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Paleoenvironmental Studies in Southwestern Yukon

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ABSTRACT. The St. Elias Mountain region has occupied an important place in the study of the Quaternary because it presents a relatively accessible non-polar icefield and an array of environments from tundra to boreal forest. Paleoenvironmental studies in southwestern Yukon have documented the broad-scale climatic changes of the past 20 000 years, although few studies exist with well-dated sequences at high temporal resolution. *Picea glauca* arrived across the entire region around 10 000 years ago; however, the details regarding its migration pathways are not well known. Available records indicate few major changes in the composition of the boreal forest vegetation since that time. A slightly more intense fire regime in the early to mid Holocene has been suggested, but this conclusion is based on only a few studies. Variations in the tree line during the Holocene have been examined, but these studies also lack details. There is no evidence for more extensive grasslands in the area during the Holocene. Paleolimnological studies indicate that changes in populations of aquatic organisms have occurred in response to either Holocene climates or watershed variability.

Key words: Quaternary, Holocene, boreal forest, Yukon, Kluane Lake, paleoecology, pollen analysis, paleolimnology, climatic change, dendroclimatology, fire history

RÉSUMÉ. La région du mont St. Elias occupe une place importante dans l'étude du Quaternaire parce qu'elle recèle un champ de glace non polaire relativement accessible ainsi qu'une panoplie d'environnements, allant de la toundra à la forêt boréale. Des études paléoécologiques effectuées dans le sud-ouest du Yukon ont permis de documenter les changements climatiques à grande échelle des 20 000 dernières années, et ce, même s'il existe peu d'études dotées de séquences bien datées de grande résolution temporelle. *Picea glauca* est arrivée dans toute la région il y a environ 10 000 ans. Cependant, les détails concernant sa voie de migration ne sont pas bien connus. Les données disponibles indiquent peu de changements majeurs dans la composition de la forêt boréale depuis cette période. Un régime des feux un peu plus intense de l'Holocène inférieur à l'Holocène moyen a été suggéré, mais cette conclusion ne repose que sur un petit nombre d'études. Les variations caractérisant la limite des arbres pendant l'Holocène ont été examinées, mais ces études ne sont également pas suffisamment détaillées. Il n'existe pas de preuve qu'il existait des prairies à plus grande échelle dans la région pendant l'Holocène. Des études paléolimnologiques indiquent que des changements caractérisant les populations d'organismes se sont produits en raison de la variabilité des climats ou dans des bassins hydrographiques de l'Holocène.

Mots clés : Quaternaire, Holocène, forêt boréale, Yukon, lac Kluane, paleoécologie, analyse du pollen, paléolimnologie, changement climatique, dendroclimatologie, historique des feux

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INTRODUCTION

The St. Elias Mountains of southwestern Yukon and adjacent areas have intrigued Quaternary scientists for well over a century. The presence of relatively accessible icefields provided an opportunity to study glacial processes and how they produce landforms and affect the surrounding landscape. The retreat of glaciers exposed land to colonization by plants and thus was of interest to ecologists interested in primary succession. Results from studies in this region therefore informed the interpretation of data from areas deglaciated by the Laurentide Ice Sheet many millennia ago. Southwestern Yukon is the easternmost portion of Beringia, the exposed land mass that formed a land bridge

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between Asia and North America during the full glacial period, allowing humans to colonize North America. The area is therefore of interest for understanding the implications of biogeographic connections between the Palearctic and Nearctic realms. Late glacial and Holocene ecosystem development in this region is of interest in its own right as well. The differences between the boreal forest in southwestern Yukon and other boreal forest communities across Canada, the impact of substantial tephra deposition, the existence of unique grassland communities, the spatial pattern of plant migrations, and the impact of the spruce bark beetle are just a few of the questions that paleoenvironmental studies here can address. Finally, paleoecological studies of the Holocene in this very dry area of the boreal forest may provide information to use as an analogue for future conditions in a biome that is already exhibiting the impacts of anthropogenic climate change.

Glacier studies in the Wrangell-St. Elias Mountain Range, which traverses the Canada-United States border, began more than a century ago (e.g., Russell, 1898; Tarr and Martin, 1914); these early studies presented evidence of fluctuations in glacier margins and discussed their possible causes. In a classic group of studies, Denton and associates (Denton and Stuiver, 1966, 1967; Denton and Karlén, 1973, 1977) examined Holocene glacier variations in the northeastern St. Elias Mountain Ranges and identified alternating periods of glacier advance and retreat, and Denton and Karlén (1973) also discussed corresponding variations in the tree line. More recently, an ice-core record from Mt. Logan identified complex interactions in the climate system (Fisher et al., 2004, 2008). These studies have provided a broad climatic context for paleoecological analyses of the area and indicate that southwestern Yukon can potentially provide key paleoclimate details, but they have left many questions unanswered. For example, from their interpretation of the $\delta^{18}O$ variations from the Mt. Logan ice cores and Jellybean Lake sediments, Fisher et al. (2004) concluded that ~AD 800 corresponds to the beginning of the Medieval Warm Period in the region and that the Little Ice Age ended around AD 1840. However, the timing and nature of the transition between major climatic regimes throughout the Holocene and the spatial patterns of climate variability and impacts across the region require further study. Paleoenvironmental studies from lake sediments and from tree-ring records have begun to provide some answers.

Southwestern Yukon is in the boreal forest biome, which is a relatively uniform and low-diversity vegetation association across all of northern North America (La Roi, 1967). Botanical studies such as those by Johnson and Raup (1964) and others summarized by Cody (1996) have illustrated the ranges of the major boreal tree taxa in southwestern Yukon and documented the low diversity, even compared to other areas of boreal forest, of the forests in the Shakwak Trench and Dezadeash regions. Both the absence of lodgepole pine (*Pinus contorta*), black spruce (*Picea mariana*), and larch (*Larix laricina*) from the Shakwak Valley and the rare occurrence of white birch (*Betula papyrifera*) and alder (*Alnus* spp.) throughout the region are phenomena that require explanation. Paleoecological studies could provide insight into these and other biogeographic questions raised by earlier studies.

