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Holocene Evolution of Lakes in the Bluefish Basin, Northern Yukon, Canada

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ABSTRACT. This study documents the Holocene evolution of lakes located in the Bluefish Basin, northern Yukon, on the basis of lake lithology, distribution of plant macrofossils, and radiocarbon dating of the basal organic material in sediment cores obtained from former lake basins. Basal organic matter from former lake basins is radiocarbon-dated to the late Holocene (< 3770 yr. BP), whereas the ^{14}C ages from the polygonal peat plateaus (~2 m thick) that surround most of the former lake basins cluster in the early Holocene (between 11 435 and 8200 yr. BP). Plant macrofossil distribution in four out of five cores obtained in former lake basins indicates a transition from emergent aquatic vegetation to wetland and terrestrial-type vegetation, suggesting a gradual decline in water levels. The fifth core analyzed for macrofossils showed evidence of sudden lake drainage. The absence of ^{14}C ages from the middle Holocene (7000 to 4000 yr. BP) suggests that the lakes had a greater spatial coverage and water levels during that period, a conclusion supported by the greater surface area occupied by the former lake basins relative to modern lakes and by the fact that the middle Holocene was a wet period in northern Yukon. The gradual decrease in water levels during the late Holocene could be attributed to partial drainage of lakes, increased evaporation under a drier climate, or a combination of both. A comparison with other regional climate records indicates a change toward drier climate conditions around 4500 yr. BP as a result of a reconfiguration in large-scale atmospheric circulation patterns, suggesting a climate-driven change in hydrological conditions.

Key words: thaw lakes, lake levels, Holocene, lake sediments, plant macrofossils, radiocarbon dating, Bluefish Basin, northern Yukon

RÉSUMÉ. La présente étude retrace l’évolution des lacs de l’Holocène situés dans le bassin Bluefish, dans le nord du Yukon. Elle s’appuie sur la lithologie des lacs, la répartition des macrofossiles de plantes et la datation par le radiocarbone des matières organiques de base se trouvant dans les carottes de sédiments provenant d’anciens bassins lacustres. La datation par le radiocarbone de la matière organique de base d’anciens bassins lacustres fait remonter cette matière à l’Holocène supérieur (< 3 770 ans avant le présent), tandis que la datation par le radiocarbone des plateaux de tourbe polygonaux (~2 m d’épaisseur) qui entourent la plus grande partie du groupement d’anciens bassins lacustres remonte à l’Holocène inférieur (entre 11 435 et 8 200 ans avant le présent). La répartition des macrofossiles de plantes dans quatre des cinq carottes provenant des anciens bassins lacustres laisse voir une transition allant d’une végétation aquatique émergente à une végétation de zone humide et de type terrestre, ce qui attesterait du déclin graduel des niveaux d’eau. Dans la cinquième carotte, les macrofossiles présentaient des preuves d’un assèchement lacustre soudain. L’absence de datation par le radiocarbone de l’Holocène moyen (de 7 000 à 4 000 ans avant le présent) laisse entrevoir que les lacs s’étendaient sur de plus grandes aires et que les niveaux d’eau étaient plus élevés pendant cette période, conclusion qui est appuyée par la plus grande surface occupée par les anciens bassins lacustres relativement aux lacs contemporains et par le fait que l’Holocène moyen était une période humide dans le nord du Yukon. La diminution graduelle des niveaux d’eau pendant l’Holocène supérieur pourrait être attribuée à l’assèchement partiel des lacs, à l’évaporation accrue lors d’un climat plus sec ou à une combinaison des deux. La comparaison avec d’autres relevés climatologiques régionaux indique un changement s’orientant vers des conditions climatiques plus sèches environ 4 500 ans avant le présent, changement découlant de la reconfiguration de la circulation atmosphérique à grande échelle, ce qui laisse entendre que les conditions hydrologiques auraient évolué en raison du climat.

Mots clés : lacs thermokarstiques, niveaux des lacs, Holocène, sédiments lacustres, macrofossiles de plantes, datation par le radiocarbone, bassin Bluefish, nord du Yukon

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INTRODUCTION

In the western Canadian Arctic lowlands, lakes and drained lake basins occupy a great portion of the landscape. Climate change in this region has already resulted in changes in hydrological factors, including precipitation, evaporation, runoff, the duration and frequency of ice cover, and the extent of permafrost (Woo, 1996; Rouse et al., 1997). In recent years, many studies have examined the impact of these factors on the distribution and surface area of lakes in the western Arctic (e.g., Smith et al., 2005; Frohn et al., 2005; Hinkel et al., 2005, 2007; Labrecque et al., 2009), and the direction of change seems to be affected mainly by the response of permafrost. For example, in the discontinuous permafrost zone, lakes have shown a substantial decrease in their surface area due to an increase in subsurface drainage as permafrost thaws (Osterkamp et al., 2000; Yoshikawa and Hinzman, 2003; Christensen et al., 2004; Riordan et al., 2006), whereas in areas underlain by continuous permafrost, lakes show signs of expansion (Smith et al., 2005), shrinkage (Smol and Douglas, 2007), or little variation (Plug et al., 2008).

To assess the magnitude and significance of lake responses to present-day climate change, we need to understand the effects of past climate change on hydrological conditions, including lake distribution and lake-level fluctuations, from the late Quaternary to today. Such information can be retrieved by analyzing the distribution of the former lake basins in conjunction with paleohydrological analyses of lake sediments (such as the stratigraphic sequence of diatoms, pollens, and macrofossils). These analyses provide the basis for understanding the natural range of variability in lake-level fluctuations in relation to long-term climate change (Lamoureux and Bradley, 1996; Wolfe et al., 1996; Vardy et al., 1997; Pienitz et al., 2000; Moser et al., 2000; MacDonald et al., 2000; Edwards et al., 2000; Eisner et al., 2005; Ellis and Rochefort, 2006). We can reconstruct long-term regional lake-level variations by analyzing sediment cores from multiple lakes within the same region. Synchronous changes in the different lakes would suggest that the lake levels are influenced mainly by climate, whereas non-synchronous changes would tend to reflect non-climatic factors (e.g., geomorphic effects) (Digerfeldt, 1988; Magny, 2004). Compilations of lake-level data at a regional scale have suggested that in some western Arctic lakes, the water level responded to modifications in regional atmospheric circulation patterns, such as the Arctic Oscillation or Pacific Decadal Oscillation (e.g., Street-Perrott and Roberts, 1983; Harrison and Metcalfe, 1985; Harrison and Digerfeldt, 1993; Yu and Harrison, 1995; Anderson et al., 2005). In other lakes, however, water levels showed no relation with climate change, as their variation was dependant on local events (e.g., Henselmann, 1970). These divergent observations arise from the thermokarstic nature of most lakes in the western Arctic; the water levels of such lakes react to both climatic and geomorphic events (Billings and Peterson, 1980).

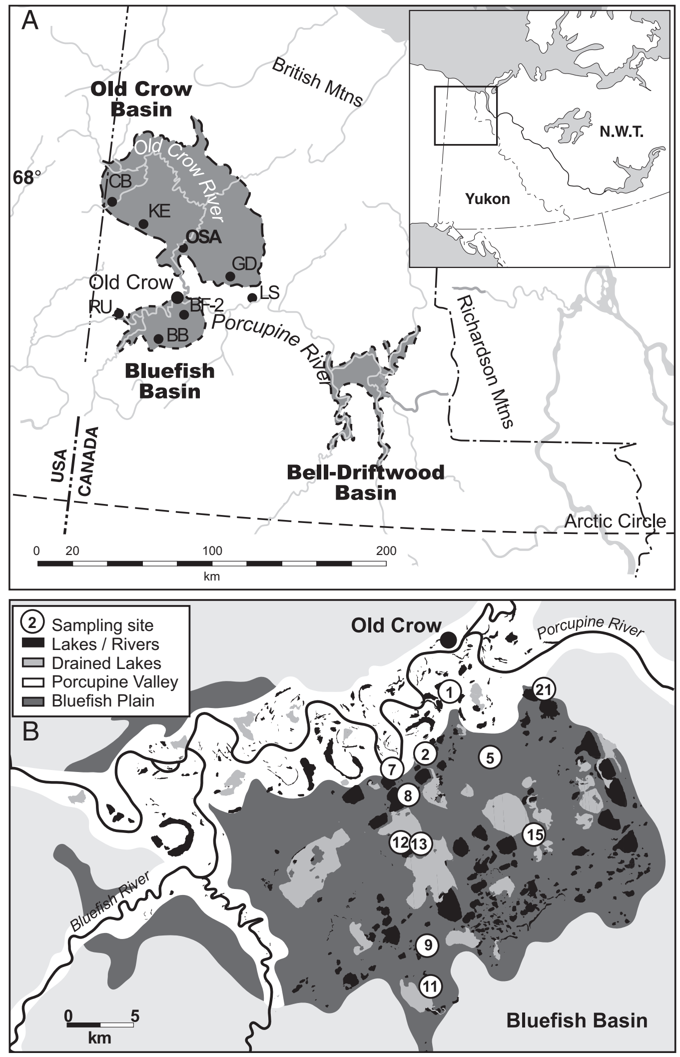

FIG. 1. A) Map of northern Yukon showing the location of areas referred to in text. The notations CB, KE, OSA, GD, LS, RU, and BB refer to sites mentioned in Ovenden (1982). B) Map of Bluefish Basin, northern Yukon, showing physiographic units and sampled sites.

