12 500 Years
of Midge-Inferred Climatic History
For Interior Alaska

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Abstract

Freshwater midge fossils were used to reconstruct palaeotemperatures and palaeolake levels for Birch, Jan and Windmill Lakes, interior Alaska. Midge-inferred mean July air temperatures indicate a cold period (10 600 to 9700 $^{14}$C yr BP, Birch Lake; 10 500 to 10 000 $^{14}$C yr BP, Windmill Lake) overlapping with the Younger Dryas. Warming is apparent at 9700, 9000 and 11 400 $^{14}$C yr BP at Birch, Windmill and Jan Lakes, respectively. Inferred temperatures peak at $\sim$10 000 $^{14}$C yr BP at Jan Lake, and gradually decline throughout the Holocene, possibly indicating an early Holocene Thermal Maximum. Mid-Holocene cooling from 7000 to 6000 $^{14}$C yr BP at Windmill Lake aligns with Picea glauca decline throughout interior Alaska. Midge-inferred lake levels parallel results of earlier sedimentological research at Birch Lake. Maximum lake depths peak around 12 000, 10 400 and 8000 $^{14}$C yr BP, synchronous with three midge-inferred cold periods.

Keywords

Chironomidae fossils, temperature, lake-level, Younger Dryas, Holocene
To my Mother
(1945-2005)

love patience & wisdom
Acknowledgements

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Christina Bleskie, thank you for the countless chironomids, true organizational skills and a great friendship. Palaeo-girl adventures in Chironobus were supplemented with Erin’s enthusiasm in all things North … the legend lives on. Thanks to Shelley MacIsaac who first told me that the air bubbles weren’t chironomid heads. Many chironomids were saved from eternal burial by Linda Fiechter and Marianne Chase. To all Kelownans, I am sincerely grateful to have your support, advice, adventures and true friendship. Special love and thanks to the Radomske family for many cups of tea, words of wisdom and a home in British Columbia.

I am lucky to have been given unsurpassed love from my mother and father. Poppy, you are always by my side.

The most wonderful result of my thesis was finding Brendan, the love of my life.
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Class Hexapoda (Insecta), Order Diptera

**Family Ceratopogonidae**
- Genus *Bezzia* Kieffer
- Genus *Dasyhelea* Kieffer

**Family Chaoboridae**
- Genus *Chaoborus* Lichtenstein
  - Species *C. americanus* (Johannsen)
  - Species *C. trivittatus* (Loew)

**Family Chironomidae**

Subfamily Tanypodinae
- Tribe Macropelopiini
  - Genus *Procladius* Skuse
- Tribe Pentaneurini
- Subfamily Chironominae
  - Tribe Chironomini
    - Genus *Chironomus* Meigen
      - Species *C. plumosus* L.
    - Genus *Cladopelma* Kieffer
    - Genus *Cryptochironomus* Kieffer
    - Genus *Cyphomella* Seetler
    - Genus *Demicryptochironomus* Lenz
    - Genus *Dicrotendipes* Kieffer
    - Genus *Einfeldia* Kieffer
    - Genus *Harnischia* Kieffer
    - Genus *Microtendipes* Kieffer
    - Genus *Omisus* Townes
    - Genus *Pagastiella* Brundin
    - Genus *Parachironomus* Lenz
    - Genus *Paralauterborniella* Lenz
    - Genus *Paratendipes* Kieffer
    - Genus *Phaenopsectra* Kieffer
    - Genus *Polypedilum* Kieffer
    - Genus *Sergentia* Kieffer
      - Species *S. coracina* (Zetterstedt)
- Genus *Stenochironomus* Kieffer
- Genus *Stictochironomus* Kieffer

Tribe Pseudochironomini
- Genus *Pseudochironomus* Malloch

Tribe Tanytarsini
- Genus *Cladotanytarsus* Kieffer
  - Species *C. mancus* group

Class Hexapoda (Insecta), Order Diptera
Family Chironomidae

Genus Corynocera Zetterstedt
Species C. ambiguа Zetterstedt
Species C. near ambiguа Zetterstedt
Species C. oliveri Lindeberg type

Genus Micropsectra Kieffer
Species M. atrofasciа/radialis type

Genus Paratanytarsus Bause
Genus Stempellina Bause
Genus Stempellinella Brundin
Genus Tanytarsus van der Wulp
Species T. lugens Kieffer type

Subfamily Orthocladiinae

Genus Corynoneura Winnertz
Genus Cricotopus van der Wulp
Genus Eukiefferiella Thienemann
Genus Heterotrissocladius Spårсk
Species H. marcidus (Walker) group
Species H. subpilosus Brundin group

Genus Limnophyes Eaton
Genus Nanocladius Kieffer
Genus Orthocladius van der Wulp
Genus Paracladius Hirvenoja
Genus Parakiefferiella Thienemann
Species P. sp. B type
Species P. nigra Brundin
Species P. triquetra type

Genus Parametriocnemus Goetghebuer
Genus Paraphaenocladius Thienemann
Species P. pseudirritus (Strenzke)

Genus Psectrocladius Kieffer
Genus Pseudorthocladius Goetghebuer
Genus Pseudosmittia Goetghebuer
Genus Smittia Holmgren
Genus Synorthocladius Thienemann
Genus Thienemanniella Kieffer
Genus Zalutschia Lipina
Species Z. sp. A
Species Z. zalutschicola Lipina

Subfamily Prodiamesinae
Genus Monodiamesa Kieffer
Species M. tuberculata Sæther

Subfamily Diamesinae
Genus Pagastia Oliver
Genus Protanypus Kieffer

Class Hexapoda (Insecta), Order Ephemeroptera
Class Hexapoda (Insecta), Order Trichoptera
Class Arachnida, Order Acari
List of Plant Names

_Picea glauca_ (Moench) Voss  white spruce
_Picea mariana_ (Miller) Britton, Sterns & Poggenburg  black spruce
_Pinus contorta_ Douglas ex Loudon  lodgepole pine
_Tsuga mertensiana_ (Bongard) Carrière  mountain hemlock
_Larix laricina_ (Du Roi) K. Koch  tamarack
_Betula papyrifera_ Marshall  paper birch
_Betula glandulosa_ Michaux, Fl.  shrub birch
_Alnus_ Miller (including _Alnus crispa_ Aiton)  alder (green alder)
_Populus tremuloides_ Michaux  quaking aspen
_Populus balsamifera_ L.  balsam poplar
_Salix_ L.  willow
_Artemisia_ L.  sage-brush
_Poaceae_ (formerly Gramineae)  grass
_Cyperaceae_  sedge
_Carex rostrata_ Stokes  beaked sedge
_Potamogeton_ L.  pondweed
_Potamogeton cf. richardsonii_ (A. Bennett)  Richardson’s pondweed
_Polypodiaceae_  fern
_Empetrum_ L.  crowberry
_Dryas octopetala_ L.  mountain avens
_Nuphar polysepalum_ Engelmann  spatterdock water lily
_Nymphaea alba_ L.  European white water lily
_Nymphaea odorata_ Aiton  fragrant white water lily
_Nymphaea tetragona_ Georgi  pygmy water lily
_Brasenia schreberi_ J.F.Gmelin  watershield
_Nymphoides_ Seguier  floating heart (buckbean)
### Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>¹⁴C yr BP</td>
<td>radiocarbon years before present</td>
</tr>
<tr>
<td>cal yr BP</td>
<td>calibrated ¹⁴C yr BP</td>
</tr>
<tr>
<td>CONISS</td>
<td>constrained incremental sum of squares cluster analysis</td>
</tr>
<tr>
<td>JtempN</td>
<td>mean July air temperature (New et al. 2002) †</td>
</tr>
<tr>
<td>LGM</td>
<td>last glacial maximum</td>
</tr>
<tr>
<td>LOI</td>
<td>loss on ignition</td>
</tr>
<tr>
<td>NADW</td>
<td>North Atlantic Deep Water</td>
</tr>
<tr>
<td>P-E</td>
<td>precipitation minus evaporation (effective moisture)</td>
</tr>
<tr>
<td>R²</td>
<td>coefficient of determination</td>
</tr>
<tr>
<td>RMSEP</td>
<td>root mean square error of prediction</td>
</tr>
<tr>
<td>WAPLS</td>
<td>weighted averaging partial least squares</td>
</tr>
<tr>
<td>YD</td>
<td>Younger Dryas</td>
</tr>
</tbody>
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It is a common circumstance for one to ponder upon human's beginnings.

It is not my quest to explain the driving force that steers us towards recreating our biological, geographical or cultural evolution. That may be a philosophical or, perhaps, even sentimental journey through history. My purpose is to join in palaeocologists' efforts to reconstruct environments through which our ancestors may have lived.

Two million years ago an immense change was wrought upon the earth's climate, and thus on life. This period, called the Quaternary, is often referred to as the Ice Age. Actually, it was several "ice ages" that arose in the past two million years until 10 000 years ago, the start of the Holocene. These ice ages are identified by large areas of glaciation in the Northern Hemisphere, and lowering of sea and lake levels. The ice ages are separated in time by periods of warmth, called interglacials. It is conjectured that our current epoch, the Holocene, is an interglacial.

Of extreme interest is the Bering Land Bridge, the likeliest route for human migration into North America. As glaciers drew sea water away from the scant 150 m depth at the strait, land emerged. Climate changed dramatically. And we entered North America. But what were the exact conditions as humans first walked the bridge? How did summer and winter temperatures fluctuate? Was barren aridity a concern? To answer these questions, a range of multi-proxy palaeoenvironmental variables must be measured.
Chapter 1  Literature Review

Introduction

Limnology encompasses the understanding of the biological, chemical, physical and biogeochemical components of lakes, rivers and all other inland waters (Wetzel 2001). In addition to supporting an abundance of floral and faunal life, lakes accumulate records of the past within their sediments. Communities of freshwater organisms live in changing environments and their remains are preserved in lake-bottom sediments after death. These assemblages of organismal remains, in effect, preserve snapshots of climatic conditions during those periods of time. Palaeolimnologists have expanded the limnological timeframe, using these snapshots to reconstruct a lake's entire history, including past water temperatures, nutrient levels, salinities, and other environmental parameters (Brooks et al. 2001; Heinrichs et al. 2001; Walker et al. 2003).

Palaeoecological work is both qualitative and quantitative. Research has led to detailed quantitative modelling approaches, such as transfer functions and other regression-calibration techniques, using a variety of faunal and floral proxy indicators (Walker 2001). These statistical techniques are important in reconstructing temperatures and other climatic variables of global interest, especially in the wake of increasing awareness of climatic change.

Larval head capsule fossils from Order Diptera (true flies) are typically the most abundant insect remains found in lake sediments. Diptera, one of the youngest orders of insects, is comprised of more than 40 families and dates back to the Triassic period, e.g. Psychodidae (Filho and Brazil 2003; Labandeira 1997). Head capsules and mandibles of three Dipteran families: Chironomidae (non-biting midges), Ceratopogonidae (biting midges) and Chaoboridae
(phantom midges) preserve well in lake sediments and are abundant and readily identifiable. Excellent preservation of head capsules and evidence of climate-induced fluctuations in midge communities allow the palaeoecologist to infer past climatic trends (Hofmann 1988; Walker 2001). The value of midges in palaeoecological research has been demonstrated in most parts of the world. Most palaeoecologists are convinced of strong, although perhaps complicated relationships between midge distributions and climate (Battarbee 2000; Walker 1987; Walker et al. 1991b).

Chironomidae & Their Palaeoecological Significance

Family Chironomidae includes >10 000 species of non-biting midges (Cranston 1995a). They are generally considered to be innocuous, other than causing occasional bouts of human allergic reactions to adult wing scales or larval haemoglobins (Cranston 1995b). They are found in all climatic regions: tropical, temperate, arctic, and antarctic. The majority of chironomid species undergo an aquatic-terrestrial life cycle and spend three of their four life stages (egg, larva, pupa) in water. For palaeoecological purposes, it is the larval stage that is studied. The larvae are found in lakes of varying salinities, marine littoral systems, peat bogs, marshes, streams, submerged wood, and other sundry locations, such as dung piles and pitcher plants (Pinder 1995). Because of their ubiquity, chironomids are excellent candidates for palaeoecological studies. In addition, some chironomid species (or genus groups) are particularly sensitive to environmental conditions, for example, surface water temperature, air temperature, salinity, oxygen levels, lake productivity, acidification, and water depth (Hofmann 1988; Rossaro 1991; Sæther 1979).
General Life History of Chironomidae

Briefly summarizing the holometabolous life cycle of chironomids, Oliver (1971) notes larval feeding habits, development and temperature dependence. Eggs are laid on water surfaces within a gelatinous matrix; duration of this egg stage is likely temperature-dependent (Oliver 1971). The larval stage is the longest, varying from a few months to years. Chironomid larvae are diverse in their habitats and ecological requirements and can physiologically withstand climatic extremes, such as long-term desiccation and freezing tolerance (Pinder 1995). Chironomids undergo four aquatic larval moults (Oliver 1971). The first stage or instar is typically planktonic; larvae swim freely in the water column and feed indiscriminately on suspended algae and detritus. Larvae are largely benthic as 2nd, 3rd and 4th instars and remain on or within lake sediments. Many species construct larval cases using sediment grains and silk-like threads, while others are free-living predators. Some species are omnivores and can feed both selectively and non-selectively on available resources. The pupal stage is comparatively short-lived, hours to days in length, whereas adults generally live days or weeks (Oliver 1971). The main purpose of the pupal stage is reorganization of the larva into imago form, while that of the ephemeral adult is to reproduce and disperse.

Suitability of Chironomidae for Palaeoecological Research

Each chironomid releases four chitinous head capsules into the water body as it moults (Walker 2001). These head capsules remain fossilized in the sediments for thousands of years. In Quaternary sediments, the head capsules do not undergo chemical or physical changes during "fossilisation", but are preserved as original remains. Thus, they are often referred to as "sub-fossils". In this research, the term "fossil" will be used, as samples are representative of individuals whose deaths occurred thousands of years ago.

The characteristic of chironomids that makes them particularly useful for palaeoecological research is their rapid response to changing environmental conditions. Walker
& Mathewes (1989a) claimed that chironomids were sensitive to temperature changes and that northern limits were, thus, linked to water surface and air temperatures. Chironomids have also been used as indicators of lake status, in particular, lake trophic levels (Gerstmeier 1989; Lindegaard 1995; Sæther 1975b; Sæther 1979; Wiederholm 1981). For instance, North American lakes have been divided into trophic types such as ultraoligotrophic, indicated by *Heterotrissocladius oliveri*, oligotrophic, characterized by *Tanytarsus* species, *Monodiamesa tuberculata* and *H. changi*, and strongly eutrophic, distinguished mainly by *Chironomus plumosus*. *Sergentia coracina* may indicate mesotrophy, while *Zalutschia zalutschicola* may indicate dystrophy (high dissolved organic matter).

Hofmann (1988) describes seven main reasons why chironomids are suitable for palaeoecological research:

1. chironomid communities within lakes are highly diverse,
2. species are adapted to particular ecological conditions and habitats,
3. head capsules preserve well and in abundance, even in small units of sediment,
4. identification of the fossils is possible with modern larval keys,
5. due to the ecological requirements of taxa, the fossil record is indicative of ecological conditions at the time of sedimentation,
6. successional changes in chironomid communities are documented over time in the sediment and
7. faunal successions are indicative of changing ecological conditions during lake development.

Hofmann (1988) cautions against using fossil chironomids as indicators of trophic status, and stresses that, in shallow lakes (<3 m), chironomid succession is closely related to climatic changes.
Statistical Analysis

Chironomid fossil data have been traditionally represented using biostratigraphic diagrams. These stratigraphies are used to examine trends and changes in chironomid species' relative abundances, representing past community changes. A qualitative assessment can then be inferred based on ecological and biogeographical knowledge of the chironomid genera and species. Walker & Paterson (1983) used chironomid stratigraphies to trace the progressive change in chironomid fauna from a cold *Heterotrissocladius* community to a warm *Chironomus* community, and finally to the *Chironomus-Monopsectrocladius* community indicative of acidic peat-pools in the Canadian Maritimes.

Walker et al. (1991b) created the first transfer function model for chironomid fossils. In order to create the transfer function, surface sediment samples from a transect of eastern Canadian lakes were collected along with modern environmental data for each lake. Canonical correspondence analysis (CCA) was used to determine the environmental variables that had the strongest correlations to the modern species assemblages. Chironomid distributions were found to be strongly correlated with summer surface water temperatures and moderately correlated with lake depth (Walker et al. 1991a; Walker et al. 1991b). The model developed from the surface sample data was then applied to fossil data derived from long sediment cores extending thousands of years into the past. These fossil data were entered into the transfer function model, generating a palaeotemperature reconstruction for the lake. Currently, models are evaluated using jackknifed R² and RMSEP values, but statisticians question the capabilities of these values for testing robustness of the model and suggest using plots of residuals against predicted values (Racca and Prairie 2004).

Assumptions

A major assumption in midge palaeoclimatology is that successful midge reproduction, survival and dispersal is (directly and/or indirectly) related to temperature. Climatic changes can
induce changes to air and water temperatures above or below a specific midge’s optimum. This, in turn, will cause either extirpation or dispersal of midge species according to their temperature optima and tolerances. Chironomids are thought to undergo mainly passive dispersal through the initial movements from eclosion site, swarming dispersal through wind actions or slightly more active dispersal during oviposition (Armitage 1995). Whether the dispersal is active or passive, long-term temperature shifts will create conditions conducive to successful dispersal of suitably adapted species to new habitats.

Insects, like other ectotherms, exhibit an intrinsic relationship between physiology and air temperature. For instance, ectotherms grow to larger body sizes in colder environments (Atkinson and Sibly 1997). It has been shown that the duration of the egg stage in chironomids is temperature dependent (Oliver 1971). The link between aquatic larval growth and surface water temperatures is central to palaeoecology. This link stems in part from the solubility of oxygen, which decreases with warmer water temperatures. Certain midge species, mainly of the genus *Chironomus*, have unique physiologies that allow them to survive in extremely low oxygen conditions (Cranston 1995a). The presence of high O₂-affinity haemoglobins in their body fluids (causing a red blood-like colouration) differentiates this group of warm stenotherms from other midges.