This paper summarizes paleoenvironmental studies in southwestern Yukon. It is geographically restricted to the region centered on Kluane Lake and the Shakwak Trench and concentrates on data collected along or near the Alaska Highway and Haines Road (Fig. 1). The study area extends westward to the Alaska border, eastward to the Whitehorse region, and northward to the areas of Beaver Creek and Carmacks. We will include some discussion of northernmost British Columbia to the south.

Radiocarbon dating is the major method used to determine the ages of Holocene and late Pleistocene deposits. Radiocarbon ages are not the same as calendar ages unless they are calibrated using standard calibration curves (Reimer et al., 2004, 2009). Calibrated radiocarbon dates are designated as cal yr BP (calibrated years before present), with AD 1950 used by convention as the base year (i.e., year zero). In this paper, we will use cal yr BP, ka (1000 years before present), or AD or BC, as appropriate.

METHODS

Paleoenvironmental methods are largely standardized, permitting the comparison and synthesis of results across studies. The basic data are obtained from sediment cores collected in lakes or from wetlands. The cores are subsampled at intervals, and properties or components of the cores are measured or extracted. Typically small samples are taken; microfossils, such as pollen, chironomids, diatoms or ostracodes, are extracted using a standard protocol and mounted on microscope slides, and the organisms are identified and counted. Dates are derived from several depths in the cores using radiocarbon or ^{210}Pb dating methods, and age-depth relations are used to develop the chronology. The result is a time series depicting the changes in organism abundance at the site over time, and these changes can be interpreted in paleoecological or paleoenvironmental terms. Recent methodological advances are providing better dated, more detailed, and more robust characterizations of past environments. Older studies, while still valuable for understanding general patterns, are being superseded by new studies that use these innovations.

Paleoenvironmental reconstructions are based on knowledge of the environmental requirements of the proxy organisms used to formulate them. The ecological requirements of organisms found as fossils in lake sediments can be determined from modern calibration datasets. These datasets are derived from a geographically dispersed series of lakes that span the range of environmental conditions expected over the time period of interest, in this case the late glacial (~15 – 11 ka) and Holocene (last 11 700 cal yr BP). Both the surface sediment (the uppermost centimetres) and various aspects of the environment, such as water chemistry,

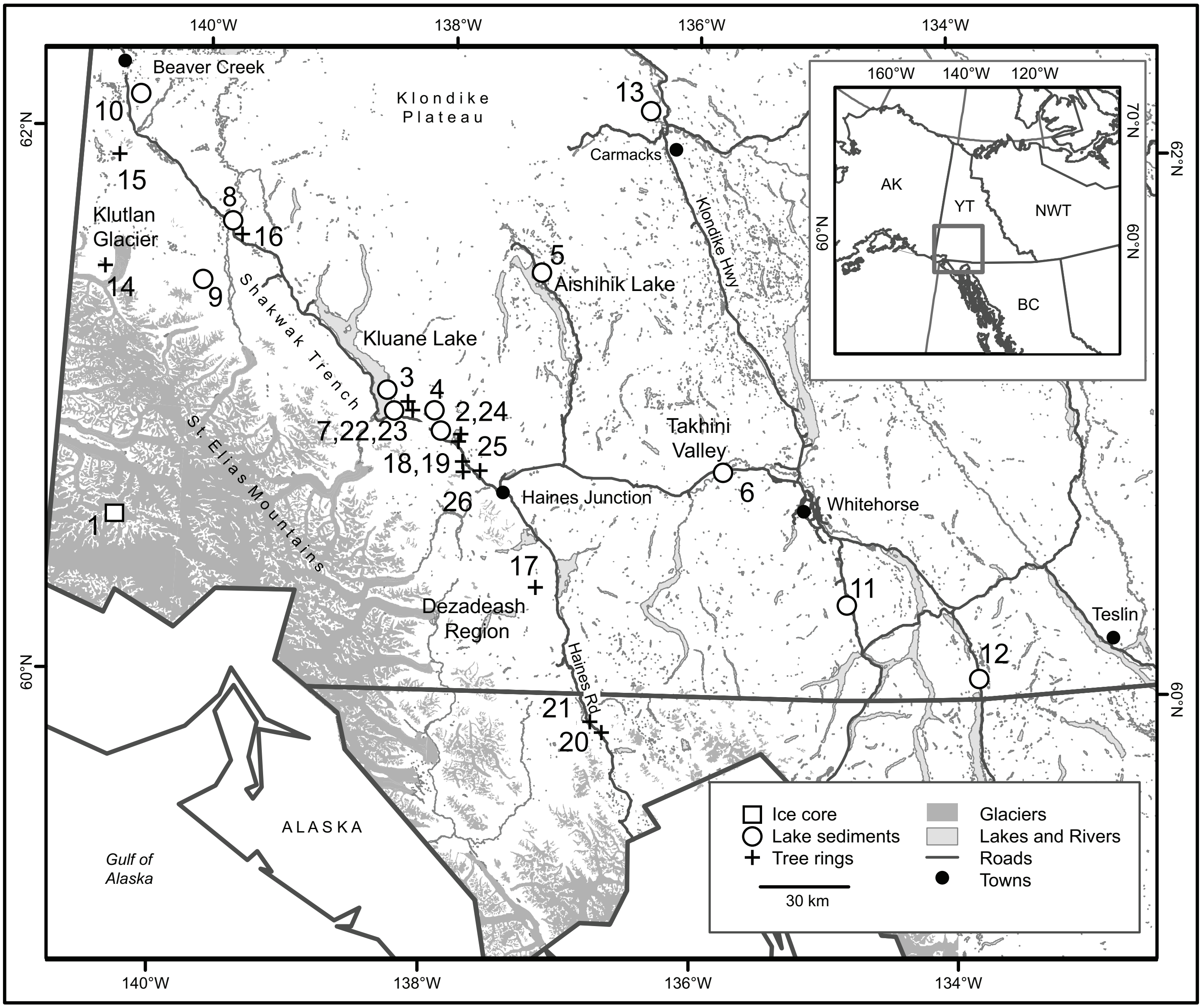

FIG. 1. Map of southwestern Yukon showing location of sites discussed in the text. Numbers correspond to site names in Table 1.

climate, and landscape characteristics, are sampled in or at the series of lakes. Statistical relationships are then derived between the presence and abundance of microorganisms (the proxies) extracted from the sediments and the environmental variable or variables that best explain the distributions of these organisms across a region. These statistical parameters (called transfer functions) are used in turn to estimate (reconstruct) the environmental variables in the past from the fossil assemblages of these organisms isolated from the core. The derivation of these statistical relationships is not straightforward, and much research has been done to ensure that the reconstructions are valid. For example, from the study area, Bunbury and Gajewski (2008) showed that interannual variability in lake water chemistry had secondary effects on these statistical relationships, and that the between-lake differences in chemistry were the primary factor calibrated using the statistical relations.

