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HOLOCENE ENVIRONMENTAL VARIABILITY INFERRED FROM LAKE SEDIMENTS, SOUTHWEST YUKON TERRITORY, CANADA

JOAN BUNBURY

Thesis submitted to the Faculty of Graduate and Postdoctoral Studies
In partial fulfillment of the requirements for a
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HOLOCENE ENVIRONMENTAL VARIABILITY INFERRED FROM LAKE SEDIMENTS, SOUTHWEST YUKON TERRITORY, CANADA

Abstract

Lake sediment cores collected from four lakes (Upper Fly Lake 61.04°N, 138.09°W, 1326 m a.s.l.; Jenny Lake 61.04°N, 138.36°W, 817 m a.s.l.; Donjek Kettle 61.69°N, 139.76°W, 732 m a.s.l.; Lake WP02 61.48°N, 139.97°W, 1463 m a.s.l.) in the southwest Yukon provide records of postglacial climatic variability in the region. A 13,000 year pollen record from Upper Fly Lake indicated that herbaceous tundra existed on the landscape from 13.6 to 11 ka, followed by birch shrub tundra until 10 ka, when *Picea* forests were established in the region. Pollen-, chironomid-, and ostracode-inferred paleoclimate reconstructions showed a long-term cooling with increasing moisture from the late glacial through the Holocene. The early and mid-Holocene were warm and dry, with cool, wet conditions after 4 ka, and warm, dry conditions over the last 100 years. Chironomid accumulation rates provided evidence of millennial-scale climate variability, and the chironomid community responded to rapid climate changes.

Late Holocene environmental variability was investigated through the analysis of paleoproduction indices (sediment loss-on-ignition, biogenic silica) and chironomid and ostracode communities. Coherent trends were revealed among the four lakes and pairs of sites located closer together showed more similarities than more distant sites located in similar environments (alpine tundra or boreal forest). Chironomid-inferred paleotemperature estimates are inconsistent with other data from the region, however certain fluctuations in paleoproduction indices and changes in abundance and composition of the chironomid and ostracode communities compare well with interpretations based on independent paleoclimate records. The White River Ash event (1147 cal yrs BP and 1953 cal yrs BP) impacted three of the four aquatic ecosystems studied, with a greater impact occurring at sites with greater ash thickness.

Interannual variability in the lake environment is of lesser concern when deriving inference models relating organisms to environmental variables, and the results presented here provide guarded optimism that the sampling methodology applied in paleolimnological studies is appropriate in this region.

DEDICATION

To the memory of my father
Arthur Corbet Bunbury
1924-2009

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I thank my supervisor, Konrad Gajewski, for tolerating me as an undergrad, teaching me as a Master's student, and educating (and encouraging, and frustrating) me as a doctoral student. I truly appreciate your mentorship and the support that you have provided to me over the years in my quest for higher education.

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To the Laboratory for Paleoclimatology and Climatology – and all of the members that have achieved degrees (or continue to work on them) while I have pursued mine; the people changed, but the dynamic research environment remained. Special recognition goes out to B. Podtritske, R. Zalatan, and M.-C. Fortin for their friendship, and M. Peros and A. Viau, for either answering my questions or pointing me in the right direction.

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To my family for being my family and to my friends who are also my family - knowing that you were there was both comforting and reassuring, and there were plenty of times while I pursued this degree that I required both comfort and reassurance. Thank you.

HOLOCENE ENVIRONMENTAL VARIABILITY INFERRED FROM LAKE SEDIMENTS, SOUTHWEST YUKON TERRITORY, CANADA

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CHAPTER ONE

INTRODUCTION

Purpose

This thesis investigates the effects of environmental variability operating on different temporal scales on aquatic ecosystems in the southwest Yukon over the postglacial period. Climate changes are a more gradual environmental change that occur on a number of timescales whereas, in comparison, volcanic events are abrupt and catastrophic. All of these environmental fluctuations and extreme events generate changes in the aquatic ecosystem. Therefore, the overall purpose of this work is to investigate the influence that different scales of environmental change have had on aquatic ecosystems during the Late Quaternary in the southwest Yukon.

Background

A Paleolimnological Approach

Lake sediments are regarded as valuable sources of information for reconstructing past environments (Birks and Birks 1980; Smol 2008). Autochthonous and allochthonous organic and inorganic material comprise the sediments, and the results of different sedimentary analyses can be used to infer past lake conditions (Lowe and Walker 1997). Sediment variables used to infer paleoproductivity include sediment organic content and biogenic silica content. Organic matter contained within lake sediments is a combination of organic material that has been transported from the watershed and biological activity within the lake, including organism remains. Generally, the greater the relative abundance of organic matter in the sediments the greater the production within the lake (Delcourt & Delcourt 1991). Biogenic silica is produced primarily by diatoms (as well as chrysophytes and sponges) in freshwater environments (Wetzel 2001), and an increase in concentration suggests greater primary production (Conley and Schelske 2001).

Information obtained from the remains of freshwater organisms contained within lake sediments can provide insight into past lacustrine conditions, as well as the past climate. Two groups of organisms widely used to reconstruct paleoenvironments are chironomids and ostracodes (Griffiths and Holmes 2000; Walker 2001). These small animals live at the sediment-water interface in lakes and different taxa have quantifiable ecological preferences. Both organisms have parts that preserve well in lake sediments and can be identified to either genus or species level to determine the taxa that once lived in the lake. By analyzing the modern abundance and distribution of these organisms in the context of measured environmental variables at a spatial series of lakes, inference models can be developed to quantitatively reconstruct past environmental conditions, including climate, and are then used to aid in the interpretation of organism remains in sediment cores.

Methods and Models

In this work, two approaches are used to quantitatively reconstruct past climates: the Modern Analogue Technique (MAT) and multivariate transfer functions. A significant difference between these two methods is that the MAT estimates a given point in the past by comparing it with one point, whereas the transfer function approach estimates the past based on a model developed from a number of sites.

All quantitative reconstructions methods depend on two datasets. The first is a time series from a sediment core, from which an assemblage of microfossils is identified from a series of samples throughout the core. The second is a spatial array of samples from a series of lakes. The uppermost sediments, deposited in the past few years, are collected and the same group of microfossils are extracted and identified from each site. In addition, components of the modern environment (e.g. water chemistry, climate variables, etc.) are sampled, computed, or estimated. This results in a dataset that contains both environmental and species data for each lake.

In the modern analogue method, every sample from the core is successively "compared" to each of the modern samples. The comparison comprises computation of the dissimilarity of the two samples, modern and fossil, using a dissimilarity measure, such as Euclidean distance. In practice, the squared chord distance dissimilarity measure is typically used in paleoecology as it is one of the simpler metrics that maximizes the "signal" component of the data from the "noise" (i.e. random effects such as competition, predation, dispersal, etc.; Prentice 1980; Overpeck et al. 1985). The modern sample with the smallest dissimilarity to the fossil sample is the modern analogue, although in reality several modern samples may be selected. The value of the environmental variable associated with the modern analogue is considered to be the value for that period in time. This is then repeated for all samples at various levels in a sediment sequence to provide a continuous record of the environmental variable of interest through time.

The transfer function approach is a mathematical model that is developed based on the organism and environmental data in the modern calibration set (Birks 1995; Birks 1998; Smol 2008). This regression-type approach relies on the application of empirical data to model the response of different taxa to an environmental variable of interest. Species responses can then be used to estimate values of a given variable through time based on the subfossil assemblages.

Several assumptions are made when using this technique with paleolimnological data (Birks 1995). Ecological assumptions include: 1) the various taxa are affected in some way by the environment, 2) the environmental variable being reconstructed is, or is related to, an ecologically important variable in the ecosystem being studied, 3) the species encountered in the modern training set also exist in the subfossil assemblages and ecological responses to the environmental variables under study have not changed over time, 4) the statistical models used for modelling species response to environmental variables are appropriate, and 5) other environmental variables have little influence on the outcome. Statistical assumptions are discussed in Birks (1998).

The actual method has a number of steps. First, a relation is established between the species and the environment (i.e. species-environment relation) using ordination methods applied to the data from the modern calibration set (or "training set"). These multivariate methods and associated plots are effective for visualizing the species-environment relation by organizing species and samples along environmental gradients (represented by the axes). Species and samples in close proximity to one another imply that the samples are similar in both species composition and relative abundance (Lepš and Šmilauer 2003).

Initially, the species data are analysed using detrended correspondence analysis (DCA) to estimate the diversity of the organism community (Lepš and Šmilauer 2003). Longer gradient lengths (~4.0 standard deviation (SD) units) indicate that species found at one end of the gradient are less likely to occur with those found at the other end (ter Braak 1995; Legendre and Legendre 1998; Lepš and Šmilauer 2003). A shorter gradient length (~2.0 SD units) suggests a greater likelihood of similar species being encountered across the assemblages. The length of the DCA gradient is used to determine whether to employ unimodal techniques (e.g. canonical correspondence analysis) or linear methods (e.g. redundancy analysis) to the species data in further analyses and transfer function development. More details on DCA are found in Hill and Gauch (1980), Legendre and Legendre (1998), and ter Braak (1995), whereas information on unimodal and linear techniques can be found in ter Braak (1995), ter Braak and Šmilauer (2002), Lěps and Šmilauer (2003), and Smol (2008).

Once the environmental variables that "best explain" the species-environment relation in the training set are chosen, then a transfer function can be developed for an environmental variable that shows a strong relation with the species data. The Gaussian response curves (this functional form is assumed) of the different species to the environmental variable are then used to develop a model describing the multivariate species-environment relationship. The model is then solved using the subfossil assemblages to reconstruct the variable of interest through time.

Several linear and unimodal techniques exist for this purpose and are explained in Birks (Birks 1995), and Birks (Birks 1998). In this thesis, weighted-averaging partial-least-squares regression (WAPLS; unimodal technique) and partial-least-squares (PLS; linear technique) provided the most reliable models, as assessed by the performance statistics and residuals (based on cross-validation). Typically, models with a high coefficient of determination (r^2), low root-mean-squared-error of prediction (RMSEP), and low mean and maximum bias, with the fewest components are the most reliable (Birks 1998). The r^2 and the RMSEP indicate the strength of the transfer function, or how well the environmental variable can be inferred from a species assemblage.

Cross-validation of the model is performed using bootstrapping or jackknifing (Birks 1995; Birks 1998). Generally, jackknifing is "leave-one-out" substitution where one sample is excluded from the modern training set to form the test set, whereas bootstrapping removes one sample and substitutes it with another sample in the training set to form the test set. In both cases many iterations are performed (i.e. 1000) to select many combinations of the training and test sets to ensure robust performance statistics.

Study Area - The Southwest Yukon

The interior southwest Yukon is on the leeward side of the St. Elias Mountains, which provide an orographic barrier for warm, moist air masses originating in the Gulf of Alaska. As these air masses are forced up over the mountains, significant precipitation occurs, resulting in dry air masses reaching the interior. Recently, high-resolution long-term records of the moisture regime in the region were established through oxygen-isotope records from the Mount Logan ice core (Fisher et al. 2004; Fisher et al. 2008), and Jellybean Lake and Marcella Lake sedimentary carbonates (Anderson et al. 2005; Anderson et al. 2007).

Although several lake sediment studies from the region use pollen as a proxy to determine the post-glacial vegetation and ultimately infer the past climate (e.g. Cwynar 1988; Wang and Geurts 1991; Lacourse and Gajewski 2000), biological proxies have been underutilized. Prior to this work, only one post-glacial chironomid-inferred quantitative reconstruction existed from the region (Barley 2004), however it had poor chronological control and has not yet been formally published. A tree-ring study presenting temperature reconstructions was recently published however it only extended back 300 years (Youngblut and Luckman 2008). Thus, there is a need for quantitative paleo-temperature reconstructions of the postglacial period to better understand how climate variability may impact ecosystems in the boreal forest of the region.

In the future, there are suggestions that the boreal forest may become drier, with a concomitant increase in fires. Because the southwest Yukon is always relatively dry due to the rainshadow effect of the St. Elias Mountains, analysis of lake sediment cores from this region may thus provide partial analogues of the nature of the boreal forest in the future. Studies of the long-term response of the Southwest Yukon region to climate variability may help us to understand the future across a broad area of the boreal forest.

Objectives

This thesis is written in article format where the chapters are designed to respond to specific objectives.

Objective 1: Quantify past climates in the southwest Yukon

The objective of Chapter Three was to quantify climate change in the southwest Yukon during the postglacial period. Pollen, chironomid, and ostracode data from Upper Fly Lake were used to derive estimates of mean-July temperature, total annual precipitation, and water depth by applying both transfer function and modern analogue technique methodologies. This site thus provides the first multiple-proxy paleoclimate records from the region. Multi-proxy approaches are particularly useful as results utilizing different reconstruction methods and proxies can be compared to strengthen the interpretation. This chapter compared the new reconstructions with other data derived from a variety of proxies, providing a broad review of paleoclimates in northwestern North America.

Objective 2: Understand the impact on aquatic ecosystems of environmental variability at several temporal and spatial scales

The research presented in Chapter Five has three inter-related objectives. The first was to present a series of chironomid-inferred paleo-temperature reconstructions from four lakes in the southwest Yukon. These high-resolution reconstructions based on the transfer function methodology contribute further knowledge on the temperatures in the region over the past 2000 years. Although the changes in the moisture regime of the region were interpreted from ice cores from Mount Logan, and sediment analysis of two lake cores, the temperature history is less well known. The four lakes sampled are located in different geographic contexts and contribute data on the magnitude of spatial and temporal climate variations in the region. Chironomid, ostracode, and sedimentary data from the four sites are compared with the new reconstructions, as are available independent climate records to assess aquatic ecosystem response to environmental change. The final objective of this chapter was to examine the impact of the deposition of the White River tephra on aquatic environments. Presumably, the effect of the ash input diminishes with distance from the source vent, so lakes were chosen, subject to availability, at varying distances from the source. This research utilized a high-resolution, multi-proxy approach to investigate the nature and impacts of two different scales of environmental change that have occurred over the past 2000 years in the southwest Yukon.

Chapter Four provides some information on the distribution of the White River Ash across western Canada. This is provided as background, and this chapter includes new information about the depth of the ash that accumulated in some lakes from the region.

Objective 3: Methodological issues

Given the reliance on the statistical calibration methodology (i.e. transfer functions) in the two chapters mentioned above, but also generally in paleoecology, it was important to understand the effects of the sampling methodology used in paleolimnological studies. This objective was addressed in Chapter Two. Transfer functions are based on the assumption that the environmental data (e.g. water temperature, pH, nutrients, etc.) collected at one point in time at each lake adequately represents the "environment" in which the organism was living at the time of sampling. However, it is general knowledge that lake environments are quite variable from year-to-year due in part to their relation with climate, which suggests that the year of sampling may have an effect on transfer function development. This question was investigated in Chapter Two.

Previous work by the author has examined the distribution of freshwater ostracodes in the southwest Yukon, providing basic data about the organism-environment relations in northern environments. There are few published modern calibration data for ostracodes from northern Canada. This modern calibration set was used to reconstruct water depth in Chapter Three however it was observed that the training set was lacking modern analogues during the Lateglacial and the early Holocene. As surface-sediment samples and corresponding water chemistry were available at many locations across the Canadian Arctic islands, a study on the biogeography of freshwater ostracodes across the Canadian Arctic was prepared and is presented in Appendix A. This is a project that contributes toward the eventual goal of obtaining a continent-wide array of sites for calibration purposes.

Thesis Organization

This thesis contains 3 main chapters and 1 appendix that have been written as individual manuscripts for peer-reviewed journals, or in the case of Chapter Four, a contribution to the in-house journal of the Yukon Geological Survey. My supervisor Konrad Gajewski was the co-author of these works. The chapters are presented in order of publication, and references in the works already published are in the format of the individual journals.

Chapter Two, entitled “Does a one-point sample adequately characterize the lake environment for paleoenvironmental calibration studies?” was published in the Journal of Paleolimnology in 2008 (39: 511-531).

Chapter Three entitled “Postglacial climates inferred from a lake at treeline, southwest Yukon Territory, Canada” was published in Quaternary Science Reviews in 2009 (28: 354-369).

Chapter Four entitled “Variations in the depth and thickness of the White River Ash in lakes of the southwest Yukon” was published in Yukon Exploration and Geology 2008, L.H. Weston, L.R. Blackburn and L.L. Lewis (eds.) in 2009 (pp. 77-84).

Chapter Five is entitled “Aquatic ecosystem response to late Holocene environmental variability in the southwest Yukon” and will be submitted for publication in 2009.

Appendix 1 entitled “Biogeography of freshwater ostracodes in the Canadian Arctic Archipelago” was published in Arctic in 2009 (62: 324-332).

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CHAPTER TWO

DOES A ONE-POINT SAMPLE ADEQUATELY CHARACTERIZE THE LAKE ENVIRONMENT FOR PALEOENVIRONMENTAL CALIBRATION STUDIES?

Abstract

A major goal of paleolimnological studies is the quantification of past environmental conditions. This is accomplished by computing transfer functions relating organism assemblages to environmental factors. The environmental data are typically comprised of a point sample of water chemistry and other environmental variables that are collected at the same time as a surface-sediment sample. We explore whether the year of sampling of the environmental variables affects the parameterization of organism-environment relations, in particular chironomids, ostracodes and diatoms. Canonical correspondence analyses revealed that the year of sampling is of secondary importance when relating the organism assemblages to environmental variables, but only with the major explanatory variables. A chironomid-inferred bottom-water temperature partial-least-squares transfer function revealed similar performance statistics between the years. Taxon optima and tolerances were computed for both years using weighted-averaging, and the results are comparable. A paired t-test computed on the proxy-inferred bottom water temperature values indicated that the results between the two years are not statistically different. The results of this study provide guarded optimism that the methodology of estimating transfer functions as currently applied is not entirely determined by the particular year when the data were collected, although more case studies are needed.

Introduction

A major goal of paleolimnological studies is the quantification of past environmental conditions. Frequently, it is the change through time in some environmental variable (e.g. pH, temperature) that is of interest, but these variables may leave no direct trace in the sediment. However, it may be possible to infer this change through the use of some proxy indicator. Commonly, subfossil assemblages of some organism can be used to derive such environmental series through the application of a transfer function. This is based on a space-for-time substitution, where the present-day organism assemblages are sampled from the modern sediments of a spatial series of lakes. Water chemistry and other characteristics of the lake environment are sampled at the same time.

The first step in a paleolimnological study is thus to assess the organism-environment relations from a set of lakes along some environmental gradient (e.g. temperature, pH, total phosphorus). These are referred to as calibration or training sets, and different aquatic organisms including chironomids (e.g. Barley et al. 2006), ostracodes (e.g. Viehberg 2005), and diatoms (e.g. Bouchard et al. 2004) have been used in these studies. The statistical calibration methodology is based on the assumption that the point sample represents the “environment” in which the organism is living, just as the subfossils extracted from the sediment sample are supposed to be a representative sample of the aquatic community. It is recognized that this is only a crude approximation, but practical considerations usually do not allow the complete characterization of the lake environment over the entire lake volume, for the entire season, and over several years. Violations of this assumption are probably less critical for the sediment sample, as the sediment integrates several years of accumulation and contains organisms from many parts of the lake. In comparison, the properties of the water column are more variable. The methodology works only to the extent that the spatial differences between the sites are much greater than the annual and interannual differences within any lake.

Paleolimnologists acknowledge this and other problems (e.g. Birks 1995; 1998), and there have been a few studies addressing the impact of environmental variability on the development of transfer functions. For example, Siver and Hamer (1992) studied the seasonality of certain algae in relation to their potential for reconstructing the seasonal variability of water chemistry. They found that the flora represented in the surface sediments grew primarily during late autumn. Bradshaw et al. (2002) studied the seasonal variability of total phosphorus in relation to the diatoms in an effort to improve calibration sets. Models based on spring total phosphorus concentrations only slightly improved the results, but the lack of improvement may be due to the small size of the dataset (23 lakes). Köster and Pienitz (2006) investigated diatom seasonality in relation to environmental variables, derived a transfer function, and applied this to 1000-year fossil record. They suggest that accounting for seasonality may improve paleolimnological inference models. Other studies have assessed the influence of within-lake variability on, for example, cladoceran (e.g. Kattel et al. 2007), chironomid (e.g. Heiri 2004; Eggermont et al. 2007), and macrofossil (e.g. Zhao et al. 2006) sediment assemblages. However, whether interannual variability of the environment affects the parameterization of transfer functions has not been sufficiently studied.

Many studies document the chemistry of spatial series of lakes (e.g. Armstrong and Schindler 1971; Hamilton et al. 2001) and other studies have monitored the seasonal or interannual variability of the water chemistry and physical properties (e.g. Schindler et al. 1974; Sorvari et al. 2000), and phytoplankton populations and communities (e.g. Pearsall 1930; 1932; Riley 1939; Scheffer and Robinson 1939; Hutchinson 1944; Brock 1985; Talling 1993; Harris and Baxter 1996; Watson et al. 1997) of one or several lakes. One conclusion of these studies is that the chemical and physical variables are to some extent correlated with climate, suggesting that the year of sampling may strongly influence the species-environment relations and ultimately, the computation of paleoenvironmental transfer functions.

In this paper we address one question: does the year of sampling of the environmental variables affect the parameterization of organism-environment relations? In the years 2000 and 2006, we measured environmental variables and collected water samples from a set of 41 lakes in the southwest Yukon Territory and northern British Columbia, Canada. Diatoms, chironomids, and ostracodes have been identified from the surface sediments of these lakes and the organism–environment relations have been studied (Wilson and Gajewski 2002; 2004; Bunbury and Gajewski 2005). The combination of two years of environmental data collected during a similar time period (early summer), together with three groups of organism assemblage data from the same set of 41 lakes, has resulted in a dataset that can be used to investigate this question.

We recognize that there is a limit to the results that can be obtained because this was not a planned experiment. However, this will provide a first approximation towards answering this question. In this study, we assume the microfossils in the sediment are measured without error, as do all workers using this approach, and that the sediment assemblage is representative of the organisms in the lake. In addition, because a sediment sample accumulates several years of deposition and integrates the microfossils that grew under the conditions present in those years, it is reasonable to compare these organism assemblages to environmental datasets collected in different years, as this is what is done in practice.

Methods

Field and Laboratory Methods

A description of the field methods, water chemistry analysis, organism extraction and identification, and the study area are presented in Wilson and Gajewski (2002; 2004), and Bunbury and Gajewski (2005). Basically, a surface-sediment sample was collected using either a Glew gravity corer (Glew 1991) or an Ekman dredge from the deepest part of a series of lakes (Figure 2.1). Water samples were collected and analysed using standard methods.

Diatom data from 41 lakes were available in Wilson and Gajewski (2002). Only 39 of the sites were used in Wilson and Gajewski (2004), therefore chironomids were extracted and identified from the 2 remaining sites (Appendix B) in order to retain the same set of lakes in all three comparisons performed here. Ostracode data were available from 31 of the sites (Bunbury and Gajewski 2005), and data from 10 lakes were added for this study (Appendix C).

Environmental data for the year 2000 is found in Wilson and Gajewski (2002). In 2006, we returned to all 41 lakes to collect water chemistry samples and measure environmental variables to compile a comparable dataset (Appendix D) to the one that had been collected in 2000. Secchi depth was removed as an environmental variable from all analyses because measurements were often constrained by shallow lake depths, thereby not accurately representing water clarity.

Data Analysis

Organism-environment relations

Wilson and Gajewski (2002; 2004) document datafile preparation for the year 2000 data. For example, mean values were substituted for missing data, and the trace metal variables were selected based on 50% of the data points being above detection limits; see the original papers for full details. The same approach was used in 2006 with the following exceptions. Surface-water pH was averaged from 2 different measurements taken by Oakton handheld pH meters. Alkalinity measured in the laboratory was missing for Cub, Kusawak, Little Louise, Scout and West Twin Lakes, therefore a regression was computed relating field and laboratory measurements of alkalinity (not shown), and the modelled values substituted. Alkalinity values of Grayling Lake appeared unreasonable for both field and laboratory values based on previous years' data (unpublished); the mean of the modelled alkalinity values was substituted in this one instance.

Detrended correspondence analysis (DCA; Hill and Gauch 1980) and canonical correspondence analysis (CCA; CANOCO 4.5; ter Braak and Šmilauer 2002) were used for all analyses. DCA with detrending by linear segments and non-linear rescaling of axes revealed gradient lengths indicating unimodal methods were appropriate for chironomids (2.7 standard deviation units (SD)), ostracodes (3.8 SD), and diatoms (4.1 SD). The DCA gradient length was shorter for chironomids (2.7 SD), suggesting a redundancy analysis (RDA) might also be applicable. However, the results of the CCAs and the RDAs were comparable (not shown), therefore the CCAs are presented to make comparisons between the different proxies easier to interpret.

Different environmental variables are important for each group of organisms and those used in the analyses of the organism-environment relations are outlined in Wilson and Gajewski (2002; 2004) and Bunbury and Gajewski (2005). Bottom water temperature (Tb), and bottom dissolved oxygen (DOb) were added to the ostracode environmental dataset as we thought these to be potentially important variables not included in the original analysis. Strontium (Sr) and the strontium-calcium ratio (Sr/Ca) were not included in the analysis as strontium was not measured in 2000.

The ordinations for chironomids and diatoms were performed using 38 species and 29 environmental variables, and 130 species and 24 environmental variables, respectively.

Ostracodes were absent in the sediments of 4 lakes. Because the ordination techniques we used do not accommodate complete species absence at a site (Lepš and Šmilauer 2003), the analyses for ostracodes were performed on the remaining 37 lakes using 30 species and 31 environmental variables.

Environmental variable transformations were determined based on the frequency distribution of the values of the variables in each year (not shown). It was necessary to apply different transformations to sulphate (SO_4), total phosphorus (TP), and filtered total phosphorus (TPF) because the shape of the histograms varied between the two years. Depth (Depth), specific conductance (Cond), calcium (Ca), magnesium (Mg), dissolved organic carbon (DOC), total Kjeldahl nitrogen (TKN), silica (Si), and iron (Fe) were square-root transformed; area, sodium (Na), chloride (Cl), chlorophyll a (Chla), aluminum (Al), manganese (Mn) and molybdenum (Mo) were log transformed; and all other variables were left untransformed. Sulphate, TP, and TPF were log transformed in 2000 and square-root transformed in 2006.

Transformations applied to the species data were based on the original papers; chironomids were square-root transformed, ostracodes were log transformed, diatoms were left untransformed, and rare species were downweighted in the DCAs and the CCAs. Biplot scaling was applied to the chironomid analyses, whereas Hill's scaling was applied to the ostracode and diatom CCAs. Leverage diagnostics in CANOCO 4.5 (ter Braak and Šmilauer 2002) were used to check on the influence of outliers and, where applicable, samples were made supplementary.

To reduce the number of collinear environmental variables, we first performed a series of constrained CCAs where each environmental variable was individually selected to determine its marginal effect in the analysis (Lepš and Šmilauer 2003). Only significant ($p < 0.05$, 499 Monte Carlo permutations) variables were included in further analyses. Second, preliminary CCAs were run to check for variables with high variance inflation factors (VIF), which were sequentially removed, resulting in VIFs < 10 in all analyses. Lastly, step-wise regression (forward selection) was used to identify the variables that together best explain the variation in the species data.

Intra-set correlations are presented for the variables chosen in the forward selection procedure, and to assist in explaining the relative importance of each environmental variable to the composition of the given organism community (ter Braak 1986). More specifically, these correlations are related to the rate of change in the assemblages that can be expected by the per unit change of the environmental variable in question. We chose to use these correlations instead of the canonical coefficients, as the covariance of other variables incorporated into the model is considered in the computation of the intra-set correlations, thereby increasing their stability (ter Braak 1986).

Development of inference models

For the chironomid data, inference models were derived to determine the potential impact of inter-annual variability on the reconstructions that would be estimated from those models. Sediment loss-on-ignition (LOI) was measured only once using the same sediment from which the organisms were extracted, therefore development of an inference model of this variable was not appropriate. The CCAs conducted on the two years' data revealed bottom water temperature (Tb) as an important variable explaining the variance in the species data in 2000, and surface-water temperature (Ts) in 2006. Tb was selected as the variable to prepare inference models for the two years, and to assess differences in species optima and tolerances between years. This variable was selected over Ts because the ratio between the first and second eigenvalues (λ_1/λ_2) was greater in CCAs constrained to Tb (2000 = 0.53, 2006 = 0.51) than it was in CCAs constrained to Ts (2000 = 0.16, 2006 = 0.36) indicating a better relation between the chironomids and Tb. Generally, better inference models can be developed for environmental variables that have higher λ_1/λ_2 (ter Braak and Prentice 1988).

Detrended canonical correspondence analysis (DCCA) (ter Braak 1986) was used to evaluate the percent variance explained in the chironomid data, with Tb as the sole constraining variable in each year. DCCA with detrending by linear segments revealed gradient lengths of 1.2 standard deviation units (SD) when using the 2000 data and 1.1 SD using the 2006 data. Transfer functions were developed for both years using partial-least-squares regression and calibration (PLS), weighted-averaging regression and calibration WA), and weighted-averaging partial-least-squares regression and calibration (WA-PLS). The cross-validation performance statistics indicated that the PLS model outperformed the

WA and WA-PLS models in both years (not shown). Therefore, the PLS results are presented here.

The PLS models for each year were assessed using leave-one-out cross-validation (jack-knifing), and compared based on model performance statistics. Weighted-averaging regression and calibration (WA) was used to estimate the optima and tolerances of the 38 chironomid species to Tb in both years. The predicted (jackknifed) optima and tolerance values were used instead of the estimated (apparent) values as the estimated values tend to be over-optimistic (Birks 1995). Transfer functions were developed using the computer program C2, version 1.4.3 (Juggins 2003), and the chironomid data were square-root transformed in both the PLS and WA analyses.

To assess if proxy-inferred values differed depending on which year's data was used, we ran the PLS model for 2000 and 2006 and applied it to the chironomid data. A paired t-test was used to evaluate whether the difference between the predicted (jack-knifed) reconstructed bottom water temperature values between the years was statistically significant.

Results

Organism-environment relations

Chironomids

In the 2000 and 2006 data, 9 variables were identified as statistically significant ($p < 0.05$, 499 Monte Carlo permutations) in the constrained CCAs after the removal of those with the highest variance inflation factors (Table 2.1). LOI explained the largest proportion of the variance in the species data in both years (14.8%), followed by Tb (10.9% and 10.6%), and Depth (12.1% and 10.0%). Statistically significant variables in the forward selection process using the 2000 data were LOI ($p = 0.002$), Tb ($p = 0.002$), Alk ($p = 0.014$), and TP ($p = 0.010$), and using the 2006 data were LOI ($p = 0.002$), Ts ($p = 0.012$), and Alk ($p = 0.024$) (Figure 2.2). These variables account for 18.0% of the variance in the species data on the first two CCA axes (eigenvalues of 0.17 and 0.11 respectively) using the 2000 data, and 15.8% of the variation on CCA axes 1 and 2 (eigenvalues of 0.16 and 0.09 respectively) using the 2006 data.

Correlations between the environmental variables and the ordination axes (as revealed by intra-set correlations) indicate that LOI and bottom temperature contribute to CCA axis 1 in 2000, TP contributes to axis 2, and Alk to axes 2 and 3 (Table 2.2). Similar intra-set correlations exist between variables and axes in 2006, however Ts replaces Tb as the second variable contributing to axis 1, and also contributes to axes 2 and 3. A scatterplot depicting Tb and Ts indicates that this dataset contains two populations of lakes, deep and shallow (Figure 2.3).

Lakes, species, and variables are situated in the same relative location on the biplots using data from both years (Figure 2.2). Three Guardsmen and Little Louise Lakes have lower surface and bottom water temperatures, whereas Sulphur, WHA and Little Hungry Lakes have higher surface and bottom water temperatures due to their shallow lake depth (i.e. 3 m or less). Stella, L1, L2 and Blanchard Lakes all have sediment with high percentages of organic content (LOI), while Fox Point and Small Lakes have sediment with low percentages of organic content, and alkaline lake water.

Psectrocladius (*Allo/Mesopsectrocladius*), *Tanytarsus* sp. C, and *Tanytarsus pallidicornis* type occur in lakes with greater sediment organic content (LOI), whereas percentages of *Nanocladius* and *Parakiefferiella* cf. sp. B are negatively correlated with LOI and positively correlated with Alk. *Glyptotendipes*, *Tanytarsus lugens* group, and to a lesser extent *Cladopelma* and *Microtendipes* inhabit lakes with warmer surface and bottom water, while *Heterotrissocladius* and *Micropsectra atrofasciata* are found in lakes with cooler surface and bottom water.

Ostracodes

Leverage diagnostics revealed that the Mg/Ca ratio in Emerald Lake had an extreme influence on the analysis using both the 2000 and the 2006 data (23.1x and 16.4x, respectively). In the 2006 analysis, St. Elias Lake had an influence on the environment ordination (3.4x). These two samples were made supplementary in the CCAs so as not to influence the definition of the ordination axes (ter Braak and Šmilauer 2002), but they were included on the biplot to observe where they ordinated.

The constrained CCAs indicate 6 variables are statistically significant in the 2000 data and 7 variables are significant in the 2006 data, after the removal of variables with high

VIFs (Table 2.1). Mg/Ca individually explained a large amount of the variance (33.1% in 2000 and 30.4% in 2006) in the species data in both years, as did several other variables (see Table 2.1). Forward selection chose Mg/Ca ($p = 0.002$), Tb ($p = 0.002$), Depth ($p = 0.010$), and K ($p = 0.016$) as the statistically significant variables that explain 18.7% of the variance in the ostracode data on the first two canonical axes (Figure 2.4). This procedure selected only two variables using the 2006 data; Mg/Ca ($p = 0.002$) and Depth ($p = 0.002$), yet a similar amount of variance in the ostracode data was explained (17.3%). Eigenvalues for CCA axis 1 and 2 are 0.39 and 0.21 in 2000, and slightly lower in 2006 (0.36 and 0.19). Intra-set correlations revealed that the Mg/Ca ratio is correlated with CCA axis 1, and Depth is correlated with CCA axis 2 in both the 2000 and 2006 analyses (Table 2.3). Tb and K are also highly correlated with axis 2 in 2000.

The plot of lakes and environmental variables reveal a similar relation among the variables and cases between the two years, as does the species plot (Figure 2.4). Teapot, Grayling, Long, and Fox Point are deep lakes with cooler bottom water and ordinate together in the 2000 analysis. Several lakes have very low Mg/Ca ratios (e.g. Otter Falls, Decourcy, Ash, K819, Atthilu), whereas only a few have high Mg/Ca ratios in both years (Emerald, Keyhole, Jenny, Sulphur).

Ilyocypris bradyi, *Limnocythere itasca*, *Candona acutula*, and *Candona compressa* inhabit lakewater with high Mg/Ca ratios, whereas *Cyclocypris globosa*, *Cyclocypris serena*, and *Cyclocypris* sp. are found in water with low Mg/Ca ratios. Although their scores differ on CCA axis 1 in the two years, values of *Candona ikpikpukensis*, *Limnocythere* sp., *Ilyocypris gibba*, *Candona rawsoni*, and *Cytherissa lacustris* are correlated with CCA axis 2 (defined by variables associated with Depth) in both years.

Diatoms

Seven variables were identified as statistically significant in the constrained CCAs using both the 2000 and the 2006 environmental data, after variables with high VIFs were removed (Table 2.1). In 2000 and 2006, when selected as the sole constraining variable, Depth explained 25.5% and 22.4% of the variance, and Alk explained 24.4% and 22.3%, respectively. Other variables could also explain much of the variance when selected individually (see Table 2.1).

Depth ($p = 0.002$; $p = 0.004$), Alk ($p = 0.002$; $p = 0.004$), and Area ($p = 0.024$; $p = 0.018$) were the variables chosen using forward selection in both 2000 and 2006 (Figure 2.5). Together, these variables explained 11.5% of the variance when using the 2000 environmental data, and 10.5% variance with the 2006 data. Eigenvalues for CCA axis 1 and 2 in 2000 were 0.28 and 0.22, and slightly lower in 2006 (0.25 and 0.19). Intra-set correlations from analyses conducted on both years of data revealed Depth and Alk were correlated with CCA axis 1, and Area was correlated with axes 2 and 3 (Table 2.4).

As with the analyses based on the other 2 groups of organisms, lakes, species, and environmental variables were positioned in the same relative location on the ordination plots in both years (Figure 2.5). Three Guardsmen, Pine and Wolverine Lakes have a relatively large surface area, whereas Little Hungry, Decourcy and Patrick Lakes are small. Long, Grayling and PC Lakes are relatively deep, whereas Ash and KL1 Lakes are shallow. Emerald, Keyhole, and Small Lakes have higher values of alkalinity than other lakes on the joint plot.

Abundances of *Nitzschia frustulum* v. *bulnheimiana*, *Denticula valida*, and *Cymbopleura* cf. *subaequalis* were correlated with Alk, percentages of *Fragilaria cyclopum* and *Cyclotella* aff. *comensis* were positively correlated with Depth, whereas values of *Encyonopsis silesiacum* (Bleisch) Mann and *Nitzschia fossilis* were negatively correlated. Abundances of *Navicula* aff. veneta were correlated with both Depth and Alk, while percentages of *Achnanthes ricula* aff., *Fragilaria brevistriata* and *Fragilaria capucina* were correlated with Area.

Inference models

The PLS one-component model that was developed using chironomids and the 2000 Tb data had a higher jack-knifed r^2, a lower jack-knifed maximum bias, and a lower RMSEP than the model developed using the 2006 Tb data (Figure 2.6). A one-component model was selected because the prediction error of the second component was greater in the models produced using both years' data (Birks 1998). The estimated (apparent) and predicted (jack-knifed) r^2 were higher with the 2000 model (estimated = 0.61, predicted = 0.38) than they were with the 2006 model (0.60, 0.35). The root-mean-squared-error (RMSE) and the root-mean-squared-error of prediction (RMSEP) were both lower with the 2000 model (RMSE =

2.51°C, RMSEP = 3.18°C) than with the 2006 model (2.87°C, 3.67°C). In addition, the estimated and predicted maximum bias was lower with the 2000 model (estimated = 3.90°C, predicted = 5.04°C) than with the 2006 model (4.50°C, 6.94°C). A paired t-test revealed that the predicted proxy-inferred values generated by the transfer functions were not statistically different ($t = -4.16$, $df = 40$, $p = 0.0002$).

The optimum and tolerance of each of the 38 chironomid taxa to Tb were generated for both years using WA (Table 2.5). In general, values of both optima and tolerances were comparable whether computed using the 2000 or 2006 data. Approximately 50% of the optima were within 0.5°C of each other when computed with the 2-years data and nearly 80% were within 1°C. Many of the taxa for which the difference in the optima computed using the 2000 and 2006 data greater than 1°C were those found in a small number of lakes, where it would be expected that the estimated value would be less reliable. Although optima computed using data from the year 2000 were equally smaller or larger than those computed using data from the year 2006, the tolerances from the year 2000 were in most cases smaller than those of 2006. However, the tolerances generated from the 2000 data overlap those produced using the 2006 data, indicating that the statistics are similar between the years (Table 2.5).

Discussion

The fundamental issue is whether a one-point sample can adequately characterize the lake environment, as this is the basis of quantitative paleolimnology using various transfer function methods. Within-lake spatial differences and seasonal changes all contribute to the total variability of environmental samples, and there have been studies that address the importance of this variability. Our interest was in the importance of interannual variability in exploratory multivariate analyses of organism-environment relations. We approached this research by inquiring whether the year of sampling of the environmental variables affects the parameterization of organism-environment relations.

It appears that, in spite of the differences in the environmental conditions between the two years, the year of sampling does not overly affect the organism-environment relations derived from these data. Environmental variables were positioned in the same relative location on the ordination plots, and the primary forward-selected variables were the same in both years for each of the three groups of organisms. The eigenvalues and percent variance explained by CCA axes 1 and 2 are consistently lower in 2006 than in 2000 for all groups, suggesting that more of the variation in the species data is explained by the environmental variables in 2000 than in 2006 (ter Braak 1995); however, the differences are not great.

Physical features of the lake (temperature, surface area and/or depth) are important variables in explaining the distribution of chironomids, ostracodes, and diatoms, as the interaction among these variables determines the relative amounts of shallow and deep water environments available to the organisms (Håkanson 2004), as well as the temperature of the water in these environments. The chironomid-environment analysis included Tb in 2000 and Ts in 2006 in the forward selection process (Figure 2.2). A positive relation appears to exist between these variables in shallow lakes; however, this relation is not as clear in deep lakes (Figure 2.3), although there are fewer cases of the latter. In the ostracode-environment analysis based on the 2000 data, both Depth and Tb were selected by the forward selection process, and were correlated with the same axis (Table 2.3). Warmer temperatures and higher insolation at the surface of the lake during the summer months cause shallow lakes to heat through to the bottom, and deep lakes to thermally stratify. This affects both the chironomid and ostracode community composition in this region.

Water depth can also affect variables such as sediment-size distribution, which is related to organic matter and may influence community composition (Brinkhurst 1974). Chironomids and ostracodes are benthic organisms that can be found in both deep and shallow lakes, however few species dwell in both environments. In comparison, diatoms can be planktonic, benthic, or periphytic, and the majority of the lakes in this set with a large surface area are relatively shallow and provide a variety of habitats to support different species.

Chironomids and diatoms are ubiquitous organisms that inhabit both high- and low-pH environments. In the southwest Yukon, lakes are neutral to alkaline (pH values 7.5 to 9.4 in 2000; 8 to 9.3 in 2006) and different taxa from these two groups are found in neutral and alkaline lakes (Wilson and Gajewski 2002; 2004). However, most ostracode species require a pH above 7.0 to exist (Delorme 1991), and even higher values to be well preserved in the sediments after death. Therefore, the alkalinity gradient is more important as an explanatory variable for the chironomid and diatom taxa; because ostracodes require an alkaline environment simply to exist, they are found only along a small portion of the gradient. With all three groups of organisms, the dominant variables that would be expected to influence the distribution are identified in the ordinations irrespective of the year of environmental data used in the analysis.

The chironomid-derived bottom water temperature models developed for the two years are comparable, however the 2000 model outperforms the 2006 model (Figure 2.6). The cross-validation maximum bias is high in both years given the range of the data, but this is likely due to the dominance of shallow lakes with warm bottom temperatures in this dataset (33 lakes < 10 m = ; 8 lakes > 10 m). The WA models produced generally lower taxon tolerances in 2000 than in 2006, suggesting less between-lake variability in environmental measurements during the year 2000. The estimated optima, however, are quite similar in both years, especially if the number of lakes with the taxon is higher. It is perhaps not surprising that these estimated parameters are similar, as the organisms would only be found in the lake if it could tolerate the inter-annual variability present in the region.

For our purposes, this study indicates that the limited environmental measurements typically made in the context of a paleolimnological study sufficiently characterize the environment for the statistical methodology used. However, this study would need to be repeated in different regions to determine if this is generally the case.

Conclusions

Interannual variability in the lake environment is of concern when deriving inference models relating organisms to environmental quantities. A sediment sample may integrate several years of input, so the year of sampling may cause statistical calibration to differ, depending on when the water sample was collected and other environmental parameters were measured. However, we found that the year of sampling is of secondary importance when relating the organism assemblages to environmental variables, but only with the major explanatory variables.

These results are limited to two different years and three organism datasets in one region. Nevertheless, they provide guarded optimism that the methodology of estimating transfer functions as currently applied is not entirely determined by the particular year when the data were collected. Further work is needed to ensure that these results are general and not simply due to the particular situation studied here.

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Table 2.1: p-values ($p < 0.05$, 499 Monte Carlo permutations) and percent variance explained by each environmental variable in a constrained CCA where each variable is used as the sole constraining variable. p-values in bold indicate the variables that were included by the forward selection process after variables with high variance inflation factors were removed. Forward-selected variables in a given year are indicated by * .

	Chironomids				Ostracodes				Diatoms			
	2000		2006		2000		2006		2000		2006	
Variable	p-value	%expl var	p-value	%expl var	p-value	%expl var	p-value	%expl var	p-value	%expl var	p-value	%expl var
Depth	**0.002**	12.1	**0.002**	10.0	**0.002***	20.7	**0.008***	20.0	**0.002***	25.5	**0.006***	22.4
Alk	**0.014***	7.0	**0.018***	7.0	0.002	27.8	0.002	26.6	**0.002***	24.4	**0.002***	22.3
Cond	**0.026**	6.4	**0.036**	6.6	0.002	24.1	**0.004**	24.0	**0.022**	17.5	**0.020**	17.6
Mg	0.030	6.5	0.046	6.5	0.002	27.9	0.002	29.2	0.008	20.7	0.006	21.0
Tb	**0.002***	10.9	0.002	10.6	**0.002***	23.1	**0.008**	19.8				
K					**0.006***	18.5	**0.018**	19.4	**0.012**	19.0	**0.006**	20.2
LOI	**0.002***	14.8	**0.002***	14.8								
TP	**0.002***	9.2	**0.004**	8.4								
DOC	**0.002**	9.5	**0.002**	8.4								
Mg/Ca					**0.002***	33.1	**0.002***	30.4				
Alk/Ca					0.002	26.2	**0.002**	24.8				
Carb					**0.002**	21.7	**0.002**	24.2				
Elev												
TKN	0.004	9.6	**0.002**	9.5								
Area									**0.020***	17.3	**0.030***	17.3
Si									**0.048**	16.5	**0.008**	19.8
Na									**0.038**	16.6		
Fe	**0.032**	6.9										
Mn	**0.026**	6.9										
DOb			**0.038**	6.9								
Ts			**0.004***	8.1								
SO_4					**0.042**	14.1						
Mo											**0.004**	22.2

Table 2.2: Intra-set correlations for the first three axes of the forward-selected variables in the chironomid analyses for 2000 and 2006. LOI = loss-on-ignition, TP = total phosphorus, Tb = bottom water temperature, Ts = surface water temperature.