In the continuous permafrost zone of the western Canadian Arctic, several lacustrine plains host thousands of lakes that provide breeding habitat for aquatic animals, waterfowl, and caribou herds. Three of the largest are the Old Crow, Bluefish, and Bell-Driftwood basins located in northern Yukon (Fig. 1). These basins are situated in the transition zone between the boreal forest and tundra ecoregion, a region that is sensitive to the changing climate. The objective of this study was to determine whether the observed modern trends toward decreasing lake water level in this region (Labrecque et al., 2009) are unique to the ongoing present-day climate change, or part of the natural variability in lake levels over time. The reconstruction of the Holocene evolution of lakes is based on lake lithology, distribution of plant macrofossils, and radiocarbon dating of the basal organic material in sediment cores. These cores were obtained from former lake basins and then compared with other regional paleoclimate records. This study contributes to the knowledge of paleohydrologic conditions of

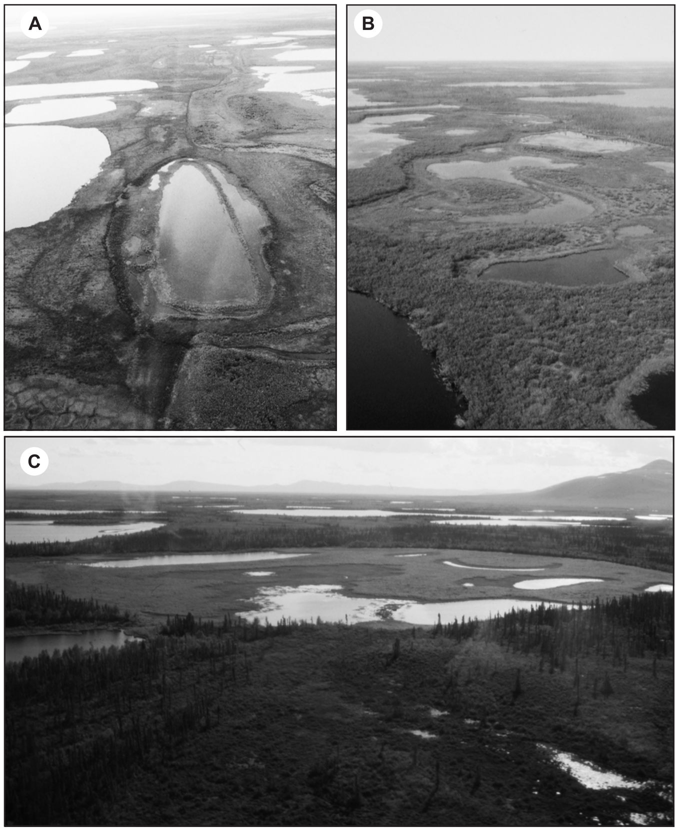

FIG. 2. Photographs of (A and B) elongated thermokarst lakes and (C) former lake basin in the Old Crow Basin, northern Yukon, taken in August 1997. Fields of vision are 2.5 km for A and B and 1.5 km for C.

lakes in the western Arctic (Wolfe et al., 1996; Vardy et al., 1997; Edwards et al., 2000; Hinkel et al., 2003; Eisner et al., 2005) and to our understanding of how climate influences the water balance of lakes in a region strongly affected by the recent climate warming.

STUDY AREA

Quaternary and Physiographic Setting

Because of logistical constraints, this study focuses only on the eastern portion of the Bluefish Basin (Fig. 1), located approximately 200 km west of the Mackenzie Delta in the northern Yukon, rather than on the much larger Old Crow Basin located a few kilometers farther north. The Bluefish Basin was formed by the Laramide orogeny during the early Tertiary, with subsequent infilling of late Tertiary and Quaternary clastic sediments originating from the neighbouring Old Crow and Keele ranges. During the late Pleistocene, most of the northern Yukon, including the Old Crow region, remained ice-free (Hughes, 1972). However, the neighbouring Laurentide and Cordilleran ice sheets profoundly affected the hydrology of this region (Lemmen et al., 1994). During the last glacial maximum, the Laurentide Ice Sheet blocked the Peel and Porcupine rivers when it reached the eastern edge of the Richardson Mountains at McDougall Pass, creating an extensive glacial lake (glacial Lake Old Crow) that occupied the Old Crow, Bluefish, and Bell-Driftwood basins (Fig. 1). Despite numerous studies undertaken in the region following the pioneer work of Hughes (1969), the chronology of the flooding of these basins is still not well established. Early studies (Morlan, 1980; Hughes et al., 1989; Matthews et al., 1990) indicate that the maximum expansion of glacial Lake Old Crow occurred around 30 000 BP, while more recent studies suggest a maximum inundation of the basins younger than 24 000 BP (Dyke et al., 2002; Zazula, 2003). During the presence of glacial Lake Old Crow, more than 7 m of silty-clay sediments were deposited in the basins. The glacial lake drained by about 14 000–12 000 BP through the Ramparts of the Porcupine, which allowed for permafrost to aggrade in the glaciolacustrine sediments (Morlan, 1980). Stable oxygen isotope analysis of the segregation ice in the glaciolacustrine sediments has uniform $\delta^{18}O$ values (-24.5 ± 0.1‰; n = 9; Lacelle, 2002) similar to those of pore water extracted from sediments deposited by glacial Lake Agassiz (Remenda et al., 1994), indicating that permafrost aggraded through the freshly exposed sediments before the onset of the early Holocene warm interval. This late Pleistocene establishment of permafrost in the Old Crow, Bluefish, and Bell-Driftwood basins is a unique condition related to the drainage of glacial Lake Old Crow, as permafrost has been a long-term component of the cryosphere in the surrounding region since the late Tertiary/early Pleistocene (e.g., Lauriol et al., 1997; Froese et al., 2000).

The Bluefish Basin covers over 205 000 ha and has two physiographic units: the Bluefish Plain (132 000 ha) and the Porcupine River Valley (74 000 ha). The latter is located 40–50 m lower than the Bluefish Plain as a result of the incision of the Porcupine River following the drainage of glacial Lake Old Crow. Analysis of 1:250 000 scale maps (NTS sheet numbers 116N and 116O) using ArcGIS indicates that the Bluefish Plain contains over 560 lakes. These lakes average 12 ha in surface area, and no lake exceeds 500 ha (Table 1). Lakes occupying an area of 100 ha or less constitute 97% of the lakes on the Bluefish Plain, and their frequency rapidly decreases with increasing size. Most lakes in the Bluefish Plain are flat-bottomed and shallow (< 250 cm deep; averaging 161 ± 65 cm; n = 10), and they tend to be elongated essentially at a right angle to the prevailing summer wind direction (Fig. 2).

At present, a large portion of the Bluefish Plain is scarred by former lake basins infilled by peat and an assemblage of shrubs (*Salix* spp., *Betula glandulosa*), grasses (*Nuphar polysepalum*, *Carex* spp., *Andromeda polifolia*, *Oxycoccus microcarpus*) and mosses that colonized the lake basins during episodes of low lake levels (Fig. 2). In contrast to existing lakes, the former lake basins average 120 ha in area, and three of them exceed 500 ha (Table 1). Although the former lakes are less numerous (53), their size and distribution suggest that they covered a much larger surface area than the modern lakes. The present and former lake basins in the Bluefish Plain are frequently surrounded by polygonal peat

TABLE 1. Size and distribution of lakes and former lake basins in the Bluefish Basin, northern Yukon.

	Surface Area (ha)			
Physiographic Units	Total Area (ha)	Number	Average Size	Maximum
Bluefish Plain	132 000			
Lake	6800	562	12	431
Former lake basins	6380	53	120	1350
Porcupine River Valley	74 000			
Lakes	2220	315	7	260
Former lake basins	970	37	26	180

plateaus ca. 2 m thick that are covered by a sparse black spruce forest (*Picea mariana* (Mill.)). Radiocarbon dating of the basal peat provided early Holocene ages (Litchi-Fedorovich, 1973, 1974; Ovenden, 1982). According to these authors, the warm climatic conditions during the early Holocene and the presence of permafrost allowed for high sub-aerial peat accumulation rates due to increased primary productivity and low organic matter decomposition.

The present-day climate in the Old Crow region is characterized by a continental sub-Arctic regime, with long cold winters, short mild summers, and relatively low precipitation. The mean annual air temperature recorded at the Old Crow meteorological station is -9.0 ˚C (January: -31.1 ± 4.8 ˚C; July: 14.6 ± 1.4 ˚C; Environment Canada, 2004). Total annual precipitation recorded at the meteorological station amounts to 265 mm, with half of the amount falling as snow (Environment Canada, 2004). Cyclonic activities are responsible for some of the precipitation, but during the summer months, rainfall frequently results from local convection (Wahl et al., 1987). These climatic conditions ensure the presence of continuous permafrost in the region. Permafrost is ca. 60 m thick, and the depth of the active layer varies between 30 and 60 cm, depending on the physical properties of the surface sediments and vegetation type (Smith and Burgess, 2002).