There has been debate about inferring lake water temperatures from midge fossils (Warwick 1989). Warwick (1989) briefly discusses the confounding factor of lake depth on chironomid response to air temperatures. For instance, deeper lakes often stratify, resulting in a cool hypolimnion not greatly affected by air temperatures. Also stressed is the role of sediment type on chironomid assemblages. Warwick (1989) states that increased mineral accumulation may favour influxes of midges such as *Parakiefferiella* sp. A (*P. nigra* in this paper) and *Heterotrissocladius*. This seems to be linked to low nutrients and organic matter in new bottom sediments. Walker & Mathewes (1989b) countered this argument, suggesting that the evidence used by Warwick did not demonstrate a statistically significant sediment-chironomid relationship.

Warner and Hann (1987) also warn against placing too high a value on midge temperature reconstructions. They argue that a *Heterotrissocladius* community is indicative of oligotrophic conditions, increased sedimentation and turbidity, rather than strictly climatic
influences, such as air temperature. Again, Walker and Mathewes (1987) convincingly argue that *Heterotrissocladius*’ distribution is best explained by climate. *Heterotrissocladius* is present only in cold montane, alpine or northern lakes. Its presence in temperate lakes occurs only in the cold, deep, profundal zone of large lakes. Their views are supported by numerous studies showing relationships between climatic variables and midges, (e.g. Brodersen et al. 2004; Lotter et al. 1997; Walker and MacDonald 1995), particularly *Heterotrissocladius*, (e.g. Sæther 1975a). It is also stressed that palaeolimnological studies be done mainly on shallow water bodies where the impact of climate is most pronounced. Finally, Warner and Hann (1987) caution that identification only to genus level will lead to interpretations of a “general nature”. Species have distinct niches that are not discernable when lumped under one genus. Walker (2001) discusses the balance between increased taxonomic resolution and misidentification. The optimal level of identification depends on the project goals and analyses, and the identification methods used by the chironomid worker.

**Midge Reconstruction Capabilities**

Walker et al. (1991a) found evidence of Allerød—Younger Dryas climatic oscillations in Atlantic Canada, mainly through increased abundances of the cold water indicators, *Heterotrissocladius* and *Protanyopus*. Subsequent research in the same area indicated even more extreme temperature oscillations, as calculated using an expanded chironomid model (Walker et al. 1997). The discrepancy between cooling estimates derived from the original model and the expanded model leads to questions regarding model precision and highlights that palaeoecologists should emphasize trends, rather than exact temperature values. In addition, Kurek et al. (2004) performed a high resolution chironomid reconstruction of Speck and Surplus Ponds in Maine, USA and concluded that chironomids were not capable of reconstructing small palaeotemperature changes. They cautioned against the use of chironomids for reconstructions other than large temperature shifts.

Chironomid inference models are now widely used to estimate past temperatures (Barley et al. in press; Barley 2004; Heinrichs et al. 1997; Heiri et al. 2004). Currently, midge transfer
functions are developed using mean July air temperatures gathered from environmental databases, such as the Canadian Climate Normals and GIS models of these data (New et al. 2002). Investigations have shown that surface water temperatures in lakes correlate strongly with mean July air temperatures, which are more accessible and reliable than measured lake water temperatures (Livingstone and Lotter 1998). Palaeosalinity records have also been derived from chironomid and diatom transfer functions (Heinrichs et al. 2001; Heinrichs et al. 1997). Using new regression models, Heinrichs et al. (2001) found that there is no “best” model for chironomid salinity inferences and that the palaeoecologist must compare results among different models.

Chironomid research has paralleled diatom analysis. Diatoms, like chironomids, are important palaeolimnological and palaeoclimatic tools capable of reconstructing temperature and salinity (e.g. Cumming and Smol 1993; Heinrichs et al. 1997). Temperature reconstructions from both proxies are not often performed on the same lake, and further investigation would clarify relationships between temperature, chironomids and diatoms.

In addition to palaeotemperature and palaeosalinity studies, chironomids have been used to estimate changes in hypolimnetic anoxia (Clerk et al. 2000). Assemblages allow inferences of oxygen level changes through indicator species groups, such as *Chironomus* and *Procladius*. Higher oxygen levels are indicated by the presence and increased abundances of genera such as *Protanytus*, *Heterotrissocladius*, and *Micropsectra* type. Although it is known that oxygen solubility in water is strongly related to temperature, it is not known which factor most influences assemblage composition. Current research into chironomid and oxygen relationships are being explored using live larvae and respiration chambers (Brodersen et al. 2004). Larvae respond to changing oxygen concentrations in two ways: as oxy-regulators or oxy-conformers. At low oxygen conditions in warm lakes, oxy-regulators are able to maintain high respiration rates, whereas oxy-conformers are unable to regulate respiration rates and must depend on higher levels of dissolved oxygen already present in cold waters.

Chironomid palaeoecology is also used to acquire information on biodiversity through habitat changes. For instance, Rück et al. (1998) discovered a chironomid genus (*Robackia*) which had never before been found in British Columbia. This genus is indicative of large warm rivers and its fossils could be used to identify such environments in the past.
The rise and fall in the surface level of closed basin lakes can indicate P-E balance changes (Abbott et al. 2000; Edwards et al. 2001). Past lake-level fluctuations have been inferred using a variety of biological indicators and sedimentary evidence (Abbott et al. 2000; Hofmann 1998), for instance, profundal to littoral ratios of chironomids, and planktonic to benthic ratios for cladocera and diatoms (Hofmann 1998). Diatom-based transfer function models have successfully inferred palaeolake-levels (Moser et al. 2000). Certain chironomid species or species groups are sensitive to lake depth, perhaps due to O₂ levels or substrate differences, rather than temperature. Whatever its cause, this change is registered in assemblages and identifiable in transfer functions.

The ecologies and distributions of many North American chironomids are not completely known. Temperature and oxygen preferences for species in other parts of the world have been estimated, e.g. the Po River, Italy (Rossaro 1991). Chironomids live in distinct niches within lake sediments, some preferring the littoral and sub-littoral zones, and others the cooler profundal zones of deep lakes. Typically, chironomids with high anoxic tolerances are from tribe Chironomini, while those with lower tolerances belong to subfamily Orthocladiinae. It may be that chironomids are directly sensitive to oxygen levels and indirectly sensitive to temperature due to complex ecosystem dynamics, such as temperatures effects on O₂ solubility in water (Battarbee 2000; Brodersen et al. 2004).

Midge-inferred palaeoreconstruction is a rapidly growing field. New models for inferring such environmental variables as anoxia, total phosphorus and chlorophyll a have been developed (Brodersen and Lindegaard 1999). The geographic extent of such studies is rapidly expanding, now extending to Alaska, Yukon and the Canadian high Arctic (Barley 2004; Walker 2001).

The Climate and Environment of Interior Alaska

Interior Alaska was a special place during the Quaternary glaciations. Its large ice-free areas served as refugia for plants and animals. Eastern Beringia ( "Beringia" of Hultén (1937))
was also important in the migration of humans and other large mammals between Eurasia and North America. In particular, human dispersal patterns into North America may be strongly linked to climate, thus information on temperature and precipitation changes may expand our understanding of these migrations.

The Tanana Valley follows the Tanana River northwestward from the Alaskan Range to Fairbanks, Alaska (see Figure 1.1 for location of sites and lakes). Although the Tanana Valley was unglaciated during the last glacial maximum (LGM), its proximity to the glaciers of the Alaska Range affected its climate, which was perhaps more dry and cool. Elevation in the Tanana Valley ranges from $<300$ to $900$ m (Bigelow and Edwards 2001).

The Nenana Valley lies west of the Tanana Valley and has a similar northwest-southeast orientation, extending from the Alaskan Range at the border of Denali National Park to the Yukon River. Like the Tanana Valley, the Nenana was unglaciated during the LGM serving as a biological refugium. The headwaters of the Nenana River begin in the Alaska Range and flow northwestward to the city of Nenana (Bigelow and Edwards 2001). Elevation in the Nenana Valley ranges from $<300$ to $900$ m.

The Late Pleistocene

The Late Pleistocene in interior Alaska was an important time for humans and other organisms. Two archaeological sites in the Tanana Valley—Dry Creek and Healy Lake Village—have radiocarbon dates suggesting human occupation as early as $11 000$ $^{14}$C yr BP (Ager 1975). Pollen evidence indicates a shift from steppe-tundra to shrub-tundra at $\sim14 000$ $^{14}$C yr BP (Ager 1975; Ager 1983). The Late Pleistocene is characterized in pollen records as a cold and dry herb zone ($14 000$ to $12 000$ $^{14}$C yr BP) followed by a birch zone between $12 000$ and $10 000$ $^{14}$C yr BP (Edwards et al. 2001). Palaeo-lake levels and pollen evidence indicate warming at $12 000$ $^{14}$C yr BP, but conditions were still cool and dry in this birch shrub zone.
The Younger Dryas

The Younger Dryas (YD), named for a cold-loving herb, *Dryas octopetala*, is a cold reversal occurring just before the Pleistocene-Holocene transition. The YD occurred between 11 000 and 10 000 $^{14}$C yr BP. Radiocarbon dating of Late Pleistocene sediments is, however, complicated by radiocarbon plateaux within the YD. This cooling, often identified by a light-coloured silty layer in lake sediments, has been reported globally. Originally thought to be a European climatic event, it has been reported from Greenland, Atlantic North America, Pacific North America, interior North America, southwestern Alaska, South America and New Zealand (Bigelow and Edwards 2001; Briner et al. 2002; Engstrom et al. 1990; Hansen and Engstrom 1996; Kuhry et al. 1993; Mathewes 1993; Mathewes et al. 1993; Mayle et al. 1993; Peteet 1995; Walker et al. 1991a).

The mechanism behind the YD cooling is perhaps linked to either oceanic circulation changes or solar variability (Broecker 2003). The most likely cause is a collapse of thermohaline circulation in the North Atlantic Ocean. There is evidence for a massive influx of freshwater into the Atlantic from proglacial Lake Agassiz prior to the YD (Teller et al. 2002). Such outburst floods occurred before three major cooling events in the past 11 000 $^{14}$C years: YD, Pre-Boreal Oscillation (PBO) event (~9900 to 9700 $^{14}$C yr BP), and the 8200 cal yr cooling event (7700 to 7200 $^{14}$C yr BP) (Teller et al. 2002). The retreat of the Laurentide Ice Sheet allowed floods from Lake Agassiz to drain enormous amounts (9500 km$^3$) of freshwater into the North Atlantic Ocean. Since freshwater is less dense than saltwater, this decreased the ocean’s surface density, and thereby halted formation of North Atlantic Deep Water (Broecker 2003; Stocker and Marchal 2000). Others suggest that the influx of meltwater instead caused the North Atlantic Deep Water to form at an intermediate ocean depth in a warmer shallower mode (Lehman and Keigwin 1992; Rahmstorf 1994).

A second theory suggests that solar variability may have affected thermohaline circulation (Bond et al. 2001). Together these two influences may have induced the cooler YD temperatures. Heiri et al. (2004) compared a number of proxy reconstructions (chironomids, pollen) with $^{10}$Be (10 Beryllium), ice-rafted debris and Laurentide ice sheet datasets from the European Alps. Midge and pollen temperature reconstructions align best with the meltwater flux
data, suggesting that freshwater additions to the Atlantic influenced thermohaline circulation, in turn influencing climate.

Researchers record a glacial advance of Mount Waskey in the Ahklun Mountains, southwestern Alaska, interpreted as cooling during the YD (Briner et al. 2002). Eleven ages calculated using $^{10}\text{Be}$ and $^{26}\text{Al}$ cosmogenic exposure techniques and one radiocarbon date from a lake sediment core constrain the timing between $\sim 10\,800$ and $9700\,^{14}\text{C}$ yr BP. The YD is also reported from Pleasant Island, Glacier Bay, southeastern Alaska through fossil pollen data (Engstrom et al. 1990; Hansen and Engstrom 1996). Lodgepole pine parkland was replaced by shrub and herb tundra around $10\,800$ to $9800\,^{14}\text{C}$ yr BP, strongly suggesting a cold reversal.

The Younger Dryas has also been reported on the nearby British Columbia coast, where pollen and foraminifera indicate cooling between $11\,000$ and $10\,200\,^{14}\text{C}$ yr BP (Mathewes et al. 1993). Cold-water foraminifera indicators peaked between $11\,070$ and $10\,170\,^{14}\text{C}$ yr BP. In addition, pollen spectra from many sources show peaks in mountain hemlock abundance, a cold wet indicator, around the Pleistocene—Holocene transition. Mathewes (1993) reviews palynological records which indicate cooling between $10\,700$ and $10\,000\,^{14}\text{C}$ yr BP.

The Holocene

Palynological studies indicate that the early to mid-Holocene was likely warm and dry, as Edwards et al. (2001) inferred from an increase in Populus pollen. Temperatures continued to warm as Picea glauca pollen increased at $8500\,^{14}\text{C}$ yr BP. At $7500\,^{14}\text{C}$ yr BP, conditions became moister, as indicated by the expansion of Alnus, and by lake-levels inferred near modern levels due to increased precipitation. Ager (1975; 1983) records the appearance of Alnus at $\sim 8400\,^{14}\text{C}$ yr BP at both Birch and Hardy Lakes in the Tanana Valley. Climate begins to cool slightly at $6000\,^{14}\text{C}$ yr BP until present, as indicated by increasing Picea mariana (Edwards et al. 2001). Between $8000$ and $6000\,^{14}\text{C}$ yr BP, declining Picea pollen is thought to indicate warmer and drier climate (the Hypsithermal interval – Holocene warming) (Ager 1975; Ager 1983).
palaeobotanical consensus indicates a warm and dry early to mid-Holocene, but independent data from other proxies (e.g. midges) is needed to solidify this claim.

Modern Alaskan climate is continental in its interior, with warm summers and long harsh winters. Average mean July temperatures range from 11 to 23°C, while winters are much colder with mean January temperatures at ~ -22°C (Ager 1983). In Fairbanks, Alaska, there has been an increase of annual air temperatures of about 1.2°C in the past 100 years (Alaska Climate Research Center 1999). This change is mostly indicative of summer change, not winter temperature increase. The Alaskan Range in the south prevents moist Pacific air masses from reaching interior Alaska; thus, mean annual precipitation is low, e.g. 276 mm at Fairbanks (1961-1990 mean) (Muhs et al. 2001). In the Tanana Valley mean temperatures range from -20°C in January to 23°C in July (Carlson and Finney 2004). Climate in the Nenana Valley is similar to that in the Tanana. Mean summer temperatures of 11 °C and mean winter temperatures of -17 °C have been recorded at Denali National Park, with annual precipitation around 370 mm/year (Bigelow and Edwards 2001).

Vegetation in the Tanana Valley consists mainly of boreal forest: white spruce (Picea glauca), black spruce (Picea mariana), balsam poplar (Populus balsamifera), paper birch (Betula papyrifera), quaking aspen (Populus tremuloides) and tamarack (Larix laricina) (Ager 1983). Birch forests in the interior Tanana Flats west of the Tanana Valley have been succeeded by bogs as climatic warming decreases the percentage of permafrost (Jorgenson et al. 2001). Since the mid-18th century approximately 47% of the permafrost has been degraded, causing soil settlement of 1 to 2.5 m and subsequent colonization by aquatic plants and organic mats. Currently, 35% of birch forest has been lost to bog and fen formation. It is estimated, based on current warming trends, that all lowland birch forests will be eradicated within 100 years (Jorgenson et al. 2001).

The Nenana Valley vegetation is also largely comprised of boreal forest. Dominant tree species include black and white spruce (Picea mariana and P. glauca), paper birch (Betula papyrifera), balsam poplar (Populus balsamifera), quaking aspen (P. tremuloides) and tamarack (Larix laricina). Surrounding floodplains are commonly covered by shrub willow (Salix spp.) and other ruderal or pioneering herb plants.
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Figure 1.1  Map of Alaska, indicating locations mentioned in the text: BL – Birch Lake, DL – Dune Lake, GL – Grandfather Lake, JL – Jan Lake, SL – Sands of Time Lake, WL – Windmill Lake, WN – Wien Lake, AP – Antifreeze Pond, Yukon. Shaded arrows indicate location and flow direction of the Nenana (left) and Tanana (right) Rivers.
Chapter 2  Midge-Inferred Climatic Oscillations Recorded from Birch Lake, Tanana Valley, Interior Alaska

Abstract

Midge fossils are used to reconstruct 12 500 radiocarbon years of climatic history at Birch Lake, Alaska, including palaeotemperatures and palaeolake-levels. Temperature reconstructions indicate the presence of a cold period dated at 10 600 to 9700 $^{14}$C yr BP potentially representing the Younger Dryas. Midge-inferred temperatures indicate two other cold periods (12 300 to 11 200, and 8500 to 7700 $^{14}$C yr BP) distinguished by Heterotrissocladius, Paracladius and Parakieferiella nigra communities, as well as high numbers of Micropsectra atrofasciata/radialis type. Cold periods were separated by warm episodes at 11 200 to 10 600 $^{14}$C yr BP and 9500 to 8500 $^{14}$C yr BP, dominated by Chironomus and Pentaneurini, and including increasing numbers of “warm” indicator species. Midge reconstructions indicate oscillating lake levels with three high water periods peaking at ~12 000, 10 400 and 8000 $^{14}$C yr BP.

Introduction

The looming effects of global climatic change have pressed us towards improvements in our knowledge of past climatic conditions. The use of a number of sedimentological and biological climatic proxies has produced scenarios of palaeotemperatures, palaeolake-levels, pH and alkalinity changes, and vegetation patterns. These reconstructions rely on many biological indicators, such as chironomids, diatoms, pollen, crustaceans, molluscs, and other invertebrates.
In recent years, chironomids (Diptera, Chironomidae) have been recognised as the most promising tool for palaeotemperature reconstructions (Battarbee 2000).

