicates glaciolacustrine deposition.

The lower clayey silt layer occurring in all boreholes (Figure 2) is interpreted to have been deposited in a low-energy shallow lacustrine environment, possibly in relation to recession of ancestral Great Slave Lake.

The silty sand layer in the feature occurring between two clayey silt layers (Figure 2) indicates a change to a shallow near-shore depositional environment, possibly similar to the environment of Yellowknife Bay.

The upper clayey silt layer is absent below the peatland (Figure 2). These sediments are interpreted to have been deposited in a low-energy pond environment adjacent to the peatland.

All layers of sediment appear to follow the general topography of the feature (Figure 2). The contact of the lower clayey silts and the clays is also domed in a similar fashion, implying a significant amount of ground ice within the underlying clays below the termination depths of the boreholes.

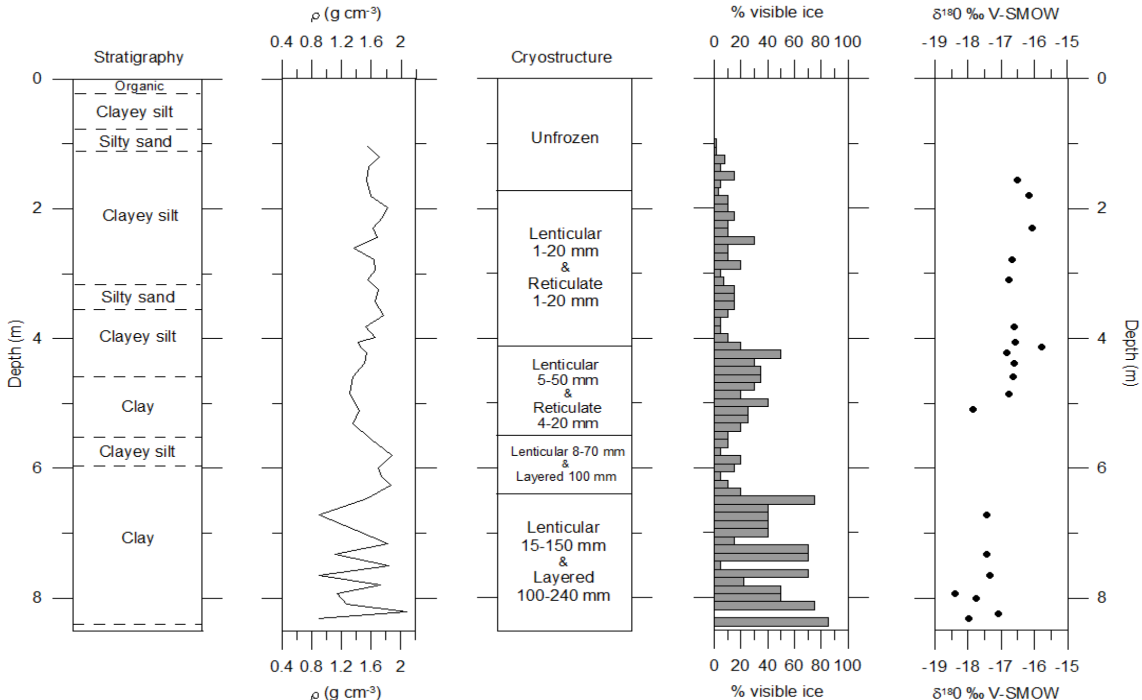


Figure 3. Stratigraphy, frozen bulk density ($\rho$), cryostructures, visible ice, and $\delta^{18}O$ values at BH04 (top of feature is approximately 4 m above the surface of the peatland).

5.2 Cryostructure, ice content, and topography

Ground ice at BH04 accounts for 54% of the lithalsa's raised topography at that location in relation to the sediment reference height, leaving 46% of lithalsa height unaccounted for. The occurrence of additional ground ice at depth to account for this relief is plausible, given the ice-rich nature of these sediments and known depth to bedrock below the peatland of 9 m.

Lenticular cryostructures on the order of 1 mm were common in the ice-poor top 4 m of substrate. Larger lenticular structures 50-100 mm or thicker, were common below 4-m depth in the clays. The deeper ground ice has led to about 2.8 m of heave, based on the difference in height between the clay units of BH01 and BH04.

The abundance of ice lenses 1-10 mm thick is similar to some sections of other lithalsas (Allard et al. 1996; Iwahana et al. 2012). The ice at BCSA was sometimes non-horizontally oriented, suggesting that it formed either in vertical veins, or ground heave was responsible for the reorientation of horizontal lenses. Some heavily tilted lenses (30-60°) were recorded within BH03, BH04 and BH05, and appear similar to Iwahana et al.'s (2012) description of tilted ice lenses within a lithalsa.