Origin and Age of Lakes

Since the lakes in the Old Crow region are resting on ice-rich glaciolacustrine sediments and tend to be rounded or elliptical, a thermokarst origin is most commonly proposed (Mollard and Janes, 1985). The thermokarst lakes would have developed after permafrost had been established in the Old Crow, Bluefish, and Bell-Driftwood basins following the drainage of glacial Lake Old Crow. In fact, basal ^{14}C ages from the polygonal peat plateaus that currently surround the infilled lake basins are clustered between 11 000 and 9000 yr. BP (Litchi-Fedorovich, 1973, 1974; Ovenden, 1981). Sediments collected in the Mackenzie Delta region and interpreted to be thaw-lake detritus have also been radiocarbon-dated between 12 800 and 6500 yr. BP, with a peak centred around 10 000 yr. BP (Rampton, 1988). A similar timing of thaw lake development was also observed along the Alaskan Coastal Plain (Carson, 1968; Hinkel et al., 2003; Eisner et al., 2005). On the basis of this age distribution, Mackay (1992) concluded that many of the thaw lakes located in the western Arctic originated during the early Holocene warm period (Ritchie et al., 1983; Burn, 1997; Kaufman et al., 2004), an interval of regional thickening of the active layer and thermokarst development in ice-rich sediments (Rampton, 1982; Murton and French, 1994; Burn, 1997; Lacelle et al., 2004).

If the assumption of a thermokarst origin for most lakes in the Bluefish Basin is accurate, then these lakes would have evolved differently from non-thaw lakes (Carson, 1968; Jorgenson and Shur, 2007). Thaw lakes form as a result of disturbance of the land surface and the ground thermal regime. This disturbance can be attributed mainly to climate warming, but other causes include surface wetting, removal of vegetation by fire, human activity, or local erosion. In our case, the early Holocene warm interval led to the melting of ground ice in the glaciolacustrine sediments and subsidence of the land surface, which allowed for the formation of ponds in the depressions. These small depressions later expanded or coalesced with other nearby ponds or lakes by thermal erosion of the adjacent ice wedges and ground ice, and subsidence increased even more beneath the growing water body. As the hydrological conditions evolved, the lakes may have drained catastrophically by stream capture or breaching. Basins that have drained completely by catastrophic process show an abrupt transition from lacustrine sediments to terrestrial type vegetation (Ovenden, 1986). However, the lakes may also drain only partially, and depending on the local climatic conditions, they can also lose water gradually through evaporation. These partially drained basins can fill in with vegetation that shows a transition from aquatic communities to wetlands and terrestrial type vegetation consisting of an assemblage of peat, grasses, and shrubs (Billings and Peterson, 1980; Ovenden, 1982). Once a lake is drained, either completely or partially, permafrost may once again build in the former lake basin, leading to the aggradation of ground ice. After a future disturbance in the ground thermal regime, the described sequence of events can begin again.

Although a thermokarst origin is assumed for most lakes in the region, other hypotheses have also been advanced. First, Ovenden (1982) proposed that some lakes in the Old Crow and Bluefish basins might be remnants of glacial Lake Old Crow that are due to the undulation in the lakebed. By contrast, Plafker (1964) and Allenby (1988, 1989) suggested that since the Bluefish Basin is delimited by the Kaltag fault, the lakes could be features associated with neotectonic movements (Norris, 1981). The possibility of neotectonic movement in the Bluefish Basin is made evident by interglacial sediments located ca. 40 m above the present-day level of the Porcupine River in the Bluefish Basin (Matthews et al., 1990). Elsewhere in Canada, the interglacial sediments are situated closer to the modern level of the rivers. In addition, the base of the non-glacial lacustrine unit 3 of Ch'ijee Bluff, dated to the late Tertiary, is located ca. 16 m above the modern bed of the Porcupine River (Matthews et al., 1990). In its current context, it is difficult to explain how this lake would have been possible without involving one or numerous rises of the basin during the Quaternary. In the Old Crow Basin, evidence for neotectonic movement is even more obvious, notably the fact that the Old Crow River completely changed its flow direction in the Quaternary. In the past, the Old Crow River flowed east and reached the Porcupine River near the Driftwood Basin (Duk-Rodkin et al., 2004). Following a subsidence of the central region in the Old Crow Basin, the Old Crow River diverted south to reach the Porcupine River near the Bluefish Basin. The subsidence of the basin appears to be ongoing: the sinuosity index of the Old Crow River reaches its maximum between Black Fox Creek and Johnson Creek. In this section, the slope of the river is negligible (< 0.5˚) over a linear distance of 15 km (Rocheleau, 1997).

Finally, the lakes located on the active or abandoned terraces of the rivers that incised the glaciolacustrine sediments are associated with the fluvial dynamics of these rivers, and are consequently termed riverine lakes. From ^{14}C dating of the silt and sand alluvial terraces, Lauriol et al. (2002a) determined that these lakes were all of Holocene age, consistent with the establishment of the hydrological system following the drainage of glacial Lake Old Crow from the area.

METHODS

Twenty cores were extracted from the centres of former lake basins in the eastern section of the Bluefish Basin in April 2001 to determine through radiocarbon dating and plant macrofossil analyses if the decrease in water level in these basins was linked to changing climatic conditions (i.e., a gradual decline in water level), or associated with erosional processes (i.e., a rapid decline in water level). The lake sediments sampled had an average thickness of 44 ± 12 cm, and a maximum thickness of 65 cm was reached before the late Pleistocene glaciolacustrine sediments were encountered. In addition, a core was extracted from one of the polygonal peat plateaus, up to 200 cm thick, that surround the former and current lake basins. The polygonal peat plateau was sampled to determine whether it was formed at the same time as those studied by Litchi-Fedorovich (1974) and Ovenden (1982) in the Bluefish and adjacent Old Crow basins and to reconstruct the Holocene landscape evolution of the basin.

The locations of the sampling sites were predetermined using geo-referenced aerial photographs and located with a hand-held GPS unit, since more than a metre of snow covered the sites at the time of sampling. The thick snow cover also made it impossible to access the western portion of the basin. The cores were collected using a modified SIPRE ice-corer, which is a motor-driven hollow auger with an inner diameter of 5.5 cm. The cores were extracted in 5–10 cm long segments, scraped to remove drilling contamination, and then placed frozen in high-density polyethylene bottles.

Given that the lithology of the lake sediments collected from the former lake basins was visually similar, the basal organic sediments (undifferentiated peat) of eight cores (BF-1, 5, 7, 8, 11, 12, 13, and 21) were randomly chosen to be dated by conventional radiocarbon methods at the Radiocarbon Dating Laboratory, Université Laval, Quebec. Five samples from the peat plateau (BF-2) were also removed from the core for radiocarbon dating. Before being submitted for radiocarbon analysis, the samples were washed in distilled water, filtered through a 0.3 mm mesh sieve, and dried at 60 ˚C. To facilitate their comparison with previously reported radiocarbon ages from other paleo-records, the results are presented as uncalibrated ^{14}C yr. BP, using Libby's ^{14}C half-life of 5568 years. The fact that the former lake basins were cored in their centres should have minimized sediment mixing by slumping, waves, currents and bioturbation, which would result in older ^{14}C ages (Murton, 1996).

Plant macrofossil analysis of the recovered cores was also undertaken to document vegetational succession of former lake basins. Five former lake basins (BF-5, 7, 9, 12, and 15) were chosen to assess whether gradual or abrupt hydrological changes occurred prior to the accumulation of organic matter in the lakes. These cores were chosen to include a broad distribution of basins across the entire sampling area. Extraction of macrofossils was performed according to the technique described in Ovenden (1981). Sub-samples of 118 cm^3 of organic material were taken at 5 cm intervals spanning the length of the core. The samples were gently washed through a series of stacked sieves to separate the 1.4 mm, 1 mm, and 0.5 mm organic fractions. Vascular plant remains, including seeds, leaves, buds, and twigs, were isolated using a binocular microscope. To identify the macrofossil specimens, we used the modern reference collections housed at the Geological Survey of Canada, Ottawa, and the keys with illustrations in Cody (2000), Martin and Barkley (1961), and Lévesque et al. (1988). The results were graphed using the Tilia graph© software.

RESULTS AND INTERPRETATION

The general stratigraphy of the polygonal peat plateaus that surround the former lake basins in the Bluefish Basin consists of 1–2 m of black aquatic peat overlain by *Sphagnum* spp. moss and underlain by non-carbonated glaciolacustrine silts and clays. The ^{14}C results, including those that Ovenden (1981) obtained from the base of the peat plateaus

TABLE 2. Conventional radiocarbon dates from the base of thick peat plateaus resting on glaciolacustrine sediments in the Bluefish and Old Crow basins, northern Yukon.

Site	Laboratory Number	Depth (cm)	^{14}C Age (yr BP)	Reference
Bluefish Basin				
BF-2	UL-2711	20[1]	470 ± 80	This study
BF-2	UL-2771	40[1]	2810 ± 90	This study
BF-2	UL-2772	105[1]	4570 ± 90	This study
BF-2	UL-2760	115[1]	4640 ± 100	This study
BF-2	UL-2387	155[2]	8200 ± 90	This study
RU			9850 ± 245	Ovenden (1981)
BB			10025 ± 140	Ovenden (1981)
Old Crow Basin				
Ch'ijee Bluff	GSC-121		10740 ± 180	Litchi-Fedorovich (1974)
CB			12455 ± 300	Ovenden (1981)
KE		160	13365 ± 210	Ovenden (1981)
LS			9235 ± 115	Ovenden (1981)
GD			12805 ± 290	Ovenden (1981)
OSA	S1779	212-218	11435 ± 270	Ovenden (1982)

[1] Obtained within the cored peat sequence.
[2] Basal radiocarbon dates.

in the Bluefish Basin (BB and RU; Fig. 1), are clustered at the onset of the Holocene, ranging from 13 365 ± 210 to 8200 ± 90 yr. BP (Table 2). However, the dates obtained from the Old Crow Basin are approximately 2000 years older than those from the Bluefish Basin (Table 2). This result is somewhat surprising considering that the Old Crow Basin is currently situated at a lower elevation than the Bluefish Basin. The ^{14}C dates obtained within the 150 cm thick cored peat sequence at BF-2 indicate that accumulation rates were high until ca. 3000 yr. BP, after which the accumulation rate declined rapidly (Fig. 3). Ovenden (1982) observed similar rates in peat accumulation in the Old Crow Basin, suggesting that similar climatic and hydrological conditions existed at both sites even though glacial Lake Old Crow drained from the basins at slightly different times.

