Holocene lake-level recession, permafrost aggradation and lithalsa formation in the Yellowknife area, Great Slave Lowland

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ABSTRACT

The Great Slave Lowland occupies the north shore of Great Slave Lake. After glaciation, it was inundated by Glacial Lake McConnell and ancestral Great Slave Lake. Holocene lake-level recession around Yellowknife is determined from accelerator mass spectrometer ages of peat and detrital organics. In the last 8000 years, recession occurred at about 5 mm/year, and permafrost is youngest near the modern shoreline and older at higher elevations. Silty-clay sediments are abundant, and lithalsas (ice-rich permafrost mounds within mineral soils) occurring within 40 m above the present lake level are less than 6000 years old. They are common on Yellowknife River alluvium deposited within the last 3000 years. Lithalsas on this surface are assumed to have developed as permafrost aggraded into saturated sediments, and ground ice has formed within the last 250 years.

RÉSUMÉ

L'écorégion « Great Slave Lowland » se situe sur la rive nord du Grand lac des Esclaves. Suite à la déglaciation, elle a été inondée par le lac glaciaire McConnell, ainsi qu'un précurseur du Grand lac des Esclaves. La récession holocène du niveau du lac près de Yellowknife a été déterminée en datant des tourbes et des débris organiques par spectrométrie de masse par accélérateur (AMS). Pendant les 8000 dernières années, le niveau du lac a baissé d'environ 5 mm par année, le pergélisol le plus jeune se retrouve donc près du littoral moderne, alors que le plus âgé se retrouve sur les terres plus élevées. Les argiles limoneuses abondent et l'on retrouve des lithalses (buttes cryogènes riches en glace) plus jeunes que 6000 ans jusqu'à 40 m au-dessus du niveau du lac moderne. Celles-ci se retrouvent souvent sur les sédiments alluviaux de la rivière Yellowknife qui furent déposés durant les 3000 dernières années. Les lithalses sur ces surfaces se sont probablement développées avec l'expansion du pergélisol dans des dépôts saturés, la glace de sol s'étant formée durant les derniers 250 ans.

1 INTRODUCTION

The Great Slave Lowland is a low-relief, Precambrian granitic bedrock plain extending about 250 km along the north shore of Great Slave Lake (Fig. 1), and includes Yellowknife, the capital of the Northwest Territories, which resides near the present-day shoreline at 62.4°N latitude and 114.4°W longitude. Following retreat of the Laurentide Ice Sheet, inundation by Glacial Lake McConnell and ancestral Great Slave Lake resulted in extensive deposition of silts and clays throughout the Lowland. In a cold-continental setting, permafrost aggradation into these sediments has given rise to widespread discontinuous permafrost with extensive ice-rich permafrost mounds (i.e. lithalsas) across the region (Wolfe et al. 2014).

The primary purpose of this paper is to establish a preliminary estimate of the rate of Holocene lake-level recession in the Yellowknife area, to provide a baseline estimate of regional terrestrial emergence and permafrost aggradation. A secondary purpose is to examine the distribution of lithalsas in the Yellowknife area in relation to elevation and surficial sediments in order to estimate their age and environmental settings of formation. Permafrost within a lithalsa exposed by thaw slumping into the Yellowknife River permits direct assessments of the origin of the ice, and the age and depositional environment of the enclosing sediment.

2 BACKGROUND AND STUDY AREA

The Great Slave Lowland is bordered to the south by Great Slave Lake, and to the north by the Great Slave Upland of higher relief. As with much of northern Canada, the region was glaciated during latest, Wisconsinan, glaciation. With the retreat of the Laurentide Ice Sheet, about 13 000 cal BP, it was inundated by Glacial Lake McConnell that formed along the retreating glacial margin between about 13 000 and 9500 cal BP (Lemmen et al. 1994; Smith 1994). At its maximum extent at about 10 700 cal BP, the lake included the combined basins of Great Bear, Great Slave and Athabasca lakes (Fig. 1). Lake McConnell was largely the result of glacio-isostatic loading (Lemmen et al. 1994). Evidence of the lake exists in the form of raised deltas, strandlines, beaches and wave-washed eskers and drumlins. In the Great Slave basin, maximum lake elevation was between 320 and 350 m asl along the East Arm of Great Slave Lake (Smith 1994; Kerr et al. 2014), compared to only about 180 m asl at Fort Smith (Vanderburgh and Smith 1988), the elevation difference due to differential isostatic uplift.