	2000			2006		
Variable	Axis 1	Axis 2	Axis 3	Axis 1	Axis 2	Axis 3
LOI	0.87	0.36	-0.02	0.93	0.34	-0.14
TP	0.44	-0.60	-0.57			
Alkalinity	-0.04	-0.62	0.78	-0.03	-0.81	0.59
Tb	0.66	-0.40	-0.30			
Ts				0.48	-0.58	0.66

Table 2.3: Intra-set correlations for the first three axes of the forward-selected variables in the ostracode analyses for 2000 and 2006. Tb = bottom water temperature.

	2000			2006		
Variable	Axis 1	Axis 2	Axis 3	Axis 1	Axis 2	Axis 3
Mg/Ca	0.83	0.56	-0.00	0.82	0.57	
K	0.31	0.66	0.02			
Depth	-0.33	0.74	0.54	-0.22	-0.98	
Tb	0.49	-0.73	0.13			

Table 2.4: Intra-set correlations for the first three axes of the forward-selected variables in the diatom analyses for 2000 and 2006.

	2000			2006		
Variable	Axis 1	Axis 2	Axis 3	Axis 1	Axis 2	Axis 3
Alkalinity	0.79	-0.40	0.47	0.77	-0.54	0.33
Depth	0.78	0.49	-0.39	-0.84	0.49	-0.22
Area	-0.09	0.61	0.79	0.00	0.54	0.84

Table 2.5: Number of occurrences and predicted optimum, tolerance, and range of 38 chironomid taxa to bottom water temperature for 2000 and 2006. Units are in °C.

		2000				2006			
Taxon	Count	Optimum	Tolerance	Range		Optimum	Tolerance	Range	
Tanytarsina	41	13.5	3.9	9.6	17.5	13.9	4.3	9.7	18.2
Procladius	37	14.1	3.4	10.7	17.6	14.5	3.9	10.7	18.4
Psectrocladius (Fig. 9.61 E/F in Wiederholm)	37	14.1	3.4	10.7	17.4	13.9	4.4	9.5	18.3
Chironomus	36	13.8	3.7	10.1	17.4	13.2	4.6	8.6	17.8
Dicrotendipes	33	14.3	3.2	11.1	17.5	14.3	4.0	10.3	18.3
Orthocladiinae (unknown)	33	12.4	4.6	7.8	17.0	12.7	4.8	7.9	17.6
Pentaneurini	31	13.8	3.8	10.0	17.6	13.7	4.9	8.8	18.6
Paratanytarsus	31	12.9	4.5	8.4	17.4	12.8	5.4	7.4	18.2
Cricotopus/Orthocladius	30	13.3	4.2	9.0	17.5	13.9	4.7	9.2	18.5
Tanytarsus lugens group	28	14.3	3.8	10.5	18.1	14.6	4.5	10.1	19.1
Polypedilum	27	14.6	3.8	10.8	18.4	15.0	4.2	10.8	19.2
Cladopelma	27	14.0	3.3	10.7	17.4	14.6	4.0	10.6	18.6
Cricotopus/Orthocladius (*C. tremulus* type)	22	12.9	4.4	8.5	17.3	13.0	4.9	8.1	18.0
Cladotanytarsus	20	14.8	3.2	11.7	18.0	15.0	3.7	11.3	18.7
Cricotopus/Orthocladius (*C. cylindraceus* type)	20	13.5	4.1	9.4	17.5	13.8	4.5	9.3	18.3
Tanytarsus lugens/Corynocera oliveri type	19	11.9	4.5	7.4	16.5	11.6	4.8	6.8	16.4
Microtendipes	18	15.3	3.2	12.1	18.6	16.1	3.4	12.7	19.5
Corynocera oliveri	17	9.3	4.6	4.7	14.0	10.6	5.0	5.6	15.6
Sergentia	15	10.0	4.4	5.5	14.4	9.7	4.5	5.3	14.2
Psectrocladius spp.	14	13.6	2.3	11.3	15.9	15.0	3.9	11.1	18.9
Endochironomus	13	14.3	2.6	11.7	16.8	14.3	3.5	10.7	17.8
Micropsectra atrofasciata	13	10.4	4.5	6.0	14.9	10.7	4.5	6.2	15.2
Tanytarsus pallidicornis type	12	13.9	3.8	10.2	17.7	13.8	4.5	9.3	18.2
Nanocladius	12	13.4	4.5	8.9	17.9	13.0	5.3	7.7	18.3
Corynoneura	12	11.6	4.6	7.1	16.2	10.0	5.2	4.8	15.2
Glyptotendipes	11	12.0	5.6	6.4	17.7	12.2	6.5	5.7	18.7
Corynoneura/Thienemanniella	11	10.0	4.6	5.4	14.6	10.0	5.3	4.8	15.3
Pagastiella	9	15.0	1.5	13.5	16.5	15.7	2.0	13.7	17.7
Tanytarsus sp. C	9	14.4	3.8	10.5	18.2	14.1	3.6	10.5	17.7
Corynocera ambigua	9	12.4	6.0	6.4	18.4	12.5	5.4	7.2	17.9
Orthocladius spp.	8	13.3	4.0	9.3	17.3	12.7	5.0	7.7	17.7
Heterotrissocladius	8	9.9	4.5	5.4	14.5	9.5	4.7	4.8	14.2
Psectrocladius (Allo/Mesopsectrocladius)	7	13.6	1.5	12.1	15.2	14.6	2.3	12.3	16.9
Parakiefferiella spp. including nigra	7	10.9	4.8	6.1	15.7	9.3	4.5	4.8	13.8
Parakiefferiella cf. sp. B (Walker 1988)	7	12.0	5.6	6.5	17.6	9.0	5.7	3.3	14.7
Parakiefferiella (Fig. 367 in O&R)	6	12.1	4.5	7.6	16.6	11.0	5.2	5.8	16.2
Eukiefferiella	6	10.6	4.5	6.1	15.2	8.9	4.6	4.3	13.4
Psectrocladius (Fig. 9.61 D in Wiederholm)	5	13.0	1.5	11.5	14.5	15.5	3.4	12.1	18.8

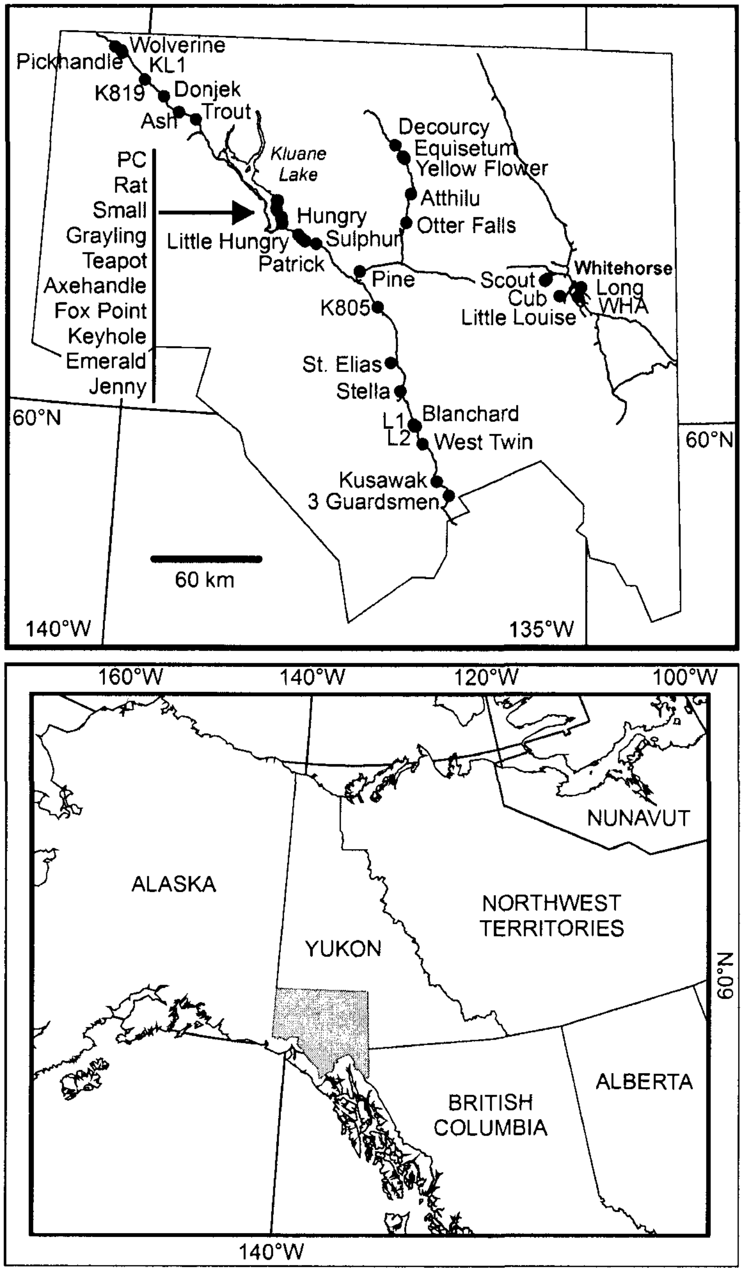

Figure 2.1: Map of the southwest Yukon and the 41 lakes sampled for this study

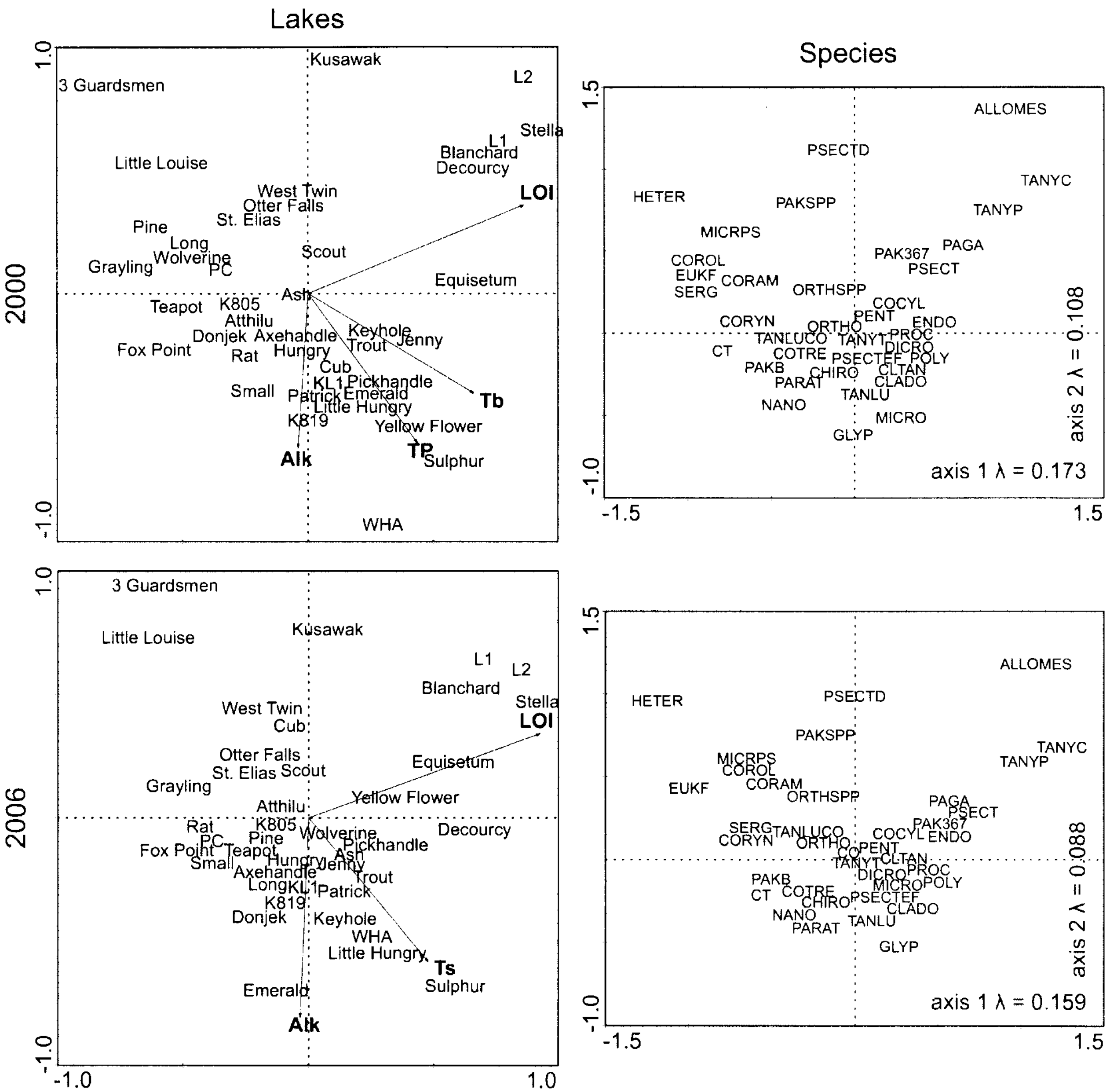

Figure 2.2: Canonical correspondence analysis biplots of lakes and species with the environmental variables that explain the majority of the variation in the chironomid data using environmental data from 2000 and 2006. For corresponding taxon list refer to Appendix B.

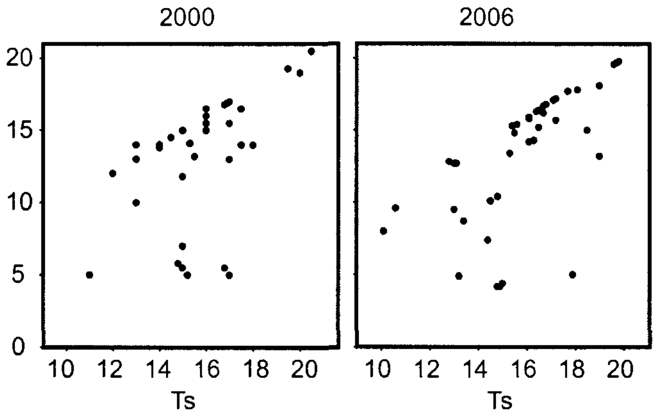

Figure 2.3: Scatterplots of the relation between surface-water temperature (Ts) and bottom water temperature (Tb) in 2000 and 2006

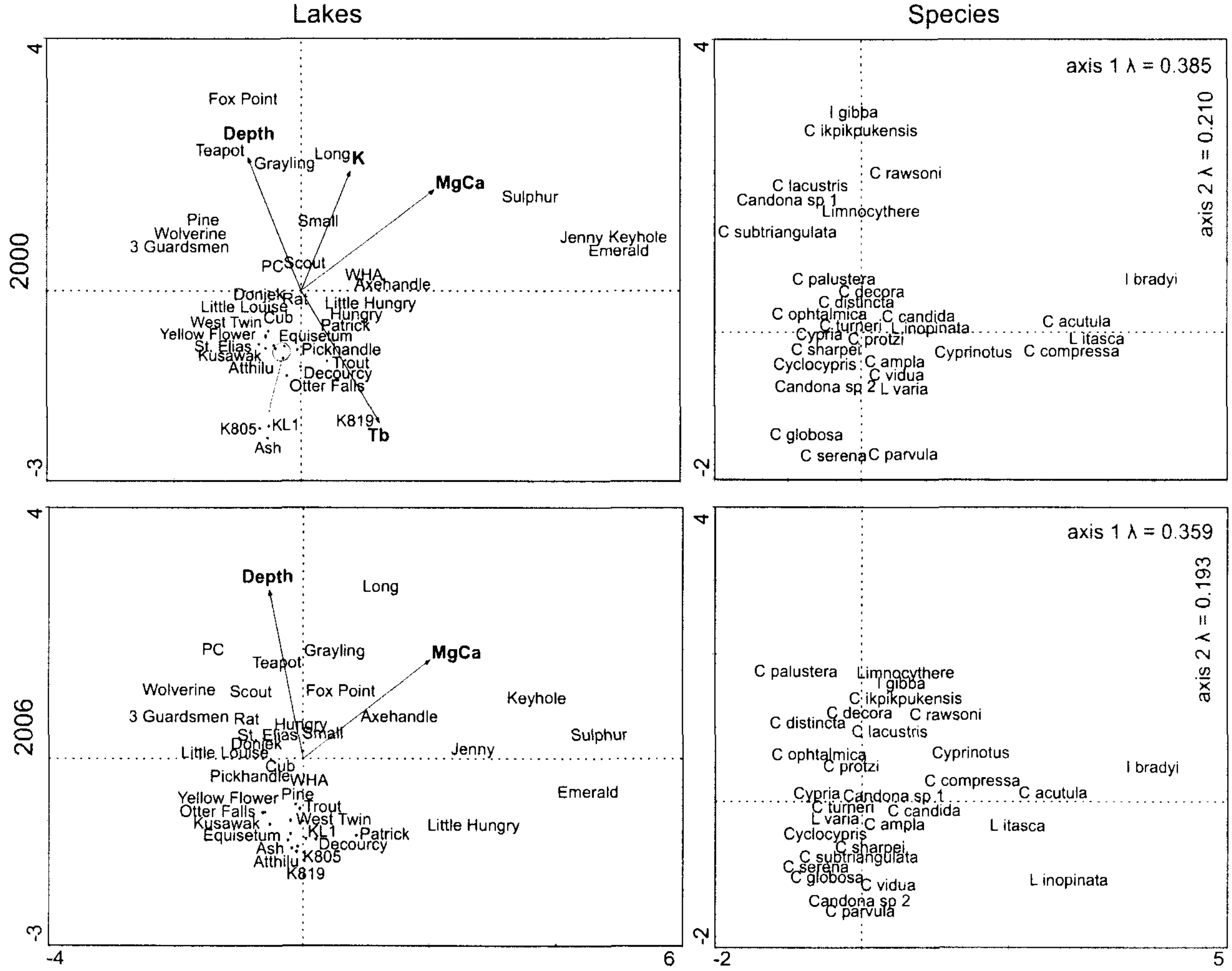

Figure 2.4: Canonical correspondence analysis joint plots of lakes and species with the environmental variables that explain the majority of the variation in the ostracode data using environmental data from 2000 and 2006.

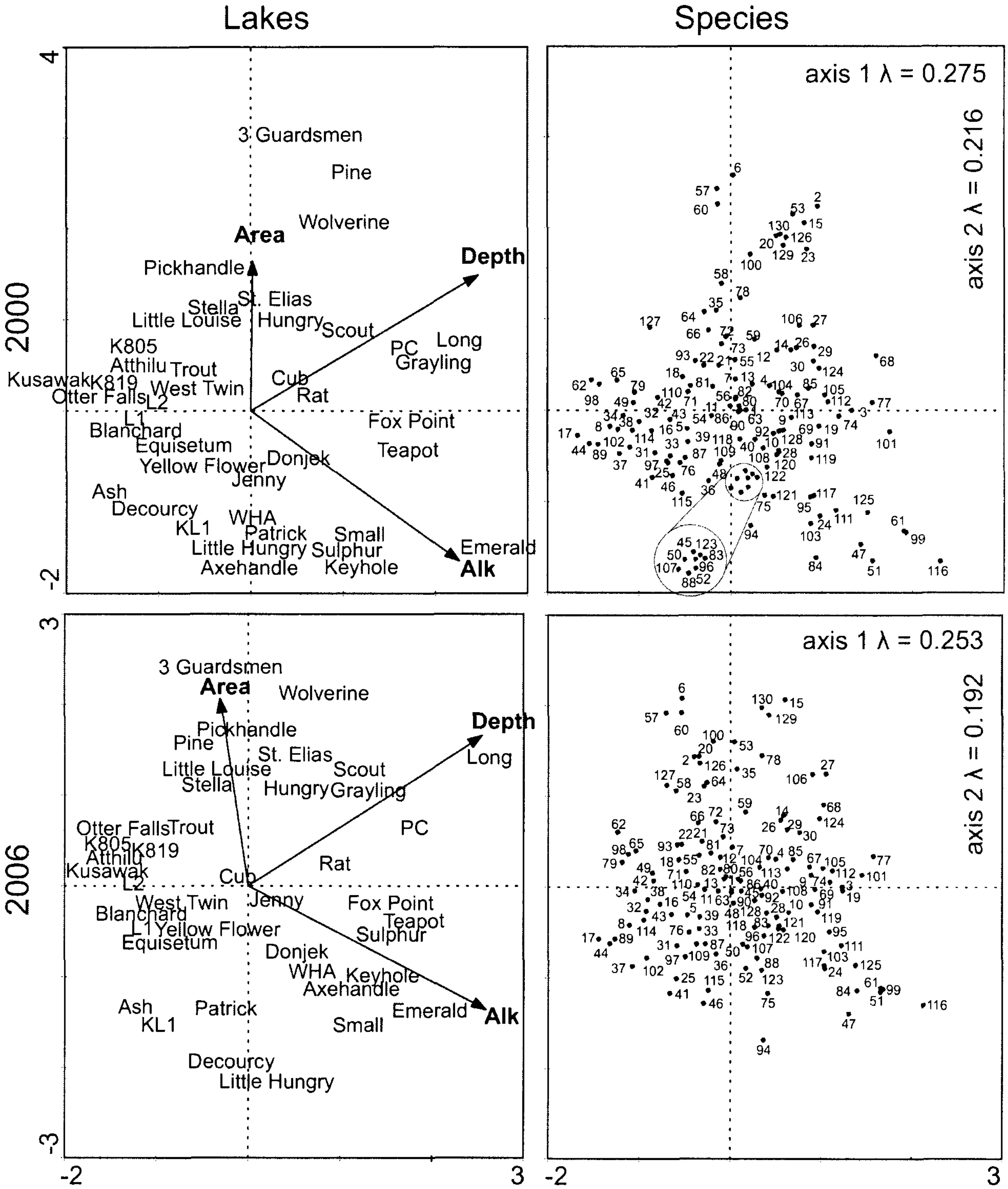

Figure 2.5: Canonical correspondence analysis joint plots of lakes and species with the environmental variables that explain the majority of the variation in the diatom data using environmental data from 2000 and 2006. For corresponding taxon list refer to Appendix E

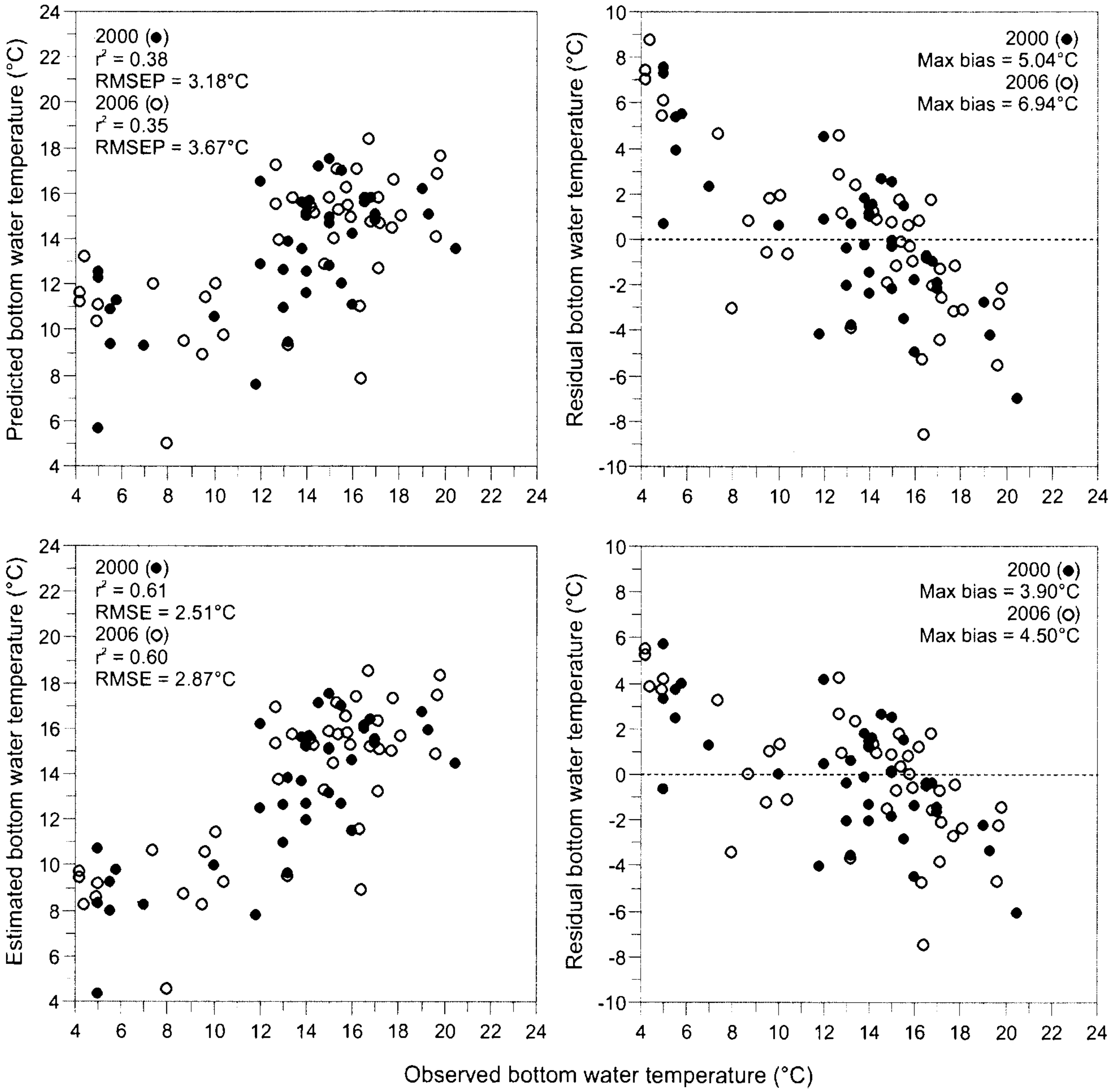

Figure 2.6: Estimated (apparent) and predicted (jack-knifed) chironomid-inferred bottom water temperatures using a one-component partial-least-squares (PLS) model for 2000 and 2006.

CHAPTER THREE

POSTGLACIAL CLIMATES INFERRED FROM A LAKE AT TREELINE, SOUTHWEST YUKON TERRITORY, CANADA

Abstract

Pollen, chironomid, and ostracode records from a lake located at alpine treeline provide regional paleoclimate reconstructions from the southwest Yukon Territory, Canada. The pollen spectra indicate herbaceous tundra existed on the landscape from 13.6-11 ka followed by birch shrub tundra until 10 ka. Although *Picea* pollen dominated the assemblages after 10 ka, low pollen accumulation rates and *Picea* percentages indicate minimal treeline movement through the Holocene. Chironomid accumulation rates provide evidence of millennial-scale climate variability, and the chironomid community responded to rapid climate changes. Ostracodes were found in the early Holocene and lateglacial, but likely disappeared due to chemical changes of the lake associated with changes in vegetation on the landscape. Inferred mean-July air temperature, total annual precipitation, and water depth indicate a long-term cooling with increasing moisture from the late glacial through the Holocene. During the Younger Dryas (12.9 to 11.2 ka), cold and dry conditions prevailed. The early and mid-Holocene were warm and dry, with cool, wet conditions after 4 ka, and warm, dry conditions since the end of the Little Ice Age.

Introduction

The southwest Yukon has long been an important region in Quaternary Studies. This mountainous area supports ice sheets and glaciers that have been studied to learn about glacial landforms (Russell 1898). The importance of the Bering Land Bridge as a connection between Asia and North America has led to numerous biogeographic (e.g. Hultén 1937) and paleoenvironmental studies (e.g. Hopkins 1967; Kontramavichus 1976; Elias 2001a), where a major goal was to gain an understanding of the full glacial biotic communities. Classic studies of late glacial and Holocene glacier fluctuations (e.g. Denton and Stuiver 1966; 1967) provided evidence that Holocene climate changes were significant enough to change alpine glacier mass balance, and led to attempts to study the global nature of glacier fluctuations (Denton and Karlén 1973; 1977; Grove 1979).

More recently, work has focused on understanding the higher-frequency climate variability of Beringia (Viau et al. accepted) using a variety of paleoclimate records. Paleoenvironmental evidence for the Younger Dryas cold interval (YD) in northwestern North America is found in lake sediment records from Alaska (e.g. Engstrom et al. 1990; Peteet and Mann 1994; Brubaker et al. 2001; Hu et al. 2002; Hu and Shemesh 2003; Yu et al. 2008), interior and coastal British Columbia (e.g. Mathewes 1993; Lacourse 2005; Chase et al. 2008), in marine sediments off of the B.C. coast (Mathewes et al. 1993), in beetle remains from Alaska (Elias 2001b), and in glacial moraines from Alaska and B.C. (Briner et al. 2002; Lakeman et al. 2008). However, the regional climates during the Younger Dryas are not entirely understood (Hu et al. 2006). Oxygen-isotope records from ice cores collected from Mt. Logan and nearby Eclipse Icefield document climate variability during the late Holocene (Holdsworth et al. 1992; Wake et al. 2002; Fisher et al. 2004), and the past 20 000 years (Fisher et al. 2008), and are used to interpret changes in the atmospheric circulation (Fisher et al. 2004; 2008). Qualitative interpretations of late glacial and Holocene paleoenvironmental sequences as well as quantitative paleoclimate reconstructions from Yukon, Alaska, and British Columbia are in agreement that the region experienced a long-term cooling trend with increasing moisture through the late Holocene (e.g. Pienitz et al. 2000; Abbott et al. 2000; Anderson et al. 2001; Palmer et al. 2002; Rosenberg et al. 2004).

The interior southwest Yukon is within the boreal forest biome and forest and alpine tundra vegetation can be studied as analogues of postglacial succession following ice-sheet retreat (Wright, 1980). Paleoecological and paleolimnological investigations using pollen (Birks 1980; Cwynar 1988; Stuart et al. 1989; Wang and Geurts 1991b; Keenan and Cwynar 1992; Cwynar and Spear 1995; Lacourse and Gajewski 2000), chironomids (Barley 2004), isotopes (Anderson et al. 2005a; Anderson et al. 2005b), and diatoms (Bradbury and Whiteside 1980), among others, have increased our understanding of the environmental variability in the region. However, quantitative climate reconstructions are virtually non-existent, and high-resolution multi-proxy records of Holocene environmental change are lacking.

The objective of this study is to quantify climate change in the southwest Yukon during the postglacial period. We provide estimates of mean-July air temperature, total annual precipitation, and water depth for the past 13 000 years using pollen, chironomids and ostracodes analyzed in a lake sediment core from a site at altitudinal treeline. The use of several proxy paleoclimate records aids in the determination of the potential precision of our reconstructions, and the similarities in the reconstructions of different indices lend more confidence to the results. The new quantitative estimates from this site can be used for comparison in other regional paleoenvironmental studies, which can then be used to further investigate the causes of natural climate variability.

Regional setting

Upper Fly Lake (unofficial name; 61.04°N, 138.09°W, 1326 m.a.s.l., 10.5 ha surface area) is located in the Ruby Range of the southwest Yukon, upslope from the Shakwak Trench (Figure 3.1). The lake lies in a well-eroded cirque basin with gneiss bedrock overlain by glacial till (Fulton 1995; Wheeler et al. 1997). Vegetation in the basin is comprised of shrub willow (*Salix*), dwarf birch (*Betula*) and various sedges (Cyperaceae), grasses (Poaceae), and other plants characteristic of forest-tundra transition zone, including individuals of white spruce (*Picea glauca*) on the surrounding slopes.

Mean January and July temperatures at Otter Falls Station (61.03°N, 137.05°W, 830 m.a.s.l.) are -16.4°C and 13.1°C, respectively, and total annual precipitation is 297 mm (Environment Canada 2000). Mean annual daily temperatures are -1.4°C and discontinuous permafrost is widespread in the region, particularly at higher elevations (National Atlas

Information Service 1995). The region is located 200-km northeast of the Gulf of Alaska, and is subject to a rain-shadow effect of the St. Elias Mountains.

Materials and Methods

Field Methods

A 298-cm lake sediment core was raised from Upper Fly Lake on August 4, 1997 from a lake depth of 4 m. A zodiac and a rubber raft anchored in the lake served as a coring platform and casing was used to ensure the same hole was re-entered on subsequent drives. Cores were recovered using a modified Livingstone piston sampler, and the uppermost unconsolidated sediment was collected using a clear plastic tube fitted with a piston. The uppermost 30 cm of sediment were extruded in 1-cm intervals into plastic bags at the base camp. Cores were extruded in the field, wrapped in plastic wrap and aluminum foil, transported to the University of Ottawa, Ontario and stored at 4°C.

Laboratory Methods

To determine changes in mineral content, magnetic susceptibility was measured on the cores at 1-cm intervals using a Bartington MS2 meter (Thompson et al. 1975). Sediment organic and carbonate content were measured at 1-cm intervals using sediment loss-on-ignition (LOI; Heiri and Lemcke 2001). The residual LOI is considered to represent the silicate content. Biogenic silica was extracted from the sediments using a wet-alkali digestion technique and determined using a spectrophotometer (DeMaster 1981; Parsons 1984).

A core chronology was established using ^{210}Pb, the date of a tephra layer, and accelerator mass spectrometry (AMS) radiocarbon dating. Samples for ^{210}Pb analysis were sent to Flett Research Ltd., and a constant rate of supply (CRS) model was applied to the ^{210}Pb values from the uppermost 10 cm of sediment. The tephra layer is the result of the White River Ash (WRA) event that deposited ash in the region 1147 cal yrs BP (Clague et al. 1995). Seven radiocarbon dates were measured at Beta Analytic Ltd. on hand-picked macrofossils (i.e. fragments of moss and other plant material, chironomid head capsules, other aquatic organic matter), and in one instance a twig fragment. Radiocarbon ages were calibrated to calendar years using the IntCal calibration dataset (Reimer et al. 2004) and CALIB 5.0.1 (Stuiver and Reimer 1993).

For pollen analysis, either 0.5 or 1 cm^3 of sediment was subsampled and processed using standard methods including treatment with 10% HCl, 10% KOH, HF, and an acetolysis solution (Faegri and Iversen 1989). A known volume of *Lycopodium* spores was added to each sample to allow for the calculation of pollen concentrations. At least 300 grains were identified per level (min = 343, max = 571, mean = 447) in a total of 66 levels through the core. Identifications were achieved using 400x magnification and occasionally 1000x under oil immersion. Taxonomy followed Faegri and Iversen (1989), Moore et al. (1991), Kapp et al. (2000) and the Laboratory for Paleoclimatology and Climatology, University of Ottawa pollen reference collection.

Between 1 and 11.25 cm^3 of sediment was subsampled and processed using standard methods for chironomids (Walker 2001). Head capsules were hand-picked with forceps from a Bogorov sorting tray, dried on to a coverslip and mounted on slides using Entellan©. Where possible, at least 50 head capsules were identified at each level in 54 levels (min = 7.5, max = 201.5, mean = 72.5). The level with 7.5 head capsules was included in Figure 3.5, but removed from all analyses; all other levels had counts > 15, but 17 levels had counts < 50. Identifications were made under 200x to 400x magnification and taxonomy followed Wiederholm (1983), Walker (1988), Heiri et al. (2004), Brooks (2006), Larocque and Rolland (2006) and Brooks et al. (2007).

For ostracodes, between 0.5 and 9.5 cm^3 of sediment was subsampled and processed using standard methods (Holmes 2001). Organic sediment samples were soaked overnight in 10% potassium hydroxide, whereas carbonate sediments were soaked up to 3 hours in 3% hydrogen peroxide, and/or for 48 hours in 5% sodium hexametaphosphate. Processed samples were sieved through 50 μm Nitex© mesh, valves were hand picked using a 0/5 brush under 10x magnification and mounted on micropaleontological slides using gum tragacanth. Of the 95 levels processed, only 52 had identifiable adult ostracodes (min = 1; max = 65, mean = 19). Identifications were achieved using 20x to 40x magnification and taxonomy followed Delorme (1968; 1970a; 1970b; 1970c; 1971).

Data Analyses

All data analyses were performed and presented using C^2 version 1.4.3 (Juggins 2003), unless otherwise indicated.

Pollen

Pollen data are presented as percentages of all terrestrial pollen grains and spores; taxa that constitute < 1% of the total pollen sum were combined into "Other" categories. Pollen accumulation rates were estimated for each level by multiplying the pollen concentration by the sedimentation rate, determined using the age-depth model. Spores are presented in Figure 3.3, however they were removed from all statistical analyses. A principal components analysis (PCA) was used to summarize the variation in a correlation matrix of 20 taxa and 66 samples of untransformed pollen data.

The modern analogue technique (MAT; Overpeck et al. 1985) was used to reconstruct mean-July air temperature (TJul) and total annual precipitation (PAnn). Modern pollen assemblages were extracted from the North American Modern Pollen Database (Whitmore et al. 2005), including sites north of 50°N and west of 110°W. Samples with pollen sums < 150 grains were excluded. The dissimilarity between the modern and fossil pollen assemblages was measured using squared-chord distance (SCD; Overpeck et al. 1985), and TJul and PAnn for the Upper Fly Lake pollen assemblages were estimated using the average of the top five analogues. Sample-specific standard errors were generated using 1000 bootstrap simulations (Birks 1995; Juggins 2003).

Chironomids

Chironomid taxa are presented as percentages of all head capsules. Taxa with < 2 capsules present or < 2% abundance in a sample were combined into Other Chironomidae and were not included in quantitative analysis. Chironomid accumulation rates were estimated as above. A principal components analysis (PCA) was performed on the correlation matrix of 19 species and 53 samples to summarize the variance in the chironomid data. Species data were square-root transformed prior to analysis.

Both a transfer function and the modern-analogue technique (MAT) were used to estimate mean-July air temperature (TJul) and water depth (Depth) using the chironomid data. A modern calibration set was compiled using data from Barley et al. (2006), Wilson & Gajewski (2004), and Bunbury & Gajewski (2008). This new dataset contains 186 sites and is comprised of 82 taxa and 19 environmental variables; dissolved inorganic carbon was not included as it was not measured at all lakes. Environmental data transformations and taxa selection followed Barley et al. (2006).

The temperature optimum of each taxon was calculated using weighted-averaging regression and calibration. A detrended correspondence analysis (DCA using CANOCO 4.5; ter Braak and Šmilauer, 2002) of the modern chironomid dataset revealed a gradient length of 3.6 SD units, deeming unimodal methods appropriate to determine the variables that best explain the variance in the species data (ter Braak 1995). Preliminary canonical correspondence analyses (CCA) were run to assess collinear environmental variables and to determine outliers. The FOREST variable had a variance inflation factor > 20 and was removed. Lakes A07, A19, U27, U58, KW03, and KW14 had extreme influence (> 8x) as determined by the leverage diagnostics in CANOCO 4.5 and were removed from the final ordination and the development of the inference model. Forward selection revealed TJul and Depth as statistically significant variables that best explain the variance in the chironomid data ($p > 0.05$, 999 Monte Carlo permutations).

Detrended canonical correspondence analyses (DCCA; CANOCO 4.5) were performed on the modern calibration dataset constrained to each of TJul and Depth, and revealed gradient lengths of 2.4 and 1.5 SD units, respectively. Both unimodal and linear methods were applied to the modern calibration sets (not shown), and the model with the best performance statistics and residuals was used to reconstruct each variable (not shown; Birks 1998). A weighted-averaging partial-least-squares (WAPLS) 3 component model was applied to the fossil chironomid data to reconstruct mean-July air temperature and water depth.

The MAT was also used to estimate TJul and Depth from the fossil chironomid data. SCD was used to measure the dissimilarity between the modern and the fossil chironomid assemblages, and the value of mean-July air temperature and water depth for each fossil sample was estimated using the average of the top five analogues. Sample-specific standard errors were generated for both models using 1000 bootstrap simulations.

Ostracodes

Ostracode data are presented as percentages of all adult valves and accumulation rates estimated as above. A PCA of the correlation matrix computed from 8 species and 52 samples was used to summarize the variation in the log-transformed ostracode data. The modern calibration dataset from Bunbury & Gajewski (2008) was used to estimate water depth from the fossil ostracode data using the MAT. The dissimilarity between the modern and the fossil assemblages was measured using squared-chord distance (SCD), and the water depth for each fossil sample was estimated using the average of the top five analogues. Prior to the analyses, levels in the fossil ostracode dataset containing fewer than 10 specimens were removed, reducing the dataset to 34 samples. Sample-specific standard errors were generated using 1000 bootstrap simulations.

Results

Sediment Stratigraphy

Basal sediments (285-298 cm) were comprised of grey silt and clay, with low organic and carbonate content (< 5%), high silicate content, and high (up to 210 SI) magnetic susceptibility values (Figure 3.2). Marl sediments (up to 27% carbonate content) with light grey and dark grey-brown laminations occurred between 220 cm and 285 cm. In this section of the core, the silicate content decreased from ~80 to ~50%, organic content rose from 15 to 40%, and magnetic susceptibility was < 5 SI. The uppermost 220 cm of the sediment sequence was primarily dark-brown gytta with infrequent pale laminations, high-organic content (typically > 30%), low-carbonate content (< 5%), moderate silicate content (up to 70%), and magnetic susceptibility values ~10 SI. The White River Ash (WRA) tephra layer is visible at 53 cm and apparent in the magnetic susceptibility curve. Biogenic silica values increased from 200 cm to the top of the core. Diatoms and other sources of biogenic silica in the sediments apparently undergo dissolution through time making this variable difficult to interpret; therefore it will not be discussed further.

Chronology

The chronology was based on the 7 ^{210}Pb age determinations (Table 3.1), 6 ^{14}C dates (Table 3.2), and the White River Ash (WRA) age; the radiocarbon date from 34-36 cm was not included in the model as it was older than the well-dated WRA (Clague et al. 1995) that was positioned at 53 cm. The two ^{14}C dates from 221-223 cm and 256-259 cm were statistically indistinguishable. Although the δ^{13}C/^{12}C ratio for the younger date was lower, there was no rationale to choose between the two dates when developing the age-depth curve. We therefore retained both dates when we fit a loess (alpha = 0.6, lambda = 2) to 13 age determinations to derive the age-depth model (Figure 3.2). The slope of the age-depth curve is constant for sediments older than 4 ka, however we recognize the ambiguity in age estimates between approximately 6 and 12 ka. All ages in this paper are reported with respect to the zero date of AD 1997 (1 ka = 1000 years before AD 1997). The clearance of ice from the Shakwak Trench is not well dated, however a date of 12 500 ^{14}C yr BP (Denton and Stuiver 1966; 1967; ~14 700 cal yrs BP) is close to our basal date of 13.6 ka.

Accumulation Rates

Pollen accumulation rates (PAR) were low prior to 11 ka (Figure 3.2). They remained relatively high between 10.7 and 5.5 ka then declined, reaching minimum values around 1.5 ka. PAR subsequently increased during the past 1.5 ka.

Chironomids began to accumulate in the sediments ~13.3 ka. They increased in abundance rapidly at a time that corresponds to a decrease in magnetic susceptibility and an increase in sediment organic content. Chironomid accumulation rates (CAR) remained relatively high between 12.5 and 10 ka, and then were low between 9.5 and 4.5 ka. CAR were higher again between 4.5 and 3.5 ka, then lower during the late Holocene with another peak ~0.5 ka and a large increase over the last 20 years.

Ostracodes started to accumulate in the sediments ~13.2 ka. Ostracode accumulation rates (OAR) then increased, reaching a first maximum around 12.2 ka. OAR then decreased to zero between 11.3 to 11.2 ka. Following a brief second increase, OAR quickly fell to zero and ostracodes were absent from the core after ~10 ka.

Pollen

The earliest pollen assemblages, prior to ~12.5 ka, indicate an herbaceous tundra dominated by Cyperaceae, Poaceae, and *Salix* pollen (Figure 3.3). Pollen spectra indicative of an herbaceous tundra environment continued to dominate the landscape with high values of *Artemisia* between 12.9 and 11.2 ka, corresponding to the timing of the Younger Dryas. During this time *Betula* pollen percentages increased, non-arboreal pollen (NAP; particularly Poaceae and Cyperaceae) were high, and *Populus* and Cupressaceae remained relatively high even though their percentages were very low. Around 11 ka values of *Betula* pollen were high, *Alnus crispa* pollen percentages began to increase, and around 10 ka *Picea* pollen increased and *Betula* decreased, suggesting forest establishment at sites downslope from Upper Fly Lake. Of the *Picea* grains that could be distinguished, 84% were *Picea glauca*, therefore, all *Picea* pollen are combined in the diagram, as there was no tendency through time in the percentages of *P. mariana* or *P. glauca*. Today, *P. glauca* is the only spruce species growing in the region. *Picea* dominated the pollen assemblage for the remainder of the Holocene with slightly lower percentages between 3.2 and 2 ka, and higher values again from 2 to 0.7 ka. Poaceae, Cyperaceae, and *Pinus* pollen all increased during the last 6 ka. Ninety-six percent of the *Pinus* pollen are type diploxylon. Accumulation rates of the local taxa generally decreased between 11 and 0.5 ka, as did tree pollen, suggesting changes in lake sedimentation were the dominant control on their values (Figure 3.4).