The general stratigraphy of the lake sediments obtained from the former lake basins consists of 30 to 60 cm of black aquatic peat overlain by *Sphagnum* spp. moss and underlain sharply by non-carbonated glaciolacustrine silts and clays. The eight ^{14}C dates on organic sediment obtained from the base of the aquatic peat in the basins range from 3770 ± 100 to 410 ± 100 yr. BP. However, no relation exists between the ^{14}C age and the thickness of organic sediments accumulated in the lake basins (Table 3). No lacustrine sediments were encountered in the stratigraphic sequence overlying the glaciolacustrine sediments in the cores, suggesting that the ^{14}C ages of the basal aquatic peat represent the onset of lake level decrease that occurred as the lake basins were gradually being infilled by organic sediments. Individual charcoal and charred macrofossils were occasionally found in the peat, suggesting that even though it was a humid environment, fires were present in the area and might have disturbed permafrost equilibrium. However, considering that only a few individual charred macrofossils were recovered, fire disturbance probably did not modify the local succession of vegetation.

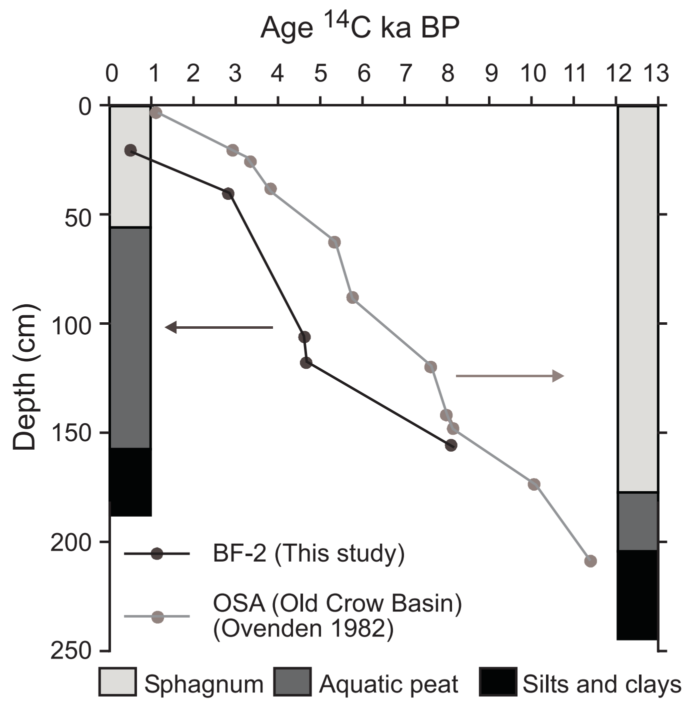

FIG. 3. Radiocarbon age versus depth of organic sediments of thick peat deposits in the Bluefish Basin (Site BF-2) and the Old Crow Basin (Ovenden, 1982). Also shown is the general stratigraphy of peat deposits.

According to Billings and Peterson (1980) and Ovenden (1982), the observed sequence in plant macrofossils combined with radiocarbon dating can provide information on the changing hydrological conditions at the site. The core extracted from site BF-12 (Fig. 1) penetrated through 10 cm of *Sphagnum* spp. moss underlain by 30 cm of aquatic peat before the glaciolacustrine silts and clays were encountered. Figure 4 shows the depth distribution of plant taxa from the BF-12 core, which was subdivided into two zones on the basis of floral species composition and seed abundance. The plant macroremains recovered in zone 1 (25–40 cm)

TABLE 3. Conventional radiocarbon dates obtained from the basal organic sediments (undifferentiated peat) accumulated in former lake basins in the Bluefish Basin, northern Yukon (see Fig. 1B for location of samples).

Site	Laboratory Number	Depth (cm)	^{14}C Age (yr. BP)
BF-13	UL-2395	50	410 ± 100
BF-7	UL-2368	35	1660 ± 70
BF-5	UL-2393	50	1720 ± 60
BF-21	UL-2397	30	1990 ± 90
BF-11	UL-2394	60	2140 ± 90
BF-12	UL-2389	40	2220 ± 110
BF-8	UL-2377	35	2460 ± 110
BF-1	UL-2388	35	3770 ± 100

suggest that around 2220 ± 110 yr. BP, the site was poorly drained and dominated by aquatic plants with some shrubs. Plants such as the emergent marsh cinquefoil (*Potentilla palustris*), shoreline sedges (*Carex* spp.) and grasses (Poaceae) dominated the aquatic floral assemblage. Willows (*Salix* spp.) were the dominant shrubs, but others identified include shrub/small tree birch (*Betula* spp.), dwarf birch shrubs (*Betula nana*/*glandulosa* type), green alder (*Alnus crispa*), and ericaceous shrubs, mostly leatherleaf (*Chamaedaphne calyculata*), with some *Vaccinium*. In zone 2 (0–25 cm), emergent aquatic plants declined and were replaced by ericaceous shrubs. The decline in the emergent marsh cinquefoil and coinciding increase in sedges portray a sedge meadow and signify a gradual change towards shallow-water conditions. Shrubs continue to be abundant and diverse and consist of the same elements seen in zone 1. However, zone 2 is distinguished by an abundance of the ericaceous leatherleaf, a low evergreen shrub commonly found in bogs, muskegs, peaty swales, and lake margins (Cody, 2000). *Sphagnum* spp. moss, which was rare in zone 1 (< 5%), increases in zone 2 from 15–20% to 75% near the surface. The prevalence of abundant *Sphagnum* spp. moss and the low retrieval of plant macrofossils in the upper portion of zone 2 (Fig. 4) portray a continued decline of water levels.

Of the four other sites analyzed for macrofossils, three (BF-9, 7, and 5) showed lithology and plant macrofossil distributions similar to those at BF-12 (Mercier, 2002). The core extracted from site BF-9 showed an abundance of aquatic crustaceans (*Daphnia ephippia*) and shoreline sedges between 20 and 35 cm**.** In zone 2, the concentration of *Carex* spp. increased, and at 10 cm from the surface, *Sphagnum* spp. moss became abundant. The plant macrofossils recovered from site BF-5 suggest that at around 1720 BP, the site was poorly drained and corresponded to a shallow aquatic environment dominated by emergent aquatic plants and shoreline sedges (*Carex* spp., *C.* cf. *aquatilis*, *Ranunculus* spp., *Potentilla palustris*, and *Chamaedaphne calyculata*). In the upper 35 cm (zone 2), the aquatic plants were replaced by shrubs (*Betula* spp.) and moss (*Sphagnum* spp.). This pattern suggests a gradual change toward shallower water conditions. At site BF-7, with a basal ^{14}C date of 1660 yr. BP, zone 1 (20–50 cm) also corresponds to a poorly drained, shallow aquatic environment dominated by *Carex aquatilis* and *Potentilla* spp., primarily *P. palustris*. In zone 2 (0–20 cm), the emergent aquatic plants declined and were replaced by shrubs (*Betula* spp.) and moss (*Sphagnum* spp.). There is also an abundant concentration of charred particles in this zone.

In general, the distribution of plant macrofossils in cores BF-12, 9, 7, and 5 reflects a gradual hydrological change from a poorly drained area to the formation of a peatland and paludification as the water level decreased. However, site BF-15 does not seem to have experienced a gradual decline in water conditions. The core extracted from this site is composed entirely of *Sphagnum* spp. moss overlying the glaciolacustrine sediments, suggesting that this lake was drained catastrophically (Fig. 5). Within the moss, ericaceous shrubs of bog rosemary (*Andromeda polifolia*) and small cranberry (*Oxycoccus microcarpus*) dominate the macrofossil distribution. This fact suggests that the ^{14}C age distribution from former lake basins is mostly related to a gradual decrease in lake levels between 3770 and 410 yr. BP that was induced by climate, and not by local geomorphological factors. Only one of the five lakes examined shows any evidence in the plant macrofossil distribution for an abrupt change in lake level related to thaw lake evolution. However, a partial drainage of the lakes by stream capture or breaching, followed by subsequent decrease in water levels by evaporation, cannot be ruled out as a possible explanation for the observed macrofossil distribution.