RESULTS AND DISCUSSION

Modern Studies for Interpreting Paleoenvironmental Data

Modern organism assemblages from southwestern Yukon, including pollen (Birks, 1977; Lacourse, 1998; Whitmore et al., 2005), diatom (Wilson and Gajewski, 2002), chironomid (Wilson and Gajewski, 2004), and ostracode (Bunbury and Gajewski, 2005) assemblages, have also been analyzed in relation to the environment. Several characteristics of the lake environment (e.g., water depth, organic matter content of the sediments, and water chemistry) affect the composition of the species assemblages found in these lakes. The transfer functions derived using these data, in combination with those from other studies, have been applied successfully to fossil assemblages to reconstruct past environments in lakes of southwestern Yukon.

TABLE 1. Site number, site name, and reference for sites shown in Figure 1 and mentioned in the text.

Site no.	Site name	Reference
1	Mt. Logan	Fisher et al., 2008
2	Sulphur Lake	Lacourse, 1998; Lacourse and Gajewski, 2000
3	Keyhole Lake	M. Vetter, unpubl. data; Whittmire, 2001
4	Upper Fly Lake	Bunbury and Gajewski, 2009a, 2012
5	Long Last Lake	Keenan and Cwynar, 1992
6	Two Horsemen Lake	Keenan and Cwynar, 1992
7	Jenny Lake	Stuart et al., 1989; Bunbury and Gajewski, 2012
8	Donjek Kettle	Bunbury and Gajewski, 2012
9	Lake WP02	Bunbury and Gajewski, 2012
10	Antifreeze Pond	Rampton, 1971; Vermaire and Cwynar, 2010
11	Jellybean Lake	Anderson et al., 2005, 2007
12	Marcella Lake	Anderson et al., 2007
13	Seven Mile Lake	Anderson et al., 2011
14	Wolverine Plateau	Cropper and Fritts, 1981; W.E.S. Henock and M.L. Parker, unpubl. data
15	Hazel Creek	Davi et al., 2003
16	Donjek Bridge	Schweingruber et al., 1992; Briffa et al., 1993
17	Kathleen Lake	Schweingruber et al., 1992; Briffa et al., 1993
18	BeFT	Ayotte, 2002
19	BeF	Ayotte, 2002
20	TaFT	Ayotte, 2002
21	TaF	Ayotte, 2002
22	Jenny Lake	Zalatan, 2002; Zalatan and Gajewski, 2005
23	Christmas Creek	Zalatan, 2002; Zalatan and Gajewski, 2005
24	Sulphur Lake	Zalatan, 2002; Zalatan and Gajewski, 2005
25	Kloo Lake	Zalatan, 2002; Zalatan and Gajewski, 2005
26	Haines Junction	Zalatan, 2002; Zalatan and Gajewski, 2005

An interdisciplinary study of the Klutlan Glacier area by researchers from the University of Minnesota documented the processes of moraine formation and ecosystem development immediately following deglaciation (Wright, 1980). The study was motivated by attempts to interpret late Pleistocene landforms and lake sediment cores from Minnesota, which had revealed puzzling aspects related to the origin of the lakes and the nature of the basal sediments. Studies of the modern vegetation and pollen deposition (Birks, 1977, 1980a), as well as the limnology of several lakes (Whiteside et al., 1980), provided a means to interpret pollen (Birks, 1980b) and paleolimnological sequences (Bradbury and Whiteside, 1980) on moraines of the Klutlan Glacier area (Driscoll, 1980a, b; Watson, 1980; Jacobson and Birks, 1980). These studies provided insight into landscape evolution on stagnant ice, although they are imperfect analogues to the situation south of the Laurentide Ice Sheet in late glacial times.

Full-Glacial and Late Glacial Conditions in Beringia

Yukon comprises the easternmost portion of the Beringian Region, an area that was mostly unglaciated during the Wisconsinan. Because sea levels were lower during much of the glacial period, this land area was much larger than at present, and it formed a connection between Asia and North America along which humans traveled to colonize the Americas. Differing interpretations of paleontological and paleoecological studies led to a long controversy about the nature of the Beringian environment during the full glacial, a controversy centred on the difference between tundra-type and steppe environments. The nature of the Beringian environment has been the subject of numerous articles, books, and synthesis volumes (e.g., Hopkins et al., 1982; Brigham-Grette and Elias, 2001; Blinnikov et al., 2011).

The climate during the transition between the full glacial (~20 – 15 ka) and the Holocene has recently been synthesized using all available pollen diagrams from the region; past climates were calibrated using the modern analogue method (Viau et al., 2008). These results broadly resemble those obtained from oxygen isotopes extracted from the Logan Ice Core (Fisher et al., 2008). In southwestern Yukon, there is evidence of warming beginning around 12 000 cal yr BP and continuing until approximately 8000 cal yr BP (Fig. 2). Across all of Beringia, the full glacial was cold and dry, and there is a suggestion of maximum temperatures and precipitation, in at least some seasons, in the early Holocene (Viau et al., 2008).

The area of Kluane Lake was covered with ice during the full glacial, and only the westernmost part of our study area, near the Alaskan border, contains full glacial records. Rampton (1971) prepared a pollen diagram from Antifreeze Pond in the unglaciated zone, which showed significantly cooler temperatures during the full glacial. More recently, Vermaire and Cwynar (2010) analyzed a new core from the same site and another pond nearby; they re-dated the sediments, using accelerator mass spectrometry (AMS) on macrofossils extracted from the sediment, which should provide more reliable ages. The cores from the lake spanned at least the past 20 000 years, but deeper sediment could not be reliably dated; thus, high spruce pollen and macrofossils in basal sediments may represent a warm period during Wisconsinan times, but the timing is unclear. The pollen and macrofossil record does, however, provide a detailed record of the nature of the late glacial and Holocene environment of the area. During the late glacial, the area supported herbaceous tundra. The lake was relatively unproductive, with a high sedimentation rate caused by a large influx of inorganic matter.