Chironomids

Prior to ~13 ka, the chironomid assemblages were comprised of taxa with colder temperature optima, such as *Paracladius*, *Micropsectra insignilobus*-type, *Heterotrissocladius* and Other Tanytarsina (Figure 3.5). *Psectrocladius (Psectrocladius)* noticeably dominated the assemblage ~12.8 ka, and the concurrent presence of *Microtendipes* suggests a brief warm period. During the Younger Dryas (between 12.9 and 11.2 ka), *Micropsectra insignilobus*-type had high percentages and high accumulation rates. Other taxa present in the core during this time interval include *Sergentia*, Other Tanytarsina, *Procladius*, and *Microtendipes*, however the accumulation rates of the latter, warm-adapted taxa declined quickly (Figure 3.6). After 11.9 ka, Other Tanytarsina and *Sergentia* became more abundant, with the former having values between 30 and 40% from 11.5 to 5.5 ka (Figure 3.5). Following the Younger Dryas, the accumulation rate of the cold-adapted taxon *Micropsectra insignilobus*-type declined, while the accumulation rates of several chironomid taxa increased (Figure 3.6). This increase in CAR corresponds to the time of arrival of *Picea* into the region (Figure 3.3). *Chironomus* increased considerably after 10 ka, peaking around 7.5 ka, and declined after 5 ka. Percentages and accumulation rates of *Cricotopus/Orthocladius* increased after 5.5 ka, with peak values between 4.5 and 3.5 ka. Around 4.2 ka, *Psectrocladius* (undifferentiated) and *Micropsectra insignilobus*-type appeared briefly in the core. Between 4 and 1 ka the assemblages were dominated by *Cricotopus/Orthocladius*, *Sergentia*, Other Tanytarsina, and to a lesser extent *Chironomus* and *Paratanytarsus*, and *Sergentia* became more abundant after 1 ka. Taxa with warmer optima comprised a large part of the assemblage in the most recent sediments and include *Corynocera oliveri*-type, Other Tanytarsina, and to a lesser extent, *Psectrocladius (Psectrocladius)*, *Chironomus*, *Procladius*, and *Stempellinella/Zavrelia* (Figure 3.5).

Ostracodes

Prior to 13 ka, the ostracode assemblages were comprised of an unknown Limnocytherid and *Cytherissa lacustris* (Figure 3.7). *Candona candida* and *Cyclocypris globosa* increased just prior to 12.5 ka, but counts were very low, with 13 or fewer valves in a sample. *Candona rectangulata* appeared shortly thereafter. These three ostracode taxa were present throughout the Younger Dryas, with *C. candida* and *C. globosa* more abundant than *C. rectangulata* (Figure 3.7). Between 11.7 and 11.1 ka, valve counts were low (< 13), corresponding to a decline in sediment carbonate content (Figure 3.2). After 11.1 ka, total valve counts increased, as did the number of taxa present. *Cyclocypris ampla* appeared in the record around 11 ka and by 10.8 ka *Candona paraohioensis* appeared for a period of about 100 years, followed by *C. protzi* for ~200 years. After 10.5 ka, total valve counts decreased (13 or fewer), *C. paraohioensis* and *C. protzi* disappeared from the core, and by 10.4 ka, so did *C. candida*. *C. ampla* comprised a large portion of the ostracode assemblages between 10.6 and 10 ka, after which ostracodes were no longer present in the core.

Principal Components Analysis

A principal components analysis (PCA) was individually applied to each of the fossil organism datasets to summarize temporal changes in species composition (Figure 3.8). The first two axes of the PCA on the pollen data explain 46.0% of the variation in the pollen data (Figure 3.8a). Taxa typically found in the tundra (*Salix*, Cyperaceae, Poaceae, *Oxyria*, Chenopodiaceae, and *Artemisia*) are positively correlated with PCA axis 1, and forest pollen types (*Picea* and *Alnus*) are negatively correlated. Taxa positively correlated with PCA axis 2 include *Picea*, *Pinus*, *Populus*, Ericaceae, Cyperaceae, and Poaceae whereas *Betula* is negatively correlated with this axis. Sample scores on PCA axis 1 indicate a decreasing trend up to 9 ka, slightly negative values until 1 ka and a slight increase subsequently (Figure 3.8d). Sample scores on PCA axis 2 decreased from maximum values at 13 ka reaching minimum values between 11.5 and 10 ka. Scores increased slowly between 10 and 3.3 ka, and more rapidly in the past 4 ka.

The first 2 principal components explain 35.7% of the variation in the chironomid data (Figure 3.8b). *Micropsectra insignilobus*-type, *Procladius*, and *Psectrocladius (Psectrocladius)* were dominant during the late glacial and are positively correlated with PCA axis 1, whereas *Cricotopus/Orthocladius*, *Sergentia*, *Paratanytarsus* and *Chironomus* were dominant during the Holocene and are negatively correlated with this component. Sample scores on this axis show a decreasing trend from the base of the record to 2 ka, with abrupt excursions at 8.2 ka and 4.2 ka (Figure 3.8d). *Psectrocladius* (undifferentiated), *Heterotrissocladius*, and *Paracladius* types have colder optima and are positively correlated with PCA axis 2, whereas Other Tanytarsina types, *Dicrotendipes*, *Chironomus*, and Orthocladiinae sp. 2 have warmer optima and are negatively correlated with this component. From 2 ka to the present, sample scores increase on PCA axis 2 and show abrupt transitions at 13 ka, 11.2 ka, and 8.4 ka.

The first 2 axes of the ostracode PCA explain 40.0% of the variance in the ostracode data. *Cyclocypris ampla* is positively correlated with PCA axis 1, and *Cyclocypris. globosa* and *Candona rectangulata* are negatively correlated with this component (Figure 3.8c). *C. candida* and *C. ampla* are highly positively correlated with PCA axis 2, and *C. globosa* and *Limnocythere* sp. are negatively correlated with this component. *C. ampla* and *C. candida* have warmer optima, whereas *C. globosa* and *C. rectangulata* are tolerant of colder conditions and are taxa found today in modern sediments in the Canadian Arctic (Bunbury and Gajewski, unpublished).

Climate Reconstructions

Prior to 11 ka dissimilarities are high, so climate estimates are less reliable during this time period (Figure 3.9). Total annual precipitation (PAnn) reconstructed using the pollen data indicate relatively low values prior to 10 ka and values similar to today for the Holocene (360 mm).

Pollen-inferred mean-July air temperatures (TJul) were highest during the early Holocene, with values consistently over 14°C between 10 and 7 ka. This was followed by a small but long-term decrease in temperature. These results broadly coincide with the chironomid-based reconstructions using the MAT that show warmer conditions between 13 and 12.3 ka, cool temperatures between 12.3 and 11.2 ka, followed by an abrupt increase beginning at 11.2 ka. The increase in temperature reconstructed using chironomids is more abrupt than that observed in the pollen reconstruction. There is no tendency in the dissimilarities between modern and fossil chironomid assemblages. A gradual, long-term decrease in temperature occurs in the chironomid-based reconstruction between 5.5 and 1.4 ka, after which inferred temperatures increase, a trend that is not evident in the pollen-inferred record. Results based on the WAPLS transfer function method are similar to those based on the MAT, however the trend is less pronounced and the range of the reconstructed TJul is smaller (WAPLS = 7.0-12.3°C; MAT = 5.4-13.1°C).

Changes in water depth are affected by both precipitation and evaporation. The water depth reconstructions based on chironomids are the inverse of the TJul time series, with high water levels between 12.5 and 10.5 ka, shallower water between 10 and 4 ka, and higher levels again during the past 4 ka. Although errors are large, the ostracode-inferred water depth reconstruction generally resembles that derived from chironomids.

Discussion

Postglacial vegetation changes and lake evolution

Formation of the lake basin occurred ~13.6 ka and chironomids colonized the lake ca. 13.3 ka, prior to the establishment of ostracodes at 13.2 ka. Early chironomid assemblages contained two cold stenotherms (*Paracladius* and *Heterotrissocladius*) that are typically found today at high latitudes and altitudes or in deep temperate lakes (e.g. Olander et al. 1999; Porinchu and Cwynar 2000; Wilson and Gajewski 2004; Barley et al. 2006). *Heterotrissocladius* has been recorded in abundance in postglacial sediments from both North America and Europe, however it typically declines rapidly following ice sheet retreat in response to warming (Walker and Cwynar 2006).

An abrupt increase in carbonate content, gradual increase in organic content, rapid increase in chironomid accumulation rates (CAR), and a shift to warm-adapted chironomid taxa after 13 ka all indicate a brief increase in lake production (Figures 3.2 and 3.5) as a result of warmer mean-July air temperatures. During the summer, greater production occurred in both the lake and the watershed, contributing to increasing values of organic content in the sediments. Increased photosynthetic production within the lake also assists in biologically induced inorganic precipitation of lacustrine carbonates (Dean 1981).

Reduced lake production occurred towards the end of the Younger Dryas (11.5 to 11.2 ka) in response to cooler, drier conditions as indicated by the reconstructed total annual precipitation and mean-July air temperature estimates. The increase in silicates, slight increase in magnetic susceptibility, and decrease in carbonate and organic content may have been caused by increased deposition of loëss in the watershed. Today, loëss derived from the Slims River can frequently be seen in the Kluane Lake area to the west of Upper Fly Lake, and it is likely that greater amounts of loëss were formed in the late glacial. Typically, higher magnetic susceptibility suggests greater mineral input into the lake and since the pollen-inferred precipitation reconstructions suggest dry conditions, the increased inorganic material could be loëss.

Immediately following the Younger Dryas (11.2 ka), lake production once again increased and taxa adapted to warmer conditions *Dicrotendipes*, *Microtendipes*, *Chironomus*, and Other Tanytarsina (Brooks et al. 2007) began to increase in abundance. As climate conditions improved, the PAR also increased, suggesting an overall increase in pollen production in the watershed due to more dense or productive vegetation cover. As vegetation density increases around a lake, watershed-scale hydrological changes (i.e. runoff, infiltration) occur that reduce alkalinity and lower pH within the lake. Decreasing values of calcium carbonate in the lake water likely caused the disappearance of ostracodes from the record, as these organisms require well-buffered water and circum-neutral pH for their survival and shell preservation (Delorme 2001). The nature of the sediments suggests a similar successional pattern identified in lakes in recently deglaciated terrain (Engstrom et al. 2000; Fritz et al. 2004), however, the pollen record from Upper Fly Lake suggests that forest did not grow in the immediate vicinity of the lake during the Holocene; this is discussed below.

Between 11 and 10 ka, the climate in the southwest Yukon was warm and dry, and it has been suggested that the aridity delayed the establishment of *Picea* in the region

(Anderson et al. 2005b). However, the accumulation rates of certain pollen taxa suggests natural succession was occurring at this time; an increase in the accumulation rates of *Populus* followed by Cupressaceae is seen in boreal forest pollen sequences elsewhere (e.g. northern Quebec after 6ka; Gajewski et al. 1993) suggesting a successional stage prior to *Picea* forest establishment (Figure 3.4; Peros et al. 2008). After 10 ka, the composition of the pollen assemblages show little change up to the present day.

Between 10 ka and 4.5 ka, chironomid accumulation rates (CAR) were very low, and pollen accumulation rates (PAR) increased. Mean-July air temperature and water depth estimates infer warmer conditions, total annual precipitation estimates indicate increasing moisture compared to the previous period, and the presence of *Chironomus* and Other Tanytarsina suggests a warmer and more productive lake environment (Brooks et al. 2007). After 4.5 ka and up to ~1 ka both PAR and CAR were low, suggesting decreased production in both the lake and the watershed. Over the past 1000 years, PAR increased in response to warmer conditions that corresponded in time to the Medieval Warm Period, followed by declining values during the Little Ice Age. The high values of PAR and CAR in the uppermost samples reflect either greater productivity in both the terrestrial and aquatic ecosystems, and/or more accurate sedimentation rates estimated by ^{210}Pb dates.

There is little evidence in the record from Upper Fly Lake of significant treeline movement during the Holocene. *Picea* pollen percentages and PAR are low, and apart from an increase in the lake sediments ca. 10 ka, there are few fluctuations in *Picea* percentages in the subsequent record (Figures 3.3 and 3.4). In a pollen record from the central Yukon, in a setting similar to that found at Upper Fly Lake (shrub tundra with occurrences of *P. glauca*), *Picea* pollen percentage diagrams showed few changes in the Holocene, as was seen here. However, the accumulation rates were higher before 5000 yrs BP, which was inferred as an upslope movement of treeline (Cwynar and Spear 1991). At Upper Fly Lake, it appears that the *Picea* pollen curve is simply reflecting regional, as opposed to local, dynamics of the *Picea* populations. The increase in *Picea* pollen at this site occurred synchronously with increases observed in other sequences at lower elevation, but in close vicinity to Upper Fly Lake. *Picea* arrived in the Kluane Lake region approximately 8.5 ^{14}C kyr BP (9.5 cal kyr BP; Stuart et al. 1989; Lacourse and Gajewski 2000; Whittmire 2001). At other sites in the southwest Yukon *Picea* arrived between 9 and 8.5 ka (Wang and Geurts 1991a), suggesting a rapid migration into the southwest Yukon at this time; the small differences in the arrival of *Picea* between these sites is likely a result of the variations in the chronologies. Sources of the *Picea* pollen at Upper Fly Lake may be from forests upwind of the site (Markgraf 1980), or from the forest at lower altitudes as upslope transport of tree pollen is common in mountainous regions (Fall 1992). Further evidence for a lack of *Picea* surrounding Upper Fly Lake during the Holocene is the low PAR values, which are more typical of tundra environments. However, the PAR in Upper Fly Lake may be low not only because tundra environments tend to have low pollen production but also because the surface area of the lake is quite large (10.5 ha) compared to those typically used for pollen analysis, thereby diluting the amount of pollen that accumulates in the sediments.

Although it has traditionally been thought that *Picea* rapidly migrated up the Mackenzie valley as the corridor opened (Ritchie and MacDonald 1986), new interpretation of full-glacial pollen data from Alaska (Brubaker et al. 2005), *Picea* macrofossil data from the Yukon (Zazula et al. 2006), and *Picea glauca* DNA evidence from Alaska (Anderson et al. 2006) all suggest refugia that would have provided new source regions for *Picea* forests in the southwest Yukon. This may explain the rapid migration of *Picea* into the southwest Yukon between 9 and 8.5 ka. However, the few available sites from the region do not permit the migration route to be determined.

Regional climate variability during the past 13 ka at Upper Fly Lake

Multi-proxy paleoclimate reconstructions from Upper Fly Lake exhibit greater variability during the late glacial and early Holocene, followed by a less variable mid-Holocene and again increasingly variable conditions after 4 ka, albeit reduced in comparison to the early part of the record. This pattern is similar to that observed at the continental scale (Figure 3.10; Viau et al. 2006). Although this discussion is based on our chosen chronology, a difference of up to 800 years could exist if we had rejected one or the other of the overlapping dates.

The pollen and chironomid derived reconstructions indicate long-term cooling from the early through the mid-Holocene, followed by moisture conditions similar to today since 4 ka. Lake-level estimates from Marcella Lake in the southwest Yukon reveal a comparable moisture record (Anderson et al. 2005b), and Eastern Beringian mean-July temperature anomalies inferred from pollen averaged over 13 sites also show a cooling trend over the past 8000 cal yrs BP (Viau et al. accepted). Midge-inferred July temperatures combined from 6 subalpine sites in interior southern B.C. exhibit a long-term cooling trend, as do reconstructions from two lakes in the same region (Pellatt et al. 1998; Palmer et al. 2002; Rosenberg et al. 2004; Chase et al. 2008). However a site located in boreal forest in the southwest Yukon suggests warming from the early through the mid-Holocene and cooling thereafter (Barley 2004).

A cooling trend is also summarized on the chironomid principal components analysis (PCA) axis 1 where there is a gradual change from positive to negative sample scores from the late glacial through the Holocene (Figure 3.10). Superimposed on the long-term cooling trend revealed by PCA axis 1 are abrupt changes to more negative or more positive sample scores found on PCA axis 2. There are also periods of distinctive increases in the chironomid accumulation rates (CAR), the frequency of which correspond well with millennial-scale climate variations (Viau et al. 2002; 2006). These variations indicate times of climate transitions, and when the CAR evidence is combined with the abrupt changes in chironomid sample scores on PCA axes 1 and 2, suggest that the chironomid community has responded to climate change over the past 13 ka at Upper Fly Lake. This trend is seen to a lesser extent in the pollen PCA and is likely the result of lower sampling resolution of the pollen data (Figure 3.8d). Another explanation is that the pollen data integrate information from several ecosystems, therefore they would not necessarily only record changes in, for example, the tundra vegetation.

The onset and termination of the Younger Dryas (YD) is dated between 12.9 and 11.2 ka at Upper Fly Lake. At this time, *Artemisia* pollen is abundant, and *Micropsectra insignilobus*-type dominates the chironomid assemblages (Figure 3.10). High values of *Artemisia* pollen are indicative of a cold, dry climate, and increases during the YD are documented in records from southern Yukon (Cwynar 1988), Alaska (Engstrom et al. 1990; Hu et al. 1995; 2002), central Russia (Khotinsky and Klimanov 1997), and Europe (Heiri et al. 2007). The chironomid *Micropsectra insignilobus*-type is regarded as a cold stenotherm (Brooks et al. 2007) that has been found in late glacial sediments in Russia (Ilyashuk and Ilyashuk 2007), and was recently identified in late glacial sediments from the Italian Alps (Larocque and Finsinger 2008).

The chironomid-inferred mean-July air temperature (TJul) estimates indicate warmer temperatures (9-12°C) at the beginning of the YD (before 12 ka), however evidence from Alaska (e.g. Engstrom et al. 1990; Elias 2001b; Hu et al. 2002; 2006) and British Columbia (e.g. Mathewes 1993; Lacourse 2007) all suggest cooler temperatures at this time. Although the dissimilarities between modern and fossil pollen are large in the pollen-based reconstructions suggesting potential non analogues and therefore less reliable reconstructions, they are not unusual in the chironomid-based reconstruction, which also indicates a slight warming at this time. Water depth (Depth) estimates inferred from both chironomid and ostracode data indicate that the greatest depths occurred after 12 ka, corresponding with colder TJul estimates derived from both pollen and chironomids (Figure 3.10). However, the chironomid-inferred Depth values appear overestimated, particularly those reconstructed using the weighted-averaging partial-least-squares (WAPLS) method.

Inconsistencies in the chironomid-inferred reconstructions during the YD and between 2 and 1 ka may be due to a negative relation between air temperature and water depth, but could also simply be a consequence of the spatial distribution of sites in the modern chironomid calibration set. Modern analogues during the early part of the YD (12.9 to 12 ka) are found in deep lakes (7-27 m) in northern B.C., where thermal stratification of these lakes would result in cold temperatures in the hypolimnion. *Procladius,* which is found in the profundal area of lakes (Brooks et al. 2007), comprises over 20% of the chironomid assemblage during the period in question. However, mean-July air temperatures at the lakes that contain the modern analogues are relatively warm, resulting in an overestimation of TJul values. During the latter part of the YD (12-11.2 ka) the water depth estimates appear exaggerated. This occurs for a similar reason that TJul are overestimated in the first part of the YD; because the dominant taxa in these levels (*Micropsectra insignilobus*-type) is frequently found in deep lakes in the calibration set. Between 2 and 1 ka, mean-July air temperatures are comparable to those reconstructed during the YD, which implies that this period was as cold as the YD in this region. The calibration set encompasses lakes from British Columbia, Alaska, Yukon Territory, and the Canadian Arctic Islands. The modern analogues selected for samples of ages 2-1 ka are from lakes from the middle to high Arctic. A histogram of the mean-July air temperatures in the calibration set (not shown) indicates that there are no samples spanning a portion of the temperature gradient (i.e. low Arctic sites). Therefore, we conclude that these paleoclimate reconstructions could be improved with the addition of more arctic and alpine sites to ensure that there are data along the entire mean-July air temperature gradient.

The coldest temperatures reconstructed during the YD (post 12 ka) are 7-9.5°C (up to 2.8°C cooler than today). Midge-inferred temperature reconstructions from southern B.C. during the late glacial are 8-10°C (Palmer et al. 2002) which compare well with the inferred values in this study. Pollen-inferred TJul estimates for samples between 13.4 and 12 ka are less reliable due to non-analogue situations, and values using the chironomid data appear overestimated, as explained above.

Although there are inconsistencies in the reconstructions at this time, increases in *Artemisia* pollen and *Micropsectra insignilobus*-type chironomids correspond to the time of the onset of the YD as dated in the GISP2 temperature record (Alley 2000; 2004). However, based on the chironomid-inferred TJul, the termination of the YD occurs ~300 years later at Upper Fly Lake (Figure 3.10) with the chosen chronology. Lacourse (2007) suggested that the temporal lag may exist due to delays in the climate system or in the ecosystem response time, but we cannot resolve this issue with our data.

Climates following the YD were warm, with maximum mean-July air temperatures reconstructed between 9.8 and 7.4 ka using pollen data and between 10.8 and 5.6 ka using chironomid data, which coincide with the timing of maximum warmth found in other records from western North America (Figure 3.10; Kaufman et al. 2004). Chironomid-inferred TJul increased abruptly, becoming 4-6°C warmer in just over 400 years, whereas the increase in pollen-derived values (~5°C) was more gradual (1000 years). The increase in temperature occurred when *Picea* became dominant in the pollen spectra, after which the estimates are consistently 3-5°C warmer than chironomid-inferred values. This may occur since the pollen record is dominated by taxa found at lower elevations (Figure 3.3). The TJul estimates derived from the chironomid data are similar to the TJul values following the YD reconstructed from midge data at Windy and Thunder Lakes in southern B.C. (Chase et al. 2008).

Pollen-derived total annual precipitation (PAnn) and water depth (Depth) estimates for Upper Fly Lake inferred from ostracodes and chironomids (WAPLS technique) suggest drier conditions between 11 and 10 ka and compare reasonably well with lake-level reconstructions from Marcella Lake (Anderson et al. 2005b). However, this interpretation is somewhat contradicted by the chironomid Depth reconstructions using the MAT as several of the analogues found during this time are from deep lakes (Figure 3.10). PAnn reconstructions increased ~9.8 ka and correspond broadly with lake level increases from Birch and Jan Lakes in Alaska ~9000 yrs BP (10 000 cal yrs BP; Abbott et al. 2000; Barber and Finney 2000), and Marcella Lake in the southwest Yukon ~10 000 cal yrs BP (Anderson et al. 2005b). An ice core record from Mt. Logan exhibits more positive $\delta^{18}O$ values also suggesting wetter conditions in the interior at this time (Fisher et al. 2008).

At 8.2 ka, the long-term cooling represented by the chironomid sample scores on PCA axis 1 is punctuated by an abrupt deviation to negative values, and the sample scores on PCA axis 2 show a small, but sharp increase (Figure 3.10). This coincides with the timing of a global cooling event initiated by the final collapse of the Hudson Bay ice sheet (Alley et al. 1997; von Grafenstein et al. 1998; Barber et al. 1999). However, given the possible alternative chronologies, the timing of this cooling at Upper Fly Lake could be up to 400 years earlier or later. Although the coincidence of this event in the chironomid record is intriguing, we cannot establish the correlation with certainty. Regional evidence of this event includes glacial advances in the St. Elias Mountains and the southern B.C. Coast Mountains (Denton and Karlén 1973; Menounos et al. 2004), and treeline retreat in northern B.C. (Pisaric et al. 2003). Lake sediment records from southern B.C. and Alaska also suggest variations around this time, yet the data are not as clear (Chase et al. 2008; Yu et al. 2008). At this site, interpretation of the chironomid PCA scores and the increase in Depth inferred from chironomids suggest cool, wet conditions at 8.2 ka.

Kurek et al. (2004) questioned the utility of chironomids in reconstructing small-scale climate episodes, and proposed that either the proxy is insensitive to these changes, or that the effects of cooling at 8.2 ka in their area of study (Maine, U.S.A.) were not significant. Although it may be difficult to quantify these rapid climate events, the abrupt changes in the sample scores on PCA axis 1 around 8.2 ka suggest that the chironomid community is responding to centennial-scale climate variability.

Reconstructed PAnn increased slightly through the early and mid-Holocene, however values remained below modern until ~5 ka. The chironomid-inferred Depth reconstructions using the MAT indicate a similar increasing trend, yet those inferred using the WAPLS method remained stable (Figure 3.10). Based on the above, we interpret the period between 8 and 5 ka as relatively warm and dry, which compares well with the investigations of alpine ice patches in the southwest Yukon that indicate either a warmer or drier period between 7700 and 5500 cal yrs BP (Farnell et al. 2004), and the Marcella Lake lake-level reconstruction that suggests dry conditions between 7500 and 5000 cal yrs BP (Anderson et al. 2005b).

At 4.2 ka, the chironomid-inferred Depth estimates show a brief decrease and there is a slight shift in the chironomid PCA scores on both axes. This coincides with the timing of a widespread drought (Booth et al. 2005), multiple glacial advances in southern B.C. (Menounos et al. 2008), an obvious sharp decrease in $\delta^{18}O$ values in the Mt. Logan ice core (Figure 3.10; Fisher et al. 2008), and more negative $\delta^{18}O$ values of Jellybean Lake sedimentary carbonates (Anderson et al. 2005a). The PAnn estimates are low between 4.5 and 3.5 ka, and it has been suggested that the interior Yukon was drier due to an intensified, eastward-located Aleutian Low (Anderson, 2005a).

Between 4 and 2 ka, PAnn estimates at Upper Fly Lake were similar to modern, TJul estimates reconstructed using the MAT are near present-day values, and inferred Depths increased (Figure 3.10). The pollen record indicates an increase in the abundance of tundra pollen (Cyperaceae and Poaceae), which is concurrent with an increase in cold-adapted chironomid taxa (*Paracladius* and *Sergentia*) replacing warm-adapted types (Other Tanytarsina and *Chironomus*; Figure 3.5). Combined, this evidence suggests a cool, wet climate and this interpretation concords with increased lake levels at Marcella Lake (Anderson et al. 2005b), and more positive $\delta^{18}O$ values at Jellybean Lake (Anderson et al. 2005a). In addition, there is evidence of glacial advances in the St. Elias Mountains and northern Coast Mountains of B.C. during this time (Denton and Karlén 1973; 1977; Clague et al. 2004)

Between 2 and 1 ka, the TJul reconstructions inferred from chironomids using the MAT suggest conditions were as cold as those that existed during the YD in the southwest Yukon, whereas the pollen-inferred TJul values indicate warm conditions (Figure 3.10). The inconsistency appears to be due to the lack of samples in the modern chironomid calibration set, discussed above.

Between 1.3 and 0.8 ka pollen-inferred TJul values indicate warmer conditions existed during the Medieval Warm Period. During this time, chironomid TJul and Depth estimates are increasing. In the period following (~0.5 to 0.2 ka) pollen-based TJul and chironomid-inferred Depth estimates decreased suggesting cooler conditions existed during the Little Ice Age (Figure 3.10). However, changes are slight and not consistently recorded in the chironomid reconstructions. Since ~0.15 ka, chironomid-inferred TJul values reconstructed using the MAT have increased and Depth estimates have decreased. These data combined with regional tree-ring evidence (Youngblut and Luckman 2008), and $\delta^{18}O$ records from Jellybean Lake (Anderson et al. 2005a) indicate that a warmer and drier climate has prevailed in the southwest Yukon since the end of the Little Ice Age.

Conclusions

Pollen, chironomid, and ostracode records from Upper Fly Lake provide a detailed summary of the late glacial and Holocene climates in the southwest Yukon. Quantitative reconstructions compare well with other proxy climate records from Yukon, Alaska, and B.C. and indicate that cold and dry conditions existed during the Younger Dryas, followed by a warm, dry mid-Holocene, cooler conditions thereafter, and warmer conditions since the end of the Little Ice Age. Vegetation surrounding the lake has consisted primarily of herbaceous and shrub birch tundra and the evidence provided here shows little indication of treeline movement at this site. Chironomid accumulation rates provide evidence for millennial-scale climate variations during the late glacial, the early Holocene, and the late Holocene, and abrupt shifts in the chironomid community composition appear to be related to millennial-scale variations related to changes in temperature.

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Table 3.1: Lead-210 dates from the lake sediment core at Upper Fly Lake, southwest Yukon

Depth (cm)	Years before present[a] at bottom of sediment section (CRS model estimate)
3.0-4.0	6.8
4.0-5.0	13.7
5.0-6.0	20.3
6.0-7.0	27.6
7.0-8.0	32.9
8.0-9.0	38.4
9.0-10.0	42.8

[a] Before AD 1997

Table 3.2: AMS radiocarbon dates from the lake sediment core at Upper Fly Lake, southwest Yukon

Depth (cm)	Lab Code	Conventional Radiocarbon age (yr BP)	2-sigma calibrated age range (cal yr BP)[a]	Median calibrated age (cal yr BP)	Ages before AD 1997 (ka)[b]	$\delta^{13}C/^{12}C$ (‰)	Material
34-36[c]	Beta – 229092	1490 ± 40	1302-1420	1361	1408	-26.3	Macrofossils
69-71	Beta – 229093	2440 ± 40	2355-2547	2451	2498	-22.2	Macrofossils
106-107	Beta – 229976	3570 ± 40	3816-3978	3897	3944	-25.6	Macrofossils
149-153	Beta – 229977	5350 ± 40	5996-6221	6108.5	6155.5	NA	Macrofossils
221-223	Beta – 229094	9540 ± 80	10652-11162	10907	10954	-32.4	Macrofossils
256-259	Beta – 229978	9650 ± 70	10767-11202	10984.5	11031.5	-28.6	Macrofossils, twig fragment
278-281	Beta – 229095	11120 ± 90	12889-13189	13039	13086	-24.1	Macrofossils

[a] Calibration was based on IntCal04 (Reimer et al. 2004).
[b] Dates were converted from cal yr BP to AD 1997 (year of core collection; see text for details).
[c] The date from 34-36 was not used in the chronology (see text for details).

Table 3.3: Sites used for comparison with the records from Upper Fly Lake, southwest Yukon, indicated in Figure 3.1.

No.	Site name	Latitude (°N)	Longitude (°W)	Reference	Data source
1	Lake of the Woods	49.05	120.18	Palmer et al. 2002	chironomids
2	North Crater	49.18	120.08	Palmer et al. 2002	chironomids
3	Southern BC	49.48	122.62	Menounos et al. 2004	glaciers
4	Frozen	49.59	121.46	Rosenberg et al. 2004	chironomids
5	3M	49.65	121.50	Pellatt et al. 1998	chironomids
6	Cabin	49.65	121.25	Pellatt et al. 1998	chironomids
7	Windy	49.81	117.88	Chase et al. 2008	chironomids
8	Misty	50.62	127.27	Lacourse 2005	pollen
9	Eagle	51.05	118.17	Rosenberg et al. 2004	chironomids
10	Thunder	52.23	119.35	Chase et al. 2008	chironomids
11	Northern BC	56.25	130.08	Clague et al. 2004	glaciers
12	BC2	58.47	124.47	Pisaric et al. 2003	stomates
13	Pleasant Island	58.35	135.67	Engstrom et al. 1990	pollen
14	Marcella	60.07	133.81	Anderson et al. 2005	lake sediments
15	Kettlehole	60.07	133.81	Cwynar 1988	pollen
16	Jellybean	60.35	134.80	Anderson et al. 2005	lacustrine carbonate del 18O
17	Mt. Logan	60.62	140.52	Fisher et al. 2008	ice core del 18O
18	Sulphur	60.95	137.98	Lacourse and Gajewski 2000	pollen
19	Jenny	61.04	138.36	Stuart et al. 1989	pollen
20	Keyhole	61.08	138.37	Whittmire 2001	pollen
21	U60	62.75	136.63	Pienitz et al. 2000	diatoms
22	Antifreeze	62.33	140.82	Barley 2004	chironomids
23	Monkshood	64.57	138.25	Cwynar and Spear 1991	pollen
24	Honeymoon	64.63	138.40	Cwynar and Spear 1991	pollen
25	Jan	63.57	143.90	Barber and Finney 2000	lake sediments
26	Birch	64.30	146.67	Abbott et al. 2000	lake sediments
27	Hundred Mile	61.81	147.84	Zu et al. 2008	lacustrine carbonate del 18O
28	Ongoke	59.25	159.42	Hu et al. 2006	biogenic silica
29	Arolik	59.47	161.12	Hu et al. 2006	biogenic silica
30	Nimgun	59.48	161.00	Hu et al. 2002	pollen
31	Ognivuk	59.57	159.37	Hu et al. 1995	pollen
32	Grandfather	59.80	158.52	Hu et al. 1995	pollen
33	GISP2	72.59	38.46	Alley 2004	ice core temperature

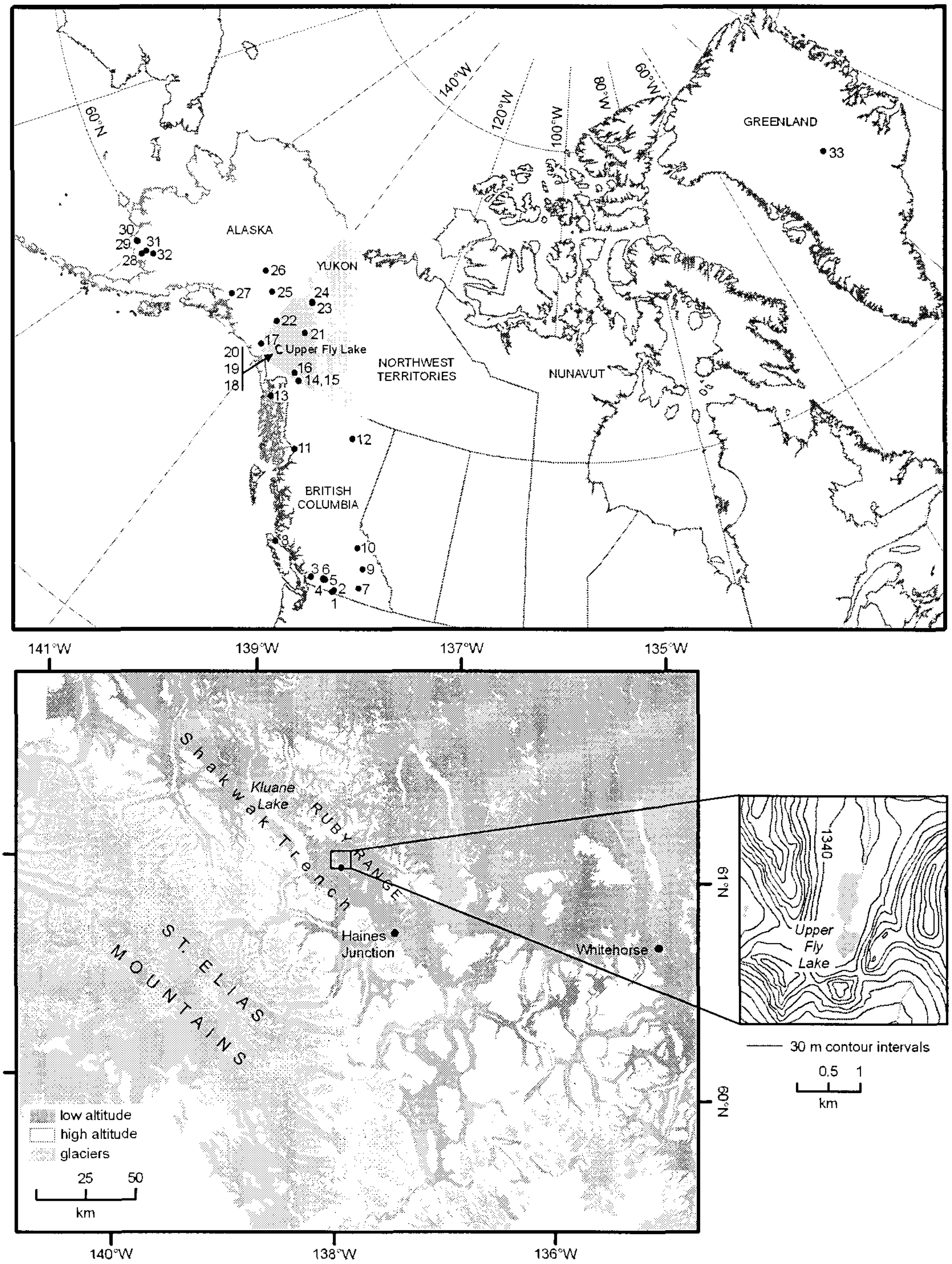

Figure 3.1: Location map of Upper Fly Lake, southwest Yukon. Other sites listed in Table 3.3.

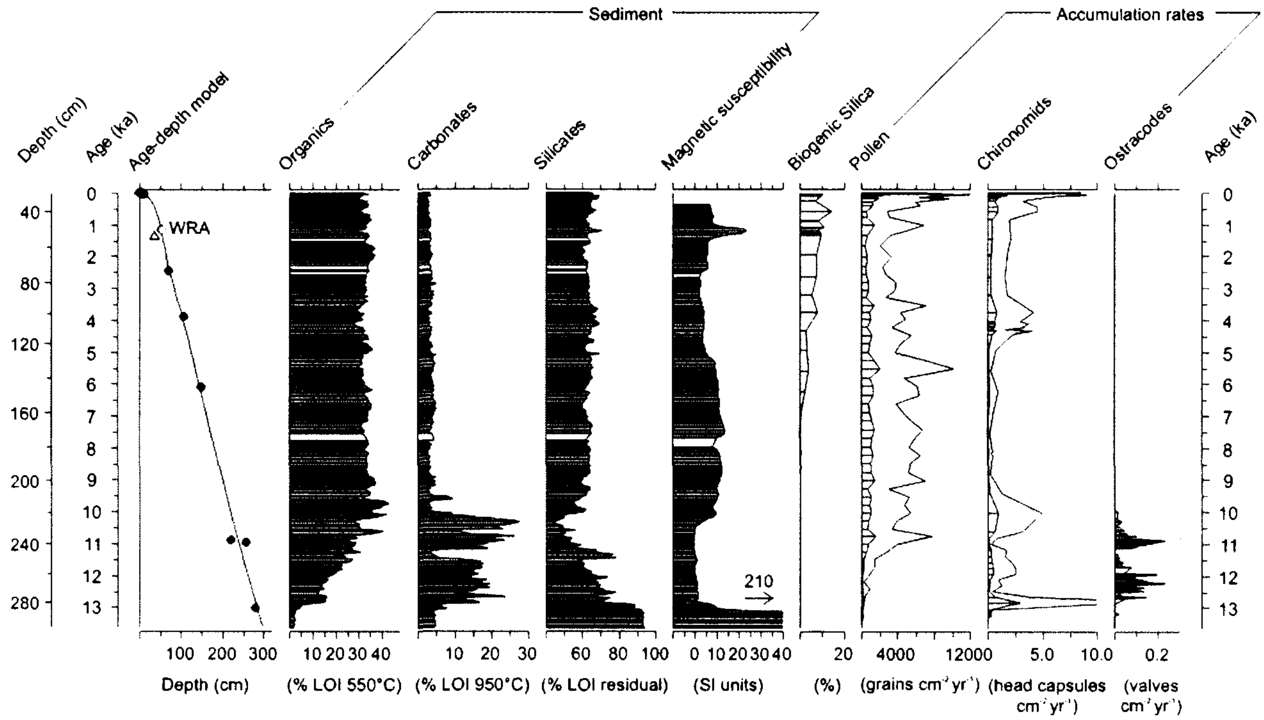

Figure 3.2: Age-depth model, sediment characteristics, and accumulation rates of pollen, chironomids, and ostracodes from Upper Fly Lake, southwest Yukon. The open circle on the age-depth curve represents the date of the White River Ash (WRA), and the open triangle represents the date not used in the development of the chronology. The second curve in the accumulation rate graphs corresponds to 5x exaggeration. Ages are ka (= 1000 yrs) before AD 1997.

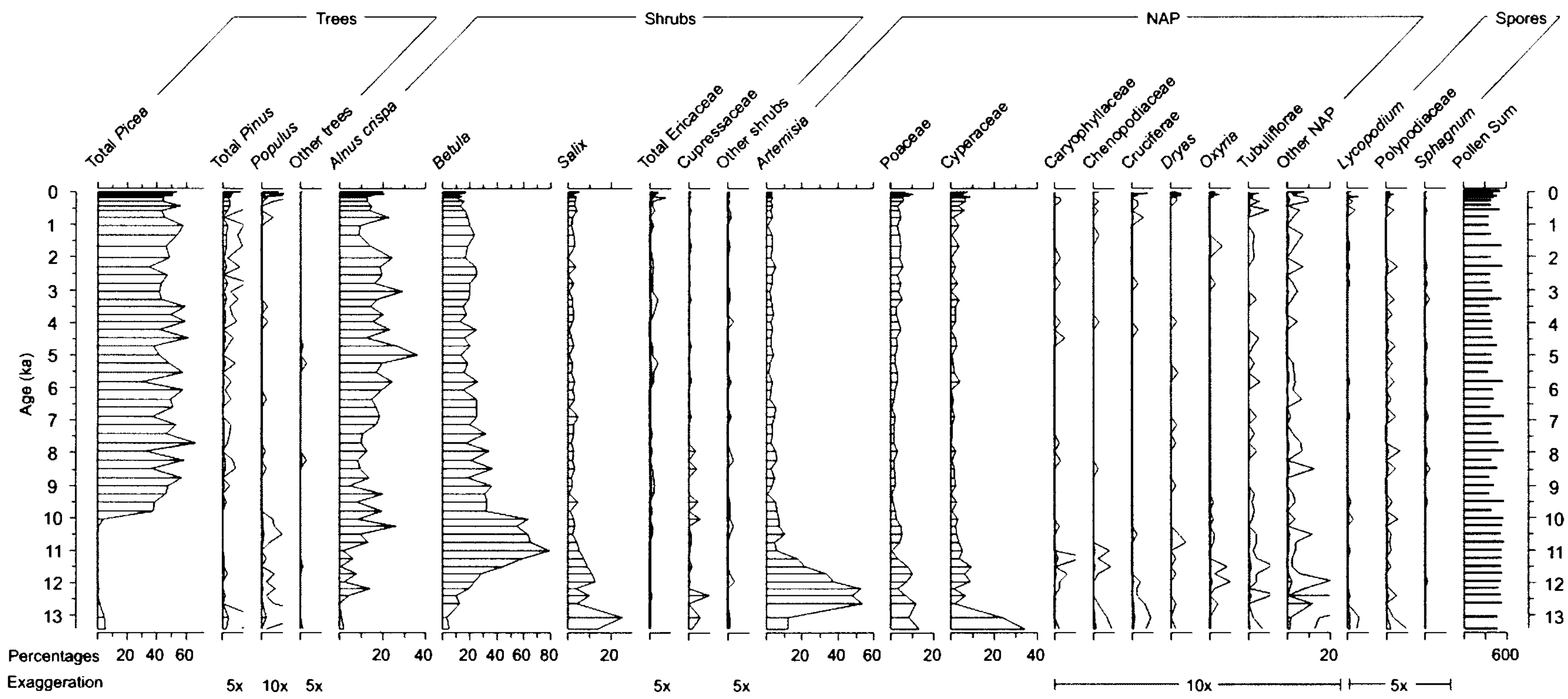

Figure 3.3: Percentages of pollen taxa from Upper Fly Lake, southwest Yukon. Graphs of types with low percentages have a second curve corresponding to either 5x or 10x exaggeration. Pollen types in the category Other trees include *Abies*, *Larix*, *Tsuga* and deciduous trees; in Other shrubs include *Corylus*, *Cornus*, and *Myrica*; and in Other NAP include several rare types. Note varying scales. Ages are ka before AD 1997.

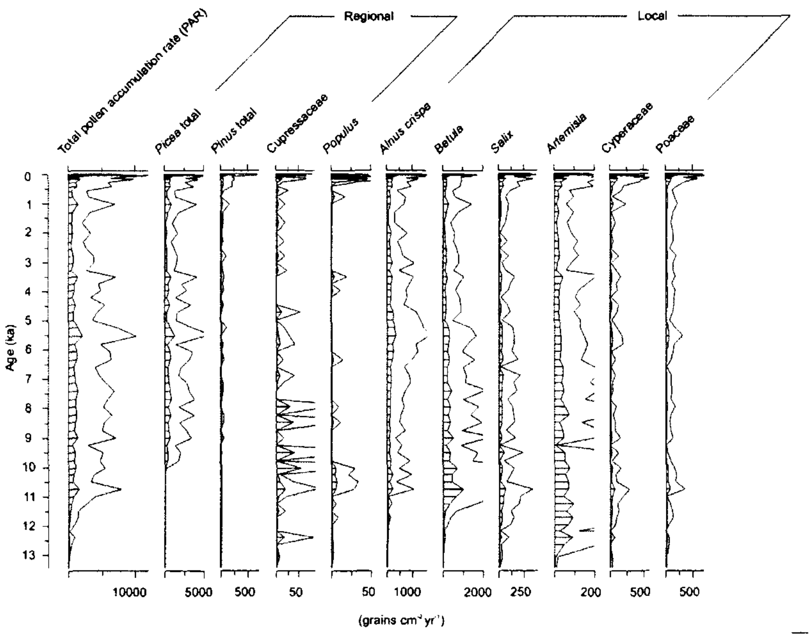

Figure 3.4: Total pollen accumulation rate (PAR) and accumulation rates of select pollen taxa from Upper Fly Lake, southwest Yukon. Taxa are categorized into regional and local types. A second curve corresponds to 5x exaggeration. Note varying scales. Ages are ka before AD 1997.