DISCUSSION

Comparison of ^{14}C Age Distribution to Regional Holocene Climate

Overall, the radiocarbon ages (clustered to the late Holocene; Table 3) and plant macrofossil assemblages from former lake basins in the Bluefish Basin seem to indicate a gradual decrease in lake water level induced mainly by climate changes, but evidence for geomorphic changes related to thaw lake evolution is also present. A comparison of the ^{14}C age distribution obtained from the former lake basins to the regional climate record supports the theory that climate was a major factor responsible for the observed change in hydrological conditions and landscape evolution (Fig. 6). In the northern Yukon, the early Holocene was warm and dry. Insects (Matthews and Telka, 1997), molluscs such as *Vertigo coloradensis* (Lauriol et al., 2002a), and isotopic evidence from endostromatolites (Clark et al., 2004) suggest that summer air temperatures during this period were up to 7˚C warmer than those of today. Gypsum concretions within cliff-top eolian deposits that accumulated at the Ramparts of the Porcupine River (Lauriol et al., 2002b) indicate the presence of a very dry climate in the northern Yukon around 10 000 yr. BP. From a study of lakes in the Mackenzie Delta, Edwards et al. (2001) estimated that precipitation during the early Holocene was ca. 60–90% of

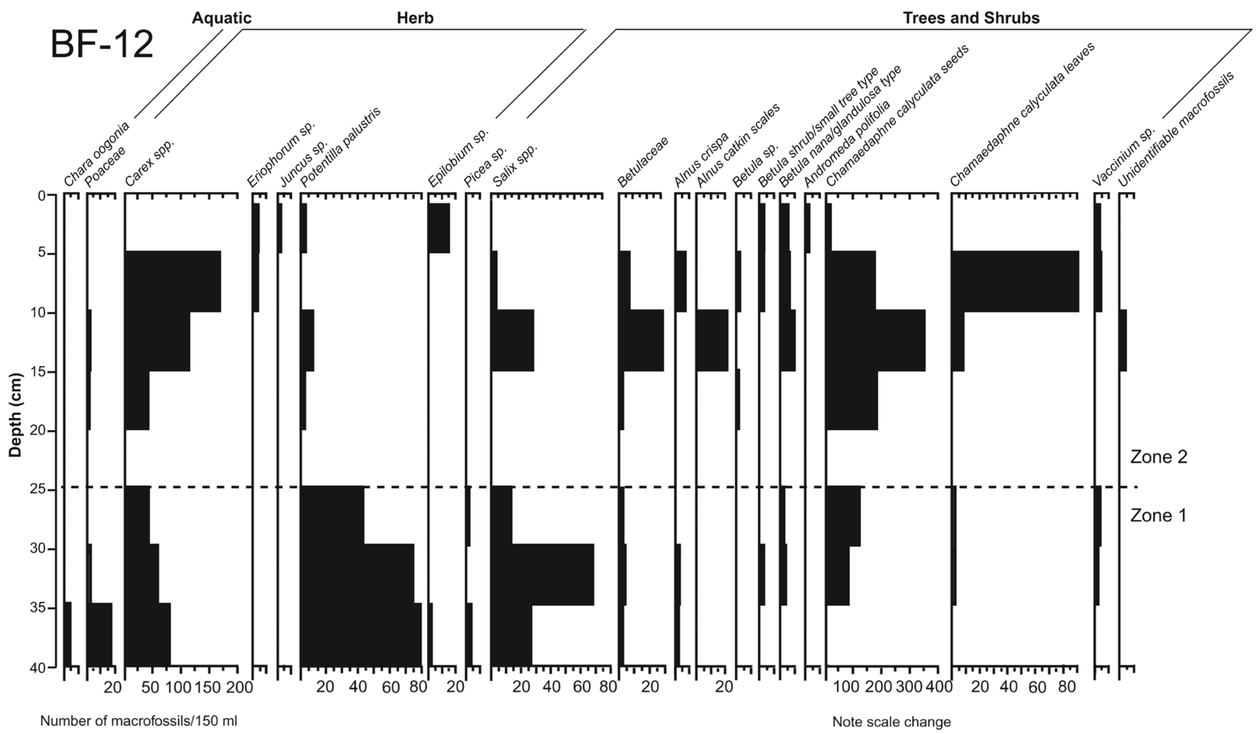

FIG. 4. Plant macrofossil concentrations per 150 ml of organic sediments from site BF-12, a former lake basin in the Bluefish Basin, northern Yukon.

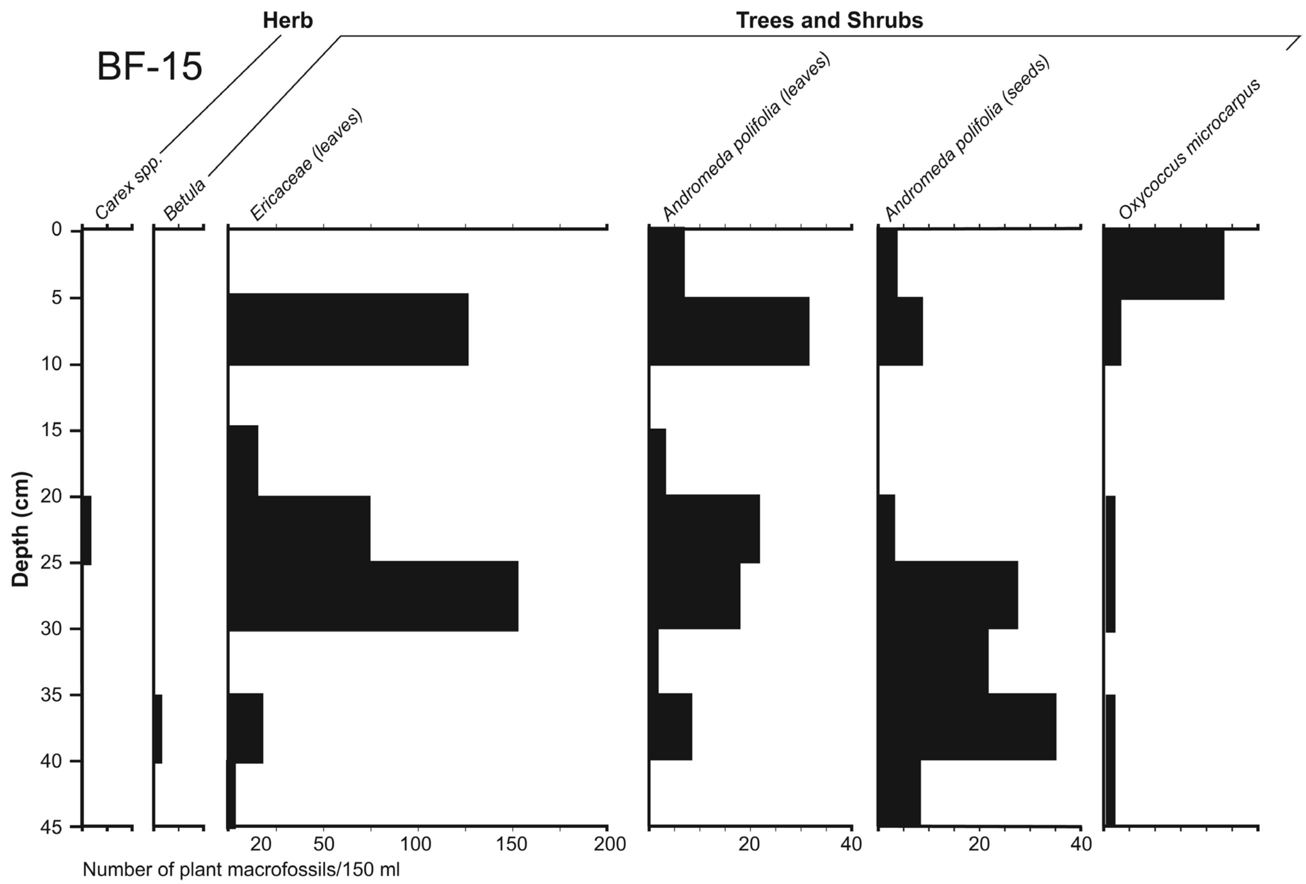

FIG. 5. Plant macrofossil concentrations per 150 ml of organic sediments from site BF-15, a former lake basin in the Bluefish Basin, northern Yukon.

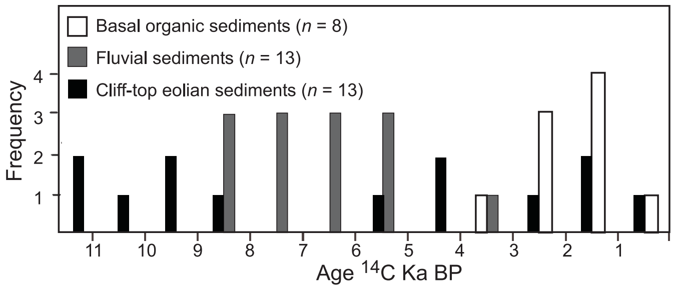

FIG. 6. Temporal distribution of ^{14}C ages obtained from basal organic sediments in former lake basins of the Bluefish Basin, from fluvial sediment accumulation along the Porcupine and Old Crow rivers (Lauriol et al., 2002a), and from cliff-top eolian deposits at the Ramparts of the Porcupine (Lauriol et al., 2002b).

today's precipitation. Since the Bluefish Basin has a more continental climate than the Mackenzie Delta, the estimated precipitation can be considered as a maximum value. During the middle Holocene, temperatures cooled somewhat but were still slightly warmer than present-day temperatures because of greater insolation (Ritchie et al., 1983). Precipitation increased rapidly during the middle Holocene as the post-glacial sea level rose, bringing cold, humid air from the Beaufort Sea farther inland (Burn, 1997). On the basis of paleo-channel measurements of the Old Crow and Porcupine rivers, Lauriol et al. (2002a) suggested that precipitation during the middle Holocene was ca. 150% that of the present day. A middle Holocene wet phase was also observed in the central Yukon (Pienitz et al., 2000). Temperatures reached present-day values around 4500 yr. BP, but during the last two decades, the region has experienced one of the most dramatic warming trends in the Canadian Arctic. The age of 4500 yr. BP also marks the beginning of a drier climate in the northern Yukon, as indicated by the reactivation of cliff-top eolian deposits at the Ramparts of the Porcupine (Lauriol et al., 2002b).