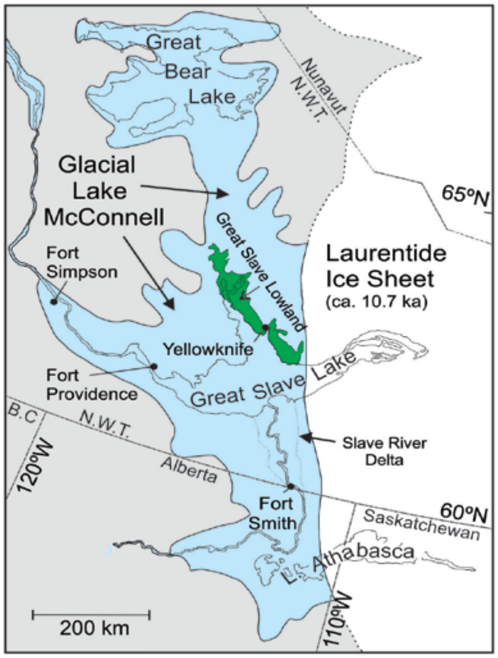

Fig. 1. Great Slave Lowland, Northwest Territories with approximate margin of the Laurentide Ice Sheet and extent of Glacial Lake McConnell at about 10 700 cal BP

During recession, the lake first separated from the Great Bear basin, and remained in existence until about 9500 cal BP, when the remaining two basins separated (Lemmen et al. 1994). The resulting ancestral Great Slave Lake continued to decline due to differential uplift, towards its present elevation of 156 m asl, constrained by the Mackenzie River outlet at Fort Providence (Vanderburgh and Smith 1988).

Glacial Lake McConnell and ancestral Great Slave Lake left prominent signatures on the Lowland landscape, with silt and clay covering nearly 70% of the land area (Wolfe et al. 2014). The Lowland area, being submerged to depths of 100 to 150 m, was a deepwater basin for fine-grained glaciolacustrine sediment deposition. During recession of ancestral Great Slave Lake, waves and rivers re-worked and re-deposited sediments in nearshore environments (Fig. 2A). Consequently, glaciolacustrine and lacustrine deposits are broadly distributed across the region.

The area presently experiences a continental subarctic climate, with an annual mean air temperature of -4.1°C, cold winters (-25.6°C January mean), warm summers (17.0°C July mean), and an average of 281 mm of precipitation with 40% falling as snow (Environment Canada, 2015). The area occupies poorly-drained low relief terrain characterized by numerous water bodies separated by fens, peatlands, mixed woodlands, white birch (Betula papyrifera) and black spruce (Picea mariana) forests and bedrock outcrops (Fig. 2A and B). Permafrost is extensively discontinuous (Heginbottom et al. 1995) and lithalsas, which are permafrost mounds formed by ice segregation in fine-grained sediment, are locally widespread with nearly 1800 identified in the region west of Yellowknife (Wolfe et al. 2014).

Lithalsas in the Yellowknife area are typically circular to elongate, 25 to 50 m wide and up to 300 m long and 8 m high. They are typically vegetated by birch or birch-spruce forests and commonly occur along the margins of small ponds, which in some cases represent thermokarst ponds related to thawing of former lithalsa terrain (Fig. 2A). The raised topography of lithalsas, combined with the typical deciduous (birch) forest cover makes these features readily recognizable in the field and on stereo aerial photographs, which were used by Wolfe and Kerr (2014) to map the lithalsa distribution in the area.

Terrestrial emergence accompanied lake-level recession throughout the Great Slave Lake basin. Given the low gradient of the Lowland region, in some areas a few metres of elevation adjustment resulted in considerable land exposure over a short time period (Fig. 2B).

Permafrost aggradation followed terrestrial emergence, though the regional climate has varied during the Holocene. Prior to 6000 cal BP, exposed terrain north of the Lowland was dominated by tundra, shrub tundra and spruce forest tundra (Huang et al. 2004), implying conditions colder than present. Between 6000 and 3500 cal BP treeline moved northward of its present position in response to climate warming (Moser and MacDonald 1990; MacDonald et al. 1993), and it is uncertain if permafrost was locally sustained within the Lowland at that time. The regional climate cooled, but was variable, from about 3000 Cal BP to present (Huang et al. 2004). Local mean annual air temperatures have recently warmed at a rate of about 0.3°C per decade since the 1940s (Riseborough et al. 2013) with an accelerated trend of about 0.6°C per decade since 1970 (Hoeve et al. 2004), consistent with a pan-Arctic warming trend beginning AD 1966 (IPCC 2013).

Smith (1994) reconstructed the rate of lake-level lowering of Glacial Lake McConnell and Great Slave Lake from radiocarbon-dated buried wood in raised deltaic sediments on the southern side of Great Slave Lake. Based primarily on woody debris collected along former delta-front positions of the Slave River delta (Fig. 1), Vanderburgh and Smith (1988) estimated the Holocene lake-level recession of Great Slave Lake to be about 2 mm per year from 7000 14C yr BP (about 8000 cal BP) to present. Although long-term uplift rates for the Yellowknife area are unknown, present-day uplift is reported to be on the order of 6.3 +/- 0.06 mm per year based on a time series of 15 years (Mazzotti et al. 2011).