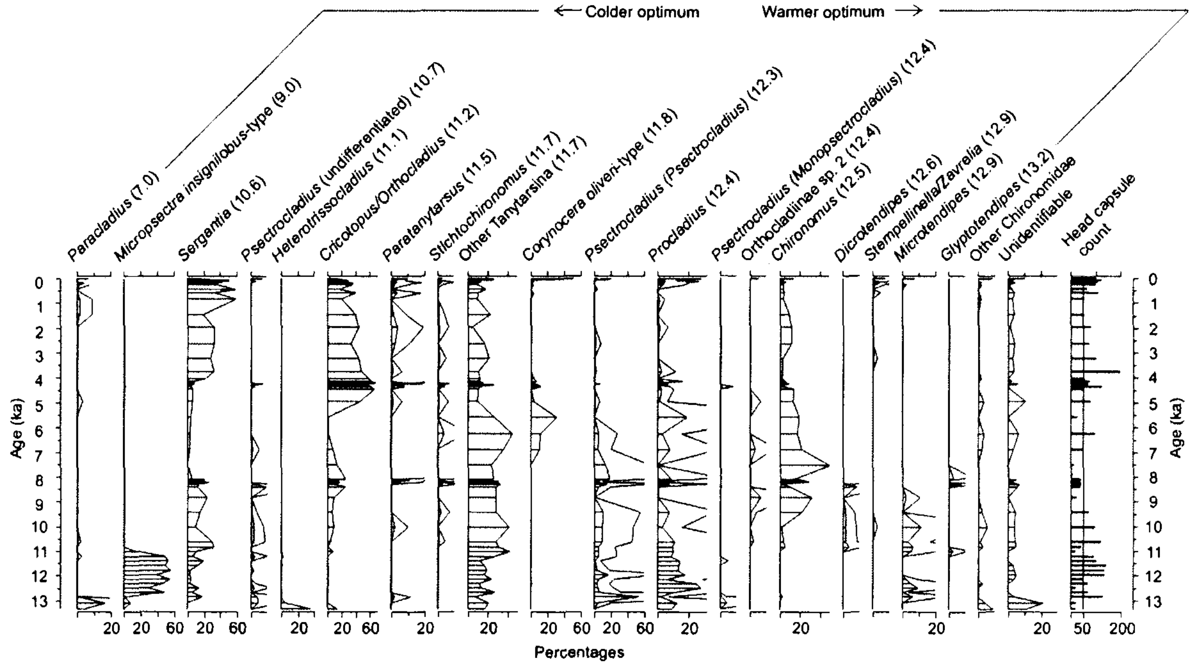

Figure 3.5: Percentages of chironomid taxa from Upper Fly Lake, southwest Yukon. Taxa are organized on a gradient from colder to warmer temperature optima, in parentheses, generated using weighted-averaging regression and calibration. A second curve on select graphs corresponds to 5x exaggeration. Note varying scales. Ages are ka before AD 1997.

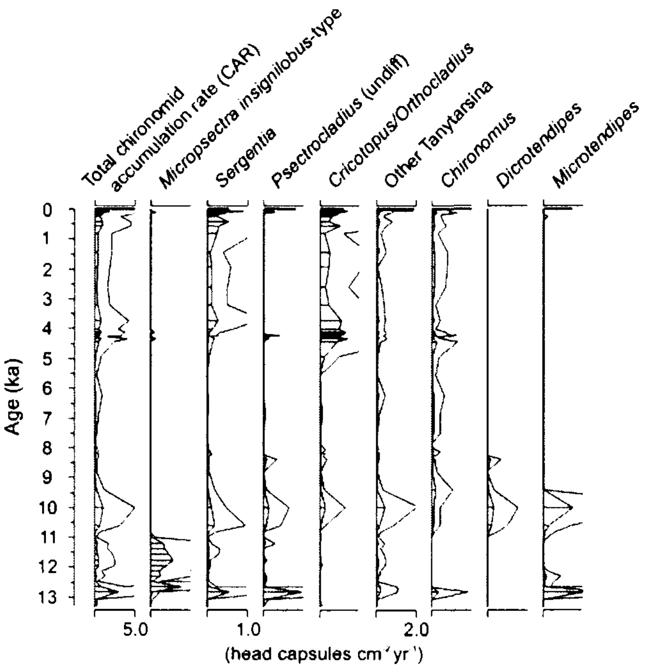

Figure 3.6: Total chironomid accumulation rate (CAR) and accumulation rates of select chironomid taxa from Upper Fly Lake, southwest Yukon. A second curve corresponds to 5x exaggeration. Note varying scales. Ages are ka before AD 1997.

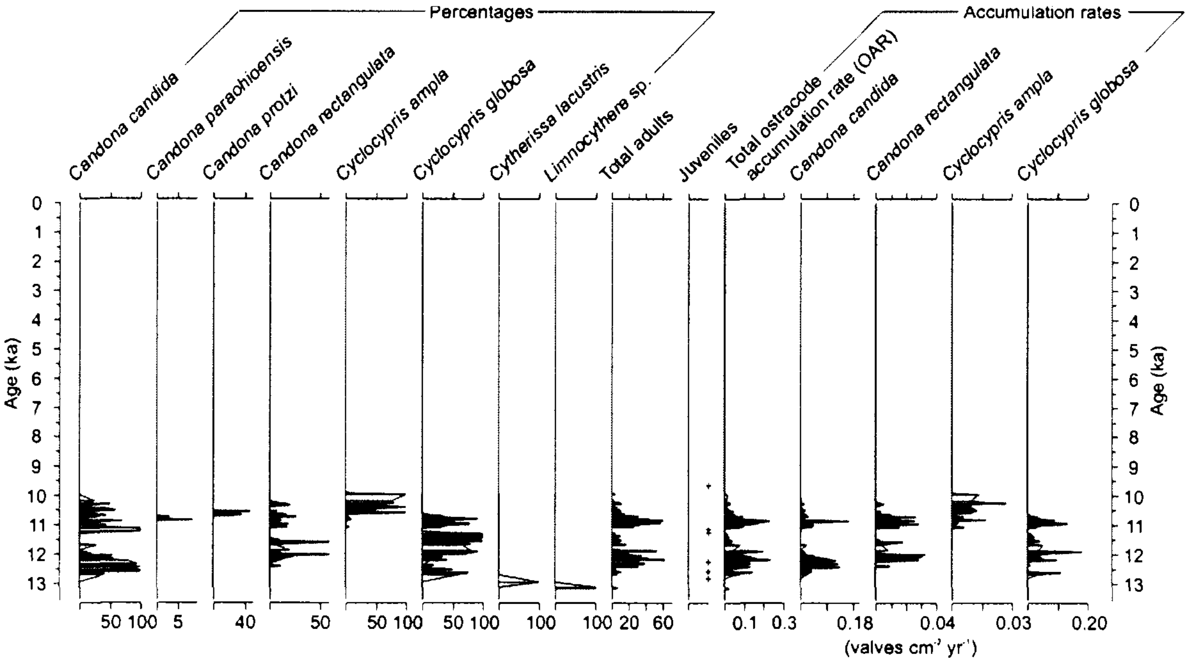

Figure 3.7: Percentages, total adults, total ostracode accumulation rate (OAR), and accumulation rates of select ostracode taxa from Upper Fly Lake, southwest Yukon. Note varying scales. Juveniles are shown for levels where juvenile ostracodes were encountered, but adults were not. Note varying scales. Ages are ka before AD 1997.

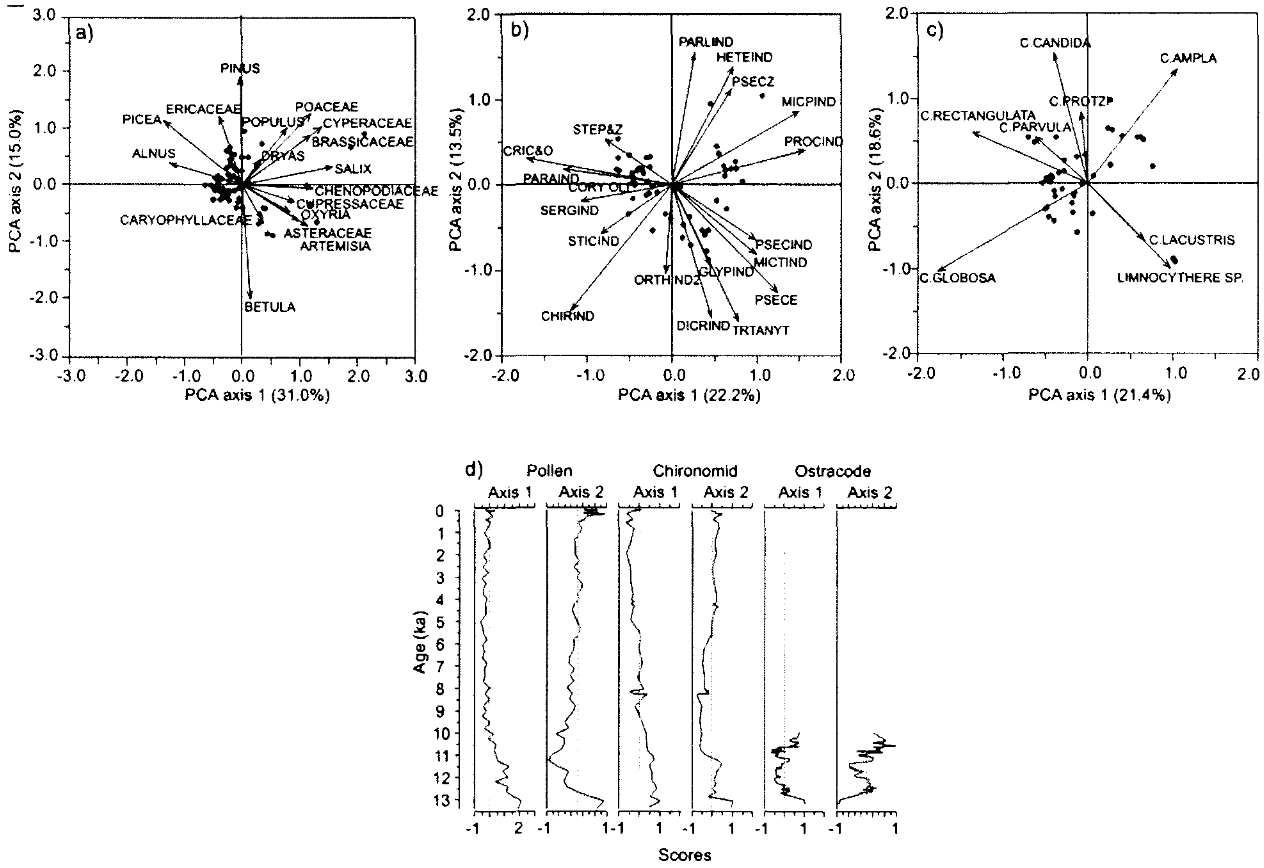

Figure 3.8: Principal components biplots for a) pollen, b) chironomids, c) ostracodes, and d) time-series graphs of pollen, chironomid, and ostracode sample scores for PCA axes 1 and 2, from Upper Fly Lake, southwest Yukon. Ages are ka before AD 1997. Abbreviations of chironomid taxon are as follows: CHIRIND = *Chironomus*, DICRIND = *Dicrotendipes*, GLYPIND = *Glyptotendipes*, MICTIND = *Microtendipes*, SERGIND = *Sergentia*, STICIND = *Stichtochironomus*, CORY OLI = *Corynocera oliveri*-type, STEP&Z = *Stempellinella/Zavrelia*, HETEIND = *Heterotrissocladius*, PARLIND = *Paracladius*, PSECIND = *Psectrocladius* undifferentiated, PSECINDE = *Psectrocladius (Psectrocladius)*, ORTHIND2 = Orthocladiinae sp. 2, PROCIND = *Procladius*, PSECINDZ = *Psectrocladius (Monopsectrocladius)*, trtanyt = Other Tanytarsina, CRIC&O = *Cricotopus/Orthocladius*, PARAIND = *Paratanytarsus*, MICPIND = *Micropsectra insignilobus*-type.

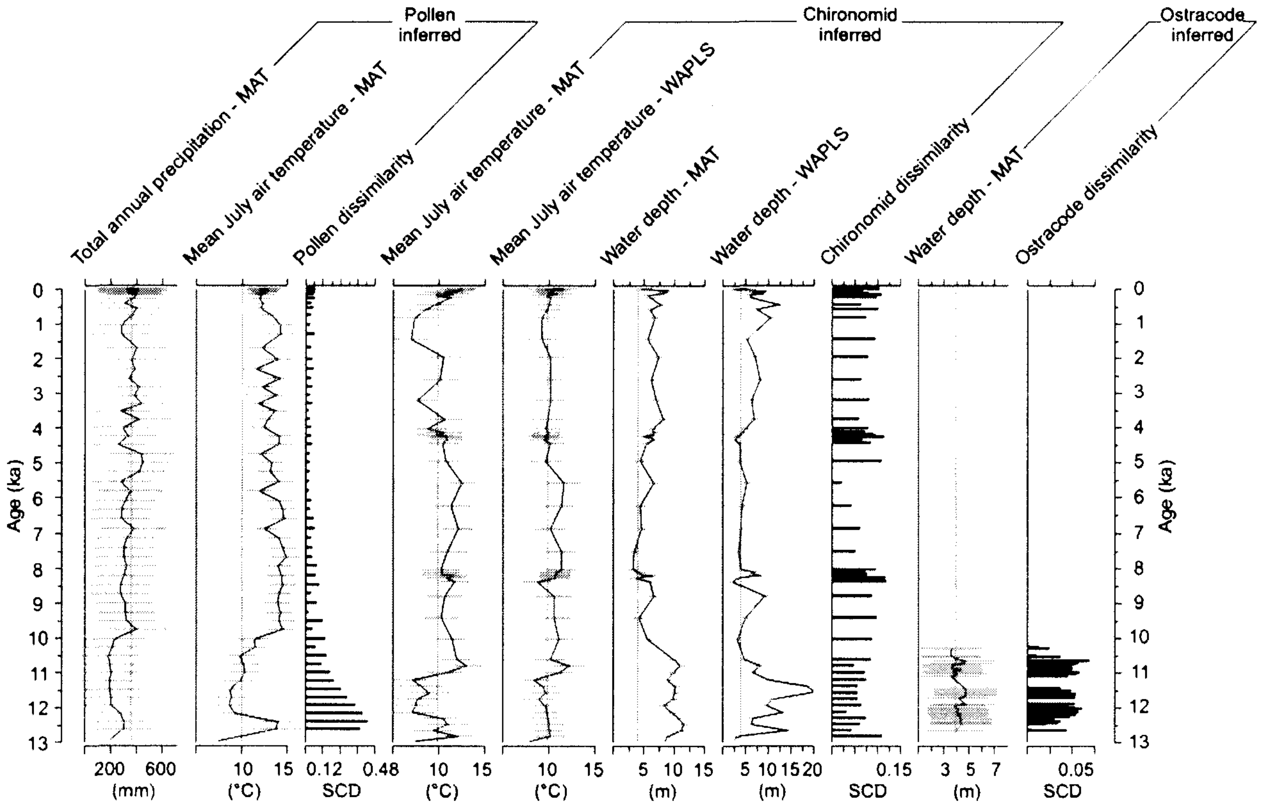

Figure 3.9: Total annual precipitation, mean-July air temperature, and water depth based on pollen, chironomid, and ostracodes using either the modern analogue technique (MAT) or weighted-averaging partial-least-squares regression (WAPLS) transfer function technique. Horizontal lines indicate the sample-specific standard errors generated based on 1000 bootstrap simulations (Juggins, 2003). Pollen dissimilarity, chironomid dissimilarity, and ostracode dissimiliarity were measured using squared chord distance (SCD). The modern value for the climate variables for this site (annual precipitation of 360 mm and mean-July air temperature of 9.9°C, from the Modern Pollen Database (Whitmore et al. 2005)), and water sampling depth (4 m) are plotted on the corresponding graph for reference. Ages are ka before AD 1997.

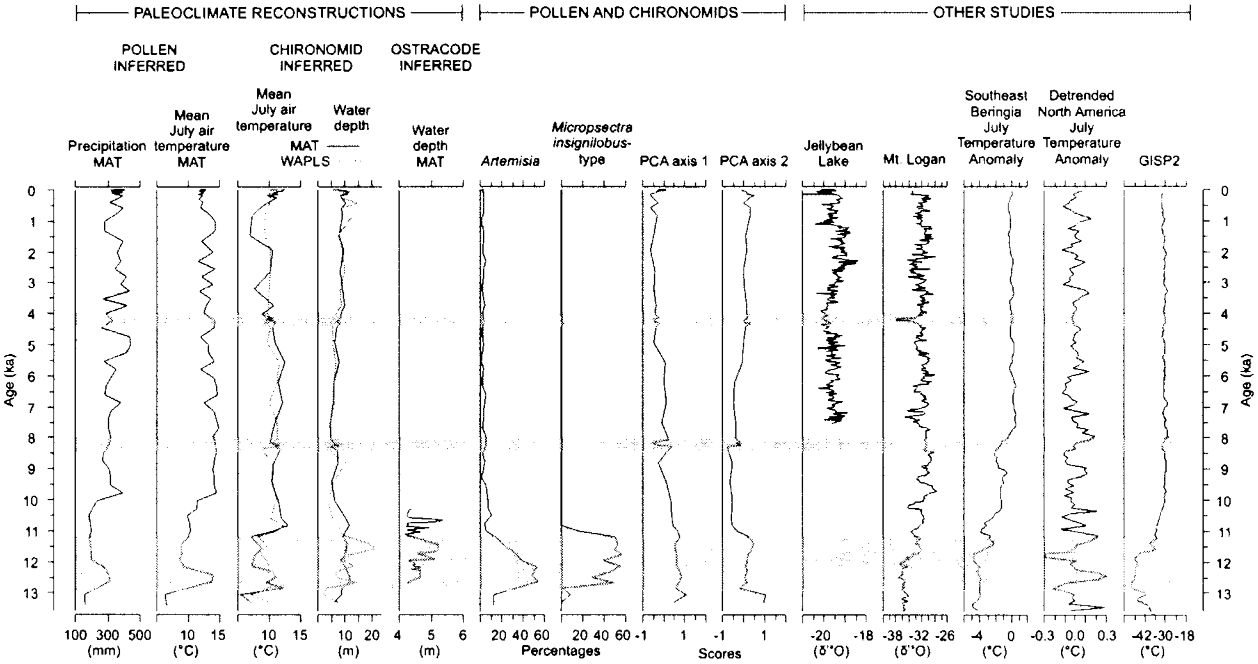

Figure 3.10: Summary diagram of paleoclimate reconstructions and key pollen (*Artemisia*) and chironomid (*Micropsectra insignilobus*-type and PCA axes 1 and 2 scores) curves from this study compared with an oxygen isotope record from lacustrine carbonates from Jellybean Lake (Anderson et al. 2005a), an oxygen isotope record from the Mt. Logan ice core (Fisher et al. 2008), a regional pollen-based July temperature anomaly curve (Viau et al. accepted), a detrended July temperature anomaly curve for North America (Viau et al., 2006), and a mean annual temperature reconstruction from Greenland (GISP2; Alley 2000; 2004). Gray zones highlight time periods. Ages are ka before AD 1997.

CHAPTER FOUR

VARIATIONS IN THE DEPTH AND THICKNESS OF THE WHITE RIVER ASH IN LAKES OF THE SOUTHWEST YUKON

Abstract

The purpose of this study is to document the depth and thickness of the White River Ash in lakes across the southwest Yukon for use in paleoenvironmental impact studies. Sediment cores were sampled from seven lakes located within the plume of the eastern lobe of the White River Ash (1147 cal years BP). Site locations are between 92 and 254 km from Mount Churchill, Alaska, the probable source for the White River Ash. Based on magnetic susceptibility measurements, the depth of the sediment above the ash layer in the lakes ranges between 38 and 98 cm; these differences are due to factors associated with sedimentation rates. The thickness of the ash ranges between 0.1 and 32 cm and typically increases with proximity to the source vent. These results can be used in paleoenvironmental studies to assist in the interpretation of the impact of volcanic ash events.

Introduction

The White River Ash event

Explosive volcanic eruptions such as the White River Ash (WRA) event eject large quantities of ash into the atmosphere that become deposited in both terrestrial and aquatic environments. Tephra is incorporated into lake sediments by falling directly on the lake surface, and through deposition within the watershed and transportation to the lake via runoff. Evidence suggests the eruption that produced the WRA occurred in late autumn or early winter (West and Donaldson, 2001), therefore, the tephra would have been deposited on frozen lake surfaces and would not have been incorporated into the sediments until during the spring melt. The ashfall would have impacted both the aquatic and terrestrial communities in the region, though the extent of the impact would be a function of the quantity of ash deposited in a given site. Therefore, this event provides a "natural experiment" to evaluate the impacts of catastrophic events on ecosystems through the analysis of fossils in lake sediments.

The objective of this study is to assess the variations in depth and thickness of the WRA from seven lakes in the southwest Yukon. The results from this study can then be used in paleoenvironmental studies to aid in the interpretation of the impact of these types of events on terrestrial and aquatic ecosystems.

Regional Setting

The southwest Yukon is located in the rainshadow of the St. Elias Mountains resulting in a semi-arid climate with total precipitation values <300 mm annually (Environment Canada, 2004). Mean annual daily temperatures are below 0°C, and discontinuous permafrost is widespread throughout the region, particularly at higher elevations (National Atlas Information Service, 1995). Dominant trees in this part of the boreal forest are white spruce (*Picea glauca*), balsam poplar (*Populus balsamifera*), and trembling aspen (*Populus tremuloides*; Johnson and Raup, 1964), and bogs with stands of black spruce (*Picea mariana*) can be found further north. Natural grasslands are interspersed with open forest stands, particularly in the vicinity of Kluane Lake and in the Aishihik Lake region (Vetter, 2000). Alpine-tundra types including dwarf birch (*Betula*), willow (*Salix* spp.), grasses (Gramineae), and sedges (Cyperaceae) are found at higher elevations.

The region is geologically complex, and is underlain by a variety of bedrock types including intrusive bodies composed of granodiorite, quartz diorite, quartz monozite and granite. Gneiss and volcanic rock are also present, and till is abundant, particularly in the Kluane Lake Region (Gabrielese *et al.*, 1977; Fulton, 1995).

Seven sediment cores recovered from lakes located within the eastern lobe of the White River Ash plume were used for this study (Figures 4.1 and 4.2). Lakes vary in their ionic composition, but are generally bicarbonate rich and dominated by either calcium or magnesium, with higher ionic concentrations occurring near Kluane Lake (see Chapter 2). Surface areas of the lakes vary between 0.1 and 143 ha, and core collection depth ranged between 2.5 and 11 m (Table 1). Both Sulphur Lake (Sulphur) and Upper Fly Lake (Upper Fly) lack an obvious inflow, yet both have a stream outflow, whereas the other sites are kettle lakes with only groundwater inputs. Vegetation surrounding the lakes varies; Sulphur, Lake WA01 (WA01), Emerald Lake (Emerald), Jenny Lake (Jenny), and Donjek Kettle (Donjek) are situated in the boreal forest, Upper Fly is in the forest-tundra transition zone, and Lake WP02 (WP02) is located in alpine tundra.

Methods

Field Methods

Lake sediment cores were collected from Emerald and Donjek in August 1996; Sulphur and Upper Fly Lakes in July/August 1997; Jenny Lake in May 2003; WP02 in July 2006; and WA01 in July 2008. All sediment cores were retrieved using a modified Livingstone piston sampler, and the unconsolidated uppermost sediments were extruded into plastic bags in the field. The length of the core that is extruded in this manner depends on the cohesiveness of the sediments and varies for each site (Figure 4.3). The remainder of the cores were extruded, wrapped in plastic wrap and aluminum foil and transported back to Ottawa where magnetic susceptibility was measured. Only the uppermost sections of the lake sediment cores are discussed in this study.

Laboratory Methods

Magnetic susceptibility

Magnetic susceptibility is a non-destructive sediment logging technique that measures the ability of the sediments to be magnetized, values typically reveal the amount of magnetic minerals that are present within the sediments (Dearing, 1994). Increases in concentrations of magnetic minerals in lake sediment cores are generally interpreted as periods of increased erosion in the watershed. For example, greater precipitation would transport inorganic allochthonous material to the lake, which would then become incorporated into the sediments (Lowe and Walker, 1997). Other material that causes high magnetic concentrations in lake sediments includes volcanic ash, due to the presence of magnetite, a common mineral that dominates magnetic susceptibility measurements when present in a sample (Dearing, 1994).

A Bartington MS2C Core Sensor with a 6 cm-internal diameter was used to measure magnetic susceptibility at 1 cm intervals on the seven lake-sediment cores. Whole cores were fed through a loop sensor, and the meter computed susceptibility values as a weighted mean of the individual measurements (Nowaczyk, 2001). Units are dimensionless and the base units are either in centimetres, grams, seconds (CGS) or metres, kilograms, seconds (International System of Units; SI). Although the values are slightly different, for the purposes of this study the interpretation of the results is not affected.

Results

Magnetic susceptibility of sediment in southwest Yukon lakes

In all seven lake-sediment cores, maximum values of magnetic susceptibility occur where the White River Ash is present (Figure 4.2). Both WP02 and Donjek have very high maximum values (533 SI units and 392 CGS units, respectively), followed by more moderate maximum values at WA01 (28.7 SI units), Upper Fly (23.7 CGS units), and Emerald (17 CGS units), and low maximum values at Sulphur (4.81 CGS units) and Jenny (2.97 SI units). All sites have low magnetic-susceptibility values in the portions of the cores where there is no volcanic ash. WP02 and Donjek have the highest minimum values (6.7 SI units and 6.2 CGS units, respectively), Upper Fly and Sulphur have small, positive values (1.9 CGS units and 1.6 CGS units, respectively), whereas Jenny, Emerald, and WA01 have negative values

(-1.4 SI units, -0.7 CGS units, and -0.8 SI units, respectively). Magnetic concentrations appear more variable throughout the cores from Donjek and Upper Fly prior to the ash deposition, whereas the remaining sites show stable, low magnetic concentrations aside from where the White River tephra is present.

White River Ash depth in southwest Yukon lakes

The White River Ash layer is shallowest in Donjek with only 38 cm of sediment accumulation over the past 1200 years (Table 2). Comparable sediment accumulation rates above the ash are found at Upper Fly (54 cm), Emerald (51 cm), WP02 (50 cm), and WA01 (51 cm), whereas Sulphur (90 cm) and Jenny (98 cm) have almost twice the accumulation.

White River Ash thickness in southwest Yukon lakes

The thickest layers of White River Ash found in lake sediments from these sites are at WP02 (32 cm) and Donjek (27 cm; Table 2). WA01 has 11 cm of ash, whereas Jenny, Emerald, and Upper Fly all have less than 1 cm (0.3, 0.3, and 0.1 cm, respectively). Sulphur has no visible ash layer however the magnetic susceptibility values indicate an increase coinciding with the timing of the White River Ash (Lacourse and Gajewski, 2000). Note that the estimate of ash thickness is not exact due to the averaging of the magnetic signal by the sensor.

Discussion

Magnetic concentrations in lake sediments

Carbonate lake sediments at Jenny, Emerald, and WA01, result in weak, negative magnetic susceptibility values due to the diamagnetic behaviour of calcium carbonate (*e.g.*, precipitated calcite, ostracodes, and molluscs) found in the sediment (Figure 4.2; Dearing, 1994). The weak, positive values throughout the cores at the other sites suggest paramagnetic sediments that contain minerals comprised of iron (*e.g.*, biotite, olivine; Dearing, 1994).

The White River Ash is ferrimagnetic based on the strong, positive susceptibility values at all sites; this is due to the presence of the mineral magnetite that comprises 2.1% of the weight of the White River Ash (Lerbekmo and Campbell, 1969). Very high (*i.e.*, >300 regardless of unit) magnetic concentrations at Donjek and WP02 are the result of the volume of White River Ash that occurs in the sediments at those sites (Figure 4.3), as large bulk samples record higher values than small samples of the same material (Dearing, 1994). Magnetic concentrations of the White River Ash at the other sites are lower, and are a reflection of the reduced amount of ash in those sediments. The particularly low values at Jenny and Sulphur Lakes may be a result of the large surface area at those two sites, where the ash becomes more diluted in the sediments than it would at the lakes with a smaller surface area.

White River Ash thickness and distance from the source

The thickness of the White River Ash layer in lake sediments is expected to decrease with increasing distance from the source. This holds true for six of the seven lakes, but not for WA01, which has an 11 cm thick ash layer and is located the furthest from the source in this study (Tables 1, 2). WA01 is a bowl-shaped kettle lake with a very small surface area (0.1 ha) surrounded by steep slopes. As the tephra was deposited it would have become concentrated in a small area at the bottom of the lake (referred to as sediment focusing). In addition, as the snow on the surrounding slopes melted in the spring, any ash within the basin would have been washed into the lake, thereby increasing the amount accumulated in the sediments. A lake sediment core collected from a slightly larger lake with less steep slopes across the Aishihik Road from WA01 revealed no visible ash layer, suggesting the importance of the morphology of the lake and surrounding basin to the ash layer thickness at Lake WA01.

White River Ash depth and sedimentation rates

The amount of lake sediment that has accumulated above the White River Ash is comparable at five of the seven sites, indicating similar sediment accumulation rates over the past 1200 years (Figure 4.3). Greater sedimentation rates have occurred at both Jenny and Sulphur since the White River Ash event, and may be due to larger sediment input to the sites as well as sediment focusing. The steep-sided bathymetry of Sulphur Lake causes accumulated material within the sediment to move downslope to the bottom of the lake where the core sample was collected within an 11 m-deep section . A similar situation exists at Jenny Lake however it is more likely the result of the steep slope alongside the lake close to the area where the core was collected. During periods of increased precipitation or snowmelt inorganic allochthonous material becomes entrained and deposited in the lake and eventually forms part of the sediments.

Conclusions

Magnetic susceptibility in lake sediments is highest where the White River Ash is present, and greater volumes of ash result in much higher magnetic susceptibility measurements. The thickness of the White River Ash typically decreases with increasing distance from the source vent and lake sedimentation over the past 1200 years is fairly consistent between the sites. However, sediment focusing can increase the amount of ash incorporated into the sediments of a given site. The findings from this study will be considered in a paleoenvironmental study exploring the impact of the White River Ash event on aquatic ecosystems in the region.

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Table 4.1: Location, surface area, core collection depth, and distance from Mount Churchill for the seven study lakes.

Lake	Latitude (°N)	Longitude (°W)	Elevation (m)	Surface area (ha)	Core collection depth (m)	Distance from Mount Churchill (km)
WP02	61.48	140.00	1463	0.65	4	92.6
Donjek	61.69	139.76	732	0.6	6	110.1
Emerald	61.07	138.37	820	8.4	7	181.6
Jenny	61.04	138.36	817	19.9	4	183.0
Upper Fly	61.09	138.09	1326	10.5	4	196.2
Sulphur	60.95	137.98	854	142.6	11	205.7
WA01	61.25	136.93	991	0.1	2.5	254.7

Table 4.2: Depth and thickness of the White River Ash found in the sediments of the seven lakes. Ash depth is based on magnetic susceptibility measurements (1-cm resolution), and ash thickness is based on magnetic susceptibility measurements and visual inspection.

Lake	Ash depth (cm)		Ash thickness (cm)
	Start	Finish	
WP02	50	82	32
Donjek	38	61	27
Emerald	50	51	0.3
Jenny	98	99	0.3
Upper Fly	53	54	0.1
Sulphur	89	90	Not visible
WA01	51	62	11

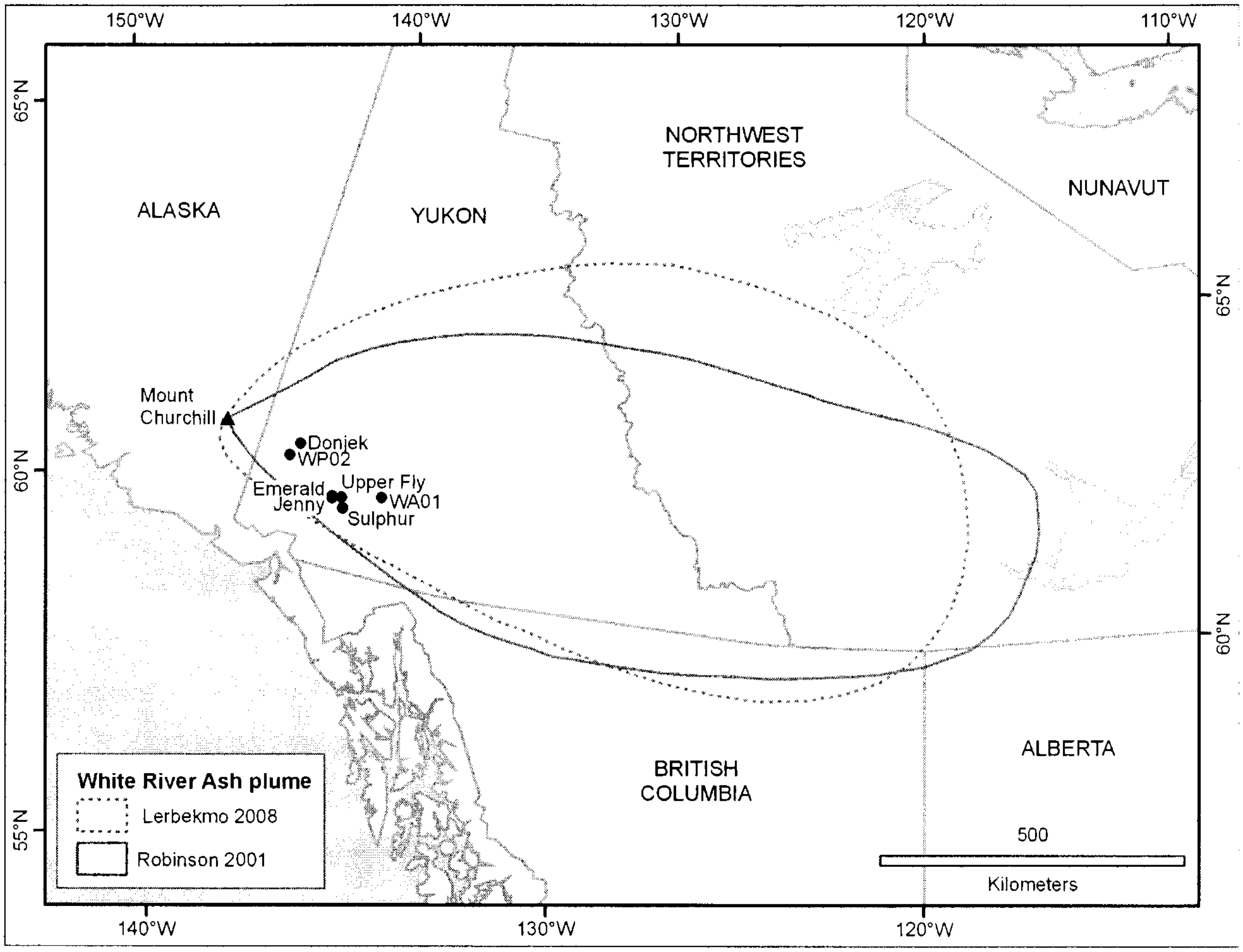

Figure 4.1: The extent of the eastern lobe of the White River Ash after (Robinson 2001) and (Lerbekmo 2008). Location of the seven study lakes and Mount Churchill are provided for reference.

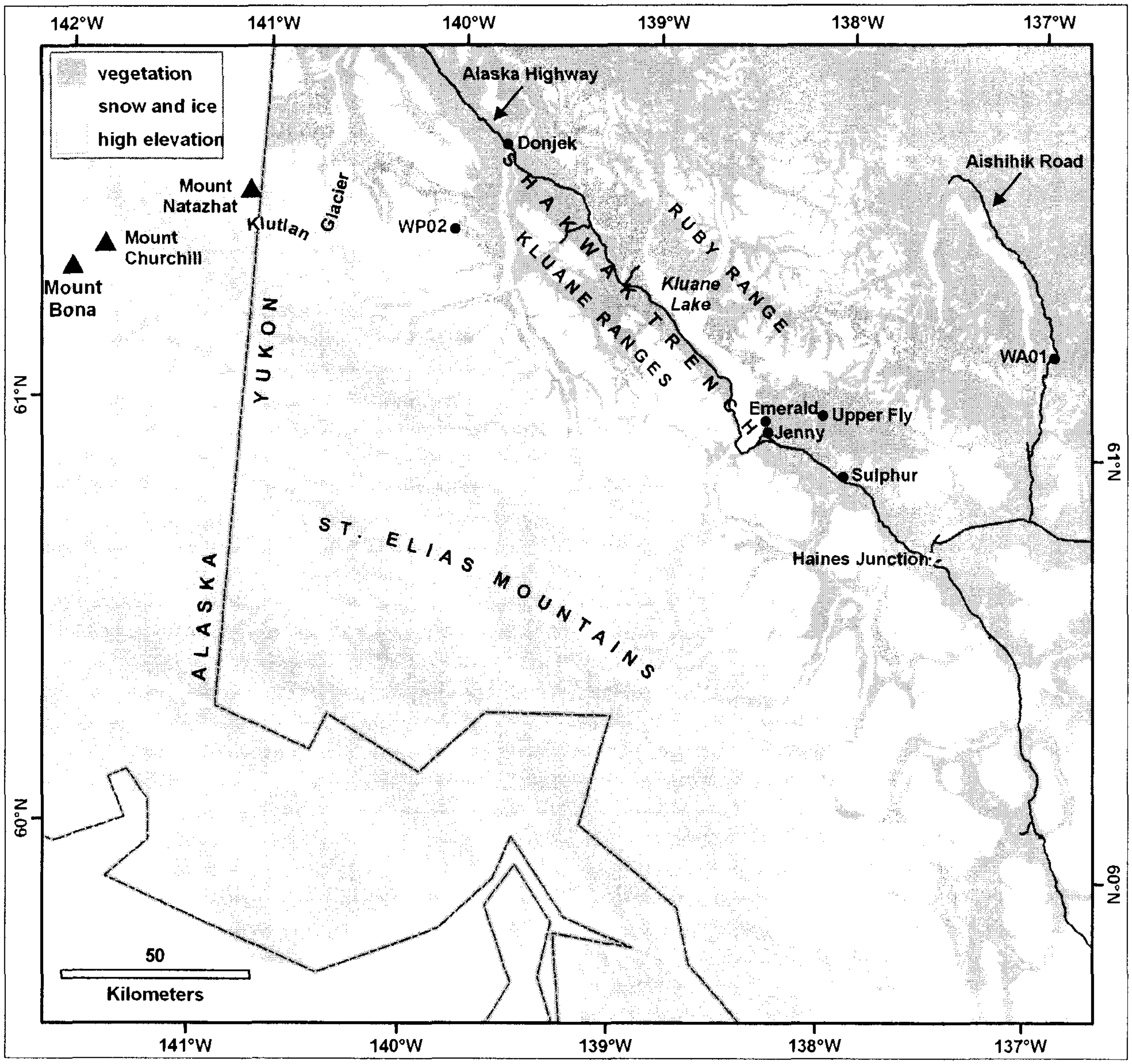

Figure 4.2: Map showing more detailed locations of the seven lakes. Mount Churchill, Mount Natazhat, Mount Bona and the Klutlan Glacier are provided for reference.

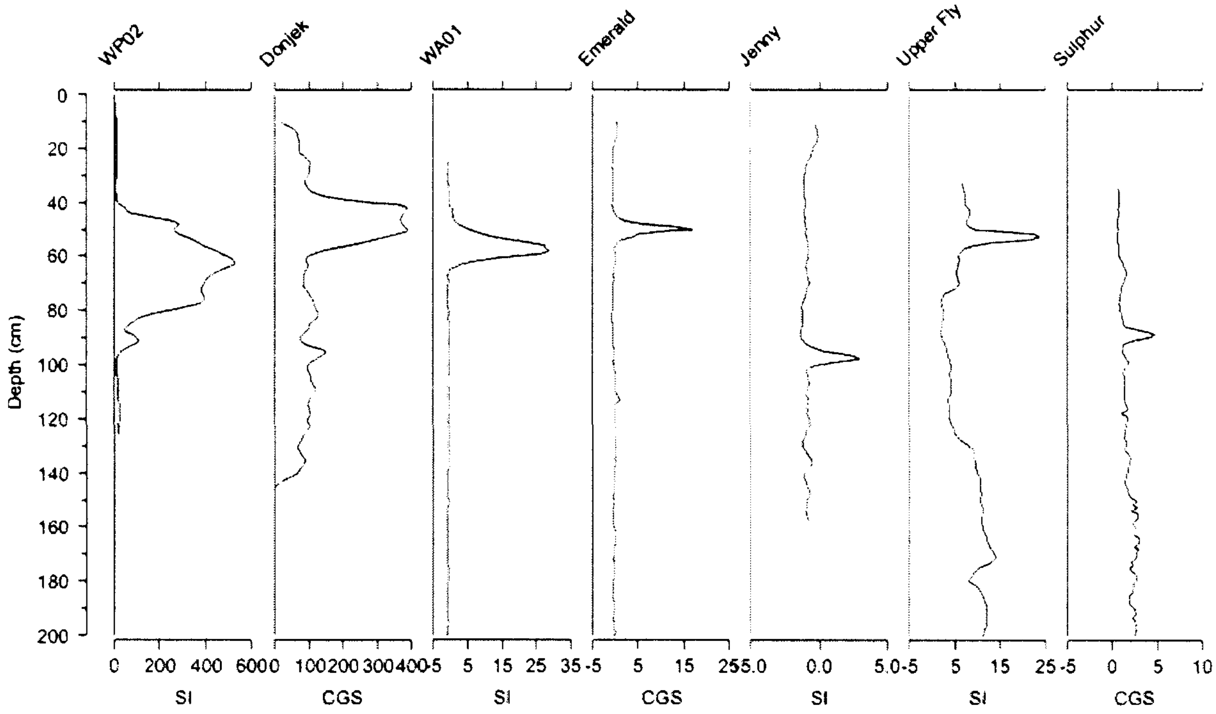

Figure 4.3: Magnetic susceptibility profiles for the seven study lakes. Note that different units were used.

CHAPTER FIVE

AQUATIC ECOSYSTEM RESPONSE TO LATE HOLOCENE ENVIRONMENTAL VARIABILITY IN THE SOUTHWEST YUKON

Abstract

Four lake sediment cores from lakes in the southwest Yukon were used to assess the effects of climate change and volcanic ash input on aquatic ecosystems during the late Holocene. Analysis of paleoproduction indices (sediment loss-on-ignition, biogenic silica) and chironomid and ostracode communities revealed coherent trends among the four lakes, and differences between sites appeared related to differences in water chemistry and lake size. Pairs of sites located closer together showed more similarities than more distant sites located in similar environments (alpine tundra or boreal forest). Chironomid-inferred paleotemperature reconstructions are not consistent with other data from the region, however certain fluctuations in paleoproduction indices and changes in abundance and composition of the chironomid and ostracode communities compare well with interpretations based on the independent paleoclimate records. The White River Ash event impacted three of the four aquatic ecosystems studied, with a greater impact occurring at sites with greater ash thickness.

Introduction

Analysis of hemispheric-average temperature changes has shown that the current warming seems to exceed any of the past millennium IPCC (2007). Details of the Little Ice Age are quite well known, and it is recognized that it was global in extent; however knowledge of the Medieval Warm Period is less established and there is still much debate about its geographic extent (Overpeck et al. 1997; Gajewski and Atkinson 2003; Wanner et al. 2008; Kaufman et al. 2009; Esper and Frank 2009; Jones et al. 2009). Recently, a set of paleoclimate reconstructions inferred from lake sediments at sites spanning northern North America, Greenland, Iceland, and Fennoscandia were compiled to assess the climate variations in northern latitudes over the past 2000 years (Kaufman 2009). However, none of the 14 records presented were from the Yukon, leaving a gap in the spatial distribution of sites across North America.

High-resolution oxygen isotope records from an ice core on Mount Logan (Fisher et al. 2004; Fisher et al. 2008), and from Jellybean and Marecella Lake sediments (Anderson et al. 2005; Anderson et al. 2007) have been used to infer changes in the moisture regime of the southern Yukon during the Holocene. These authors interpret changes in moisture conditions in the southwest Yukon in the context of variability in the extent and position of the Aleutian Low Pressure Centre. Significant "shifts" in the Mount Logan and Jellybean Lake records at AD 800 and AD 1840 are interpreted as indicating the beginning of the Medieval Warm Period and the end of the Little Ice Age in the region. However, oxygen isotope records primarily respond to changes in source and trajectory of air masses and precipitation regime; they provide little information about temperature conditions during the past millennium in this region (Fisher et al. 2004).

Several records from the southwest Yukon provide information about changes in temperature on both long (13,000 years) and short (300 years) timescales. Bunbury and Gajewski (2008a) inferred mean-July temperatures from pollen and chironomids preserved in the sediments of Upper Fly Lake, and Youngblut and Luckman (2008) used 7 tree-ring chronologies to reconstruct maximum June-July temperatures in the region. However, the paleotemperature records from Upper Fly Lake only documented the general tendencies during the past 2000 years due to the low temporal resolution of the samples, whereas the short tree-ring records only spanned the second half of the Little Ice Age (i.e. the last 300 years).

Other important factors that can potentially influence aquatic and terrestrial ecosystems at a regional scale include explosive volcanic eruptions. These events eject large quantities of ash into the atmosphere that can potentially alter global climates (Ruddiman 2001). At a local-to-regional scale, the ash fallout lands on the surface of lakes and the surrounding landscape and can potentially affect both terrestrial and aquatic ecosystems (e.g. Edmondson 1984; Birks and Lotter 1994; Lotter et al. 1995; Heinrichs et al. 1999). A body of literature exists that assesses the effects of volcanic ash deposition on diatom community composition and abundance (e.g. Barsdate and Dugdale 1972; Abella 1988; Lotter and Birks 1993; Hickman and Reasoner 1994; Barker et al. 2000; Telford et al. 2004). These events alter nutrient availability through chemical weathering of the ash that increases available silica within a lake. When this is combined with a reduction in the amount of phosphorus available from the sediments due to the physical boundary created by the ash, the silica-phosphorus ratio within the lake increases, thereby contributing to a more abundant and/or diverse diatom community.

Organisms that inhabit the interstitial areas at the sediment-water interface could be affected by ash deposition due to decreased access to food resources, but also by the physical effects of large ash volumes that could potentially smother taxa that live at the bottom of the lake (Edmondson 1984). Changes in the chironomid community composition and abundance following tephra events have been recognized (Tsukada 1972; Heinrichs et al. 1999; Araneda et al. 2007).

