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Utilisation d'indicateurs biologiques (Chironomides, ordre des diptères) et sédimentaires, dans le cadre de la reconstruction des variations paléoclimatiques durant l'Holocène, sur l'île de Southampton (Nunavut, Canada)

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Thèse présentée
pour l'obtention
du grade de Philosophiae doctor (Ph.D.)
en Sciences de l'Eau

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Résumé

Cette thèse présente pour la première fois, une étude paléolimnologique de l'île de Southampton (Nunavut, Canada). Basées sur des indicateurs biologiques (chironomides) et sédimentaires (XRF, analyses de grains, NCS), les séquences stratigraphiques de deux lacs localisés au nord-est de cette île, ont permis de reconstruire l'histoire environnementale de cette région depuis les 6000 dernières années. Suite à une période tumultueuse associée à un maximum thermique jusqu'à 4400 ans BP, cette région a connu une phase beaucoup plus stable de 3500 ans BP à aujourd'hui. Cet apparente stabilité a cependant été perturbée par des changements rapides mais non permanents, associés à un maximum thermique durant le médiéval (~ AD 1160 à AD 1360) et un évènement de petit âge glaciaire (~ AD 1360 à AD 1700). En complément de cette étude, une nouvelle fonction de transfert et un guide taxonomique ont été développés pour le nord-ouest du Québec. De plus, une méthode novatrice de récupération des capsules de chironomides à l'aide du kérosène a été testée avec succès. Dans un contexte de changements globaux et de modélisation climatique, cette thèse apporte de nouvelles données paléoclimatiques sur une région arctique peu étudiée, et contribue à l'effort de recherches scientifiques dans les régions limitrophes au Bassin de Foxe.

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Abstract

This thesis presents a first paleolimnological study for two north-eastern Southampton Island (Nunavut, Canada) lakes. Biological (Chironomids) and sedimentological (XRF, grain size, CNS) analyses were carried out on stratigraphic sequences to reconstruct past environmental history of this region since the past 6000 years. Following an unstable period related to a Holocene Thermal Maximum that lasted until 4400 BP, this region shift to a more stable environment that lasted from 3500 BP until now. This relative stability was however perturbed by short-lived events related to a Medieval Warming Period and a Little Ice Age that lasted from ~ AD 1160 to AD 1360 and ~ AD 1360 to AD 1700 respectively. Those paleoclimatic reconstructions were made possible with the development of a new transfer function for the northwestern Quebec. In order to refine the tools available for the chironomid laboratory analyses, this thesis successfully tested a new flotation technique using kerosene. A new taxonomic guide for the eastern part of Canada was also developed. As part of concerted studies around the Fox Basin region, this thesis provides important paleoclimatic data of a little known arctic region. With a now well accepted global warming, this thesis will benefit climate modeling and their ability to model past, present and future environmental changes.

Remerciements

Manet alta mente repostum

Le souvenir reste profondément gravé dans le cœur. Ce souvenir de trois années qui semblent s'être envolées dans le temps tellement elles ont passé vite. Ce souvenir d'une période importante d'une vie qui n'aurait jamais pu être accomplie sans la collaboration de plusieurs personnes.

Je tiens particulièrement à remercier ma directrice, Isabelle Larocque, qui a toujours été là pour faire progresser mes connaissances dans un domaine de recherche aussi vaste que passionnant. Merci aussi à mon co-directeur, Pierre Francus, pour m'avoir ouvert l'esprit sur plusieurs domaines (e.g. la sédimentologie et le Mac !) et pour avoir toujours été là pour répondre à mes questions et faire progresser la qualité générale de cette thèse.

Je l'ai considéré comme un second co-directeur officieux tant sa participation à mon projet de recherche a été importante, je tiens donc à remercier Reinhard Pienitz.

Je remercie également les membres du comité d'évaluation, Alain Rousseau, Roberto Quinlan, Irene Gregory-Eaves et Landis Hare, pour avoir lu et jugé ce travail. Merci aussi à Vicky Tremblay, Stéphanie Cuven et Jean-François Crémer pour leur contribution de près ou de loin à cette recherche.

Et pour terminer, merci à mes parents et surtout à l'amour d'une vie, Windy, pour être toujours là près de moi et pour ne jamais avoir cessé de croire en moi.

Vivre, vraiment vivre,
c'est se poser des questions, ce n'est pas connaître les réponses.
C'est le désir de voir ce qu'il y a derrière la prochaine colline qui nous permet
d'aller plus loin.
Nous ne devons jamais arrêter de nous poser des questions,
de vouloir comprendre.
Et même lorsque nous savons que nous ne trouverons jamais les réponses,
nous devons continuer à nous poser des questions.

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Première Partie

Introduction

Chapitre 1

INTRODUCTION

1.1 Mise en contexte

L'avènement de l'ère industrielle au début du $20^{\text{ième}}$ siècle a engendré une consommation croissante de diverses ressources naturelles, notamment des combustibles fossiles générateurs de gaz à effets de serre. Ces gaz, tels que le dioxyde de carbone, le méthane et les oxydes nitreux ont soulevé de vifs débats au sein des différentes communautés scientifiques, politiques et sociales, sur leur capacité à bouleverser le climat terrestre. Ces modifications climatiques anormalement rapides et de nature anthropique, se traduisent entre autres, par une augmentation de la température moyenne de la basse atmosphère. Ce réchauffement global, qui est particulièrement amplifié aux pôles, commence à avoir des impacts majeurs sur les latitudes arctiques et subarctiques. En effet, les observations montrent entre autres que 1) la banquise arctique s'amenuise d'environ 32 000 km^2 par année et s'est amincie de 1,3 m, soit 40 % de son épaisseur totale, en seulement 30 ans (Johannessen *et al.*, 1995; Dickson, 1999; Johannessen *et al.*, 1999; Rothrock *et al.*, 1999; Comiso, 2002); 2) la température moyenne du pergélisol, soit la couche terrestre de surface qui se maintient constamment à une température inférieure ou égale à 0 degrés Celsius (°C) durant au moins 2 années consécutives, a augmenté depuis les dernières décennies en Alaska, dans le nord ouest Canadien, en Sibérie et dans l'Europe du Nord (Richter-Menge *et al.*, 2006); et 3) la limite nord de la forêt boréale en Russie et au Canada s'est déplacée davantage vers des latitudes plus hautes (Schiermeier, 2006; Richter-Menge *et al.*, 2006).

Prévoir les effets potentiels du réchauffement climatique sur les écosystèmes nordiques représente un défi de taille pour la communauté scientifique. Les modèles de prédictions se basent sur des données qualitatives (observations enregistrées dans les archives) et quantitatives (données récoltées par des appareils de mesures) qui couvrent généralement une très courte période de temps (moins de 100 ans pour les données quantitatives) et qui ne représentent pas nécessairement les variations naturelles du climat puisqu'elles concordent avec l'essor de l'activité humaine à l'échelle globale. Il est donc nécessaire d'utiliser l'information passée, qui représente le climat naturel des écosystèmes, pour mieux décoder et accroître la véracité des modèles de prédiction du climat futur. Cette information mettra en évidence l'impact réel des changements actuellement observés. De plus, elle permettra aussi de décrire d'éventuels bouleversements passés ainsi que leurs impacts sur les écosystèmes terrestres. Elles offrent donc une vision passée de ce que pourra être, sous toute réserve, le futur.

Ce projet de recherche multidisciplinaire s'intègre parfaitement dans l'optique d'un raffinement des modèles climatiques, puisqu'il apportera des données nouvelles sur une région arctique peu ou pas étudiée. Les patrons climatiques ainsi reconstruits, permettront de mieux comprendre comment ce milieu a évolué depuis la dernière déglaciation et comment il est affecté par le réchauffement climatique récent.

1.1.1 Contenu de la thèse

Cette thèse se propose de reconstruire le climat naturel de l'île de Southampton depuis la fin de la dernière déglaciation. L'originalité de cette thèse repose sur le couplage des informations biologiques et sédimentaires contenues dans les sédiments lacustres arctiques. L'application de cette méthode permettra d'élargir notre compréhension dans l'utilisation de ces indicateurs afin d'étendre la couverture paléoclimatique en Arctique et enrichir les bases de données existantes sur lesquelles se baseront les futurs modèles de prédictions climatiques.

La thèse se divise en quatre parties. La première (Chapitre 1) présente une introduction générale qui vise à développer les différents concepts sur lesquels se base cette étude. Les sujets suivants sont notamment abordés : le climat terrestre, le milieu arctique, la paléoclimatologie, le milieu lacustre, la sédimentologie lacustre, la biologie des chironomides et finalement les différentes méthodes d'analyses utilisées pour les reconstructions climatiques impliquant des indicateurs biologiques. Cette partie inclut par la suite la problématique et les objectifs de cette thèse ainsi qu'une succincte description des sites choisis pour la réalisation de cette étude et de la méthodologie impliquée. Finalement, cette introduction informe le lecteur de la contribution scientifique et humaine de cette étude.

La deuxième partie est composée de 3 articles constituant autant de chapitres. Le deuxième chapitre traite du développement d'une méthode novatrice de récolte des capsules de chironomides. L'utilisation du kérosène, aussi connu en Angleterre sous le nom d'huile de paraffine, permet de séparer spécifiquement les composés riches en chitine, telles que les capsules de chironomides, du reste des particules organiques et minérales composant le sédiment lacustre, et ce, sans affecter l'efficacité du processus et les analyses qualitatives et quantitatives subséquentes.

Le troisième chapitre présente la reconstruction paléoclimatique d'un lac localisé dans la partie nord de l'île de Southampton depuis la création de ce dernier, soit durant les 6000 dernières années. La résolution de l'étude offre un portrait global des variations climatiques majeures qui se sont succédées au cours du temps et qui ont affecté tous les constituants sédimentaires du lac, dont entre autres, les chironomides et la matrice physico-chimique du sédiment. Cette étude apporte de nouvelles données sur le relèvement isostatique et la stabilité climatique de cette région.

Le quatrième chapitre dresse un portrait à plus haute résolution temporelle du climat sur l'île de Southampton au cours du dernier millénaire. Dans le cadre de l'étude d'un deuxième lac au nord de cette île, l'utilisation conjointe d'indicateurs sédimentaires et biologiques a permis de découvrir que malgré la forte résilience climatique de cette région arctique, le lac étudié a positivement réagi à d'importants forçages climatiques naturels dont les effets sont reconnus pour avoir touché une grande partie de l'hémisphère nord. Cette étude renforce aussi l'importance d'inclure des analyses sédimentologiques lors de l'interprétation de données sédimentaires biologiques telles que les chironomides.

Le premier article présenté dans la deuxième partie de la thèse a été publié. Le deuxième a été accepté récemment. Le dernier sera soumis prochainement à une revue reconnue dans le domaine de la paléolimnologie. Ces deux derniers articles ont été présentés lors d'un symposium international et d'un atelier de travail sur l'Arctique. Les références sont les suivantes :

Chapitre 2:

- **Rolland N**, Larocque I (2006) The efficiency of kerosene flotation for extraction of chironomid head capsules from lake sediment samples. Journal of Paleolimnology 37:565-572.

Chapitre 3:

- **Rolland N**, Larocque I, Francus P, Pienitz R, Laperrière L. Holocene climate inferred from biological (Diptera : Chironomidae) analysis in a Southampton Island (Nunavut, Canada) lake. The Holocene (accepté)
- **Rolland N**, Larocque I, Francus P, Pienitz R, Laperrière L (2006) Paleolimnological history of Southampton Island (Nunavut, Canada). 10th International Paleolimnology Symposium, Duluth, Minnesota, USA.

Chapitre 4:

- **Rolland N**, Larocque I, Francus P, Pienitz R, Laperrière L. Late Holocene chironomid assemblages in a northern Southampton Island (Nunavut, Canada) lake: evidence of a medieval warming period (à soumettre).
- **Rolland N**, Larocque I, Francus P (2007) Chironomids as indicators of Late-Holocene climate in a northern Southampton Island (Nunavut, Canada) lake. 37th Annual Arctic Workshop, Institude of Earth Sciences, University of Iceland.

La troisième partie de la thèse présente une conclusion générale de cette étude (Chapitre 5), suivie de la liste des références utilisées tout au long de la thèse.

La quatrième et dernière partie de cette thèse présente en annexe, un article sur lequel l'auteur de cette thèse a travaillé au court des trois dernières années. Ce dernier traite des effets de différents facteurs physico-chimiques sur la distribution des chironomides le long d'un gradient environnemental dans le nord-ouest du Québec. Ce travail présente par conséquent une fonction de transfert qui permet de reconstruire dans ces régions la température moyenne de l'air au mois d'août le long d'une séquence stratigraphique lacustre. Cet outil est la base et la raison même de cette thèse de doctorat car il a ouvert la voie aux reconstructions paléoclimatiques présentées dans les chapitres 3 et 4 de cette thèse. En deuxième annexe, la quatrième partie de cette thèse présente aussi le chapitre 4 d'un guide visuel de la taxonomie des chironomides sub-fossiles du Québec à l'île d'Ellesmere. Ce guide s'intègre entièrement à cette thèse et représente un chapitre à part entière, mais pour des raisons de simplification de la lecture de cette thèse, il a été inclus en tant qu'appendice. Les références sont les suivantes :

- Larocque I, Pienitz R, **Rolland N** (2006) Factors indicating the distribution of chironomids in lakes distributed along a latitudinal gradient in northwestern Québec, Canada. Canadian Journal of Fisheries and Aquatics Sciences 63:1286-1297

- Larocque I, **Rolland N** (2006) A Visual guide to sub-fossil chironomids from Quebec to Ellesmere Island. Rapport de recherche R-900, Institut National de la Recherche Scientifique, Québec, Canada, 116 pp.

1.2 Le climat terrestre

D'un point de vue métaphysique, le climat peut se définir comme l'expression statistique des variations quotidiennes des événements météorologiques à un endroit précis. Il est donc exprimé le long d'un intervalle de temps, et la distribution des différents paramètres environnementaux obtenus à divers endroits permet de définir la variabilité climatique d'une région (Bradley, 1999).

D'un point de vue plus pragmatique, le climat est tout simplement un état météorologique escompté sur une période de temps prédéfinie. Il est la résultante des radiations solaires et des interactions non linéaires entre différents systèmes internes tels que l'atmosphère, les océans, la biosphère, les surfaces terrestres et la cryosphère (Bradley, 1999; Grassl, 2001). Chaque système réagit différemment aux variations journalières, mensuelles, saisonnières et annuelles selon leur aptitude à emmagasiner et retenir l'énergie thermique transmise par les rayons solaires. De ces systèmes, l'atmosphère étant l'élément qui a la plus faible capacité thermique, elle influencera les événements météorologiques sur de très courtes périodes de temps sans nécessairement affecter le bilan annuel climatique. À l'inverse, les océans possèdent une très grande résilience thermique et agissent comme des tampons contre les variations saisonnières de température (Bradley, 1999).

Parallèlement à ces mécanismes de régulations internes, il existe des systèmes externes non influencés par ces derniers et dont l'activité a régulé le climat terrestre depuis probablement la formation de la Terre et de son atmosphère. Parmi eux se trouvent l'activité volcanique et tectonique, l'activité solaire et les variations orbitales terrestres (Bradley, 1999).

C'est vers la fin du 19$^{\text{ième}}$ siècle, que l'écossais James Croll émit l'hypothèse que les glaciations qui ont eu lieu sur Terre par le passé, sont principalement la résultante des variations dans les paramètres orbitaux terrestres (Bradley, 1999). Cette hypothèse fut par la suite élaborée plus concrètement en 1941 par Milutin Milankovitch, et finalement vérifiée, améliorée et confirmée mathématiquement par André Berger vers 1977 (Berger, 1988; Berger et Loutre, 2004; Bradley, 1999).

La Terre, troisième planète du système solaire, se déplace autour du Soleil le long d'un axe plan, l'écliptique. De par les forces gravitationnelles générées par le Soleil, la Lune et les autres planètes du système solaire, la rotation de la Terre se fait selon une ellipse, dont l'excentricité (le rapport longueur/largeur) a varié sur une période d'environ 95800 ans, passant d'un cercle presque parfait (excentricité de 0), à une ellipse longue et étroite (excentricité de 6 %). Cette variation de l'écliptique a affecté l'intensité et l'amplitude des variations thermiques de chaque saison. Actuellement la Terre est le plus proche du Soleil en janvier (3) (le périhélie) et le plus loin du Soleil en juillet (5) (l'aphélie). La conséquence de cette variation de distance Terre/Soleil est qu'au périhélie, la Terre reçoit environ 3,5 % plus de radiation solaire que la moyenne annuelle alors qu'à l'aphélie elle en reçoit 3,5 % moins. L'excentricité actuelle est de l'ordre de 1,67 % (Murdin, 2001).

Conjointement à ce déplacement elliptique, la Terre tourne sur elle-même le long d'un axe orienté de 23,4° par rapport au plan de l'écliptique. Ce mécanisme, appelé l'obliquité, définit les latitudes des cercles polaires et tropicaux. Elle influence la quantité de radiations solaires arrivant au sol et affecte principalement les régions polaires. L'obliquité varie de 21,8 à 24,4 % selon une fréquence d'environ 41000 ans. La rotation de la Terre autour de son axe nord/sud ainsi que la variation d'obliquité au cours du temps génèrent un mouvement d'oscillation qui détermine les moments auxquels le périhélie et l'aphélie ont lieu, soit la précession des équinoxes. Contrairement à sa position actuelle (janvier), il y a 11000 ans, le périhélie a eu lieu lorsque l'hémisphère nord était tourné vers le Soleil, soit à la mi-juin (Murdin, 2001).

L'addition des effets respectifs de ces paramètres orbitaux a eu un impact sur les périodes de glaciation/déglaciation et donc sur l'histoire du climat terrestre. Selon Milankovitch, les conditions propices à une glaciation généralisée sont 1) une obliquité minimale, 2) une excentricité importante, et 3) l'arrivée de l'été dans l'hémisphère nord lors de l'aphélie. Cet état idéal aurait permis de générer suffisamment d'humidité dans l'air pour accroître les précipitations dans les hautes latitudes et donc l'accumulation et la compaction de neige (Bradley, 1999).

Les dernières glaciations/déglaciations ne sont pas uniquement la conséquence des variations orbitales. En effet, la circulation atmosphérique, générée par la différence de température des masses d'air entre les tropiques et les pôles, a eu aussi une grande influence sur les périodes de glaciation (Bradley, 1999). Cette différence de température est conjointement liée à la circulation océanique et à la charge thermique des différentes masses d'eau en profondeur et à la surface des océans. En effet, les océans exercent un rôle important dans la régulation de la température de la basse atmosphère via les mécanismes de chaleur sensible (transfert direct de chaleur entre la surface de l'eau et celle de l'atmosphère) et de chaleur latente (transfert de chaleur via l'évaporation de l'eau) (Grassl, 2001). Parallèlement à ces mécanismes directs, il existe des mécanismes indirects comme celui relié à la charge en dioxyde de carbone (CO_2) dans les différents compartiments organiques de la colonne d'eau, qui est très influencé par la température du milieu. Ainsi, si un réchauffement des masses d'eau est constaté, la recherche de l'équilibre stoechiométrique entre les deux compartiments déplacera le CO_2 vers le système atmosphérique (Wallace, 2001). Cet effet de rétroaction positive augmentera l'absorption des rayons infrarouges terrestres par les molécules de CO_2 et, parallèlement, favorisera l'élévation de la température de la basse atmosphère bouleversant ainsi la circulation atmosphérique. À l'inverse, lors d'un refroidissement, l'absorption de CO_2 par les océans diminuera l'absorption des rayons infrarouges et de ce fait la température de l'air (Bradley, 1999).

Les changements climatiques résultent donc de forces internes et/ou externes au système terrestre. Ces mécanismes de régulation forment un système relativement complexe et cyclique (p. ex. cycle de Milankovitch). Cette cyclicité des événements climatiques a visiblement été modifiée depuis l'expansion des activités humaines reliées à une utilisation de ressources non renouvelables telles que les combustibles fossiles. Diverses recherches ont démontré que les variations atmosphériques en CO_2 et méthane

(CH_4) au cours du passé sont de même amplitude que celles observées depuis le dernier siècle, cependant, les changements récents (anthropiques) ont été beaucoup plus rapides (Pearson et Palmer, 2000). Les effets de ces changements accélérés nécessitent donc une compréhension approfondie des événements climatiques passés ainsi que leurs effets sur les différents écosystèmes terrestres notamment le milieu arctique qui, de par sa position circumpolaire, est très affecté par cette accélération anthropique du cycle des variations climatiques.

1.3 L'Arctique

L'Arctique est défini comme la région au nord de la limite des arbres (forêt boréale), soit plus précisément la région où la température moyenne en juillet est de 10 °C. D'un point de vue d'océanographe, il s'agit de la limite marine où se trouve la zone de rencontre entre les eaux de surface de l'Arctique (froides et peu salées) et les eaux du sud (chaudes et très salées) (Murray, 1998). Ce grand territoire est composé de pergélisols traversés par de grands fleuves, et d'une vaste étendue d'eau (l'Océan Arctique) dont la couverture de glace varie de $16x10^6$ km^2 en mars à environ $9x10^6$ km^2 en septembre (Murray, 1998). Conjointement aux paramètres orbitaux qui induisent une faible radiation annuelle (nulle en hiver et très forte en été) et à l'albédo généré par la glace de surface et la couverture nuageuse, le climat arctique est froid et sec (précipitations annuelles variant entre 200 et 500 mm) (AMAP, 1998).