Interior Alaska is an area of great interest to palaeoecologists and archaeologists. Its proximity to the glaciated Alaska Range, and its unglaciated status during the Last Glacial Maximum created refugia for plants and animals. Interior Alaska is also home to many early human settlements—for example, Dry Creek and Healy Lake Village sites in the Nenana and Tanana Valleys, respectively, have radiocarbon dates suggesting human occupation as early as 11 000 $^{14}$C yr BP (Ager 1975; Yesner 2001). Mason et al. (2001) suggest that the Dry Creek Denali complex may be the important type site for the Nenana Valley and potentially Alaska. Artifacts, dating from 12 000 to 9000 years old, have been found in the Dry Creek loess beds, followed by a possible unoccupied period and subsequent reoccupations between 4700 and 3400 $^{14}$C yr BP (Thorson and Hamilton 1977). Human occupations (Denali) tended to follow lake or river edges (Mason et al. 2001), thus the Tanana and Nenana River Valleys were likely important sites for human occupation in Alaska. Reconstructions of past climatic conditions, especially temperature patterns, may thus help us understand early human migrations and settlement.

The interval between 12 000 and 10 000 $^{14}$C yr BP was a period of dramatic changes in Alaska. A number of biological and glacial records indicate the possible effect of the Younger Dryas (YD) cold event in northwestern, southwestern, southeastern and coastal Alaska (Briner et al. 2002; Elias 2000; Engstrom et al. 1990; Hansen and Engstrom 1996; Hu et al. 2002; Hu et al. 1995; Peteet and Mann 1994). Interior Alaska, bounded in the north by the Brooks Range and in the south by the Alaska Range, contains few records suggesting this cooling, (e.g. Bigelow and Edwards 2001). The Broken Mammoth site in the Tanana Valley indicates a “culturally sterile” hiatus, lacking artifactual and faunal remains, from 11 000 to 10 500 $^{14}$C yr BP between Cultural Zone 3 (large ungulates) and Cultural Zone 4 (birds and mammals) (Yesner 2001). Bigelow et al. (1990) note another hiatus at Dry Creek site, in the neighbouring Nenana Valley. The hiatus coincides with increased wind intensity at approximately 11 100 to 10 700 $^{14}$C yr BP.

Precipitation and evaporation balances have been reconstructed for a number of interior Alaskan lakes (Barber and Finney 2000; Bigelow and Edwards 2001). For example, Barber & Finney (2000) used sedimentological techniques to infer lake depths at Birch and Jan Lakes over
the last 12 500 $^{14}$C years. Multi-proxy lake-depth reconstructions at Marcella Lake were used to determine changes in effective moisture in southwestern Yukon Territory (effective moisture influences lake levels through control of water-tables) (Anderson et al. 2005). Lake level changes were also studied at Birch, Dune, Jan and Sands of Time Lakes (Edwards et al. 2001).

Lake level fluctuations are often inferred from core transects (Digerfeldt 1986). Single deep-water core investigations have produced mostly qualitative inferences, while transect coring results yield a more quantitative analysis (Abbott et al. 2000). In addition to sedimentological analysis, pollen and macrofossils are often used to infer palaeo-lake levels (Edwards et al. 2000).

Barley et al. (in press) have developed midge-temperature and midge-lake depth transfer functions for northwestern North America and eastern Beringia. The Beringian training set, first used at Antifreeze Pond, Yukon (Barley 2004), is used in this study to reconstruct past temperatures and lake level changes at Birch Lake for the past 12 500 $^{14}$C years. Furthermore, this study attempts to critically assess the ability of the Beringian transfer function to reliably reconstruct lake depths. If accurate palaeolake-level reconstructions are possible, midge fossils will provide important proxy evidence of past changes in precipitation - evaporation balance. The ability to use a single downcore proxy for both temperature and lake level reconstructions would simplify palaeohydrological studies.

**Birch Lake, Tanana Valley**

Birch Lake belongs to a chain of lakes in the Tanana and the parallel Nenana Valleys (see Figure 2.1 for location of Birch Lake and other sites mentioned throughout the chapter). Located 77 km southeast of Fairbanks, Alaska along the boundary between the Tanana Lowland and the Yukon-Tanana Upland, Birch Lake (64°18'N, 146°40'W; 275 m elevation) has a surface area of 3.01 km$^2$ and a drainage basin of 37.0 km$^2$ (Barber and Finney 2000). It comprises two basins with maximum depths of 12 m (north basin) and 14 m (south basin).
Birch Lake is surrounded by Birch Creek Schist (Precambrian?) and granitic bedrock on all sides, except the west. Quaternary eolian sediments and colluvium mantle the bedrock on the adjacent southern Yukon-Tanana Upland. Late Pleistocene sand and gravel outwash from the Tanana River dams the western edge of the lake; thus, Birch Lake was likely created approximately 14 000 $^{14}$C yr BP by aggradation of the Tanana River (Ager 1975). The Alaska Department of Fish and Game has blocked the outlet with a concrete weir (Barber and Finney 2000).

Mean annual temperature at Birch Lake is -3.44°C in a region of discontinuous permafrost with mean annual precipitation of 328 mm (Barber and Finney 2000). Mean air temperature is 15.1°C in July and -22.5°C in January (New et al. 2002). Extreme temperatures in the Tanana Valley range from -45°C to summer temperatures of 32°C (Ager 1975; Carlson and Finney 2004). The vegetation around Birch Lake consists mainly of boreal forest with white spruce ($Picea glauca$), black spruce ($P. mariana$), balsam poplar ($Populus balsamifera$), paper birch ($Betula papyrifera$), quaking aspen ($Populus tremuloides$) and tamarack ($Larix laricina$) (Ager 1983). Ground cover is mainly $Equisetum$, mosses and heaths (Ager 1975).

Many archaeological sites have been uncovered and dated on the Tanana River, with two sites close to Birch Lake (Broken Mammoth and Mead sites 25 to 30 km east of Birch Lake) (Bigelow and Powers 2001). It has been assumed that Late Pleistocene climatic fluctuations did not greatly affect human migration in the Tanana Valley (Bigelow and Powers 2001).

**Methods**

*Midge Analysis*

Birch Lake core 97b was obtained from a depth of 12.9 m in the south basin in 1997 by researchers from the University of Alaska and the University of Illinois using a Livingstone corer (Finney pers. comm.). The 7.16 m core was shared among researchers for a variety of
investigations, including sedimentology, palynology, ostracod isotope analysis and midge analysis.

For my research, 121 intervals representing the top 6.0 m of the core were analysed. As measured from the lake surface, the intervals begin at 1290 cm depth (surface sample) and end at 1898 cm. The two uppermost intervals, 1290 and 1300 cm, were the only ones so widely spaced. Sediment samples between 1300 and 1697 cm were spaced 3 cm apart. All subsequent intervals were spaced at 4 cm.

Each sample was prepared following Walker (2001). Samples were deflocculated in 5% KOH on low heat until steam appeared within the beaker. They were then washed on a 95 μm mesh sieve with reverse osmosis water with gentle teasing apart of the particles with a flat metal stir stick. Carbonates were removed using 5% HCl on low heat. Although there was no reaction, all samples underwent the carbonate removal process for consistency. Samples were again washed on the 95 μm mesh sieve with reverse osmosis water and returned to the beaker for picking.

Chironomid head capsule picking was done on Bogorov counting trays under dissecting microscopes at 25 to 50X magnification. The samples were diluted with water, and the entire sample counted in order to eliminate picking size bias. Head capsules were transferred to coverslips with a maximum of 30 heads per cover slip. The glass slips were then air dried and mounted with Entellan® onto microscope slides, and dried for 3-5 days. Remains of all midge families were picked from the samples, as well as those of black flies (Simuliidae), water mites (Acari), mayflies (Ephemeroptera), and any other distinguishable insect head capsule or mandible. Minimum head counts of 40 to 50 are suggested, particularly for samples displaying a "typical" diversity, and was the target for each sample (Heiri et al. 2003; Quinlan and Smol 2001).

Identification was performed on an Olympus BX51 compound microscope at 200X and 400X total magnifications using modern larval keys from Wiederholm (1983) and Oliver and Roussell (1983) and fossil guides of Walker (1996; 1988) and Uutala (1990). Laboratory photographs were available for reference at the Palaeo-Lab at the University of British Columbia.
– Okanagan. Fossil head capsules were identified by variations in menta, ventromental plates, antennal pedestals, antennal spurs, premandibles and mandibles. Some chironomids of the tribe Pentaneurini and subtribe Tanytarsina were only identified to this level, but most fossil heads were divided into genus groups, with a few having sufficient characteristics to place them into species groups. Occasionally chironomid head capsules split longitudinally, resulting in two mirror image halves. This split is most often observed in the mentum with each visible half entered into the data as a half count.

Photographs of all type specimens and mystery midges were taken using a DMX 12000 digital camera mounted to an Eclipse 800 compound microscope (Nikon, Melville, New York, USA). Images were compared with midges from the Beringia training set (Barley, pers. comm.). Photographs of each type specimen are included in Appendix A as a record of the taxonomy used and to facilitate taxonomic standardisation.

**Radiocarbon Chronology**

Birch Lake was initially dated by Ager (1975) using bulk sediments and was estimated to be more than 15 000^{14}C years old. Abbott et al. (2000) redated the lake when it was cored for sedimentological work; thus, Birch Lake is now thought to be at least 1000^{14}C years younger (Ager 1975). Here, to be consistent with palynological work being published on the same core, I adopt the chronology developed by Finney and Bigelow (pers. comm.). The following is a synopsis of their procedure.

Since core 97b was not directly dated, this core’s chronology was developed via correlation to adjacent core G/H. Eight AMS^{14}C dates (Table 2.1) were obtained from macrofossils and *Picea* pollen in core G/H and calibrated with CALIB rev. 5.0.2 (Stuiver and Reimer 1993; Stuiver et al. 2005). An age-depth model was developed for core G/H using these dates and a combination of linear (for top half of core) and 3rd order polynomial (bottom half) regressions. Ages for each level in core G/H were calculated from this model.

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Dates for levels in core 97b (the core used in my analysis) are inferred by correlation to core G/H (the core dated). Correlation was based on eight tie points, five peaks and one dip in magnetic susceptibility, one LOI rise and the birch rise (Table 2.2; Figure 2.2). Linear interpolation of depths facilitated correlation between tie points (Figure 2.3). The resulting Birch Lake (core 97b) chronology is shown in Figure 2.4.

Data Analysis

Midge fossil data were analysed using multivariate regression and calibration techniques in the program C2 version 1.4 Beta (build 33) (Juggins 2005) and the Beringian midge transfer function (Barley et al. in press; Barley 2004; New et al. 2002). This transfer function was developed using surface samples from 136 British Columbian, Yukon, Alaskan, and Canadian Arctic lakes. Temperature and lake-level reconstructions were made on 121 core intervals from Birch Lake using weighted averaging partial least squares (WAPLS), cross validation using 1000 bootstraps and square-root transformed species counts. All samples were included in the stratigraphies (Figures 2.5 to 2.7) and in the dataset used for temperature and lake level reconstructions.

Midge biostratigraphic diagrams were created using relative abundances of total identifiable midges. Biostratigraphic zones were identified using CONISS (constrained incremental sum of squares cluster analysis) as implemented in Zone version 1.2 (Juggins 1991) (Figure 2.7). A Shannon Diversity Index was calculated for all intervals using PC-ORD, version 4 (McCune and Mefford 1999; Shannon 1948). Results are represented in Figure 2.8B.
Results

Zone B-1 (1898 – 1811 cm; prior to 11 400 $^{14}$C yr BP)

Zone B-1 is constrained to a short period of time, representing only 1000 to 1500 $^{14}$C years. Although the age-depth model suggests a basal age of 12 400 $^{14}$C yr BP, the basal AMS radiocarbon date in core G/H indicates an earlier date, 12 780 ± 60 $^{14}$C yr BP at 1834.3 cm (Table 2.1).

The earliest midge assemblage is dominated by *Chironomus*, Pentaneurini, *Corynocera oliveri* type and other Tanytarsina, each representing over 20% of the identified community (Figures 2.5 to 2.7). Less common (<5% each) are *Cladopelma*, *Corynoneural*/*Thienemanniella*, *Psectrocladius* (subgenus *Psectrocladius*), *Paracladius*, *Parakieferiella nigra*, *Procladius* and *Limnophyes*.

A large increase in the number of chironomid species occurs midway in this zone. Warm indicators, such as *Stempellinella/Zavrelia*, *Dicrotendipes* and *Cladopelma*, begin to make small contributions (<5%) to the midge assemblage. Also present in small numbers are *Cricotopus/Orthocladius*, *Parakieferiella* sp. B type, and *Protacladius*. A decline to very low values in *Chironomus*, Pentaneurini and *Corynocera oliveri* type occurs. Cold-loving *Micropsectra atrofasciata/radialis* type numbers increase sharply to 55% of the community and remain high (+33%) until zone B-2. Three other cold indicators (*Heterotrissocladius*, *Paracladius* and *Parakieferiella nigra*) appear in significant numbers (between 15 to 20%) at 1858 cm. *Heterotrissocladius* disappears completely at 1813 cm, while *P. nigra* declines slightly. Coincident with this cold *Heterotrissocladius*-community is the first significant appearance of *Sergentia* (5% relative abundance) which declines with *Heterotrissocladius* at 1813 cm.

Reconstructed mean July air temperature is $-12^\circ$C, slightly lower than modern, falling to $10^\circ$C at 12 200 $^{14}$C yr BP (Figure 2.8). Temperatures drop to $-9.5^\circ$C at 11 750 $^{14}$C yr BP. Midge-inferred cold periods are also periods of low midge diversity as seen in Figure 2.8. Midge-inferred lake levels are low (~6 m) rising sharply to 13 m by 11 400 $^{14}$C yr BP (Figure 2.9). Mean sample errors for both temperature and lake-level reconstructions are shown in Figure
2.10. Modern analogue testing using squared chord distance revealed that most samples had good or adequate analogues, but there were some no-analogue assemblages as compared to the Beringian training set (Figure 2.11).

Zone B-2 (1811 – 1673 cm; 11 400 – 8600 $^{14}$C yr BP)

Zone B-2 is characterized by a large increase in Chironomus percentages which recover to ~40% by 1760 cm and remain high until zone B-3. Pentaneurini species and C. oliveri type recover to >10% and >15%, respectively, then declining to <3% by the end of the zone. Parachironomus and warm indicators, Polypedilum, Endochironomus and Cryptochironomus increase in low percentages (<5%) at ~1788 cm. Micropsectra atrofasciata/radialis type numbers remain high (+33%) until ~1798 cm. Paracladius peaks at 1808 cm at >25% of the midge community and Sergentia percentages remain negligible.

The midsection of zone B-2 exhibits an increase in four cold-stenothermous midges. Parakiefferiella nigra (>30%) and Paracladius (10%) rise for two brief periods (1748 and 1728 cm), with similar peaks of Micropsectra atrofasciata/radialis type bracketing them at 1753 cm and 1713 cm. Both P. nigra and Paracladius almost disappear from the Birch Lake record after this time. Corynocera oliveri type numbers rise to ~18% at this time and begin to decline to less than 5%. Sergentia increases in abundance to ~15% by the end of the zone.

Another increase in the number of species occurs just after 1708 cm. Parakiefferiella triquetra type arrives at Birch Lake with a 9% abundance, while Glyptotendipes, Microtendipes, Cyphomella/Harnischia/Paracladopelma, Ceratopogonidae and Pseudochironomus arrive at <5% abundances. Endochironomus reappears (12%) at this time, as well. Cladotanytarsus mancus type, Dicrotendipes and Psectrocladius (subgenus Psectrocladius) peak (~6 to 17%) between 1703 cm and 1670 cm.
Temperatures abruptly increase to 13°C until 10 700 $^{14}$C yr BP and fall by ~2°C from 10 600 to 9700 $^{14}$C yr BP (Figure 2.8). Temperature warms at 9700 $^{14}$C yr BP to 13°C. Warm conditions persist for the period until 8600 $^{14}$C yr BP. Midge diversities again match inferred temperatures, decreasing and increasing simultaneously. Lake levels rise again (to 7 m) from 10 600 to 10 000 $^{14}$C yr BP, then return to ~5 m for the remainder of the zone (Figure 2.9). Many samples had weak or no analogues (Figure 2.11).

**Zone B-3 (1673 – 1608 cm; 8600 – 6900 $^{14}$C yr BP)**

Midge counts were low (mainly between 15 and 45 per sample) throughout zone B-3. Tanytarsina percentages are at their lowest in zone B-3 (<10%), while *Chironomus* is at its highest (up to 55%). *Sergentia* also peaks to 54% at the beginning of the zone, declining to a stable population of ~15% throughout the Holocene. Pentaneurini, *Corynocera oliveri* type and *Micropsectra atrofasciata/radialis* type numbers remain between 5 and 15%. *Doithrix/Pseudorthocladius* type appears once in low abundance (<4%) at 1636 cm. At this time, *Heterotrissocladius* reappears, increasing to compose 11% of the midge community.

A gap in the presence of a number of species occurs in zone B-3. These include *Cladopelma, Psectrocladius (Psectrocladius), Corynoneural/Thienemanniella, Stempellinella/Zavrelia, Cyphomella/Harnischia/Paracladopelma, Ceratopogonidae, Parakieferiella triqueta* type, *Cladotanytarsus mancus* type and *Pseudochironomus*.

Inferred temperatures drop to ~11°C at 8500 $^{14}$C yr BP and return to 12°C at 7700 $^{14}$C yr BP (Figure 2.8). Midge diversities were at their lowest throughout the zone and remained low even when inferred temperatures returned to modern. Inferred lake depths increased from 5 to 10 m at 8000 $^{14}$C yr BP, remaining high until B-4 (Figure 2.9). Most samples had no or weak analogues (Figure 2.11).
Zone B-4 (1608 – 1290 cm; 6900 $^{14}$C yr BP to present)

Zone B-4 encompasses the past 6900 $^{14}$C years at Birch Lake. *Chironomus* numbers drop to 10 to 20%, and *Tanytarsina* numbers increase to ~20%. Semi-terrestrial chironomids *Doithrix/Pseudorthocladius* type and *Limnophyes* occur consistently and *Pseudosmittia/Smittia* reappear occasionally in this zone. *Micropsectra atrofasciata/radialis* type numbers remain below 10% throughout zone B-4, except for a brief interval at 1481 cm where it peaks over 17%.