Given difference in maximum elevation of Glacial Lake McConnell between the northern and southern sides of the basin, we hypothesize that the rate of Holocene lake-level recession for the north shore of Great Slave Lake and the Yellowknife area, exceeded that for the south shore of the lake derived from the Slave River Delta by Smith (1994). Therefore, this study derives a preliminary estimate of the rate of Holocene lake-level recession for the Yellowknife area. The implications of lake-level recession are assessed in the context of local permafrost landscape evolution by reconstructing shorelines and examining lithalsa distribution and cryostratigraphy in the

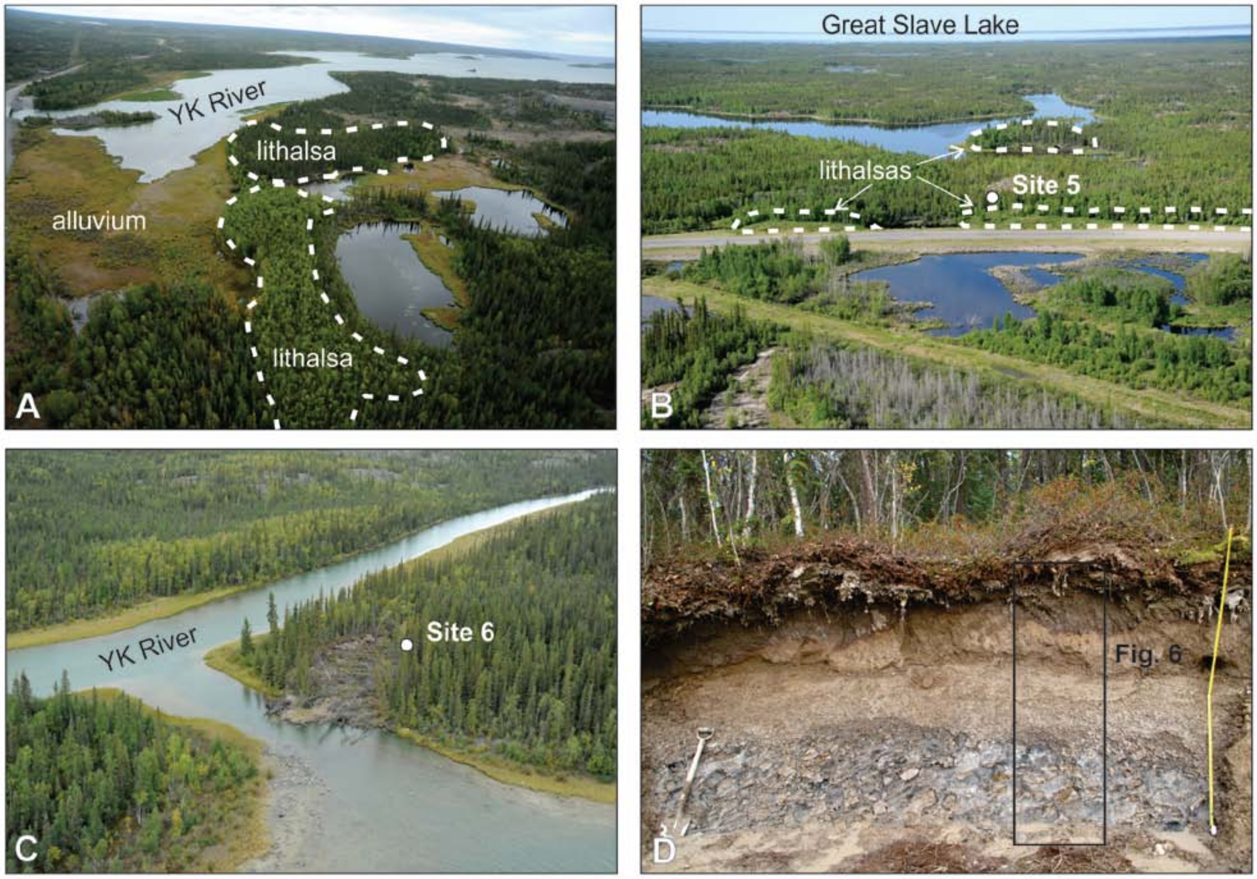

Fig. 2. Lithalsa and ground ice examples in the Great Slave Lowland. A) Yellowknife River extending southward into Back Bay on Great Slave Lake, with alluvial plain and lithalsas in the foreground; B) Lithalsa terrain at Site 5 along NWT Highway 3 near Boundary Creek at an elevation of about 10 m above the present level of Great Slave Lake; note Great Slave Lake at a distance of about 7 km in background; C) Ground ice slump at Site 6 along the Yellowknife River; D) Slump headwall at Site 6 exposing alluvial and lacustrine sediments with segregated ground ice at depth.

Yellowknife area in relation to elevation and surficial sediments in order to estimate their ages and environmental settings of formation.

3 METHODS

3.1 Peatland cores and lake-level recession

Accelerator mass spectrometer (AMS) dating of peatland sites represents a means to establishing the timing of lake-level recession in the Great Slave Lowland, where terrestrial organic accumulation occurred following emergence. Peatlands are relatively rare in the Lowland representing less than 2% of the total surface terrain cover (Wolfe and Kerr 2014). Unlike permafrost areas further south, peat plateaus are uncommon in the Great Slave Lowland, as the surrounding terrain underlain by unconsolidated sediments typically also contains permafrost (Morse et al. in press). Peatland sites selected for dating were typically near, but above, ponds and did not appear to have undergone alterations in hydrology that, especially, would have affected peat initiation.