Dans un contexte de réchauffement climatique, il est capital de bien comprendre le mode de fonctionnement de cet écosystème en pleine mutation et dont le potentiel de rétroaction positive sur les changements anthropiques actuels n'est pas négligeable (AMAP, 1998). En effet, selon les observations et les modèles catastrophistes, l'augmentation de la température de la basse atmosphère favorisera la fonte du pergélisol (Stokstad, 2004) et de la banquise (Kerr, 1999) avec pour conséquences le largage de gaz à effets de serre comme le CO_2 et le CH_4 dans l'atmosphère, l'augmentation du débit des grands fleuves arctiques (Peterson *et al.*, 2002), l'augmentation des niveaux marins suite à la fonte des grands glaciers, la modification de la circulation thermohaline profonde de l'Atlantique Nord (Häkkinen et Rhines, 2004) et la disparition des lacs arctiques peu profonds (Smith *et al.*, 2005). D'un côté plus social et politique, les bouleversements arctiques toucheront toutes les populations locales et soulèveront des débats politiques sur l'accessibilité et la souveraineté de cet environnement (AMAP, 1998; Kerr, 2002).

Comme mentionné précédemment, la rareté des données quantitatives disponibles, et la difficulté d'accès à cet environnement jusque-là très hostile, ont généré une base de données qui caractérise les changements récents, mais qui ne permet pas de connaître en profondeur les variations cycliques depuis la dernière déglaciation (Larocque *et al.*, 2001). Cependant, lors du retrait des grands glaciers, et suite au relèvement isostatique qui s'est opéré et qui continue de nos jours, beaucoup de lacs arctiques ont été créés et ont évolué au cours des 8000 dernières années soit durant l'Holocène. Ces lacs, dont ceux en altitude sont plus vieux que leurs homologues près du niveau marin, représentent des milieux de choix pour l'étude du climat arctique. Ils constituent une source d'archives relatant les événements passés avec une très grande résolution temporelle (Schiermeier, 2004). De nombreuses études récentes ont ainsi pu mettre en évidence les transformations qui s'opèrent dans les écosystèmes lacustres depuis les 150 dernières années (Birks *et al.*, 2004; Michelutti *et al.*, 2002; Michelutti *et al.*, 2003; Moritz *et al.*, 2002; Smol *et al.*, 2005). Ces lacs, comme nous le verrons par la suite, peuvent donc nous aider à reconstruire via les sciences paléoclimatiques, les perturbations climatiques qui ont eu lieu depuis la dernière déglaciation (Miller *et al.*, 2005).

1.4 La paléoclimatologie

La paléoclimatologie est l'étude des systèmes climatiques passés, et donc de la dynamique de ces systèmes sur une échelle décennale (10^2) à millénale (10^3) (Seidov *et al.*, 2001). Cette science se base sur les différentes sources chimiques, physiques et biologiques qui se retrouvent piégées dans les compartiments terrestres et aquatiques (paléoarchives), telles que les glaces des grands glaciers terrestres, ainsi que les tourbières et les archives sédimentologiques des océans et des lacs.

De ces compartiments, les lacs ressortent comme des milieux essentiels aux études paléoclimatiques, notamment en Arctique (Bradley, 1999; Smol, 2005; Smol *et al.*, 2005). La nature particulière de leur mode de création puis de fonctionnement favorise l'accumulation de sédiment (comblement). Lorsque les forces hydrodynamiques ne sont pas suffisantes pour déplacer ce matériel sédimentaire, les sédiments enregistrent la dynamique de l'écosystème lacustre à travers le temps. La paléolimnologie, concentre alors ses activités sur l'interprétation des séquences sédimentaires lacustres et sur les processus pouvant altérer ces dernières. Le but recherché est la reconstruction des conditions passées et des paramètres de régulation qui les ont influencés. La paléolimnologie offre donc les outils à la compréhension des trajectoires que prendront les écosystèmes en fonction des conditions climatiques futures.

1.5 Le système lacustre

Les lacs contiennent trois types d'archives dont l'importance historique est fonction de leur temps de résilience (Cohen, 2003). L'eau est la première archive possible. Son temps de résilience (jours < t < 1000 ans) dépend de la taille du bassin concerné, des gains externes (intrants) et des pertes internes (extrants). Ce compartiment lacustre peut fournir des renseignements sur la nature géologique du bassin versant qui se déverse dans le lac, ainsi qu'à plus courte échelle, sur la productivité du milieu. La géomorphologie des lacs, telles que les lignes côtières, forme le deuxième type d'archives disponibles. Elle offre entre autres la possibilité de retracer les diverses variations du niveau d'eau du lac grâce aux marques d'érosion qui ornent le paysage périlacustre. La dernière archive, la plus importante pour les études paléoclimatiques, est l'information conservée dans les sédiments.

1.5.1 Formation des sédiments lacustres

Les sédiments proviennent d'apports exogènes et endogènes au milieu lacustre (Figure 1.1). La matière allochtone provient entre autres de l'érosion du bassin versant, des débris organiques (feuilles, humus, branches) et inorganiques transportés par les rivières, et des dépôts atmosphériques tels les grains de pollen, les cendres volcaniques et les poussières. La matière autochtone est la résultante de l'activité biologique et chimique au sein même de la colonne d'eau. Ces processus aquatiques produisent des résidus tels que des pelotes fécales (zooplancton), cellules mortes (phytoplancton), macrorestes et organites provenant de la précipitation de composés chimiques. L'exportation verticale des particules sédimentaires inorganiques et organiques vers le système benthique du lac, les expose à diverses contraintes physiques, chimiques et biologiques. Ces dernières peuvent en altérer la forme, l'état et les propriétés, et par conséquent réduire leur potentiel d'archive pour les études paléolimnologiques.

Selon Cohen (2003), la sédimentation lacustre est contrôlée par six processus : 1) la géologie du bassin versant (topographie, composition des roches), qui influence le taux de sédimentation possible dans le lac ainsi que la nature physico-chimique de ces sédiments, 2) le climat du bassin versant, qui influence directement la nature et l'abondance de la végétation, des précipitations et indirectement les forces érosives qui agissent sur le substrat, 3) le mode de formation et de morphologie du lac, 4) la position du lac dans le système hydrologique de la région étudiée, 5) la nature de la circulation d'eau interne, c'est-à-dire, les effets des courants sur la remise en suspension des sédiments et leur déplacement horizontal, qui génèrent un effet de concentration des sédiments à certains endroits du bassin (« sediment focusing »), et influencent aussi le potentiel redox et donc les processus de diagenèse, et 6) la production organique dans la colonne d'eau, qui contrôle positivement l'abondance de matière organique dans les sédiments.

Tous ces processus vont générer différents patrons de sédimentation qui, couplés aux phénomènes de dégradation des particules sédimentaires lors de leur exportation verticale, vont encourager l'utilisation de certains types de lacs pour les études paléolimnologiques. En effet, les lacs dans lesquels se retrouvent les caractéristiques favorisant l'accumulation sédimentaire tout en minimisant les perturbations chimiques et biologiques, permettront d'obtenir de longues séquences chronologiques pour des analyses à hautes résolutions et sur de longues périodes de temps. De plus, les lacs ayant des cycles de sédimentation saisonniers formeront des sédiments laminés (dits varvés), composés d'une succession de couches minérales et détritiques, dont chaque couplé représente une année de production.

Les archives sédimentologiques offrent donc aux paléolimnologistes les outils nécessaires à des reconstructions quantitatives des conditions environnementales passées grâce notamment aux développements mathématiques des dernières années (ter Braak, 1996; Lepš et Šmilauer, 2003). Comme nous le verrons plus tard, l'utilisation de fonctions de transfert qui relient les conditions environnementales actuelles de plusieurs lacs avec l'ensemble des espèces (assemblage) retrouvées à la surface de chacun des lacs, permet de quantifier des variables passées (p. ex. température), en fonction des assemblages retrouvés dans les différents niveaux des carottes de sédiment étudiées.

1.5.2 Utilisation de l'information contenue dans les sédiments lacustres

Les études paléolimnologiques exploitent différentes sources d'informations enregistrées par les sédiments lacustres au cours du temps, soit lors de leur formation et de leur évolution. Ces sources d'informations géologiques, chimiques et biologiques représentent des indicateurs des conditions environnementales passées (Cohen, 2003). Il convient de faire une précision sur les termes souvent employés en français pour les caractériser, notamment au niveau de l'utilisation du terme « proxie » qui réfère plus à un substitut direct d'une variable environnementale, et non à une caractérisation indirecte de cette dernière. Le terme indicateur sera donc privilégié pour le reste de la partie francophone de ce document.

Comme précisé précédemment, les différentes forces qui s'exercent sur les particules sédimentaires pendant et après leur dépôt, filtrent l'information qu'elles ont enregistrée, ce qui rend parfois leur interprétation difficile. La taphonomie, soit l'étude des processus qui affectent les indicateurs fossiles dans les sédiments entre la période post-dépôt et pré-analyse par les paléolimnologues, permet de mieux comprendre ces transformations, et augmente la justesse de l'interprétation des résultats.

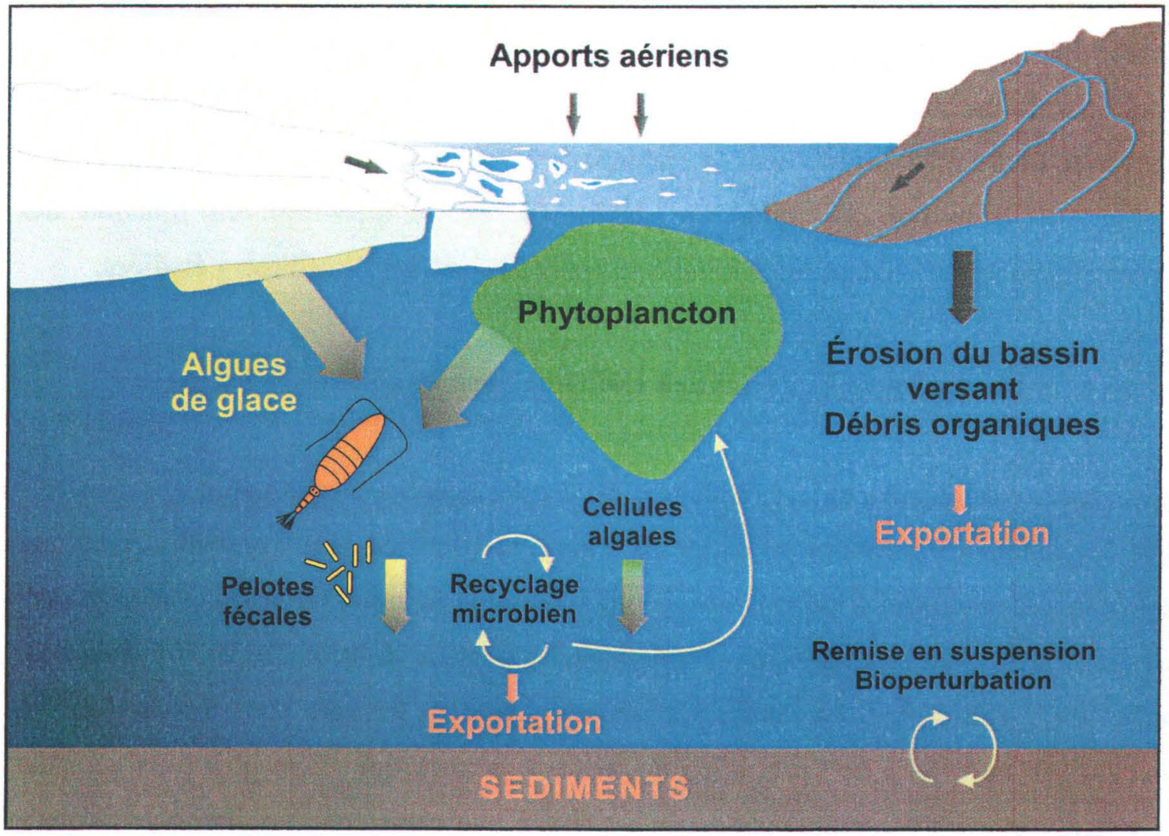


Figure 1.1 Schématisation des différents processus intervenant dans la formation des sédiments lacustres.

Pour illustrer l'importance de la connaissance des processus taphonomiques, prenons comme exemple les pigments photosynthétiques qui, lors de leur exportation vers le domaine benthique, subissent des transformations moléculaires durant lesquelles certains ions et groupes atomiques sont progressivement perdus par des dégradations physico-chimiques et biologiques. La dégradation de ces éléments augmente progressivement leur stabilité, ce qui se traduit par une diminution de leur solubilité, et une augmentation de leur résistance face aux attaques microbiennes et physiques. Par exemple, la *chlorophylle a* se transforme en *pheophytin a* suite à la perte de son magnésium, puis en *pheophorbide a* suite à la perte de son groupe phytyl. Tout ce processus tend à la formation d'un produit intermédiaire très stable, la *chlorophyllide a* (Leavitt et Hodgson, 2001; Wetzel, 2001). Les chlorophylles non dégradées sont donc très rares, et grâce aux études biochimiques sur leur évolution au sein de l'écosystème lacustre, il a été possible d'utiliser les résidus chlorophylliens comme indicateurs de certaines conditions environnementales passées.

Tous les indicateurs (biologiques principalement) conservés dans les sédiments ne sont pas propices à une utilisation en paléolimnologie, notamment par la rareté de certaines espèces, leur mauvaise conservation et la difficulté à les identifier (Bradley, 1999). Parmi les indicateurs sédimentaires couramment utilisés, les analyses de la nature et de la texture des grains, ainsi que des analyses géochimiques, permettent des descriptions paléohydrologiques et physiques du lac et de son bassin versant (Last, 2001). Les analyses texturales du sédiment lacustre offrent notamment l'opportunité de reconstruire les conditions hydrologiques passées qui ont influencé les processus sédimentaires du lac et par extension la communauté biologique qui dépend de cette matrice sédimentaire. Parallèlement à cela, la composition organique et inorganique du sédiment apporte de précieux renseignements quand à l'état trophique du lac et l'apport détritique de son bassin versant. Ces informations peuvent donc améliorer l'interprétation des observations faites sur la communauté biologique du lac. Parmi cette dernière, les diatomées dominent grâce à leur abondance et à leur biodiversité hors du commun. Ces deux caractéristiques démontrent leur sensibilité à une variété de paramètres limnologiques et hydroclimatiques, leur permettant de reconstruire fidèlement des variables comme le pH et l'état trophique d'un milieu aquatique (Stoermer et Smol, 1999). Cependant, leur utilisation a mis en évidence des lacunes au niveau de leur potentiel de reconstruction de facteurs physiques (p. ex. température de l'air) lorsque des facteurs non environnementaux (p. ex. pH) ne sont pas stables au cours du temps (Larocque et Bigler, 2004).

Il existe un lien étroit entre la température d'un milieu aquatique, tel un système lacustre, et celle de la basse atmosphère terrestre (Livingstone et Lotter, 1998). Cette relation, qui souvent peut se traduire par une relation mathématique simple, ne reflète cependant pas nécessairement l'intervalle de temps nécessaire à l'équilibre thermique entre les deux milieux dont la capacité calorifique diffère fortement. Dépendamment du forçage hydrologique qui s'opère sur le lac, la température de la colonne d'eau peut ne pas être influencée par celle de l'air et ne pas représenter un lien étroit entre ces deux milieux (Bradley, 1999). Dans le cadre de modélisation du climat, l'utilisation d'indicateurs biologiques exclusivement aquatiques pour reconstruire quantitativement la température de l'air peut donc parfois biaiser les résultats obtenus lors de l'extrapolation des données avec leurs analogues modernes. Dans une telle situation, il est donc essentiel d'utiliser des indicateurs biologiques dont le cycle de vie les expose à un milieu aquatique et aérien.

Grâce à leur grande diversité, les insectes ont su s'imposer dans la quasi-totalité des biotopes terrestres et aquatiques. Leurs variétés de formes et d'exigences biologiques, les rendent très utiles dans la caractérisation de l'état physico-chimique d'un milieu. De ce grand nombre d'espèces, les insectes ayant une partie aquatique et aérienne dans leur cycle de vie, notamment les chironomides (insectes non piqueurs), ressortent comme des indicateurs de choix pour la mise en évidence des variations de température passées (Walker *et al.*, 1991; Walker *et al.*, 1997; Brooks et Birks, 2001; Larocque *et al.*, 2001; Brooks et Birks, 2004; Kurek *et al.*, 2004).

1.6 Les chironomides en paléoclimatologie

Avant de développer sur l'utilité des chironomides en paléoclimatologie, il incombe de décrire en profondeur la biologie de ces insectes afin de mieux interpréter la relation étroite entre leur cycle de vie et les variations saisonnières de leur environnement.

1.6.1 Biologie et écologie des chironomides

Les chironomides, membres de l'ordre des diptères, sont des mouches non piquantes holométaboles, c'est-à-dire, qui ont un état nymphal entre le passage de la larve à l'adulte (Cranston, 1995). Il existe plus de 10000 espèces (25 % des insectes aquatiques) de chironomides réparties à travers les différents écosystèmes associés à un milieu aquatique (Rossaro, 1991). De par les processus de sélection naturelle, l'amplitude des diverses conditions physico-chimiques retrouvées à l'échelle globale a favorisé la diversification de ces insectes afin de leur permettre de s'adapter à de nouvelles niches écologiques. Ainsi, les chironomides sont aptes à vivre dans des milieux extrêmes de température, pH, salinité, altitude et conditions trophiques. Par exemple, les larves des Chironominae et de certains Tanypodinae, possèdent une hémoglobine ayant une très grande affinité avec l'oxygène dissous dans l'eau. La synthèse de cette protéine leur permet donc de tolérer des milieux très pauvres en oxygène, notamment dans des bassins lacustres très eutrophiés (Hilsenhoff, 1991).

Le développement des chironomides compte sept stades de vie soit l'œuf, quatre stades larvaires, la nymphe et finalement l'imago (adulte) (Tokeshi, 1995) (Figure 1.2). La ponte des œufs débute généralement au crépuscule alors que la femelle dépose sur des substrats attenants à la surface de l'eau, ou directement sur l'eau, un ou des sacs mucilagineux remplis d'œufs. Les milieux sombres sont privilégiés pour éviter toute forme de prédation visuelle. En moyenne, une femelle pond entre 20 à 2000 œufs, selon sa taille. Les œufs, dont la taille varie encore une fois en fonction de l'espèce de 170 µm de long et 70 µm de large à 612 µm de long et 135 m de large, sont de forme elliptique et entourés par un chorion qui les protège des agressions extérieures telle la dessiccation.

L'œuf requiert entre 2,5 et 6 jours pour se développer et éclore dans des conditions optimales de température et de salinité. Certaines espèces nécessitent plus de 100 jours dans des conditions froides (< 5 °C) telles que celles rencontrées dans les milieux arctiques (Pinder, 1995).

L'éclosion de l'œuf s'opère par des mouvements de torsion et de flexion de la larve jusqu'à la rupture du chorion. La larve alors transparente commence son premier stade de vie larvaire soit le premier instar. La larve est composée d'une capsule céphalique sur laquelle se retrouve un mentum, des antennes et des mandibules. Le reste du corps est long, cylindrique, segmenté et recourbé. La morphologie du premier instar est chez certaines espèces très différentes des autres instars. L'identification des individus en se basant uniquement sur le premier stade larvaire est donc relativement difficile. Le premier instar est planctonique, il se déplace au gré des courants et peut, grâce aux soies qui recouvrent son corps, parcourir verticalement la colonne d'eau lorsqu'il se trouve dans un milieu où le courant est faible (Pinder, 1995). À partir de ce stade de vie, chaque mue apporte des changements dans la morphologie de la larve, notamment au niveau de la forme de la capsule céphalique et du mentum, des mandibules et prémandibules ainsi que des soies internes. À la troisième mue, la larve atteint son stade de quatrième instar.

La période de développement de l'œuf, puis du premier instar représente des phases critiques. En effet, les paramètres physico-chimiques (température, pH, vélocité du courant) du milieu d'oviposition, tout comme la présence de prédateurs, affectent le taux de mortalité des œufs et des jeunes larves. De plus, malgré la présence d'une réserve énergétique vitelline disponible peu après l'éclosion, et du sac mucilagineux riche en hydrate de carbones qui englobe les œufs, la larve doit avoir accès rapidement à une source de nourriture pour finaliser son développement. Les taux de recrutement et de dispersion des premiers instars à travers l'écosystème sont donc très variables, et ne peuvent caractériser la variation d'un paramètre environnemental en particulier (Tokeshi, 1995).