Eight more chironomid species appear at very low percentages (1-6%) during this latter part of the Holocene. *Pagastiella, Paralauterborniella, Corynocera ambigua* and *Stempellina* arrive at Birch Lake in low numbers at the beginning of zone B-4. *Nanocladius* appears at 1566 cm, *Psectrocladius* cf. *septentrionalis* at 1516 cm, *Stictochironomus* shortly thereafter and, finally, *Parametriocnemus/Paraphaenocladius*’ sole appearance, almost 6%, at 1446 cm.

Reconstructed temperatures hover around 13°C for the remainder of the Holocene (Figure 2.8). The inferred modern temperature is 13°C. Midge diversities reached modern values at 6500 $^{14}$C yr BP. Lake depth decreases for the 3rd time to 5 m until 5000 $^{14}$C yr BP, and then increases to 8 m until the modern depth of 10 m is inferred (Figure 2.9). Most samples had weak or no analogues (Figure 2.11).

Discussion

The Birch Lake record provides the first midge-inferred mean July air temperature and maximum lake depth reconstructions for interior Alaska. Integration of these new data with evidence derived from earlier pollen and sediment studies allows details of past environmental conditions in the region to be better resolved, especially in relation to climate.
Radiocarbon Chronology

Dating late-glacial sediments is often difficult due to radiocarbon plateaux and the high variability of $^{14}$C in the atmosphere at that time (Goslar et al. 1999). Furthermore, because late-glacial sediments are often carbon poor, palaeoecologists must frequently cope with small radiocarbon samples, derived from bulk sediments or remains of aquatic organisms. At Birch Lake, an inversion is evident in the basal radiocarbon dates: $11\,420 \pm 120\, ^{14}$C yr BP (1758.5 cm), $12\,150 \pm 70\, ^{14}$C yr BP (1815 cm), $11\,840 \pm 100\, ^{14}$C yr BP (1842 cm) and $12\,780 \pm 60\, ^{14}$C yr BP (1864 cm) (Table 2.1). Three of the four intervals were dated using unidentified seeds and macrofossils; thus, the material may have an aquatic origin. They are potentially susceptible to the hardwater effect (uptake of older carbon) yielding older-than-expected dates. Abbott et al. (2000), however, state that the lack of limestone in Birch Lake’s watershed would make the $^{14}$C reservoir age effect insignificant.

Despite these difficulties, comparison of the Birch Lake pollen and LOI records with those from other interior Alaskan sites suggests that the Birch Lake chronology is fairly accurate. Aside from the date reversal in the lower half of the core, the radiocarbon dates follow in logical sequence. The age-depth model has a good fit to the available dates and loss on ignition (LOI) data from core G/H support the inferred timing of the Pleistocene—Holocene transition (Figures 2.2 and 2.4).

An earlier core places Birch Lake’s age at approximately 15 000 $^{14}$C yr BP, dated using bulk sediment (Ager 1975). Older-than-expected dates are more likely to arise when dating bulk sediments due to contamination from old organic or carbonate carbon. Midge data is, therefore, compared to pollen summaries of interior Alaska dated using AMS dating of organic materials (Edwards et al. 2001).
Climate and Vegetation

Midge-inferred temperature reconstructions at Birch Lake depict an oscillating pattern of cold to warm temperatures. In addition to an early Late Glacial cold interval, the record includes cold oscillations potentially corresponding with the Younger Dryas and an 9000 to 8000 $^{14}$C yr BP cold event (Figure 2.8A). Overlaying a lowess smoothed curve emphasizes this pattern. The Shannon Diversity Index reveals decreased diversity during each of these three cold periods (Figure 2.8B).

The Early Late-glacial

Birch Lake’s record began (pre-12 350 $^{14}$C yr BP) with a slightly cooler than modern climate as midge-inferred temperatures range between 11 and 13°C (Figure 2.8). Corynocera oliveri type peaked (40%) during this period. C. oliveri type is found in surface sediments of tundra lakes (Porinchu and Cwynar 2000) and usually only above 60°N in shallow lakes from cold regions (Barley 2004). Potentially confused morphologically, C. oliveri type and Tanytarsus lugens type are often taxonomically grouped together, representing cold and possibly oligotrophic conditions (Brooks and Birks 2000; Gandouin and Franquet 2002; Lotter et al. 1997).

The identification of fossil C. oliveri type is still problematic, due to similarities with Tanytarsus lugens type in the grouping and prominence of the three median teeth. Walker (1996) and Brooks (pers. comm.) differentiate T. lugens type by large surface teeth prominently placed in the mandible, but the mandibles are often dissociated from the head capsules. C. oliveri larvae were first described from a fossil specimen found in association with adult male hypopygia, and have yet to be reared to the pupal or adult stage (Hofmann 1984). Hofmann (1984) includes line drawings of the fossil head capsule, including mentum and mandible, largely matching with C. oliveri type specimens found in Birch Lake. Other characteristics, such as elongate antennal pedestals and a strong curvature to the mentum can help distinguish fossil C. oliveri type (Barley...
2004). Despite the taxonomic difficulties, their ecologies appear satisfactorily similar to infer cold tundra-like conditions.

Edwards et al. (2001) summarize independent pollen and lake-level data from four sites in interior Alaska—Birch, Dune, Jan and Sands of Time Lakes. Pre-12 000 \(^{14}\text{C}\) yr BP vegetation was an herb zone associated with a cold and dry palaeoclimate. Previous palynological studies at Birch Lake indicate a pre-14 000 \(^{14}\text{C}\) yr BP time period dominated by herbaceous plants and shrubs, such as *Artemisia* and *Salix* (Ager 1975). Bulk sediment dating indicates that this herb zone was replaced by *Betula* shrubs around 14 000 \(^{14}\text{C}\) yr BP (Ager 1975). Edwards et al. (2001) delineate interior Alaska’s vegetation history slightly differently, placing more importance on AMS dates which establish the herb-birch transition at 12 000 \(^{14}\text{C}\) yr BP (Abbott et al. 2000). The bulk sediment dates are likely

Pollen studies identify 12 000 to 10 000 \(^{14}\text{C}\) yr BP as the Birch zone, slightly warmer than the preceding herb zone, but still cool and dry (Edwards et al. 2001). The midge record at Birch Lake infers a more complicated climate during this period—a cold episode punctuated by warming, perhaps indicative of the slightly warmer, yet still cool environments inferred by increasing *Betula* pollen.

Between 11 900 and 11 200 \(^{14}\text{C}\) yr BP, midge-inferred temperatures decline by about 2°C. The midge community during these 700 years is strongly represented by cold-stenothermic chironomids: *Heterotrissocladius*, *Parakiefferiella nigra* and a particularly high percentage of *Paracladius* (25% peak). Analysing midge communities from Yukon and Northwest Territories, Walker et al. (2003) found *Paracladius* only from lakes located in arctic tundra environments. *Heterotrissocladius* and *P. nigra* were mainly found in arctic tundra lakes, but also occurred in alpine, forest-tundra and deep forest lakes. From 11 200 to 10 600 \(^{14}\text{C}\) yr BP, midge inferences indicate a warm interval, lagging 850 years after the appearance of *Betula* pollen in high abundances (60 to 70%) (Ager 1975; Edwards et al. 2001).
Cold conditions returned to the Tanana Valley from 10 600 to 9700 $^{14}$C yr BP. The change in temperature (a drop of 2 to 3°C) is largely influenced by a *Heterotrisocladius-Parakiefferiella nigra-Paracladius* community and a *Micropsectra atrofasciata/radialis* type peak. This cold episode broadly overlaps with the YD as dated in Europe (11 000 to 10 000 $^{14}$C yr BP) (Isarin and Bohncke 1999; Mangerud et al. 1974; Peteet 1995), and eastern North America (ca. 10 800 to 10 000 $^{14}$C yr BP) (Mayle et al. 1993; Walker et al. 1991). Despite radiocarbon dating uncertainties due to atmospheric $^{14}$C variability, this cold episode may demonstrate the Younger Dryas' existence in interior Alaska. Younger Dryas records from the north Pacific include a cold episode reported from Pleasant Island, Glacier Bay through pollen data between ~10 800 and 9800 $^{14}$C yr BP (Engstrom et al. 1990; Hansen and Engstrom 1996). A palynological record from Kodiak Island indicates a YD episode between 10 800 and 10 000 radiocarbon years ago (Peteet and Mann 1994). A reversal during this period, evident as a striking decrease in Polypodiaceae (fern) spores (the "Fern Gap") and increases in *Empetrum* and *Artemisia*, is a strong indication of cooling. At both Grandfather Lake and Ongivinuk Lake in the northern Bristol Bay region of southwestern Alaska, decreased *Betula* and increased *Artemisia* once again indicate YD cooling between 10 800 and 9800 $^{14}$C yr BP (Hu et al. 1995). Mathewes (1993) reviews palynological records from the Olympic Peninsula, Washington, which indicate a cold period between 10 700 and 10 000 $^{14}$C yr BP.

The Younger Dryas, however, is not clearly evident in midge-inferred temperatures from Antifreeze Pond, Yukon. Barley (2004) reports a more prolonged cold interval extending from 10 800 to 8500 $^{14}$C yr BP. This cold period at Antifreeze Pond was inferred largely by high (~18%) percentages of the midge *Zalutschia* type A, found in lakes from cold regions in the Beringia training set. A more complete investigation of the core segment may be necessary since only three temperatures were reconstructed between 10 500 and 9000 $^{14}$C yr BP. Finer resolution sampling might distinguish two periods of cooling.

Although no changes in the Birch Lake pollen record indicate YD-like episodes (*Betula* remains at 60 – 75% until 9200 $^{14}$C yr BP) (Ager 1975), pollen inferences from nearby Windmill Lake hint at the late Pleistocene cooling (Bigelow and Edwards 2001). At Windmill Lake in the
Nenana Valley a shift from birch to herb pollen (Artemisia and Poaceae) occurs between 10 500 and 10 200 $^{14}$C yr BP (Bigelow and Edwards 2001). The midge record at Birch Lake and the pollen record from Windmill Lake both indicate a delayed start to the YD as compared to the traditional timing of onset in eastern North America ca. 10 800 $^{14}$C yr BP (Mayle et al. 1993). Pollen records at other interior Alaskan lakes (Dune Lake, Sands of Time Lake, etc.) do not indicate cooling at this time (Edwards et al. 2001). Ager and Brubaker (1985), summarizing the pollen history for interior Alaska (Harding Lake, Tanana Valley and Eightmile Lake, Alaska Range (Ager 1983)), indicate a Populus-Salix zone (Populus, Salix, Gramineae and Cyperaceae community) at 11 500 to 9500 $^{14}$C yr BP not recorded in the Birch Lake pollen.

Bigelow & Edwards (2001) indicate that slow sedimentation rates record only long-lived changes in the vegetation and that changes in major pollen taxa can obscure changes in rare taxa. The midge signal at Birch Lake is strong and suggests finer scale climatic changes during this time period (10 600 to 9700 $^{14}$C yr BP) than the pollen records.

Despite the regional cause of the YD cooling (freshwater fluxes from glacial Lake Agassiz into the North Atlantic Ocean (Teller et al. 2002)), worldwide effects are being reported (e.g. Briner et al. 2002; Cole and Arundel 2005; Mathewes 1993) as reviewed by Peteet (1995). Thus, it is not unlikely that the midge signal at Birch Lake represents the YD.

The Early Holocene

The Early Holocene is represented by a spruce-birch (Picea-Betula) forest pollen assemblage—Ager zone 3A (10 000 to 9000 $^{14}$C yr BP) (Ager 1975). Midge-inferred mean July air temperatures in this period hover around 13°C, slightly cooler than modern. Climate cools slightly by about 1°C at 9000 $^{14}$C yr BP. At this time the spruce-birch forest was replaced by a shrub tundra (Picea-Alnus-Betula) pollen assemblage—Ager zone 3B, which continues to dominate the landscape.
Zone B-3 (in this paper) is delineated by low midge counts and diversity which may have lead to the cooler reconstructed temperatures from 8500 to 7700 $^{14}$C yr BP (Figures 2.5 to 2.8). First instar chironomids increase in the latter half of the zone. The decrease in midge numbers and diversity may be attributed to cooler climatic conditions, whereas high numbers of first instars may indicate meromictic conditions (Walker, pers. comm.).

At approximately 8400 $^{14}$C yr BP, *Alnus* expands to ~20% of the vegetation for the remainder of the Holocene, and *Picea* declines until ~6500 $^{14}$C yr BP (Ager 1975). AMS dates infer a later *Picea* decline at Birch Lake (~7000 to 6000 $^{14}$C yr BP) (Bigelow 1997) in (Carlson and Finney 2004). Although aligning well with the bulk sediment dates of Ager (1975), the midge-inferred cold period is likely too early (by ~1500 $^{14}$C years) to indicate cooling at the *Picea* decline. Other lakes in interior Alaska also indicate *Picea glauca* declines: nearby Jan Lake at ~6000 $^{14}$C yr BP (Carlson and Finney 2004), and Wien Lake at ~7500 $^{14}$C yr BP. Hu et al. (1993) have suggested that cold conditions were likely responsible for the *Picea* decline, but the Birch Lake midge data do not support this contention. The age of the midge-inferred cold episode ca. 8500 to 7700 $^{14}$C yr BP does not correspond closely with any well-known climatic event. It occurs after the Preboreal Oscillation (ca. 9900 to 9600 $^{14}$C yr BP) (Björck et al. 1997), and prior to the "8200 cal yr event" (ca. 7700 to 7200 $^{14}$C yr BP).

Human occupation of the Tanana River Valley by the Denali complex (defined by core and blade technology) peaked between ~8500 to 8000 cal yr BP (~7700 to 7000 $^{14}$C yr BP) (Mason et al. 2001). Mason et al. (2001) suggest that cold and arid conditions may have enhanced lichen growth providing better forage for caribou, an important food source for humans. Cold winters are often associated with reduced snow depth allowing caribou to travel and feed more easily. Although midge-inferred temperatures increase slightly at 7700 $^{14}$C yr BP, midge diversities remain low until 6500 $^{14}$C yr BP, suggesting slower amelioration of climate during this period.
Lake Levels

The feasibility of reconstructing lake depths via midge transfer functions has been discussed by a number of researchers (Hofmann 1998; Korhola et al. 2000; Walker 2001; Walker et al. 2003). The small natural fluctuations in most lakes' water levels may not be adequately recorded by midge communities. Walker et al. (2003) also discuss the difficulty in differentiating among midge community changes attributable to temperature versus lake level fluctuations. Walker (2001) suggests that lake depth reconstruction will only be feasible where water levels have increased or decreased by 3 to 4X (Walker 2001). Such changes are unlikely in many settings, but can occur in closed basin lakes.

Although the Beringian chironomid surface sample set was originally developed as a temperature reconstruction tool, maximum lake depth and mean July air temperature each explained 12% of the variance in the midge distributions (Barley 2004). So far this model has only been used to reconstruct lake levels at Antifreeze Pond, Yukon, a shallow (2 m deep) lake not thought to have undergone large water level fluctuations. Therefore such inferences were not made with utmost confidence (Barley, pers. comm.).

At Birch Lake extreme depth fluctuations over the past 12 700 $^{14}$C yr BP have been inferred from lithological analysis on multiple core transects across both basins, as well as sonic resonance sounding (Abbott et al. 2000). Twenty-two seismic reflection profiles were taken across Birch Lake. Trace acoustic stratigraphies were created and surfaces associated with past water level fluctuations were identified.

Abbott et al. (2000) found that Birch Lake was seasonally dry prior to 12 700 $^{14}$C yr BP. Lake depth then increased to 18 m until 11 600 $^{14}$C yr BP (Figure 2.9B). Midge-inferred lake depth reconstructions reproduce these results closely (Figure 2.9). Midge reconstructions indicate high water levels (~10 to 18 m deep) between 12 400 and 11 400 $^{14}$C yr BP. Inferred temperatures range between 9 and 12°C during this “wet” period. Pollen from Birch Lake indicates the pre-12 000 $^{14}$C yr BP climate as cold and very dry (Ager 1975; Edwards et al. 2001). Similar water level changes have been reported at Jan Lake, also in the Tanana Valley (Barber and Finney 2000).
The appearance of Sergentia between 12 400 and 11 400 \(^{14}\)C yr BP may be an ecological indication of rising water levels. Sergentia is typically designated as a cold indicator, but is more strongly associated with deepwaters in the eastern Beringian training set (Barley 2004). Some Sergentia species exhibit diel vertical migration, similar to that of Chaoborus trivittatus, (Oliver 1971).

Between 11 400 and 10 600 \(^{14}\)C yr BP, midge-inferred lake depths fall to 5 m. Sediment-inferred water levels dropped to 17 m below overflow level (BOL), and stayed between 14 and 17 m BOL from 11 600 to 10 600 \(^{14}\)C yr BP (Figure 2.9B) (Abbott et al. 2000). This is also the time when midges infer warming, suggesting a warm, arid period influenced by increased evaporation and decreased precipitation.

The second midge-inferred lake level rise (to 7 m) occurred from 10 600 until 10 200 \(^{14}\)C yr BP; sediment inferences indicate a rise at 10 500 \(^{14}\)C yr BP (Figure 2.9). Midge and sediment inferences indicate a subsequent (10 000 to 8500 \(^{14}\)C yr BP) lake level decrease. Sediment-inferred lake levels were at 6 to 9 m BOL, increasing for the 3\(^{rd}\) time somewhere between 8500 and 8000 \(^{14}\)C yr BP (Abbott et al. 2000). Midge inferences also indicate a rise at 8500 \(^{14}\)C yr BP.

The Sergentia increase in Birch Lake at 8400 \(^{14}\)C yr BP to almost 60% of identified midges may mark a significant point in Birch Lake's ontogeny. It continues to thrive at percentages between 15 and 34% throughout the rest of the Holocene. Midge-inferred temperatures are at a low (~10 to 11°C) at this time and lake depth reconstructions indicate higher lake levels, climbing to depths between 8 and 17 m, until 6700 \(^{14}\)C yr BP. From sedimentological studies, Birch Lake is surmised to have mostly remained in positive hydrologic balance (at overflow level), with the possibility of intermittent low lake stands, since about 8000 \(^{14}\)C yr BP (Abbott et al. 2000). The midge data largely concur with the sedimentological reconstruction, but infer low lake levels from 6500 to 5000 \(^{14}\)C yr BP.