Cores were obtained from peatlands in the Yellowknife area, ranging in elevation from 205 m asl near the margin with Great Slave Upland to 165 m asl within the Lowland. Elevations were derived from multiple sources, including topographic base maps, GPS and Lidar data (where available), and were conservatively estimated the nearest 5 metres (± 2 m). Elevations were derived for both the sample sites and the nearby surface water levels. Local surface water levels were used as the estimates of land surface elevation at the time of terrestrial emergence, as these discounted the effects of heave due to permafrost aggradation and ground ice formation and accumulation of peat above the actual mineral surface, which is variable and can locally exceed 3 m.

In most instances, coring was undertaken with a CRREL corer using a 7.6 cm diameter core barrel, although at one site (Site 4) a peat auger was used to drill multiple boreholes to confirm stratigraphic contacts. Holes were cored/augered through the active layer and underlying frozen peat, and into the underlying sediment. In all cases, in situ organic samples were collected from the base of the peat unit and above the mineral sediment for AMS dating by Beta Analytic and AMS ages were converted to calendar years using Calib©7.0.4 (2014). In situ basal ages are considered to represent the minimum-limiting ages of peat accumulation, and thus for terrestrial emergence. In instances where two cores were obtained from the same site (e.g. Sites 3 and 4), the older of the two AMS ages was used to represent the limiting age. At one site, detrital organics (wood charcoal) collected from within the underlying subaqueous alluvial sediments were also dated to bracket emergence. These detrital ages are considered to represent maximum-limiting ages of subaqueous alluvial deposition in relation to former Great Slave Lake levels.

3.2 Shoreline reconstruction and landscape evolution

Relations between lake-level history and landscape evolution were examined using topographic Canadian Digital Elevation Data (CDED) available from GeoGratis (http://geogratis.cgdi.gc.ca/), combined with published surficial sediment and lithalsa distributions for the Yellowknife area (Wolfe and Kerr 2014). Topographic data were used to reconstruct raised shoreline levels. Timing of sediment deposition or reworking, including beach sands and alluvial silts, as well as the maximum-limiting ages of lithalsas, were estimated from their elevations and discussed in the context of reconstructed lake-level recession rates.

A slump exposing near-surface sediments and ground ice, situated on an island in the Yellowknife River about 1 km (Fig. 2C) north of Back Bay, was examined to determine sediment and ground ice origin and age. Debris along a portion of the headwall was cleared to expose at 2.2 m high by 6 m wide section (Fig. 2D). This was measured, sketched and photo-documented, noting stratigraphic contacts and ice-textures. Sediment samples were collected for grain size analysis, Atterberg limits, and moisture content performed by the Geological Survey of Canada. Ice samples were collected from the lower portion of the section, where visible ice content exceeded 70%, and waters were submitted to the NWT Taiga Lab for isotopic analysis. In situ roots within unfrozen and frozen portions of the exposure were collected for AMS dating by Beta Analytic.

4 RESULTS AND DISCUSSION

4.1 Peatland cores and Holocene lake-level recession

Table 1 summarizes AMS ages, locations, depths, material and depositional environments of organic samples. Figure 3A illustrates the near-surface stratigraphy and AMS ages derived from seven peatland cores at five sites of varying elevation in the Lowland. Core depths vary from about 1.5 m at Site 2 to 4.5 m at 5 and peat thicknesses range from 93 to 295 cm. Calibrated AMS ages range from about 8000 to 1100 ^{14}C years BP. A general relation is apparent between basal peat AMS ages and elevations across the area (Fig. 3B).

Sediments immediately underlying peat at these sites are typically clayey-silts, with layers of sandy-silt and silty-clay at greater depths (Fig. 3A). Note that at Site 3, bedrock was encountered beneath a relatively thin layer of sediment underlying peat. These fine-grained sediments most likely represent alluvial or lacustrine sediments pre-dating terrestrial emergence. At Site 5, near Boundary Creek 30 km west of Yellowknife, detrital charcoal contained within clayey-silt sediments date to about 1710 (1810 to 1610) and 1460 (1533-1395) Cal BP, respectively, with an apparent age reversal relative to depth of deposition (Fig. 3A). These ages indicate deposition within a subaqueous environment, possibly either a shallow bay of ancestral Great Slave Lake or a former alluvial plain of Boundary Creek. In either case, the charcoal was most likely derived from a burned, forested surface at a higher elevation. This is significant, as it indicates that terrestrial emergence here must have occurred between about 1460 (the age of the younger detrital organics) and 1170 (the age of the basal peat) Cal BP, at a site presently about 10 m above, and more than 6 km inland of, Great Slave Lake (Fig. 2B). Thus, given the low elevation gradient, considerable terrestrial emergence occurred over a relatively short time period.