5.3 $\delta^{18}O$ interpretation

Isotopic results at BCSA reflect values typical of recent meteoric waters. Local summer precipitation records indicate $\delta^{18}O$ values ranging from -22 to -11 ‰ (Gibson and Reid 2010). Most $\delta^{18}O$ values from BCSA boreholes are within this range, suggesting a large portion of the ice at BCSA is formed from summer-fed surface water. Local water sources also appear to be major sources of water for ice segregation. The adjacent BCSA pond ($\delta^{18}O$ value of -15.6 ‰) is likely a major source of ice lens water due to its proximity to the lithalsa and the relatively high permafrost temperatures at depth, facilitating temperature-induced water migration. The near-surface $\delta^{18}O$ value of -22.7 ‰ at BH01 suggests an increased influence of snow on surface water composition in the peatland. Minor $\delta^{18}O$ variations of 1-2 ‰ in clay (Figure 3) suggest an open groundwater system and ample water supply (Iwahana et al. 2012).

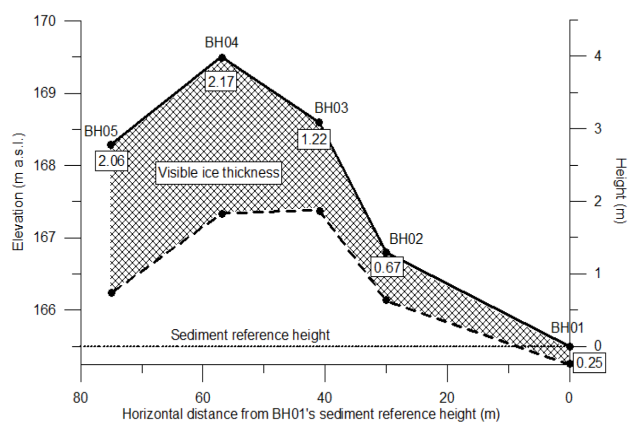


Figure 4. Borehole elevation (with organic cover removed), and distance from BH01, with total thickness of visible ice in each borehole. The reference height is the top of mineral sediment at BH01 in the peatland.

5.4 Radiocarbon interpretation

The chronology of BCSA begins between 12.7 and 9.5 cal ka BP, when Glacial Lake McConnell covered the GSL and fine-grained clays were deposited within a relatively deepwater basin. As water levels lowered, shallow-water clayey silt lacustrine deposition occurred in a slightly higher-energy environment. When local bedrock outcrops were exposed, near-shore deposition resulted in a layer of silty sand over the shallow water clayey silt. With further lake recession, we suggest that a pond remained in a topographic low next to the emerging peatland, and rapid lacustrine/alluvial deposition took place between 1200 and 400 yr BP over the areas of BH02-05, as noted by the detrital organic sample recovered at 3.5 m depth in BH04 (Table 1), perhaps due to seasonal flooding by Boundary Creek.

Continued terrestrial emergence exposed the mineral sediment comprising the present lithalsa, sometime after 700 yr BP. Permafrost aggraded downward into the substrate at BH02-05 with ice lens growth supplied by water migration from lower saturated sediments and the adjacent pond.

Ice segregation formed thick ice lenses while slowly desiccating surrounding fine-grained clays. Depressions on the lithalsa surface formed small pockets for peat accumulation, and terrestrial emergence is indicated by a radiocarbon date of approximately 400 cal BP from sedges under the peat pocket at DP5. At present, the lithalsa has risen 3.7 m above the adjacent peat surface due to ice segregation occurring at depth. The formation of this lithalsa appears to be similar to that studied by Iwahana et al. (2012) where lake shallowing and microclimatic factors exposed the mineral ground surface, allowing for permafrost aggradation and, over time, frost heave.

## 6 CONCLUSIONS

We draw several conclusions from this investigation:

1. The lithalsa contains an ice-rich core, responsible for the raised topography of the feature. The sediment sequence is domed and sub-parallel with the surficial relief, whereas the same layers were observed horizontally beneath the adjacent peatland. The total differential heave between the peatland and lithalsa is 3.7 m.

2. $\delta^{18}O$ values in lithalsa ice ranged from -18.8 ‰ to -15.1 ‰, indicating the lithalsa core is composed of isotopically-modern water.

3. $^{14}C$ dates of 720-660 cal BP and 460-300 cal BP recovered within the lithalsa indicate growth initiated after terrestrial emergence within the last 700 to 400 years.

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