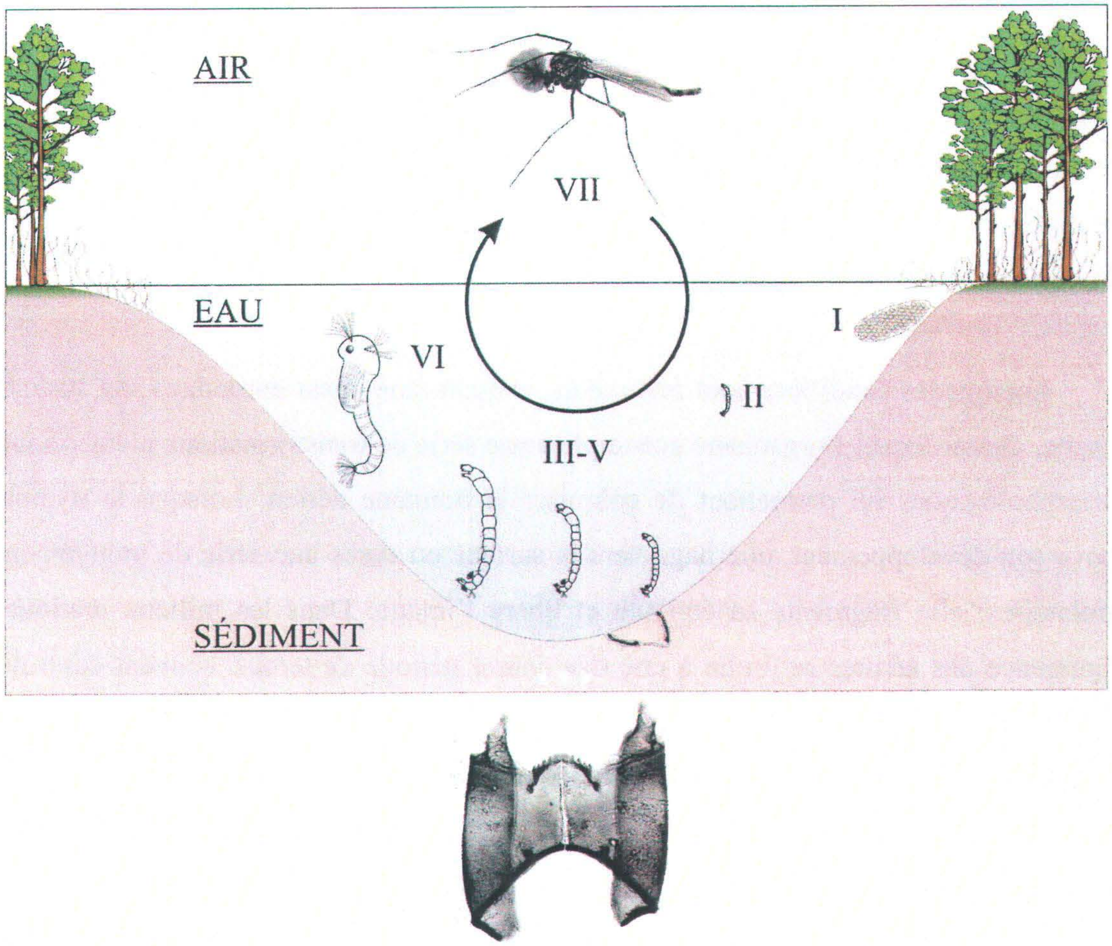


Figure 1.2 Schématisation du cycle de vie des chironomides de l'œuf (I) à l'imago (VII) en passant par les stades larvaires (II-V) et de nymphe (VII). Modifié de Los Angeles County West Vector & Vector Borne Disease Control District. Photo de l'adulte © Saskatchewan Aquatic Insects.

Vers la fin du premier instar, les larves migrent vers le domaine benthique, où elles débutent alors un mode de vie supra et endobenthique. Certaines entreprennent alors la construction d'un tube qui leur offre une protection contre les prédateurs, et leur évite d'être délogées par les courants de fond (Berg, 1995). Les larves adoptent alors un ou plusieurs modes d'alimentation, tels que collecteur de fines particules déposées sur le substrat (détritivores), filtreur des particules en suspension dans l'eau, brouteur/racleur, déchiqueteur et prédateur direct. Selon leur disponibilité dans le milieu, la diversité de leur mode d'alimentation leur permet donc d'utiliser différentes sources d'alimentation. Les chironomides sont donc herbivores (algues, macrophytes), omnivores (détritus) et/ou carnivores (microorganismes et invertébrés) (Berg, 1995).

Lorsque les conditions sont favorables, le quatrième instar entre dans son stade de nymphe, durant lequel l'organisme accomplira une série de transformations métaboliques et morphologiques lui permettant de coloniser le domaine aérien. Lorsque la nymphe achève son développement, elle nage vers la surface où après une série de mouvements ondulatoires, elle fragmente sa cuticule et libère l'imago. Dans les milieux arctiques, l'émergence des adultes se limite à une très courte période de temps, souvent contrôlée par la photopériode et des variations très faibles de température qui maximisent les chances de rencontre entre les partenaires (Langton, 1995).

Le voltinisme, soit le nombre de générations qu'une population produira chaque année, varie selon une relation linéaire négative entre les espèces et les latitudes des zones géographiques étudiées. Les faibles températures des hautes latitudes arctiques, et la présence d'un couvert de glace sur les lacs, limitent beaucoup la vitesse de développement des populations d'insectes (Armitage, 1995). La durée de la période d'hivernage (« overwintering »), qui est généralement traversée en état de diapause par les deuxièmes et troisièmes instars, représente une étape clef dans la capacité des larves à poursuivre les mues successives jusqu'à l'éclosion de l'adulte (Tokeshi, 1995). Les chironomides arctiques requièrent donc souvent plus d'une année pour finaliser leur cycle de développement. Cependant, lorsque les conditions sont optimales (longue saison estivale) certaines espèces sont univoltines et bouclent leur cycle de vie en une année.

L'adulte représente le dernier stade de développement des chironomides, celui-ci étant généralement très court (Armitage, 1995). Cette phase, durant laquelle ils se concentrent sur leurs activités de reproduction, représente leur seule période de contact avec le milieu aérien et donc avec les fluctuations de température de la basse atmosphère. Les variations thermiques peuvent donc être considérées comme une force de sélection naturelle puisqu'elles limiteront la ponte, et par conséquent le développement des espèces non tolérantes aux nouvelles conditions environnementales. Conjointement à la relative rapidité de développement des chironomides qui répondront alors rapidement aux variations environnementales, cette phase aérienne justifie l'utilisation des chironomides dans les recherches paléoclimatiques.

De par leur abondance et l'intense recyclage qu'ils orchestrent, les chironomides représentent des éléments clefs de certains réseaux alimentaires aquatiques, et entretiennent aussi un rôle étroit avec les populations humaines (Hilsenhoff, 1991). Certains peuples africains utilisent des larves de chironomides pour leur alimentation. Les peuples occidentaux ont concerté leurs efforts sur des cultures de chironomides pour inclure cette source d'alimentation riche en protéines à la diète des poissons élevés dans leurs installations aquicoles. Comme nous le verrons dans la prochaine section, les chironomides ont aussi été utilisés pour caractériser l'état trophique de certains lacs et réservoirs afin de surveiller l'évolution des ressources en eau potable dont dépendent certaines populations. Les chironomides sont de nos jours très utilisés comme appâts de choix pour la pêche sportive. Cependant, hormis la nuisance visuelle lors de l'émergence de milliers de spécimens, ces insectes ont aussi des côtés négatifs sur la santé humaine, en provoquant certaines allergies et symptômes cliniques plus graves, tel l'asthme, et en étant des vecteurs de transports de bactéries telles que le choléra (Broza *et al.*, 2005). Selon les experts, l'hémoglobine retrouvée chez certaines espèces serait responsable de ces réactions immunitaires (Cranston, 1995).

L'intérêt des chironomides dans les études paléolimnologiques, réside dans le mode de conservation des larves dans les sédiments. Ces dernières sont principalement constituées d'une capsule céphalique riche en chitine, qui forme l'exosquelette antérieur de l'organisme et qui rappelons le, est propre à chaque espèce. La chitine, un polyoside formé d'unités de N-acétyl-D-glucosamine reliées entre elles par des liaisons glucosidiques β1-4, provient de l'excrétion par l'épiderme d'une solution azotée transparente qui durcit en contact avec le milieu environnant (Bourdeau et Quirion, 1996). Dans un milieu anoxique et proche d'un pH neutre, les liaisons atomiques de cette molécule lui confèrent une très bonne résistance aux agressions chimiques et, dans un degré moindre, aux agressions mécaniques (Cohen, 2003). À chaque mue ou à leur mort, la partie organique des larves se dégrade laissant derrière elle cette cuticule qui se retrouve alors recouverte progressivement de matière sédimentaire. Chaque niveau sédimentaire sera donc constitué de l'assemblage en chironomide vivant au moment de son dépôt.

1.6.2 Historique de l'utilisation des chironomides en paléolimnologie

Pour des raisons historiques, l'effort de recherches scientifiques sur les chironomides s'est principalement fait sur des espèces de l'hémisphère nord (Walker, 1995). Longtemps après l'étude de Andersen en 1938, le début des années 1960-70 a marqué l'apparition d'études sur ce groupe d'insectes afin de démontrer qualitativement puis quantitativement le lien étroit entre certaines espèces, et les niveaux trophiques et de pollution des cours d'eau et des lacs étudiés (Walker, 2001). Ces recherches avaient comme objectif de mieux retracer l'impact humain sur ces milieux, et permettaient de connaître rapidement les niveaux trophiques pré- et post-industriels afin d'améliorer les efforts de leur suivi au cours du temps (Saether, 1975; Saether, 1979).

Les premières analyses multivariées sur les chironomides, furent entreprises par Boudée en 1983, lors de l'étude des conditions trophiques du lac Maratoto en Nouvelle Zélande. Basé sur les données des sédiments de surface de 12 lacs, ce travail permit de caractériser les assemblages de chironomides en fonction de divers paramètres physico-chimiques, notamment la productivité et la turbidité. Une fois ces assemblages connus, Boudée reconstruit l'histoire postglaciaire du lac durant laquelle il est passé d'un système oligotrophique à un système dystrophique suite au réchauffement postglaciaire et à l'apparition d'un climat plus humide (Walker, 2001).

L'étude approfondie des chironomides correspondait à une période de prise de conscience des effets anthropiques sur les milieux aquatiques, notamment les effets des fertilisants, des pesticides agricoles (eutrophisation), des émissions industrielles de métaux lourds et d'acide sulfurique/nitrique (acidification). La toxicité des éléments chimiques d'origine anthropique, affecte les environnements aquatiques à différents niveaux trophiques. Les chironomides répondent généralement à ces polluants en développant, suite à des modifications génétiques, des malformations physiologiques caractéristiques au niveau des capsules céphaliques (Madden *et al.*, 1994). Ces malformations touchent principalement le mentum et les mandibules (Martinez *et al.*, 2004). De plus, à très forte concentration, certains polluants deviennent létaux pour beaucoup de chironomides. Les études paléolimnologiques se sont donc intéressées à ces déformations, et aux changements de biodiversité afin de reconstruire l'évolution de la contamination de certains bassins depuis le début de l'industrialisation (Warwick, 1985; Ilyashuk et Ilyashuk, 2001). Les efforts de recherche sur les changements climatiques récents, et le désir constant de modéliser le mieux possible le climat futur et le devenir des écosystèmes terrestres et aquatiques, ont non seulement mis sur le devant de la scène les études paléoclimatiques, mais aussi les chironomides, grâce notamment à leur capacité à reconstruire les températures depuis la dernière déglaciation. Ces reconstructions, dont la précision peut atteindre les 1 °C environ, se basent sur des fonctions de transfert dont le but est d'associer un assemblage de chironomides à une température (ou d'autres facteurs environnementaux).

Ce lien étroit entre les communautés de chironomides et des variables climatiques telles que la température de l'air et de l'eau a cependant donné naissance dans les années 1990 à un vif débat principalement orienté sur la certitude de l'existence d'une relation directe et indirecte entre les changements observés dans les communautés de chironomides et ces variables. Dans une revue détaillée sur l'utilité des chironomides en paléoécologie, Walker (1987) mit de l'avant l'importance scientifique de ces insectes en évoquant plus explicitement leur utilité potentielle comme indicateur du climat passé. Suite à cet article, Warner et Hann (1987) initièrent un débat ouvert sur l'interprétation des changements observés dans les communautés de chironomides en fonction d'éventuels changements climatiques directs et indirects. Ils évoquèrent notamment l'importance de plusieurs facteurs endogènes et exogènes aux lacs; tels que leurs états trophiques, leurs profondeurs, la végétation de leurs bassins versants et leurs compositions sédimentaires; comme principaux moteurs de cette diversité d'assemblages observés. Ils portèrent beaucoup de doute sur la validité des assomptions faites par Walker (1987) dans cette science encore trop jeune et peu détaillée selon eux. De tels débats, quoiqu'utiles pour promouvoir et améliorer toute science émergente, semblent pourtant dans ce cas précis relativement inattendu étant donné que tous les facteurs mis de l'avant par Warner et Hann (1987) sont tous directement ou indirectement liés au climat qui prévaut dans le bassin versant des lacs. En réponse à cela, Walker et Mathewes (1989a) publièrent une étude appuyant l'idée que les changements observés dans les assemblages de chironomides d'un lac de Colombie Britannique (Canada) à la fin du pléistocène/début de l'Holocène, soit une période caractérisée par une augmentation rapide de la température de la basse atmosphère, ont un lien à la fois direct et indirect avec cette variation rapide de la température. Dès le début de l'Holocène, la disparition massive de taxons oligotrophes froids appartenant au groupe *Heterotrissocladius* et la comparaison des résultats avec d'autres indicateurs biologiques (pollen), confirmèrent l'importance relative du climat dans la régulation des populations de chironomides à la fin du pléistocène/début de l'Holocène. Cette étude apporta donc une preuve de plus de la capacité des chironomides à caractériser les variations climatiques passées. Il ne manquait alors qu'une étude statistique exhaustive pour renforcer cette école de pensée. Grâce aux développements des méthodes d'analyses multivariées (développées dès 1986, mais actualisées depuis dans ter Braak, 2002), Walker *et al.* (1991) réalisèrent un modèle statistique (analyse canonique des correspondances) de la distribution des chironomides retrouvés dans les sédiments de surface de lacs du Labrador (Canada). Cette première étude fit ressortir l'importance de la température de l'eau de surface en été comme variable expliquant le mieux la distribution des chironomides dans ces lacs. D'autres variables, telles que la profondeur maximale de chaque lac, expliquèrent aussi cette distribution. En se basant sur ces méthodes statistiques amplement acceptées en paléoécologie, les auteurs apportèrent donc une preuve de plus dans l'influence directe et indirecte du climat sur la distribution des chironomides et donc leur rôle comme indicateurs des variations climatiques passées. Malgré cette avancée majeure, Hann *et al.* (1992) critiquèrent ouvertement la méthode et les conclusions de l'article de Walker *et al.* (1991). Par le bief d'une lettre ouverte à l'éditeur, Hann et al. (1992) mirent de nouveau en doute l'affirmation selon laquelle les chironomides peuvent reconstruire directement des variations climatiques. En réponse, Walker et al. (1992) expliquèrent de nouveau point par point les conclusions de leur étude et mirent fin à ce débat public. Hormis le malaise généré pas de tels débats, ces derniers stimulèrent positivement la recherche sur les chironomides fossiles afin de vérifier plusieurs points de discordance entre ces auteurs.

1.6.3 Établissement des fonctions de transfert

Pour réaliser de tels modèles de reconstruction, les sédiments de surface d'une série de lacs (transect) situés le long d'un gradient environnemental (p. ex. température) sont recueillis puis analysés en laboratoire (Figure 1.3 a, c). Lors de l'échantillonnage, des données physico-chimiques du lac et de son bassin versant sont mesurées, telles que la profondeur du lac, la température de l'eau, la température de l'air (généralement calculée à partir de stations météorologiques environnantes), le pH, la concentration en oxygène dissous et la végétation couvrant le bassin versant (Figure 1.3 b). Les lacs sélectionnés le long de ce transect fourniront les échantillons nécessaires à la fonction de transfert. Pour chaque lac, les capsules identifiées représentent un assemblage de chironomides qui caractérise les conditions environnementales de ce lac. Ces assemblages sont alors mis en relation avec les données physico-chimiques par le biais d'une analyse factorielle des correspondances (e.g. DCA, Detrended Canonical Analysis) (Figure 1.3 d). Cette méthode statistique d'exploration des données, permet de vérifier dans un plan bidimensionnel, quelles sont les variables physico-chimiques qui expliquent le mieux la distribution observée dans les assemblages de chironomides. Elle permet également de vérifier la variabilité entre chaque lac, et donc de modifier en conséquence le transect si les assemblages de chironomides se ressemblent trop, ce qui diminuerait l'efficacité de la fonction de transfert. Le facteur environnemental expliquant le mieux la variabilité observée entre les divers assemblages de chironomides est alors choisi pour l'établissement de la fonction de transfert. Cette dernière est alors développée en utilisant pour chaque taxon, l'optimum mesuré pour ce facteur. Cet optimum représente, dans le cas d'une distribution unimodale des taxons le long de ce facteur (Figure 1.4), la valeur d'abondance maximale de chaque taxon à une valeur donnée de ce facteur. Plus le taxon aura une distribution proche de cet optimum, et donc une tolérance faible (p. ex. sténotherme dans la cadre de la température), plus il sera en mesure de détecter des changements très faibles dans la valeur du facteur considéré lors de la reconstruction. La fonction de transfert est alors testée pour en vérifier sa puissance (Figure 1.3 e), et par la suite appliquée à des assemblages de chironomides le long d'une carotte de sédiment (Figure 1.3 f).

Plusieurs modèles ont ainsi été créés, chacun améliorant progressivement la précision des prédictions et les possibilités de reconstruire de nouvelles variables et zones géographiques (Norvège, Scandinavie, Suède, Arctique Canadien de l'Est) (Brooks et Birks, 2000; Larocque *et al.*, 2001; Olander *et al.*, 1997; Olander *et al.*, 1999; Walker *et al.*, 1997). Il a ainsi été possible de reconstruire l'histoire de différents lacs, et d'apporter des preuves régionales de certains événements climatiques passés (Battarbee *et al.*, 2001; Fallu *et al.*, 2005; Kurek *et al.*, 2004; Porinchu et Cwynar, 2002). Récemment, un modèle a été crée pour l'ouest du Québec et est présenté en Annexe A de cette thèse (Larocque *et al.*, 2006). Cette fonction de transfert a été notamment utilisée dans les chapitres 3 et 4 de la présente thèse afin de modéliser les variations passées de la température de l'air dans la région d'étude.

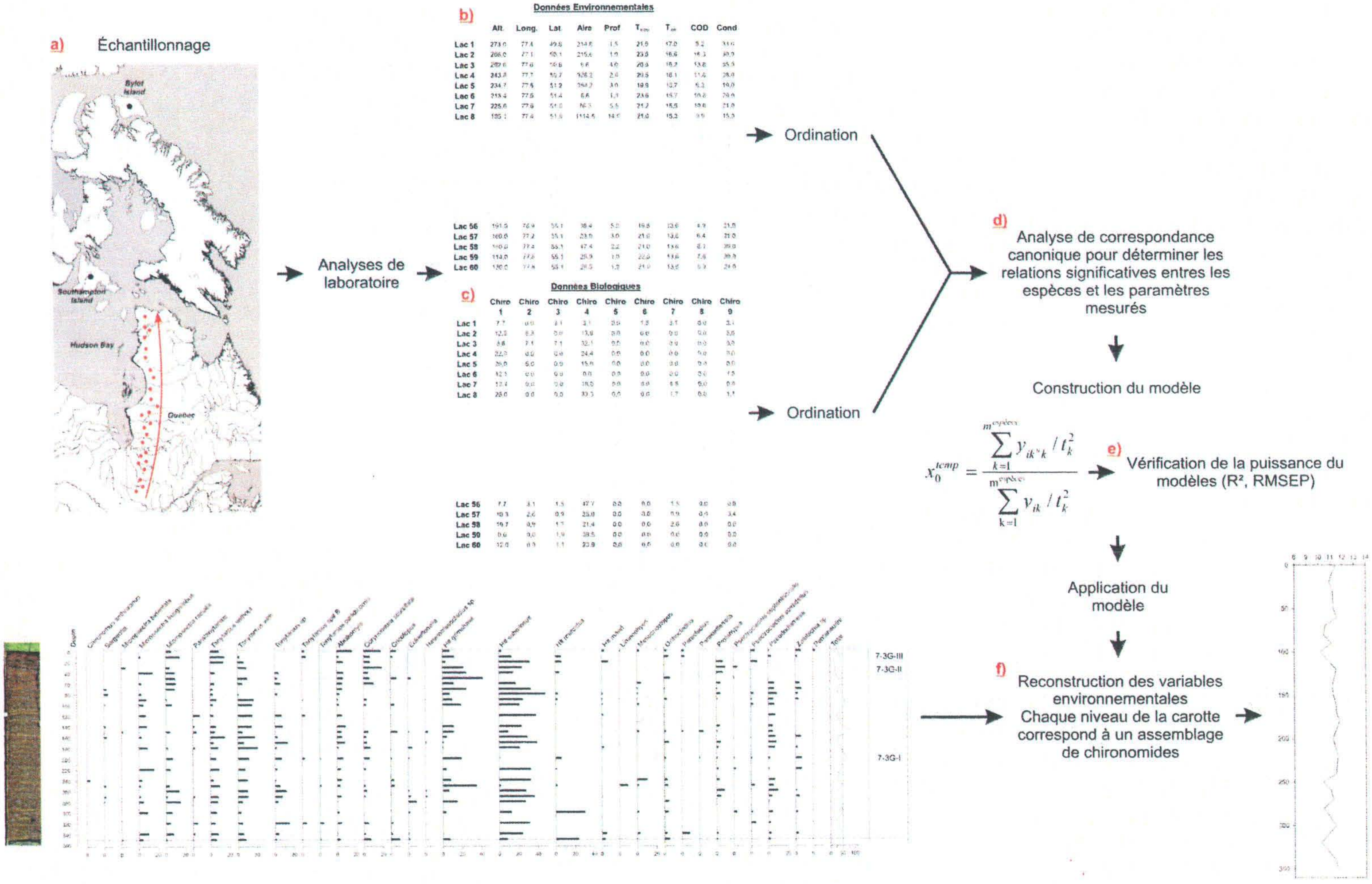


Figure 1.3 Schématisation d'une fonction de transfert.