A preliminary Holocene lake-level reconstruction may be derived for ancestral Great Slave in the Yellowknife region from the AMS ages obtained beneath the peatlands in the region. Figure 3B illustrates the derived lake-level recession rate for the Yellowknife area using calibrated radiocarbon ages. A rate of approximately

Table 1. AMS dates used to infer late Holocene lake-level recession and terrestrial emergence in the Great Slave Lowland.

Site	Age (^{14}C BP)	2σ range (Cal BP)	Lat. (°N)	Long. (°W)	Elev.[1] (m asl)	Depth (m)	Material	Depositional environment
1	7130 ± 40	8020-7865	62.5537	114.0172	210 / 205	2.95	Peat	terrestrial
2	6730 ± 30	7670-7515	62.4796	114.4013	210 / 205	1.30	Wood	terrestrial
3	6580 ± 40	7565-7430	62.4564	114.5311	195 / 195	2.35	Wood	terrestrial
3	5880 ± 30	6780-6640	62.4564	114.5311	195 / 195	2.45	Peat	terrestrial
4	1870 ± 30	1880-1725	62.5061	114.2759	185 / 175	1.55	Wood	terrestrial
4	1590 ± 30	1545-1410	62.5061	114.2759	185 / 175	1.55	Peat	terrestrial
5	1240 ± 30	1270-1075	62.5280	114.9606	170 / 165	0.93	basal peat	terrestrial
5	1770 ± 30	1810-1610	62.5280	114.9606	170 / 165	2.20	burned wood	alluvial
5	1570 ± 30	1533-1395	62.5280	114.9606	170 / 165	2.55	burned wood	alluvial
6	modern	na	62.5275	114.3128	165 / 156	0.85	in situ root	terrestrial
6	80 ± 30	260-25	62.5275	114.3128	165 / 156	1.80	in situ root	alluvial

[1] Elevations include collection elevation and local surface water (lake/pond/or stream) elevation. Local water level elevations, rather than collection elevations, are used in lake-level reconstructions.

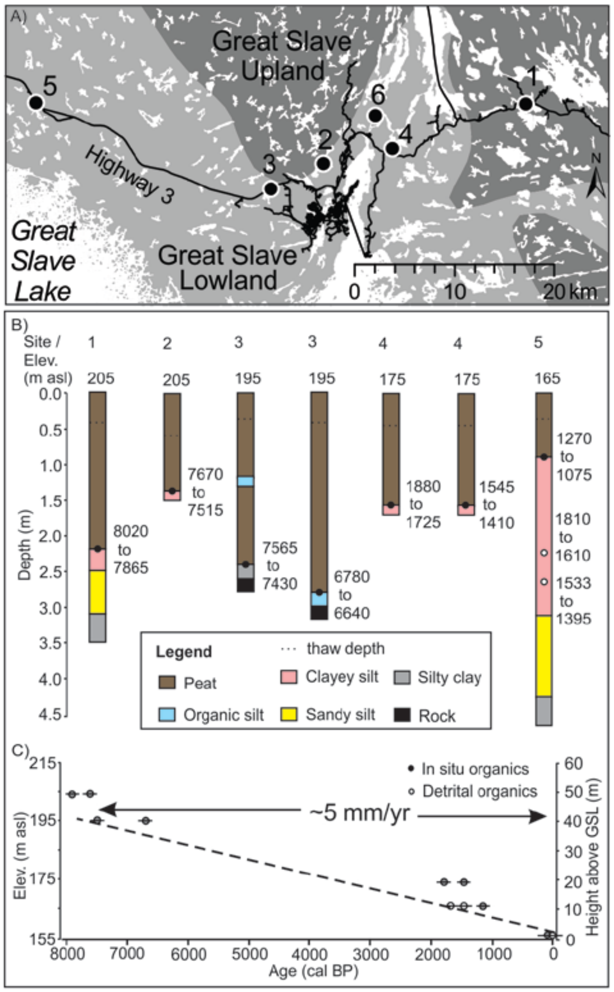

Fig. 3. Elevation-age relations in the Great Slave Lowland. A) Near-surface stratigraphy and AMS ages beneath terrestrial peatlands at varying elevations. B) Calibrated AMS ages in relation to elevation. Dashed line represents approximation of lake-level recession and terrestrial emergence.

5 mm/year is inferred. This is roughly two and half times that of the southern side of Great Slave Lake (Smith and Vanderburgh 1988). This may be attributed to either a true difference in the rates of Holocene post-glacial isostatic adjustment as hypothesized, or to differences in methodology (i.e. in situ terrestrial peatlands dated in this study versus allochthonous buried logs used on the Slave River Delta). Although Smith (1994) also estimated the rate prior to 8000 Cal BP (18 mm/year) no estimate is made for Yellowknife, though it may be significantly greater.