It is generally assumed that spruce and other trees migrated into the Shakwak Trench area from the east after the Mackenzie valley corridor opened up and Cordilleran ice melted away. However, recent work suggests that *Picea*, *Populus*, and other trees survived the glacial period in Alaska (Brubaker et al., 2005; Anderson et al., 2006) and northern Yukon (Zazula et al., 2006). This survival has implications for understanding the arrival of trees in the study area, as they could have migrated into the Kluane area from any direction.

Postglacial Vegetation History

Major climate variations in southwestern Yukon were identified by records of glacier fluctuations (Denton and Stuiver, 1966, 1967; Denton and Karlén, 1973, 1977); this influential work illustrated Holocene (interglacial) climate variability and suggested an alternation between warm and cold periods every 2500 years. Using similar studies, these results were extrapolated to the entire world, although there was some controversy over whether glacier fluctuations were in fact synchronous worldwide. Global asynchronicity leaves open the question of a climatic control on glacier fluctuations and suggests that perhaps local dynamics could be more important (Grove, 1979).

The glacial fluctuation results provide a context within which to interpret paleovegetation records, which are provided by studies of the fossil pollen assemblages from lake sediments. Since records from lake sediments are continuous (unlike those from glacier fluctuations) and lake distribution is spatially extensive (lakes can be located away from ice sheets and are widely distributed at lower altitudes, as well as on upper parts of the mountains), they provide important information about past environments throughout the region. Past climates can also be quantified by applying transfer functions to fossil pollen assemblages from lake sediments (e.g., for this area, Viau et al., 2008; Viau and Gajewski, 2009). Previous reviews of the paleoecology of southwestern Yukon include Ritchie (1985, 1987), Wang and Geurts (1991), and Cwynar and Spear (1995).

After the Second World War, the Alaska Highway permitted easier access to the area, which allowed researchers such as Hansen (1953) to analyze numerous peat deposits along the route. These sections were not dated, as radiocarbon dating had just been proposed at that time but was not well developed. Peat sections between Whitehorse and approximately Haines Junction and south of Haines Junction along the Haines Road contained both *Pinus* and *Picea* pollen (and occasional *Abies* grains), whereas in sections between Milepost 1000 and the Alaska border, only small amounts of pollen other than spruce were found. Hansen interpreted the pine pollen from the Haines Road as originating from coastal regions, given the absence of pine in the area today. The pollen records from the mostly short peat sections provide little information; in some cases, all

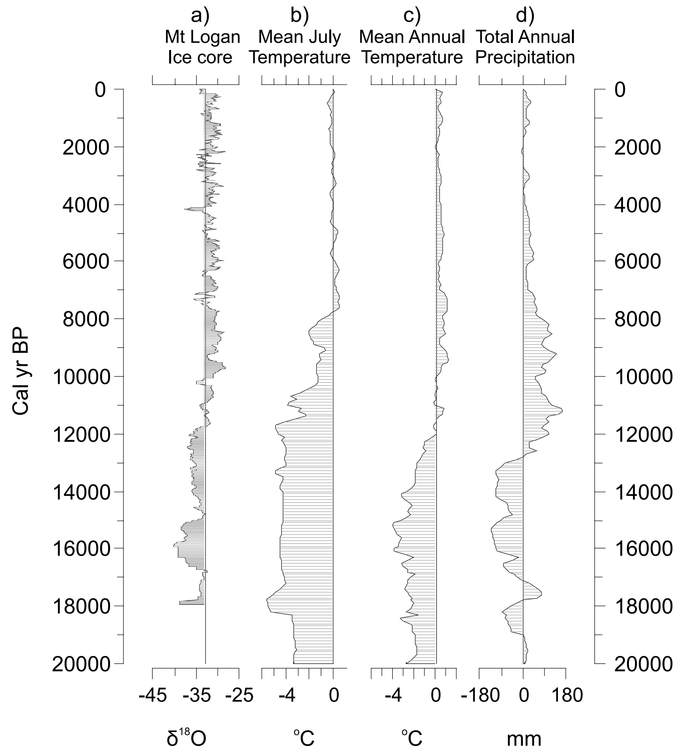

FIG. 2. Climate of southwestern Yukon from the full glacial to the present. a) Oxygen isotope ratios from Mt. Logan ice core from Fisher et al. (2008), b) pollen-based mean July air temperature anomalies (from present) for southwestern Beringia (60˚–65˚ N; 125˚–150˚ W), c) eastern Beringia (Alaska and Yukon) mean annual air temperature anomalies, and d) eastern Beringia total annual precipitation anomalies (Viau et al., 2008).

of the pollen was from spruce. Interestingly, some sections south of Teslin showed the continuous deposition of grass pollen; Hansen (1953) remarked on this, but reached no conclusions. A number of other pollen profiles, many from poorly dated peat profiles and available only in unpublished theses, have been summarized by Wang and Geurts (1991).

From the Kluane Lake region, Stuart et al. (1989), Lacourse and Gajewski (2000), Bunbury and Gajewski (2009a), and Whittmire (2001) presented pollen records from Jenny Lake, Sulphur Lake, Upper Fly Lake (at the tree line), and Keyhole Pond, respectively. Data from the Aishihik region are available from Wang and Geurts (1991), Keenan and Cwynar (1992), and Ravindra (2009). Across the entire area, the pollen diagrams broadly resemble each other (Fig. 3). Prior to 8.5 ka, most pollen diagrams show a period of high *Betula* percentages, along with nonarboreal pollen (NAP) including *Artemisia* and Poaceae (Gramineae) (Stuart et al., 1989; Wang and Geurts, 1991; Keenan and Cwynar, 1992; Lacourse and Gajewski, 2000). Maximum *Betula* and NAP percentages are found prior to 10 ka, with a transition zone that includes peaks in *Populus* or *Juniperus* pollen or both at many, but not all, sites. This whole period is interpreted as a tundra-type environment, although the presence of large quantities of *Populus* and *Juniperus* pollen suggests a situation different from tundra systems of today (Peros et al., 2008). All sites record a major increase in *Picea* (mostly white spruce, *P.*