The ^{14}C ages derived from basal organic sediments of former lake basins tend to have a temporal distribution very similar to that of ^{14}C ages derived from the eolian sediments, proxies for a dry and windy climate. No ^{14}C dates obtained from basal organic sediments or eolian deposits fall within the 8000 to 5000 yr. BP wet interval, the period in which all but one (3607 yr. BP) of the ^{14}C dates from fluvial sediments along the Porcupine and Old Crow rivers are clustered (Fig. 6). This pattern suggests that the lakes in the Bluefish Basin occupied their maximum surface area during the wet period of the middle Holocene. The higher water levels during the middle Holocene probably prevented the accumulation of organic matter in the lake basin, and, as shown in Table 1, the surface area of these former lake basins was approximately 10 times that of the modern lakes. Lakes in the Mackenzie Delta region (Michel et al., 1997) and along the Alaskan Coastal Plain (Carson, 1968; Eisner et al., 2005) also reached their maximum extent around 6000 yr. BP before they began to decrease in size around 3500 yr. BP. The clustering of ^{14}C ages from basal organic sediments of former lake basins together with those from the eolian sediments strongly suggests that the gradual decrease in water levels in the late Holocene was caused by a change toward drier climate conditions. However, given the natural evolution of thaw lakes, a partial drainage of the lakes by stream capture or breaching cannot be ruled out as a possible explanation for the observed decrease in water level, and a greater number of radiocarbon ages from other lakes would be needed to support this alternative scenario.

The synchronous lake development in the Alaskan Coastal Plain, the Mackenzie Delta, and the northern Yukon suggests a regional change in hydrological conditions. Such a change could be attributed to a regional reconfiguration of atmospheric circulation due to the melting of the large ice sheets and associated rise in sea level. During the last glacial maximum (ca. 18 000 yr. BP), the presence of a large anticyclone located over the Laurentide Ice Sheet prevented westerlies from reaching the region (Bartlein et al., 1998), and as a result, the dominant winds in the northern Yukon originated from the northeast (Hopkins, 1982; Dyke, 1996). After the Laurentide Ice Sheet had receded from the Mackenzie Delta, the establishment of anticyclones in the northeastern Pacific caused a strengthening of westerlies that resulted in the dry climate of the early Holocene (11 500 to 8000 yr. BP) (Bartlein et al., 1998; Abbott et al., 2000). As most of the Laurentide Ice Sheet had melted by 8000 yr. BP, the 8000 to 4500 yr. BP wet period in the northern Yukon could have been caused by the post-glacial rise in sea level, which brought the cold humid air from the Beaufort Sea farther inland (Burn, 1997). The present-day dry climate over the northern Yukon is attributed to the influence of marine polar air masses coming from low-pressure systems in the Bering Strait and the Chukchi Sea (Wahl et al., 1987). Our chronological data, combined with the cliff-top eolian deposits, indicate that this type of circulation began around 4500 yr. BP. Therefore, the observed decrease in the water level of modern lakes is not unique to the ongoing climate change, a situation that also affects other geomorphological features in the area (Lacelle et al., 2004; Fisher et al., 2006).

SYNTHESIS AND CONCLUSION

This reconstruction of variations in lake level in the Bluefish Basin (northern Yukon) during the Holocene suggests that the geomorphic characteristics of the basin evolved throughout the Holocene by means of interactions between climate, permafrost, and vegetation. A schematic diagram of the major events that shaped the Bluefish Basin as known today is shown in Figure 7. Following the drainage of glacial Lake Old Crow at 14–12 000 yr. BP (Morlan, 1980), prevailing cold temperatures allowed permafrost to aggrade through the glaciolacustrine sediments and form segregated ice lenses. This process is evident in the Pleistocene glaciolacustrine sediments, where the segregation ice has a uniform $\delta^{18}O$ composition of -24.5 ± 0.1‰, very similar to the isotopic composition of glacial Lake Agassiz pore waters in

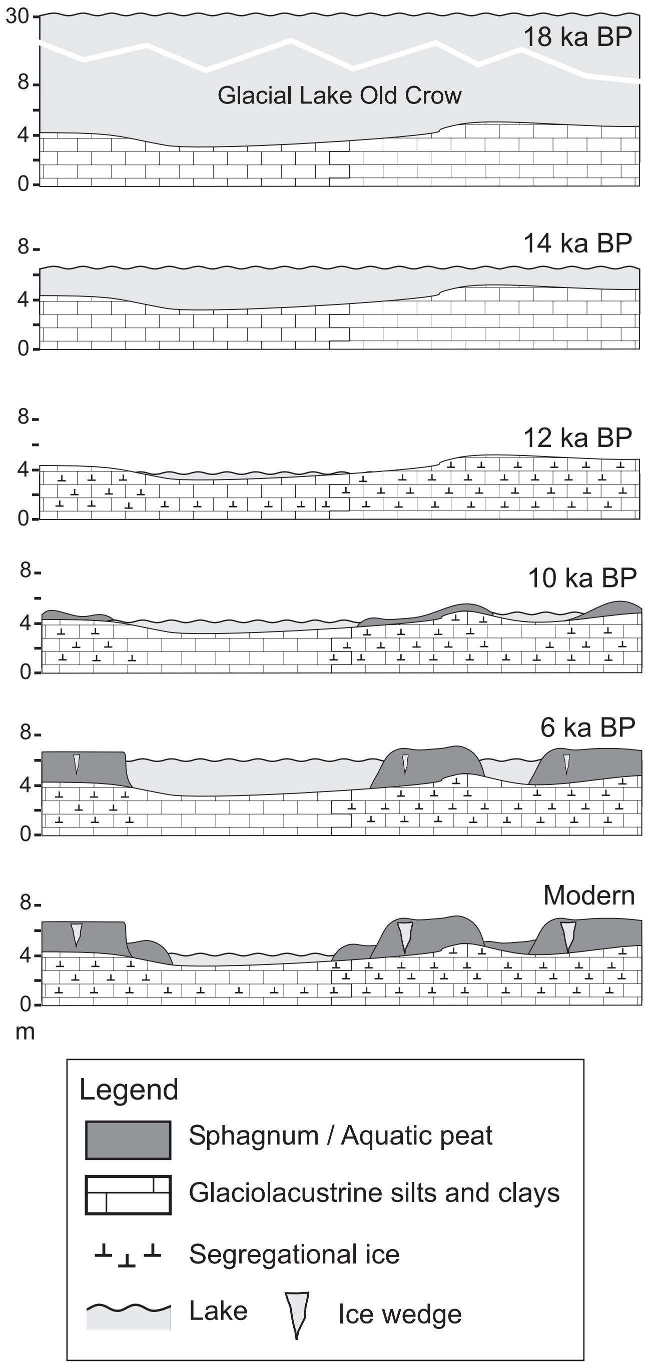

FIG. 7. Schematic diagram of the major events that shaped the Bluefish Basin as observed today.

clays (Remenda et al., 1994). The warmer conditions during the early Holocene led to local thawing and subsidence of the land surface and ponding of the melted segregated ice in the depressions. In addition, the prevailing warm conditions and greater net primary productivity (compared to modern conditions) allowed for high peat accumulation rates (Ovenden, 1982; Vardy et al., 1997). Thick, subaerial peat plateaus began to form during the early Holocene (10 740 to 8200 yr. BP; Table 2). Following the early Holocene warm interval, a significant climatic cooling occurred around 6000 yr. BP, allowing permafrost conditions in the western Canadian Arctic to approach modern conditions (Vardy et al., 1997). This cooler period was associated with an important increase in precipitation. The absence of radiocarbon ages from former lake basins during this wet mid-Holocene interval suggests that lakes had reached their maximum water levels and surface extent. It is suggested that the rapid buildup of peat and the aggradation of permafrost helped to contain the increased precipitation during the middle Holocene, resulting in the lake basins that are currently surrounded by thick peat plateaus (Fig. 7). Thermal erosion along the shores of the middle Holocene lakes probably steepened the sides of some of the peat plateaus, as observed today. Given that the peat accumulation rate on these plateaus remained high during the mid-Holocene, the absence of ^{14}C ages from basal organic matter in lake basins suggests that either the water level was too high to allow organic sediments to accumulate in the basin, or alternatively, that the lakes did not undergo a decrease in water level until the late Holocene. Peat accumulation on the plateaus was greatly reduced during the late Holocene in response to declining primary productivity associated with the much cooler and drier climate. In parallel, lakes in the area began to experience a reduction in their water level. Basal organic matter ^{14}C ages from eight former lake basins are all within the late Holocene (< 3770 yr. BP). Analyses of plant macrofossils in cores from five widely distributed basins suggested a gradual decrease in water level in four of the five basins, as the emergent aquatic vegetation that first colonized the basins was followed by wetland plants and then by terrestrial-type vegetation. The gradual decline in water levels is likely due mostly to increased evaporation under drier climate conditions. However, a partial drainage of the lakes by stream capture or breaching cannot be ruled out, since one core showed evidence for sudden lake drainage. It is safe to confirm that if the observed climate warming continues, these basins may dry up completely and become invaded by shrubs. However, how quickly this could occur is currently unknown. Because of the proximity of the basins and the similar climate regime that influences them, the results presented in this study can probably be extended to the lakes in the nearby Old Crow Basin.

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REFERENCES

Abbott, M.B., Finney, B.P., Edwards, M.E., and Kelts, K.R. 2000. Lake-level reconstructions and paleohydrology of Birch Lake, central Alaska, based on seismic reflection profiles and core transects. Quaternary Research 53:154–166.

Allenby, R.F. 1988. Origin of rectangular and aligned lakes in the Beni Basin of Bolivia. Tectonophysics 145:1–20.