The White River Ash is a bi-lobate tephra resulting from two Holocene eruptions that occurred 1952 cal yrs BP and 1147 cal yrs BP (Lowdon and Blake 1968; Clague et al. 1995). The earlier eruption deposited ash that extends along the Yukon-Alaska border, whereas the second, more explosive event covered most of southern Yukon and spans as far west as Great Slave Lake in the Northwest Territories (Lerbekmo and Campbell 1969; Lerbekmo et al. 1975; Robinson 2001). Prevailing winds at the time of the eruptions were responsible for the deposition of the ash in different directions; today, upper atmosphere winds in the Yukon-Alaska region blow eastward in winter and northward in summer, suggesting summer deposition for the northern lobe and winter deposition for the eastern lobe (Workman 1979;

West and Donaldson 2001). Although the location of the source of the White River Ash is not entirely clear (i.e. Mount Churchill, Alaska or a vent under the Klutlan Glacier (Chapter 4; Richter et al. 1995; Lerbekmo 2008), this is of lesser importance in our assessment, as the ash deposition was presumably a one-point-in-time event across the southwest Yukon and, in any event, we have a record of the extent of the ash impact through the measure of the ash thickness in sediment cores.

In this study, we will present information on the effects of the deposition of the White River tephra on four lake environments located at different distances from the source. Two of the lakes are in alpine tundra and two are in boreal forest environments. Aquatic environments closer to the vent experienced greater tephra inputs, and we hypothesize that these had a greater impact on the ecosystem. Telford et al. (2004) found that sites with >1 cm ash layer showed greater impacts to the ash inputs. Assessment of the changes in the chironomid and ostracode communities and sediment characteristics above and below the ash layer will be used to determine the impact of this event.

An extensive literature has been shown that lake sediments can be used to reconstruct past environmental conditions, both directly and indirectly related to climate (Birks and Birks 1980; Delcourt and Delcourt 1991; Smol 2008). In freshwater lakes, organic, carbonate and biogenic silica content represent a large proportion of the sediments. Sources of organic and carbonate content are both autochthonous and allochthonous (Dean 1981; Wetzel 2001; Kalff 2001), whereas biogenic silica is derived primarily from diatoms but also includes chrysophytes and freshwater sponges (Wetzel 2001; Kalff 2002), and increases in concentration are indications of greater primary production of these organisms (Conley and Schelske 2001). The organic, carbonate, and biogenic silica content of sediments are useful in paleoecological studies as large numbers of determinations can quickly be obtained and used to develop high-resolution records. These variables have been used to infer paleoproductivity (Kaplan et al. 2002; Fortin and Gajewski 2009b). However, their use in determining ecosystem-level properties, such as total ecosystem production, remains under discussion (Fortin and Gajewski 2009a). Remnants of biological organisms extracted from lake sediments provide a well-known source of paleoenvironmental information. Chironomids and ostracodes are benthic aquatic organisms that live in or on the sediments of lakes (Walker et al. 1991; Griffiths and Holmes 2000). The abundance and distribution of chironomids is affected by both temperature and food source (e.g. Olander et al. 1999; Wilson and Gajewski 2004; Barley et al. 2006), whereas ostracodes are primarily affected by changes in hydrology, ion concentration and ionic composition (among other factors; Forester 1987). The two organisms mentioned here are consumers that rely on primary production as a food resource and the chemical conditions within a lake for their existence. By combining the sedimentary variables with the known ecological requirements of the different aquatic organisms, an integrated picture of the past aquatic ecosystem can be developed.

The purpose of this research, which is focused on environmental variability of the last 2000 years in the southwest Yukon, is threefold. First, we present a series of chironomid-inferred paleotemperature estimates from four lakes in the southwest Yukon. These new high-resolution reconstructions will contribute further knowledge on climate variations over the past 2000 years in the region, and on the magnitude of the temperature changes that existed during that time. The sites are from different geographic and environmental contexts and thus represent a replicated set of paleoclimate reconstructions. Second, we compare chironomid, ostracode, and sedimentary data from the four sites with independent climate records from the region to assess aquatic ecosystem response to environmental changes related to climate. Lastly, we examine the impact of the White River tephra deposition on the aquatic environment. Presumably, the effect of the ash input diminishes with distance from the source vent, and so should the aquatic ecosystem response. This research uses a high-resolution, multi-proxy approach to investigate the nature and impacts of two different scales of environmental change (i.e. climate change and the effects of a volcanic eruption) that have occurred over the past 2000 years in the southwest Yukon.

Study sites

Sediment cores used in this study are from four lakes in the interior southwest Yukon (Figure 5.1). The region is semi-arid due to the orographic effect of the St. Elias Mountains to the southwest of the study area. MeanJanuary and July temperatures from Otter Falls Station (61.03° N, 137.05° W, 830 m a.s.l.) are -16.4°C and 13.1°C, respectively, and total annual precipitation is 297 mm (Environment Canada 2000). Further north at Burwash (61.22° N, 139.3° W, 807 m a.s.l.), the mean January and July temperatures are cooler

(-22° C and 12.8°C, respectively) and total annual precipitation is slightly lower (280 mm). Permafrost is widespread across the region, with sporadic discontinuous patches at lower elevation and extensive discontinuous areas at higher elevation (National Atlas Information Service 1995). All sites are within the eastern plume of the White River Ash deposition event that occurred 1147 cal yrs BP, and are at decreasing distances from Mount Churchill, Alaska (Chapter 4). We recognize the discrepancy regarding the source of the ash, however we consider the distance to Mount Churchill as a more conservative estimate, as it is further away.

Upper Fly Lake

Upper Fly Lake (unofficial name) is located at alpine treeline in the Ruby Range (61.04° N, 138.09°W, 1326 m.a.s.l., 10.5 ha surface area). The lake is underlain by gneiss bedrock (Wheeler et al. 1997) with surficial deposits of glaciolacustrine silts and clays (Fulton 1995). Vegetation characteristic of alpine tundra dominates the watershed and consist of dwarf birch (*Betula*), shrub willow (*Salix* spp.), sedges (Cyperaceae), grasses (Poaceae), and other herbaceous plants, with several individuals of white spruce (*Picea glauca*) on the warmer south-facing slopes alongside the lake. Inflow to the lake is limited to groundwater (where available due to the presence of permafrost) and precipitation, and outflow is via a stream into Fly Lake.

Jenny Lake

The complex Jenny Lake basin (61.04° N, 138.36° W, 817 m a.s.l., 19.9 ha surface area) is located in the Shakwak Trench and is underlain by gneiss bedrock, which is overlain by thick, continuous glacial till. Dominant trees surrounding the lake are white spruce (*Picea glauca*), balsam poplar (*Populus balsamifera*), and trembling aspen (*Populus tremuloides*), and parts of the boreal forest surrounding the lake are interspersed by small grasslands (bordered by shrubs e.g. *Shepherdia Canadensis, Salix* spp.) containing a variety of herbaceous plants. Jenny Lake has no visible surface inlets or outlets, limiting inflow to groundwater and precipitation, and outflow to evaporation.

Donjek Kettle

Donjek Kettle (unofficial name; 61.69° N, 139.76° W, 732 m.a.s.l., 0.6 ha surface area) is adjacent to the Alaska Highway in the Shakwak Trench, and is situated on thick, continuous glacial till underlain by intrusive rocks, particularly granodiorite and quartz diorite (Fulton 1995; Wheeler et al. 1997). Surrounding the lake is boreal forest, and major tree species include white spruce (*Picea glauca*) and poplars (*P. balsamifera and P. tremuloides*), along with willows (*Salix* spp.) and other herbaceous plants. Precipitation and evaporation appear to control the hydrological balance of the lake, as there are no surface inflows or outflows.

Lake WP02

Located on the Wolverine Plateau of the Kluane Range, Lake WP02 (unofficial name; 61.48° N, 139.97° W, 1463 m a.s.l., 0.65 ha surface area), is underlain by volcanic rock, which is overlain by a thin, discontinuous till veneer (Fulton 1995; Wheeler et al. 1997). The hummocky terrain in the lake basin is covered with alpine vegetation including shrub willow (*Salix* spp.), grasses (Poaceae), sedges (Cyperaceae), mosses, and many species of herbaceous plants (e.g. *Saxifraga* spp., *Gentiana* spp., *Aconitum* spp.). We observed no surface streams flowing into or out of the lake, therefore precipitation, groundwater and evaporation are the main hydrological controls.

Methods

Field methods

Lake sediment cores were retrieved from the four lakes using a clear plastic tube fitted with a piston lowered to the sediment on drive rods. In this way, we were able to preserve the sediment-water interface. Ropes attached to the shore were used to stabilize a zodiac or rubber rafts (Lake WP02) during the coring process.

A 298 cm lake sediment core was collected from Upper Fly Lake on August 4, 1997 (Bunbury and Gajewski, 2009); only the uppermost 70 cm, spanning the past 1700 years were used for this study. Details of core collection can be found in Chapter 3. Two adjacent cores of 164 cm and 138 cm were collected from Jenny Lake on May 27, 2003 and a third core measuring 140 cm was collected on June 1, 2003 at a water depth of 4.2 m. The sediment record analyzed here from Jenny Lake covers the past 3100 years. The uppermost sediments (10, 20, and 15 cm, respectively) were extruded into plastic bags or bottles, at either 0.5- or 1-cm intervals at the base camp. The remainder of the core was wrapped in plastic and aluminum foil for shipment to the lab and storage at 4°C. On July 9, 2006 a 147 cm lake sediment core was raised from Donjek Kettle. The uppermost 102 cm, spanning the past 2200 years were used in this study. The unconsolidated sediments at the top of the core were extruded into plastic bottles in 0.5-cm increments at the base camp. A 38-cm sediment core spanning the past 1200 years was collected from Lake WP02 on July 19, 2006 from a depth of 4.3 m, and the uppermost 5.5 cm were extruded into plastic bottles in 0.5 cm sections. The uppermost sections of the cores not extruded into plastic bottles were wrapped in plastic wrap and aluminum foil and returned to the University of Ottawa, Ontario, where they were stored at 4°C.

Laboratory methods

Core chronologies were determined using ^{210}Pb, accelerator mass spectrometry (AMS) radiocarbon dating, and the dates of a tephra layer at 1147 cal yrs BP (Clague et al. 1995) from all sites, and the one at 1952 cal yrs BP (Lowdon and Blake 1968) at Donjek Kettle. Flett Research Ltd. conducted the ^{210}Pb analysis using alpha spectrometry on the uppermost sediments from the 4 lakes. A constant rate of supply (CRS) model was used to compute the ages of the sediments with measurable ^{210}Pb activity for Upper Fly, Jenny and Donjek Lakes, and a linear regression model for the sediments from Lake WP02. Radiocarbon dates were measured at Beta Analytic Ltd. on organic matter that was separated from the sediment by hand. Both terrestrial and aquatic macrofossils were used. All radiocarbon dates were calibrated to calendar years using IntCal calibration dataset (Reimer et al. 2004) and CALIB 5.0.1 (Stuiver and Reimer 1993).

Magnetic susceptibility was measured on cores from all lakes at 1-cm intervals using a Bartington MS2 meter. This was used to determine changes in mineral content and to correlate adjacent cores from Jenny Lake (Thompson et al. 1975). This analysis also identified variations in the thickness of the ash layer at each site (Chapter 4; note however that the Donjek Kettle core used in Chapter 4 was collected 10 years earlier than the core used in this study, the latter of which has an ash thickness of 44 cm; and the Lake WP02 core used in this study was 38 cm in length). High-resolution sampling was required to identify small variations in the sediment and organism assemblages through time, with an increased sampling resolution in the uppermost sediments (1-cm increments) and around the White River Ash (0.25-cm increments; WRA) layer. Organic and carbonate content of the sediments were determined using sediment loss-on-ignition (LOI; (Heiri and Lemcke 2001), and biogenic silica (BSi) was extracted from the sediments using a wet-alkali digestion technique and determined using a spectrophotometer (DeMaster 1981; Parsons 1984). Duplicate samples of known BSi content provided by an interlaboratory study (Conley 1998) were incorporated into each extraction batch to ensure laboratory experimental control. For the LOI data from Upper Fly Lake a portion of the records used in Chapter 3 were also used here and were at 1-cm intervals, with 0.5-cm intervals around the WRA (46-56.5 cm). Twelve BSi measurements from Chapter 3 were combined with 59 new measurements for a total of 71 levels at 1-3 cm, or 0.25 cm (around the WRA; 48-56.5 cm) intervals. Sediment was scarce at certain levels in this core due to the number of analyses conducted (Chapter 3), and every effort was made to maintain as consistent a sampling regime as possible. LOI at Jenny Lake and Donjek Kettle were measured at 1-cm intervals, with 0.5-0.25 cm intervals above and below the ash (Jenny = 87-98 cm; Donjek = 25-94 cm), whereas BSi was sampled at 1 to 2 cm intervals, with 0.25-0.5 cm intervals around the ash. At Lake WP02, LOI was measured at 0.5-cm intervals, and sediment for BSi was sampled at 1 to 2-cm intervals, with 0.25 to 0.5 cm intervals above the WRA (33-38 cm). Due to differences in ash thickness (Upper Fly Lake = 0.1 cm, Jenny Lake = 0.3 cm, Donjek Kettle = 44 cm, and Lake WP02 = 32 cm), and lack of discrete layer between the ash and the sediment, sediment samples around the ash interval from both Upper Fly Lake and Jenny Lake contained a mixture of sediment and ash throughout the ash interval, whereas at Donjek Kettle and Lake WP02, 2-3 samples (up to 0.75 cm) above and below contained ash fragments.

Sediment from all four sites was analyzed for chironomid head capsules. At Upper Fly Lake, previous counts (14 levels) from Chapter 3 were combined with new counts from 66 levels, for a total of 80 levels. As outlined above, sampling intervals were from 1-3 cm (due to sediment availability), and 0.5-0.25 cm around the WRA. At Jenny Lake, the sedimentation rate was greater, as indicated by the depth of the ash in the core compared to the other sites, therefore chironomids were sampled at 1-4 cm intervals, and around the ash at the same intervals and levels as for LOI and BSi. Donjek Kettle and Lake WP02 chironomid subsampling was also done at the same intervals as LOI and BSi. Where possible, ≥50 chironomid head capsules were identified at each level, however sediment was frequently exhausted due to the multiple-proxies analyzed, high sampling resolution (0.25-cm increments) and often low concentration of head capsules, so some counts are lower (Table 5.1). Specimens were hand sorted using forceps and a Bogorov sorting tray from samples processed using standard methods (Walker 2001). Specimens were dried on a coverslip, mounted using Entellan©, and identified under 200x to 400x magnification. Taxonomic resources included Wiederholm (1983), Walker (1988), Heiri et al. (2004), Larocque and Rolland (2006), and Brooks et al. (2007), and the Appendix from Barley (2004) to maintain consistency between the modern and fossil chironomids for reconstruction purposes.

Preliminary investigations indicated that ostracodes were abundant in Jenny Lake sediments, present infrequently and in low abundance in Donjek Kettle sediments, and absent from Lake WP02 and Upper Fly Lake sediments over the past 2000 years (see Chapter 3). Therefore, ostracodes were only analyzed from Jenny Lake. Between 2 and 18.2 cm^3 of sediment was subjected to ~3 freeze-thaw cycles to promote disaggregation (Griffiths and Holmes 2000), sieved through 50 μm Nitex© mesh, after which adult valves were hand picked from the sediment using a 0/5 brush under 10x magnification. Ostracodes were present in all 76 levels evaluated (sampling intervals between 0.25 and 4 cm; min. = 1, max. = 189, mean = 76), and identifications were made under 20x to 40x magnification using (Delorme 1970a; Delorme 1970b; Delorme 1970c; Delorme 1970d; Delorme 1971) as taxonomic references.

Chironomid data are presented as concentrations of head capsules per cm^3 of sediment ($hc \cdot cm^{-3}$). For the chironomid data, taxa present in ≤2 samples or with values of <1 $hc \cdot cm^{-3}$ are considered rare, and grouped into Other Chironomidae. This category also included unidentifiable and unknown head capsules. Total chironomid accumulation rates were estimated for each level in each lake sediment core by multiplying the head capsule concentration by the sedimentation rate, which was calculated using the age-depth curve for each lake. Ostracode taxa from Jenny Lake are presented as concentrations of all adult valves per cm^3 of sediment ($v \cdot cm^{-3}$), and accumulation rates were calculated as for chironomids. All diagrams were prepared using C2, version 1.5 (Juggins, 2007).

Data Analysis

Detrended correspondence analysis (DCA) is an ordination technique useful for detecting major trends in community data. It was applied to the chironomid and ostracode data to determine the distance between the taxa along gradients of species composition. A short gradient length (~1-1.4 standard deviation (SD) units) would indicate a small change in species composition, where similar taxa would be encountered in assemblages across the entire gradient, whereas a long gradient length (~4 SD units) suggest that taxa at one end of the gradient are not found in assemblages with taxa at the opposite end (Legendre and Legendre 1998; Lepš and Šmilauer 2003).

After removal of rare types, the DCAs were performed on chironomid concentration data matrices of 12 taxa and 80 samples for Upper Fly Lake, 18 taxa and 76 samples for Jenny Lake, 14 taxa and 73 samples for Donjek Kettle, and 22 taxa and 41 samples for Lake WP02 using detrending by segments and non-linear rescaling of axes. The ostracode concentrations data matrix contained 9 species and 76 samples. All organism data were log-transformed for the analyses, and rare taxa were downweighted to reduce their influence in the ordinations. Subsets of sediment, organism and DCA data from each lake between 1300 and 800 cal yrs BP was used to address the effect that the White River Ash had on aquatic ecosystems in the region.

An inference model was developed to estimate mean-July air temperature (TJul) from the chironomid data using a modern calibration dataset compiled from Barley et al. (2006), Wilson and Gajewski (2004), and Bunbury and Gajewski (2008b), in the computer program C2 (Juggins, 2003). This resulted in a dataset containing 186 samples, 74 species, and 17 environmental variables. Rare taxa selection, environmental variable selection, environmental data transformations, and model development followed Barley et al. (2006); however dissolved inorganic carbon was not available for all sites and was not included as a predictor variable. Using weighted-averaging regression and calibration (WA), the mean-July temperature optimum for each taxon was determined. A detrended correspondence analysis (DCA) performed on the species data revealed a gradient length of 3.63 (SD units), therefore a canonical correspondence analysis (CCA) was applied to determine the variables that best explain the variance in the chironomid data (CANOCO 4.5; (ter Braak and Šmilauer 2002). Initial CCAs were performed to assess collinearity among the variables, and to identify possible outliers. The FOREST variable had a variance inflation factor >20, and lakes A07, A25, U27, U58, KW03, and KW14 had extreme influence (>8x) as determined by the leverage diagnostics in CANOCO 4.5. Therefore, this variable and these sites were not included in the final ordination or in the development of the inference model. Forward selection revealed mean-July temperature (TJul) as a statistically significant ($p < 0.002$; 500 permutations) variable in explaining the variance in the chironomid data.

The best performance was from a weighted-averaging partial-least-squares (WAPLS) 2-component model (bootstrapped $r^2 = 0.69$, maximum bias = 2.9°C, root-mean-squared-error of prediction (RMSEP) = 1.7°C), which was applied to the fossil chironomid data to reconstruct mean-July air temperature (TJul) at each site. Typically, the best models are those with the fewest components, where the addition of the next component should provide a 5% or more reduction in the value of the RMSEP (Birks 1998). With our model, the reduction in the RMSEP from component 1 to component 2 was only 4%, however the residuals on component 1 exhibited a distinct trend which was not apparent after adding a second component. Mean-July air temperature reconstructions are presented as anomalies from the mean of the estimated values of a given record. The dissimilarity between the modern and fossil chironomid assemblages were assessed using the squared chord distance (SCD; Overpeck et al. 1985).

Results

Chronology

Details of chronology development are presented in Appendix F. At Upper Fly Lake, two ^{14}C dates and 7 ^{210}Pb dates are available from the section of the core analyzed for this study (Tables 5.2 and 5.3). The results of the ^{210}Pb show that the activity in the bottom section analyzed is 1.8 Bq/g, whereas background is estimated at 1.5 Bq/g. Therefore, background has likely not been reached in this core. Two ^{14}C dates and 8 ^{210}Pb dates were used to assign ages to the Jenny Lake sediment core (Tables 5.2 and 5.4). Although a third date was available, we did not incorporate it into the chronology (Appendix F). The decrease in ^{210}Pb activity indicates that background was reached, and a CRS model was applied to the data to determine the ages. Three ^{14}C dates and 11 ^{210}Pb dates were available from Donjek Kettle to establish a chronology, however only 2 of the ^{14}C dates were used (Tables 5.2 and

5.5; Appendix F). Although background was not reached with the ^{210}Pb dates, the decline in activity through most of the sections presented suggests the CRS model estimates are reasonable. At Lake WP02, one ^{14}C date and 11 ^{210}Pb dates were used to establish the chronology; a second ^{14}C date was not incorporated (Tables 5.2 and 5.6; Appendix F). Due to background not being reached, a linear regression model was applied to the ^{210}Pb data to assign ages to the uppermost sections. All ages are presented in calibrated years before present, where 0 = AD 1950. This results in decreasing negative values in the figures from AD 1950 to the dates of core collection (Upper Fly = AD 1997, Jenny = AD 2003 and Donjek Kettle and Lake WP02 = AD 2006).

Sediment stratigraphy

The sediment core from Upper Fly Lake was comprised of dark brown gyttja with organic content between 25 and 37% (measured by loss-on-ignition at 550°C; LOI 550°C), which decreased over the period of record (Figure 5.2a). Periods of increased organic content between 1600 and 1400 cal yrs BP, 1000 and 850, 650 to 450, and 100 cal yrs BP up to the present day, were separated by a reduction in organic content, with a marked decrease at the time of the White River Ash (WRA; 52-53 cm). Carbonate content (measured by loss-on-ignition at 950°C) was generally low (2-4%) with slightly elevated values prior to 900 cal yr BP and during the past ~200 cal yrs BP. There was a distinct decrease associated with the White River Ash, and the lower values of both organic and carbonate content were due to replacement of sediment by the ash. Biogenic silica (BSi) percent dry weight ranged between 4 and 24%, and increased through the record, with greater short-term variability from 850 cal yrs BP to the present.

The lake sediment core from Jenny Lake was a plain gray marl with occasional light gray and dark gray-brown laminations (Figure 5.2b). Organic and BSi content were low (<19% and <13%, respectively), and carbonate content was high (>22%, with the exception of the sample taken at the level of the WRA; 92-93 cm). Values of organic matter were relatively constant between 3100 and 500 cal yr BP, followed by a decrease and subsequent increase around 100 cal yr BP. Lower carbonate content was evident between 3000 and 2750, 1950 and 1400, 950 to 850, and 200 cal yrs BP to the present day. BSi content showed opposite tendencies to carbonate content and ranged between 0.5 and 13%.

Lake sediments from the Donjek Kettle core were dark brown with organic content <16% and carbonate content <11% (Figure 5.2c). These sediment variables showed broadly similar trends, with decreased values between 2000 and 1900 cal yrs BP, and at the WRA. An increase in organic content occurred between 1000 and 900 cal yrs BP, and again after 0 cal yrs BP (AD 1950), meanwhile carbonate remained consistent from 1100 cal yrs BP to the top of the core. BSi values ranged between 0 and 8%, with the highest values between 1100 and 800 cal yrs BP, and declining values thereafter. A thick layer of White River Ash was located between 33 and 77 cm.

Dark brown gyttja with moderate to high organic content (4-29%) characterized the sediment from Lake WP02 (Figure 5.2d). Organic and carbonate content both increased during the record, however the carbonate content comprised <6% of the sediments. BSi content also increased and became very high (58%), with the highest values from 100 cal yrs BP to 0 cal yr BP. Low values occurred immediately following the WRA and between 700 and 500 cal yrs BP. Details on ash thickness at each of the lakes can be found in Chapter 4.

Accumulation rates

Chironomid accumulation rates (CAR) at Upper Fly Lake were low between 1700 and 1200 cal yrs BP (Figure 5.2a). Following 1200 cal yrs BP, values gradually increased with a noticeable peak at 470 cal yrs BP, after which they were low again until large values occurred in the uppermost sediments. At Jenny Lake the chironomid accumulation rates (CAR) were similar to those of ostracodes (OAR; Figure 5.2b), with relatively low values in sediments below the WRA. Prominent increases in the accumulation rates of both organisms occurred ~1800 cal yrs BP, 630 cal yrs BP, and from 150-30 cal yrs BP, and broadly corresponded with increased BSi. Just above the WRA at 1120 and 1040 cal yrs BP, sharp increases in the OARs occurred, whereas CARs increased ~900 cal yrs BP. Donjek Kettle CARs were higher between 2100 and 2000 cal yrs BP corresponding with higher organic and carbonate content and lower biogenic silica values (Figure 5.2c). CARs were lower between 2000 and 1900 cal yrs BP which broadly coincided with higher values of organic, carbonate, and biogenic silica content. A prolonged period of low CARs lasted until about 1100 cal yrs BP after which rates remained elevated until 900 cal yrs BP. After this time, rates were low until the uppermost sediment sample. The accumulation rate of chironomids at Lake WP02 exhibited increases between 1147 to 1050 and between 975 to 875 cal yrs BP, as well as after AD 1910 (Figure 5.2d). In all lakes, there was a step-change in the ARs of both organisms in the uppermost sediments that is caused by better dating resolution in the section provided by ^{210}Pb.

Chironomids

Assemblages

At Upper Fly Lake, *Sergentia*, *Cricotopus/Orthocladius*, Other Tanytarsina, *Chironomus*, and *Paratanytarsus* were relatively abundant from 1700 to 1000 cal yrs BP. All of these taxa subsequently increased in abundance until 470 cal yrs BP, after which they sharply declined, suggesting a change in environmental conditions (Figure 5.3a). The concentrations of two taxa with colder mean-July temperature optima, *Sergentia* and *Cricotopus/Orthocladius*, decreased at the very top of the record, whereas several taxa with warmer temperature optima, (e.g. *Chironomus anthracinus*-type, *Procladius*, *Psectrocladius* (*Psectrocladius*), and *Corynocera oliveri*-type) increased, suggesting warmer conditions existed at Upper Fly Lake since the beginning of the 20th century. The results of a Detrended Correspondence Analysis (DCA) performed on the chironomid data from Upper Fly Lake revealed a gradient length of 2.1 standard deviation units (SD units; Figure 5.4a). This suggests that chironomid compositional turnover was low during this time (ter Braak 1995; Lepš and Šmilauer 2003). DCA axes 1 and 2 explained 37.5% and 11.4% of the variance in the chironomid data at Upper Fly Lake. *Corynocera oliveri*-type, *Psectrocladius* (*Psectrocladius*), and *Procladius* are located on the left side of the plot, and *Corynoneura arctica*-type on the right. The former have high concentrations in the uppermost sediments, whereas the latter is found at the base of the record. Sample scores on DCA axis 1 remained unchanged until early in the 20th century when they decreased, and on axis 2 scores were more variable with lower scores between 500 and 250 cal yrs BP, and then again after 150 cal yrs BP.

The Jenny Lake chironomid record over the past 3000 years exhibited greater variability than that examined from Upper Fly Lake (Figure 5.3b). The most common taxa in the core were Other Tanytarsina and *Chironomus anthracinus*-type, and to a lesser extent *Cricotopus/Orthocladius* and *Psectrocladius* (*Psectrocladius*). A number of taxa were present in low concentrations until 200 cal yrs BP, after which both warm and cold tolerant taxa increased in abundance. A comparable gradient length (2.2 SD units) revealed by the DCA on the chironomid data at Jenny Lake indicated similar species compositional turnover to that at Upper Fly Lake (Figure 5.4b). The variance explained on DCA axis 1 was 25.7%, and on axis 2 was 10.8%. Taxa found in the uppermost sediments (*Psectrocladius* (*Allopsectrocladius* and *Mesopsectrocladius*) and *Dicrotendipes*) were located on the left side of the graph, whereas *Chironomus anthracinus*-type and *Glyptotendipes* were situated on the right side of the plot and although they were present throughout most of the record, they did not increase in the uppermost sediments. Chironomid sample scores on DCA axis 1 decreased until 1700 cal yrs BP, then increased until 400 cal yrs BP, and declined thereafter (Figure 5.4b). Scores on DCA axis 2 showed small variations to higher followed by lower scores between 1400 and 1000 cal yrs BP. They then increased to 600 cal yrs BP after which they decreased with a slight shift to higher scores at 200 cal yrs BP.

Four abundant chironomid taxa and many rare types comprised the assemblages at Donjek Kettle since 2100 cal yrs BP (Figure. 5.3c). *Chironomus-anthracinus*-type was encountered throughout the record, and generally higher concentrations occurred after the date of the White River Ash. *Sergentia* was also present throughout the core, but in low abundance (<5 hc·cm^{-3}). Other Tanytarsina dominated the assemblages (up to 50 hc·cm^{-3}) before 900 cal yrs BP, and *Procladius* was also present during this time. The occurrences of other taxa were infrequent and they were only found intermittently in the core. A number of taxa with both warm and cold temperature optima were present in the lake at the base of the record. At Donjek Kettle the turnover in species composition was 2.2 SD units, and the variance in explained was 25.7% on DCA axis 1, and 15.7% on DCA axis 2 (Figure 5.4c). *Chironomus anthracinus*-type is positioned on the left side of the plot, and dominated in the sediments after 1100 cal yrs BP, whereas *Procladius* is on the right side of the plot and occurred in sediments prior to 900 cal yrs BP. Sample scores decreased from the base of the record to the present day and were punctuated by lower scores between 2000 and 1900, and 1120 to 975 cal yrs BP, and higher scores between 975 and 850 cal yrs BP. On DCA axis 2, scores decreased up to 1800 cal yrs BP, and increased up to the timing of the White River Ash at 1147 cal yrs BP. A period of lower sample scores occurred between 1147 and 840 cal yrs BP, followed by steady values to the top of the record.

The most diverse chironomid fauna encountered in this study was at Lake WP02 (Figure 5.3d). Taxa present over the past 1200 years at this site had a broad range of temperature optima (6.8°C to 12.9°C) and contained taxa not frequently encountered at the other three sites (e.g. *Hydrobaenus/Oliveridia*, *Heterotrissocladius maeaeri*-type, *Zalutschia* sp.). The presence of *Hydrobaenus/Oliveridia* at the base of the core suggests conditions were cold prior to 1100 cal yrs BP. Following this time, several taxa with cooler temperature optima were abundant, indicating an improvement in climate conditions. Around 650 cal yrs BP, concentrations of *Micropsectra*, Other Tanytarsina, and *Zalutschia lingulata*-type declined, and these taxa were replaced by *Zalutschia* type B, and to a lesser extent, *Heterotrissocladius maeaeri*-type. Although the number of chironomids encountered at Lake WP02 was higher, the species compositional gradient was comparable to the previous sites (2.2 SD units), and the variance in the chironomid data explained by the DCA was 34.0% on axis 1 and 12.1% on axis 2 (Figure 5.4d). Taxa situated on the right-hand side of the plot were more abundant in the bottom half of the record and included *Corynocera* types, *Cricotopus/Orthocladius*, and in lower concentrations *Dicrotendipes* and *Hydrobaenus/Oliveridia.* Sample scores on DCA axis 1 from Lake WP02 were lower from the base of the record up to 130 cal yrs BP, with a tendency toward higher scores thereafter. On DCA axis 2, scores were high and then quickly declined at about 1100 cal yrs BP, after which they gradually increased, followed by a decrease after 130 cal yrs BP.

Mean-July temperature reconstructions

The ranges of the estimated mean-July temperature anomalies (TJul) from the four sites are similar, with the exception of site WP02 (Figure 5.5; Upper Fly = 2.8°C, Jenny = 2.9°C, Donjek = 2.1°C, WP02 = 6.2°C). The cool reconstructed temperatures at the base of the core at Lake WP02 led to the increased temperature range however this may be a reflection of the affect of the ash deposition on the chironomid assemblages (below). Nonetheless, the TJul values from Lake WP02 exhibited similar tendencies to TJul reconstructed from chironomids at both Upper Fly Lake and Donjek Kettle. Similarly, the variability in reconstructed temperatures was low in Upper Fly Lake, but the range is increased by warm temperatures reconstructed in the uppermost sediments.

July temperatures were lower at Jenny Lake and Donjek Kettle prior to 1550 cal yrs BP. Between 1500 and 1100 cal yrs BP, temperatures increased at Jenny Lake and Donjek Kettle, but there was little change reconstructed at Upper Fly Lake. Temperatures were slightly warmer than previously at Upper Fly Lake between 1000 and 250 cal yrs BP. At Jenny Lake the record was more variable, and oscillated around the mean from AD 1500 to the present. At Donjek Kettle there was a slight but persistent warming from 1100 cal yrs BP to the present. A similar trend occurred at Lake WP02, except that maximum temperatures were reached at approximately 150 cal yrs BP. Temperatures have decreased since that time at Lake WP02.

The squared chord distances (SQD) are higher at Lake WP02 than at the other sites. There is no long-term tendency in the values of the SQD, although there is a suggestion of higher values with warmer temperatures.

Ostracode Assemblages at Jenny Lake

Candona acutula was the most abundant species in the record, with higher concentrations between 2000 and 1500 cal yrs BP, immediately following the White River Ash deposition, and after 200 cal yrs BP (Figure 5.6). *Candona candida* was also present throughout the core, but in lower concentrations and had greater abundance prior to 2400 cal yrs BP, between 1400 and 1200, after the White River Ash, and again between 500 and 100 cal yrs BP. *Candona decora* was most abundant between 1400 and 1000, and 400 and 200 cal yrs BP, whereas *Ilyocypris bradyi* occurred between 2400 and 2000, and 1100 to 200 cal yrs BP. *Cyclocypris ampla* and *Cypridopsis vidua* showed similar tendencies through time, with high values between 2900 and 1700, 1100 and 1000, and from 200 cal yrs BP up to the present day, whereas *Limnocythere itasca* was most abundant after 200 cal yrs BP. A DCA computed on the ostracode data revealed a slightly longer gradient length than found with the chironomid data (2.5 SD units; Figure 5.4e). A large portion of the variance in the ostracode data was explained by the first two axes (axis 1 = 42.5%, axis 2 = 13.7%). Species found on the left side of the plot had greater concentrations in the uppermost sediments, whereas *Candona decora* is situated on the right side of the plot and declines in the uppermost sediments. Ostracode sample scores on DCA axis 1 had lower values up to 1800, between ~1000 and 500, and after 200 cal yrs BP, with higher values from 1300 to 1000, and 450 to

250 cal yrs BP. Scores on the second DCA axis are higher up to 1700 cal yrs BP, after which the tendencies are comparable to the first DCA axis.

Effects of the White River Ash – 1300 to 800 cal yrs BP

To investigate the potential impact of the White River Ash event (WRA; 1147 cal yrs BP) on the aquatic communities, the period from 1300 to 800 cal yrs BP was investigated in more detail. Modern studies indicate that aquatic environments respond immediately to ash input (Kurenkov 1966; Wissmar et al. 1982a; Wissmar et al. 1982b; McKnight and Dahm 1990; Lee 1996), whereas paleoecological studies have revealed that aquatic ecosystems return to conditions that existed prior to the eruption anywhere between 10 to 300 years (Barsdate and Dugdale 1972; Abella 1988; Lotter et al. 1995; Barker et al. 2000). Therefore, this period provides an adequate time frame to assess the environmental conditions that existed before and after the ash input, and to separate out the effects of the ash deposition from those of climate variables. At Donjek Kettle we extend the base of our time frame to 2150 cal yrs BP to evaluate the effect of the second White River Ash (WRA2; 1953 cal yrs BP). A varve-inferred record of mean summer temperature anomalies from Iceberg Lake (Loso 2009) and a moisture record from nearby Marcella Lake inferred from $\delta^{18}O$ charaphytic algae encrustations (Anderson 2005) are used as independent climate records to aid in the interpretation of the records from our four lakes. More negative values of the reported $\delta^{18}O$ values suggest wetter conditions, whereas more positive $\delta^{18}O$ values indicate conditions were drier in the region.

The ash input to Upper Fly Lake was minimal and appeared to have little to no effect on the aquatic environment. There was little change in BSi values, organic and carbonate content, chironomid ARs, and the chironomid scores on DCA axis 1 (Figure 5.7a). At the time of ash deposition, decreased organic and carbonate content in the sediments, as well as lower CARs are caused simply by the displacement of sediment by ash. The DCA sample scores are inverse to the Iceberg Lake temperature anomaly pattern suggesting that the chironomid community composition of Upper Fly Lake was more influenced by climate changes than to the ash input during this period.

At Jenny Lake, immediately following ash deposition, some changes occurred (Figure 5.7b). As at Upper Fly Lake, the BSi content was virtually unchanged following the ash deposition. A brief carbonate content decrease is a consequence of the ash in the sediments, but the organic content declined by 6% during the ash deposition and did not return to pre-eruption values until ~1130 cal yrs BP. CARs increased rapidly at the time of ash deposition, and although there was variability in the values, chironomids continued to be abundant until after 1100 cal yrs BP. Total head capsule counts are low in the sediments immediately following the WRA (due in part to the small volumes available from the fine resolution sampling), so changes in the relative abundance of the taxa are difficult to estimate. Taxa that were present in the sediments both before and after the event were *Cricotopus/Orthocladius*, Other Tanytarsina, and *Chironomus-anthracinus* type. Ostracode accumulation rates did not change at the time of the WRA, but increased after 1125 cal yrs BP. The ostracode sample scores were more variable at this time with *Candona acutula* and *Candona candida* present before and after the ash event. Changes in abundance between these species and *Candona decora* occurred after 1130 cal yrs BP, when conditions at Jenny Lake appeared comparable to those that existed prior to the eruption.

The sediment organic and carbonate content at Donjek Kettle decreased during and after the WRA event, but returned to pre-eruption values by 1075 and 1065 cal yrs BP, respectively (Figure 5.7c). In contrast, BSi values increased considerably following the ash input and continued increasing until reaching peak values at 1065 cal yrs BP. Immediately following the ash input, CARs were first reduced, but then increased and remained elevated until 900 cal yrs BP. The sample scores on DCA axis 1 decreased at 1120 cal yrs BP and remained low until 960 cal yr BP. Concentrations of *Chironomus anthracinus*-type increased post-eruption, as did Other Tanytarsina, and to a lesser extent *Sergentia*.

The second (older) ash event deposited a thinner layer of tephra (44 cm vs. 1.25 cm) than the first. Values of sediment organic content, sediment carbonate content, and chironomid accumulation rates all declined prior to the deposition of the ash (1945 cal yr BP), and increased gradually after the ash event, remaining high until about 1900 cal yrs BP. There was a change in the composition of chironomid assemblages above the WRA2, and although concentrations of *Chironomus anthracinus*-type were the same above and below the ash, Other Tanytarsina decreased in abundance and were replaced by rare taxa (e.g. *Psectrocladius* (*Allopsectrocladius* and *Mesopsectrocladius*), *Microtendipes*, and Other Chironomidae).

At Lake WP02 the sediment organic, carbonate and BSi content all gradually increased after the ash event (Figure 5.7d). The CARs increased after 1125 cal yrs BP. The gradual change to lower sample scores on DCA axis 2 between 1100 and 1075 cal yrs BP represents a change in the chironomid assemblages from more rare types (e.g *Hydrobaenus/Oliveridia* and Other Chironomidae) to common types. An assessment of the response of the aquatic ecosystem to the ash event at this site difficult as sediment was unavailable from below the ash. However, after 1075 cal yrs BP, changes in the various parameters became more gradual suggesting any impact that the ash may have had was over.

Discussion

July temperatures over the past 2000 years in the southwest Yukon

The study sites include two pairs of lakes located ~90 km from each other along the southeast-northwest trending Shakwak Trench. Upper Fly and Jenny Lake are located southeast of Kluane Lake whereas Donjek Kettle and Lake WP02 are to the northwest. One site from each pair are located at lower elevation in the boreal forest (Jenny Lake and Donjek Kettle), whereas the other site from each pair are located above treeline (Upper Fly Lake and Lake WP02) upslope from the Trench. The two lakes within a region resembled each other more than those in similar environments.

In general, the Upper Fly Lake and Jenny Lake mean-July temperature anomalies showed similar tendencies, and revealed more variable temperatures in the boreal forest than in the tundra (Figure 5.5). Generally, temperatures fluctuated more between 1500 and 300 cal yrs BP (AD 450 to 1650), with cooler temperatures from 300 to 50 cal yrs BP (AD 1650 to 1900). These sites indicate that a cool phase dominated to the southwest of the region around 500 cal yrs BP (AD 1450). In contrast, at 400 cal yrs BP (AD 1550) the Upper Fly Lake temperature estimates indicated warmer conditions prevailed and Jenny Lake records indicated the opposite. These minor variations are not considered further.

The two longest records are from the boreal forest sites, which both indicate cooler conditions from 2000 to 1500 cal yrs BP (BC 50 to AD 450), followed by temperatures around the mean until ~300 cal yrs BP. After this the records diverged, with conditions at Jenny Lake showing cooling and those at Donjek Kettle indicating warming, which revealed that the smaller scale variability was not clearly in phase between these sites.

The mean-July temperature anomalies at Lake WP02 and Donjek Kettle also resembled each other. At both sites, temperatures were around the mean from 1100 to 300 cal yr BP (AD 850 to 1650) followed by a warming trend. Thus, in these reconstructions, a ”Medieval warming” is not apparent, nor are cooler temperatures associated with the Little Ice Age.

A review of the dissimilarity (SQD) values indicates that non-analogue situations are not solely responsible for the inconsistencies in the reconstructions (Figure 5.5). At Upper Fly Lake, Jenny Lake, and Donjek Kettle the squared chord distances are reasonable considering the taxonomic richness of chironomid taxa in the reconstructions for each site (Overpeck et al. 1985; Sawada 2006). Values of the SQD at Lake WP02 are generally higher, particularly after 600 cal yrs BP (AD 350) so the reconstructions are less reliable. This occurs when *Zalutschia* type B begins to increase in abundance at this site (Figure 5.3d). In the modern training set, this taxon is only found in deep, arctic lakes (>6 m; Barley et al. 2006), which suggests cooler conditions, and/or increased moisture. However most of the analogues during this time period are from the Yukon, Alaska, and British Columbia, where modern conditions are warmer. In the uppermost sediments (after 0 cal yrs BP (AD 1950)), it appears that cooler conditions are being reconstructed due to the abundance of *Micropsectra* and to a lesser extent *Sergentia*, both of which have some of the coldest temperature optima of the chironomids presented (Figure 5.3d).

Differences in the lake environment may be affecting the climate reconstructions at Jenny Lake. The marl sediments indicate a hard-water lake during the period of record, and modern-day water chemistry has higher values of alkalinity (210 mg l^{-1}). This is quite different than the organic sediments and more dilute conditions at the other three lakes (Upper Fly alkalinity = 101 mg l^{-1}, Donjek = 150 mg l^{-1}, WP02 = 11 mg l^{-1}; Wilson and Gajewski 2004). In addition, Wilson and Gajewski (2004) attributed alkalinity as an important factor explaining chironomid species distribution in the region. Therefore, we propose that the chironomid taxa at this site may be affected by changes in the lake environment; although changes in the lake chemical environment is itself affected by climate variability, the indirect effect may be masking the climate signal.

The oxygen-isotope ($\delta^{18}O$) curves from Mount Logan, Jellybean Lake and Marcella Lake provide information on fluctuations in the Aleutian Low Pressure Centre which in turn affect moisture in the region (Fisher et al. 2004; Anderson et al. 2005; Anderson et al. 2007; Fisher et al. 2008). Fluctuations in the extent and position of the Aleutian Low affect the source and trajectory of air masses that originate in the Gulf of Alaska and provide a source of moisture first to Mount Logan, and then to the interior southwest Yukon. More negative $\delta^{18}O$ values in the Mount Logan and Jellybean Lake records indicate a strong, eastward Aleutian Low, whereas more positive values indicate that the centre was weaker and more westward. Generally speaking, a weaker, more westward centre delivers more precipitation to the interior. The $\delta^{18}O$ record from Marcella Lake is interpreted as drier conditions when values are more positive and wetter conditions with the opposite.

Variations in the Upper Fly Lake anomalies over the past 1700 years correspond with the Jellybean Lake oxygen isotope record from sedimentary carbonate, suggesting that periods of lower temperatures were also more arid. In comparison, Donjek Kettle and Lake WP02, which are located further north, are out of phase with our Upper Fly Lake reconstruction and the Jellybean Lake record. Although the tendency in the Donjek Kettle record corresponds reasonably well with the Iceberg Lake varve-inferred mean summer temperature reconstructions from Alaska (Loso 2009), the anomalies at our site are higher after 700 cal yrs BP (AD 1250). Lake WP02 temperature anomalies also exhibit a similar trend as the Donjek Kettle record and the Iceberg Lake record. Mean-July temperature anomalies at both Donjek Kettle and Lake WP02 increased more rapidly after 300 cal yrs BP (AD 1650), which corresponds with the timing of a "shift" to more arid conditions in the Marcella Lake record.

After AD 1960 temperature anomalies indicated warmer conditions at both Upper Fly Lake and Donjek Kettle, with the warmest conditions in the Upper Fly Lake record being reached in AD 1995. In comparison, temperatures warmed at Jenny Lake and Lake WP02, however they remained below the mean. This warming is consistent with the recent contemporary warmth identified in the Iceberg Lake varve sequence (Loso 2009) and tree-ring evidence from the region (Youngblut and Luckman 2008), and also corresponds with recent warming at other Arctic sites (Kaufman et al. 2009).