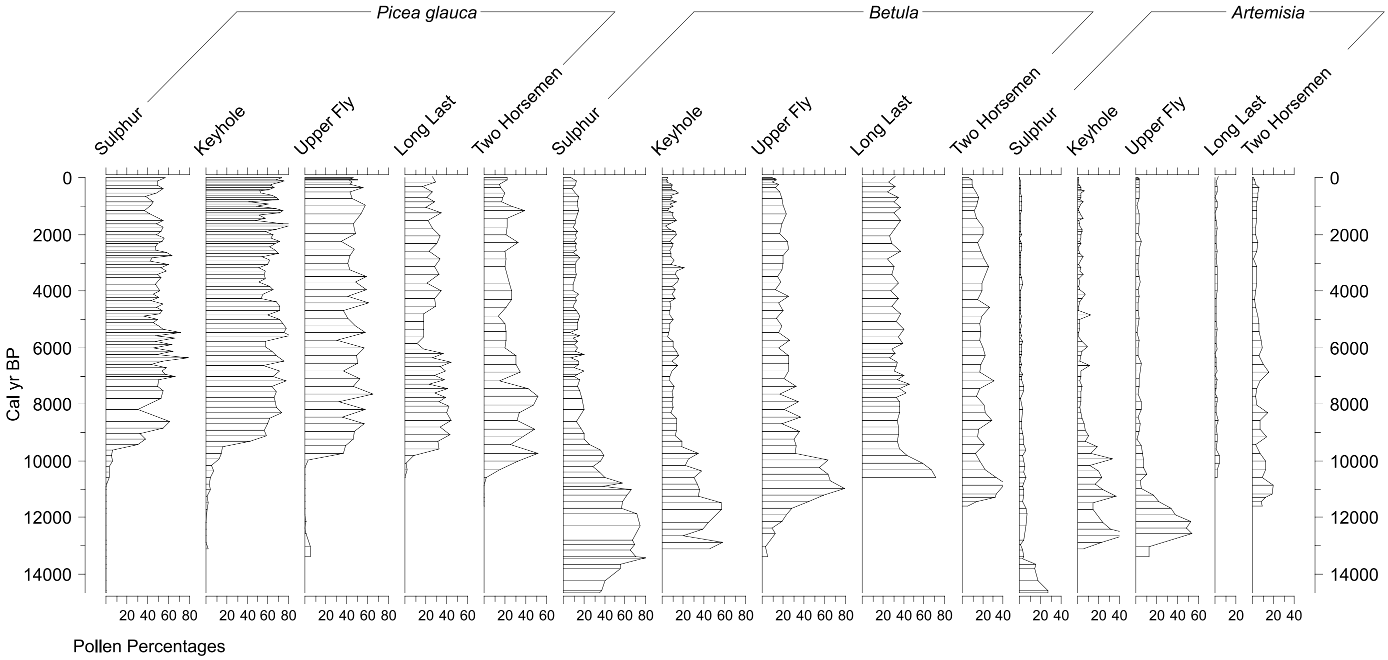

FIG. 3. Summary of pollen records from southwestern Yukon. Sources for pollen data are Sulphur Lake: Lacourse and Gajewski, 2000; Upper Fly Lake: Bunbury and Gajewski, 2009a; Keyhole Lake: M.A. Vetter, unpubl. data; Two Horsemen and Long Last Lakes: Keenan and Cwynar, 1992.

glauca) between approximately 10 and 9 ka. Given the possible errors associated with the chronologies, this increase appears to be synchronous across the region and to record a warming period that permitted the survival of spruce. Keenan and Cwynar (1992) discuss the history of spruce in the region in more detail. *Picea* pollen remained dominant through the mid to late Holocene, with little variability, consistently among sites (Fig. 3).

Alnus is rarely found on the landscape in the Kluane region today. The low percentages of *Alnus* in pollen diagrams from the area could indicate long-distance transport, and these diagrams therefore record an increase in alder pollen from outside of the region. At 6 ka, *Alnus* pollen increased elsewhere across southern Yukon (Cwynar and Spear, 1995). *Alnus* pollen percentages increased at the expense of *Picea* at sites in southwestern Yukon as well (5 ka at Jenny, Keyhole, and Long Last Lakes around 7–5 ka; but again, the dating is not secure) and remained relatively high until the past 2 ka (Stuart et al., 1989; Wang and Geurts, 1991; Keenan and Cwynar, 1992; Cwynar and Spear, 1995; Lacourse and Gajewski, 2000). At Jenny Lake, this increase in *Alnus* was interpreted as spruce-alder woodland (Stuart et al., 1989), but given the low values of *Alnus* pollen and the lack of *Alnus* shrubs in the area today, this interpretation seems unlikely. *Picea mariana* (black spruce) pollen increased in abundance at the same time at a site southwest of Whitehorse, before decreasing again around 4 ka (Cwynar, 1988). A similar sequence was observed in Long Last Lake in the northern Aishihik region, although at much lower percentages, which may reflect long-distance transport from sources to the east (Keenan and Cwynar, 1992). During the past 1.5–2 ka, Poaceae increased in the Aishihik region (Wang and Geurts, 1991; Keenan and Cwynar, 1992); *Alnus* decreased in Jenny Lake, and *Picea* pollen increased.

A pollen diagram from Upper Fly Lake, located at the tree line just to the east of Kluane Lake, shows similar changes in *Alnus*, *Picea*, and Poaceae (Bunbury and Gajewski, 2009a). Tree line movements during the Holocene were not obvious in this pollen record, but Rampton (1971) found spruce logs buried by the White River Ash in alluvial fans at elevations above the present tree line, providing evidence that the alpine tree line was higher at some times in the past. Using pollen records to identify tree line movements in alpine areas is not easy, as Bunbury and Gajewski (2009a) discuss, because pollen grains are transported both upslope and downslope, and pollen influx, although potentially aiding in the interpretation, is difficult to estimate and calibrate. Certainly, the issue of past tree line movements in the area is not resolved.