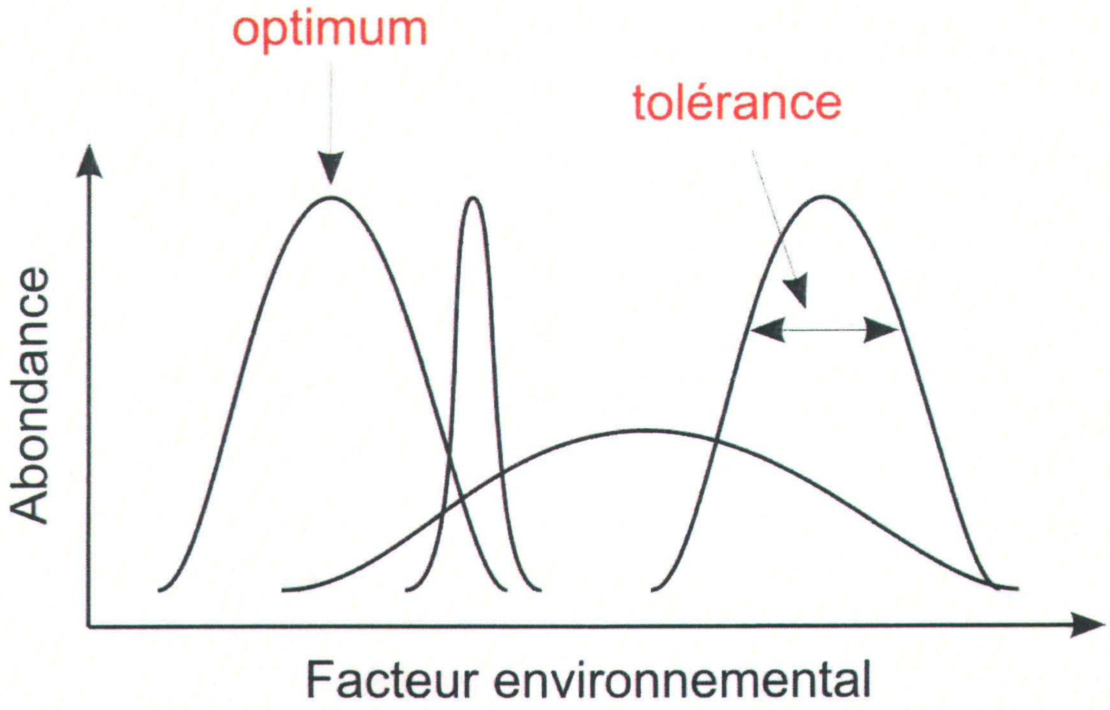


Figure 1.4 Abondance relative de quatre taxons de chironomides le long du gradient d'un facteur environnemental.

1.7 Problématique

Contrairement aux observations faites pour le reste de l'Arctique, les quelques études orchestrées dans les régions entourant le sud du bassin de Foxe, Labrador et Nord-du-Québec, ont, jusqu'à présent, fait état de la relative stabilité climatique de cette région qui semble avoir un temps de résilience plus important face aux modifications environnementales récentes et/ou passées (Pienitz *et al.*, 2004a). Dans une étude de synthèse, l'ACIA (2004) présenta un modèle des variations de la température de l'air entre 1954 et 2003. Ce modèle démontre clairement que sur un bilan annuel (Figure 1.5a) ces régions ont connu une augmentation de température de 0,5°C, soit 2 à 3 °C de moins que les régions de l'Ouest Canadien ou du Haut Arctique Canadien. Durant la période hivernale (Figure 1.5b), ces régions ont par ailleurs vu leur température moyenne diminuer de 0,5°C, contrairement au reste du Haut Arctique Canadien qui a connu des augmentations de plus de 3-4°C. Les modèles de reconstructions climatiques pour l'est du Canada révèlent cependant leur faiblesse de prédiction dans les régions limitrophes du bassin de Foxe (Smol *et al.*, 2005). Cette faiblesse résulte du manque d'études réalisées à ce jour dans cette région, et surtout de la période très courte couverte par les données météorologiques (< 50 ans) servant la plus part du temps à l'élaboration de ces modèles. Dans une étude exhaustive sur la modélisation de l'étendue de la période du maximum thermique durant l'Holocène, Kaufmann *et al.* (2004) présenta une série de figures sur lesquelles il apparaît clairement que les régions limitrophes au bassin de Foxe sont absentes des modèles de reconstructions climatiques. La carte géographique de répartition des sources sur lesquelles se basent ces modèles (Figure 1.6) révèle la grande disparité dans la couverture spatiale des données disponibles en Arctique. En comparant cette figure avec la figure 1.5, il ressort clairement que les différentes études paléoclimatiques se soient concentrées principalement là où les changements climatiques et environnementaux ont été les plus importants depuis la deuxième moitié du 20$^{\text{ième}}$ siècle. Cette limite réduit considérablement la dimension spatio-temporelle de notre compréhension des événements climatiques passés, notamment depuis la disparition du glacier laurentien, et, par conséquent, diminue la véracité des modèles de prédictions climatiques futures. Il est donc primordial de concentrer une partie de l'effort de recherche arctique sur les régions limitrophes du bassin de Foxe, et plus spécialement sur des régions très peu documentées comme l'île de Southampton. Cette étude s'ajoutera aux quelques études pertinentes disponibles pour le Nord québécois et le Labrador (p. ex. Pienitz *et al.*, 2004b; Saulnier-Talbot, 2007).

1.8 Objectif et sous-objectifs de cette thèse

Reconstruire qualitativement et quantitativement à l'aide des chironomides les variations paléoenvironnementales de deux écosystèmes lacustres au nord de l'île de Southampton. Ces données de reconstructions paléoclimatiques seront couplées à des données sédimentologiques dans le but d'augmenter la véracité du modèle climatique régional proposé pour l'Holocène sur l'île de Southampton.

L'atteinte de cet objectif principal a orienté cette thèse vers le développement de 3 sous-objectifs :

1) Développer une nouvelle technique de récolte des capsules de chironomides afin de maximiser le rapport temps d'analyse en laboratoire / nombre d'échantillons à analyser.
2) Développer une nouvelle fonction de transfert pour l'est du Canada
3) Développer un nouveau guide taxonomique

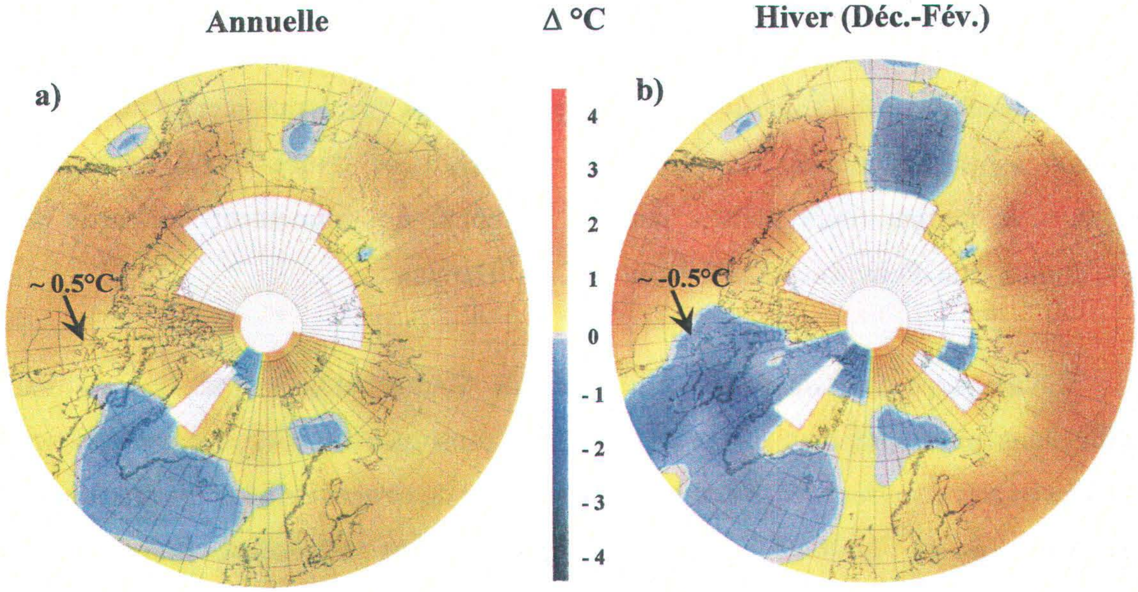


Figure 1.5 Variations de la température de l'air (°C) entre 1954 et 2003. La flèche indique la position de l'île de Southampton (ACIA, 2004).

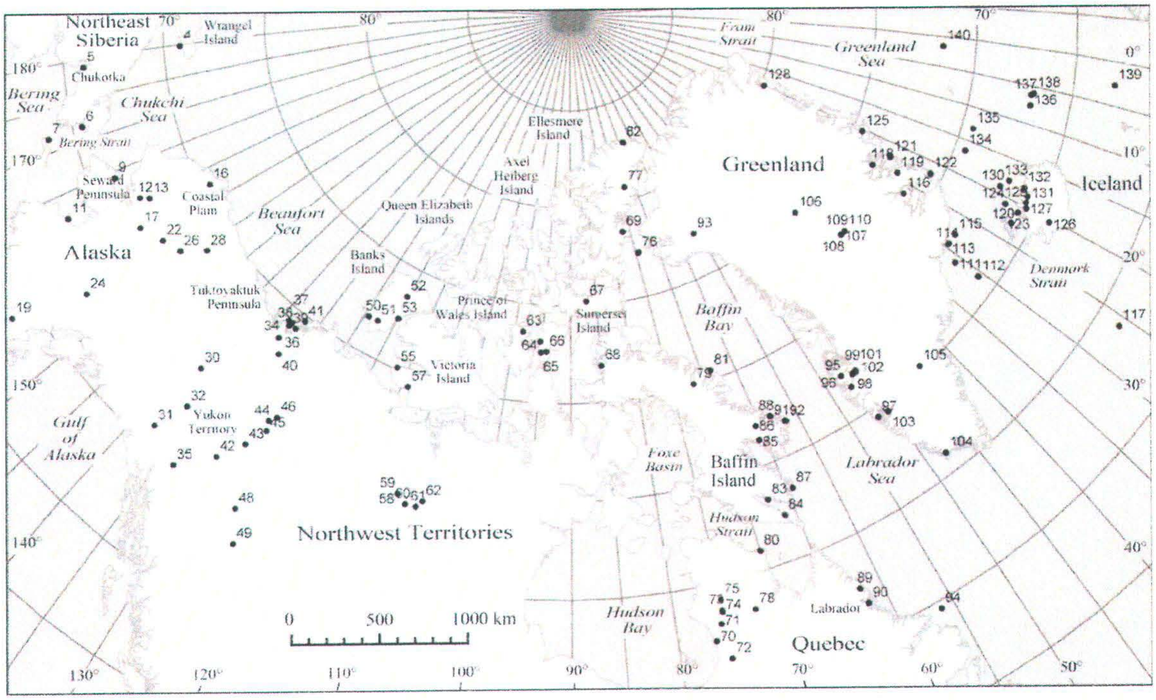


Figure 1.6 Positionnement géographique des différentes études utilisées lors de la modélisation du maximum thermique durant l'Holocène en Arctique (Kaufmann, 2004).

1.9 Sites de l'étude

Ce projet s'intègre dans une étude multidisciplinaire sur l'île de Southampton dans le nord de la baie d'Hudson (Figure 1.7). Cette île est un lieu de migration et de refuge pour plusieurs espèces arctiques d'oiseaux, de poissons d'eau douce et de mammifères terrestres et marins (ours blancs, morses, caribous) qui alimentent en partie une population locale d'environ 1000 habitants à Coral Harbour.

D'une superficie de 40663 km², l'île de Southampton est scindée en deux subdivisions physiographiques. La première est constituée de roches précambriennes riches en gneiss et autres roches granitoïdes provenant du plateau de Melville qui forme la partie vallonnée de l'île. La deuxième est formée de roches paléozoïques non déformées provenant du silurien et de l'ordovicien. Ces dernières sont riches en schistes, calcaires et recouvertes par endroits de tourbe marécageuse (Heywood et Sanford, 1976).

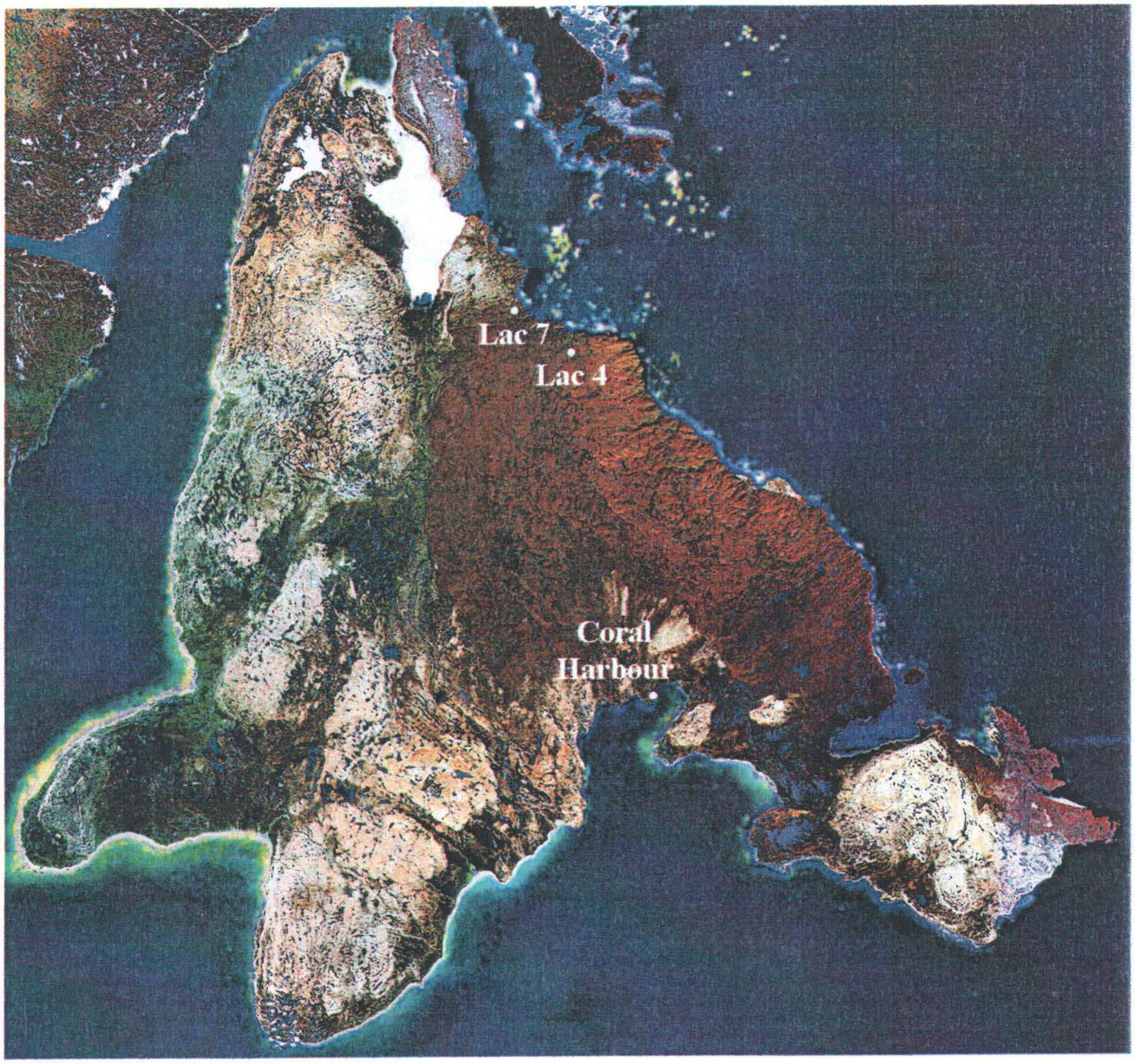


Figure 1.7 Vue Satellite (composite de 130 images) de l'île de Southampton ainsi que des deux lacs étudiés. Les images satellites ont été extraites à l'aide du logiciel Google Earth (© 2005 EarthSat).

De par sa situation géographique et sa position proche du cercle arctique, cette île est soumise à trois régimes différents de courants océaniques soit les eaux froides de l'Océan Arctique en provenance du bassin de Foxe, les eaux de surface plus chaudes de l'Atlantique Nord à l'est et les eaux de surface plus douces de la baie d'Hudson au sud. L'île se situe donc à l'apex du point de rencontre de ces eaux forts différentes, ce qui, conjointement à la topographie de la zone précambrienne, engendre des conditions hydrologiques et climatiques à court terme très variables sur toute la surface de l'île. Les conditions climatiques à Coral Harbour, de 1933 à 2002, sont présentées à la Figure 1.8 (Environnement Canada, 2002). Selon ces données, la température moyenne de juillet (et dans une moindre mesure celle de septembre), soit la période probable d'éclosion des larves de chironomides (Tokeshi, 1995), a augmenté significativement depuis la dernière moitié du 20$^{\text{ième}}$ siècle ($p_{\text{value}} = 0{,}0015$).

La topographie de la zone précambrienne permet théoriquement d'obtenir des lacs protégés du vent, dont la profondeur peut atteindre probablement plus de 40 m. Comme mentionné précédemment, les études paléolimnologiques privilégient ce type de lac afin d'obtenir des séquences stratigraphiques les plus longues possible avec éventuellement des sédiments laminés. Dans le cadre de cette thèse, deux lacs au nord de l'île ont été choisis dans cette région montagneuse, loin de toutes éventuelles influences humaines directes. Pour chacun des lacs, les données physico-chimiques de la colonne d'eau lors de l'échantillonnage en juillet 2004 sont présentées dans le tableau 1.1.

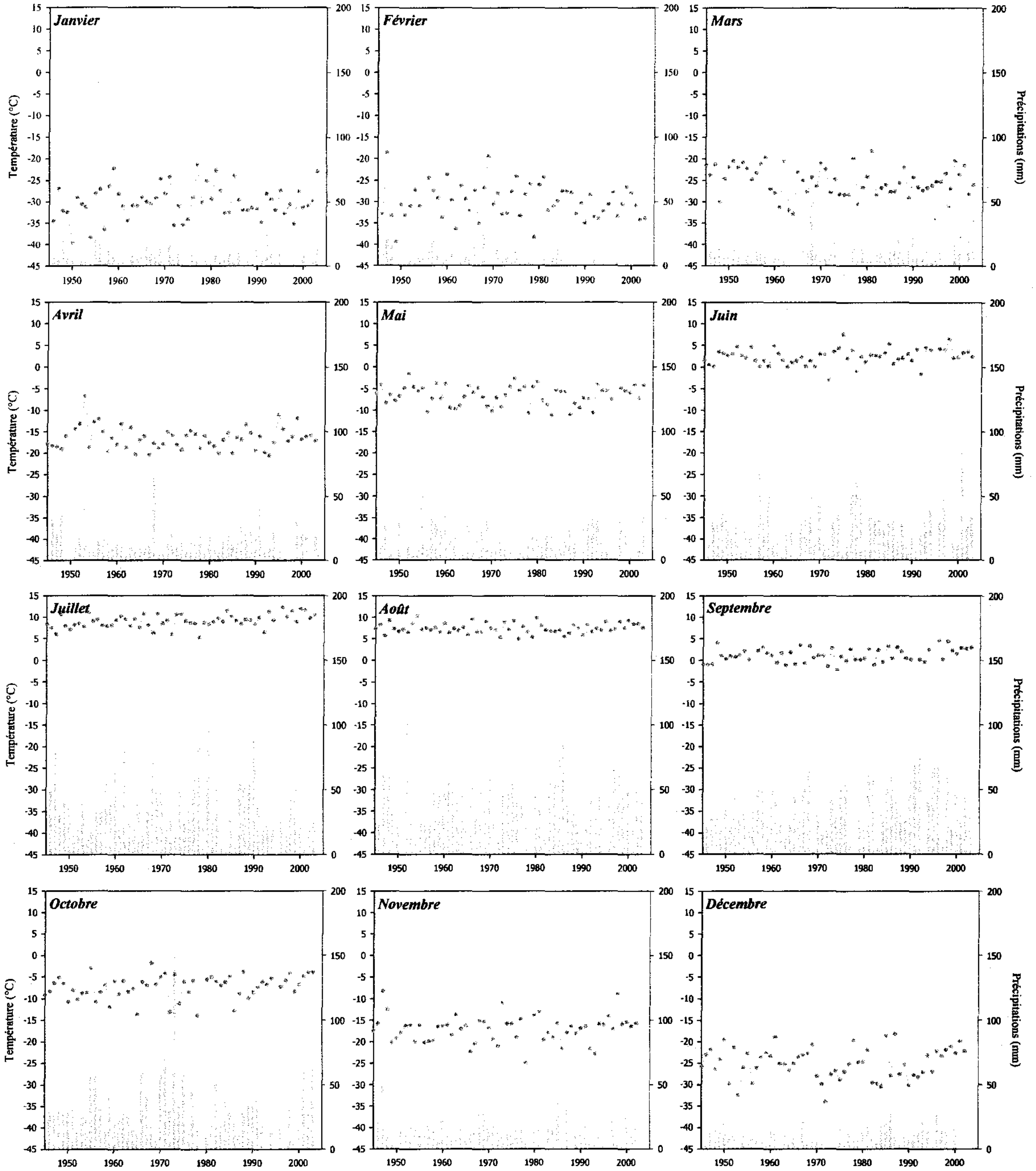


Figure 1.8 Variation de la température moyenne (lignes) et du total des précipitations (histogrammes) pour chaque mois de 1945 à 2002 à l'aéroport de Coral Harbour, île de Southampton, Nunavut, Canada (Environnement Canada, 2002).