4.2 Shoreline reconstruction and landscape evolution

Figure 4 depicts the present-day (Fig. 4A), and + 40 m reconstructed (Fig. 4B), shorelines in the Yellowknife area. At present, the Yellowknife River flows along a 6 km channel from Tartan Rapids (TR in Fig. 4A), with broad alluvial plains and two main islands along the river, into

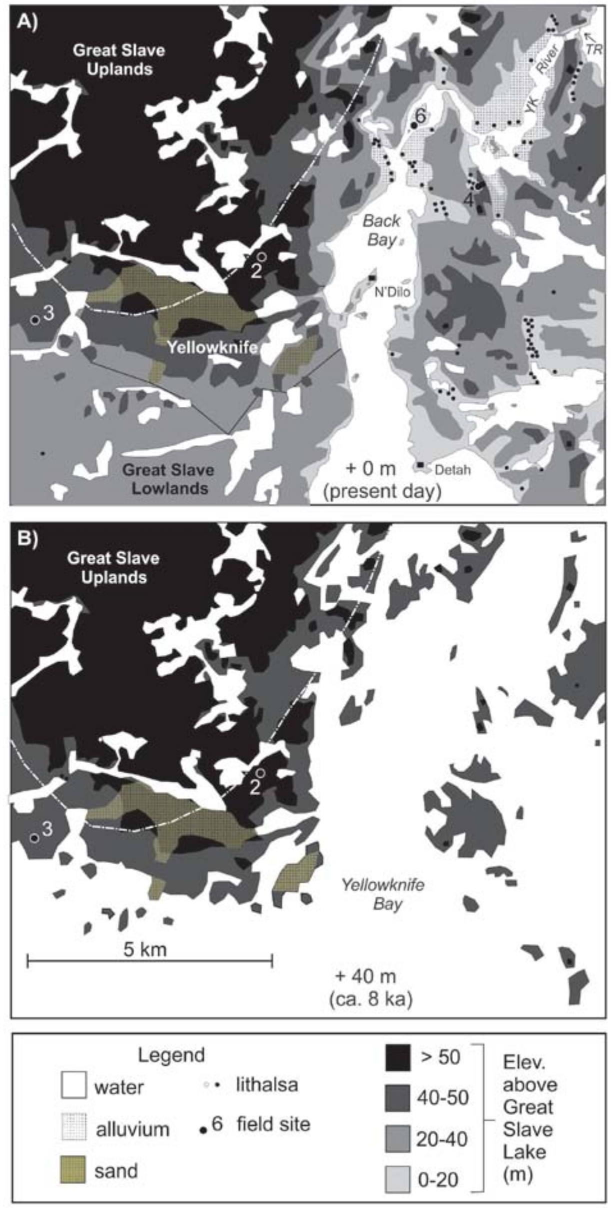

Fig. 4. Shoreline reconstructions based on elevation in the Yellowknife area, with surficial sediment and lithalsa distributions. A) Present-day shoreline, also showing + 20, + 40 and >50 m elevations. B) Shoreline configuration at + 40 m, and showing > 50 m elevation relative to present day lake level. TR = Tartan Rapids

Back Bay on Great Slave Lake where alluvial plains also occur at the north end of the bay (Fig. 4A). In contrast, with lake levels at + 40 m relative to present-day elevation this was part of the larger Yellowknife Bay (Fig. 4B), and the river entered Great Slave Lake several kilometres tothe north (not shown in figure). At that time, lake levels were locally near the dividing limit between the Great Slave Upland and Lowland, and the surface of sandy outwash deposits in the Yellowknife area were reworked as beaches (Fig. 4B). With lake-level recession, the Yellowknife River became confined to the present-day channel, with alluvium deposited in shallows along the margins of the river. Based on the local relief, this occurred when the lake was less than + 20 m relative to present-day level (Fig. 4A).

Utilizing the Holocene lake-level recession of about 5 mm per year over the last 8000 years, the + 40 m shoreline relative to present-day is estimated at about 8000 Cal BP (Fig. 4B). Thus, most of the Great Slave Lowland was terrestrially exposed within the last 8000 years. More specifically, in the local Yellowknife area, Back Bay formed about 4000 years ago when lake levels were about + 20 m relative to present. The Yellowknife River was not confined to its present channel below Tartan Rapids until about 3000 years ago, when lake level was about + 15 m. Tartan Rapids itself is relatively new, as Prosperous Lake above the rapids is less than + 2 m relative to Great Slave Lake. Similarly, most of the alluvium along the Yellowknife River was deposited within the last 3000 years, and probably more recently.

Lithalsa distribution in relation to elevation and alluvial deposits in the Yellowknife area provides further insight into potential timing of permafrost aggradation. Figure 5 shows the frequency distribution of lithalsas mapped in Figure 4, relative to their elevation and, based on lake-level recession rates, their maximum age. Whereas most lithalsas reside within + 30 m of present lake level, and are thus no older than 6000 years, more than half reside with + 15 m, and thus have formed potentially within the last 3000 years. Notably, nearly all lithalsas formed within + 10 m of present lake level elevation (the last 2000 years) have developed on alluvium of the Yellowknife River and Back Bay. This suggests that these saturated clayey-silt deposits, in close proximity to a water source, are conducive to lithalsa formation during permafrost aggradation. Noting the location of other lithalsas in Figure 4, it is likely that these have similarly formed where alluvium or nearshore lacustrine sediments were deposited.