Midge inferences range between 6 and 10 m deep over the past 900 years underestimating the modern 14 m depth of the south basin. The appearance of a number of terrestrial and semi-terrestrial chironomids (Doithrix/Pseudorthocladius type, Limnophyes and Smittia/Pseudosmittia) throughout the last 6700 \(^{14}\)C years may indicate fluctuating water depths.
These midges may have colonised the lake margins during low stands. Their presence may explain the lower than expected lake depth reconstructions. It has been suggested that terrestrial, semi-terrestrial and lotic chironomids be excluded from calibration sets, as they are “irrelevant taxa” when investigating lentic habitats (Schnell 2005). I emphasize that it is the trend in the reconstructed water levels that is significant. Large uncertainties are associated with individual depth inferences.

This first attempt at using midges to reconstruct past lake levels in Alaska indicates a good correspondence between the midge inferences and the sedimentological results. All three periods of deep water align with both proxies and water fluctuations are of similar magnitudes and durations.
Conclusions

The Birch Lake record affirms the presence in interior Alaska of large-scale climatic changes in the late Pleistocene. Midge-inferred temperatures support the claim for an Alaskan Younger Dryas event dating from \(\sim 10600 \text{ to } 9700 \text{^}{14C} \text{ yr BP}\). The next step at Birch Lake may be reaffirming these quantitative reconstructions with other proxies (e.g. diatoms). Although warm conditions persisted throughout most of the Holocene, an early Holocene cold event is also recorded from 8500 to 7700 \text{^}{14C} \text{ yr BP}: about 1500 \text{^}{14C} \text{ years before the } \textit{Picea glauca} \text{ decline in interior Alaska.}

I also propose the use of midge transfer functions as a proxy for reconstructing large water level fluctuations in deep lakes. Water level changes inferred via midge analyses and independent seismic reflection profiling and trace acoustic stratigraphies revealed similar lake level histories. The midge-inferred mean July air temperature and lake depth reconstructions serve to expand our knowledge of the climatic environment for interior Alaska, specifically the Tanana Valley. The Birch Lake record provides the first fossil midge reconstructions for interior Alaska. Midge proxy records appear to be a valuable supplement to palynological reconstructions in eastern Beringia.
References


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Teller J.T., Leverington D.W. and Mann J.D. 2002. Freshwater outbursts to the oceans from glacial Lake Agassiz and their role in climate change during the last deglaciation. Quaternary Science Reviews 21: 879-887.


Broken Mammoth & Mead sites

Figure 2.1 Map of Alaska, indicating Birch, Jan & Windmill Lakes and other locations mentioned in the text: BL – Birch Lake, DL – Dune Lake, GL – Grandfather Lake, JL – Jan Lake, SL – Sands of Time Lake, WL – Windmill Lake, WN – Wien Lake, AP – Antifreeze Pond, Yukon. Shaded arrows indicate location and flow direction of the Nenana (left) and Tanana (right) Rivers.
Figure 2.2  Loss on ignition curves (% at 500°C) for core 97b (A) and core G/H (B). Broken line in B between 1590 and 1640 cm represents overlap between cores G and H.
Figure 2.3 Linear interpolation of eight tie points (see Table 2.2) used for correlating Birch Lake cores 97b and G/H.
Figure 2.4 Birch Lake radiocarbon age-depth model developed for core 97b using correlation to core G/H (Finney, pers. comm.) (A). Loss on ignition curve for core 97b (B). Horizontal dashed line indicates Pleistocene-Holocene transition at 10,000 $^{14}$C yr BP inferred from LOI rise. Vertical dashed line indicates position of 10,000 $^{14}$C yr BP in the radiocarbon chronology.
Figure 2.5 Birch Lake midge stratigraphy (Part A) showing relative abundances (%) of identified midges. Five shades represent identified midge counts per interval: black = 50+, darkest grey = 40-49, grey = 30-39, light grey = 20-29, lightest grey = <20. Temperature optima for midge taxa from left to right are 11.0 to 12.3°C, as calculated using weighted averaging in Barley (2004).
Figure 2.6  Birch Lake midge stratigraphy (Part B) showing relative abundances (%) of identified midges. Five shades represent identified midge counts per interval: black = 50+, darkest grey = 40-49, grey = 30-39, light grey = 20-29, lightest grey = <20. Temperature optima for midge taxa from left to right are 12.4 to 12.8°C, as calculated using weighted averaging in Barley (2004).
Figure 2.7  Birch Lake stratigraphy (Part C) showing relative abundances (%) of identified midges (* no temperature optima available; ** calculated as % of all midges; *** raw counts/mL). Temperature optima for midge taxa from left to right (12.9 to 13.9°C) (Barley 2004). CONISS (constrained incremental sum of squares cluster analysis) calculated using Zone version 1.2 (Juggins 1991).
Figure 2.8 Birch Lake midge-inferred mean July air temperatures (A) and Shannon Diversity values (B). Thick lines are lowess smoothed curves. Grey bands indicate generally accepted dates for the Younger Dryas from 10 800 to 10 000 $^{14}$C yr BP and an early Late-Glacial from 12 250 to 11 150 $^{14}$C yr BP.
Figure 2.9 Birch Lake midge-inferred lake-level reconstruction (A) and sedimentological lake-level reconstruction (Abbott et al. 2000) (B). Grey bands in A indicate deep zones, 12 400 to 11 400 $^{14}$C yr BP, 10 600 to 10 200 $^{14}$C yr BP and 8350 to 6700 $^{14}$C yr BP. Thickness of black line in B indicates uncertainty. Sedimentological inferences in B are calculated as depths below overflow (overflow is at 0 m, at the basin top) and the lake is considered at its deepest water level when inferences approach 0 m.
Figure 2.10 Sample specific error bars for midge-inferred mean July air temperature (A) and lake level (B) reconstructions.
Figure 2.11 Results of analogue testing for Birch Lake with the Beringia training set. Vertical dashed lines indicate 75 and 95% confidence intervals at 13.7 and 17.8 squared chord distances, respectively. Intervals below 75% have good analogues; those greater than 95% are considered to have no analogues and those between are considered weak analogues.
Table 2.1 Birch Lake AMS radiocarbon dates from core G/H (Abbott et al. 2000; Finney pers. comm). Calibrated dates are 50% cumulative probabilities (Stuiver and Reimer 1993; Stuiver et al. 2005).

<table>
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<th>Source core</th>
<th>Depth below water surface in core G/H (cm)</th>
<th>Depth below sediment-water interface (cm)</th>
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<th>$^{14}$C yr BP ± 1 standard deviation</th>
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Table 2.2  Correlation tie points between cores G/H and 97b (ms = magnetic susceptibility; loi = loss-on-ignition).

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<th>97b depth (cm)</th>
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<td>loi rise</td>
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Chapter 3  Climatic Records from Windmill Lake, Nenana Valley and Jan Lake, Tanana Valley, Interior Alaska

Abstract

Jan Lake, Tanana Valley and Windmill Lake, Nenana Valley, interior Alaska were investigated using freshwater fossils from three Dipteran families (Chironomidae, Chaoboridae, and Ceratopogonidae). Palaeotemperature reconstructions from Windmill Lake reveal a cold period (~2°C cooler than Holocene temperatures) from about 10 500 to 10 000 $^{14}$C yr BP, perhaps representing the Younger Dryas. Windmill Lake midges also infer a mid-Holocene cooling from 7000 to 6000 $^{14}$C yr BP aligning with a Picea glauca decline reported from interior Alaska. Jan Lake’s midge-inferred temperatures do not indicate a corresponding cold period. Low chironomid counts throughout Jan Lake’s core preclude robust reconstructions.

Early Holocene warming is also inferred from the arrival of water lilies (Nuphar polysepalum) at Windmill Lake after 10 000 $^{14}$C yr BP. Midge-inferred temperatures rise to modern at 5700 $^{14}$C yr BP, followed by a dramatic increase in Nuphar sclereid counts at 5200 $^{14}$C yr BP. Mid to early Holocene midge assemblages at Jan Lake were comprised of a large percentage of phantom midges, Chaoborus trivittatus and C. americanus. C. americanus indicates a fishless lake system.
Introduction

Researchers have focussed on the Tanana and Nenana Valley’s lake systems as key sites for the reconstruction of interior Alaska’s past climates. Palynological work has dominated much of the palaeoanalysis in eastern Beringia (Ager 1975; Anderson et al. 1994), but is supplemented by recent fossil beetle, midge and diatom analyses (Barley et al. in press; Barley 2004; Elias 2000; Racca et al. unpublished manuscript).

Two significant climatic events are reported from interior Alaska: a *Picea glauca* decline potentially linked to cooling temperatures (Carlson and Finney 2004; Hu et al. 1993) and the Younger Dryas (Bigelow et al. 1990). The Younger Dryas (YD), a climatic reversal from 11 000 to 10 000 $^{14}$C yr BP (Mangerud et al. 1974; Peteet 1995), was first recorded in Europe, then the Atlantic seaboard of North America (10 800 to 10 000 $^{14}$C yr BP) (Mayle et al. 1993a). In the past few decades, the YD has been cited from locations around the world, e.g. Europe, the Canadian Atlantic, southwestern USA and South America (Cole and Arundel 2005; Kuhry et al. 1993; Mayle et al. 1993b; Peteet 1995). Cooling episodes overlapping the YD chronozone have also been inferred throughout much of Alaska (Briner et al. 2002; Elias 2000; Engstrom et al. 1990; Hansen and Engstrom 1996; Hu et al. 2002; Hu et al. 1995; Peteet and Mann 1994).

A consensus on the global impact of the Younger Dryas has yet to be achieved. Important to this are records from interior Alaska, the unglaciated eastern end of Beringia. Midge research in the Tanana Valley has uncovered a likely YD signal at Birch Lake (Chapter 2), but no other quantitative record of temperature declines between 11 000 and 10 000 $^{14}$C yr BP has been found in the Tanana Valley. Recently, pollen researchers have reported a potential YD correlate at Windmill Lake, Nenana Valley (Bigelow and Edwards 2001). The intent of the research reported here is to reconstruct late Quaternary temperatures at Windmill Lake, Nenana Valley and Jan Lake, Tanana Valley from midge remains preserved in the lakes’ sediments.

This research also makes the first attempt in Beringian studies to examine the palaeoecological potential of sclereid cells. Sclereids are sclerenchyma cells (otherwise known as idioblasts) found within leaves and stem tissues of water lilies (*Nymphaeaceae*) and other plants (e.g. *Menyanthaceae*, *Nymphoides*) (Foster 1956; Gaudet 1960; Kuo-Huang et al. 2000). Often
present in lake sediments, sclereids are overlooked and rarely recorded consistently throughout sediment cores.

Study Areas & Environmental Settings

Jan Lake, Tanana Valley

Jan Lake (63°34'N, 143°54'W) is located approximately 175 km southeast of Birch Lake in the Tanana River valley, southeast of Fairbanks, Alaska (Carlson and Finney 2004), and has a surface area of 14.3 ha, drainage basin of 0.643 km² and maximum lake depth of 12 m (Barber and Finney 2000). Jan Lake sits on metamorphic bedrock near the limit of the last glaciation and is thought to have formed by alluvial damming (Barber and Finney 2000).

Jan Lake was not glaciated and the lake’s catchment is considered a glacial refugium for *Picea glauca* and *P. mariana*. Today the vegetation around Jan Lake consists mainly of mixed forest with white spruce (*Picea glauca*), black spruce (*P. mariana*), paper birch (*Betula papyrifera*), balsam poplar (*Populus balsamifera*) and quaking aspen (*P. tremuloides*) (Carlson and Finney 2004).

Bordered in the south by the Alaska Range and in the north by the Brooks Range, interior Alaska has a continental climate (warm summers; harsh winters) and comparatively low precipitation (274.8 mm near Jan Lake) (Ager and Brubaker 1985). Mean annual, mean July and mean January air temperatures are -4.0°C, 14.5°C and -23.2°C, respectively (New et al. 2002).
Windmill Lake, Nenana Valley

Windmill Lake is located at ~640 m elevation approximately 240 km west of Jan Lake in the northwest-southeast trending Nenana Valley (Bigelow and Edwards 2001). Windmill Lake has a surface area of ~2 ha and a maximum depth of 4 m. The lake is a nearly closed, single basin underlain by diabase bedrock. One seepage drains from the southeast margin of the lake.

Vegetation in the Nenana Valley consists largely of boreal forest with white and black spruce (P. glauca and P. mariana), paper birch (Betula papyrifera), quaking aspen (Populus tremuloides) and cottonwood (P. balsamifera) (Bigelow and Edwards 2001). Tamarack (Larix laricina), along with black spruce and ericaceous shrubs can be found in areas with poor drainage. At Windmill Lake the vegetation also includes shrub birch (B. glandulosa), alder (Alnus crispa), various willow species (Salix) and in poorly drained areas heaths and sedges. The lake is surrounded by a sedge (Carex rostrata) mat.

Summer temperatures are cool at Windmill Lake with a mean July air temperature of 10.8°C (New et al. 2002). Current mean January air temperature is -19.3°C and mean annual temperature is -4.86°C (New et al. 2002). More precipitation falls in the Windmill Lake area (405.8 mm annually) than at Jan Lake. Windmill Lake has a weak thermocline at ~300 cm (Bigelow and Edwards 2001). Bottom dissolved oxygen levels are low, but the lake is not anoxic during summer months.

Methods

Midge Analysis

Both cores were collected using a modified Livingstone piston corer on frozen lake surfaces in early spring (Cwynar, pers. comm.). A 7.5 cm diameter corer was used at Windmill
Lake and for the upper 243 cm of the Jan Lake core. A 5 cm diameter corer was used below 243 cm at Jan Lake.

Thirty-six and 39 samples were examined from Jan and Windmill Lakes, respectively. Each sample underwent preparation following Walker (2001). Samples were individually deflocculated in 5% KOH on low heat until steam appeared within the beaker. They were then washed on a 95 μm mesh sieve with water while gently teasing apart particles with a flat metal stir stick. Carbonates were removed using 5% HCl on low heat. Although there were no reactions with the Jan and Windmill Lake samples, all samples underwent carbonate removal for consistency. Samples were again washed on the 95 μm sieve with water and the residue returned to the beaker for picking.

Chironomid head capsule picking was done in Bogorov counting trays under dissecting microscopes at 25 to 50X magnification. The samples were diluted with water and the entire sample counted in order to eliminate picking size bias. Midge head capsules were transferred individually to cover slips at a maximum of 30 heads per cover slip. The glass slips were then air dried and mounted with Entellan® onto microscope slides, and dried for 3-5 days. All midge fossils (Chironomidae, Ceratopogonidae, Chaoboridae) were sorted from the samples, as well as flatworm egg capsules, Trichoptera (caddisfly) mandibles and remains of water mites (Acari) and Ephemeroptera (mayfly).

Midge identification was performed on an Olympus BX51 compound microscope at 200X and 400X total magnifications. Identification followed modern larval keys from Wiederholm (1983) and Oliver and Roussel (1983) and fossil guides of Walker (1996; 1988) and Uutala (1990). Laboratory photographs were available for reference at the Palaeo-Lab at the University of British Columbia – Okanagan. Fossil head capsules were identified by variations in menta, ventromental plates, antennal pedestals, antennal spurs, premandibles and mandibles. Some chironomids of the tribe Pentaneurini and subtribe Tanytarsina were only identified to this level. Most fossils, however, were assigned to genus or sometimes species groups. Occasionally chironomid head capsules split longitudinally, resulting in two mirror image halves. This split is most often observed in the mentum with each visible half entered into the data as a half count.
Photographs of all type specimens and mystery midges were taken using a DMX 12000 digital camera mounted to an Eclipse 800 compound microscope (Nikon, Melville, New York, USA). Photographs of each type specimen are included in Appendix A as a record of the taxonomy used and to facilitate taxonomic standardisation.

**Sclereid Analysis for Windmill Lake**

While scanning Windmill Lake samples, all sclereids were picked and mounted along with the midges (see Appendix B for detailed description of sclereid processing and morphologies). Sclereid morphologies matched those of *Nuphar polysepalum*. Sclereids were counted individually and the number of finger-like projections per sclereid was also noted. Sclereids mL⁻¹ are included in the Windmill Lake stratigraphy.

**Radiocarbon Chronologies**

The Jan and Windmill Lake midge cores were not directly dated, thus correlation with adjacent dated pollen cores was necessary to develop the radiocarbon chronologies. Twenty-two AMS dates and the age-depth model (upper core: 3rd order polynomial regression; lower core: linear interpolation) were published in Carlson & Finney (2004) for the adjacent Jan Lake pollen core (Table 3.1). Nine AMS dates and the age-depth model (2nd order polynomial regression) are published for the adjacent Windmill Lake core (Bigelow and Edwards 2001)(Table 3.2). Three inconsistent dates between 298 cm and 303 cm in Jan Lake were excluded from the chronology calculations (5 220 ± 150, 10 010 ± 60 and 22 180 ± 140 ¹⁴C yr BP).

The Jan Lake midge core is correlated to the pollen core via six tie points: the initial LOI rise, three peaks and two dips in LOI (Table 3.3; Figure 3.1). Correlation at Windmill Lake relied
on six tie points, including the LOI rise and several LOI peaks and dips (Table 3.4; Figure 3.2). For both lakes, linear interpolation was used to facilitate correlation at levels lying between these tie points. The resulting Jan and Windmill Lake midge chronologies are shown in Figures 3.3 and 3.4.

Data Analysis

Midge fossil data were analysed using multivariate regression and calibration techniques in the statistical software program C2 version 1.4 Beta (build 33) (Juggins 2005) and the Beringian midge transfer function (Barley et al. in press). This transfer function was developed using surface samples from 136 British Columbian, Yukon, Alaskan and Canadian Arctic lakes. Temperature and lake-level reconstructions were made on 34 intervals from Jan Lake and 33 intervals from Windmill Lake using weighted averaging partial least squares (WAPLS), cross validation using 1000 bootstraps and square-root transformed species percentages.

All intervals were included in the datasets used for temperature and lake level reconstructions. Minimum head capsule counts of 40 to 50 are suggested, particularly for samples displaying a "typical" diversity (Heiri et al. 2003; Quinlan and Smol 2001). Sclereid counts from Windmill Lake were analysed on a presence and absence basis, i.e. one sclereid = one cell count. Sclereid counts were standardised into counts mL$^{-1}$.