Le lac 4, également nommé Lac à l'île (65°05'70''N, 83°47'49''W), se situe proche de Cape Arvinguaq, au nord-est de l'île. Localisé entre deux flancs de collines, ce lac recueille principalement les eaux de deux rivières. À sa partie proximale, il est coupé en deux par une presqu'île, qui influence vraisemblablement beaucoup l'écoulement et la déposition des sédiments dans le lac. La végétation environnante est constituée d'une toundra riche en lichens, mousses, des éricacées telles que les cassiopées tétragones (*Cassiope tetragona*), des dryades octopétales (*Dryas octopetala*) et des feuillus nains du type Salix (*Salix arctica*). La profondeur maximale mesurée de 36,5 m ne correspond probablement pas au point le plus profond du lac car de la glace recouvrait encore sa surface lors de l'échantillonnage le 14 juillet 2004.

Le lac 7, (65°12'45''N ; 83°47'49''W), se situe à l'extrémité nord de la zone précambrienne, proche de Cape Bylot. Alimenté par un cours d'eau très ramifié, ce lac est coincé entre un flanc de falaise abrupte et une colline à pente plus douce. La végétation rencontrée est identique à celle du lac 4. Il n'y avait pas de glace lors de l'échantillonnage du lac le 16 juillet 2004.

Tableau 1.1 Paramètres physico-chimiques des lacs étudiés. Les mesures in-situ de la colonne d'eau proviennent d'un Hydrolab™. La profondeur maximale des mesures était de 15 m.

Variables		Lac 4	Lac 7
Élévation (m)		100	155
Profondeur maximale du lac (m)		36,5	19,0
Disque de Secchi (m)		3,6	5,9
Température (°C)	surface	3,64	4,20
	5 m	3,55	3,96
	15 m	3,73	3,81
pH (unité de pH)	surface	6,34	6,93
	5 m	5,54	7,10
	15 m	5,49	7,20
Conductivité ($mS.cm^{-1}$)	surface	0,009	0,083
	5 m	0,009	0,084
	15 m	0,009	0,085
Oxygène dissous ($mg.L^{-1}$)	surface	13,70	14,20
	5 m	12,59	12,01
	15 m	12,14	11,60

1.10 Matériel et Méthodologie

1.10.1 Récolte des échantillons

Les échantillons ont été prélevés au point le plus profond des deux lacs à l'aide d'un carottier à gravité modifié de type Livingstone (lac 4) et d'un carottier à percussion (lac 7) dont le diamètre interne des tubes était de 6,7 cm. La récolte, ou la prise en considération, d'une carotte par lac peut sembler insuffisante devant la variabilité interne de chacun des systèmes lacustres choisis. Il a cependant été prouvé que les couches sédimentaires prélevées au point le plus profond d'un bassin lacustre, représentent significativement l'entièreté de la population de chironomides de ce dernier (Heiri, 2004). L'obtention à ce point d'une très bonne image de l'assemblage général du lac provient du transport régulier de particules sédimentaires du littoral au domaine benthique profond du lac (Anderson et Battarbee, 1994). Grâce à ce mécanisme, suffisamment de capsules céphaliques de chironomides littoraux sont ainsi déplacées. Les carottes de sédiments ont été conservées dans leurs tubes respectifs, et protégées lors du transport pour éviter tout remaniement vertical du sédiment. De retour au laboratoire de l'INRS-ETE, les carottes ont été entreposées et conservées verticalement dans une chambre froide à température contrôlée de 4 °C.

1.10.2 Analyses en laboratoire

À l'aide du scanographe médical Siemens Somaton Volume Access du Laboratoire Multidisciplinaire de Scanographie de Québec, INRS-ETE, un topogramme de chaque carotte a été réalisé. Cette étape essentielle a permis d'obtenir une radiographie 2D de chaque carotte de sédiments afin de détecter d'éventuelles laminations, et de déterminer le plan approprié pour le sectionnement longitudinal des carottes à l'aide d'un outil Dremel™ et d'un fin fil métallique. Une analyse visuelle du sédiment a suivi cette étape afin de déterminer la structure et la couleur du sédiment via une charte de Munsell®. Les demi-carottes ont ensuite été protégées de la dessiccation en étant recouvertes d'un film plastique puis enveloppées dans un sac plastique opaque et finalement, conservées dans la chambre froide.

Des analyses géochimiques non destructives sur les demi-carottes ont été entreprises à l'aide d'un « ITRAX™ core scanner » au sein du Laboratoire de Géochimie, Imagerie et Radiographie des Sédiments (GIRAS), INRS-ETE. Cet appareil a permis d'obtenir pour chaque demi-carotte 1) une photo couleur haute résolution de la surface du sédiment, 2) un profil radiographique à haute résolution (100 μm), et finalement 3) les profils des éléments chimiques majeurs détectés par micro-fluorescence X (XRF) à haute (100 μm) et moyenne résolution (1000 μm).

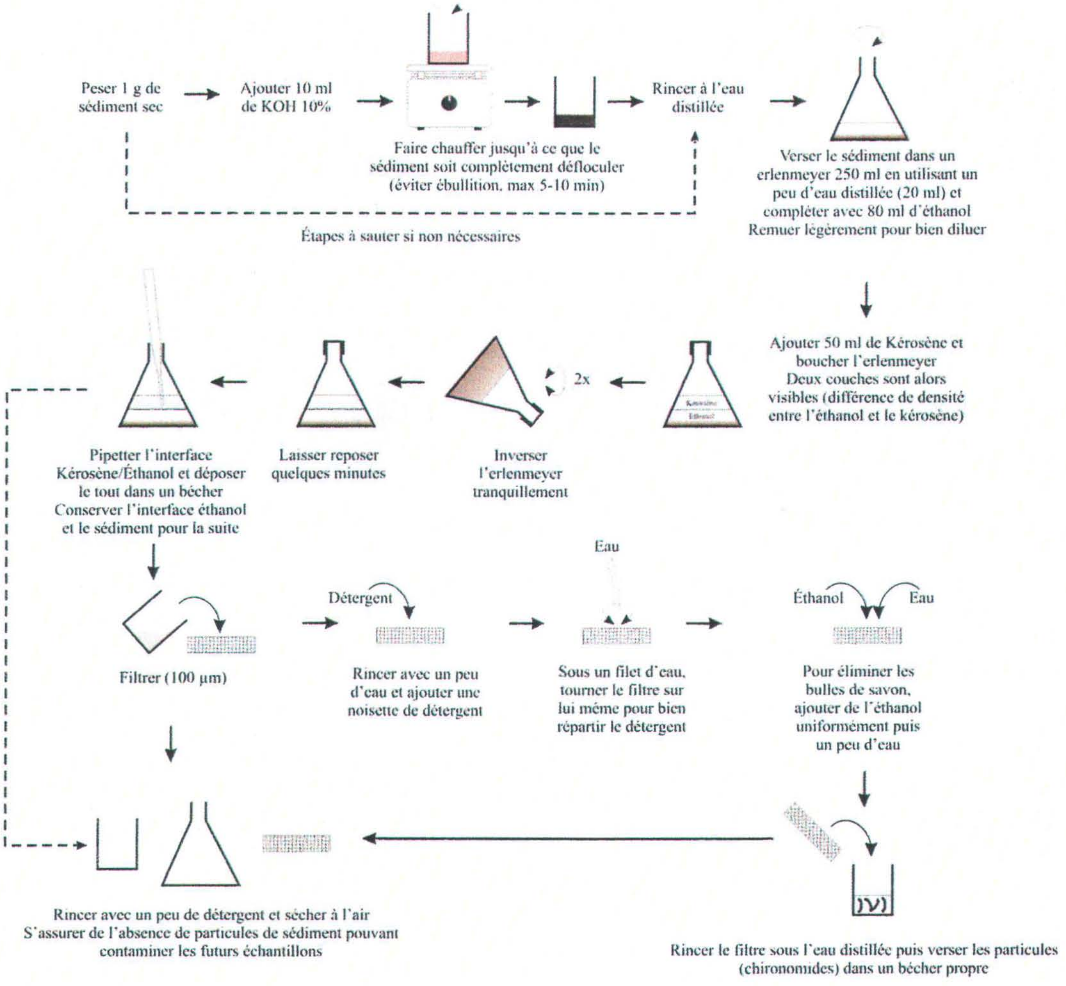
Après vérification des données obtenues à l'étape précédente, une demi-carotte de chaque lac a été sous-échantillonnée verticalement tous les 0,5 cm. Les variations dans les modes de sédimentation, la nature et la texture des grains composant les sédiments ont été mises en évidence par des analyses de granulométrie faites à l'aide d'un compteur à particules laser, Fritsch Analysette 22. Une estimation de l'abondance de matière organique dans le sédiment a été calculée par la méthode de perte au feu (LOI) à 550 °C pendant 5 heures (Heiri *et al.*, 2001). Cette estimation de l'abondance de matière organique a ensuite été vérifiée par une analyse de la concentration en carbone, azote et soufre (CNS) à l'aide d'un LECO CHNS-932, disponible à l'INRS-ETE.

Les capsules céphaliques de chironomides ont été extraites du sédiment à un pas d'échantillonnage de 1 cm pour les premiers 10 cm, puis à un pas de 1-2 cm pour le reste de chaque demi-carotte. Pour chaque sous-échantillon, environ 1 g de matériel déshydraté a été traité 10 min dans une solution chaude de KOH à 10 % v/v. Cette solution a par la suite été filtrée sur une maille de 100 μm. Le sédiment retenu par cette maille a été utilisé pour le processus de séparation sélective de la matière chitineuse à l'aide du kérosène (Rolland et Larocque, 2006) (Figure 1.9). Les particules sédimentaires ainsi prélevées ont été disposées dans un plat strié de type Bogorov. À l'aide d'un microscope binoculaire à faibles grossissements (35-60x), les capsules céphaliques ont été retirées et colées sur des lames minces à l'aide d'une résine synthétique hydrosoluble (Hydro-Matrix). Tel que décrit par Heiri et Lotter (2001), Larocque (2001) et Quinlan et Smol (2001), un minimum de 50 capsules céphaliques a été systématiquement prélevé dans chaque sous-échantillon. L'identification des chironomides a été réalisée sous un microscope binoculaire à forts grossissements (> 200x) à l'aide de plusieurs guides taxonomiques (Cranston, 1982; Oliver et Roussel, 1983; Wiederholm, 1983; Brooks *et al.*, 1997 ; Rieradevall et Brooks, 2001; Larocque et Rolland, 2006; Brooks *et al.*, 2007).

La chronologie de chaque demi-carotte a été réalisée à l'aide de datations radiométriques sur les radio-isotopes naturels du carbone (^{14}C) et du plomb (^{210}Pb). Le plomb, dont la demi-vie isotopique est de 22,3 ans, a permis de dater les niveaux supérieurs et donc récents (< 150 ans) de chaque demi-carotte. La datation du radiocarbone ^{14}C, dont la demi-vie est de 5568 ans, a permis de dater les niveaux inférieurs des demi-carottes. Les datations ^{14}C ont été réalisées à l'aide d'un accélérateur de particules (AMS) sur des acides humiques (Lac 4 et 7), des macrofossiles terrestres (Lac 4), des capsules céphaliques de chironomides (Lac 7) et sur la coquille d'un bivalve marin (Lac 7). Les dates obtenues ont par la suite été calibrées à l'aide du logiciel Calib 5.0.1 (Stuiver *et al.*, 2005) en tenant compte, pour les dates ^{14}C, des divers effets réservoirs des milieux de provenances des échantillons.

Les résultats d'analyses de granulométrie sont représentés graphiquement sous la forme d'un graphique 2D (« contour plot ») afin de mettre en évidence les variations dans la distribution de la taille des grains (Beierle *et al.*, 2002), ainsi que les changements de symétrie (skewness) et d'aplatissement (kurtosis) de ces distributions. Le classement des particules selon leur taille se base sur les recommandations de Last (2001). Les profils stratigraphiques de l'abondance des éléments chimiques et de l'abondance par gramme des chironomides sont représentés par des diagrammes réalisés à l'aide du logiciel C2 (Juggins, 2003). Un indice de diversité de Hill a été calculé par le biais du logiciel Primer 6 (Clarke et Gorley, 2006) afin de mesurer le rapport entre le nombre et l'abondance relative des taxons de chironomides identifiés à chaque niveau des demi-carottes (Bourdeau et Quirion, 1996). Les données biologiques ont été analysées par le logiciel Zone (Juggins, 1992b) afin de faire ressortir statistiquement les divisions dans les assemblages de chironomides, caractérisant ainsi des changements majeurs dans leur population. Cette dernière analyse repose sur la méthode CONISS (« Constrained Cluster Analysis by Incremental Sum of Squares »).

Les assemblages de chironomides ont permis de reconstruire la température moyenne de l'air en août durant les périodes couvertes par les demi-carottes. Cette analyse a été faite à l'aide d'un modèle d'inférence établi pour le nord-ouest du Québec (Larocque *et al.*, 2006, chapitre 3) et étendu récemment jusqu'à l'île d'Ellesmere en passant par le Labrador. La concordance des données de chaque niveau des demi-carottes par rapport au sédiment de surface des lacs utilisés dans le modèle a été vérifiée par des analyses canoniques des correspondances via le logiciel Canoco (ter Braak and Šmilauer, 2002).



Le KOH, l'éthanol et le kérosène sont potentiellement toxiques

Toutes les manipulations doivent être faites sous la hotte et porter toujours des gants

Si toutes les précautions sont respectées, aucune odeur ne sera décelable dans le laboratoire

Figure 1.9 Protocole pour l'extraction des capsules de chironomides à l'aide de Kérosène.

1.11 Contributions et apports à l'avancement des connaissances

1.11.1 Contribution de la thèse à l'avancement des connaissances

Cette thèse présente pour la première fois une étude paléoclimatique sur l'île de Southampton, une région arctique « oubliée » des récentes recherches climatiques menées en Arctique. Cette thèse repose tout d'abord sur le développement et la vérification de l'efficacité d'une méthode novatrice d'extraction de capsules de chironomides du reste des particules sédimentaires lacustres (Chapitre 2). Cet article répond parfaitement à la volonté et l'habilité de l'auteur de cette thèse à raffiner les techniques utilisées lors de l'analyse des capsules de chironomides piégées dans les sédiments lacustres. Cet article, une première dans le domaine de la paléolimnologie, a et aura un impact important dans ce domaine. L'intérêt démontré par nos collègues suite à la publication de ces résultats nous porte raisonnablement à croire que cette nouvelle méthode deviendra un standard, et sera citée dans tous les articles ayant trait aux chironomides.

L'objectif principal de cette thèse, soit des reconstructions paléoclimatiques à l'aide des chironomides, nécessita la création d'une nouvelle fonction de transfert pour l'est du Canada, spécialement le nord-ouest Québécois (Annexe A). Ce modèle de reconstruction climatique s'ajoute à celui disponible pour le Labrador et l'île de Baffin (Walker *et al.*, 1997) avec cependant une taxonomie beaucoup plus riche et une meilleure représentativité des espèces pour notre région d'étude.

Le développement de cette fonction de transfert représenta une opportunité pour réaliser un guide taxonomique répondant davantage aux attentes des chercheurs dans le domaine des chironomides fossiles. Ce guide hors du commun (annexe B), est d'une importance majeure dans le domaine de l'étude des chironomides. Sa simplicité et la qualité unique dans le domaine des photos, offrent aussi bien aux utilisateurs débutants que confirmés, un outil pratique facilitant l'identification des capsules de chironomides. Ce guide reste néanmoins en harmonie avec les guides déjà existants, il apporte cependant une nouvelle vision de ce que l'auteur de cette thèse conçoit comme étant indispensable pour répondre aux besoins actuels et futurs des utilisateurs.

L'utilisation conjointe de ces deux outils indispensables a permis de documenter l'historique climatique de deux lacs nordiques de cette île durant l'Holocène. Le premier lac (Chapitre 3) a notamment procuré de nouvelles informations concernant la séparation du nord de l'île avec le milieu océanique du bassin de Foxe, ainsi que des dates du maximum thermique durant l'Holocène. La plus haute résolution obtenue lors de l'étude du deuxième lac (Chapitre 4) a également permis de documenter et dater des événements climatiques importants durant le dernier millénaire, tels que le réchauffement au moyen âge et le petit âge glaciaire. Outre l'importance de documenter continuellement l'histoire climatique des environnements dans lesquels nous évoluons, cette thèse apporte des données indispensables à la modélisation des trajectoires que prendront les écosystèmes arctiques suite aux bouleversements climatiques actuels et futurs. De plus, l'utilisation conjointe de données biologiques et sédimentologiques a augmenté la véracité de l'interprétation des résultats, particulièrement dans le chapitre 4. Cette méthode ouvre la voie à l'importance à accorder à ce couple, lors de l'utilisation des chironomides en paléoclimatologie.

<u>En résumé cette thèse :</u>

- propose et confirme l'utilité d'une nouvelle méthode d'extraction des capsules de chironomides d'une matrice sédimentaire (Chapitre 2)
- Présente une nouvelle et prometteuse fonction de transfert pour l'est du Canada (Annexe A)
- présente un tout nouveau guide taxonomique qui, en comparaison avec ce qui existe déjà, est un outil qui facilite et accélère l'identification des chironomides et améliore l'expérience (« feeling ») des utilisateurs (Annexe B)
- documente l'histoire du nord de l'île de Southampton durant l'Holocène, soit environ les 6000 dernières années (Chapitres 3-4)

- démontre l'importance de coupler des données biologiques et sédimentaires pour améliorer l'interprétation des résultats observés dans le cadre d'études paléolimnologiques.
- appuie l'utilité des chironomides à reconstruire des évènements climatiques précis.

1.11.2 Contributions de l'auteur

Cette thèse repose d'abord et avant tout sur des connaissances multidisciplinaires qui ont amené l'auteur à travailler étroitement avec différents représentants spécialisés en tout ou partie dans les sciences biologiques, sédimentaires et paléoclimatiques. Les trois autres articles présentés sont l'œuvre de l'auteur de cette thèse. Ils ont tous été pensés et rédigés par ce dernier. Tous les coauteurs des articles ont cependant apporté une vision et des points de vues différents ou complémentaires à ceux de l'auteur. Ils ont aussi tous été conviés à améliorer l'aspect linguistique de ces articles. L'interprétation des résultats et les aspects scientifiques de cette thèse représentent donc le point de vue de l'auteur qui en assume la totale responsabilité.

L'idée et la volonté de développer une nouvelle méthode d'extraction des chironomides proviennent entièrement de l'auteur de cette thèse. Les analyses de laboratoire ont cependant été confiées en partie à Isabelle Larocque, directrice de l'auteur de cette thèse, qui a identifié tous les chironomides retrouvés dans la couche « éthanol » de chaque échantillon. Ses conseils et critiques ont aussi été requis lors de l'interprétation des résultats et de la méthode choisie par l'auteur pour démontrer mathématiquement l'efficacité de cette technique d'extraction.

Le développement de la fonction de transfert revient à Isabelle Larocque (Annexe A). L'auteur de cette thèse a cependant participé au début de son doctorat à la préparation des échantillons. Cet article représenta une occasion pour former l'auteur de cette thèse aux diverses analyses statistiques employées en paléolimnologie.

Les carottes de sédiments prélevées sur l'île de Southampton proviennent d'un travail d'équipe conjointement et également réalisé entre l'auteur de cette thèse et Pierre Francus, codirecteur de ce dernier, Reinhard Pienitz du Centre d'Études Nordiques de l'Université Laval et son étudiante à la maîtrise Laurence Laperrière. Une partie de la logistique entourant la campagne d'échantillonnage a été réalisée par l'auteur de cette thèse. Toutes les étapes subséquentes d'analyses en laboratoire ont été réalisées par l'auteur de cette thèse, hormis les datations des échantillons qui ont été confiées à des laboratoires externes à l'Institut National de la Recherche Scientifique et les analyses directes de carbone, azote et soufre qui ont été confiées à Sébastien Duval et Anissa Bensadoune de l'Institut National de la Recherche Scientifique à Québec. La partie sédimentologique, plus particulièrement l'utilisation du scanner à microfluorescence X (ITRAX™) et la réévaluation des données générées, ont requis l'aide précieuce de Pierre Francus et de son associé de recherche Jean-François Crémer.