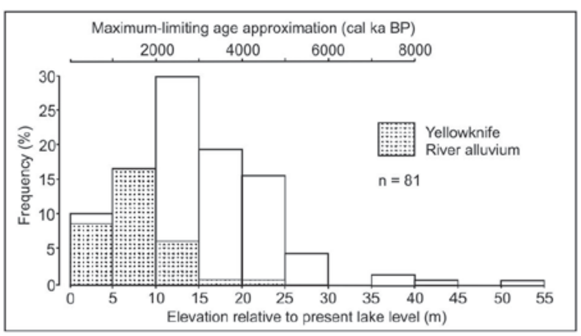

Fig. 5. Lithalsa occurrence by elevation in the Yellowknife area also showing occurrence of lithalsas on Yellowknife River alluvium and maximum-limiting age approximations based on Holocene lake-level recession rates.

4.3 Recent ground ice formation

Regarding the abundance of lithalsas along the Yellowknife River, a retrogressive thaw slump (Site 6) on an island in the river, 1 km north of Back Bay (Fig. 4A),

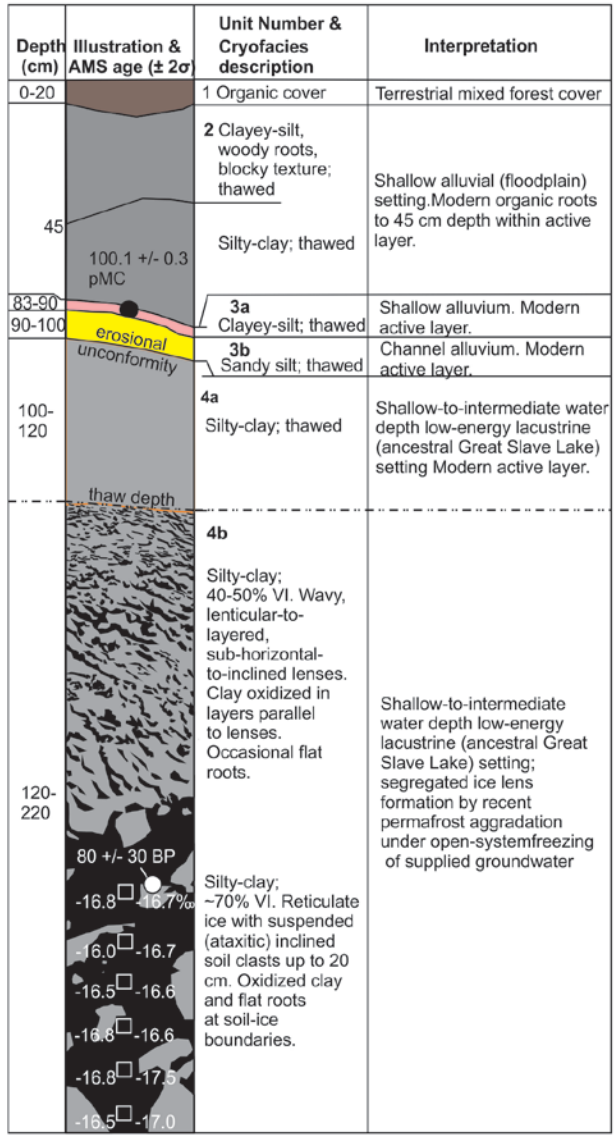

Fig. 6. Cryofacies description, analytical results (including AMS age and δ18O values) and environmental interpretation of ground ice exposure in slump at Site 6 on the Yellowknife River.

was examined to assess the origin of the ice, and the age and depositional environment of the enclosing sediment. The slump has regressed landward from the river by about 40 m (Fig. 2 C) and the elevation of the ground surface at the headwall (Fig. 2D) is about 8 m above river elevation. Figure 6 shows the stratigraphic and analytical results, and interpretation of the section and Table 1 includes results from two AMS ages at this site. An organic cover (Unit 1), comprised primarily of un-decomposed moss, extended to 20 cm depth, below which an unfrozen clayey-silt (Unit 2) with a blocky texture extended to a maximum depth of about 90 cm, with abundant woody roots in the upper 20 to 45 cm. This unit contained nearly equal amounts of clay (< 4 µm) and silt (< 63 µm to 4 µm), and a small fraction of fine-grained sand, and was a low-plasticity clay in which the existing water content of 28% dry weight was slightly above the plastic limit of 23%. A thawed, undulating clayey silt and sandy silt unit (3A and 3B) extended across the section from about 83 to 100 cm depth. The clayey-silt sub-unit contained 70% silt, 27% clay and minor sand, and was a low plasticity clay with a water content of 19% at about the plastic limit. An AMS age from a root contained within the sediments was modern. The sandy-silt sub-unit contained 71% silt, 10% clay and 19% fine sand, with a moisture content of 16%. A silty-clay (Unit 4), with an erosional upper contact with Unit 3, extended to the base of the exposure. This was divided into two sub-units based on the thaw depth at time of observation. The upper thawed sub-unit (4a) extended from 100 to 120 cm depth, and contained 51% clay, 46% silt and 3% sand, and was an intermediate plasticity clay with a moisture content of 30%, which was well above the plastic limit of 20%, and approaching the liquid limit of 38%. The lower frozen sub-unit (4b) extended from 120 cm to the base of the exposure at 220 cm. It contained 58 to 64% clay, 35 to 40% silt and a small fraction of fine-grained sand, and an intermediate plasticity clay. Ice content within the frozen sub-unit increased substantively from 40 to 70% visible ice by volume, and ranged from wavy lenticular to layered sub-horizontal to inclined lenses to reticulate ice with suspended ataxtic soil clasts up to 20 cm in diameter. Moisture content of the combined soil and ice in the upper portion of the sub-unit was 45%, equivalent to the liquid limit. In contrast, the moisture content of the soil component (without excess ice) obtained from a clay clast in the lower portion of the sub-unit was 36%, still exceeding the plastic limit of 23%. Oxygen isotopic values of the excess ice from between 160 and 200 cm depth ranged from -16.0 to -17.5‰ and the δ18O value of a single ice crystal was -16.6‰. Co-isotopic ratios of δ18O/ δD fall within the range of natural lakes in the area (Gaanderse 2015), confirming a modern water source for the ice. An AMS age of an in situ root along a sediment-ice margin in the section was 80 ± 30 ^{14}C BP.