Aquatic ecosystem response to environmental changes over the past 2000 years

Organic content and biogenic silica content are indices of lake productivity (Delcourt and Delcourt 1991; Conley and Schelske 2001), whereas changes in carbonate content can be used to infer the past chemical conditions within a lake. This information can further be combined with data on species abundance and changes in community composition to infer long-term variations in the aquatic ecosystem. General tendencies indicated that the organic and carbonate content of the sediments at all sites showed parallel changes on longer timescales, but not necessarily on shorter ones. Biogenic silica (BSi) concentrations typically increased when organic and carbonate content decreased and *vice versa*, and both the chironomid and ostracode accumulation rates increased when BSi values were higher.

At Upper Fly Lake, lower BSi production in the early part of the record may in part be explained by partial diatom dissolution (Figure 5.2a). Analyses of BSi at levels below those reported here indicated that complete diatom dissolution had occurred deeper in the core (Chapter 3). In addition, Upper Fly Lake is relatively large and lower values of BSi have been found in modern sediments from large lakes compared to smaller lakes (Fortin and Gajewski 2009a).

As indicated above, carbonate production is a considerable component of the Jenny Lake aquatic ecosystem compared to the other three sites. Sources of carbonate in the sediments are in the form of charophytic algae encrustations and molluscs (personal observation), as well as ostracodes. The charoyphyte encrustations are the result of bioinduced calcium carbonate precipitation that is common in hydrologically closed basin lakes with high ion concentrations in solution (Dean 1981). Modern data from Jenny Lake indicates that the ion concentrations are elevated (pH = 8.65, specific conductance = 606 μS cm^{-1}; refer to Chapter 2) which would support $CaCO_3$ precipitation. *Candona acutula*, *Limnocythere itasca*, and *Ilyocypris bradyi* were found in lakes in the southwest Yukon that were saturated with respect to calcite (Bunbury and Gajewski 2005), which is required for $CaCO_3$ precipitation. At least one of these taxon was present in every level sampled in the Jenny Lake core (Figure 5.6), providing further evidence of $CaCO_3$ precipitation. The importance of ion concentrations may therefore have been of greater direct importance in affecting the ostracode community than temperature variability at different times over the past 2000 years.

Decreased carbonate production and increased BSi production at Jenny Lake ~200 cal yrs BP (AD 1750; Figure 5.2b) corresponded with the timing of the maximum advance of the Kaskawulsh Glacier (Reyes et al. 2006). In turn, the chironomid and ostracode accumulation rates increased considerably, and there were changes to the chironomid community composition as taxa not present in the preceding period were reintroduced to the lake (Figure 5.3b; i.e. *Micropsectra*, *Psectrocladius* (*Allopsectrocladius* and *Mesopsectrocladius*), and *Dicrotendipes*). Although not evident at any of the other sites, or in any of the other proxies from this site, there was a short-lived increase in the chironomid accumulation rates at Upper Fly Lake ~1480 cal yrs BP (AD 520; Figure 5.2a), during the time the Little Ice Age was considered to be occurring based on the varve record from Alaska (Loso 2009).

The two records from sites to the northwest indicated increased and greater variability in the BSi record after 150 cal yrs BP (AD 1850; Figure 5.2c and d). During this time, the Aleutian Low moved to the east, resulting in drier conditions in the interior (Anderson et al. 2005). This also appears to have influenced the structure of the chironomid community at Lake WP02. Other changes to the chironomid community also occurred at AD 1940 at Lake WP02, and AD 1960 at Upper Fly Lake, which appear to be attributed to warmer drier conditions inferred from tree-rings (Youngblut and Luckman 2008), glacial retreat (Denton and Karlén 1973), and varves in Alaska (Loso 2009).

Aquatic ecosystem response to the White River Ash event

The effects of the White River Ash (WRA) event on aquatic environments in the southwest Yukon was more apparent at sites that had greater ash input. The ash input was substantially greater at the two northwestern lakes, as was the response. At Upper Fly Lake neither the aquatic ecosystem, as determined by the sediment variables, nor the chironomid community in terms of abundance or composition appears to have been influenced by the ash input (Figure 5.7a). This is not surprising, as the ash was barely noticeable in the sediment.

However, at Jenny Lake (ash thickness = 0.3 cm) just 10 km to the southwest of Upper Fly Lake, the small ash input appears to have immediately reduced organic production, which in turn affected the chironomid accumulation rates, and community composition (Figure 5.7b). This effect was short-lived, and the WRA impacted that lake environment for, at most, 20 years. It is not clear what caused a decrease in organic production, as it was not due to a decrease in biogenic silica or chironomid production. Once the organic content of the sediments increased again, so did the accumulation rate of the ostracodes.

Although ash layers <1 cm generally had little effect on aquatic environments in Mexico (Telford et al. 2004), we propose that the results at Jenny Lake may be due to the high-carbonate nature of the site. *Cricotopus/Orthocladius* was one of the chironomid taxa found in the sediments immediately above the ash, and has been observed elsewhere above ash layers (Figure 5.3b; Heinrichs et al. 1999). *Chironomus anthracinus*-type was present in elevated concentrations immediately following the ash event; this genus is opportunistic and is often encountered following significant environmental change (Brooks et al. 2007).

At Donjek Kettle, after the earlier ash event, as organic production increased, so did the chironomid accumulation rates and the system returned to pre-eruption conditions ~40 years (Figure 5.7c). This is also reflected in the chironomid community structure. After the later ash event, primary production (BSi) increased considerably and remained elevated for around 80 years. This is seen to a smaller extent after the lower ash; although this is not unexpected, as the thickness of the second ash layer was much was smaller (44 cm vs. 1.25 cm). This increased diatom production may have provided a food source for the chironomid community. After about 80 years, the effects of the ash on the system were no longer detectable.

The increase in BSi production following the ash may be a result of elevated silica-phosphorus ratios (Si:P). Silica-rich tephra deposited in lakes is chemically weathered which contributes to elevated silica levels. In addition, thick ash layers create a barrier between the sediments and the water column, thereby reducing phosphorus release from the sediments. This increases the Si:P, resulting in an increase to diatom production. Although we do not know the phosphorus content of our sediments, we speculate that this occurred given the similar response to that found in other studies (Barker et al. 2000; Telford et al. 2004). The small fluctuations in BSi in the past 1000 years seem to parallel the Iceberg Lake temperature reconstruction suggesting the impact of temperature on aquatic production during this time.

Interestingly, at both Jenny Lake and after both ashes in Donjek Kettle, there is a two-peaked response in BSi and the chironomid accumulation rates (Figures 5.7b and c). Although the time between response for each ash event is not the same, the nature of the responses are similar. Although we cannot make any conclusions based on the data presented, the results are intriguing, since a similar response was found by Barker et al. (2000), which they attributed to the effects of "chronic" and "acute" ecosystem change. Future studies of this nature should ensure that high resolution analyses are performed for a long enough period to capture these two types of ecosystem change; this could become especially important in the context of future global warming.

Following the ash at Lake WP02, reduced primary production, seen in both total organic matter and BSi, may have led to a decrease in chironomid production as well (Figure 5.7d). Above the ash, *Hydrobaenus/Oliveridia* was present in greater abundance and is typically found in cold, oligotrophic environments (Figure 5.7d; Brooks et al. 2007). As the aquatic ecosystem recovered, the chironomid community changed to taxa typically found in shallow more productive lakes (e.g. *Corynocera* types, Other Tanytarsina), and based on the small changes in ecosystem parameters and chironomid production since 1075 cal yrs BP (AD 875), suggests that the system recovered within 70 years.

Unfortunately, we were unable to obtain a useful core below the ash, so we cannot compare what the conditions were like before the ash, nor can we see if there was a comparable response to the earlier ash. However, the fact that both ash events were observed in the core from Donjek Kettle, and a subsequent response, which suggests that this area would be particularly suitable to obtain Holocene sequences and perform detailed multi-proxy analyses to assess multiple ecosystem responses to both short-term and long-term environmental variability.

Conclusions

Results from four lakes in the southwest Yukon indicate that aquatic ecosystems have responded to late Holocene environmental variability. Although our chironomid-inferred mean-July temperature anomalies appear less than reliable, comparison of measures of paleoproductivity and the chironomid and ostracode communities with independent temperature and moisture records from the region show that the aquatic environment responded to climate changes during the late Holocene. The aquatic ecosystems and the chironomid and ostracode communities have also responded to environmental variability caused by changes in atmospheric circulation related to the Aleutian Low. Three of the four sites studied showed an aquatic ecosystem response to the deposition of the ash which altered chironomid abundance and community composition. The ostracode community was affected at the one site where ostracode subfossils were preserved. The effects of the ash deposition on a high carbonate system with minimal ash input was 20 years at most, whereas more productive lake environments with greater ash input took between 70 and 80 years to recover.

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Table 5.1: Summary of chironomid head capsule counts from four lakes in the southwest Yukon.

Lake	Levels	Sampling interval (cm)	Sediment subsampled (cm^3)	Min. count	Max. count	Mean count
Upper Fly	80	0.25-3	0.3-8	3	203.5	49
Jenny	76	0.25-4	1-16.8	1	209	50.6
Donjek	73	0.25-2	1-14.1	4	135	36.9
WP02	41	0.25-2	1-2	9.5	320.5	108.5

Table 5.2: AMS radiocarbon dates from the lake sediment cores, southwest Yukon

Lake and Depth (cm)	Lab Code	Conventional Radiocarbon age (yr BP)	2-sigma calibrated age range (cal yr BP)[a]	Median calibrated age (cal yr BP)	$\delta^{13}C/^{12}C$ (‰)	Material
Upper Fly 34-36	Beta – 229092	1490 ± 40	1302-1420	1361	-26.3	Macrofossils
Upper Fly 69-71	Beta – 229093	2440 ± 40	2355-2547	2451	-22.2	Macrofossils
Jenny 31.5-34.5[b]	Beta – 256717	2070 ± 40	1945-2144	2044.5	NA	Macrofossils
Jenny 69.5-71.5	Beta – 255709	1040 ± 40	907-1057	982	-24.6	*Picea* twig
Jenny 105-107	Beta – 255710	1820 ± 40	1691-1865	1778	NA	Twig, macrofossils
Donjek 26-27.5[b]	Beta – 255707	1350 ± 40	1227-1336	1281.5	-34.2	Moss fragments
Donjek 82-83	Beta – 255708	1820 ± 40	1691-1865	1778	-33.8	Plant fragments
Donjek 96-98.5	Beta – 256716	2160 ± 40	2041-2311	2176	NA	Macrofossils
WP02 17-17.5	Beta – 255711	430 ± 40	428-536	482	-29.4	Moss fragments
WP02 36.5-38[b]	Beta – 255712	480 ± 40	475-556	515.5	-29.5	Moss/plant fragments

[a] Calibration was based on IntCal04 (Reimer et al. 2004).

[b] These dates were not used in the respective chronologies (see text for details).

Table 5.3: Lead-210 dates from the sediment core at Upper Fly Lake, southwest Yukon

Depth (cm)	^{210}Pb total activity (Bq/g)	Years before present[a] at bottom of sediment section (CRS model estimate)
3.0-4.0	15.5	6.8
4.0-5.0	12.8	13.7
5.0-6.0	10.5	20.3
6.0-7.0	8.9	27.6
7.0-8.0	6.8	32.9
8.0-9.0	5.5	38.4
9.0-10.0	4.2	42.8
10.0-11.0	3.4	
14.0-15.0	2.3	
19.0-20.0	1.8	
24.0-25.0	1.8	

[a] Before AD 1997

Table 5.4: Lead-210 dates from the sediment core at Jenny Lake, southwest Yukon

Depth (cm)	^{210}Pb total activity (Bq/g)	Years before present[a] at bottom of sediment section (CRS model estimate)
0.0-1.0	9.6	10.0
1.0-2.0	7.4	28.2
2.0-3.0	4.6	55.4
3.0-4.0	1.5	81.0
4.0-5.0	0.6	109.2
5.0-6.0	0.3	
6.0-7.0	0.1	
7.0-8.0	0.1	

[a] Before AD 2003

Table 5.5: Lead-210 dates from the sediment core at Donjek Kettle, southwest Yukon

Depth (cm)	^{210}Pb total activity (Bq/g)	Years before present[a] at bottom of sediment section (CRS model estimate)
0.0-0.5	9.6	1.0
0.5-1.0	13.6	4.7
1.0-1.5	10.1	10.4
1.5-2.0	7.9	16.9
2.0-2.5	7.9	25.7
2.5-3.0	6.6	36.6
3.0-3.5	4.4	45.8
3.5-4.0	4.2	55.7
4.0-4.5	3.3	64.0
4.5-5.0	2.8	73.4
5.0-5.5	2.4	82.0
5.5-6.0	1.8	
6.0-6.5	1.7	
7.0-7.5	1.7	
8.0-8.5	1.7	
10.5-11.0	1.9	

[a] Before AD 2006

Table 5.6: Lead-210 dates from the sediment core at Lake WP02, southwest Yukon

Depth (cm)	^{210}Pb total activity (Bq/g)	Years before present[a] at bottom of sediment section (Linear regression model estimate)
0.0-0.5	29.7	0.5
0.5-1.0	31.6	2.7
1.0-1.5	26.9	8.2
1.5-2.0	21.6	15.5
2.0-2.5	17.3	23.9
2.5-3.0	11.9	33.6
3.0-3.5	10.4	44.3
3.5-4.0	7.5	55.2
4.0-4.5	6.8	58.2
4.5-5.0	6.5	61.1
5.0-5.5	5.8	63.9

[a] Before AD 2006

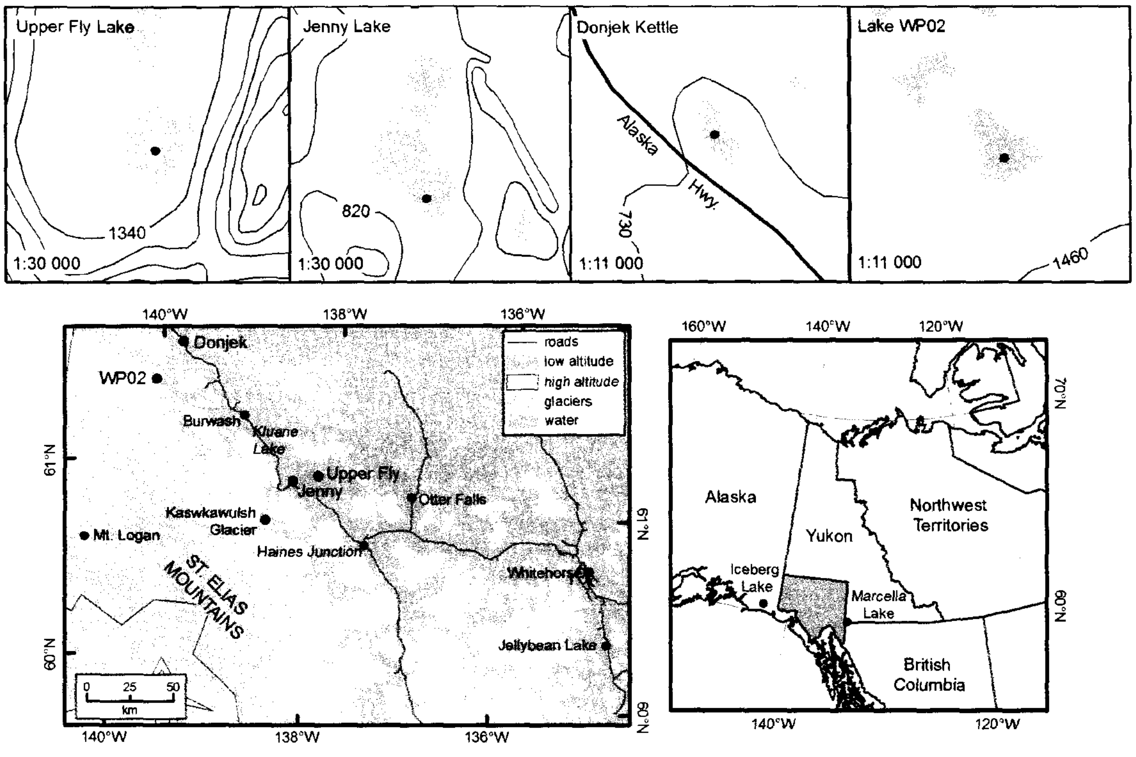

Figure 5.1: Location maps of Upper Fly Lake, Jenny Lake, Donjek Kettle, and Lake WP02, in the southwest Yukon. Haines Junction and Whitehorse are provided for reference, and other sites are mentioned in the text. Contour individuals on individual site maps are 30 m and coring sites are indicated.

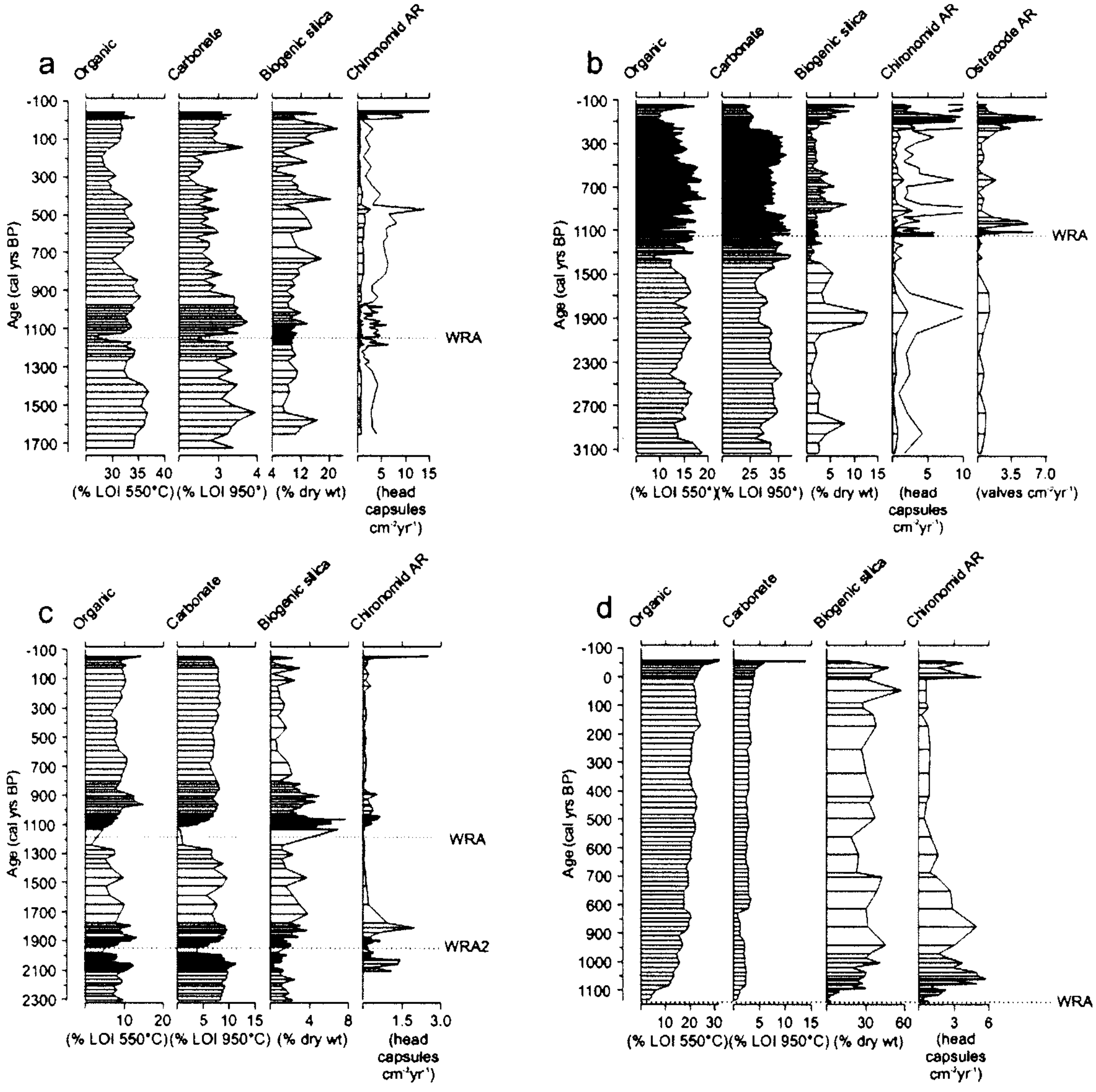

Figure 5.2: Sediment organic content (Organic), sediment carbonate content (Carbonate), biogenic silica content, and accumulation rates (AR) of organisms from Upper Fly Lake (a), Jenny Lake (b), Donjek Kettle (c), and Lake WP02 (d), southwest Yukon. The White River Ash layers (WRA; 1147 cal yrs BP and WRA2; 1953 cal yrs BP) are indicated by the dashed lines. Second lines on chironomid accumulation rate curves in (a) and (b) are 5x exaggeration. Note different scales on the x and y axes. Ages are in calibrated years before present (0 = A.D. 1950).

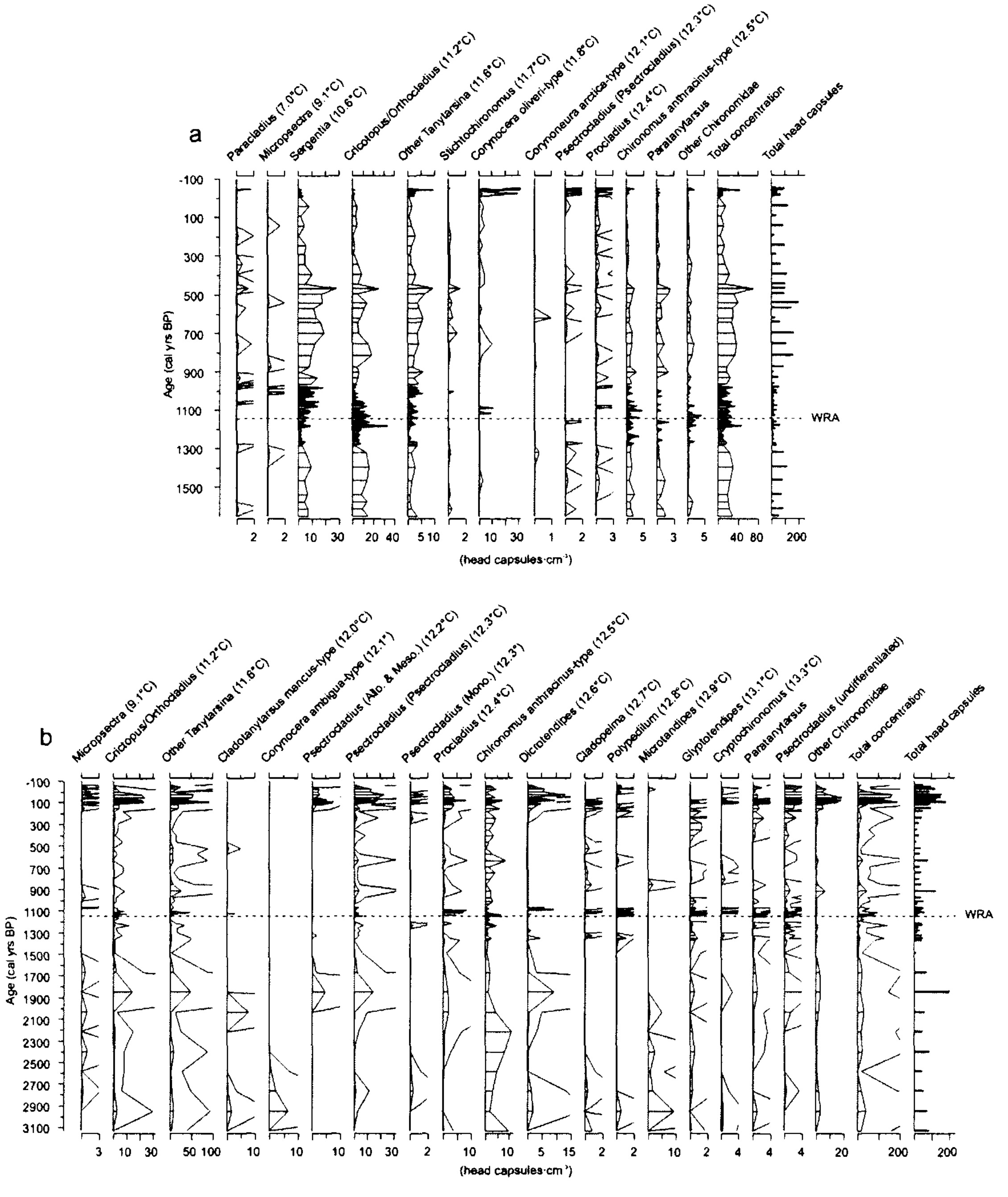

Figure 5.3: Concentrations of chironomid taxa from (a) Upper Fly Lake, (b) Jenny Lake, (c) Donjek Kettle, and (d) Lake WP02, southwest Yukon. Taxa are organized on a gradient from colder to warmer temperature optimums estimated using weighted-averaging regression and calibration; types without optima were not present in the calibration set. Rare types are combined into Other Chironomidae. A second curve on a graph indicates 10x exaggeration. The two White River Ash events (WRA; 1147 cal yrs BP and WRA2; 1953 cal yrs BP) are indicated by the dashed line. Note different scales on the x and y axes. Ages are in calibrated years before present (0 = A.D. 1950).

Figure 5.3 (cont'd): Concentrations of chironomid taxa from (a) Upper Fly Lake, (b) Jenny Lake, (c) Donjek Kettle, and (d) Lake WP02, southwest Yukon. Taxa are organized on a gradient from colder to warmer temperature optimums estimated using weighted-averaging regression and calibration; types without optima were not present in the calibration set. Rare types are combined into Other Chironomidae. A second curve on a graph indicates 10x exaggeration. The two White River Ash events (WRA; 1147 cal yrs BP and WRA2; 1953 cal yrs BP) are indicated by the dashed line. Note different scales on the x and y axes. Ages are in calibrated years before present (0 = A.D. 1950).

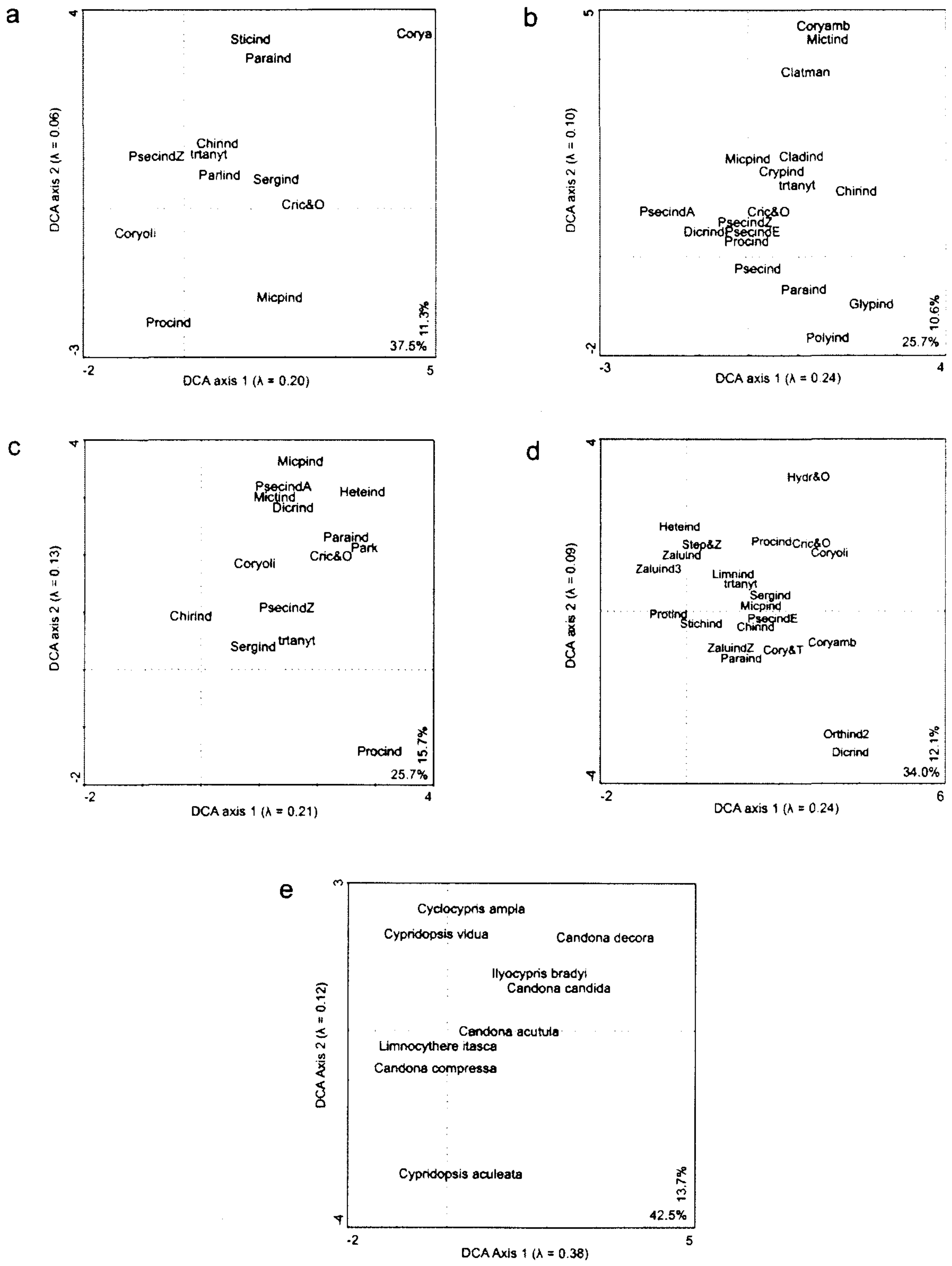

Figure 5.4: See next page for caption.

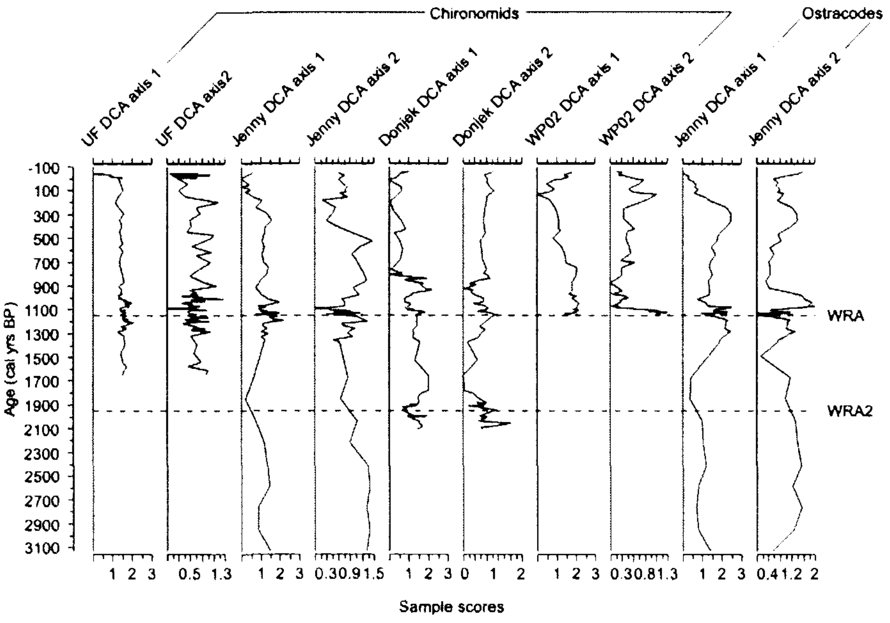

Figure 5.4: Detrended correspondence analysis plots of and corresponding sample scores of chironomid taxa from (a) Upper Fly Lake (12 taxa), (b) Jenny Lake (18 taxa), (c) Donjek Kettle (14 taxa), (d) Lake WP02 (22 taxa), and (e) ostracode taxa from Jenny Lake (9 taxa). Abbreviations for the chironomid taxa are: Chirind = *Chironomus anthracinus*-type, Cladind = *Cladopelma*, Clatman = *Cladotanytarsus mancus*-type, Coryamb = *Corynocera ambigua*-type, Coryoli = *Corynocera oliveri*-type, Cory&T = *Corynoneura/Thienemanniella*, Cric&O = *Cricotopus/Orthocladius*, Dicrind = *Dicrotendipes*, Glypind = *Glyptotendipes*, HeteindA = *Heterotrissocladius grimshawi*-type, HeteindB = *Heterotrissocladius maeaeri*-type, Hydr&O = *Hydrobaenus/Oliveridia*, Limnind = *Limnophyes/Paralimnophyes*, Micpind = *Micropsectra*, Mictind = *Microtendipes*, Orthind2 = Orthocladiinae sp. 2, Paraind = *Paratanytarsus*, Park = *Parakiefferiella*, Parlind = *Paracladius*, Polyind = *Polypedilum*, Procind = *Procladius*, Protind = *Protanypus*, Psecind = *Psectrocladius* (undifferentiated), PsecindA = *Psectrocladius (Allopsectrocladius & Mesopsectrocladius*, PsecindE = *Psectrocladius (Psectrocladius)*, PsecindZ = *Psectrocladius (Mesposectrocladius)*, Sergind = *Sergentia*, Step&Z = *Stempellinella/Zavrelia*, Sticind = *Stichtochironomus*, trtanyt = Other Tanytarsina, Zaluind = *Zalutschia* (undifferentiated), Zaluind3 = *Zalutschia* type B, ZaluindZ = *Zalutschia lingulata*-type. Note different scales. Ages are in calibrated years before present (0 = A.D. 1950).

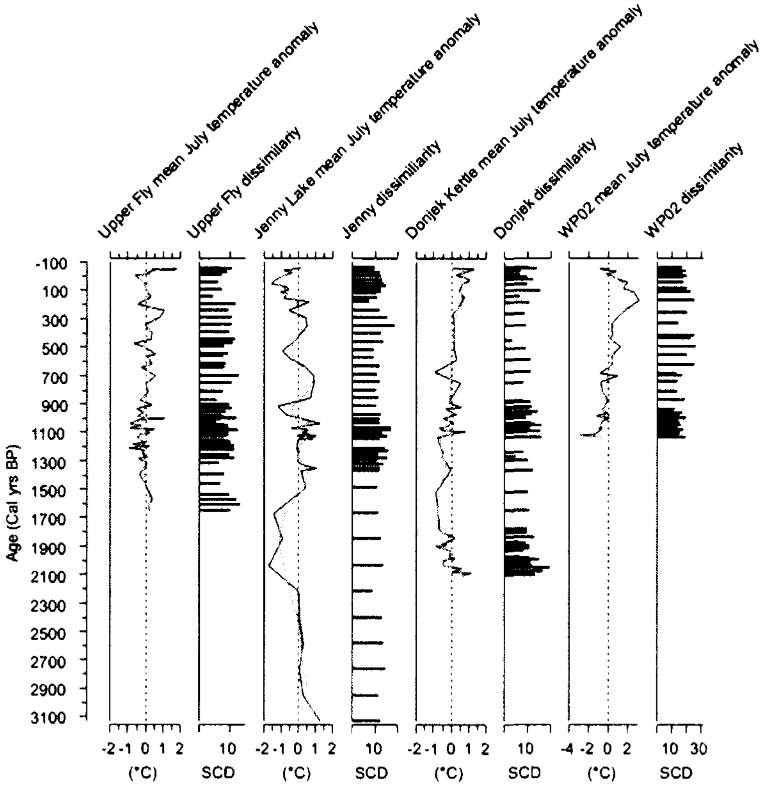

Figure 5.5: Chironomid-inferred mean-July temperature anomalies estimated using a 2-component weighted-averaging partial-least-squares model and fossil chironomid dissimilarities measured using squared-chord distance (SQD). Gray lines represent a loess smoother (0.1 span) through the data. Note different scales. Ages are in calibrated years before present (0 = AD 1950).

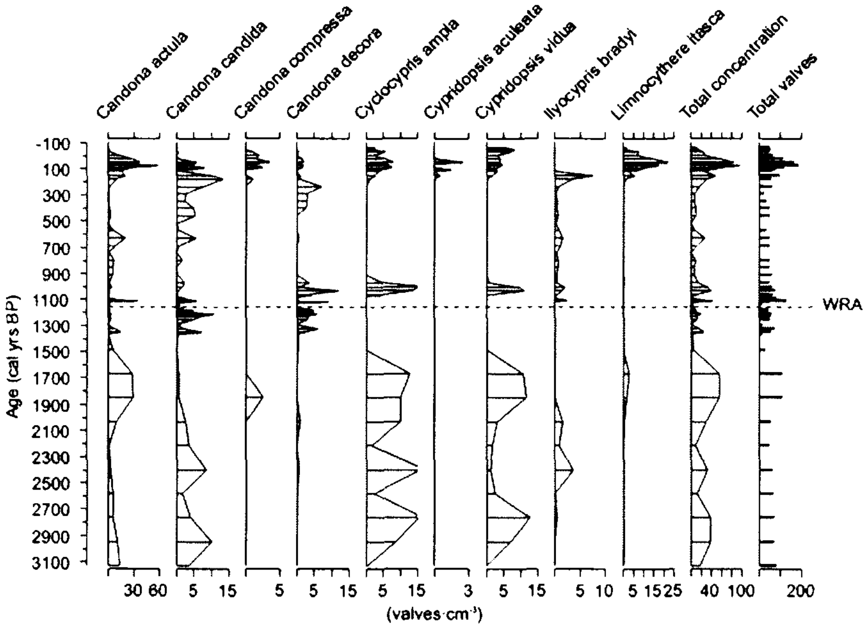

Figure 5.6: Concentrations of ostracode taxa from Jenny Lake, southwest Yukon. The White River Ash event (WRA; 1147 cal yrs BP) is indicated by the dashed line. Note different scales. Ages are in calibrated years before present (0 = AD 1950).

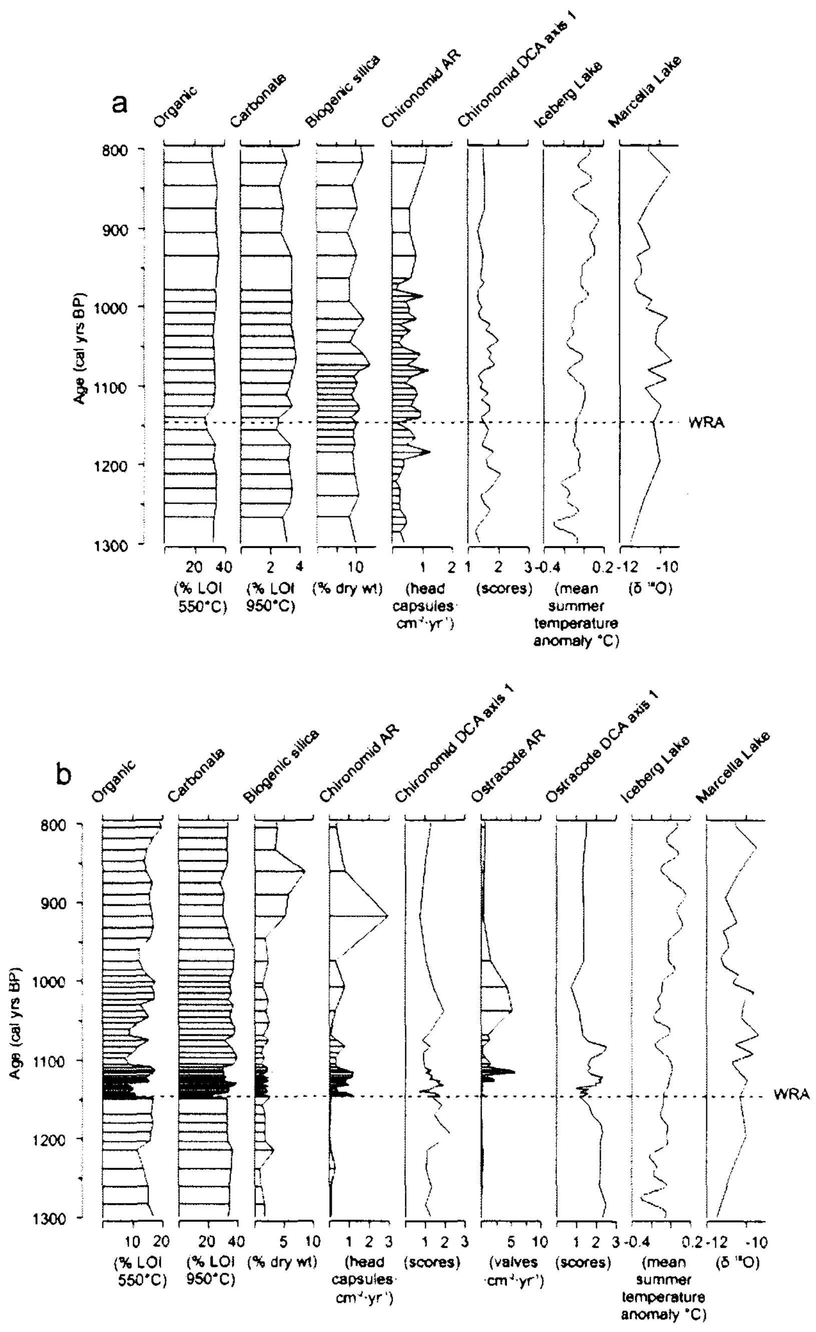

Figure 5.7: Sediment organic content (Organic), sediment carbonate content (Carbonate), biogenic silica content, accumulation rates (AR) of organisms, and organism DCA axis 1 from Upper Fly Lake (a), Jenny Lake (b), Donjek Kettle (c), and Lake WP02 (d), southwest Yukon. Iceberg Lake mean summer temperature anomalies are from Loso (2009) and Marcella Lake δ18O data are from Anderson (2005). The White River Ash (WRA; 1147 cal yrs BP) is indicated by the dashed line on (a) and (b) and the gray bars on (c) and (d) and the older White River Ash (WRA2; 1953 cal yrs BP) is indicated by the second gray bar on (c). Dashed lines indicate an ash layer <1 cm, and gray bars are ash layers >1 cm. Note different scales on the x and y axes. Ages are in calibrated years before present (0 = AD 1950).

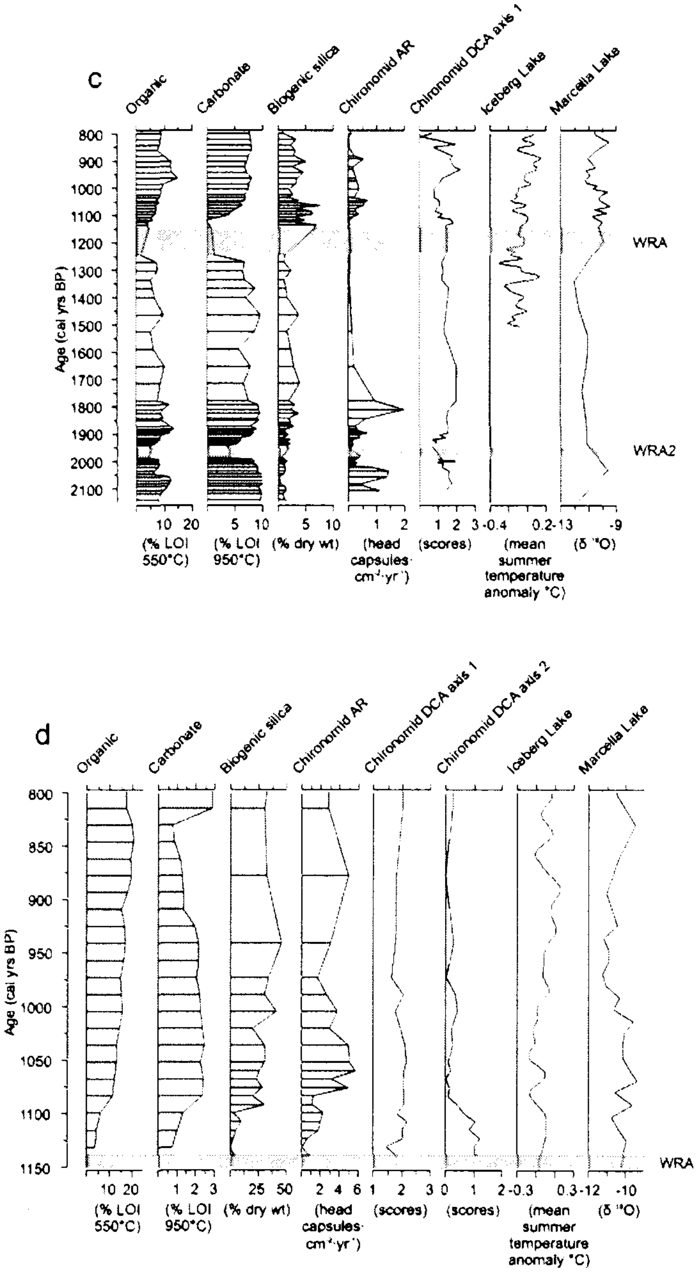

Figure 5.7 (cont'd): Sediment organic content (Organic), sediment carbonate content (Carbonate), biogenic silica content, accumulation rates (AR) of organisms, and organism DCA axis 1 from Upper Fly Lake (a), Jenny Lake (b), Donjek Kettle (c), and Lake WP02 (d), southwest Yukon. Iceberg Lake mean summer temperature anomalies are from Loso (2009) and Marcella Lake δ18O data are from Anderson (2005). The White River Ash (WRA; 1147 cal yrs BP) is indicated by the dashed line on (a) and (b) and the gray bars on (c) and (d) and the older White River Ash (WRA2; 1953 cal yrs BP) is indicated by the second gray bar on (c). Dashed lines indicate an ash layer <1 cm, and gray bars are ash layers >1 cm. Note different scales on the x and y axes. Ages are in calibrated years before present (0 = AD 1950).