Le guide taxonomique présenté en Annexe B provient d'un travail conjoint entre Isabelle Larocque et l'auteur de cette thèse. La maquette originale des fiches d'identification provient de l'auteur de cette thèse. Ce dernier a entièrement travaillé sur les prises de vues des capsules de chironomides, ainsi que sur le long et fastidieux travail de retouche numérique et de finalisation des fiches. Les descriptions morphologiques et écologiques sont le fruit de Isabelle Larocque, tout comme la réalisation de la fonction de transfert sur laquelle se base ce guide (Larocque *et al.*, 2006, Annexe A).

Deuxième Partie

Articles

Chapitre 2

THE EFFICIENCY OF KEROSENE FLOTATION FOR EXTRACTION OF CHIRONOMID HEAD CAPSULES FROM LAKE SEDIMENT SAMPLES

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Article publié dans *Journal of Paleolimnology* 37:565-572

Résumé

Le kérosène, une huile minérale, est couramment utilisé lors de l'extraction des coléoptères piégés dans des particules sédimentaires des milieux lotiques ou lentiques. La présente étude se propose de tester l'efficacité du kérosène lors de l'extraction de capsules céphaliques de chironomides retrouvées dans 10 échantillons de sédiments lacustres ayant des contenus en matières organiques et des âges différents. Les résultats révèlent la très grande efficacité de ce processus de flottaison, sans égard à l'état physique (apparence) des capsules céphalique (entière ou moitié). L'efficacité moyenne d'extraction est de 89,3 ± 8,0 %. Sur les 57 taxons ainsi récoltés, 46 possèdent une abondance relative dont la marge d'erreur par rapport à une extraction sans le kérosène, se situe entre -1 et 1 %. Les marges d'erreur maximum (4,3 %) ont été associées aux taxons ayant de grosses capsules céphaliques, tels que *Corynocera oliveri*-type, dont la taille de la capsule (400-500 µm) favorise vraisemblablement la rétention des particules sédimentaires et en diminue la flottabilité. Malgré cette marge d'erreur observée, une analyse canonique des correspondances ne permet pas de discerner de différences statistiques entre cette méthode et la méthode conventionnelle de récolte. Cette dernière confirme donc la fiabilité de cette méthode.

Abstract

Kerosene, a grade mineral oil, is commonly used to extract beetles from sediment. Here, the use of kerosene to extract chironomid head capsules was tested on 10 samples from sediment of different lakes, with different organic matter content as measured by loss on ignition, and estimated ages. Our results revealed that this flotation tool is very effective in extracting either full or half chironomid head capsules. The mean extraction efficiency was 89.3 ± 8.0 % with an estimated relative abundance error ranging from -1 % to 1 % for 46 of the 57 identified taxa. Larger chironomids (400-500 µm width), which are often full of sediment particles, have the highest relative abundance error, with a maximum of 4.3 % for *Corynocera oliveri*-type. A canonical correspondence analysis showed that, despite this small bias, samples retrieved with the kerosene flotation do not differ from the whole sample assemblages. These results give us confidence in the use of this flotation technique for chironomid sample preparation.

2.1 Introduction

Chironomids (Insecta: Diptera: Chironomidae) are non-biting midges recognized to be sensitive to a variety of environmental variables. Recent developments, driven by the need to better predict climate change effects on the environment, have increased the use of chironomid transfer functions to reconstruct quantitatively physical and chemical variables such as air and water temperature (Walker *et al.*, 1991; Lotter *et al.*, 1997; Walker *et al.*, 1997; Olander *et al.*, 1999; Brooks and Birks 2001; Larocque *et al.*, 2001; Porinchu *et al.*, 2002; Heiri *et al.*, 2003; Velle *et al.*, 2005, Larocque *et al.*, 2006), total phosphorus (Brooks *et al.*, 2001; Langdon *et al.*, 2006), chlorophyll a (Brodersen and Lindegaard 1999), oxygen availability (Quinlan *et al.*, 1998), lake depth (Korhola *et al.*, 2000) and metal contamination (Brooks *et al.*, 2005). Chironomids have also been used for dating sediments (Fallu *et al.*, 2004) and to reconstruct past temperature from $\delta^{18}O$ (Wooller *et al.*, 2004).

Chironomid head capsules are usually removed from the sediment by a so-called "universal method", well described in Walker (2001), and consisting of picking each head capsule, one by one, from the whole sediment particles under a binocular microscope. This method, although thorough, is unfortunately extremely time-consuming. Picking a minimum of 50 head capsules required for quantitative analysis (Heiri and Lotter, 2001; Larocque, 2001; Quinlan and Smol, 2001) can take up to one day, depending on the concentration of head capsules in the sediment. The picking efficiency also depends on the analyst's ability to distinguish the smallest capsules and the degree of magnification used.

As described in Coope (1986), kerosene, a grade mineral oil also called paraffin oil, can be used to concentrate insects from any sediment materials. Proctor (2001) compared the efficiency of this method for aquatic mites analysis and concluded that, combined with live picking, kerosene flotation can yield the highest number "of mites per minute of sampling effort". Gandouin *et al.* (2005) and Ruiz *et al.* (2006) used kerosene flotation to extract chironomid head capsules from lake sediment, but, to our knowledge, the method was never rigorously tested. Here, we present the first analysis of a chironomid extraction efficiency using kerosene on sediment of different compositions and ages in order to determine if this method is an adequate alternative for future chironomid analysis.

2.2 Study sites

To test the extraction method, we used the sediment from four lakes in western Quebec, one lake on Southampton Island (Nunavut) and two lakes from the Peace-Athabasca Delta (PAD), Alberta (Table 2.1). The sediment used came from different time slices, represented by different sample depths in the cores.

2.3 Material and methods

2.3.1 Sampling and sediment preparation

The chosen samples came from cores used for different projects: a chironomid training set being developed in Quebec (Larocque *et al.*, 2006), a flood reconstruction of the PAD lakes (Larocque *et al.,* unpublished data) and a climate reconstruction of Southampton Island (Rolland *et al.*, unpublished data). All cores were taken at the deepest part of the studied lakes with either a Renberg gravity corer (Quebec lakes), a gravity and a percussion corer (Southampton Island) or a Glew (1989) corer (PAD lakes). The samples were either wet (Quebec samples) or freeze-dried (Southampton and PAD) material. Sediment organic matter content was calculated by loss-on-ignition (LOI) at 550 °C following Heiri *et al.* (2001).

Table 2.1 Location, name and code of all the samples analysed. Cores were taken at the deepest part of the studied lakes with either a Renberg gravity corer (Quebec lakes), a gravity and a percussion corer (Southampton Island) or a Glew (1989) corer (PAD lakes).

Location	Sample name	Code	Depth (cm)	Latitude	Longitude
Québec	Lac Bédard	F1	surface	47°19'22" N	71°7'25" W
Québec	Training Set Qc Lake B	F2	surface	48°58' N	77°46' W
Québec	Training Set Qc Lake D	F3	1.5	48°45' N	78°33' W
Québec	Training Set Qc Lake E	F4	surface	48°46' N	78°23' W
Alberta	PAD05 KB-3	F5	0.5	58°50'82" N	111°28'84" W
Alberta	PAD05 KB-3	F6	1.5	58°50'82" N	111°28'84" W
Alberta	PAD09 KB-4	F7	12	58°46'46" N	111°19'48" W
Southampton Island	Lac 7-3G	F8	19	65°12'45" N	84°12'11" W
Southampton Island	Lac 7-4P	F9	41	65°12'45" N	84°12'11" W
Southampton Island	Lac 7-4P	F10	61	65°12'45" N	84°12'11" W

Legend: Depth (cm) corresponds to the layer subsampled in the core

Before the kerosene extraction, KOH (10 %) was added overnight to approximately 1 g of dry or 5 g of wet sediment. This step was followed by a short (2-5 s) ultrasonic bath treatment (Lang *et al.*, 2003). Samples were sieved though a 100 µm mesh and the remaining sediments were used for the kerosene extraction.

2.3.2 Kerosene extraction

This method is basically the same one described by Proctor (2001). Samples were poured into a 250 ml Erlenmeyer flask and 80 % ethanol was added to bring the volume to 100 ml. Then, 50 ml of kerosene was added and the flask was capped. The flask was lightly shaken and inverted up to three times in order to minimize the formation of an emulsion which increases the time of separation and/or can even prevent the separation of the two solutions. The flask was then placed on a bench and left until the kerosene and ethanol layers were completely separated (~ 15 min). The kerosene and particles interface were transferred into a 50 ml beaker using a pipette. The solution was then sieved in a 100 µm mesh. To remove any residue and odor of kerosene, a small drop of detergent was added to the sieved solution. The solution was then cleaned with distilled water followed by a small amount of ethanol and then distilled water again. The ethanol was used to eliminate soap bubbles, which might decrease the visibility, and make the head capsules float in the Bogorov tray. The solution was placed in a Bogorov counting tray and examined under a stereo microscope at 35-60x magnification. Head capsules were picked using fine dissecting forceps and mounted on a microscope slide using a water-soluble mounting medium (Hydro-Matrix). Chironomid assemblages found floating in kerosene will be referred to as “kerosene layer” in the text.

To evaluate the number and any taxonomic bias in the chironomids whose head capsules did not float following this procedure, the ethanol layer was also sieved, washed, and head capsules were mounted on microscope slides and identified. Those assemblages will be referred to as the “ethanol layer”.

Head capsules were identified under a light microscope at 400x magnification using standard taxonomic manuals (Cranston, 1982; Oliver and Roussel, 1983; Wiederholm, 1983) and following recent discussions in various chironomid workshops since 1999. Tanytarsini taxa were separated using Brooks *et al.* (1997) and unpublished keys by Brooks. In the absence of mandibles the Tanytarsini were separated by the presence (Tanytarsini with) or absence (Tanytarsini without) of a spur on their antennae pedicel. When no antennae pedicel was present they were placed in the Tanytarsini sp. category. Tanypodinae genera were separated using the position of setae following Rieradevall and Brooks (2001). Fragments containing more than half a head capsules were counted as one head capsule. Capsules that were exactly half of one head capsule were counted as half. All others fragments were disregarded. Head capsules that were unidentifiable were counted as undifferentiated.

2.3.3 Statistical analysis

A total of 10 samples were used for the analysis (Table 2.1). Each sample was divided into three treatments: 1) whole sample (including all head capsules found in the kerosene and ethanol layers), 2) kerosene and 3) ethanol layers. For each sample, the kerosene extraction efficiency (%) was calculated by the following formula: (number of head capsules in kerosene / number of head capsules in whole sample) * 100. For each sample and treatment, the relative abundance (%) of each taxon was calculated and is represented in a stratigraphic diagram (Figure 2.1). Only taxa with a relative abundance of at least 1 % in one of the ten samples available are shown in this diagram.

A canonical correspondence analysis (CCA) with a square root transformation was run using the program C2 (Juggins 2003) to explain for each sample the variance in the distribution and composition of chironomid assemblages between treatments.

For each taxon, a relative abundance error was also developed by subtracting the mean relative abundance in the kerosene layer to the mean relative abundance in the whole sample. The mean relative abundance for the two layers is the average of the ten samples.

2.4 Results

Table 2.2 gives the extraction efficiency (%) for each sample analyzed. The average extraction efficiency was 89.3 % with a minimum of 74.6 % for the sample F4 and a maximum of 97.6 % for the sample F2. These results indicate that at least 75 % of the chironomid head capsules were extracted using this method.

The number of full and half capsules picked in each layer is also provided (Table 2.2). For all the samples, the kerosene layer contained the highest number of both half and whole capsules. As all samples show similar results, the estimated age, organic content (LOI) and the sediment characteristic (dry or wet samples) do not seem to influence extraction efficiency.

Species assemblages in each sample proved to be similar between the whole sample and the kerosene layer (Figure 2.1), which is confirmed by the CCA (Figure 2.2). All the taxa (e.g. *Smittia* and *Pseudorthocladius*) that were absent in the kerosene but found in the ethanol layer always had very low abundances (< 1 %) in the whole sample (Figure 2.1). Although they had the lowest extraction efficiency, chironomid assemblages in the kerosene layer of samples F3 and F4 were still well representative of the whole sample (Figure 2.2).

The relative abundance errors for the kerosene assemblages identify the taxa under- (positive value) or over-estimated (negative value) in this layer (Figure 2.3). *Corynocera oliveri*-type, *Micropsectra radialis*-type and *Procladius* have the highest under-estimation with a maximum for *C. oliveri* of 4.3 %. *Chironomus plumosus*-type has the highest over-estimation with 2.2 %. Of the 57 taxa identified, 46 have a relative abundance error in the kerosene layer ranging between -1 % and 1 % (Figure 2.4).

Table 2.2 Number of chironomid head capsules picked and kerosene extraction efficiency (%) of 10 samples. "Whole" represents the kerosene + ethanol layers, "Kerosene" represents the number of chironomid head capsules floating only in the kerosene layer, and "Ethanol" represents the number of chironomid head capsules floating only in the ethanol layer. Extraction efficiency (%) was calculated by the following formula: (number of head capsules in kerosene / number of head capsules in whole sample) * 100. Sediment characteristics, organic matter content as measured by loss on ignition (LOI) and estimated age of the samples are also indicated.

Code	Sediment Characteristic	LOI (%)	Calibrated Years BP 1950	Number of Chironomids Head Capsules					Extraction Efficiency (%)
				Kerosene		*Ethanol*		*Whole*	
				Full	Half	Full	Half		
F1	wet	35	-	74	17	18	5	103	80.1
F2	wet	5	-	81	3	2	0	84.5	97.6
F3	wet	68	-	61	19	14	8	88.5	79.7
F4	wet	2	-	19	9	5	6	31.5	74.6
F5	dry	21	-	85	25	5	4	104.5	93.3
F6	dry	19	-	172	45	10	5	207	94.0
F7	dry	14	30	229	111	18	7	306	93.0
F8	dry	-	2269	26	42	1	2	49	95.9
F9	wet	15	4029	60	63	8	0	99.5	92.0
F10	wet	7	5629	1268	-	100	2	1369	92.6

Mean ± SD 89.3 ± 8.0

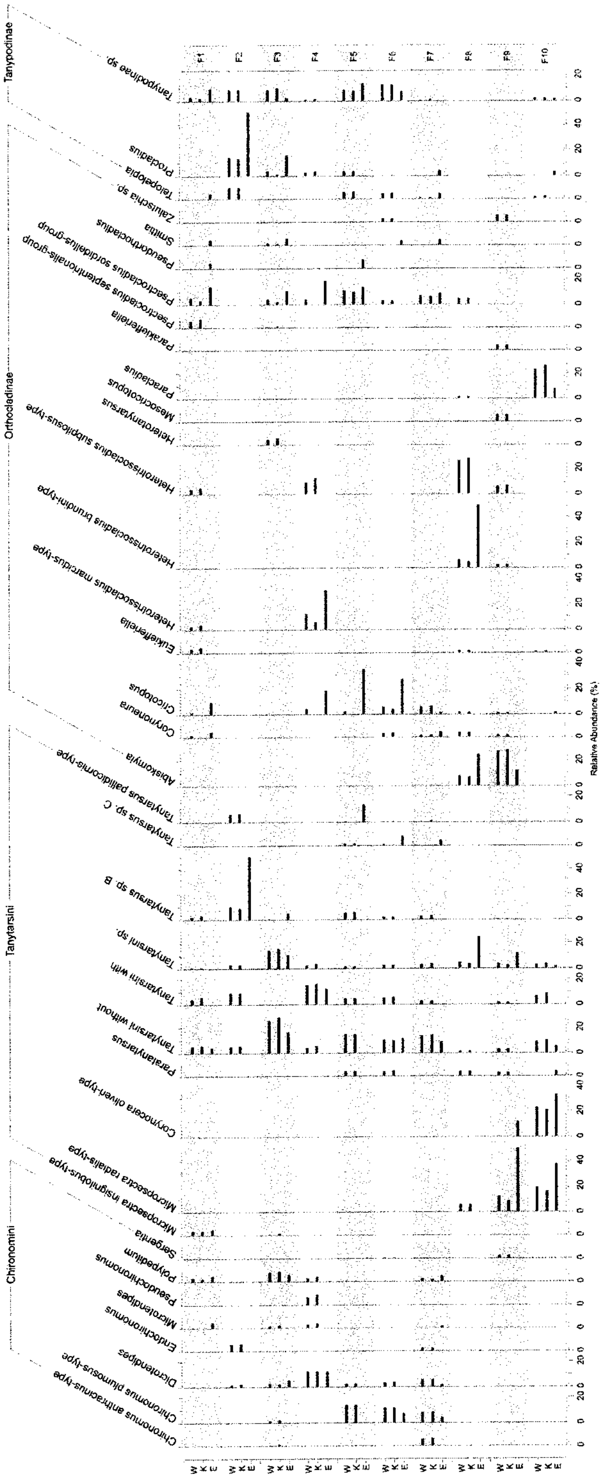

Figure 2.1 Chironomid stratigraphy (in percentage) for each sample and treatment (W: whole; K: kerosene; E: ethanol). Only the taxa with more than 1 % of abundance are represented.

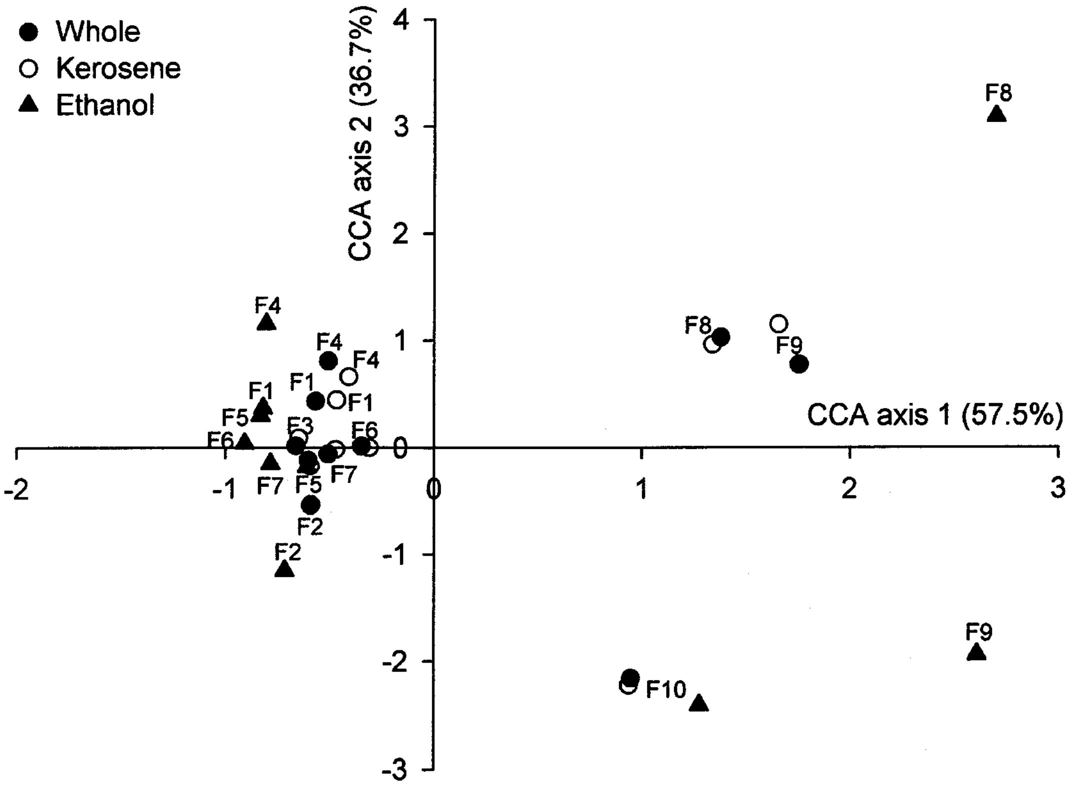

Figure 2.2 CCA analysis of the chironomid assemblages for each sample and treatment. "Whole" represents assemblages in kerosene + ethanol layers, "kerosene" represents chironomid assemblages only in the kerosene layer and "ethanol" represents the chironomid assemblages only in the ethanol layer.