———. 1989. Clustered, rectangular lakes of the Canadian Old Crow Basin. Tectonophysics 170:43–56.

Anderson, L., Abbott, M.B., Finney, B.P., and Edwards, M.E. 2005. Palaeohydrology of the southwest Yukon Territory, Canada based on multiproxy analyses of lake sediment cores from a depth transect. The Holocene 15:1172–1183.

Bartlein, P.J., Anderson, K.H., Anderson, P.M., Edwards, M.E., Mock, C.J., Thompson, R.S., Webb, R.S., and Whitlock, C. 1998. Paleoclimate simulations for North America over the past 21,000 years: Features of the simulated climate and comparisons with paleoenvironmental data. Quaternary Science Reviews 17:549–585.

Billings, W.D., and Peterson, K.M. 1980. Vegetational change and ice-wedge polygons through the thaw lake cycle in Arctic Alaska. Arctic and Alpine Research 12:413–432.

Burn, C.R. 1997. Cryostratigraphy, paleogeography and climate change during the early Holocene warm interval, western Arctic coast, Canada. Canadian Journal of Earth Sciences 34:912–925.

Carson, C.E. 1968. Radiocarbon dating of lacustrine strands in Arctic Alaska. Arctic 21:12–26.

Christensen, T.R., Johansson, T., Åkerman, H.J., Mastepanov, M., Malner, N., Friborg, T., Crill, P., and Svensson, B.H. 2004. Thawing sub-arctic permafrost: Effects on vegetation and methane emissions. Geophysical Research Letters 31, L04501, doi:10.1029/2003GL018680.

Clark, I.D., Lauriol, B., Marschner, M., Sabourin, N., Chauret, Y., and Desrochers, A. 2004. Endostromatolites from permafrost karst, Yukon, Canada: Paleoclimatic proxies for the Holocene hypsithermal. Canadian Journal of Earth Sciences 41: 387–399.

Cody, J.W. 2000. Flora of the Yukon Territory, 2nd ed. Ottawa: National Research Council Press. 669 p.

Digerfeldt, G. 1988. Reconstruction and regional correlation of Holocene lake-level fluctuations in Lake Bysjon, south Sweden. Boreas 17:165–182.

Duk-Rodkin, A., Barendregt, R.W., Froese, D.G., Weber, F., Enkin, R., Smith, I.R., Zazula, G.D., Waters, P., and Klassen, R. 2004. Timing and extent of Plio-Pleistocene glaciations in north-western Canada and east-central Alaska. In: Ehlers, J., and Gibbard, P.L., eds. Quaternary glaciations: Extent and chronology, Vol. 2, Part II: North America. Amsterdam: Elsevier. 313–346.

Dyke, A. 1996. Preliminary paleogeographic maps of glaciated North America. Geological Survey of Canada, Open File 3296.

Dyke, A.S., Andrews, J.T., Clark, P.U., England, J.H., Miller, G.H., Shaw, J., and Veillette, J.J. 2002. The Laurentide and Innuitian ice sheets during the Late Glacial Maximum. Quaternary Science Reviews 21:9–31.

Edwards, M.E., Bigelow, N.H., Finney, B.P, and Eisner, W.R. 2000. Records of aquatic pollen and sediment properties as indicators of late-Quaternary Alaskan lake levels. Journal of Paleolimnology 24:55–68, doi: 10.1023/A:1008117816612.

Edwards, M.E., Mock, C.J., Finney, B.P., Barber, V.A., and Bartlein, P.J. 2001. Potential analogues for palaeoclimatic variations in eastern interior Alaska during the past 14,000 yr: Atmospheric circulation controls of regional temperature and moisture responses. Quaternary Science Reviews 20:189–202, doi:10.1016/S0277-3791(00)00123-2.

Eisner, W.R., Bockheim, J.G., Hinkel, K.M., Brown, T.A., Nelson, F.E., Peterson, K.M., and Moore, B.M. 2005. Paleoenvironmental analyses of an organic deposit from an erosional landscape remnant, Arctic Coastal Plain of Alaska. Palaeogeography, Palaeoclimatology, Palaeoecology 217: 187–204.

Ellis, C.J., and Rochefort, L. 2006. Long-term sensitivity of a High Arctic wetland to Holocene climate change. Journal of Ecology 94:441–454.

Environment Canada. 2004. Canadian climate normals or averages 1971–2000: Old Crow A, Yukon Territory. http://climate.weatheroffice.ec.gc.ca/climate_normals/index_e.html.

Fisher, D., Dyke, A., Koerner, R., Bourgeois, J., Kinnard, C., Zdanowicz, C., De Vernal, A., Hillaire-Marcel, C., Savelle, J., and Rochon, A. 2006. Natural variability of Arctic sea ice over the Holocene. Eos, Transactions, American Geophysical Union 87:273–275.

Froese, D.G., Barendregt, R.W., Enkin, R.J., and Baker, J. 2000. Paleomagnetic evidence for multiple late Pliocene-early Pleistocene glaciations in the Klondike area, Yukon Territory. Canadian Journal of Earth Sciences 37:863–877.

Frohn, R.C., Hinkel, K.M., and Eisner, W.R. 2005. Satellite remote sensing classification of thaw lakes and drained thaw lake basins on the North Slope of Alaska. Remote Sensing of Environment 97:116–126.

Harrison, S.P., and Digerfeldt, G. 1993. European lakes as palaeohydrological and palaeoclimatic indicators. Quaternary Science Reviews 12:233–248.

Harrison, S.P., and Metcalfe, S.E. 1985. Variations in lake levels during the Holocene in North America: An indicator of changes in atmospheric circulation patterns. Géographie physique et Quaternaire 39:141–150.

Henselmann, M.L. 1970. Landscape evolution, peatlands, and the environment in the Lake Agassiz peatlands natural area, Minnesota. Ecology Monograph 40:235–261.

Hinkel, K.M., Eisner, W.R., Bockheim, J.G., Nelson, F.E., Peterson, K.M., and Dai, X. 2003. Spatial extent, age, and carbon stocks in drained thaw lake basins on the Barrow Peninsula, Alaska. Arctic, Antarctic, and Alpine Research 35:291–300.

Hinkel, K.M., Frohn, R.C., Nelson, F.E., Eisner, W.R., and Beck, R.A. 2005. Morphometric and spatial analysis of thaw lakes and drained thaw lake basins in the western Arctic Coastal Plain, Alaska. Permafrost and Periglacial Processes 16: 327–341, doi:10.1002/ppp.532.

Hinkel, K.M., Jones, B.M., Eisner, W.R., Cuomo, C.J., Beck, R.A., and Frohn, R. 2007. Methods to assess natural and anthropogenic thaw lake drainage on the western Arctic coastal plain of northern Alaska. Journal of Geophysical Research 112, F02S16, doi:10.1029/2006JF000584.

Hopkins, D.M. 1982. Aspects of the paleogeography of Beringia during the late Pleistocene. In: Hopkins, D.M., Matthews, J.V., Schweger, C.E., and Young, S.B., eds. Paleoecology of Beringia. New York: Academic Press. 3–28.

Hughes, O. 1969. Pleistocene stratigraphy, Porcupine and Old Crow rivers, Yukon Territory. Geological Survey of Canada, Paper 69-1:209–212.

———. 1972. Surficial geology of northern Yukon Territory and northwestern District of Mackenzie, Northwest Territories. Geological Survey of Canada, Paper 96-36.

Hughes, O.L., Rutter, N.W., and Clague, J.J. 1989. Yukon Territory (Quaternary stratigraphy and history, Cordilleran Ice Sheet). In: Fulton, R.J., ed. Quaternary geology of Canada and Greenland. Geology of Canada, No 1. Ottawa: Geological Survey of Canada. 58–62.

Jorgensen, M.T., and Shur, Y. 2007. Evolution of lakes and basins in northern Alaska and discussion of the thaw lake cycle. Journal of Geophysical Research 112, F02S17, doi:10.1029/2006JF000531.

Kaufman, D.S., Ager, T.A., Anderson, N.J., Anderson, P.M., Andrews, J.T., Bartlein, P.J., Brubaker, L.B., et al. 2004. Holocene thermal maximum in the western Arctic (0–180˚W). Quaternary Science Reviews 23:529–560, doi:10.1016/j.quascirev.2003.09.007.

Labrecque, S., Lacelle, D., Duguay, C.R., Lauriol, B., and Hawkings, J. Contemporary (1951–2001) evolution of lakes in the Old Crow Basin, northern Yukon, Canada: Remote sensing, numerical modeling and stable isotope analysis. Arctic 62: 225–238.

Lacelle, D. 2002. Ground ice investigation in the far northwest Canada. MSc thesis, University of Ottawa, Ottawa, Ontario.

Lacelle, D., Bjornson, J., Lauriol, B., Clark, I.D., and Troutet, Y. 2004. Segregated-intrusive ice of subglacial meltwater origin in retrogressive thaw flow headwalls, Richardson Mountains, NWT, Canada. Quaternary Science Reviews 23:681–696, doi:10.1016/j.quascirev.2003.09.005.

Lamoureux, S.F., and Bradley, R.S. 1996. A late Holocene varved sediment record of environmental change from northern Ellesmere Island, Canada. Journal of Paleolimnology 16: 239–255.

Lauriol, B., Ford, D., Cinq-Mars, J., and Morris, W.A. 1997. The chronology of speleothem deposition in northern Yukon and its relationships to permafrost. Canadian Journal of Earth Sciences 34:902–911.