CHAPTER SIX
CONCLUSIONS

Lake sediment cores collected from four lakes (Upper Fly Lake 61.04°N, 138.09°W, 1326 m a.s.l.; Jenny Lake 61.04°N, 138.36°W, 817 m a.s.l.; Donjek Kettle 61.69°N, 139.76°W, 732 m a.s.l.; Lake WP02 61.48°N, 139.97°W, 1463 m a.s.l.) in the southwest Yukon provide records of Holocene climatic variability in the region. The purpose of this study was to investigate the effects of environmental variability operating on different temporal scales on aquatic ecosystems in the southwest Yukon over the postglacial period. A paleolimnological approach was used based on the analysis of chironomid, ostracode and pollen assemblages from the lake sediment cores, as well as detailed sediment analysis. Three objectives were established for this study: 1) to quantify climate change in the southwest Yukon during the postglacial period, 2) to investigate the nature and impacts of two different scales of environmental change that have occurred over the past 2000 years in the southwest Yukon, and 3) to improve our understanding of the quantitative methodology commonly used in paleolimnology.

Objective 1: Quantify past climates in the southwest Yukon

This objective was addressed in Chapter Three by using a high-resolution, multi-proxy approach to develop quantitative paleoclimate reconstructions. The key contributions of this chapter were:

- New quantitative paleoclimate reconstructions from the southwest Yukon indicate that there was a long-term cooling, with increasing moisture, over the past 13 ka. The mid-Holocene was warm and dry (11-15.5°C, ~300 mm) with greater climate variability after 4 ka, and warmer conditions since end of Little Ice Age (11-13°C).
- The first quantitative reconstructions of the temperature and moisture conditions during the Younger Dryas (11.2-12.9 ka) in the region revealed a two-part episode that has been previously recognized in the Pacific Northwest. Mean-July temperature estimates based on chironomids, and ecological inferences from the multiple proxies indicated that conditions were warm up to 12 ka (9.5-12°C) and cold and dry thereafter (7-9 °C, ~200 mm).

- The post-glacial vegetation in the Upper Fly Lake basin has consisted primarily of herbaceous and shrub-birch tundra. The pollen evidence indicates minimal treeline movement during the Holocene.

Objective 2: Understand the impact on aquatic ecosystems of environmental variability at several temporal and spatial scales

A high-resolution study of the past 2000 years enabled the investigation of the response of freshwater ecosystems to environmental variability on several timescales. This objective was addressed in Chapter Five through the analysis of paleoproduction indices (sediment loss-on-ignition and biogenic silica), and chironomid and ostracode communities. The main findings from this chapter were:

- Chironomid-inferred mean-July temperature reconstructions as well as production indices from sedimentary variables were more similar at sites closer together suggesting spatial variations in climate have existed over the past 2000 years in the southwest Yukon. This is in spite of the fact that one of the records from each region was above treeline and the other was from the boreal forest.
- Over the long-term there was an inverse relation between biogenic silica and organic and carbonate production, and on shorter timescales similarities existed among sedimentary variables and organism accumulation rates and other proxy data from the region. This demonstrates that aquatic ecosystems are responding to environmental variability on multiple timescales.
- Aquatic ecosystems with greater tephra inputs were impacted more severely by the event with response times between 70 and 80 years, whereas sites with less ash (and less impact) returned to pre-eruption conditions within 20 years.

Objective 3: Methodological issues

Two separate studies were performed that will improve our confidence in future quantitative paleoenvironmental work. The first study (Chapter Two) assessed an important issue in the methodology currently used in paleolimnological studies: does a one-point measurement of the aquatic environment, collected at the time of the sediment sampling adequately characterize the lake environment to permit the development of transfer functions? Environmental data collected in two separate years was analyzed and organism-environment transfer functions were derived for the two datasets. The main conclusion from this chapter was that:

- Although interannual variability is of concern when deriving inference models relating organisms to environmental variables, the results developed from inference models are not entirely determined by the particular year the data were collected. Therefore, the paleolimnological sampling methodology current in use is valid in this region.

A second methodological contribution of this study was the documentation of the modern distribution of freshwater ostracodes in the Canadian Arctic Archipelago (Appendix A). Three of the 7 taxa encountered have their modern distribution limited to Arctic regions and provide data that can be used as modern analogues during the lateglacial and the early Holocene. This data contributes toward the eventual goal of obtaining a continent-wide array of ostracode samples for calibration purposes.

The findings presented above allow for overall conclusions to be made with respect to the main purpose of this dissertation that focused on the effects of environmental variability operating on multiple timescales on aquatic ecosystems. These conclusions are:

- Both pollen and chironomids provided comparable Holocene-scale trends in temperature and moisture. Changes in chironomid accumulation rates coincided with millennial-scale climate variations found in continental-scale records, and the chironomid community responded to abrupt climate changes during the Younger Dryas (12.9-11.2 ka), at 8.2 ka, and at 4.2 ka.
- Four lake sediment cores spanning the late Holocene revealed that aquatic ecosystems responded to long-term climate changes during the period of record, to centennial and multi-decadal scale climate changes, and also to catastrophic changes associated with the White River Ash event.

Future research directions

There are, of course, areas where further research is needed:

- Modern calibration sets of aquatic organism data are an essential component in the development of statistical models to quantitatively reconstruct the past. Although some progress is being made (e.g. Barley et al. 2006), there is still a need for the expansion of both chironomid and ostracode calibration sets to enhance our knowledge of the biogeography of these organisms, and to improve paleoclimate reconstructions.
- The nature of the Younger Dryas in regions surrounding the North Atlantic has been well established as a cold episode that interrupted deglacial warming and the climate that prevailed was similar to what existed during the full-glacial (Ruddiman 2001). However, in the Pacific Northwest this same cooling is not apparent during the same time period, and research to date suggests that colder conditions occurred only during the latter half of the episode (e.g. Lacourse 2007). Therefore, further high-resolution multi-proxy studies would aid in the determination of the nature of this episode across North America.
- The coherence in the temperature reconstructions over the past 2000 years between regions (southeast versus northwest sites) suggests that climate is responsible for the variations. However, it is not clear why there were differences between the two regions. Therefore, the addition of further high-resolution multi-proxy climate reconstructions would assist in resolving the spatial variation in these climate reconstructions.
- Although our study on the interannual variability of the lake environment and implications for transfer function development showed encouraging results, it does not ensure that the results will be similar in other regions, or with other organisms. Therefore, similar studies addressing the fundamental assumptions of the transfer function methodology from other regions using chironomids, as well as ostracodes and diatoms, would assist in validating this approach.

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Appendix A: Biogeography of freshwater ostracodes in the Canadian Arctic Archipelago

Abstract

Seven species of freshwater ostracodes were identified from the sediments of 43 lakes on eight islands across the Canadian Arctic Archipelago. No ostracodes were encountered in the sediments of almost half of the lakes, and were found at sites that had higher alkalinity. Several taxa, endemic to Arctic regions, are found across the Arctic Archipelago, including *Candona rectangulata* Alm, *Limnocythere liporeticulata* Delorme, and *Tonnacypris glacialis* Sars. The distributions of *Cytherissa lacustris* Sars, *Cyclocypris globosa* Sars, *Limnocythere sappaensis* Staplin, and *Limnocythere (Limnocytherina) camera* Delorme are more limited; this fact is attributed to differences in ion composition and concentrations.

Introduction

Ostracodes are small, bivalved crustaceans that occur in all aquatic habitats. They typically live at the sediment-water interface and consume organic detritus. Previous work has shown that certain taxa are often associated with specific habitats (Delorme 1990) and water chemistry (Forester 1983; Smith 1993). As with other aquatic organisms, species distributions are determined by ecological factors such as depth, temperature, and ionic composition and concentrations (De Deckker and Forester 1988; Holmes 1992; Smith and Horne 2002). The body of an ostracode is contained within a carapace made of low-magnesium calcite, and although the body generally decomposes after the ostracode dies, the shells preserve well in lake sediments. They are therefore potentially useful organisms for reconstructing past environments (Griffiths and Holmes 2000), however, their fossils have been underutilized in studies of freshwater systems relative to their potential due in part to a limited understanding of their biogeography.

The biodiversity of freshwater ostracodes in the circumpolar Arctic has been documented from Russia (e.g. Bronshtein 1988), the Siberian Arctic (e.g. Neale 1969; Wetterich et al. 2005), Scandanavia (e.g. Alm 1914 in Delorme 1968), and Greenland (e.g. Røen 1962, 1981). In North America, the ostracode fauna has been documented from Alaska (Swain 1963), the Northwest Territories (Tressler 1957; Delorme and Zoltai 1984), and the Yukon (Bunbury and Gajewski 2005). However most of the work in Canada has been limited to regions south of 60°N (Delorme 1970a; 1970b; 1970c; 1970d; 1971; 1978) and as a result, little is known about the ostracode fauna in the Canadian Arctic.

To use a group of organisms as paleoenvironmental indicators, it is necessary to first understand the ecological tolerances of the different species before attempts are made to infer past environments from fossils extracted from sediments. This is typically done by sampling a geographical array of lakes and establishing which variables best explain the distribution and abundance of the organism in question. Several studies have explored the modern distribution of ostracodes and related environmental variables, including Smith (1993), Bunbury and Gajewski (2005), and Viehberg (2006), however these datasets are limited in spatial extent and therefore provide an incomplete picture of the ecology of these organisms. More data from across the entire geographic and environmental domain of the constituent species would enhance our understanding of their modern ecology, and enable their use as quantitative paleoenvironmental indicators. These types of studies are particularly useful from northern regions as the taxa that exist there today are adapted to the cold climate, and have the potential to provide modern analogues for late-Pleistocene and early-Holocene sequences elsewhere. For example, Delorme and Zoltai (1984) identified sites in the Canadian North as potential modern analogues for Holocene and Pleistocene ostracode assemblages.

This study documents the freshwater ostracode taxa present across the Canadian Arctic Archipelago. We determine the environmental variables that affect their distribution and abundance in the Canadian North, and provide additional data on the ecology of different species. This work will improve our ability to attempt paleoenvironmental reconstructions, as well as to further document the biodiversity of the Arctic.

Study Area

Lake sediments and water chemistry data for this study were available from 43 sites along a broad area of the central and northern Canadian Arctic Archipelago (Figure A1a). The region is divided into six geologic provinces (Figure A1d). For example, sites on Devon Island are located on Paleozoic sedimentary rocks that are carbonate-rich (Wheeler et al. 1997), whereas most sites on Somerset Island are underlain by Precambrian sedimentary and volcanic bedrock. Sites on Victoria Island (KR06, KR08; unofficial site codes) are underlain by evaporitic rocks, or mafic intrusive rocks (diorite and gabbro; WB01) and those in the Fosheim region of Ellesmere Island are in an area with considerable Tertiary deposits.

Climate patterns in the Archipelago do not follow a latitudinal line as the coldest temperatures occur in the northwest and on northern Ellesmere Island (Figure A1c; Edlund and Alt 1989). Warmer temperatures occur in the low Arctic and on the Fosheim Peninsula on Ellesmere Island and nearby Axel Heiberg Island. The growing season is short, occurring between late June and August, and continuous permafrost is widespread, limiting groundwater inputs to lakes (Woo 1992).

Methods

Water chemistry and sediment samples were collected from 43 lakes between 1992 and 2004 from either a small inflatable raft or the ice surface. Water sample collection and analysis followed Environment Canada (1994) protocols, the details of which are discussed in Hamilton et al. (2001), Bouchard et al. (2004), and Gajewski et al. (2005). Sediment was sampled using either an Ekman dredge, or a piston corer with a 5-inch diameter plastic tube, and in both cases the uppermost 1-2 cm of sediment was subsampled for ostracode valves.

Between 8 and 57.5 cm^3 of sediment was subsampled and processed using standard methods for the extraction of ostracodes from lake sediments (Holmes 2001). Sediment disaggregation depended on the nature of the sediment at each site; organic sediment samples were soaked overnight in 10% potassium hydroxide, whereas carbonate sediments were soaked for 48 hours in 5% sodium hexametaphosphate. Disaggregated sediments were sieved through 125 μm stainless steel sieve or Nitex© mesh. Valves were hand picked using a 0/5 brush under 10x magnification and mounted on micropaleontological slides using gum tragacanth. None of the specimens appeared to contain soft parts (i.e. appendages etc.), however many of the samples included well-preserved adult and juvenile valves/carapaces suggesting that ostracodes were living in the lake at the time of sample collection (Forester 1983). Adult valves (including carapaces) were enumerated. All specimens are stored at the Laboratory for Paleoclimatology and Climatology, Department of Geography, University of Ottawa.

Of the 43 lakes evaluated, only 24 had identifiable adult ostracodes (min = 1; max = 102, mean = 36). In most samples, ostracode valve concentrations were very low. Ten cm^3 was initially subsampled and evaluated for adult specimens. If several individuals (i.e. > 1 valve per cm^3) were encountered then subsampling was continued until the total number of valves was 50 or greater (Bunbury and Gajewski 2005). If none or very few specimens were encountered then subsampling for that site was suspended, however ostracode presence at these sites was still recorded. In one case (Lake HW02) only one juvenile ostracode valve was encountered and this information was included in the total concentration computation for that site. At four sites where ostracodes were present the amount of sediment was depleted, therefore counts did not reach 50 (CI07, CI16, KR06 and KR08). Identifications were achieved using 20x to 40x magnification and taxonomy followed Delorme (1968; 1970a; 1970b; 1970c; 1971).

A Geographic Information System was used to assign mean-July air temperature (40 year means; Atkinson and Gajewski 2002), vegetation (CAVM team 2003), and bedrock geology (Wheeler et al. 1997) to each site. The total concentration of ostracode valves that occurred in the 43 lakes were mapped, as were the concentrations of individual ostracode species found in the 24 lakes. Maps assist in understanding the spatial distribution of the taxa in relation to mean-July temperature, vegetation, and bedrock geology.

Environmental variables considered here are those that influence ostracode distribution and include temperature and lake depth, pH, alkalinity, conductance, and ionic composition of the lake water (Griffiths and Holmes 2000). Water temperature data was missing for lake CI03, therefore the mean of the dataset (3.5°C) was substituted in that one instance. With the exception of air temperature (AirTemp), water temperature (H_2OTemp), pH, magnesium-calcium ratio (Mg/Ca), and alkalinity-calcium ratio (Alk/Ca), all environmental variables were transformed prior to data analysis. Depth, calcium (Ca^{2+}), magnesium (Mg^{2+}), sulphate (SO_4^{-2}), and alkalinity were square root transformed, and conductance (Cond), sodium (Na^+), and potassium (K^+) were log transformed. Geologic Provinces (GeolProv) and vegetation types (Veg) indicated on the maps were also included as explanatory variables.

A principal components analysis (PCA) was used to investigate the relations between the species and the environmental variables. This analysis combines variables together into separate linear components, where the first component explains the main variation in the data, and the second component explains more of the variation, but is orthogonal to the first component (Davis 1973). Percentage species data was log transformed prior to analysis and a correlation matrix was used to summarize the variation in the species dataset (CANOCO 4.5; ter Braak and Šmilauer 2002).

Results

Seven taxa were encountered from 24 lakes on eight islands in the Canadian Arctic Archipelago (Table A1; Figures. A1c, d, e, and f). Taxa with the greatest number of occurrences are *Candona rectangulata* Alm, 1914 (present in 16 lakes), *Cytherissa lacustris* (Sars, 1863) (13 lakes), and *Limnocythere liporeticulata* Delorme, 1968 (12), whereas less abundant taxa are *Tonnacypris glacialis* (Sars, 1890) (4), *Cyclocypris globosa* (Sars, 1863) (2), *Limnocythere sappaensis* Staplin, 1963 (1), and *Limnocythere (Limnocytherina) camera* Delorme, 1967 (1; Figure A2).

C. lacustris is present in lakes at lower latitudes and absent from lakes in the high Arctic (Figure A1c), whereas *C. rectangulata*, *L. liporeticulata* and *T. glacialis* are present in lakes found across the entire area (Figures. A1d, e, f). *C. globosa* is limited to the more southerly sites, and *L. camera* and *L. sappaensis* occur only on the Fosheim Peninsula on Ellesmere Island (Figure A1e).

Ostracode concentrations vary between 0.1 and 9.8 valves per cm^3 of sediment, with the highest concentrations (> 4 valves per cm^3) occurring in the Fosheim region (Figure A1b; Table A1). Concentrations of *C. rectangulata* are greater in the middle and high Arctic, whereas *L. liporeticulata* has both high and low concentrations across the entire region.

A large amount of the total variance (44%) is explained by the first two axes of the principal components analysis (PCA; Figure A3). The first axis explains 26.8% of the variance in the data and includes variables related to ion concentrations, as well as the physical variables H_2OTemp and Depth. The second and third axes explain 17.2% and 16.2% of the variation respectively, with GeolProv correlated with axis two, and AirTemp and K correlated with axis three (not shown). *C. rectangulata*, *L. liporeticulata*, and *T. glacialis* are taxa correlated with axis one, whereas *C. lacustris* is negatively correlated and *T. glacialis* is positively correlated with axis two. *L. camera* and *L. sappaensis* are positively correlated with axis three, whereas *T. glacialis* is negatively correlated. Lakes where ostracodes are present have higher ion concentrations, pH, and alkalinity and are located on the right side of the triplot, whereas sites without ostracodes have low ion concentrations, low pH, and low alkalinity values and are located on the left of the triplot (Figure A3).

A majority of the lakes have a log alkalinity/calcium ratio (Log Alk/Ca) > 1, particularly those that contain ostracodes, however, there are exceptions (Figure A4). Bicarbonate (HCO_3^-) -depleted sites (3 lakes) are those with Log (Alk/Ca) < 0 and log conductance (Log Cond) > 6, whereas bicarbonate-enriched sites (4 lakes) have Log (Alk/Ca) > 0 and Log Cond > 6 (Curry 1997, 1999). In these Arctic lakes, the bicarbonate-depleted sites are dominated by sulphate (SO_4^{2-}), and the bicarbonate-enriched lakes are dominated or enriched by sodium (Na^+) and/or chloride (Cl^-) or both (Table A2). All other lakes have lower conductance and most are dominated by Ca^+, which is more characteristic of freshwater lakes (Kalff 2002).

Convex hulls indicating species distributions as a function of conductance and the alkalinity/calcium ratio reveal the broad ranges of *C. lacustris*, *C. rectangulata*, and *L. liporeticulata*, and the narrow range of *T. glacialis*. *C. lacustris* can tolerate bicarbonate-depleted lake water dominated by SO_4^{2-}, however it is excluded from sites that are bicarbonate-enriched with high concentrations of Na^+ and Cl^-. In comparison, *L. liporeticulata* is found in lakes with high Na^+ and Cl^- concentrations. There are several sites throughout these ranges where no ostracodes were encountered. *T. glacialis* is limited to sites with Log Alk/Ca > 1, and Log Cond between 4 and 6 however this result is based only on 4 occurrences.

Discussion

The distribution of freshwater ostracodes in the Canadian Arctic Archipelago is primarily dependent upon the alkalinity of the lake water. This is a measure of the calcium carbonate in the lake water and for ostracodes to live and grow in a particular site they require an available source of calcium carbonate to construct their shells (Delorme 1991). Water temperature and lake depth also affect ostracode presence within a lake, but to a lesser extent. *C. rectangulata*, *L. liporeticulata*, and *T. glacialis* are found across the entire region because their requirements for shell creation and preservation are met and each species can tolerate the cold temperatures associated with Arctic environments. All three of these taxa are endemic to the Arctic, with *C. rectangulata* and *T. glacialis* known throughout the circumpolar region (Røen 1962; Bronshtein 1988; Delorme 1991; Little and Hebert 1997; Griffiths et al. 1998; Wetterich et al. 2008; Wojtasik 2008), and *L. liporeticulata* from the Canadian Arctic (Delorme 1991).

Sites on Victoria and Somerset Islands are warmer than sites located in the middle Arctic however we suggest that the low concentrations of *C. rectangulata* in this area are related to lower alkalinity values (Figure A1d; Table A2). In comparison, *C. globosa* is restricted to lakes in the southern portion of the study area suggesting the species inability to tolerate cooler temperatures and higher alkalinity found in our more northern sites (Figure A1e). *C. lacustris* can withstand the colder mean-July temperatures located in the middle Arctic, but is absent from lakes at high latitudes where mean-July temperatures are warmer and alkalinity is higher (Figure A1c).

Two taxa were found only once in two separate lakes on Ellesmere Island. *L. sappaensis* occurs at the site (EU01) which has the highest alkalinity, sodium, and chloride (Figure A1e; Table A2) values in the dataset. This taxon typically occurs in sodium-bicarbonate waters (Forester 1983), is common in lakes on the Canadian Prairies (Delorme 1971), and inhabits alkaline lakes in the mid-west United States (Smith 1993). Several of the lakes in the Fosheim region of Ellesmere Island have emerged from the sea and retain high values of sodium and chloride as a legacy of submergence (Hamilton et al. 2000). The presence of these two taxa appears limited to sites in the Fosheim region, however this is the only area where lakes with higher salinities were sampled. If more saline lakes from across the Canadian Arctic were to be sampled, we may be able to better determine the spatial distribution of these taxa. Other taxa in the assemblage at Lake EU01 are *C. rectangulata* and *L. liporeticulata*, indicating the ability of these two taxa to tolerate high values of Na and Cl. Delorme (1991) also found *C. rectangulata* in sites that were subject to sea spray indicating the species' tolerance to saline conditions.

L. camera is the second taxon found only once in this study, and is one of three individuals encountered at Gemini Lake. This site has high alkalinity and conductance values (though lower than those at Lake EU01; Table A2), which are attributed to elevated sodium and chloride levels. This taxon is rare, but has been encountered on the Canadian Prairies (Delorme 1971) suggesting an association with saline conditions. The identification of these rare species suggests that expanding the dataset to include more lakes may identify other taxa in the region.

Ostracodes are found at sites in the Canadian Arctic that have higher alkalinity, and the widespread species *C. rectangulata*, *L. liporeticulata*, and *T. glacialis* are present across the Arctic because they can withstand the cold temperatures. The distribution of individual species appears influenced by the composition of the lake water; *C. rectangulata* has a broad tolerance for different ions (i.e. sulphate, sodium, and chloride); however, it is absent from sites with low ion concentrations (Figure A3; Table A2). *L. liporeticulata* occurs in lakes across a wide range of alkalinity values and those dominated by sodium and chloride, but is absent from waters with a high sulphate content. *C. lacustris* can tolerate elevated sulphate values, but prefers more dilute water. In comparison, *T. glacialis* and *C. globosa* appear to have a much narrower tolerance with respect to ion content and are found at sites with lower conductance values. *L. sappaensis* and *L. camera* occupy lakes dominated by sodium and chloride, with *L. sappaensis* present only in a saline lake.

Ostracodes are neither abundant nor diverse in the Canadian Arctic Archipelago, nevertheless several taxa are found across the region, and some taxa are found in a restricted group of lakes. As is the case in southern regions, those taxa that can tolerate the cold temperatures are influenced by the ion concentration of the lake waters. The results presented in this study further our knowledge of the distribution of ostracode taxa, and provide data that can be used in future paleoenvironmental studies from the region.

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Table A1: Ostracode taxa found in 43 lakes in the Canadian Arctic Archipelago, showing total valves and concentrations (valves per cm^3) for each lake.

Lake	Latitude (°N)	Longitude (°W)	Island	*Cytherissa lacustris*	*Candona rectangulata*	*Cyclocypris globosa*
Allen	73.62	98.47	Prince of Wales			
BC01	75.18	111.93	Melville			
CI01	73.88	94.87	Somerset	10	1	
CI03	73.21	94.32	Somerset			
CI04	73.03	94.93	Somerset			
CI05	72.73	95.99	Somerset			
CI06	72.67	95.05	Somerset			
CI07	72.59	95.06	Somerset			32
CI08	72.49	95.09	Somerset	30	15	
CI09	72.27	95.09	Somerset	4		
CI10	72.01	94.87	Somerset			
CI13	72.31	94.13	Somerset			
CI16	76.50	98.16	Somerset		24	
CI17	76.60	98.87	Bathurst	54		
CI19	76.51	99.11	Bathurst		50	
CI22	75.90	99.22	Bathurst			
CI23	75.53	98.21	Bathurst	63	6	
CI28	75.29	99.80	Bathurst		1	
CI29	75.02	100.20	Bathurst			
DV01	74.99	90.36	Devon			
DV02	74.93	88.68	Devon	28	29	
DV05	75.52	92.05	Devon	42	4	
DV06	75.51	91.99	Devon	2	4	
DV07	75.53	91.97	Devon	16	33	
DV08	75.37	89.49	Devon		45	
DV09	75.58	89.32	Devon	1		
DV10	75.54	89.75	Devon			
E505	79.98	82.97	Ellesmere			
E506	80.57	84.47	Ellesmere			
EU01	79.90	84.88	Ellesmere		23	
Gemini	79.99	84.13	Ellesmere		1	
HW01	80.02	83.39	Ellesmere		44	
HW02	79.73	83.47	Ellesmere			
HW03	79.73	85.81	Ellesmere			
HW05	80.18	87.69	Axel Heiberg			
HW06	80.26	87.77	Axel Heiberg			
HW07	79.72	83.52	Ellesmere			
HW08	79.72	83.50	Ellesmere			
KR06	71.32	113.97	Victoria	16		
KR08	71.31	113.67	Victoria	14	4	
Ridge	79.94	84.62	Ellesmere		32	
WB01	72.29	109.99	Victoria			2
Wolf	73.58	98.48	Prince of Wales	2		

[1] Juvenile ostracode

Table A1 (cont'd): Ostracode taxa found in 43 lakes in the Canadian Arctic Archipelago, showing total valves and concentrations (valves per cm^3) for each lake.

Lake	*Limnocythere sappaensis*	*Limnocythere liporeticulata*	*Limnocythere camera*	*Tonnacypris glacialis*	Total valves	Concentration (valves·cm^{-3})
Allen						
BC01						
CI01		39			50	4.17
CI03		6			6	0.20
CI04						
CI05						
CI06						
CI07					32	1.45
CI08		10		2	57	0.99
CI09					4	0.13
CI10						
CI13						
CI16					24	0.61
CI17					54	1.80
CI19				5	55	1.83
CI22						
CI23		33			102	3.40
CI28					1	0.10
CI29						
DV01						
DV02					57	2.85
DV05		14			60	1.33
DV06					6	0.60
DV07		4			53	1.06
DV08				5	50	0.91
DV09					1	0.05
DV10						
E505						
E506						
EU01	21	7			51	2.22
Gemini		1	1		3	0.10
HW01		47		7	98	9.80
HW02					1[1]	0.10
HW03						
HW05						
HW06						
HW07						
HW08						
KR06		2			18	2.25
KR08		2			20	2.50
Ridge		64			96	4.80
WB01					2	0.20
Wolf					2	0.07

[1] Juvenile ostracode

Table A2: Environmental data from 43 lakes in the Canadian Arctic Archipelago.

Lake	Air temperature (°C)	Depth (m)	Specific Conductance ($\mu S \cdot cm^{-1}$)	Water temperature (°C)	pH	Ca ($mg \cdot l^{-1}$)	Mg ($mg \cdot l^{-1}$)
Allen	4.8	4.0	68	9.0	7.7	11.60	4.40
BC01	4.0	10.9	7	-0.4	8	0.17	0.176
CI01	4.5	2.0	150	1.9	7.6	22.00	3.90
CI03	4.0	0.5	40	3.5	7.5	6.60	3.90
CI04	4.0	1.0	20	0.7	7.7	3.80	1.56
CI05	5.0	1.0	70	5.8	7.6	9.50	5.90
CI06	5.0	1.0	50	1.4	7.8	9.50	3.70
CI07	5.4	5.5	80	1.1	7.8	16.00	5.90
CI08	5.2	4.0	170	7.9	8.1	28.00	13.20
CI09	5.4	4.0	30	0.1	8.2	6.30	2.10
CI10	5.6	19.0	30	1.5	7.9	5.80	1.97
CI13	5.0	0.5	80	2.6	7.9	13.80	5.10
CI16	4.0	1.0	70	3.1	8.0	16.30	2.10
CI17	2.0	3.5	80	3.1	8.0	17.50	2.50
CI19	4.0	1.0	80	4.1	8.2	19.30	2.80
CI22	4.6	8.0	90	6.9	8.1	23.00	2.90
CI23	4.5	9.5	70	1.2	8.0	18.90	0.46
CI28	4.0	0.5	40	6.7	7.9	5.00	0.76
CI29	4.8	6.5	30	2.3	7.8	1.09	1.11
DV01	4.3	4.5	91	2.0	8.4	29.20	4.80
DV02	4.8	7.5	445	2.6	7.9	140.00	17.20
DV05	4.5	11.0	153	5.1	8.6	24.20	4.30
DV06	4.4	4.0	158	8.5	8.4	25.80	4.40
DV07	4.4	5.0	148	8.0	8.4	24.70	4.30
DV08	4.7	3.0	175	10.5	8.4	27.30	6.40
DV09	4.9	15.0	167	4.2	8.4	26.80	5.20
DV10	4.7	11.0	92	7.9	8.3	11.80	5.20
E505	6.0	2.5	56	0.1	7.1	5.20	1.10
E506	4.8	14.0	19	1.1	7.0	2.50	0.60
EU01	6.7	6.5	2000	10.0	8.6	57.40	38.70
Gemini	7.6	0.1	388	0.9	8.2	31.00	16.40
HW01	6.7	3.7	366	0.7	8.2	45.10	11.40
HW02	5.4	4.5	126	4.2	7.7	13.50	2.49
HW03	3.9	13.0	524	1.9	7.8	37.70	15.20
HW05	6.8	3.7	998	2.5	8.0	38.90	17.50
HW06	6.7	3.5	293	2.5	8.0	24.10	9.86
HW07	5.8	6.0	79	0.9	7.3	9.90	1.52
HW08	5.8	8.5	98	3.0	7.5	12.10	2.10
KR06	6.8	4.5	19	0.0	7.6	5.70	2.80
KR08	6.4	3.3	420	0.1	8.1	78.00	18.80
Ridge	6.5	5.0	506	6.5	8.3	37.10	18.10
WB01	6.3	20.0	139	2.3	8.0	23.00	5.10
Wolf	4.9	6.0	65	1.5	8.4	14.60	5.30
Mean	5.1	5.8	204	3.5	8.0	22.79	6.59
Median	4.9	4.5	90	2.5	8.0	17.50	4.30

[1] Concentration was below the detection limit

Table A2 (cont'd): Environmental data from 43 lakes in the Canadian Arctic Archipelago.

Lake	Cl $(mg \cdot l^{-1})$	Na $(mg \cdot l^{-1})$	K $(mg \cdot l^{-1})$	SO_4 $(mg \cdot l^{-1})$	Alkalinity $(mg \cdot l^{-1}$ as $CaCO_3)$	Mg/Ca	Alk/Ca
Allen	1.68	0.80	0.20	2.30	57	0.38	4.89
BC01	0.4	0.36	0.09	0.5	2	1.02	11.56
CI01	1.27	0.67	0.22	2.22	72	0.18	3.26
CI03	1.28	0.56	0.16	0.40	30	0.59	4.55
CI04	0.82	0.52	0.26	3.71	11	0.41	2.89
CI05	5.91	2.00	0.52	0.11	41	0.62	4.32
CI06	0.90	0.65	0.24	2.15	34	0.39	3.58
CI07	4.50	1.60	0.29	1.61	57	0.37	3.55
CI08	3.87	2.20	0.66	25.05	92	0.47	3.27
CI09	0.88	0.55	0.15	1.62	20	0.33	3.16
CI10	1.06	0.53	0.12	1.11	20	0.34	3.43
CI13	1.99	0.89	0.28	1.69	50	0.37	3.62
CI16	1.74	1.18	0.15	0.75	50	0.13	3.07
CI17	1.90	1.78	0.51	3.70	48	0.14	2.73
CI19	1.23	1.26	0.36	6.56	53	0.15	2.75
CI22	0.39	0.49	0.69	7.54	59	0.13	2.56
CI23	0.83	0.65	0.11	0.36	50	0.02	2.64
CI28	4.46	2.00	0.23	0.12	18	0.15	3.60
CI29	8.54	4.00	0.37	1.17	3	1.02	2.74
DV01	1.64	0.70	<0.2[1]	1.10	101	0.16	3.45
DV02	4.22	2.30	0.40	395.00	68	0.12	0.48
DV05	2.28	0.90	<0.2	1.30	87	0.18	3.58
DV06	2.05	0.90	0.20	0.60	91	0.17	3.51
DV07	2.32	0.90	0.40	0.90	88	0.17	3.56
DV08	2.06	1.00	0.20	8.70	94	0.23	3.45
DV09	2.93	1.90	0.20	5.90	91	0.19	3.38
DV10	1.78	0.90	<0.2	0.80	57	0.44	4.85
E505	0.60	0.50	0.30	2.80	19	0.21	3.70
E506	1.30	0.60	<0.2	2.10	11	0.24	4.45
EU01	217.00	281.00	13.80	101.00	253	0.67	4.41
Gemini	32.70	20.30	3.40	17.30	171	0.53	5.52
HW01	31.80	8.22	1.62	3.40	180	0.25	3.99
HW02	1.94	4.55	1.46	24.40	25	0.18	1.84
HW03	48.30	24.60	3.86	89.40	44	0.40	1.15
HW05	202.00	101.00	4.17	2.10	127	0.45	3.25
HW06	16.30	11.40	1.10	17.50	100	0.41	4.14
HW07	1.40	1.71	0.59	4.90	29	0.15	2.96
HW08	1.28	4.21	0.52	5.00	45	0.17	3.72
KR06	0.80	0.25	0.15	2.20	19	0.49	3.32
KR08	1.70	1.53	1.76	128.00	106	0.24	1.35
Ridge	57.90	38.20	3.70	7.40	220	0.49	5.93
WB01	1.80	0.53	1.40	3.30	42	0.22	1.82
Wolf	1.58	0.80	0.30	4.10	69	0.36	4.71
Mean	15.84	12.36	1.16	20.74	67	0.33	3.60
Median	1.80	1.00	0.36	2.30	53	0.25	3.45

[1] Concentration was below the detection limit

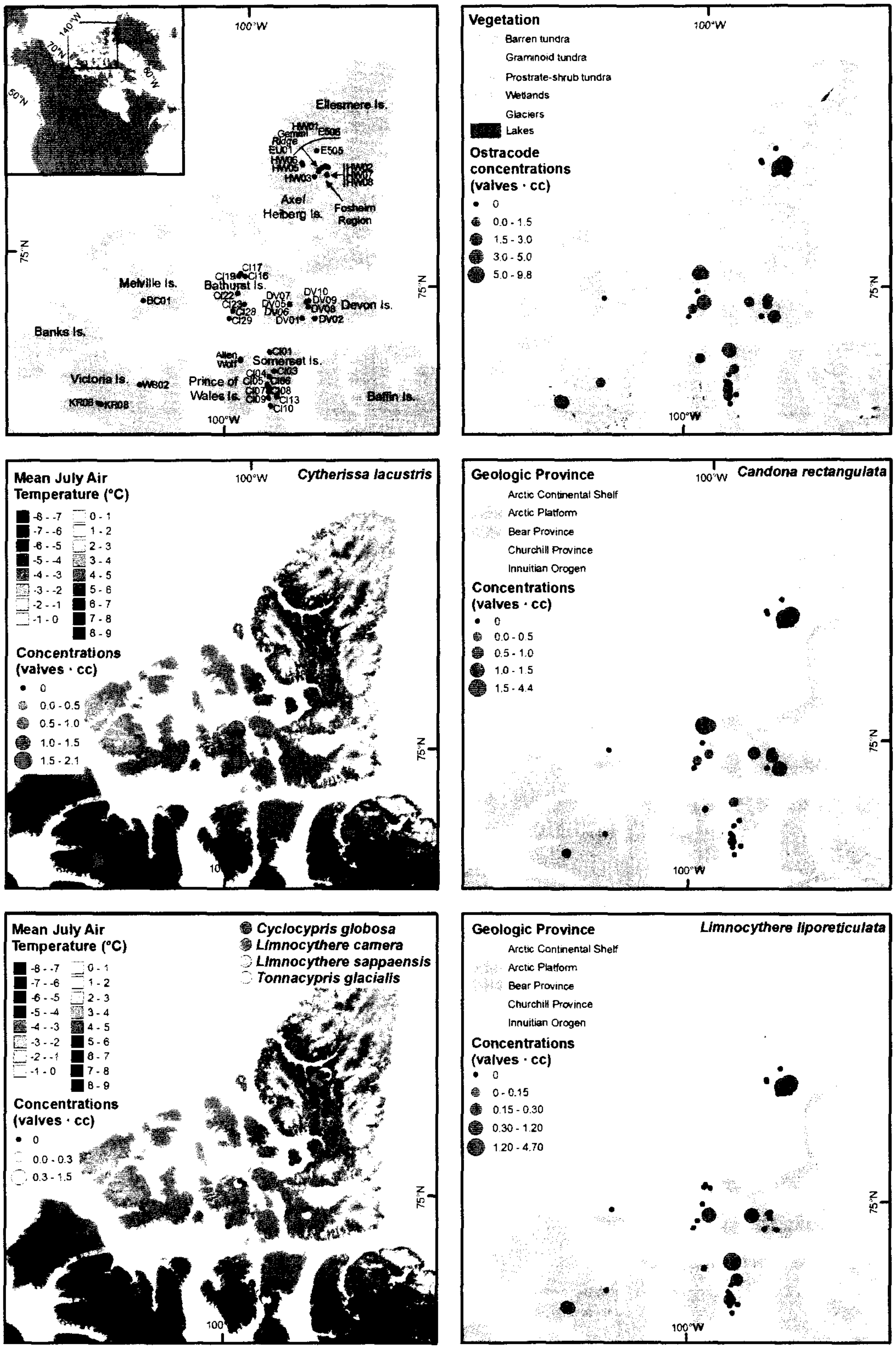


Figure A1: See next page for caption.

Figure A1: The study area in the Canadian Arctic Archipelago. a) Site locations b) Ostracode concentrations (valves · cm^{-1}) in relation to vegetation c) *Cytherissa lacustris* concentrations (valves · cm^{-1}) in relation to mean-July air temperature d) *Candona rectangulata* concentrations (valves · cm^{-1}) in relation to geologic provinces e) *Cyclocypris globosa*, *Limnocythere camera*, *Limnocythere sappaensis*, and *Tonnacypris glacialis* concentrations (valves · cm^{-3}) in relation to mean-July air temperature, and f) *Limnocythere liporeticulata* in relation to geologic provinces. Vegetation data are adapted from the (CAVM team 2003), mean-July air temperature (40 year average) are from (Atkinson and Gajewski 2002), and geologic province data are from (Wheeler et al. 1997).

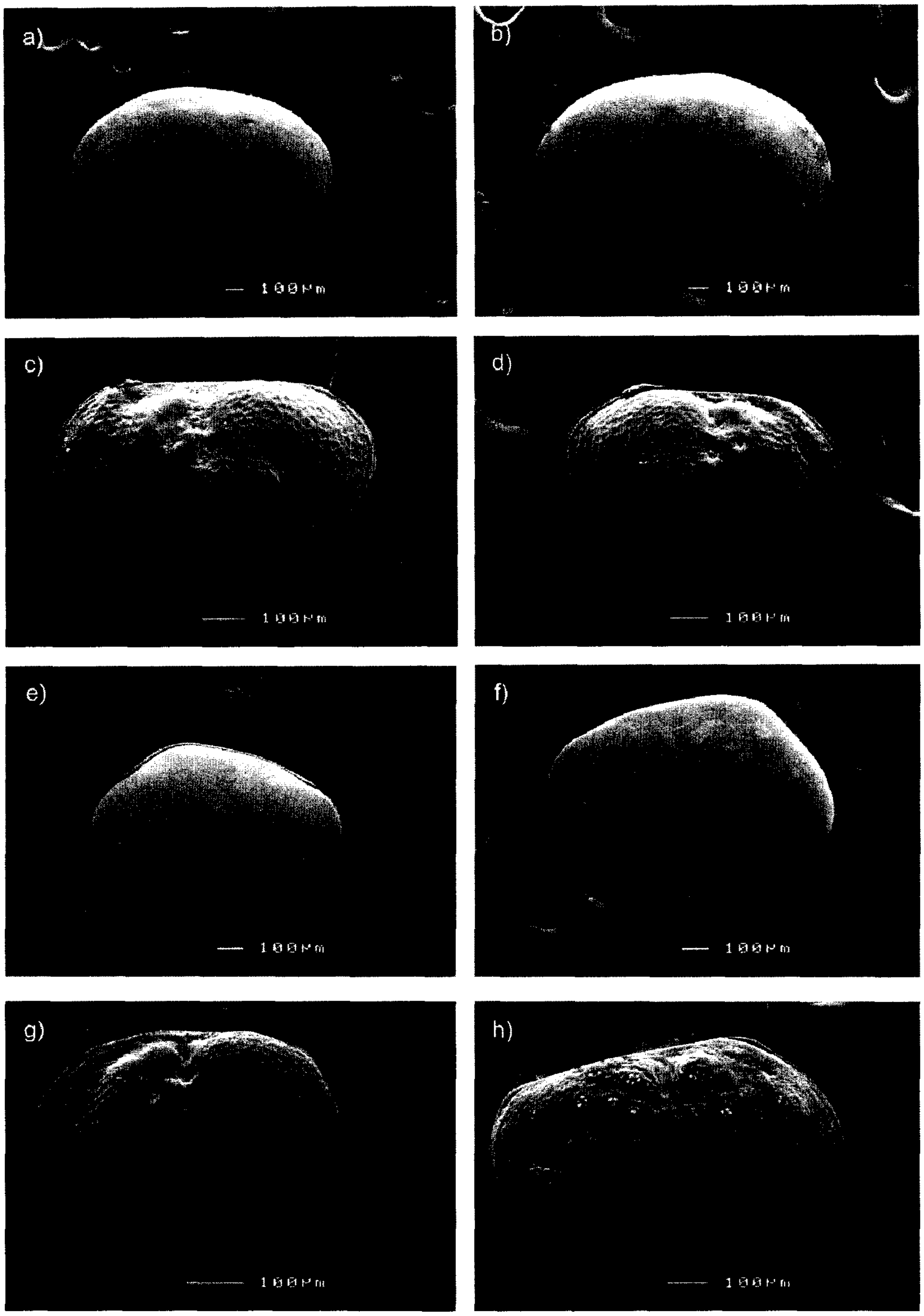


Figure A2: Scanning Electron Micrographs of 5 ostracode taxa from the Canadian Arctic Archipelago a) *Tonnacypris glacialis* left valve, b) *Tonnacypris glacialis* right valve, c) *Limnocythere liporeticulata* left valve, d) *Limnocythere liporeticulata* carapace, e) *Candona rectangulata* carapace, f) *Candona rectangulata* left valve, g) *Limnocythere sappaensis* carapace, h) *Cytherissa lacustris* carapace. Note varying scale bars.

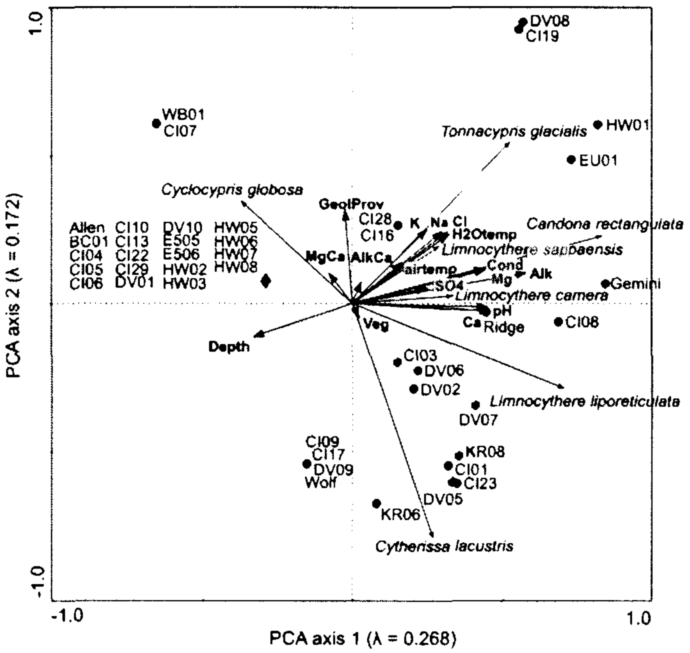


Figure A3: Principal components analysis correlation triplots of lakes, ostracode species, and environmental variables. Circles represent lakes where ostracodes are present, and the diamond represents lakes where ostracodes are absent.