Midge stratigraphic diagrams were constructed using relative abundances of identified midges. Biostratigraphic zones were chosen using CONISS (constrained incremental sum of squares cluster analysis) calculations in Zone version 1.2 (Juggins 1991) (Figures 3.5 and 3.7). A Shannon Diversity Index was calculated for all intervals using PC-ORD, version 4 (McCune and Mefford 1999; Shannon 1948). Results are represented in Figures 3.8B and 3.9B.
Results

Jan Lake

Zone J-1 (365 – 275 cm; 12 400 – 11 700 \(^{14}\)C yr BP)

Chironomid counts (<18 per interval) were extremely low, as was LOI (Figures 3.1 and 3.5). *Chironomus* and Tanytarsina dominate. Terrestrial and semiterrestrial chironomids, *Limnophyes, Smittia/Pseudosmittia* and *Parametriocnemus/Paraphaenocladius* were recorded at scattered intervals. *Chaoborus trivittatus* appears at the end of the zone (275 cm) in low numbers.

Reconstructed temperatures were about 12°C, approximately 1° lower than modern (Figure 3.8). Inferred lake levels indicate dry to very shallow depths (<5 m) (Figure 3.10). Modern analogue testing using squared chord distance revealed that few samples had good analogues; most had weak or no analogues in the Beringian training set (Figure 3.12).

Zone J-2 (275 – 175 cm; 11 700 – 4900 \(^{14}\)C yr BP)

Zone J-2 is characterised by increased species richness, but low chironomid numbers, each group representing <5% throughout the entire zone (Figure 3.5). This is an unusual assemblage, composed of *Glyptotendipes, Cricotopus/Orthocladius, Sergentia, Psectrocladius (Psectrocladius)* and *Corynoneura/Thienemanniella*. Mid-way in the zone, they are joined by *Parakiefferiella* sp. B type, *Procladius, Micropsectra atrofasciata/radialis* type, *Dicrotendipes, Polypedilum, Endochironomus* and other warm stenotherms. *Limnophyes* and *Doithrix/Pseudorthocladius* are present at the end of the zone.
High numbers (~40 to 90%) of *Chaoborus trivittatus* dominate between 270 and 185 cm (Figure 3.5). At 210 cm, *C. americanus* peaks at 40% of the assemblage, then stays between 10 and 20% until the end of the zone. *Stictochironomus* occurs once at the same time as the *C. americanus* peak.

Inferred temperatures rose sharply exceeding 17°C between 11 700 and 11 500 14C yr BP, subsequently falling to ~15°C (Figure 3.8A). At 5400 14C yr BP, temperatures drop to 13°C. Inferred lake levels also rose sharply (to ~20 m depth) at 11 700 14C yr BP and remained high until about 10 000 14C yr BP (Figure 3.10). Lake depth remained at ~10 m until 4900 14C yr BP. Midge diversity increased substantially throughout the zone, reaching a maximum at 4900 14C yr BP (Figure 3.8B). Most samples had good or weak analogues in the Beringian training set (Figure 3.12).

**Zone J-3 (175 – 41 cm; 4900 – 1000 14C yr BP)**

*Chaoborus trivittatus* remains dominant in the upper section of the core (up to 55% of the assemblage). *C. americanus* occurs at 20% midway in the zone, but percentages drop to <5% by the end of the zone. Most chironomids present in zone J-2 remain present in low percentages in J-3.

*Sergentia* represents a large proportion, between 6 and 20%, of the assemblages. Interesting additions to the assemblage are *Stenochironomus*, a plant miner (wood, stalks or water lily leaves) (Oliver and Roussel 1983) and *Corynocera ambigu*a.

Inferred temperatures remain constant (about 13°C) and midge diversities remain high until 4400 14C yr BP (Figure 3.8). Temperatures fluctuate between 13 and 15°C and diversities drop slightly throughout the remainder of the zone. Lake levels deepen from 10 to 12 m,
reaching 15 m at 1000 $^{14}$C yr BP (Figure 3.10). Most samples had good or weak analogues in the Beringian training set (Figure 3.12).

**Windmill Lake**

**Zone W-1 (450 – 408 cm; 13 750 – 12 200 $^{14}$C yr BP)**

Zone W-1 contains essentially no midges. Also absent were all other invertebrates and sclereids. One 4th instar *Chaoborus trivittatus* mandible was found at 426 cm. One and a half chironomids were found at 408 cm. The sediment was largely coarse and sandy and did not filter through the 95 μm mesh sieve.

**Zone W-2 (408 – 328 cm; 12 200 – 8600 $^{14}$C yr BP)**

Windmill Lake’s initial assemblage was composed largely of midges from the subtribe Tanytarsina (20 to 80% throughout the zone) (Figures 3.6 and 3.7). *Chironomus* were also present in significant percentages (~20%). *Psectrocladius (Psectrocladius)* and *Procladius* numbers were high (~15% and ~12%, respectively) until 376 cm when numbers dropped to <5%. Present in low percentages (<5 to 13%) were *Chaoborus trivittatus, Dicrotendipes, Cryptochironomus*, Pentaneurini and *Microtendipes*. *Cricotopus/Orthocladius* rise to ~15% by 356 cm. *Sergentia* and *Corynoneura/Thienemanniella* increase at mid-zone to ~20%. *Micropsectra atrofasciata/radialis* type and *Heterotrissocladius* occur mid-zone (~10% and 2%, respectively).
Various invertebrate mandibles, Acari and flatworm egg cases (see Appendix A for photographs) were simultaneously found with midges throughout the zone. No sclereids were found.

Midge-inferred temperatures rise from 11 to 12.5°C from 12 200 to 10 500^{14}C yr BP (Figure 3.9A). Between 10 500 and 9100^{14}C yr BP temperatures drop below 12°C, and subsequently rise to 13.5°C. Midge diversities steadily increase until 12 200^{14}C yr BP, then remain constant throughout the zone (Figure 3.9B). Low lake levels (4 to 6 m) are inferred between 12 200 and 9000^{14}C yr BP, afterwards rising to ~8 m (Figure 3.11). Modern analogue testing revealed that most samples had good analogues in the Beringian training set (Figure 3.13).

Zone W-3 (328 – 1 cm; 8600^{14}C yr BP to present)

Zone W-3 begins with a dramatic increase in Chaoborus (to >40%) and low numbers of Tanytarsina (10 to 20%). Sergentia and Procladius numbers rise steadily (~17% at 240 cm and 7% at 252 cm, respectively) and then drop to <3%. Corynoneura/Thienemanniella, Zalutschia type A and Cricotopus/Orthocladius peak at ~296 cm (~11%) and then fall to ~5%. Between 296 and 276 cm there are low numbers (<4%) of Nanocladius, Parakiefferiella sp. B type and the ceratopogonids, Bezzia and Dasyhelea type. Paraphaenocladius/Parametriocnemus and Limnophyes (semi-terrestrial) are present throughout the zone (~2 and ~12%, respectively). Paraphaenocladius/Parametriocnemus peaks at 12% at 32 cm. Doithrix/Pseudorthocladius type head capsules were found at 276 and 32 cm.

Cricotopus/Orthocladius represents 11% of the modern assemblage, which is further made up of Microtendipes, Heterotrissocladius, Cryptochironomus, Procladius, Sergentia, Pagastiella and Chironomus. Demicryptochironomus appears at 80 cm.
Acari and various invertebrate mandibles are well represented in the early half of this zone, then decline at 180 cm. Flatworm egg cases are few in the early half of the zone, but increase eightfold at 160 cm. Sclereids begin to appear in low numbers at 328 cm, and increase substantially at 212 cm (~5200 $^{14}$C yr BP).

Midge-inferred temperatures drop to $<12^\circ$C from 7000 to 6000 $^{14}$C yr BP, and once again at ~1000 $^{14}$C yr BP (Figure 3.9A). Midge diversities decrease at 7000 $^{14}$C yr BP, then remain constant until lowering again at 1000 $^{14}$C yr BP (Figure 3.9B). Inferred lake levels remain at ~8 m until 5000 $^{14}$C yr BP, afterwards rising to 12 m (Figure 3.11). Between 3700 and 2800 $^{14}$C yr BP, the lake lowers to 9 m depth. Windmill Lake's inferred modern lake depth is ~8 m. Most samples had good or weak analogues in the Beringian training set (Figure 3.13).

**Discussion**

The temperature and lake level inferences for Windmill and Jan Lakes add valuable new data, potentially revealing the magnitude of late Quaternary climatic changes at each site and on the surrounding lands. Integrating these midge-based reconstructions with earlier pollen work and recent midge inferences at Birch Lake (Chapter 2) should assist researchers in better resolving details of the Quaternary climatic and ecological history of interior Alaska. Furthermore, these results facilitate tests of 1) the Younger Dryas’ existence, and 2) a climatic cause for the mid-Holocene *Picea glauca* decline in interior Alaska.

**Radiocarbon Chronologies**

The Windmill Lake chronology is constructed from nine AMS radiocarbon dates, of which eight are samples of aquatic origin (Table 3.2); thus there is the potential of overestimation
of the true age of the sediments due to uptake of older carbon. The basis for the Jan Lake chronology appears more solid; only three (of 19) samples are of aquatic origin (Table 3.1). In Windmill Lake, the initial LOI rise aligns well with 10 000 14C yr BP (Figure 3.4). In interior Alaska (e.g. Birch Lake, Chapter 2 and Wien Lake (Hu et al. 1993)), the LOI rise commonly dates at or near the Pleistocene—Holocene boundary at 10 000 14C yr BP. The Jan Lake chronology, on the other hand, suggests that the initial LOI rise dates to ~1 600 14C yr BP (Figure 3.3). This may indicate a problem with Jan Lake’s chronology.

Climate and Vegetation

The Late Pleistocene

Windmill Lake’s early record indicates a midge-less community from 13 750 to 12 200 14C yr BP. One Chaoborus trivittatus mandible was found at 226 cm, but this may be due to contamination during sample processing or reworking of sediment via bioturbation. Diatom analysis also indicates a barren basal zone (Racca et al. unpublished manuscript), but Bigelow & Edwards (2001) suggest low water levels (8 m below modern; ~0.7 m deep) as indicated by the alga, Pediastrum Meyen. Livingstone et al. (1958) report that Pediastrum boryanum (Turpin) Meneghini colonies are found in massive numbers in the shallowest Arctic Alaskan lakes (~1 m). The absence of invertebrate life suggests that Windmill Lake was at least seasonally dry during this period.

Pollen and sediment records from Jan Lake identify an herb-tundra zone with low lake levels between 12 400 and 11 700 14C yr BP indicating colder and more arid conditions than modern (Barber and Finney 2000; Carlson and Finney 2004). Midge-inferred air temperatures are cool (<12°C) and inferred lake levels are shallow (1 to 5 m) during this period (Figures 3.8 and 3.10) signifying good agreement with palynological inferences. After this period, inferred temperatures rise quickly and briefly to ~18°C and subsequently fall to ~14°C. Unfortunately, low chironomid counts during this lower zone preclude reliable reconstructions. Figure 3.12 shows the intervals (zone J-1, 12 400 to 10 700 14C yr BP) where analogues were poor or absent.
Shannon Diversity numbers are variable at this period and may reflect a series of unsuccessful chironomid colonization attempts (Figure 3.9). Low chironomid counts and varying diversities may be construed as periods of inhospitable conditions, perhaps implying cold temperatures or great aridity.

The Younger Dryas?

At Windmill Lake the late-glacial/earliest Holocene warming trend is interrupted by a return to colder midge-inferred temperatures ca. 10 500 to 10 000 \(^{14}\text{C}\) yr BP (Figure 3.9). Higher resolution sampling is needed, but these inferences provide further evidence of the Younger Dryas existence in interior Alaska. Pollen records also indicate a cold interval as depicted by a decrease in \textit{Betula} pollen coinciding with increases in \textit{Artemisia} and Poaceae between 10 500 and 10 200 \(^{14}\text{C}\) yr BP (Bigelow and Edwards 2001). Similarly, the Birch Lake midge record indicates a cold interval ca. 10 600 to 9700 \(^{14}\text{C}\) yr BP (Chapter 2).

Inferred temperatures at Jan Lake do not indicate cooling or other temperature changes during the YD chronozone. The midge assemblages at Jan Lake were consistently high in \textit{Chaoborus trivittatus} and \textit{C. americanus} (>50%). Kurek et al. (2004) had similar high \textit{Chaoborus} situations which reconstructed unreasonably high and variable summer temperatures for Surplus Pond, Maine, USA.

\textit{Chaoborus trivittatus} undergoes diurnal vertical migration; in order to coexist with fish, they migrate to the lake bottom during the day, but return to surface waters for nocturnal feeding (Uutala 1990). High \textit{C. trivittatus} numbers coincide with high water levels from 11 500 to 10 000 \(^{14}\text{C}\) yr BP (Figure 3.10). \textit{Chaoborus} remains are most abundant in deep, stratified lakes (Barley 2004).
Holocene Temperatures

Reconstructed temperatures at Windmill Lake remain warm (about 13°C) between 9100 and 7000 $^{14}$C yr BP, but decrease to about 12°C from 7000 to 6000 $^{14}$C yr BP, approximately coinciding with the Picea glauca decline as recorded at interior Alaskan lakes (Figure 3.9). The Picea glauca decline has been dated at Jan Lake at ~6000 $^{14}$C yr BP (Carlson and Finney 2004), Wien Lake at ~7500 $^{14}$C yr BP (Hu et al. 1993), and between 8000 and 6000 $^{14}$C yr BP at Birch Lake (Ager 1975; Bigelow 1997; Carlson and Finney 2004). Windmill Lake pollen reconstructions do not indicate a distinct P. glauca decline in the mid to late Holocene (Bigelow and Edwards 2001). Midge-inferred temperatures increase at about 6000 $^{14}$C yr BP, averaging 14°C throughout the rest of the Holocene.

Temperatures are steadier at Jan Lake, gradually decreasing from about 14 to 13°C over the Holocene (Figure 3.8). This gradual cooling is consistent with an early Holocene Thermal Maximum as postulated for interior Alaska by Kaufman et al. (2004). No evidence for a warm interval in the early Holocene was found at Windmill Lake. Palynological studies on Birch, Harding, George and Jan Lakes suggest a cooling trend during the mid-Holocene (Ager 1975; Carlson and Finney 2004).

Sclereid abundance at Windmill Lake increases dramatically at 5200 $^{14}$C yr BP. Counts rise from ~2 to 18 cells mL$^{-1}$ (Figure 3.7). Inferred temperatures warm slightly during this period as well, indicating a potential link between *N. polysepalum* and mid-Holocene warming. Van Geel et al. (1981) describe *Nymphaea alba*, a close relative to *Nuphar polysepalum*, as thermophilous and infer relatively warm summer temperatures from its presence.

The appearance of *Stenochironomus* in aquatic sediments has been linked to marginal forest vegetation due to the mining nature of the larvae in submerged hardwoods (Ilyashuk et al. 2005). The presence of *Stenochironomus* in the late Holocene (4900 and 1100 $^{14}$C yr BP) at Jan Lake may, therefore, indicate increased marginal forest growth. *Stenochironomus* has also been noted as a miner in water lily leaves (Oliver and Roussel 1983), and although *Nuphar* sclereids were not counted throughout Jan Lake’s core, their presence was noted in the early Holocene.
Midge-inferred water levels at Windmill Lake deepen slightly (to about 8 m) at 9000 14C yr BP (Figure 3.11), and fossil sclereids appear for the first time at 8600 14C yr BP, indicating an early presence of *Nuphar polysepalum* (Figure 3.9B). *N. polysepalum* sclereids are consistently found in the Holocene when inferred lake depths remain at overflow level. Sclereid numbers dramatically increase at 5200 14C yr BP when lake depths increase moderately. Previous work on *Nuphar* indicates a potential link between decreased water levels (warmer and drier conditions) and increased *Nuphar* biomass (Larmola et al. 2003). Van Geel et al. (1981) also identify *Nuphar* fossil habitat as shallow waters. It was hoped that a link between fossil sclereids and lake levels could be confirmed at Windmill Lake, but this is undermined by a lack of significant oscillations in water depth. Furthermore, the relationship between littoral habitat availability and water depth depends greatly on basin morphometry. In many instances, rising lake levels may flood low-lying areas adjacent to a lake, greatly increasing the littoral habitat available for *Nuphar* growth.

Despite the continuous, gradual accumulation of sediment, Windmill Lake’s depth apparently increased from about 8 to 10 m over the Holocene. The water depth inferred from midges preserved in the lake’s uppermost sediments overestimates Windmill Lake’s current depth by about 4 m. At Jan Lake, inferred water levels decrease during the early Holocene and rise sharply at 6200 14C yr BP, before returning to the 10 m level (Figure 3.10). Inferred lake depths have increased over the last 5000 14C years from about 10 to 15 m. Although all records indicate low initial (early late-glacial) lake levels, there is little Holocene correspondence among lake levels inferred at Windmill, Jan and Birch Lakes (Chapter 2).

Thermal stratification may confound midge-inferred lake level reconstructions. These results support Walker’s (2001) contention that lake level changes can only be satisfactorily reconstructed using midges where large water level fluctuations have occurred—increasing or decreasing lake depth by a factor of 3 to 4X—or at least where sedimentological lake level analysis can be used for corroboration.
Conclusions

The Younger Dryas cold event has now been established from two sites in interior Alaska: Birch and Windmill Lakes. Midge-inferred temperatures at Windmill Lake align remarkably well with the YD (10 500 to 10 000 $^{14}$C yr BP), as recorded by the Birch Lake midge record (Chapter 2), and with the *Picea glauca* decline (7000 to 6000 $^{14}$C yr BP), as recorded by pollen records throughout interior Alaska. Jan Lake midge inferences remain warm throughout the early Holocene, potentially recording an early Holocene Thermal Maximum, but inferences may be biased due to remarkably high percentages of *Chaoborus* species. The successful midge analysis at Windmill Lake encourages further midge-related quantitative studies in interior Alaska.