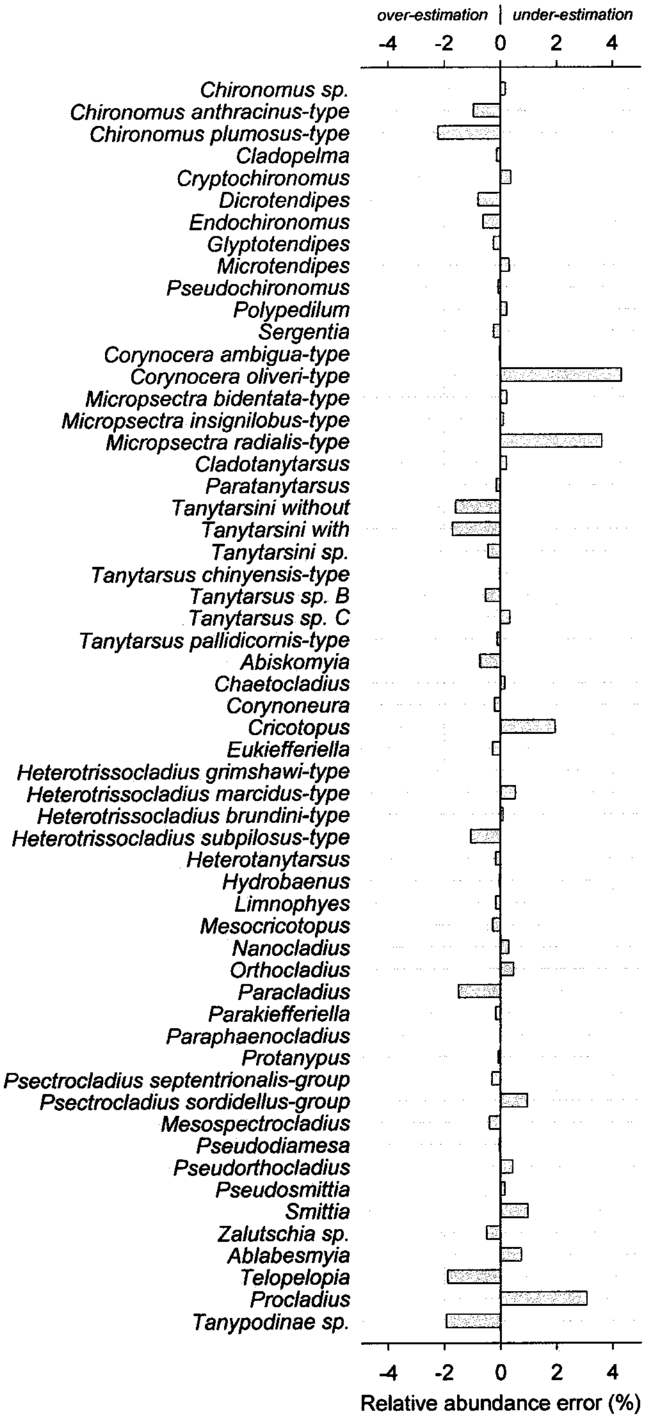

Figure 2.3 Relative abundance error of the 57 taxa identified, calculated as the % relative abundance in total assemblages minus % relative abundance in the kerosene assemblages (Mean for 10 samples). A positive value indicates an under-estimation of the taxa and a negative value indicates an over-estimation.

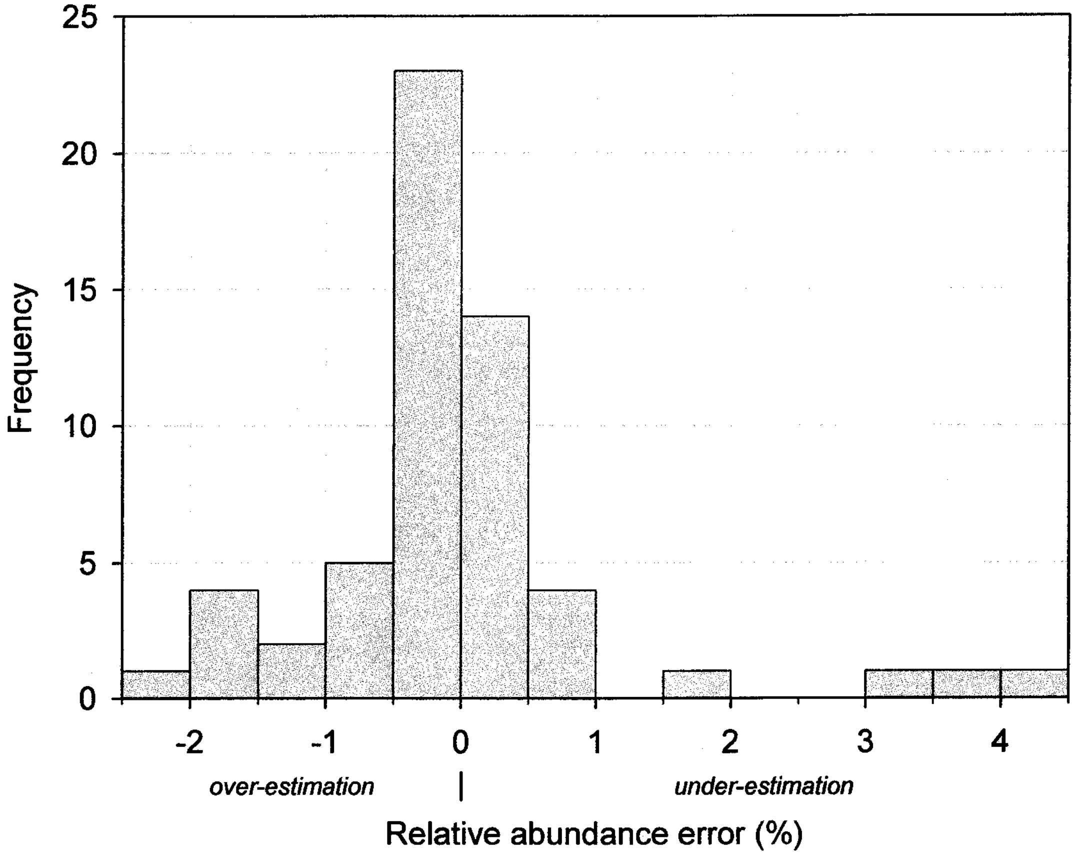

Figure 2.4 Frequency histogram of the relative abundance error. A positive value indicates an under-estimation of the taxa and a negative value indicates an over-estimation.

2.5 Discussion and conclusions

The chironomid assemblages extracted using kerosene flotation were similar to those from whole assemblages and the efficiency ratios were high, indicating that: a) most of the head capsules were floating; b) smaller head capsules or half head capsules were not overlooked by this technique; and c) the flotation technique is effective for extracting head capsules from various types of lake sediments, in wet or freeze-dried material.

A major advantage of using this technique is the short time it takes to extract and mount chironomid head capsules, compared with the "universal method". Considering that, for one sample, a complete extraction process requires only half an hour and that the set-up time of the slide another half to one hour depending on the concentration of chironomid head capsules, kerosene extraction seems to be a useful and rapid method to remove capsules from sediment particles. Although the method requires the purchase and use of more chemicals (kerosene and ethanol) than the conventional technique (using only KOH), the cost increase is counterbalanced by time savings. Furthermore, the kerosene can be filtered and reused, reducing the environmental and economical impacts of this technique.

Since most head capsules were floating, it indicates that all the taxa identified in our samples have an excellent affinity to kerosene and this attraction does not decrease whether half capsules, different types of sediment (represented by LOI %) or older samples are concerned. However, this affinity might decrease in relation to the amount of debris attached to the head capsule, and could explain the higher abundance errors (although below 4.5 %) for larger head capsules. Because they are usually intact in the sample, large taxa such as *Chironomus plumosus*-type, *Corynocera oliveri*-type, *Micropsectra radialis*-type and *Procladius* are often full of organic and mineral particles that increase their density and might decrease their flotation ability. However, based on personal observations of samples F9 and F10, which had lower efficiency rates, we cannot see any differences in the amount of debris attached to the head capsule between those taxa found in the kerosene or the ethanol layers. We believe that this apparent lower efficiency is not a sign of ineffectiveness of the kerosene flotation method but just a sign that minor adjustments need to be made in the methods such as a higher degree of deflocculation, an increase in the ultrasonic bath time or more than two flotation sequences. Despite this error, the CCA analysis proved that the chironomid assemblages from the kerosene layers are very similar to those from the whole samples. We are confident that samples extracted from the kerosene layer can be used for statistical analysis and that the method will be helpful in the development of training sets and past environmental variable reconstructions.

The shorter extraction time achieved using this flotation technique compared to the "universal method" would be a great help when extracting chironomid head capsules for dating. For example, in the study of Fallu *et al.* (2004), between 1309 and 2445 complete head capsules were extracted one by one from the sediment. We have spent two days extracting 1800 head capsules in one sample using the "universal method" for dating. We estimate that 3 to 4 hours would have been needed with the flotation method. The floating technique could potentially be used to extract head capsules for such dating purposes. Although the samples were cleaned in a detergent, the amount of kerosene still retained on the capsule surface is actually unknown. There is a possibility that this high content carbon oil might bias the estimated age when the chironomid head capsules are used for dating sediments, but this should be further evaluated before discarding the extraction method.

Every method used for extracting chironomids has its flaws but we believe that the kerosene technique is an effective and reliable method for chironomid laboratory analysis.

Acknowledgements

The sediment samples from Quebec and Southampton Island were obtained by funding from a NSERC grant to I. Larocque. The PAD samples were provided by Roland Hall. We would like to thank Reinhard Pienitz, Pierre Francus and Laurence Laperrière for logistic support during fieldwork at Southampton Island. We also thank Christoph Tobler for fieldwork assistance during sampling of the lakes in Abitibi-Temiscamingue. Finally, we thank Steve Brooks, John Smol and an anonymous reviewer for there valuables comments on the manuscript.

Chapitre 3

HOLOCENE CLIMATE INFERRED FROM BIOLOGICAL (DIPTERA: CHIRONOMIDAE) ANALYSES IN A SOUTHAMPTON ISLAND (NUNAVUT, CANADA) LAKE

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Article accepté dans *The Holocene*

Résumé

L'impact potentiel des changements globaux sur les écosystèmes arctiques et le désir constant d'amélioration des modèles de prédictions climatiques, ont motivé plusieurs recherches multidisciplinaires à se tourner sur l'histoire climatique et environnementale de ces régions. En se basant sur des indicateurs biologiques (chironomides) et sédimentaires, la présente étude expose pour la première fois un portrait paléolimnologique de l'île de Southampton, plus particulièrement d'un lac situé au nord-est de cette île. La carotte de sédiment décrite, dont la longueur totale est de 1 m, est composée d'unités sédimentaires marine et lacustre. La séquence stratigraphique de cette carotte repose pour la section lacustre sur des dates faites sur les capsules de chironomides et les acides humiques. La section marine a été datée à partir des résidus d'une coquille d'ostracode. L'histoire du lac durant l'Holocène peut être divisée en deux périodes fortement différentes. La première, échelonnée de 5569 à 4356 cal. ^{14}C BP, présente, par rapport au reste de la carotte, les plus importantes températures inférées de l'air pour le mois d'août, avec des maximums atteignant les 10 °C. L'abondance de taxons postglaciaires, tels que *Corynocera oliveri*, *Paracladius* and *Microspectra radialis*-type, ainsi que l'augmentation des éléments chimiques mesurés par micro-fluorescence X, caractérisent un environnement très instable sur le plan climatique. Durant la seconde période, de 3574 cal. ^{14}C BP à aujourd'hui, les conditions limnologiques du lac laissent présager l'atteinte d'un équilibre. Cet équilibre se traduit par une grande abondance de taxons oligotrophes froids, tel que *Heterotrissocladius subpilosus*-group, une température inférée comprise entre 8 et 9 °C et une remarquable stabilité dans l'abondance des éléments chimiques. Cette étude génère de nouvelles informations concernant le maximum thermique atteint durant l'Holocène dans une région du bassin de Foxe qui, contrairement à celles du Haut Arctique Canadien, possède vraisemblablement une résilience climatique la protégeant en partie des changements climatique actuels.

Abstract

Concerns about the effects of global warming on Arctic environments have stimulated multi-disciplinary research into the history of their long-term climatic and environmental variability to improve future predictions of climate in these remote areas. Here we present the first paleolimnological study for Southampton Island using analyses of chironomids supported by sedimentological analyses, carried out on a 1 m-long core retrieved from a lake located in the northeastern part of the island. This core was made up of marine sediments underneath 65 cm of freshwater lake sediments. A marine shell, humic-acids, and chironomid head capsules were used to date this sequence. The Holocene environmental history of the lake consisted of two major contrasting periods. The first one, between about 5570 and 4360 calibrated years BP (cal. Yrs BP), was climatically unstable, with common postglacial chironomid taxa such as Corynocera oliveri-type, Paracladius, and Microspectra radialis-type. This period also corresponded to the highest chironomid-inferred August air temperature (10 °C) for the whole record and to significant increases in major chemical elements as detected by X-ray fluorescence. During the second period, which lasted from about 3570 cal. yrs BP until the present, limnological conditions seemed to stabilize after a change to cold oligotrophic chironomid taxa, such as Heterotrissocladius subpilosus-group, with no major variations in the abundance of chemical elements. Inferred August air temperatures ranged between 8 and 9 °C. This study provided unique information on the timing of the Holocene Thermal Maximum in the Foxe Basin area, a region with very few information available on long-term climate change. This region showed, so far, relatively few signs of recent climatic change, as opposed to other regions in the High Arctic.

3.1 Introduction

Instrumental records obtained from regions surrounding the Foxe Basin, Hudson Bay, and Hudson Strait revealed that these regions were little affected by global warming, showing only slight increases (< 0.5 °C) in mean annual air temperature over the last 50 years and even a cooling during the winter season (Serreze *et al.*, 2000; ACIA 2005). These results are in sharp contrast to the warming observed in other arctic regions (Smol *et al.*, 2005), including northwestern Canada, Alaska, and the Canadian High Arctic. This discrepancy and the recent concerns about the effects of global warming on arctic ecosystems increase the need to extend our knowledge of the spatial and temporal aspects of natural climatic variations. However, neither instrumental records nor climatic models developed for arctic regions provide past and future climatic scenarios of sufficient spatial and temporal resolution. The available instrumental records cover only short time spans, now referred to as the "Anthropocene" period (Crutzen, 2002), that were already affected by anthropogenic activities and therefore might not be representative of natural climate variation in the study region. Climate model outputs should thus be validated through comparison with pre-existing conditions (e.g. Battarbee, 2000).

Combined with recent developments in statistical inference models, lake-sediment archives and their proxies have (indirectly) extended environmental "monitoring" beyond the Anthropocene to hundreds and thousands of years before present (BP). The use of biological and sedimentological indicators has provided new tools to quantitatively reconstruct physical and chemical variables through the history of the studied lakes (Smol *et al.*, 2001; Pienitz *et al.*, 2004a). Chironomids (Insecta: Diptera: Chironomidae) are the most abundant insects preserved in lake sediments and can be used to infer physical and chemical variables such as air (e.g. Larocque *et al.*, 2006) and water temperature (e.g. Walker *et al.*, 1991), total phosphorus (e.g. Langdon *et al.*, 2006), oxygen availability (Quinlan *et al.*, 1998), lake-water depth (Korhola *et al.*, 2000), and chlorophyll-a (Brodersen and Lindegaard, 1999). With their short response time to environmental shifts, these zoological indicators can provide critical information on the effects of past climatic variations on the lake's aquatic communities.

The use of sedimentological indicators, such as grain size and geochemical components, provides an extended overview of the paleohydrological, chemical, and physical conditions in the studied lake and its surrounding watershed (Last, 2001). Texture of lake sediments is a valuable tool to reconstruct past hydrological conditions that have affected the sedimentary lake processes (e.g. Folk, 1966) and, by extension, which may have controlled the biological communities. Inorganic geochemical analysis of the sediments provides important information on mineral inputs within the lake ecosystem (St-Onge *et al.*, 2007).

Located at the boundary between the Hudson Bay and the Foxe Basin (Figure 3.1a), Southampton Island might represent a frontier or transitional zone in a rapidly changing Canadian Arctic. Studies on sites located north of Southampton Island (Ellesmere and Baffin Islands) indicated a rapid and recent change in diatom and chironomid communities, probably associated with warming, whereas communities from sites located south of Southampton Island (e.g., northern Québec and Labrador) still showed little sign of change (Pienitz *et al.*, 2004b; Smol *et al.*, 2005; Saulnier-Talbot, 2007). Despite its central position in this region, studies conducted on this island have mainly focused on its Quaternary geology (Bird, 1953; Heywood and Sanford, 1976), and geomorphology (Rouault 2006).

Here we present the first paleolimnological study of Southampton Island, using chironomid and sedimentological indicators in an attempt to refine the knowledge of past climatic variability in this region. In addition, this study provides new dates for eustatic rebound and complements information already available for the Melville Peninsula (Dredge, 2001).

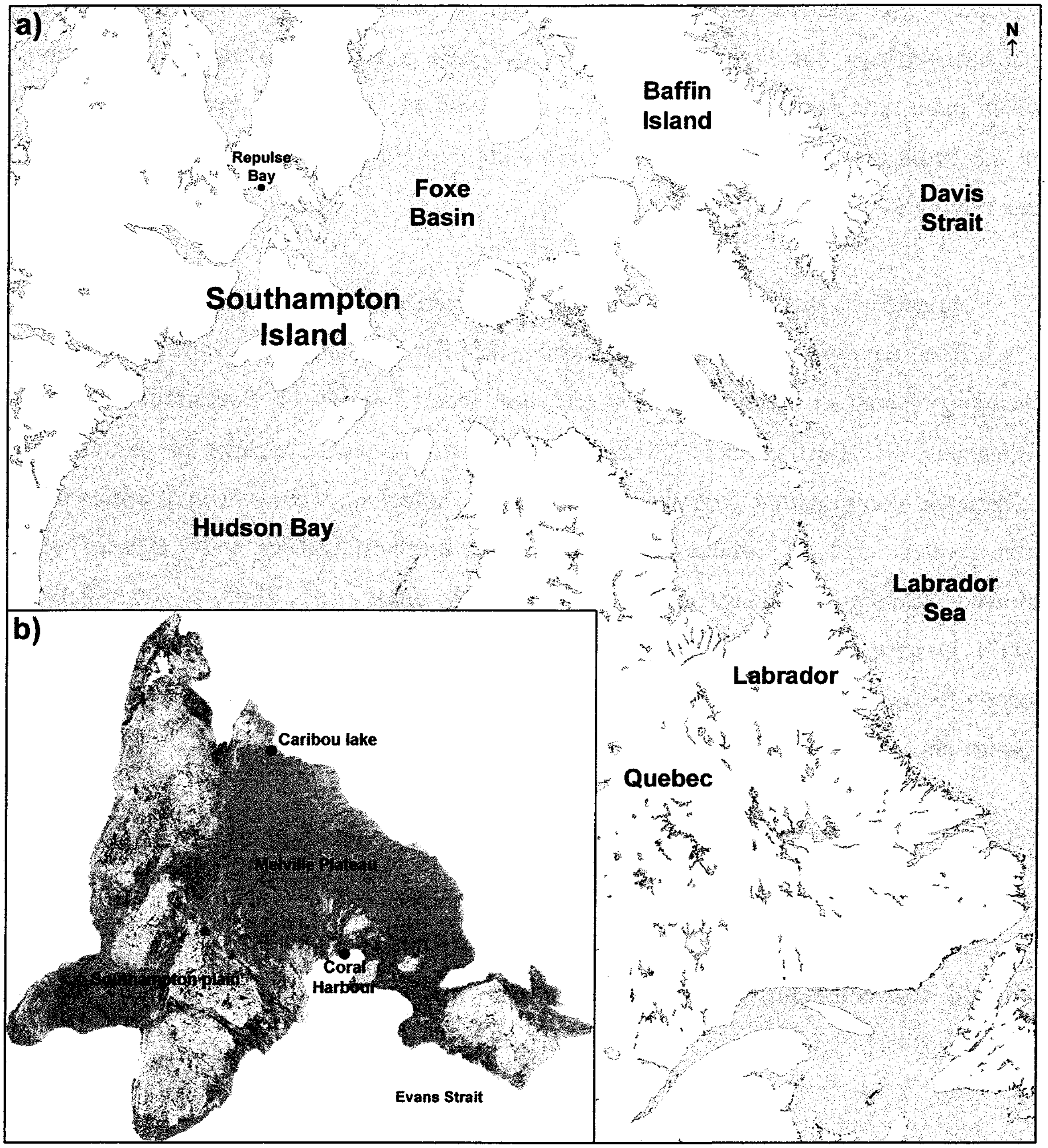

Figure 3.1 Location of the Southampton Island (a), and Caribou lake (b).

3.2 Study sites

With an area of 40663 km², Southampton Island consists of two physiographic subdivisions: 1) a mountainous area made of Precambrian rocks called Melville Plateau extending over the whole eastern part of the island, and 2) the Southampton plain, covering the western part of the island and underlained by Paleozoic rocks (Heywood and Sanford, 1976) (Figure 3.1b). Marine deposits commonly encountered below ~ 150 m a.s.l, implied to Dredge (2001) that deglaciation occurred around 7500-7000 cal. yrs BP in southern Southampton Island and 6900 cal. yrs BP in its northern part. However, a study in 2005 refined this information and revealed that deglaciation occurred from 8300 to 8200 cal. yrs BP for the southeastern part of the Island, and 6700 to 6600 cal. yrs BP for the Melville Plateau (Rouault, 2006). Mean annual temperatures recorded at Coral Harbour airport (64°12'0''N, 83°22'0''W) was -11.5 °C (1945-2002) and -10.6 °C (1993-2002) (Environment Canada, 2002).