Keenan and Cwynar (1992) prepared two pollen diagrams, one from the Takhini Valley along the Alaska Highway and a second from a site to the east of Aishihik Lake, to determine whether grasslands were more extensive in the early Holocene, as proposed by Johnson and Raup (1964). Small grasslands are common in the area (Johnson and Raup, 1964; Vetter, 2000), but neither the results of their studies, nor other pollen diagrams from the area, provide evidence that grasslands were more abundant in the early or mid Holocene. Modern studies of the grasslands and their distributions in the Aishihik and Kluane areas (Vetter, 2000, unpubl. data) indicate a strong topographical control on grassland distribution. Floristic studies have suggested some relationship with grasslands found elsewhere in the boreal forest, which perhaps is due to greater extent of grasslands during the full glacial (Vetter, 2000). More work

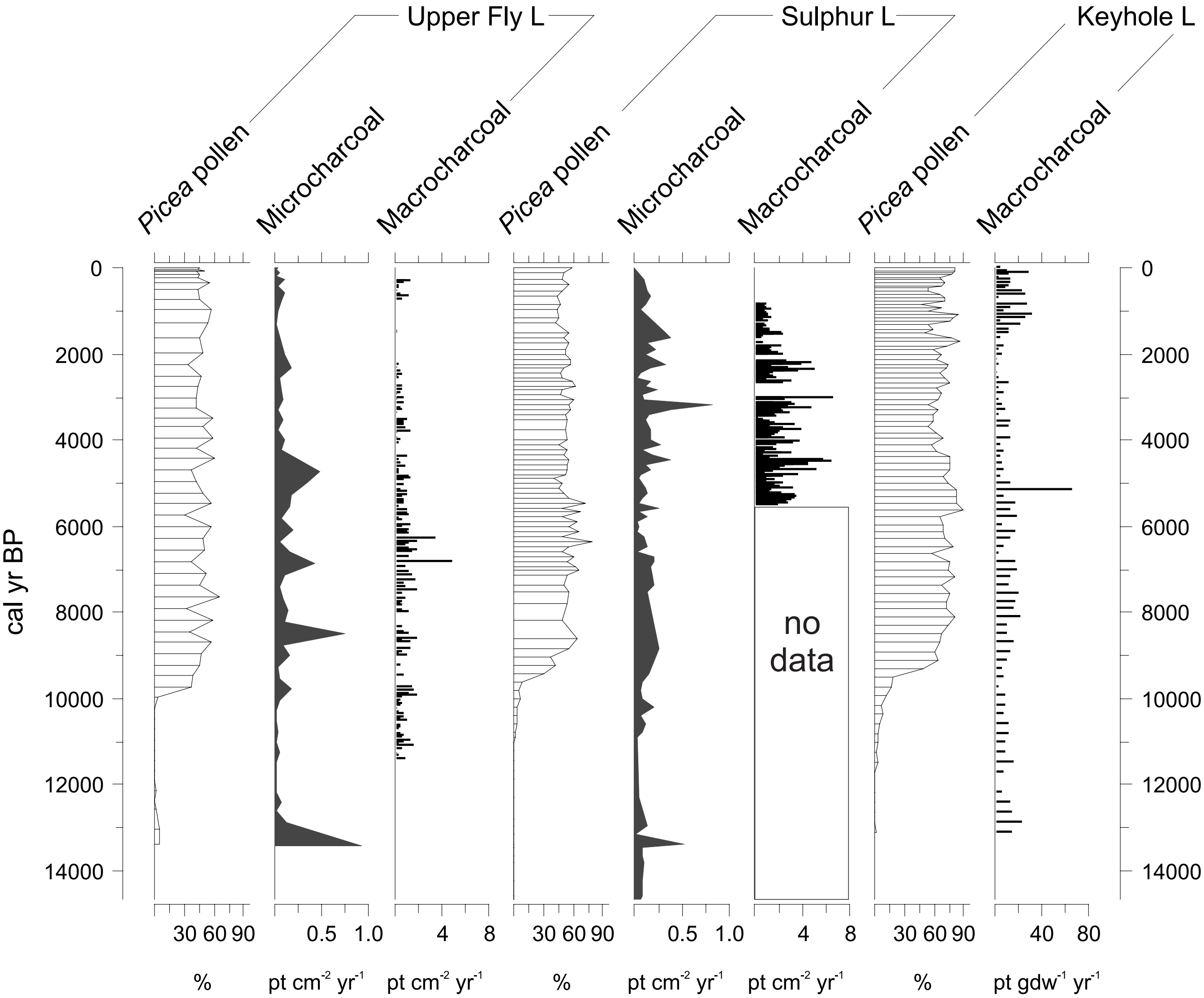

FIG. 4. Charcoal records from southwestern Yukon. Microcharcoal concentrations are from pollen slides and should indicate regional fire regime trends; macrocharcoal concentrations are based on sieved sections and should indicate local fires. Units for charcoal results are particles • cm^{-2} • yr^{-1} or particles • gram dry $weight^{-1}$ • yr^{-1}.

remains to be done on the distribution and development of these grasslands in late glacial and Holocene times.

Fires are an important component of the dynamics of boreal forest vegetation, and variations through time in the charcoal extracted from lake sediments provide information about changes in the fire regime. Charcoal abundance is determined from the same slides on which pollen is identified (microcharcoal) or counted as particles sieved directly from samples of lake sediment (macrocharcoal). Microcharcoal abundance is interpreted as an index of the regional fire regime, because small charcoal particles can be dispersed over large distances, whereas macrocharcoal abundance is interpreted as indicating the local fire history surrounding the site (Whitlock and Larsen, 2001). In this region, both microcharcoal and macrocharcoal records are available from Sulphur and Upper Fly Lakes, and macrocharcoal abundance is available from Keyhole Pond (Fig. 4). Maximum charcoal values are found between approximately 9 ka and 5 ka and correspond to high values of *Picea* pollen in the records. Further high-resolution analysis of fire history from charcoal records may provide insights into grassland history, relationships between fire and climate, and boreal forest vegetation dynamics.

Paleolimnology of the Kluane Region

There are still few paleolimnological records from the Kluane region, but a detailed multi-proxy paleoenvironmental reconstruction from Upper Fly Lake illustrates the potential of these studies (Bunbury and Gajewski, 2009a). Upper Fly Lake is today at the tree line, with only a few spruce growing on the surrounding slopes. In addition to making a detailed analysis of the sediment, we analyzed pollen, chironomids, and ostracodes from the core.