This is the first study known to the author that augments midge inferences with sclereid analysis. Fossil sclereids indicate an early Holocene (ca. 8600 $^{14}$C yr BP) presence of *Nuphar polysepalum* in Windmill Lake. A dramatic increase of sclereids at 5200 $^{14}$C yr BP coincides with warm modern temperatures and slightly elevated lake levels, perhaps linking increased effective moisture and warming conditions in the Nenana Valley. In order to effectively study the role of sclereids in palaeoecology, fossil sclereids should be sampled in conjunction with a quantitative proxy, such as Chironomidae.
References

Ager T.A. 1975. Late Quaternary environmental history of the Tanana Valley, Alaska. Report No. 54. Institute of Polar Studies, Ohio State University, Columbus, Ohio.


Figure 3.1 Jan Lake loss on ignition (500°C) for midge core (* indicates position of tie points with pollen LOI). Grey band indicates zone with low midge counts (<18/sample).
Figure 3.2 Windmill Lake loss on ignition (500°C) for midge core (* indicates position of tie points with pollen LOI). Grey band indicates zone with no midges, invertebrates or sclereids.
Figure 3.3 Jan Lake radiocarbon age-depth model developed for the midge core using correlation to an adjacent pollen core (Carlson and Finney 2004) (A). Loss on ignition curve for midge core (* indicates position of tie points with pollen LOI) (B). Horizontal dashed line indicates Pleistocene-Holocene transition at 10 000 $^{14}$C yr BP inferred from LOI rise. Vertical dashed line indicates position of 10 000 $^{14}$C yr BP in the chronology.
Figure 3.4 Windmill Lake radiocarbon age-depth model developed for the midge core using correlation to an adjacent pollen core (Bigelow and Edwards 2001) (A). Loss on ignition curve for midge core (* indicates position of tie points with pollen LOI) (B). Horizontal dashed line indicates Pleistocene-Holocene transition at 10,000 $^{14}$C yr BP inferred from LOI rise. Vertical dashed line indicates position of 10,000 $^{14}$C yr BP in the chronology.
Figure 3.5 Jan Lake stratigraphy showing relative abundances of identified midges. Grey band indicates low midge counts (<18/sample). Temperature optima left to right (11.4-13.9°C), calculated by weighted averaging (Barley 2004). CONISS calculated in Zone v1.2 (Juggins 1991).
Figure 3.6  Windmill Lake midge stratigraphy (Part A) showing relative abundances of identified midges. Grey band indicates zone with no midges, invertebrates or sclereids. Temperature optima for midge taxa from left to right are 11.1 to 12.8°C, as calculated using weighted averaging in Barley (2004).
Figure 3.7 Windmill Lake stratigraphy (Part B) showing relative abundances of identified midges (* calculated as % of all midges; ** raw counts/mL). Temperature optima for midge taxa (12.9 to 13.9°C) (Barley 2004). CONISS calculated using Zone version 1.2 (Juggins 1991).
Figure 3.8 Jan Lake midge-inferred mean July air temperatures (A) and Shannon Diversity values (B). Thick lines are lowess smoothed curves. Top grey band indicates the *Picea glauca* decline recorded in interior Alaska from 7000 to 6000 $^{14}$C yr BP. Second grey band indicates zone (12 400 to 11 700 $^{14}$C yr BP) with low midge counts (<18/sample).
Figure 3.9 Windmill Lake midge-inferred mean July air temperatures (A) and Shannon Diversity values (B). Thick lines are lowess smoothed curves. Top two grey bands indicate the *Picea glauca* decline recorded in interior Alaska from 7000 to 6000 $^14$C yr BP, and the “Younger Dryas” from 10 800 to 10 000 $^14$C yr. Third grey band indicates zone with no midges, invertebrates or sclereids from 13 750 to 12 200 $^14$C yr BP. Sclereid arrival and increase marked with thick dashed lines.
Figure 3.10 Jan Lake midge-inferred lake level reconstructions. Thick line is a lowess smoothed curve. Grey band indicates zone from 12 400 to 11 700 $^{14}$C yr BP with low midge counts (<18/sample).
Figure 3.11 Windmill Lake midge-inferred lake level reconstructions. Thick line is a loess smoothed curve. Grey band indicates possible dry zone from 13 750 to 12 200 $^{14}$C yr BP with no midges, invertebrates or sclereids. Sclereid arrival and increase marked with thick dashed lines.
Figure 3.12 Results of analogue testing for Jan Lake with the Beringia training set. Vertical dashed lines indicate 75 and 95% confidence intervals at 13.7 and 17.8 squared chord distances, respectively. Intervals below 75% have good analogues; those greater than 95% are considered to have no analogues and those between are considered weak analogues.
Figure 3.13 Results of analogue testing for Windmill Lake with the Beringia training set. Vertical dashed lines indicate 75 and 95% confidence intervals at 13.7 and 17.8 squared chord distances, respectively. Intervals below 75% have good analogues; those greater than 95% are considered to have no analogues and those between are considered weak analogues.
Table 3.1 Jan Lake AMS radiocarbon dates from a previously dated pollen core (Carlson and Finney 2004). Calibrated dates are 50% cumulative probabilities (Stuiver and Reimer 1993; Stuiver et al. 2005). Dates marked with * are not used in the chronology.

<table>
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<th>Sediment depth (cm)</th>
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<th>Cal yr BP</th>
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Table 3.2  Windmill Lake AMS radiocarbon dates from a previously dated pollen core (Bigelow and Edwards 2001). Calibrated dates are 50% cumulative probabilities (Stuiver and Reimer 1993; Stuiver et al. 2005).

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Table 3.3  Loss-on-ignition tie points between midge core and previously dated pollen core, Jan Lake.

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Table 3.4  Loss-on-ignition tie points between midge core and previously dated pollen core, Windmill Lake.

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Chapter 4  Conclusion: An Overview of Climatic Inferences for Interior Alaska

Overview

Interior Alaska served as an unglaciated refugium for animals and plants during the Pleistocene glaciations (Hultén 1937). It contains a number of archaeological sites, recording human occupation as early as 11,000 $^{14}$C yr BP in the Nenana and Tanana Valleys (Ager 1975; Yesner 2001). Therefore reconstructing climates, particularly palaeotemperatures, can reveal climatic conditions that early humans forbore during the late Pleistocene and Holocene.

Palynological and sedimentological work in interior Alaska is extensive and comprehensively reviewed (Abbott et al. 2000; Ager 1975; Ager 1983; Ager and Brubaker 1985; Barber and Finney 2000; Bigelow et al. 1990; Bigelow and Edwards 2001; Bigelow and Powers 2001; Carlson and Finney 2004; Edwards et al. 2000; Hu et al. 1993; Muhs et al. 2001). This earlier work has been broadened to include quantitative midge analysis. Barley et al. (in press) used fossil Chironomidae, Chaoboridae and Ceratopogonidae assemblages to create midge-temperature and midge-lake depth transfer function models for eastern Beringia. Prior to my research, these models had not been implemented in interior Alaska and only sparsely applied to eastern Beringian sites—Antifreeze Pond, Yukon and Zagoskin Lake, western Alaska (Barley 2004; Kurek & Cwynar, unpublished data).
A Comparison of Results from Birch, Jan & Windmill Lakes

The midge reconstructions for Birch, Jan and Windmill Lakes should collectively represent a regional climatic record. Birch and Jan Lakes lie in relatively close proximity, 175 km apart, in the Tanana Valley. Windmill Lake, in the Nenana Valley, is about 120 km southwest of Birch Lake and 240 km west of Jan Lake. Although these sites are each subjected to local climatic effects, it is unlikely that trends of late Quaternary climatic changes differed greatly among these sites.

Comparison of pollen records, and temperature and lake level reconstructions, however, reveals a distinctive signal at each lake, with some common elements (Figures 4.1 and 4.2; Table 4.1). The unique components will, at least in part, reflect noise derived from the inevitable errors associated with fossil data and transfer function models. The variability in Holocene temperature and lake level changes may in some cases be attributed to noise. In other instances, the unique elements may reflect local scale climatic factors, e.g. topography, lake bathymetry and proximity to ice sheets.

At Jan Lake, the reconstructions have questionable validity due to overwhelming dominance by *Chaoborus trivittatus* in the samples. Comparatively few other midge remains were recovered from the Jan Lake sediment. Thus, although analogues are largely adequate in the Beringia training set, temperature and lake level reconstructions should be interpreted cautiously.

The apparent timing of some events may be offset among cores due to errors in dating, core correlation and, consequently, in the derived chronologies. In retrospect, radiocarbon dating of material found in the actual cores used for midge analysis would alleviate some of the age-depth modelling difficulties. Correlation among cores can be adequately executed, but errors mount from one step to the next.

Given the variability seen among the three lakes, it is premature to make strong statements about the midge-inferred climate of interior Alaska. Higher resolution analyses for
more well-dated sites are required. Nevertheless, a few patterns deserve discussion and further investigation.

_Younger Dryas_

Midge-inferred palaeoclimatic reconstructions at Birch and Windmill Lakes show similar trends of Younger Dryas-like cooling (~3°C) in the late Pleistocene, followed by warming into the early Holocene. The midge-inferred YD is chronologically placed between 10 600 to 9700 14C yr BP at Birch Lake and between 10 500 to 10 000 14C yr BP at Windmill Lake. Midge numbers at Jan Lake were insufficient to infer the presence or absence of the YD. Palynological research indicates a potential YD signal only at Windmill Lake (see Table 4.1) (Bigelow and Edwards 2001).

Mean July air temperature estimates for the YD in Europe range between 8 and 13°C (3 to 7°C below present temperatures) (Isarin and Renssen 1999). Midge models reconstruct a cooling of 6 to 20°C (maximum summer surface water temperatures) for eastern North America (Levesque et al. 1994; Levesque et al. 1997; Mayle et al. 1993). Mean July air temperature departures from present at Birch and Windmill Lakes are less pronounced: approximately 2 to 4°C (0°C at Jan Lake) (Figure 4.1). The geographic distance of these lakes from the Atlantic and Pacific Oceans may account for the less significant climatic impacts.

_Picea Glauca Decline_

A _Picea glauca_ decline between about 7500 and 6000 14C yr BP has been reported from several interior Alaskan lakes: Birch Lake (Ager 1975; Ager and Brubaker 1985; Bigelow 1997), Jan Lake (Carlson and Finney 2004), Sithylemenkat Lake (Anderson et al. 1990) and Wien Lake
Subsequent forest succession to *P. mariana* led to initial interpretations suggesting that the decline was due to soil organic build-up and consequent waterlogging (Anderson et al. 1990), but finer pollen resolution indicates that *P. glauca* recovered and remained dominant for approximately 1000 years before replacement by *P. mariana*; thus Hu et al. (1993) favour a climatic explanation. Midge evidence supports neither interpretation at this point. Windmill Lake midge reconstructions identify cooling between 7000 and 6000 $^{14}$C yr BP, but pollen records do not indicate a *P. glauca* decline at that site. Birch Lake midges reconstruct an earlier cooling, between 8500 and 7700 $^{14}$C yr BP, which precedes both the *P. glauca* decline and the 8200 cal yr event (7700 to 7200 $^{14}$C yr BP). Finally, Jan Lake midges do not infer significant cooling in the Holocene, however, at ~6000 $^{14}$C yr BP midge diversity dropped and inferred lake levels rose drastically for a brief interval.

**Holocene Thermal Maximum**

Kaufman et al. (2004), in a multi-proxy data compilation, suggest the presence of an early Holocene Thermal Maximum in interior Alaska. Sedimentological evidence (confirmed by midge evidence, Chapter 2) from Birch Lake infers low lake levels in the early Holocene (Abbott et al. 2000), which Kaufman et al. (2004) interpret as warm and dry conditions. Also, ostracode records from Farewell Lake, northwestern Alaska range, indicate peak temperatures between 8500 and 8000 $^{14}$C yr BP (Hu et al. 1998). Lake level and pollen data from interior Alaska infer warmer and drier than present conditions from 9000 to 8500 $^{14}$C yr BP, with increasing warmth and moisture from 8500 to 7500 $^{14}$C yr BP (Edwards et al. 2001). Early Holocene midge-inferred temperatures at Jan Lake potentially indicate an early thermal maximum, but midge-inferred temperatures from Birch Lake signify a cold event between 8500 and 7700 $^{14}$C yr BP; thus, midge results offer little support for an early Holocene Thermal Maximum in Alaska. This contrasts with midge results from southern British Columbia, which indicate a pronounced early Holocene Thermal Maximum, (e.g. Rosenberg et al. 2004).
Lake Levels

Figure 4.2 shows lake level reconstructions for the three lakes. Reconstructions derived from fossil midges at Birch Lake replicate previous sediment-inferred lake levels (Abbott et al. 2000). Midge inferences from Windmill and Jan Lakes are not as straightforward or reliable as those from Birch Lake. Care must be taken when inferring palaeolake-levels as confounding effects between air temperature and water depth may be inextricable when analysing midge assemblages, especially in shallow lakes. Lake level reconstructions are only likely to be reliable where extreme changes, increasing or decreasing lake depths by at least three or four times, have occurred. Further investigation involving multiple proxy analyses would help clarify the midge-water depth relationship. Expanding our knowledge of *Nuphar polysepaltum* response to significant lake level or air temperature changes would facilitate development of a new lake level indicator.

Conclusion

There are still many difficulties to overcome in the field of midge palaeoecology. In particular, the method is limited by our knowledge of chironomid ecology and biogeographical distributions (Walker 1995). Thus, interpretations of past environmental conditions based on qualitative analysis are not as reliable as quantitative reconstructions. In addition to the ecological limitations, there are taxonomical difficulties to overcome. Newly improved fossil identification methods and tools are slowly emerging in the literature, hopefully leading to a more standardised taxonomy of fossil chironomids (Heiri et al. 2004). Increased collaboration among palaeoresearchers, ecologists and taxonomists is the key to the success of midges in the palaeoworld.
References


Ager T.A. 1975. Late Quaternary environmental history of the Tanana Valley, Alaska. Report No. 54. Institute of Polar Studies, Ohio State University, Columbus, Ohio.


Figure 4.1 Midge-inferred mean July air temperature departure from modern (°C) for Jan, Windmill and Birch Lakes, Alaska. Modern mean July air temperatures are 14.5°C (Jan Lake), 10.8°C (Windmill Lake) and 15.1°C (Birch Lake) (New et al. 2002).
Figure 4.2 Midge-inferred maximum lake depths (m) for Jan, Windmill and Birch Lakes, Alaska.
Table 4.1  Birch, Jan and Windmill Lake pollen summaries in $^{14}$C yr BP (Abbott et al. 2000; Ager 1975; Bigelow 1997; Bigelow and Edwards 2001; Carlson and Finney 2004).

<table>
<thead>
<tr>
<th>Birch Lake</th>
<th>Jan Lake</th>
<th>Windmill Lake</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>8 400 – present</strong></td>
<td><strong>5 000 – present</strong></td>
<td><strong>6 500 – present</strong></td>
</tr>
<tr>
<td>Picea (&gt;10%), Betula (30–80%), Alnus (up to 25%), Nuphar (1%)</td>
<td>Picea, Betula &amp; Alnus</td>
<td>oscillating Picea and Alnus</td>
</tr>
<tr>
<td><strong>8 400 – 6 500 $^{14}$C yr BP</strong></td>
<td><strong>6 000 – 5 000 $^{14}$C yr BP</strong></td>
<td><strong>8 300 – 6 500 $^{14}$C yr BP</strong></td>
</tr>
<tr>
<td>Picea decline</td>
<td>Picea decline</td>
<td>initial appearance of Picea &amp; Alnus</td>
</tr>
<tr>
<td><em>NOTE: AMS dates have dated the decline between 7000 and 6000 $^{14}$C yr BP</em></td>
<td></td>
<td>Alnus rises to modern levels Betula declines</td>
</tr>
<tr>
<td><strong>9 200 – 8 400 $^{14}$C yr BP</strong></td>
<td><strong>9 200 – 6 000 $^{14}$C yr BP</strong></td>
<td><strong>9 600 – 8 300 $^{14}$C yr BP</strong></td>
</tr>
<tr>
<td>Picea (2–80%), Betula (20–75%)</td>
<td>Picea, Betula &amp; Alnus</td>
<td>Populus, high Betula moderate Salix, Cyperaceae, Poaceae</td>
</tr>
<tr>
<td><strong>14 000 – 9 200 $^{14}$C yr BP</strong></td>
<td><strong>11 600 – 10 000 $^{14}$C yr BP</strong></td>
<td><strong>10 500 – 10 200 $^{14}$C yr BP</strong></td>
</tr>
<tr>
<td>Betula rise (60–75% in all samples), Salix (&lt;6 – 10%), Gramineae (&lt;5 – 10%), Cyperaceae (&lt;3 – 7%)</td>
<td>Betula rise, Salix at high</td>
<td>increasing Artemisia &amp; Poaceae, decreasing Betula</td>
</tr>
<tr>
<td><em>NOTE: AMS dates have estimated this zone start at ca. 12 000 $^{14}$C yr BP</em></td>
<td></td>
<td><strong>11 700 – 9 600 $^{14}$C yr BP</strong></td>
</tr>
<tr>
<td><strong>12 400 – 11 600 $^{14}$C yr BP</strong></td>
<td><strong>&gt;13 000 – 11 700 $^{14}$C yr BP</strong></td>
<td><strong>&gt;13 000 – 11 700 $^{14}$C yr BP</strong></td>
</tr>
<tr>
<td>moderate to high Artemisia, Cyperaceae &amp; Poaceae high Chenopodiaceae</td>
<td>Betula rise</td>
<td>low Betula</td>
</tr>
<tr>
<td></td>
<td></td>
<td>moderate to high Salix, Artemisia, Cyperaceae &amp; Poaceae</td>
</tr>
</tbody>
</table>

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Appendices
Appendix A  Midge Taxonomy & Ecology of Interior Alaska

Fossil Midge Identification & Photography

Dipteran remains, particularly midges from Families Chironomidae, Chaoboridae and Ceratopogonidae, were abundant in lake sediments from Birch, Jan and Windmill Lakes, Alaska. Photographs of each specimen were taken using a DMX 12000 digital camera mounted to an Eclipse 800 compound microscope (Nikon, Melville, New York, USA). These images document head capsule morphologies and may assist in a taxonomic standardisation of fossil midges in North America.