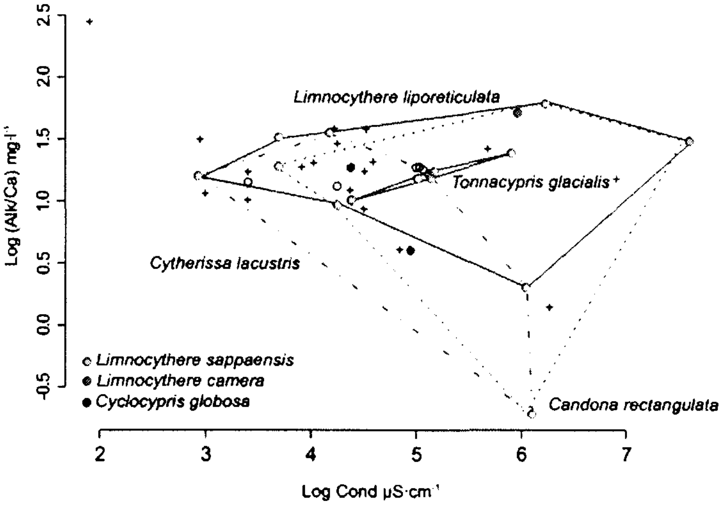
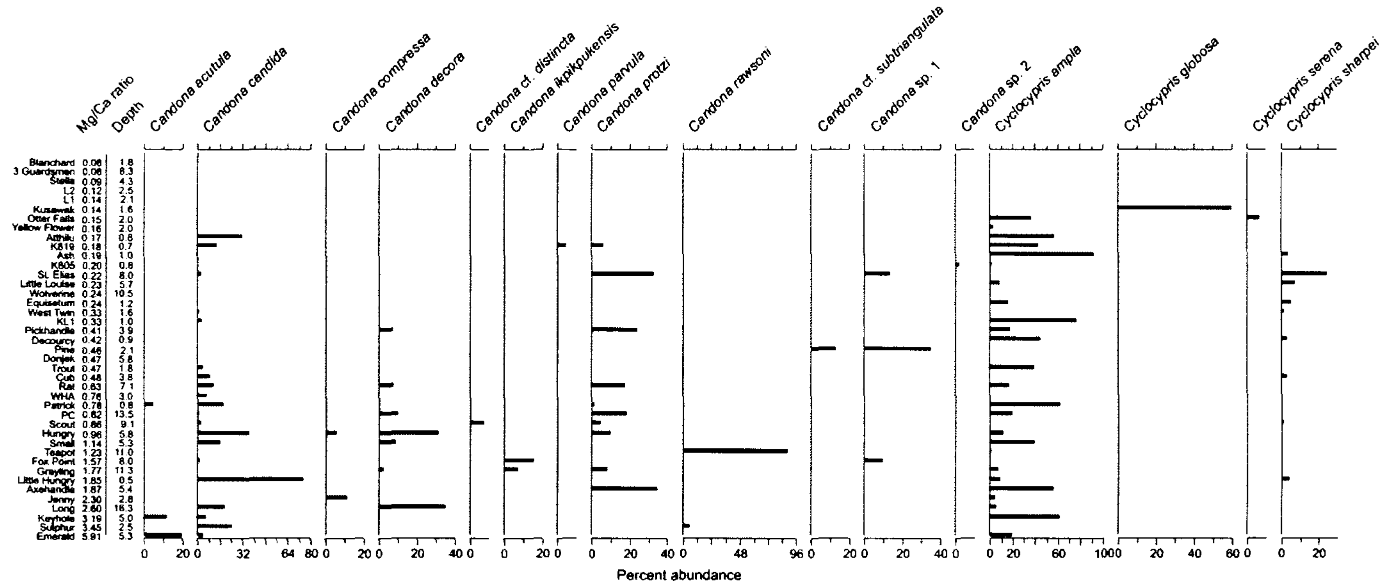


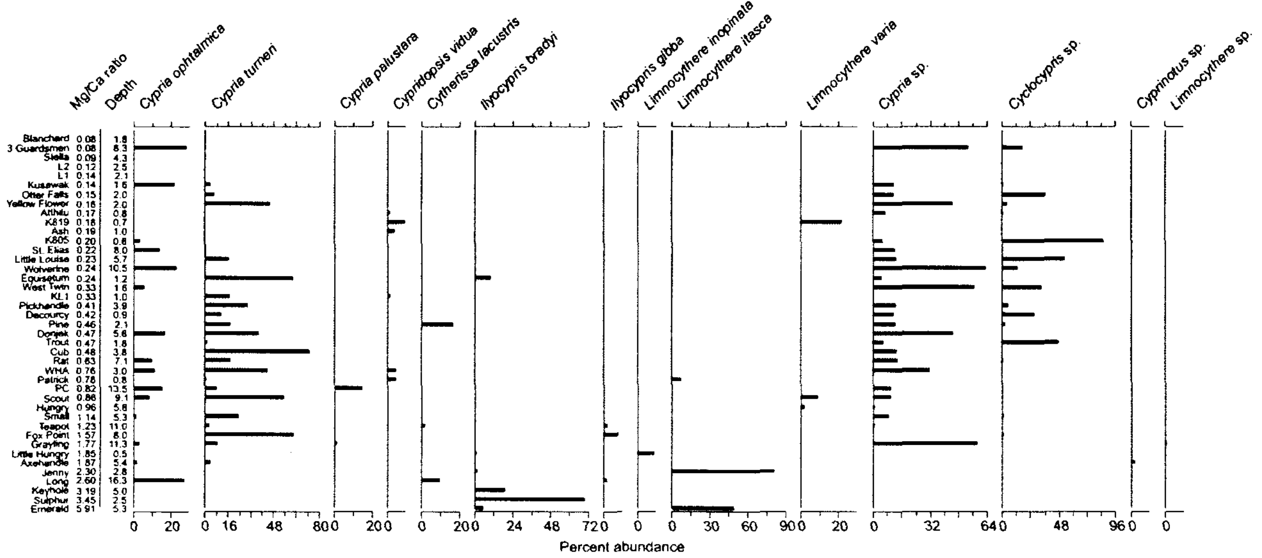
Figure A4: Distribution of lakes in the Canadian Arctic Archipelago as a function of conductance and Alkalinity/Ca^{2+} ratio. Circles indicate sites where ostracodes were present and the plus signs indicate sites where no ostracodes were found in sediment samples from the site. Convex hulls are drawn around the locations where the more abundant species were found.

Appendix B: Chironomid taxon list and % abundances from 2 additional lakes presented in Chapter 2

Code	Taxon	K805 (% abundance)	St. Elias (% abundance)
CHIRO	*Chironomus*	7.89	6.33
CLADO	*Cladopelma*	3.01	0.90
CLTAN	*Cladotanytarsus*	0.75	0.00
CORAM	*Corynocera ambigua*	0.00	6.33
COROL	*Corynocera oliveri*	1.50	0.00
CORYN	*Corynoneura*	0.00	0.00
CT	*Corynoneura/Thienemanniella*	0.00	0.00
COCYL	*Cricotopus/Orthocladius* (*C. cylindraceus* type)	2.26	1.81
COTRE	*Cricotopus/Orthocladius* (*C. tremulus* type)	0.00	0.00
CO	*Cricotopus/Orthocladius*	1.13	0.00
DICRO	*Dicrotendipes*	2.63	0.00
ENDO	*Endochironomus*	0.00	0.00
EUKF	*Eukiefferiella*	0.00	0.00
GLYP	*Glyptotendipes*	0.00	0.00
HETER	*Heterotrissocladius*	0.38	2.26
MICRPS	*Micropsectra atrofasciata*	0.00	0.90
MICRO	*Microtendipes*	0.75	0.00
NANO	*Nanocladius*	0.00	0.00
ORTHO	Orthocladiinae (unknown)	0.00	0.00
ORTHSPP	*Orthocladius* spp.	0.00	0.00
PAGA	*Pagastiella*	0.00	0.00
PAKB	*Parakiefferiella* cf. sp. B (Walker 1988)	0.00	0.00
PAK367	*Parakiefferiella* (Fig. 367 in O&R)	0.00	0.00
PAKSPP	*Parakiefferiella* spp. including *nigra*	0.00	0.00
PARAT	*Paratanytarsus*	2.26	0.90
PENT	*Pentaneurini*	0.00	0.00
POLY	*Polypedilum*	0.75	0.00
PROC	*Procladius*	3.38	1.81
PSECTEF	*Psectrocladius* (Fig. 9.61 E/F in Wiederholm)	4.14	0.45
PSECTD	*Psectrocladius* (Fig. 9.61 D in Wiederholm)	4.51	0.00
ALLOMES	*Psectrocladius* (*Allo/Mesopsectrocladius*)	1.50	0.00
PSECT	*Psectrocladius* spp.	5.26	0.00
SERG	*Sergentia*	0.00	23.08
TANYT	Tanytarsina	27.82	17.65
TANYC	*Tanytarsus* sp. C	0.00	0.00
TANLU	*Tanytarsus lugens* group	0.75	9.50
TANLUCO	*Tanytarsus lugens/Corynocera oliveri* type	0.00	0.00
TANYP	*Tanytarsus pallidicornis* type	0.00	0.00

Appendix C: Ostracode taxa from 41 lakes in the southwest Yukon presented in Chapter 2





Appendix D: Environmental variables from 41 lakes in the southwest Yukon collected in 2006. < denotes values above detection limit. These data are presented in Chapter 2.

Lake	Elevation (m)	Area (ha)	Temperature surface (°C)	Temperature bottom (°C)	Dissolved oxygen-surface (mg L^{-1})	Dissolved oxygen-bottom (mg L^{-1})	pH	Depth (m)	Secchi disk (m)
3 Guardsmen	940	17.23	10.1	8	11.8	10.04	8.4	8.3	6
Ash	808	0.75	19.8	19.8	7.63	7.63	8	1	1
Atthilu	942	36.43	17.1	17.1	11.56	11.56	8.9	0.8	0.8
Axehandle	787	1.00	15.5	14.8	9.98	9.82	8.8	5.4	5.25
Blanchard	914	2.44	15.6	15.4	9.55	9.5	8.85	1.8	1.8
Cub	880	6.70	13.1	12.7	10.18	10.09	8.9	3.8	0.6
Decourcy	966	1.75	16.7	16.7	8.99	8.99	8.8	0.9	0.9
Donjek	732	0.63	19	13.2	8.11	0.7	8.6	5.8	4.1
Emerald	820	8.38	15.4	15.3	9.87	9.66	8.75	5.3	3.2
Equisetum	991	5.4	16.7	16.2	8.37	6.66	8.35	1.2	1.2
Fox Point	790	3.75	13.4	8.7	8.91	8.16	8.45	8	2.6
Grayling	790	4.91	13.2	4.9	9.4	0.12	8.85	11.3	5.2
Hungry	920	44.69	16.3	14.3	10.6	10.32	8.7	5.8	4.5
Jenny	817	19.90	16.1	15.9	10.29	9.46	8.65	2.8	2.8
K805	732	47.31	17.7	17.7	8.48	8.48	8.5	0.8	0.8
K819	730	79.69	19.6	19.6	6.83	6.83	8	0.7	0.7
Keyhole	826	4.06	16.1	15.8	9.61	9.83	8.65	5	4
KL1	686	0.93	19.7	19.7	9.71	9.71	8.55	1	1
Kusawak	1000	6.13	12.8	12.8	9.89	9.59	8.4	1.6	1.6
L1	838	1.5	15.3	13.4	9.13	10.08	8.1	2.1	2.1
L2	878	3	16.5	15.2	9.63	9.24	8.65	2.5	2
Little Hungry	990	6.00	17.2	17.2	10.44	10.44	8.9	0.5	0.5
Little Louise	1021	9.56	10.6	9.6	8.81	8.14	8.4	5.7	4.7
Long	680	15.94	14.9	4.2	10.16	0.29	8.9	16.3	4.1
Otter Falls	899	13.53	16.4	16.3	9.14	8.76	8.55	2	2
Patrick	950	7.69	16.8	16.8	8.52	8.52	8.3	0.8	0.8
PC	799	2.00	14.8	4.2	10.66	0.2	8.6	13.5	5.8
Pickhandle	747	162.05	18.5	15	10.68	5.12	8.9	3.9	1.9
Pine	671	597.50	16.5	16.4	10.59	10.18	8.5	2.1	2.1
Rat	790	5.75	14.5	10.1	8.67	0.84	8.6	7.1	3.1
Scout	880	23.56	13	9.5	11.29	0.39	8.6	9.1	7.3
Small	799	0.63	14.4	7.4	9.41	0.51	8.8	5.3	3
St. Elias	890	17.50	14.8	10.4	9.31	10.1	8.1	8	7.8
Stella	787	23.56	16.1	14.2	9.56	10.01	8.4	4.3	3.5
Sulphur	854	142.56	17.1	17.1	9.42	9.12	8.9	2.5	1.5
Teapot	808	0.65	15	4.4	9.07	0.13	8.6	11	2.4
Trout	727	55.53	19	18.1	8.29	9.71	8.9	1.8	1.8
WHA	753	6.85	18.1	17.8	5.8	5.92	7.95	3	2.7
Wolverine	686	29.81	17.9	5	8.7	0.22	8.5	10.5	2.9
West Twin	914	8.13	13	12.7	11.36	11.7	8.4	1.6	1.6
Yellow Flwer	1021	4.25	17.2	15.7	9.81	8.91	9.3	2	0.5

Appendix D (cont'd): Environmental variables from 41 lakes in the southwest Yukon collected in 2006. < denotes values above detection limit. These data are presented in Chapter 2.

Lake	Specific conductance ($\mu S\ cm^{-1}$)	Ca ($mg\ L^{-1}$)	K ($mg\ L^{-1}$)	Mg ($mg\ L^{-1}$)	Na ($mg\ L^{-1}$)	Cl ($mg\ L^{-1}$)	SO_4 ($mg\ L^{-1}$)	Alk ($mg\ L^{-1}$)	DOC ($mg\ L^{-1}$)	TP ($\mu g\ L^{-1}$)	TPF ($\mu g\ L^{-1}$)
3 Guardsmen	36.5	4.9	0.21	0.39	2	0.2	1.3	17	1	7	7
Ash	154.4	24	1.45	4.5	1.98	0.5	3	81	23	13	10
Atthilu	185	29	0.97	4.9	3.6	0.1	8.3	93	9.8	22	12
Axehandle	376.1	19.8	6.3	37	3.6	0.4	27	200	2.5	10	6
Blanchard	121.7	21	0.47	1.62	1.05	2.4	2.2	61	7.5	18	8
Cub	266.8	27	3.3	12.9	10.3	1	111	127	20	29	10
Decourcy	337.8	25	1.57	10.6	45	0.2	13.8	188	44	51	22
Donjek	257	28	4.6	13.2	2.2	6.7	2.5	139	14.2	12	12
Emerald	652	13.7	6.3	81	13.8	1	59	350	5.9	10	6
Equisetum	217	31	3.7	7.5	4.1	1	4.1	105	27	36	13
Fox Point	1146	76	13.2	119	12.2	3	490	220	3	14	8
Grayling	347	18.1	6.3	32	6.7	0.9	107	148	2.6	12	6
Hungry	336.7	26	2.6	25	4.6	0.3	30	172	5.5	11	6
Jenny	606	27	8.4	62	9.7	0.9	168	197	16.2	11	8
K805	212.8	31	0.43	6.1	2.5	0.2	32	88	3.3	16	7
K819	289.2	45	1.75	8.1	2.9	0.5	32	127	12.7	27	15
Keyhole	513	18.8	4.8	60	5.8	0.5	60	260	4.6	16	7
KL1	428.1	55	4.4	18.2	5.1	2.3	125	107	18.6	22	20
Kusawak	65.6	9.4	0.24	1.33	1.85	1	74	39	1.6	8	6
L1	92.3	14.6	0.88	1.98	1.16	0.5	1.7	50	9.7	22	11
L2	116.3	19.1	0.54	2.3	1.36	0.5	25	36	10.8	20	9
Little Hungry	473.9	27	3.5	50	5.3	8.9	23	260	20	24	20
Little Louise	138.3	18.7	0.71	4.3	2.7	1	101	54	3.9	10	6
Long	517	20	4.5	52	15.5	1.3	77	240	6	9	7
Otter Falls	117.8	17.2	1.18	2.6	2.3	0.2	4.2	60	4.6	8	11
Patrick	373.3	36	2.6	28	3.2	0.5	23	200	8.1	26	14
PC	325.3	28	5.4	23	5.1	0.7	19	175	3.1	9	6
Pickhandle	263.5	30	2.8	12.2	5.5	4	23	123	9.9	30	17
Pine	266.2	29	2.5	13.2	3.4	0.2	8	150	3.7	9	6
Rat	318.2	32	4.9	20	5	0.7	19	178	3.1	9	6
Scout	314	23	4.9	19.7	13.7	1.3	108	176	13.6	11	8
Small	405.3	29	9.9	33	5.3	1	21	220	6.1	23	13
St. Elias	585	91	0.6	19.9	6.4	0.5	230	114	1.6	7	5
Stella	154.6	27	0.36	2.5	1.85	0.4	2.2	88	5.1	11	7
Sulphur	644	20	8.3	69	17.2	1	70	340	15.5	28	12
Teapot	538	39	7.5	48	5	0.6	135	198	2.5	13	7
Trout	240.8	21	3.7	9.9	15.8	2.9	4.1	128	18.2	21	12
WHA	661	37	7.5	28	44	73	30	230	16	23	15
Wolverine	270.4	39	1.78	9.4	2.7	6.7	29	113	15	18	12
West Twin	232.4	30	0.7	9.8	3.2	1	200	113	2.4	14	8
Yellow Flwer	237	39	3.7	6.4	3	0.8	25	112	19.9	58	24

Appendix D (cont'd): Environmental variables from 41 lakes in the southwest Yukon collected in 2006. < denotes values above detection limit. These data are presented in Chapter 2.

Lake	TKN (mg L^{-1})	Chla (µg L^{-1})	Si (mg L^{-1})	Al (mg L^{-1})	Fe (mg L^{-1})	Mn (mg L^{-1})	Mo (mg L^{-1})	LOI (%)	Carb (%)	MgCa	AlkCa
3 Guardsmen	0.04	0.30	1.31	0.02	0.006	0.0026	0.0084	18.3	4.8	0.08	3.47
Ash	0.8	0.29	4	0.025	0.175	0.0102	<0.0005	29.3	4.7	0.19	3.38
Atthilu	0.93	0.84	2.4	0.012	0.046	0.0098	0.0007	21.9	11.2	0.17	3.21
Axehandle	0.25	0.23	2.6	0.015	0.01	0.0047	0.0016	18.9	25.5	1.87	10.10
Blanchard	0.61	0.38	0.77	0.065	0.024	0.0013	<0.0005	64.9	19.2	0.08	2.90
Cub	1.23	2.69	3.2	0.013	0.006	0.0029	0.0038	35.9	28.1	0.48	4.70
Decourcy	2.2	0.31	4.8	0.02	0.048	0.0037	<0.0005	60.0	11.6	0.42	7.52
Donjek	0.71	0.25	1.06	0.012	0.012	0.0048	<0.0005	10.7	8.2	0.47	4.96
Emerald	0.42	0.34	8	0.013	0.004	<0.0005	0.0041	22.2	23.5	5.91	25.55
Equisetum	1.61	0.69	2.4	0.06	0.064	0.0104	<0.0005	58.0	8.2	0.24	3.39
Fox Point	0.3	0.50	2.9	0.013	0.04	0.0092	0.0043	11.8	9.2	1.57	2.89
Grayling	0.28	0.30	3.7	0.007	0.011	0.0069	<0.0005	8.7	5.9	1.77	8.18
Hungry	0.36	0.31	3.2	0.056	0.008	0.0029	0.0012	25.2	18.9	0.96	6.62
Jenny	1.56	0.13	5.6	0.007	0.041	0.0062	0.0009	33.4	21.3	2.30	7.30
K805	0.34	0.49	1.73	0.067	0.06	0.0008	0.0006	21.80	4.58	0.20	2.84
K819	0.6	0.70	2.8	0.108	0.117	0.034	<0.0005	14.5	22.5	0.18	2.82
Keyhole	0.41	0.20	8.8	0.01	0.005	0.0016	0.0021	29.9	33.9	3.19	13.83
KL1	0.79	0.72	1.21	0.033	0.031	0.0102	<0.0005	21.3	4.2	0.33	1.95
Kusawak	0.21	0.25	1.74	0.012	0.009	0.0006	0.0008	45.5	8.9	0.14	4.15
L1	0.67	0.23	0.51	0.016	0.042	0.0053	<0.0005	73.2	10.2	0.14	3.42
L2	1.44	0.74	1.49	0.022	0.015	0.003	<0.0005	78.0	17.6	0.12	1.88
Little Hungry	1.1	0.43	0.55	0.098	0.013	0.0028	<0.0005	33.0	27.0	1.85	9.63
Little Louise	0.22	0.22	2.6	0.012	0.016	0.0026	0.0084	12.6	2.2	0.23	2.89
Long	0.46	0.39	5.5	0.007	0.002	0.0013	0.006	24.1	11.0	2.60	12.00
Otter Falls	0.5	0.21	2.3	0.014	0.018	0.0021	0.0007	23.1	3.7	0.15	3.49
Patrick	0.71	0.49	0.81	0.013	0.034	0.0059	0.0032	27.7	22.4	0.78	5.56
PC	0.26	0.28	3.5	0.007	0.003	0.0066	<0.0005	11.9	9.0	0.82	6.25
Pickhandle	0.72	2.71	0.008	0.018	0.019	0.025	0.0007	38.2	9.1	0.41	4.10
Pine	0.24	0.19	2.9	0.028	0.001	0.0005	0.001	19.7	4.8	0.46	5.17
Rat	0.26	0.63	0.003	0.011	0.018	0.0165	0.0006	11.5	7.4	0.63	5.56
Scout	0.72	0.25	2.5	0.013	<0.001	0.0015	0.0011	35.6	23.1	0.86	7.65
Small	0.62	0.47	1.77	0.008	0.023	0.0175	0.0018	14.0	27.4	1.14	7.59
St. Elias	0.11	0.19	1.66	0.061	<0.001	0.0018	<0.0005	19.16	28.08	0.22	1.25
Stella	0.4	0.34	1.69	0.013	0.002	0.0081	<0.0005	79.9	15.9	0.09	3.26
Sulphur	0.97	0.94	7.4	0.03	0.016	0.0079	0.0007	48.4	24.8	3.45	17.00
Teapot	0.21	0.43	2.9	0.031	0.027	0.0053	0.0038	22.3	24.5	1.23	5.08
Trout	1	0.72	1.89	0.057	0.045	0.009	<0.0005	34.8	4.8	0.47	6.10
WHA	1.11	0.36	0.56	0.14	0.015	0.0145	0.0008	34.8	16.1	0.76	6.22
Wolverine	0.66	0.65	0.55	0.015	0.009	0.0047	0.0017	29.8	7.5	0.24	2.90
West Twin	0.34	0.57	1.84	0.011	0.111	0.0065	<0.0005	34.7	12.5	0.33	3.77
Yellow Flwer	2.3	3.27	0.96	0.2	0.064	0.0147	0.0011	45.3	6.2	0.16	2.87

Appendix E: Diatom names, authorities and corresponding numbers that are shown on the CCA species joint plot in Figure 2.5.

No.	Taxon name and authority
1	*Achnanthes conspicua* (A. Mayer)
2	*Achnanthes clevei* (Grun. in Cleve & Grun.)
3	*Achnanthes* cf. *delicatula* v. *engelbrechtii* (Cholnoky) Lange-Bertalot
4	*Planothidium frequentissima* (Lange-Bertalot)
5	*Achnanthes minutissima* Kütz.
6	*Achnanthes cf. ricula* Hohn & Hellerman
7	*Psammothidium rosenstockii* Lange-Bertalot
8	*Amphipleura kriegeriana* (Krasske) Hust.
9	*Amphipleura pellucida* (Kütz.) Kütz.
10	*Amphora libyca* Ehrenb.
11	*Amphora inariensis* Krammer
12	*Amphora pediculus* (Kütz.) Grun. ex A. Schmidt
13	*Amphora inariensis/pediculus*
14	*Asterionella formosa* Hass.
15	*Aulacoseira ambigua* (Grun. in Van Heurck) Simonsen
16	*Brachysira neoexilis* Lange-Bertalot
17	*Brachysira zellensis* (Grun.) Round & Mann
18	*Caloneis bacillum* (Grun.) Cleve
19	*Cocconeis neodiminuta* Krammer
20	*Cocconeis neothumensis* Krammer
21	*Cocconeis placentula* v. *euglypta* (Ehrenb.) Grunow
22	*Cocconeis placentula cf.* v. *lineata* (Ehrenb.) Van Heurck
23	*Cocconeis placentula*
24	*Craticula halophila* (Grun. ex Van Heurck) D.G. Mann in Round *et al.*
25	*Cyclotella antiqua* W.Sm.
26	*Cyclotella bodanica* v. aff. *Lemanica* (O.Müll. ex Schröt.) Bachm.
27	*Cyclotella* aff. *Comensis* Grun. in Van Heurck
28	*Cyclotella michiganiana* Skvort.
29	*Cyclotella ocellata* Pantocsek
30	*Cyclotella stelligera* (Cleve & Grun. in Cleve) Van Heurck
31	*Cymbopleura angustata (and angustata)* (W.Sm.) Cleve
32	*Encyonopsis cesatii* (Rabenhorst) Krammer
33	*Cymbella* cf. *cistula* (Ehrenb. in Hemp. & Ehrenb.) Kirchn.
34	*Cymbella delicatula* Kütz.
35	*Naviculadicta diluviana* (Krasske)
36	*Cymbella incerta* (Grun.) Cleve
37	*Cymbella incerta* v. *crassipunctata* Krammer
38	*Cymbella leptoceros* (Ehrenb.) Kütz.
39	*Encyonopsis subminuta (includes microcephala)* Krammer & Reichardt
40	*Encyonopsis* cf. *microcephala* v. *robusta* (Hust.) Krammer
41	*Encyonopsis aff. microcephala* (Grunow) Krammer
42	*Encyonema minutum* (Hilse) D.G. Mann
43	*Encyonema* cf. *ventricosum* (Agardh) Grunow
44	*Encyonema dubium* Krammer
45	*Cymbella pusilla* (Grun. ex A. Schmidt)
46	*Encyonema silesiacum* (Bleisch) Mann
47	*Cymbopleura* cf. *subaequalis (triundulate form)* Grun. in Van Heurck
48	*Cymbella* sp. 1 PISCES Pl.45, Fig.15-18 in Cumming *et al.* 1995
49	*Encyonopsis cesatiformis* Krammer
50	*Denticula kuetzingii* Grun.

Appendix E (cont'd): Diatom names, authorities and corresponding numbers that are shown on the CCA species joint plot in Figure 2.5.

No.	Taxon name and authority
51	*Denticula valida* (Pedicino) Grun. in Van Heurck
52	*Diatoma tenuis* Agardh
53	*Diploneis elliptica* (Kütz.) Cleve
54	*Epithemia argus* (Ehrenb.) Kütz.
55	*Epithemia turgida (includes v. granulata)* (Ehrenb.) Kütz.
56	*Fragilaria brevistriata* Grun. in Van Heurck
57	*Fragilaria* cf. *brevistriata* (very tiny) Grun. in Van Heurck
58	*Fragilaria aff. microstriata* Icon. Diat. vol.4, pl.39, Fig.50-52
59	*Fragilaria microstriata* Marciniak (Icon. Diat. vol.4, pl.39, Fig.46-49)
60	*Fragilaria* sp. Icon. Diat. vol.2, pl.7, Fig.53-56
61	*Fragilaria capucina* cf. v. *distans* KLB Fig.109:16 & Fig.113:16-21
62	*Fragilaria capucina* cf. v. *rumpens (Kütz)* Lange-Bertalot
63	*Fragilaria capucina complex*
64	*Fragilaria construens* (Ehrenb.) Grun.
65	*Fragilaria construens* v. *binodis* (Ehrenb.) Grun.
66	*Fragilaria construens* v. *venter* (Ehrenb.) Grun. in Van Heurck
67	*Fragilaria crotonensis* (and cf. forms) Kitt
68	*Fragilaria cyclopum* (Brutschy) Lange-Bertalot
69	*Fragilaria nanana* Lange-Bertalot
70	*Fragilaria parasitica* (W.Sm.) Grun. in Van Heurck
71	*Fragilaria pinnata* (includes v. *intercedens*)
72	*Fragilaria pseudoconstruens* Marciniak
73	*Fragilaria robusta* (Fusey) Manguin
74	*Fragilaria tenera complex*
75	*Fragilaria* sp. 1 PISCES Pl.7, Fig.3-6 in Cumming *et al.* 1995
76	*Fragilaria ulna* v. *acus* (Kütz.) Lange-Bertalot
77	*Fragilaria ulna* v. *acus group*
78	*Fragilaria* sp. 4 PIRLA Pl.5, Fig.24-26 in Cumming *et al.* 1995
79	*Gomphonema acuminatum* (Ehrenb.)
80	*Gomphonema angustum* Agardh
81	*Gomphonema gracile* Ehrenb.
82	*Gomphonema* cf. *pumilum* (Grun.) Reichardt & Lange-Bertalot
83	*Mastogloia smithii* v. *lacustris* Grun.
84	*Mastogloia smithii* Thwaites ex W.Sm.
85	*Hippodonta hungarica* (Grun.) Lange-Bertalot, Metzeltin & Witkowski
86	*Navicula cryptocephala* (includes cf. *forms*) Kütz.
87	*Navicula cryptotenella* Lange-Bertalot
88	*Navicula cryptotenella fo.* 1 PISCES / wildii Cumming *et al.* 1995 / Lange-Bertalot
89	*Kobayasiella jaagii* (Meister) Lange-Bertalot
90	*Sellaphora laevissima* (Kütz.) D.G. Mann
91	*Navicula libonensis* Schoeman
92	*Navicula microdigitoradiata* Lange-Bertalot
93	*Navicula minima* (and cf. forms) Grun. in Van Heurck
94	*Navicula* cf. *minuscula* Grun. in Van Heurck
95	*Navicula oblonga* (Kütz.) Kütz.
96	*Sellaphora pupula* (Ehrenb.) Mereschkowsky sensu lato
97	*Navicula radiosa* Kütz.
98	*Naviculadicta seminulum* (Grun.)
99	*Aneumastus tusculus* (Ehrenb.) Mann & Sickle
100	*Navicula utermoehlii* Hust.

Appendix E (cont'd): Diatom names, authorities and corresponding numbers that are shown on the CCA species joint plot in Figure 2.5.

No.	Taxon name and authority
101	*Navicula* cf. *veneta* Kütz.
102	*Navicula vulpina* (and cf. forms) Kütz.
103	*Navicula* sp. Pl.23, Fig.1 in Cumming *et al.* 1995
104	*Navicula* sp. Pl.19, Fig.13-14 in Cumming *et al.* 1995
105	*Navicula* sp. 4 PISCES Pl.22, Fig.15-17 in Cumming *et al.* 1995
106	*Navicula* aff. sp. 4 PISCES
107	*Neidium ampliatum* sensu Krammer & Lange-Bertalot
108	*Nitzschia* cf. *agnita* Hust.
109	*Nitzschia amphibia* Grun.
110	*Nitzschia bacillum* Hust. in A. Schmidt *et al.*
111	*Nitzschia dissipata* v. *media* (Hantzsch) Grun.
112	*Nitzschia draveillensis* Croste & Ricard
113	*Nitzschia cf. flexoides* Geitler
114	*Nitzschia fonticola* Grun. in Van Heurck
115	*Nitzschia fossilis* (Grun.) Grun. in Van Heurck
116	*Nitzschia frustulum* v. *bulnheimiana* (Rabenhorst) Grun. in Van Heurck
117	*Nitzschia graciliformis* Lange-Bertalot & Simonsen
118	*Nitzschia gracilis* Hantzsch
119	*Nitzschia palea* (Kütz.) W.Sm.
120	*Nitzschia paleacea* (Grun. In Cleve & Grun.) Grun. in Van Heurck
121	*Nitzschia perminuta* Lange-Bertalot
122	*Nitzschia* cf. *palea* KLB Fig.60:7
123	*Nitzschia radicula* Hust.
124	*Nitzschia* aff. *radicula* Hust.
125	*Pinnularia microstauron* (Ehrenb.) Cleve
126	*Rhoicosphenia abbreviata* (Agardh) Lange-Bertalot
127	*Simonsenia delognei* (Grun.) Lange-Bertalot
128	*Stauroneis gracilior* (Ehrenb.) Reichardt
129	*Stephanodiscus medius* Håkansson
130	*Stephanodiscus minutulus* (Kütz.) Round

Appendix F: Chronologies used in Chapter Five

This appendix presents the chronologies used in Chapter Five. The chronology for the Holocene sequence at Upper Fly Lake is discussed in Chapter Three.

Lead-210 (^{210}Pb), radiocarbon (^{14}C), and tephrochronology were used to assign ages to the sediment levels of the four cores. Radiocarbon-dated material included remains of terrestrial vegetation, aquatic vegetation, and aquatic macrofossils (Table F1). Preliminary plots of the age determinations and the well-dated White River tephra (WRA) indicated that each site had what appeared to be erroneous dates. The date of the WRA (1147 cal yr BP) assisted in distinguishing possible hard-water effects at two of the four sites (Figures F1-F4).

Age-depth curves were prepared for each site and evaluated independently to determine whether to 1) discard ^{14}C dates that were potentially anomalous in relation to others in the sequence at each of the four lakes (without accounting for possible hard-water effects) and 2) account for the possible hard-water effects at Upper Fly Lake and Jenny Lake. The chronologies in Chapter Five are reported as calibrated years before present, using the radiocarbon standard of cal yr BP = before AD 1950, and ^{210}Pb dates have been adjusted accordingly in the chronologies.

Upper Fly Lake

Two ^{14}C dates and 7 ^{210}Pb dates are available from the section of the core analyzed for this study (Figure F1, Table F1). Two potential chronologies were proposed based on these dates in relation to the WRA.

Option 1: Discarding a date from the chronology

The ^{14}C date (1361 cal yr BP) at 34-36 cm in the core is older than the well-dated WRA at 53 cm (Clague et al.1995), yet it is located above the ash in the core providing reasonable justification for discarding the date. A linear interpolation between the seven ^{210}Pb dates, the date of the WRA, and the ^{14}C date at 69-71 cm was used to develop the chronology (Figure F1).

Option 2: Correcting for the possible hard water effect in the chronology

An alternate interpretation of the dates follows. Although the younger date is older than the WRA, the two dates nevertheless fall in a line. An alternate possibility is that the dates are both good, but that there is a hard water effect. To correct for the hard water offset of the two ^{14}C dates, the intercept (intercept A = -885) of the regression of the seven ^{14}C dates from the entire 298 cm lake sediment core (see Table 3.2 in Chapter Three for details) was calculated. A second regression was computed on the seven ^{210}Pb dates and the date of the WRA, and the intercept of this regression (intercept B = -195) was subtracted from intercept A. The correction of 690 cal yrs was subtracted from the two ^{14}C dates used in this chronology (Figure F5). This followed a similar approach that was used, for example, in Peros and

Gajewski (2009). A linear interpolation between the seven ^{210}Pb dates, two corrected ^{14}C dates, and the date of the WRA was used to establish a chronology.

Chosen chronology

Option 2 was the chosen chronology for Upper Fly Lake. The corrected dates fell in line with the WRA and avoided the removal of the 34-36 cm date from the age-depth curve. The presence of ostracodes and high carbonate content in the lowermost sediments provides evidence of a potential hard water effect.

Jenny Lake

Three radiocarbon and five ^{210}Pb dates were obtained from a 138 cm core from Jenny Lake.

Option 1: Discarding a date from the chronology

The ^{14}C date located at 31.5-34.5 cm in the lake sediment core was not included in the development of either of the chronologies. This date was considerably older (2044.5 cal yr BP) than the WRA that was located more than 60 cm below (Figure F2). An age-depth curve was developed using five ^{210}Pb dates (Table F3), two ^{14}C dates and the date of the WRA. As discussed in Chapter Five, this sediments of this lake have a high carbonate content therefore a hard-water effect is likely.

Option 2: Correcting for the possible hard water effect in the chronology

The two remaining ^{14}C dates from Jenny Lake were used to compute a regression, and the intercept (intercept A = -587) was used in the computation of a correction (Figure F6). A second intercept (intercept B = -39) of a regression calculated using the ^{210}Pb dates and the WRA date was subtracted from intercept A, providing a correction of 548 cal yrs. This correction was only applied to the 1778 cal yr BP date located at 105-107 cm as the material dated was primarily aquatic macrofossils. These organisms are potentially subject to a hard-water effect as they uptake old carbon dissolved in the lake water during growth. The other date of 982 cal yr BP measured on terrestrial material was not corrected. Using linear interpolation between points, a chronology was developed using five ^{210}Pb dates, two ^{14}C dates (one corrected) and the date of the WRA.

Chosen chronology

Option 1 was the chosen chronology for Jenny Lake. It was not entirely justified to accept the second option over the first, as corrections (when used) are typically applied to all ^{14}C dates.

Donjek Kettle

Three ^{14}C dates and 11 ^{Pb}210 dates were available from the 102 cm section of the Donjek Kettle core used in this study. The WRA layer was very thick in this core (44 cm) and provided an easily identifiable marker level. Since this was essentially an instantaneous event, there is a discontinuity in the age-depth curve, as seen in Figure F3.

A ^{14}C date (1281.5 cal yr BP) from 26-27.5 cm was older than the WRA located 6 cm below, justifying removal from chronology development. The material used to measure the date were moss fragments, which may be aquatic and therefore subject to the same hard-water effect mentioned above.

A second tephra layer (WRA2) could be identified in this core from 87.5-88.75 cm. This is not as well studied as the WRA event and was the result of the eruption of Mount Churchill at some time between 1270 and 2214 cal yr BP (Table F5). For this chronology, we use Lowdon & Blake's (1968) date measured on wood as it is more reliable material. The chronology was developed using a linear interpolation between the 11 ^{210}Pb dates (Table F4), two ^{14}C dates (Table F1), the WRA, and the WRA2.

Lake WP02

Two ^{14}C dates and 11 ^{210}Pb dates were available from a 38 cm lake sediment core from Lake WP02.

The core from WP02 was shorter than the others, and extended to the WRA; there was no available sediment below the ash. Material for a ^{14}C date was extracted from immediately above the WRA (37-38 cm), however it revealed a date much younger (515.5 cal yr BP) than the WRA. Therefore, it was discarded from the chronology. As with the other sites, ages were assigned to the various depths by linear interpolation between points, which included 11 ^{210}Pb dates (Table F6), one ^{14}C date, and the date of the WRA (Figure F4).

References

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Table F1: AMS radiocarbon dates from the lake sediment cores, southwest Yukon

Lake and Depth (cm)	Lab Code	Conventional Radiocarbon age (yr BP)	2-sigma calibrated age range (cal yr BP)[a]	Median calibrated age (cal yr BP)	$\delta^{13}C/^{12}C$ (‰)	Material
Upper Fly 34-36	Beta – 229092	1490 ± 40	1302-1420	1361	-26.3	Macrofossils
Upper Fly 69-71	Beta – 229093	2440 ± 40	2355-2547	2451	-22.2	Macrofossils
Jenny 31.5-34.5[b]	Beta – 256717	2070 ± 40	1945-2144	2044.5	NA	Macrofossils
Jenny 69.5-71.5	Beta – 255709	1040 ± 40	907-1057	982	-24.6	*Picea* twig
Jenny 105-107	Beta – 255710	1820 ± 40	1691-1865	1778	NA	Twig, macrofossils
Donjek 26-27.5[b]	Beta – 255707	1350 ± 40	1227-1336	1281.5	-34.2	Moss fragments
Donjek 82-83	Beta – 255708	1820 ± 40	1691-1865	1778	-33.8	Plant fragments
Donjek 96-98.5	Beta – 256716	2160 ± 40	2041-2311	2176	NA	Macrofossils
WP02 17-17.5	Beta – 255711	430 ± 40	428-536	482	-29.4	Moss fragments
WP02 36.5-38[b]	Beta – 255712	480 ± 40	475-556	515.5	-29.5	Moss/plant fragments

[a] Calibration was based on IntCal04 (Reimer et al. 2004).
[b] These dates were not used in the respective chronologies (see Chapter 5 for details).

Table F2: Lead-210 dates from the sediment core at Upper Fly Lake, southwest Yukon

Depth (cm)	Years before present[a] at bottom of sediment section (CRS model estimate)
3.0-4.0	6.8
4.0-5.0	13.7
5.0-6.0	20.3
6.0-7.0	27.6
7.0-8.0	32.9
8.0-9.0	38.4
9.0-10.0	42.8

[a] Before AD 1997

Table F3: Lead-210 dates from the sediment core at Jenny Lake, southwest Yukon

Depth (cm)	Years before present[a] at bottom of sediment section (CRS model estimate)
0.0-1.0	10.0
1.0-2.0	28.2
2.0-3.0	55.4
3.0-4.0	81.0
4.0-5.0	109.2

[a] Before AD 2003

Table F4: Lead-210 dates from the sediment core at Donjek Kettle, southwest Yukon

Depth (cm)	Years before present[a] at bottom of sediment section (CRS model estimate)
0.0-0.5	1.0
0.5-1.0	4.7
1.0-1.5	10.4
1.5-2.0	16.9
2.0-2.5	25.7
2.5-3.0	36.6
3.0-3.5	45.8
3.5-4.0	55.7
4.0-4.5	64.0
4.5-5.0	73.4
5.0-5.5	82.0

[a] Before AD 2006

Table F5: Dates of the second White River Ash located from 87.5-88.75 cm in the Donjek Kettle lake sediment core

Reference	Data source	Conventional Radiocarbon age (yr BP)	2-sigma calibrated age range (cal yr BP)[a]	Median calibrated age (cal yr BP)
Fernald 1962	Peat above ash	1520 ± 100	1271-1690	1480.5
Fernald 1962	Peat below ash	1750 ± 100	1408-1898	1653
Lowdon & Blake 1968	Wood below ash	1990 ± 130	1691-2214	1952.5

[a] Calibration was based on IntCal04 (Reimer et al. 2004).

Table F6: Lead-210 dates from the sediment core at Lake WP02, southwest Yukon

Depth (cm)	Years before present[a] at bottom of sediment section (Linear regression model estimate)
0.0-0.5	0.5
0.5-1.0	2.7
1.0-1.5	8.2
1.5-2.0	15.5
2.0-2.5	23.9
2.5-3.0	33.6
3.0-3.5	44.3
3.5-4.0	55.2
4.0-4.5	58.2
4.5-5.0	61.1
5.0-5.5	63.9

[a] Before AD 2006

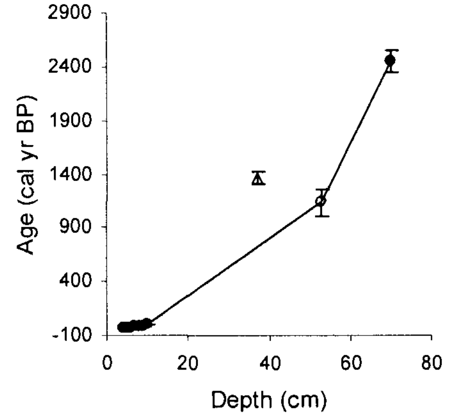

Figure F1: Age-depth curve from Upper Fly Lake (option 1)

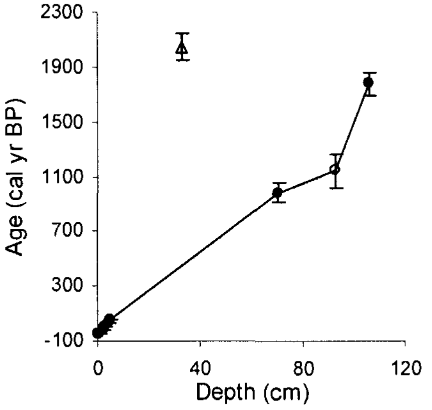

Figure F2: Age-depth curve from Jenny Lake (option 1)

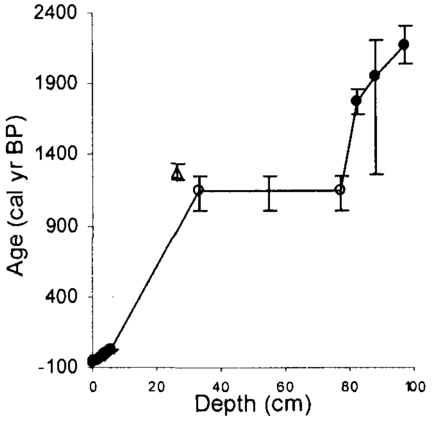

Figure F3: Age-depth curve from Donjek Kettle

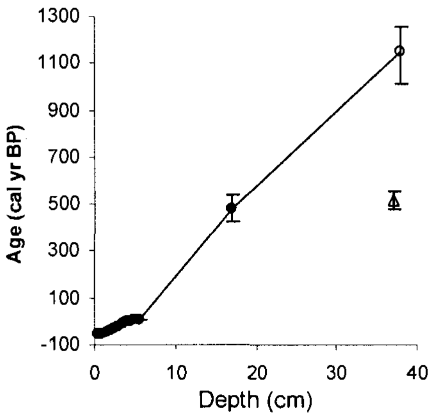

Figure F4: Age-depth curve from Lake WP02

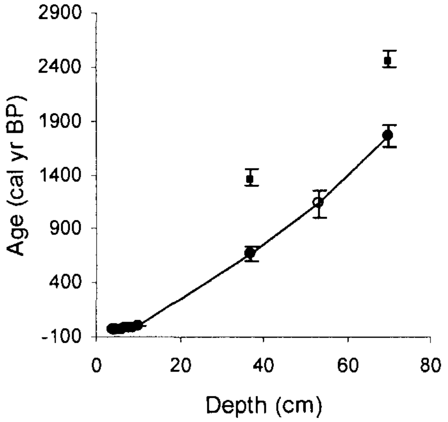

Figure F5: Age-depth curve from Upper Fly Lake (option 2)

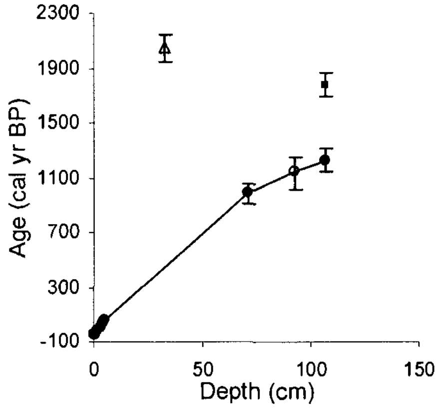

Figure F6: Age-depth curve from Jenny Lake (option 2)

Figures F1-F6: Chronologies prepared for four lakes in Chapter Five. On all graphs the solid circles are 210Pb and uncorrected 14C dates, the open triangles are discarded dates, the open circles are the White River Ash (WRA; 1147 cal yrs BP) andon the Donjek graph they are WRA and WRA2 (1953 cal yrs BP), and the solid squares are corrected dates.