Prior to 10 000 cal yr BP, *Artemisia*, *Betula*, *Salix*, and other herbaceous taxa dominated the pollen assemblages, along with cold-tolerant chironomids. Paleoclimate reconstructions based on pollen and chironomids showed an increase in temperature between 11 000 and 10 000 cal yr BP. This post-Younger Dryas warming may have caused an increase in vegetation density on the slopes surrounding the lake. Ostracodes were present in the lake soon after its formation, but they disappeared around 10 000 cal yr BP, when *Picea* pollen increased greatly. An increase in organic matter input to the lake and a decrease in carbonate content during this transition are interpreted as a decrease in pH, and this change in the lake chemistry may have caused the extinction of ostracodes from this ecosystem. Although *Picea* dominated the pollen assemblages for the remainder of the core, values during the past 10 000 years are comparable to those found today, showing little indication of any tree line movement. In the past 4000 years, temperature decreased, water depth increased, and chironomid accumulation rates increased (suggesting greater chironomid production). Fisher et al. (2008) suggest that modern-day ENSO patterns may have been established during this period.

Holocene Paleoclimates

Estimates of Holocene temperature and precipitation variability at Upper Fly Lake have been discussed above, and the record from Mt. Logan is discussed by Fisher et al. (2004, 2008). One interesting aspect of the Upper Fly Lake record is the timing of the highest *Artemisia* pollen percentages between 12 600 and 11 700 cal yr BP, which corresponds roughly to the well-known Younger Dryas (YD) cold interval. The spatial pattern of this climate oscillation in Beringia was reviewed by Kokorowski et al. (2008), who noted that many sites have insufficient resolution or dating density to contribute to our understanding of this time period. Although records for many sites in southern Alaska indicate cooling during this time, in southeastern Alaska some records are ambiguous. Although present in lake and marine records of the Pacific Northwest (Lacourse, 2007), and just to the east of the study area (Cwynar, 1988), evidence for this period was not apparent in the Logan ice core (Fisher et al., 2008) or in Beringian pollen-based regional reconstructions (Viau et al., 2008). At Upper Fly Lake, this period is marked by cold temperatures centered between 12 000 and 11 000 cal yr BP in the chironomid and pollen-based reconstructions. In lowland sites with long enough records, *Betula* pollen percentages were elevated during this time, although such high percentages are not restricted to the same time interval at Sulphur or Keyhole Lakes.

An increase in *Alnus* pollen percentages at many sites in southern Yukon around 6 ka is interpreted as an increase in available moisture (Cwynar and Spear, 1995). Although *Picea mariana* also increased at some sites in the Aishihik region around that time (e.g., Keenan and Cwynar, 1992), *Picea* populations in the Kluane region were not greatly affected (Lacourse and Gajewski, 2000).

Oxygen isotope records from sediments of Marcella Lake and Jellybean Lake to the east of our region and Seven Mile Lake located near Carmacks to the northeast (Anderson et al., 2005, 2007, 2011; Fig. 1) indicate an increase in moisture between 3000 cal yr BP and AD 1600, followed by drier conditions. It is hypothesized that these drier conditions were caused by variations in temperature and precipitation arising from changes in the position and intensity of the Aleutian Low Pressure System in the Gulf of Alaska.

Late Holocene Paleoclimates

Paleoenvironmental studies of the past 2000 years are particularly important, as these permit us to understand the natural climate changes and long-term ecosystem variability in a period with climate conditions similar to those of today, but without the significant impact of human industrial activities. For studies of this time period, tree-ring analyses provide annually resolved paleoclimate records, and ice core and lake sediment records can also be studied at high temporal resolution. For example, Bunbury and Gajewski (2012) reconstructed temperatures of the past 2000 years at four sites in the region using chironomid assemblages.

Some studies have sufficiently high resolution for the last millennium to identify the nature of climate variability during the Little Ice Age and Medieval Warm Period. For example, in the Bear Creek region near Haines Junction, regeneration in the forest-tundra was low from the late 1800s to the mid 1900s, but it has been increasing since the 1920s (Ayotte, 2002). In the 1950s, there was an acceleration in seedling establishment rate, radial growth trends (Fig. 5), and vertical growth of pre-established krummholz individuals above snow level. Tree growth seems to be influenced by summer temperatures of the current growing season.

Several tree-ring series from southern Yukon (Fig. 5) are available from the International Tree-Ring Data Bank (ITRDB) (Cropper and Fritts, 1981; NOAA – NCDC, 2012). Briffa et al. (1992), Schweingruber et al. (1993), and Gajewski and Atkinson (2003) examined these series in relation to other data from northern North America. Other series include chronologies from the tree line (Ayotte, 2002) and the forest interior (Zalatan and Gajewski, 2005), and all sites show common trends that can be associated with regional-scale climate impacts on tree growth. Tree growth was lower at most sites in the late 19th century and increased during the 20th century. In addition, decadal growth trends above or below the mean are frequently in phase among sites; for example, many of the series show increased growth during the 1940s. Youngblut and Luckman (2008) used seven tree-ring chronologies from several alpine locations to reconstruct mean June-July temperatures in the region for the last 300 years. Temperatures were generally cooler between AD 1650 and the late 1800s, although there were brief periods of relatively warm temperatures in the late 1700s at most sites and around AD 1850 and AD 1880 at some sites. In the 20th century, temperatures were warm at all sites.