Lauriol, B., Duguay, C.R., and Riel, A. 2002a. Response of the Porcupine and Old Crow rivers in northern Yukon to Holocene climate change. The Holocene 12:27–34.

Lauriol, B., Grimm, W., Cabana, Y., Cinq-Mars, J., and Geurtz, M.A. 2002b. Cliff-top eolian deposits as indicators of Late Pleistocene and Holocene climate in Beringia. Quaternary International 87:59–79.

Lemmen, D.S., Duk-Rodkin, A., and Bednarski, J.M. 1994. Late Glacial drainage systems along the northwestern margin of the Laurentide Ice Sheet. Quaternary Science Reviews 13: 805–828.

Lévesque, P.E.M., Kinel, H., and Larouche, A. 1988. Guide to the identification of plant macrofossils in Canadian peatlands. Publication No. 1817. Ottawa: Research Branch, Agriculture Canada. 65 p.

Litchi-Fedorovich, S. 1973. Palynology of six sections of Late Quaternary sediments from the Old Crow River, Yukon Territory. Canadian Journal of Botany 51:553–564.

———. 1974. Palynology of two sections of late Quaternary sediments from the Porcupine River, Yukon Territory. Geological Survey of Canada, Paper 74-23.

MacDonald, G.M., Felzer, B., Finney, B.P., and Forman, S.L. 2000. Holocene lake sediment records of Arctic hydrology. Journal of Paleolimnology 24:1–14.

Mackay, J.R. 1992. Lake stability in an ice-rich permafrost environment: Examples from the western Arctic coast. In: Robarts, R.D., and Bothwell, M.L., eds. Aquatic ecosystems in semi-arid regions: Implications for resource management. National Hydrology Symposium Series 7. Saskatoon, Saskatchewan: Environment Canada. 1–26.

Magny, M. 2004. Holocene climate variability as reflected by mid-European lake-level fluctuations and its probable impact on prehistoric human settlements. Quaternary International 113:65–79.

Martin, A.C., and Barkley, W.E. 1961. Seed identification manual. Berkeley: University of California Press. 221 p.

Matthews, J.V., and Telka, A. 1997. Insect fossils from the Yukon. In: Danks, H.V., and Downes, J.A., eds. Insects of the Yukon. Ottawa: Biological Survey of Canada (Terrestrial Anthropods). 911–962.

Matthews, J.V., Schweger, C.E., and Janssens, J.A. 1990. The last (Koy-Yukon) interglaciation in the northern Yukon: Evidence from Unit 4 at Ch'ijee Bluff Bluefish Basin. Géographie physique et Quaternaire 44:341–362.

Mercier, G. 2002. Identification des macrorestes des remplissages tourbeux d'anciens lacs thermokarstiques. Mémoire de baccalauréat, Département de Géographie, Université d'Ottawa, Ottawa, Ontario.

Michel, F.A., Fritz, P., and Drimmie, R.J. 1997. Evidence of climatic change from oxygen and carbon isotope variations in sediments of a small Arctic lake, Canada. Journal of Quaternary Science 4:201–209.

Mollard, J.D., and Janes, J.R. 1985. Airphoto interpretation and the Canadian landscape. Ottawa: Energy, Mines and Resources Canada. 415 p.

Morlan, R.E. 1980. Taphonomy and archaeology in the Upper Pleistocene of the northern Yukon Territory: A glimpse of the peopling of the New World. Archaeological Survey of Canada, Paper No. 94. 398 p.

Moser, K.A., Korhola, A., Weckstrom, J., Blom, T., Pienitz, R., Smol, J.P., Douglas, M.S.V., and Hay, M.B. 2000. Paleohydrology inferred from diatoms in northern latitude regions. Journal of Paleolimnology 24:93–107.

Murton, J.B. 1996. Thermokarst-lake-basin sediments, Tuktoyaktuk Coastlands, Western Arctic Canada. Sedimentology 43:737–760.

Murton, J.B., and French, H.M. 1994. Cryostructures in permafrost, Tuktoyaktuk Coastlands, Western Arctic Canada. Canadian Journal of Earth Sciences 31:737 – 747.

Norris, D.K. 1981. Geology: Old Crow, Yukon Territory, Geological Survey of Canada Map 1518A.

Osterkamp, T.E.L., Viereck, L., Shur, Y., Jorgenson, M.T., Racine, C., Doyle, A., and Boone, R.D. 2000. Observations of thermokarst and its impact on boreal forests in Alaska, U.S.A. Arctic, Antarctic and Alpine Research 32:303 – 315.

Ovenden, L. 1981. Vegetation history of a polygonal peatland, Old Crow Flats, northern Yukon. MSc thesis, University of Toronto, Toronto, Ontario.

———. 1982. Vegetation history of a polygonal peatland, northern Yukon. Boreas 11:209 – 224.

———. 1986. Vegetation colonizing the bed of a recently drained thermokarst lake (Illisarvik), Northwest Territories. Canadian Journal of Botany 64:2688 – 2692.

Pienitz, R., Smol, J.P., Last, W.M., Leavitt, P.R., and Cumming, B.F. 2000. Multi-proxy Holocene palaeoclimatic record from a saline lake in the Canadian Subarctic. The Holocene 10: 673 – 686, doi: 10.1191/09596830094935.

Plafker, G. 1964. Oriented lakes and lineaments of northeastern Bolivia. Geological Society of America Bulletin 75:503 – 522.

Plug, L.J., Walls, C., and Scott, B.M. 2008. Tundra lake changes from 1978 to 2001 on the Tuktoyaktuk Peninsula, western Canadian Arctic. Geophysical Research Letters 35, L03502, doi:10.1029/2007GL032303.

Rampton, V.N. 1982. Quaternary geology of the Yukon Coastal Plain. Geological Survey of Canada, Bulletin 317. 49 p.

———. 1988. Quaternary geology of the Tuktoyaktuk Coastlands, Northwest Territories. Geological Survey of Canada, Memoir 423. 98 p.

Remenda, V.H., Cherry, J.A., and Edwards, T.W.D. 1994. Isotopic composition of old groundwater from Lake Agassiz: Implications for late Pleistocene climate. Science 2669: 1975 – 1978.

Riordan, B., Verbyla, D., and McGuire, A.D. 2006. Shrinking ponds in subarctic Alaska based on 1950 – 2002 remotely sensed images. Journal of Geophysical Research 111, G04002, doi:10.1029/2005JG000150.

Ritchie, J.C., Cwynar, L.C., and Spear, R.W. 1983. Evidence from north-west Canada for an early Holocene Milankovitch thermal maximum. Nature 305:126 – 128.

Rocheleau, M. 1997. Sédimentologie des paléoplages de la plaine d'Old Crow, Territoire du Yukon, Canada. MA thesis, Department of Geography, University of Ottawa, Ottawa, Ontario.

Rouse, W.R., Douglas, M.S.V., Hecky, R.E., Hershey, A.E., Kling, G.W., Lesack, L., Marsh, P., et al. 1997. Effects of climate change on the freshwaters of Arctic and Subarctic North America. Hydrological Processes 11:873 – 902.

Smith, L.C., Sheng, Y., MacDonald, G.M., and Hinzman, L.D. 2005. Disappearing Arctic lakes. Science 308:1429, doi:10.1126/science.1108142.

Smith, S.L., and Burgess, M. 2002. Permafrost thickness database for northern Canada. Geological Survey of Canada, Open File 4173.

Smol, J.P., and Douglas, M.S.V. 2007. Crossing the final ecological threshold in High Arctic ponds. Proceedings of the National Academy of Sciences of the United States of America 104:12395 – 12397, doi: 10.1073/pnas.0702777104.

Street-Perrot, F.A., and Roberts, N. 1983. Fluctuations in closed lakes as an indicator of past atmospheric circulation patterns. In: Street-Perrott, F.A., Beran, M., and Ratcliffe, R.A.S., eds. Variations in the global water budget. Dordrecht, The Netherlands: Reidel. 331 – 345.

Vardy, S.R., Warner, B.G., and Aravena, R. 1997. Holocene climate effects on the development of a peatland on the Tuktoyaktuk Peninsula, Northwest Territories. Quaternary Research 47: 90 – 104.

Wahl, H.E., Fraser, D.B., Harvey, R.C., and Maxwell, J.B. 1987. Climate of Yukon. Climatological Studies No. 40. Ottawa: Atmospheric Environment Service, Environment Canada. 323 p.

Wolfe, B.B., Edwards, T.W.D., Aravena, R., and MacDonald, M. 1996. Rapid Holocene hydrologic change along boreal treeline, Northwest Territories, Canada. Journal of Paleolimnology 15:171 – 181.

Woo, M.-K. 1996. Hydrology of northern North America under global warming. In: Jones, J.A.A., Liu, C., Woo, M.-K., and Kung, H.-T., eds. Regional hydrological response to climate change. Boston: Kluwer Academic Publishers. 73 – 86.

Yoshikawa, K., and Hinzman, L.D. 2003. Shrinking thermokarst ponds and groundwater dynamics in discontinous permafrost near Council, Alaska. Permafrost Periglacial Processes 14: 151 – 160.

Yu, G., and Harrison, S.P. 1995. Holocene changes in atmospheric circulation patterns as shown by lake status changes in northern Europe. Boreas 24:260 – 268.

Zazula, G.D. 2003. Full-glacial macrofossils, paleoecology and stratigraphy of the Bluefish exposure, northern Yukon. Earth Sciences Occasional Papers, No. 4. Whitehorse, Yukon: Paleontology Program, Government of the Yukon. 143 p.