Identification was performed on an Olympus BX51 compound microscope at 200X and 400X magnifications with modern larval keys from Wiederholm (1983) and Oliver and Roussel (1983) and fossil guides of Walker (1996; 1988) and Uutala (1990). Head capsules were largely identified by variations in menta, ventromental plates and antennal pedestals. Most midge remains were identified as genera, genus groups or species groups.

Photographs depict diagnostic features of each taxon, for example, menta with distinct lateral and median teeth. Multiple photographs were taken of each taxon and compiled using Helicon Focus Version 2.03 Lite (Khmelik and Kozub 2004). Accompanying each midge taxon photograph is a short ecological note on the larval habitat and/or ecology.

Specimens from Orders Trichoptera, Ephemeroptera, Acari and Diptera and from Families Simuliidae and Corixidae are included at the end of the appendix. Also incorporated are photographs of unknown 3-, 4- and 5-toothed mandibles and flatworm egg capsules (Order Rhabdocoela) that were consistently counted from Windmill Lake.
Family Ceratopogonidae

Bezzia type
head capsule
lentic (littoral & profundal); algal mats in hot springs; burrowers or planktonic; widespread in NA (Courtney et al. 1996)

Dasyhelea type
head capsule
lentic (tree holes, rock pools, lakes); lotic (margins); semiaquatic climbers; widespread in NA (Courtney et al. 1996)

Family Chaoboridae

Chaoborus trivittatus
head capsule & mandibles
planktonic (night) & sprailer (day)—diurnal vertical migration (Pope et al. 1973)

Chaoborus americanus
mandible
non-migratory; indicative of fishless systems (Pope et al. 1973)
Family Chironomidae

**Procladius**
head capsule - mentum & ligula

muddy substrates small lakes; some species large deep lakes (Wiederholm 1983); all freshwater (high or low O₂, warm, cool, deep, shallow), widely distributed, even the Arctic Archipelago (Oliver and Roussel 1983)

**Protanypus**
head capsule - mentum

oligotrophic (Wiederholm 1983); cool, deep lakes (Oliver and Roussel 1983)

**Diamesa**
head capsule - mentum

cold-stenotherms, lotic waters, springs, some shallow lentic waters (Wiederholm 1983)

**Monodiamesa**
head capsule - mentum

large oligotrophic, moderately eutrophic, slow-moving streams (Wiederholm 1983)
**Corynoneura/Thienemanniella**

head capsule

ditch water to mountain streams (*Corynoneura*) (Wiederholm 1983)

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**Cricotopus/Orthocladius**

mentum

*C. brevipalpis, C. elegans, C. flavipes*: leaf miners in *Potamageton* (Berg 1950); *Cricotopus*: freshwater, saline, some associate with aquatic plants (Wiederholm 1983)

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**Cricotopus (Isocladius) sylvestris group?**

head capsule

commoner in lentic waters (Wiederholm 1983), closely associated with aquatic plants (Oliver and Roussel 1983)

---

**Cricotopus (Isocladius) obnixus group?**

head capsule - mentum

commoner in lentic waters (Wiederholm 1983); closely associated with aquatic plants (Oliver and Roussel 1983)
**Doithrix/Pseudorthocladius**  
mentum

seeps & small streams in Tennessee; 3 spp. California to BC (Wiederholm 1983)

---

**Heterotanytarsus**  
head capsule piece - mentum

ponds, littoral zone of lakes, some in slow reaches of lotic waters (Wiederholm 1983)

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**Heterotrisocladius**  
head capsule - mentum

littoral to profundal; streams, springs, ponds, puddles; *H. subpilosus* ultraoligotrophic, strongly oligotrophic; *H. marcidus* oligotrophic (Wiederholm 1983)

---

**Hydrobaenus**  
head capsule - mentum

littoral zone of lakes, small lentic water bodies, rivers, streams; northern, oligotrophic lakes (Wiederholm 1983)
**Limnophyes**
head capsule - mentum

eurytopic: aquatic, semiterrestrial, terrestrial (Wiederholm 1983); littoral: often found in margins and shallow zones (Oliver and Roussel 1983)

**Nanocladius**
head capsule - mentum

streams, lakes, rivers, ponds; symphoretic associations with Perlidae or Corydalidae; rheophilic; oligotrophic; mesotrophic; “sporadically in moderately eutrophic” (Wiederholm 1983)

**Orthocladius sp. 2**
head capsule - mentum

*Orthocladius*: cool lentic or lotic waters (Oliver and Roussel 1983)

**Paracladius**
mentum

springs, flowing & still water (Wiederholm 1983); high arctic & alpine lakes (Walker 1990); cold lakes (Oliver and Roussel 1983)
Parakiefferiella type 1
head capsule - mentum

resembles Parakiefferiella bathophila (Barley 2004); lotic & lentic (Wiederholm 1983)

Parakiefferiella type 2
head capsule - mentum

Parakiefferiella sp. B (Barley 2004); Parakiefferiella cf. bathophila (Walker 1998)

Parakiefferiella nigra
head capsule - mentum

cold, oligotrophic lakes in barren arctic, alpine tundra; common in BC late-glacial sediments (Walker et al. 1992)

Parakiefferiella triquetra type
head capsule - mentum
**Parametriocnemus**
mentum

fast-flowing streams, rivers; springs (Wiederholm 1983)

**Paraphaenocladius?**

*P. pseudirritus?*
head capsule - mentum

terrestrial, damp soil near springs, meadows & alder; semiaquatic and/or fully aquatic in streams & springs in Nearctic (Wiederholm 1983); usually terrestrial, some aquatic in small lotic water bodies in Canada (Oliver and Roussel 1983)

**Psectrocladius (Psectrocladius)**

*P. semicirculatus/sordidellus* type
head capsule - mentum

eurytopic (Wiederholm 1983); distributed widely in Canada and north of the treeline (Oliver and Roussel 1983)

**Psectrocladius (Allopsectrocladius & Mesopectrocladius)**
head capsule - mentum

*Psectrocladius*: still water (Oliver and Roussel 1983)
Zaliscia nupera

Symbrachydius

head capsule - meunium

Preotocladus septentrionalis type

Lapsophilus (Weedeholm 1983)
stream: mostly found in north, oligotrophic,
lakes, ponds, puddles, ditches, sometimes
springs, all sizes of flowing water, shallow

head capsule - meunium

Symbrachydius

Preotocladus septentrionalis type
Subfamily Chironominae

head capsule

all, except predaceous species, build cases on or within substrate (Oliver 1971)

Chironomus

head capsule - mentum

grazers (detritus), filter feeders, lentic water, soft sediments; few halophilic, halobiontic; some humic waters only (Wiederholm 1983); widely distributed, occurs north of treeline, tolerance to low O2 and pollution (Oliver and Roussel 1983)

Cladopelma

mentum

sandy, muddy lakes, streams (Wiederholm 1983); small lotic water bodies, littoral lentic waters (Oliver and Roussel 1983)

Cryptochironomus

head capsule - mentum

littoral zones in lentic or lotic waters, sandy substrates; widely distributed south of treeline only (Oliver and Roussel 1983)
Cyphomella/Harnischia
/Paracladopelma complex
head capsule - mentum

Cyphomella: large lotic water bodies;
Harnischia & Paracladopelma: large lentic lakes south of treeline (Oliver and Roussel 1983)

Demicryptochironomus
head capsule - mentum
sandy, muddy substrates in lakes and rivers (Wiederholm 1983)

Dicrotendipes
head capsule - mentum
shallow lentic or slow reaches of lotic waters, distributed widely south of the treeline (Oliver and Roussel 1983)

Endochironomus
head capsule - mentum
shallow lentic or slow reaches of lotic waters, usually associated with aquatic plants—on or in dead or living plants (some species are borers), distributed widely south of the treeline (Oliver and Roussel 1983)
**Glyptotendipes**  
head capsule - mentum  
lentic, slow lotic waters, many mine in dead or living plants, south of treeline (Oliver and Roussel 1983); some net-spinning plankton eaters (Berg 1950)

**Microtendipes**  
head capsule - mentum  
warm, littoral zones of lentic waters, slow lotic waters, stream riffles, south of treeline (Oliver and Roussel 1983); some net-spinning plankton eaters (Berg 1950)

**Omisus**  
head capsule  
small partly dystrophic lakes (Oliver and Roussel 1983)

**Pagastieilla**  
head capsule  
littoral to sub-littoral lentic waters (Oliver and Roussel 1983)

**Parachironomus**  
head capsule - mentum  
ponds, lakes, slow lotic waters (Oliver and Roussel 1983)

**Paralauterborniella**  
head capsule - mentum  
shallow zones of lentic waters (Oliver and Roussel 1983)
**Paratendipes**
head capsule - mentum

lentic and lotic water bodies, distributed widely south of treeline (Oliver and Roussel 1983)

**Phaenopsectra flavipes type**
head capsule - mentum

**Phaenopsectra**: lentic and lotic waters, deep cold lakes, distributed widely and north of treeline (Oliver and Roussel 1983)

**Polypedilum**
head capsule - mentum

*P. ophioides, P. illinoense, P. braseniae* feed superficially on *Potamogeton*; *P. sordens, P. tritum* net-spinning plankton eaters (Berg 1950)

**Sergentia**
head capsule – mentum & mandibles

acidic lakes? (Heinrich, pers. comm.); *S. coracina* cold, other spp. acidic (Heiri, pers. comm.); deep (Barley 2004); vertical migration (Oliver 1971)
**Stenochironomus**
head capsule

miners in dead or living plants (wood, stalks, and water lily leaves) (Oliver and Roussel 1983)

**Stictochironomus**
head capsule - mentum

lakes, small lentic water bodies, slow reaches of lotic waters (Oliver and Roussel 1983)

**Pseudochironomus**
head capsule - mentum

littoral regions lentic waters, slow reaches of large lotic waters, sand or gravel substrates (Oliver and Roussel 1983)

**Cladotanytarsus mancus type**
head capsule - mentum

*Cladotanytarsus*: eurytopic; streams, rivers, lakes, ponds, brackish water, hot springs (Wiederholm 1983)
**Corynocera ambigua**

mentum

Palaeartctic & Nearctic (Oliver and Roussel 1983)

*Corynocera*: mud in small cold lentic waters (Oliver and Roussel 1983)

**Corynocera oliveri type**

mentum & mandibles with large surface teeth

Palaeartctic (Oliver and Roussel 1983); north of 60° (Barley 2004)

**Micropsectra atrofasciata/radialis type**

antennal pedastals with sharp spurs

*Micropsectra*: lentic and lotic waters, distributed widely and north of treeline (Oliver and Roussel 1983)

**Paratanytarsus**

head capsule - mentum

large lentic and lotic water bodies, distributed widely and north of treeline (Oliver and Roussel 1983)
**Stempellina**
head capsule – mentum & antennal pedestal

lentic waters; only south of treeline (Oliver and Roussel 1983)

**Stempellinella/Zavrelia**
head capsule – mentum & antennal pedestal

Stempellinella: lentic water bodies; Zavrelia: lentic and shallow regions of lakes (Oliver and Roussel 1983)

**Tanytarsus sp.C**
head capsule – mentum & antennal pedestal

*T.nigricans* & *T.obediens* are net-spinning plankton eaters (Berg 1950)

**Tanytarsus lugens type**
mentum & mandible with small surface teeth
cold oligotrophic indicator (Brundin 1958)
Family Simuliidae

head capsule - mentum

lotic (slowest to quickest flows); clingers, filterers, collectors; widespread in NA (Peterson 1996)

Order Diptera?

head capsule

Order Trichoptera

mandible
dorsal sclerite

cool lotic waters; some in larger warmer lentic waters (Wiggins 1996)
Order Ephemeroptera

head capsule - mandibles
generally lotic, some lentic habitats (Edmunds Jr. and Waltz 1996)

Order Hemiptera
Family Corixidae?

forewing
generally lentic, some lotic habitats (Polhemus 1996)

Order Acari

whole body
wrinkled

whole body
brown
Unknown invertebrate mandibles

4 toothed short mandible (4-tsm)  5 toothed short mandible (5-tsm)  3 toothed dark curved mandible (3-dcm)

Order Rhabdocoela, Class Turbellaria?

flatworm eggcases (Van Geel et al. 1981)
References


Appendix B  Modern & Fossil Sclereid Analysis & Morphology

*Sclereid Preparation & Identification*

Sclerenchymatous idioblasts or sclereids are considered the most “bizarre and polymorphic of all the types of idioblasts” (Foster 1956). Often noticed in Holocene lake sediment samples, but less often counted and identified, sclereids retain their morphological shape very well through time and rigorous sampling and processing techniques.

Sclereids are specialized schlerenchyma cells present in many plants, including those belonging to the water lily family, Nymphaeaceae. The Flora of North America lists two Alaskan species of water lilies (Family Nymphaeaceae), *Nuphar polysepalum* (spatterdock) and *Nymphaea tetragona* (pygmy waterlily), and one Alaskan water shield, *Brasenia schreberi* (Family Cabombaceae; previously placed in the Family Nymphaeaceae) (Flora of North America Editorial Committee (eds.) 1993+). *Nymphaea odorata* (fragrant white water lily) is an introduced species in British Columbia and its presence is noted in Alaska by the United States Department of Agriculture and Department of Defense. *Nuphar polysepalum* is a native species with globular yellow flowers and typical heart-shaped leaves, commonly known as yellow dock or spatterdock. It is generally found in ponds and slow streams, and is noted for the edibility of its rhizome, boiled or roasted (Hultén 1968). *Nymphaea odorata* has more elaborate white petals and slitted oval leaves, while *B. schreberi* has small inconspicuous purple flowers and oval leaves lacking a slit and covered on the underside by a viscid jelly (Hultén 1968). *N. tetragona*, present in lakes, ponds and swamps, has small white flowers and oval slitted leaves (Hultén 1968).

Previous work on the sclereid morphology of modern Nymphaeaceae and Cabombaceae is limited. Sclereid morphology was presented by Gaudet (1960) describing petiolar, laminar and stipular differences. Sclereids from the petioles are typically in bipolar or “H-shaped” form, with some stellate sclereids forming, whereas laminar sclereids are often l-shaped, with occasional irregular stellate-like forms. Stipular sclereids are a simple fusiform shape.
As far as the author knows, fossil sclereids had never previously been positively identified to species in Beringia. To facilitate identification, I examined material derived from *Nuphar*, *Nymphaea* and *Brasenia* species. Specimens of both the native spatterdock (*N. polysepalum*) and *Nymphaea odorata* were collected by Prof. Klaus Broderson from Idabel Lake and Kalamalka Lake, respectively, in the Okanagan region of British Columbia, Canada. Two dried samples of *Brasenia schreberi* were obtained from Simon Fraser University herbarium (Spider Lake, Vancouver Island, BC). One dried sample of *N. tetragona* was obtained from the University of British Columbia herbarium (accession #26082; collector, J.W. Eastham; Aleza Lake, BC). Attached to the *N. tetragona* specimen was a note indicating its “fairly abundant” growth with *Nuphar*.

To release sclereid cells from their surrounding tissue, small pieces of stems and leaves of each species were manually macerated in water with mortar and pestle and treated with 5% KOH on low heat until steam appeared within the beaker. Prior to maceration, the dried herbarium samples were boiled to soften tissue and prevent breakage of cells. Samples, except *Nymphaea tetragona*, were washed on a 95 μm mesh sieve with water. Each sample was examined in Bogorov counting trays under a dissecting microscope at ~25X magnification. Sclereid cells were transferred individually to cover slips, air dried and mounted with Entellan® onto microscope slides and dried for 3-5 days. Sclereid identification was performed on an Olympus BX51 compound microscope at 200X and 400X total magnifications. Comparative photographs of sclereids from all species were taken using a DMX 12000 digital camera mounted to an Eclipse 800 compound microscope (Nikon, Melville, New York, USA). Multiple photographs were taken of each taxon and compiled using Helicon Focus Version 2.03 Lite (Khmelik and Kozub 2004).

*Brasenia schreberi* does not contain any sclereids. However, many elongate cells cover the underside of leaves and surround the stems. These are surmised to be hairs, but may be glands contributing to the viscous fluid surrounding the leaf underside and stem.

*Nuphar polysepalum* sclereids are stellate, exhibiting long finger-like projections from a short mid-stem. Typically 5 to 9 projections from each end of the mid-stem were counted. *Nymphaea odorata* sclereids have 2 to 3 short stubby projections on both ends of a long mid-
stem, in a I-shape arrangement, identical to Gaudet’s (1960) laminar sclereids. Also, N. odorata sclereids have crystal-like structures (calcium oxalate? (Franceschi and Nakata 2005)) on the surface of the long mid-stem, whereas slight bumpiness was observed on “fingers” and stems of the Nuphar polysepalum sclereids. Nymphaea tetragona leaf and stem sclereids mainly consist of 2 to 3 elongate arms attached in the middle by short stems (H-shaped). Few are aster-like, and fewer still are similar to the I-shaped sclereids found in N. odorata.

It is uncertain at this point whether the three species (Nuphar polysepalum, Nymphaea odorata and N. tetragona) contain all three sclereid types (H- and I-shaped and stellate). Individual examination of leaf, stem and petal material is necessary to characterise sclereid types. It is likely that the fossil sclereids are those of Nuphar polysepalum, as it was the only modern sample containing stellate sclereids similar to those found in the lake sediments. As well, it is the commonest water lily in interior Alaska.
Modern Material

**Brasenia schreberi**

sclereid: none
specialized cells: trichomes or glands (hair follicle cells?) on stems and underside of leaves

**Nymphaea odorata**

sclereid: usually 4 to 6 short, thin branches from ends of long main axis (I-shape); spurious branch may occasionally occur ⅓ of distance along main axis; pits may be present on branches & main axis; crystals present occasionally
**Nymphaea tetragona**

**sclereid:** most are 4 to 6 branches in an H-shape (A); some I-shapes with one end branched in a “root-like” manner (B); verrucae on branches & main axis of I-shapes

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**Nuphar polysepalum**

**sclereid:** usually 6 to 9 thick branches radiating from a short main axis (stellate) (A); verrucae on branches & main axis (B)
Fossil Material

sclereid: typically 6 to 9 thick branches radiating from a short main axis (stellate)

sclereid: rarely, flat triangular shape with short paired branches
References