Underlying silty-clay sediments from Unit 4 are interpreted as lacustrine deposits, based on their high combined silt and clay content. The clay content within this unit is lower, however, than that typical of Glacial Lake McConnell sediments, which usually exceed 70% (Gaanderse 2015), suggesting that these are not glaciolacustrine sediments. More likely, they represent ancestral Great Slave Lake deposits, likely in relation to the expanded Yellowknife Bay as depicted in Fig. 4B or are more recent. The overlying sandy-silt and clayey-silt Unit 3, with an erosional unconformity at its base, is interpreted as fluvial channel deposits, with the sandy-silt representing Yellowknife River channel deposits and the clayey-silt representing side deposits in shallower water. This would correspond to a time when the Yellowknife River was confined below Tartan Rapids and entering into the north end of Back Bay as it does today. Unit 2 sediments are interpreted as alluvial plain deposits, representing a shallow-water or seasonally-flooded environment as presently observed along the Yellowknife River shoreline.

The nature of the ground ice from 120 cm to the base of the exposure is indicative of segregated ice that formed epigenetically as permafrost aggraded into alluvial sediments following terrestrial exposure. The significant increase in volume of ice below 160 cm depth suggests freezing rates were slow with unlimited available water. Significantly, the in situ roots within these the sediments indicate the ground was unfrozen until about 80 ± 30 ^{14}C BP. This age equates to between 253 and 25 calendar years ago (Calib.©7.0.4, 2014), suggesting that permafrost aggradation into the sediment likely occurred within the last two hundred years at most. Furthermore, as the ground surface of the headwall is presently 8 m above river level, this suggests that as much as 8 m of ground ice has formed within this time period, heaving the ground surface.

Atterberg limits indicate clay-like properties of these fine-grained lacustrine and alluvial sediments, being conducive to both ice segregation and sensitivity to thaw. Field water contents, exceeding the plastic limit at the base of the active layer and within underlying frozen sediments, enable ongoing thaw slumping by promoting sliding and flowing of liquefied sediments. It is possible that slumping is further promoted by the increase in slope from surface heave through ice segregation in permafrost at depth, facilitating soil failure at the base of the active layer.

The ground ice exposure on the Yellowknife River (Site 6 shown in Fig. 4B) provides an example of comparatively recent historical permafrost aggradation into alluvial sediments, accompanied by epigenetic ground ice formation, with ongoing lake-level recession. This suggests that the processes of permafrost aggradation and ground ice (i.e. lithalsa) formation have continued under historically modern climate conditions.

5 CONCLUSIONS

The Great Slave Lowland was initially inundated by Glacial Lake McConnell, and subsequently by ancestral Great Slave Lake at about 8000 cal BP. Concerning regional terrestrial emergence and permafrost aggradation, the main conclusions of this study are:

1. In the Yellowknife area, Holocene lake-level recession of ancestral Great Slave Lake occurred at a rate of about 5 mm/year over the last 8000 years.
2. As lake-level recession exposed land within the Great Slave Lowland, permafrost aggraded into fine-grained lacustrine, alluvial and underlying glaciolacustrine sediments following terrestrial emergence. Ice-rich permafrost mounds (lithalsas) formed in some areas as permafrost aggraded into saturated sediments.
3. In the local Yellowknife area, most lithalsas formed within the last 6000 years, and many are locally associated with alluvial deposits along the Yellowknife River, which were deposited within the last 3000 years as the river became confined to a channel below Tartan Rapids.
4. The process of permafrost aggradation and ground ice formation has continued in recent historical

times along alluvial floodplains the present-day shoreline of the Yellowknife River.

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