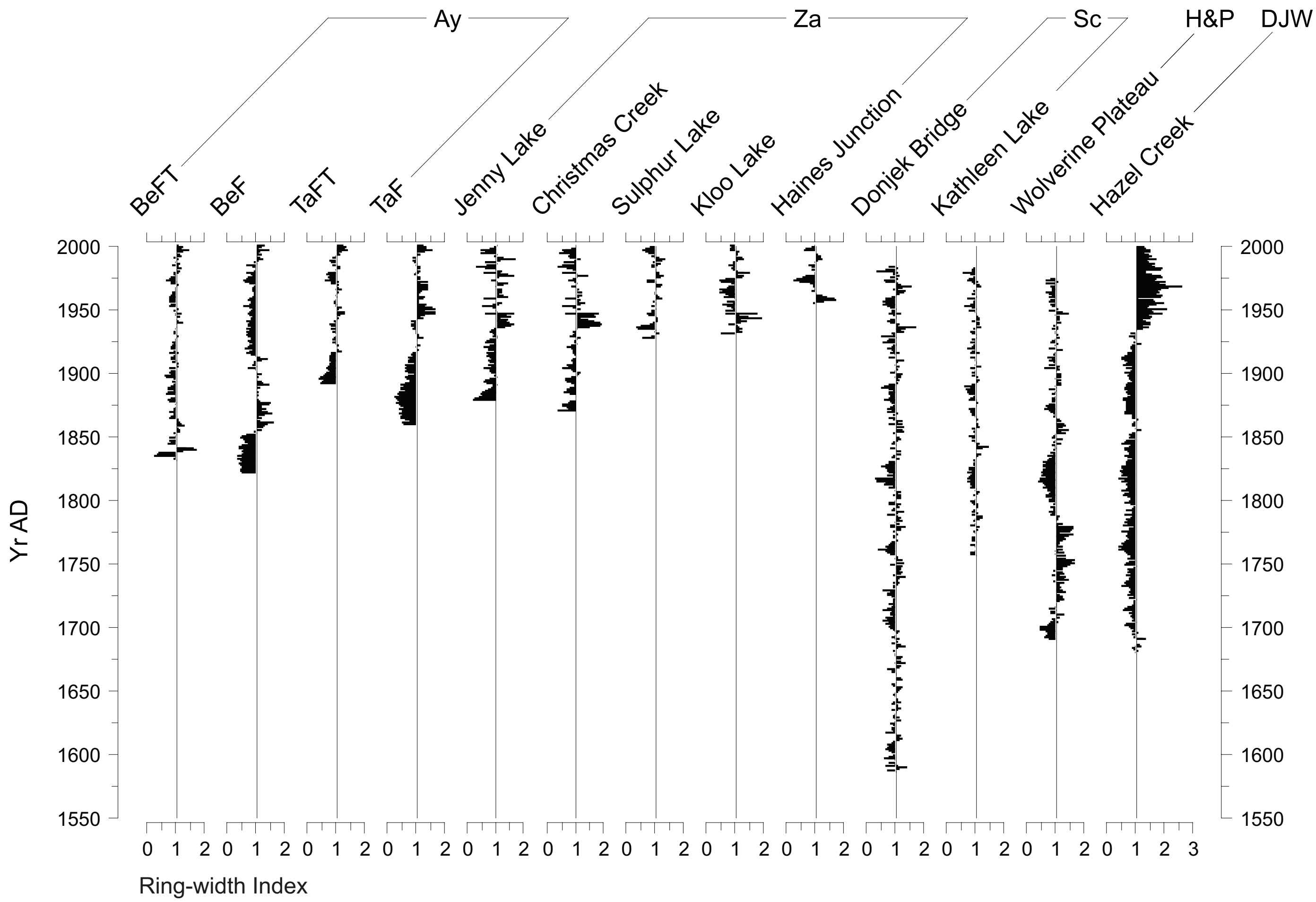

FIG. 5. Late Holocene tree-ring records from the Kluane Lake region are available from the ITRDB (www.ncdc.noaa.gov/paleo). Other series mentioned in Cropper and Fritts (1981) are either not in the database or available only as tree-ring measurements and not as chronologies. Other data are available on www.lpc.uottawa.ca. Sources are Ay: Ayotte (2002); Za: Zalatan (2002) and Zalatan and Gajewski (2005); Sc: Briffa et al. (1992) and Schweingruber et al. (1993); H&P: Henock and Parker (unpubl. data) and Cropper and Fritts (1981); DJW: Davi et al. (2003). Data are rescaled.

Other Paleoecological Studies

Paleoenvironmental studies have been completed in the context of geomorphological research in the area. Lake sediments can also be used to study past seismic activity (Doig, 1998) or water-level variations. Buried tree stumps in several areas of Kluane Lake attest to recent major changes in the water level (Bostock, 1969), and a study of Kluane Lake (Clague et al., 2006; Brahney et al., 2008) showed that glacier fluctuations have important effects on the location and altitude of the outlet, and thereby, on the water level. The White River Ash event (Bunbury and Gajewski, 2009b) had a stronger effect on aquatic communities at sites nearer to its source, with impacts lasting several decades (Bunbury, 2009; Bunbury and Gajewski, 2013).

SUMMARY

After several decades of research in southwestern Yukon, we are beginning to understand the broad-scale climate and vegetation history of the region. In spite of the interest and relative accessibility of the region, surprisingly few studies have actually been accomplished, and many of the older studies do not provide information of interest for present-day questions. The boreal forest, established around 10 000 years ago, has not varied greatly over time; but it is not yet clear whether this stability is due to a relatively steady climate or to resilient vegetation. Certainly, climate variability has affected the ecosystems during the past 10 000 years. For example, 10 000 years ago a warming climate made the region hospitable for the growth of spruce, which arrived across the entire region nearly simultaneously. However, we are only beginning to understand how this warming affected terrestrial and aquatic ecosystems. For example, the extinction of ostracodes in Upper Fly Lake can be temporally associated with this warming, or the accompanying watershed-level changes, or both, but details of the ecosystem-level changes at that time are not clear. It is also not known whether this kind of event was spatially extensive or occurred only on portions of the landscape.

Small grasslands observed throughout the region seem edaphically and not climatically controlled, but questions generated by floristic similarities and differences among grasslands scattered throughout western boreal forest regions remain. The lack of black spruce and larch, which today do not occur in the Shakwak Trench but are found in nearby areas, is probably due to the relative dryness in the trench caused by the pronounced rainshadow, but spatio-temporal variations in temperature and moisture over the Holocene are not entirely understood. Spatial patterns of past climates have not yet been clarified, nor have tree line variations through the Holocene been fully resolved: the pollen record suggests little movement of the tree line, but the macrofossil record says these movements have occurred. Paleolimnological studies have only begun, and we can make no generalization about the history of the freshwater ecosystems of the region during the Holocene. Thus, many opportunities remain to use paleo-studies in such regions to improve our understanding of ecosystem functioning in boreal regions in relation to past climate variability and our ability to predict what may happen in the future.

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