Located 155 m a.s.l near Cape Bylot in the northeastern mountainous area of the island, our sampling site (Caribou Lake, unofficial name (65°12'45''N, 83°47'49''W); Figure 3.1b) is of elongate shape (~ 500 m x ~ 170 m) with a maximum lake depth of 19 m. The lake is bordered by a steep cliff on its northern side and a gentle slope on its southern side. At the time of sediment sampling in July 2004, the lake shore was littered with large blocks and boulders and the surrounding arctic tundra vegetation was mainly composed of Ericaceae (Cassiope tetragona (L.) D. Don), Rosaceae (Dryas integrifolia Vahl), and Salicaceae (Salix arctica Pallas).

3.3 Materials and methods

3.3.1 Sampling and pre-analysis of the core

A 1-m long core (4P) was retrieved from the deepest part of Caribou Lake with a percussion corer (diameter = 7 cm) from Aquatic Research. The core was transported intact inside its sampling tube to our laboratory facilities and stored at 4°C.

A computed axial tomography imaging (CAT Scan) of the sediment core was achieved with a Siemens Somatom scanner at the Institut National de la Recherche Scientifique, Eau-Terre-Environnement (INRS-ETE), in Québec City (Duchesne *et al.*, 2006; St-Onge *et al.*, 2007). The entire core was scanned through a rotating array of x-rays (with lower and higher x-ray attenuation represented in a 2D negative image by darker and lighter zones, respectively) at a resolution of 0.1 x 0.1 cm to detect laminations, as well as to determine the appropriate plane for sectioning of the core with a rotary tool and a fine iron wire.

3.3.2 Non-destructive analyses

A geochemical analysis of the core was made with an ITRAXTM core scanner from the GIRAS laboratory (INRS-ETE). A general description of this tool is provided in Croudace *et al.* (2006). In addition to providing major chemical-element profiles along the core with X-ray fluorescence (XRF), this scanner produced high-definition optical images and radiography profiles (x-ray) of the core (St-Onge *et al.*, 2007). The x-ray profile is represented as a 2D positive image of the core, with lower x-ray attenuation represented by lighter zones and higher ones represented by darker zones. A voltage of 40 kV, a current of 40 mA, an exposure time of 425 ms, and a step size at 100 μm were used for the radiography profile. The XRF analysis was done with a molybdenum x-ray tube at a step-size of 1000 μm with a voltage of 30 kV, a current of 25 mA, and a 10 sec exposure time.

3.3.3 Destructive analyses

The half-sectioned core used for the ITRAXTM analysis was subsampled every 0.5 cm and all the subsamples were freeze-dried for 24 h. Grain-size analysis was made every 2 cm on ~ 0.3 g of freeze-dried sediment. Samples were first treated in a hydrogen peroxide solution (30 % v/v) to remove organic residue and in a 1 M sodium hydroxide solution to remove biogenic silica. The particle-size distribution was then determined with a Fritsch Analysette 22 laser particle sizer, and the results were plotted as a two-dimensional contour plot (Beierle *et al.*, 2002) with SigmaPlot. Boundaries for the particle-size distribution follow Last (2001). An estimation of the sediment organic-matter content was calculated by loss-on-ignition (LOI) at 550°C following Heiri *et al.* (2001). The analysis of total carbon, nitrogen, and sulphur content (CNS) was also made on a LECO CHNS-932.

Chironomid head capsules were retrieved every 1 cm in the uppermost 10 cm and at 2 cm intervals through the rest of the core. At least 1 g of freeze-dried sediment was treated for 10 min. in a hot (not boiling) 10 % KOH solution. The solution was then sieved on a 100 μm mesh, and the residue retained on the mesh was used for extracting midge remains. Head capsules were collected from the sediments with the kerosene-flotation technique (Rolland and Larocque, 2006). The remaining solution was placed in a Bogorov counting tray and examined under a stereomicroscope at 35-60x magnification. All head capsules picked were mounted ventral side facing up on a microscope slide with a water-soluble mounting medium (Hydro-Matrix). At least 50 head capsules (Heiri and Lotter, 2001; Larocque, 2001; Quinlan and Smol, 2001) were identified under a light microscope at 400x magnification with the help of various taxonomic guides such as Cranston (1982), Oliver and Roussel (1983), Wiederholm (1983), and a new visual guide based on high-resolution pictures (Larocque and Rolland, 2006). Tanytarsini taxa were separated with Brooks *et al.* (1997) and Brooks unpublished identification keys which are now part of a new taxonomic guide by Brooks *et al.* (2007). In the absence of mandibles, the Tanytarsini were classified by the presence (Tanytarsini with) or absence (Tanytarsini without) of a spur on their antennal pedicel. When no antennal pedicel was present they were placed in the Tanytarsini sp. category. The Tanypodinae were separated by the position of the setae, following Rieradevall and Brooks (2001). Identification of Zalutschia sp. B followed Barley *et al.* (2006). Fragments with more than half a head capsule were counted as one head capsule, whereas capsules that were exactly half one head capsule were counted as half. All other fragments were disregarded.

Dating of the sediment sequence (Table 3.1) was based on two calibrated AMS radiocarbon dates from chironomid head capsules (44.5-45.5 cm and 62 cm) and one marine shell (Macoma balthica) found at the bottom of the core (80.5 cm). Due to the absence of any terrestrial macrofossil remains in the sediments, we also used three calibrated humic-acid dates from another core (core 3G), not described in this paper, but also retrieved at the same location in July 2004 and subsampled at 0.25 cm intervals in the field (Laperrière, 2006). The carbon dates obtained were converted to radiocarbon years Before Present (BP) using the program CALIB version 5.0.1 (Stuiver *et al.*, 2005). The marine calibration for the shell includes a local reservoir effect of (Delta) δR 200 ± 50 years derived from the Evans Strait and Repulse Bay (Nunavut) regions that surround Southampton Island. For the chironomid dating, at least 1200 clean head capsules were hand-picked from the sediment as described by Fallu *et al.* (2004) and processed by Beta Analytic in Miami, Florida, USA, following an acid/alkali/acid pretreatment. The humic-acids and the marine shell were dated at the Keck Carbon Cycle AMS Facility, Earth System Science Department, UC Irvine, USA. Taking into account the compaction effect in the core 4P during transport and storage, core correlation was made by depth from the water-sediment interface and by matching of the LOI information available in each core (Figure 3.2a).

Table 3.1 AMS radiocarbon dates from Caribou lake (Humic acids, marine shell and chironomids).

Laboratory number	Core ID	Depth (cm)	Depth (cm) transposed to core 4P *	Material	^{14}C age BP	δ^{13}C	Cal. age BP	
							1 σ (68,3%)	2 σ (95,4%)
UCI-21586	3G	10.25-10.75	6.5	Humics	1660 ± 25	-25.2	1598-1529	1688-1517
UCI-21589	3G	24.75-25.25	15.8	Humics	2585 ± 25	-25.7	2748-2726	2757-2620
UCI-21585	3G	35.75-36.25	22.8	Humics	3285 ± 25	-24.6	3557-3472	3569-3450
Beta-222049	4P	44.5-45.5	-	Chironomids	6120 ± 40	-27.6	7010-6920	7160-6880
Beta-220586	4P	62-62.5	-	Chironomids	8370 ± 40	-26.7	9460-9320	9490-9290
UCI-28832	4P	80-81	-	Marine shell	7925 ± 20	3.6	6334-6204	6381-6109

The calibrated age ranges are based on the INTCAL98 and Marine04 calibration using CALIB 5.0.1 (Stuiver *et al.*, 2005). Laboratory were the Keck Carbon Cycle AMS Facility, Earth System Science Department, UC Irvine (UCI) and Beta Analytic in Miami, Florida * See text for details of core parallelization

3.3.4 Statistical analyses

Selected chemical elements (peak areas) and the abundance per gram and relative abundance of major chironomid taxa were represented in stratigraphic diagrams with the program C2 (Juggins, 2003). For the chironomid data a Hill's N1 diversity index (Hill, 1973) was calculated with Primer 6 (Clarke and Gorley, 2006). Zonation methods followed the recommendations of Birks and Gordon (1985) and Bennett (1996). Numerical zonation was carried out by optimal partitioning using sum of squares criteria (programs TRAN (Version 1.8; Juggins 1992a) and ZONE (Version 1.2; Juggins 1992b)) and the number of statistically significant zone limits was determined with the broken-stick model (software BSTICK version 1.0, Bennett, 1996). A Detrended Correspondence Analysis (DCA), with square root transformation and downweighting of rare taxa, was run to estimate the amount of chironomid-assemblage turnover along the length of the core (Bigler *et al.*, 2006). The gradient length of the first axis (>2) indicated a unimodal distribution (Lepš and Šmilauer, 2003) of the chironomid assemblages.

Chironomid assemblages (calculated as relative abundance) served to reconstruct mean August air temperatures with weighted averaging partial least squares (WA-PLS) analysis with a leave-one-out cross-validation method and a square root transformation. The calibration data set used for this reconstruction is derived from a model developed for northern Québec (Larocque *et al.*, 2006) with a coefficient of determination (r^2) of 0.76, a root mean square error of prediction (RMSEP) of 1.12 °C, and a maximum bias of 2.14 °C. The "validity" of the transfer function was estimated by various statistical methods: 1) the fit-to-temperature, 2) the presence of modern analogues, and 3) the percentage of taxa present in the fossil records and in the transfer function. These statistical analyses follow recommendations by Birks (1998). Samples from the core were passively plotted in the CCA (not shown here) of the transfer function to determine if the fossil sample were similar to the training set samples, and thus determine if the transfer function can be applied. All fossil samples were well within the training set samples indicating that 1) all fossils samples were similar to those found in the training set lakes and 2) that the transfer function can be applied.

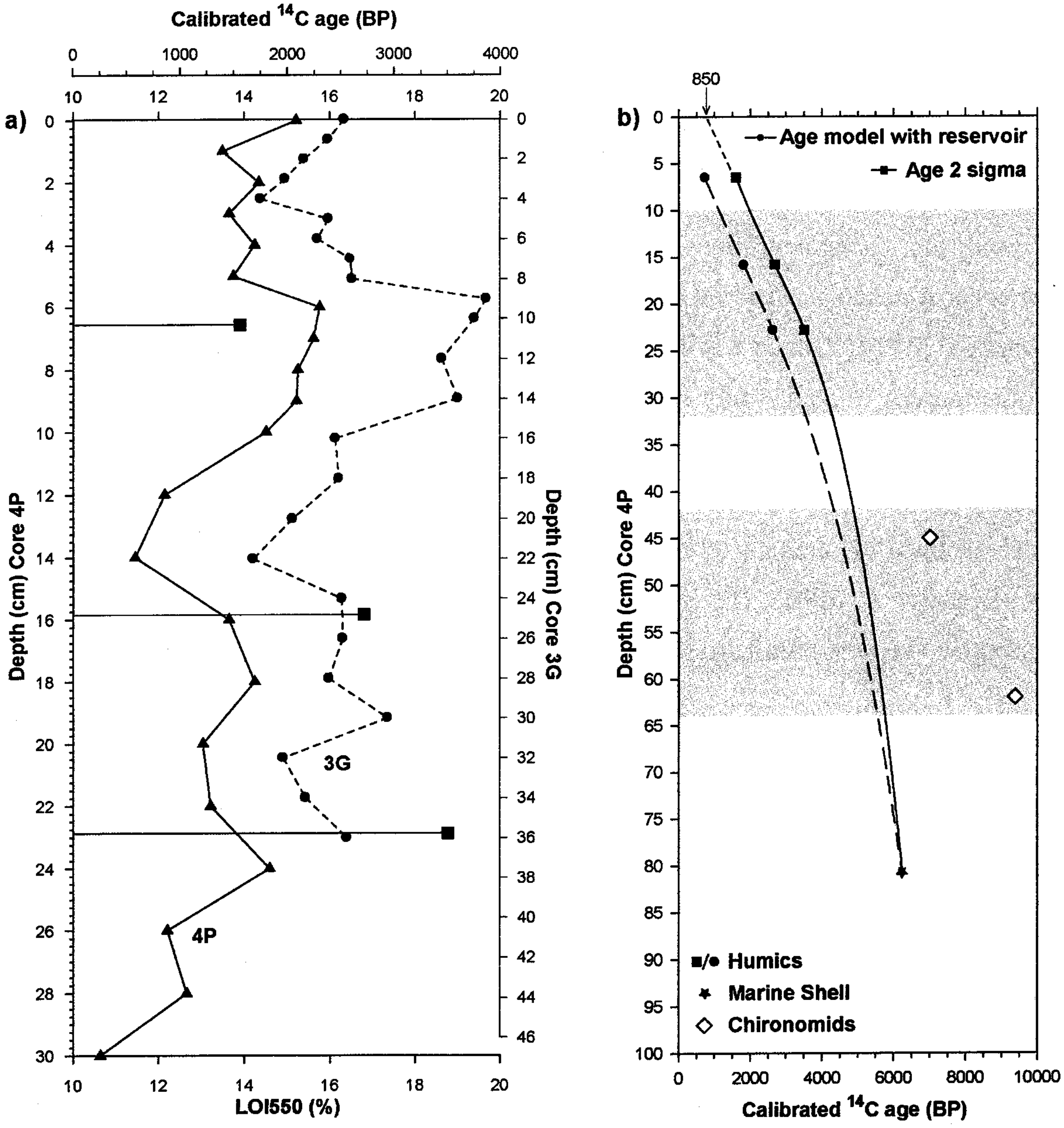

Figure 3.2 a) Loss-on-ignition (LOI) at 550°C for core 4P (plain line with triangles) and core 3G (dashed line with round dots). Depth axis of core 4P was stretched to match LOI variation in core 3G (see text). Calibrated humic-acid ^{14}C ages in core 3G are also provided (square symbols). These dates were transposed to core 4P depth axis. b) Depth-age models for core 4P using marine shell (81 cm) and humic-acid dates derived from correlation with core 3G by LOI values. See text for more details on both models. Shaded areas indicate zones derived from the chironomid analysis.

3.4 Results

3.4.1 Core chronology

Parallelization and comparison of core chronologies as shown in Figure 3.2 revealed that compaction occurred in the core that was not subsampled in the field and transported intact to the laboratory. Thus, matching of the two LOI curves required "linear stretching" of this studied core by 13 cm which corresponds to the difference in length measured in the field. Following this 13 cm linear stretch, both LOI curves presented the same trends and therefore allowed us to take the acid humic dates into consideration for our core chronology (Figure 3.2a). The acid humic dates obtained on core 3G were then transposed to core 4P. Chironomid-based dates (7020 cal BP and 9390 cal BP) were systematically older than expected (Figure 3.2b). These dates were especially older than the estimated time of deglaciation in the area (6600-6700 cal BP) (Dredge, 2001; Rouault, 2006) and have therefore been disregarded to establish our age model. Using both humic acids and marine shell dates (calibrated age 2 sigma), a cubic regression model (eq.1) was then calculated (Figure 3.2b). The intercept with this curve and the age axis revealed a "reservoir age" of the lake and its surrounding watershed of 850 years. This "reservoir age", which may have bias the humic acid dates, was then subtracted to these dates and a second age model (eq. 2) was then established and used as a reference for our core chronology.

$$\text{eq. 1}: \; y = -18.8794 + 0.0235x - 5.9896.10^{-6}x^2 + 7.6534.10^{-10}x^3$$

$$\text{eq. 2}: \; y = -1.1207 + 0.0112x - 1.6656.10^{-6}x^2 + 3.1459.10^{-10}x^3$$

3.4.2 Geochemical analyses

The optical image, the two-dimensional scan (topogram), the XRF profiles of major chemical elements (plotted as peak area), and the X-ray image from ITRAX with its grey profile are provided in Figure 3.3. This series of analyses revealed that the core consisted of two principal units: marine and lake sediments. The marine sediments (100-64 cm core depth) were characterized by low penetration of X-rays and a high content of Ca and K.

They also included many shells and pebbles. The transition from marine to lacustrine sediments at 64 cm was characterized by an abrupt change in the sediment composition, with a sharp decline in Ca concentrations and a higher porosity to X-rays as revealed by higher grey values.

Except for Sr and Zr, which declined through time, the profiles of all the selected chemical elements (Fe, Ti, Ca, K, Mn) in the lake sediments fluctuated without any visible trend from 64 to 42 cm. Only two high-magnitude declines in the peak area at 60 and 48 cm interrupted this relative stability and were correlated with holes in the half core surface (see optical image). Between 42 and 32 cm, these elements increased by ~ 30 %, with a maximum of 50 % for Fe and Ti. From 32 cm upwards, these profiles stabilized up to the top of the core and were only interrupted by two short-lived events, namely a minimum at 25 cm and a peak at 14 cm. Redox processes perturbed the Fe and Mn profiles in the upper most 4 cm of the core, as revealed by large increases of their peak area. The incoherent/coherent ratio, which may be used as an estimate of the sediment organic content (Cox, 2006 pers. comm.), did not vary significantly during the lake history.

The particle-size distribution (Figure 3.4) generally revealed well-sorted, strongly fine-skewed, and platykurtic (plateau-like distribution) sediments. The mean grain size (μm) gradually decreased through the lake's history. The marine/lacustrine transition (64-60 cm) was characterized by highly variable grain size, especially at 64 cm, where very coarse silt (~ 30 μm) and medium boulder gravel (~ 600 μm) modes were present. From 60 cm depth to the top of the core, respective modes of each level generally belonged to very coarse silt except at 22 and 16 cm where a shift to coarse silt (~ 18 μm) occurred.

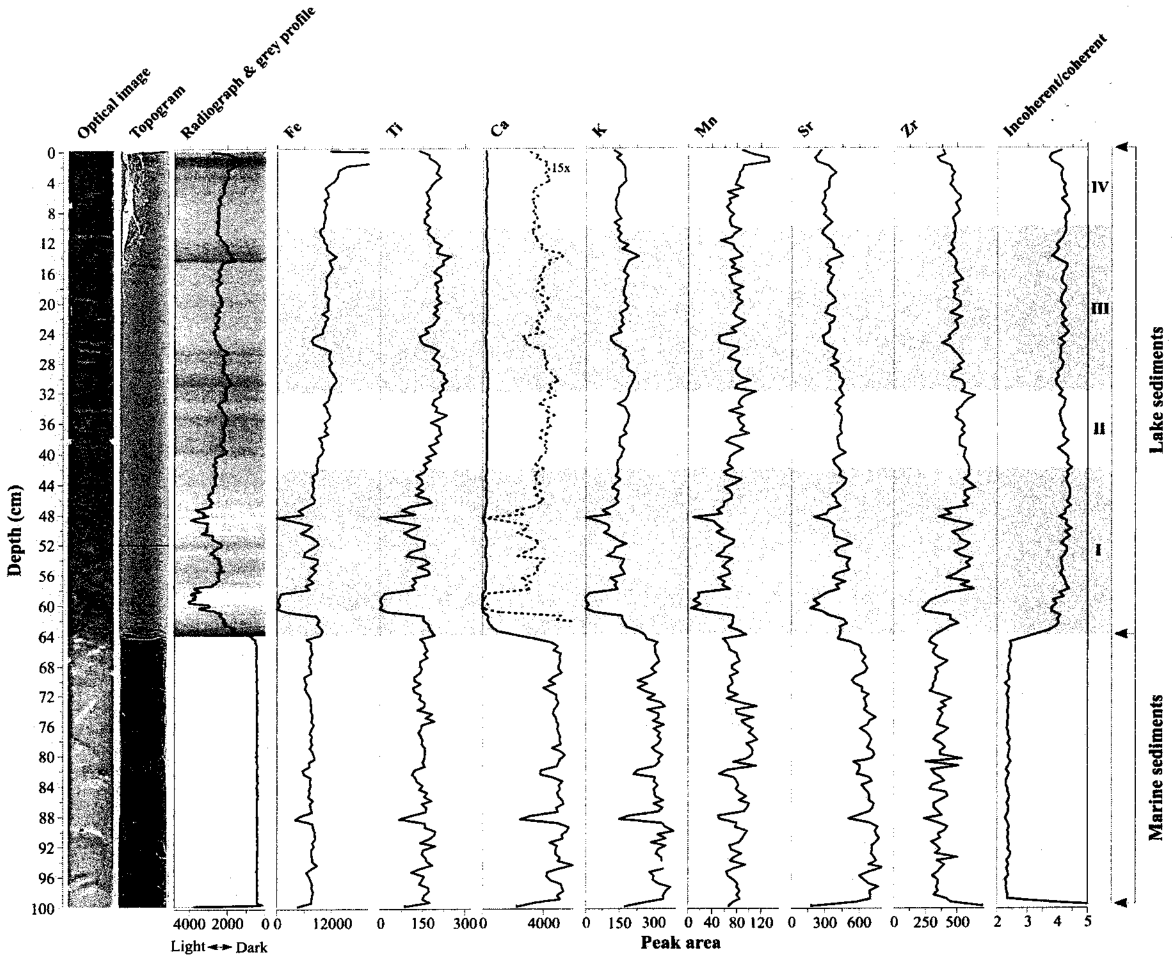

Figure 3.3 XRF profiles of major chemical elements (in peak area) of core 4P with an optical image of the half sectioned core, a two dimensional scan (topogram) of the core, and the X-ray image with its grey profile (reverse scale). X-ray image of the marine sediment is not provided as it was completely dark. Zones are derived from the chironomid analysis.

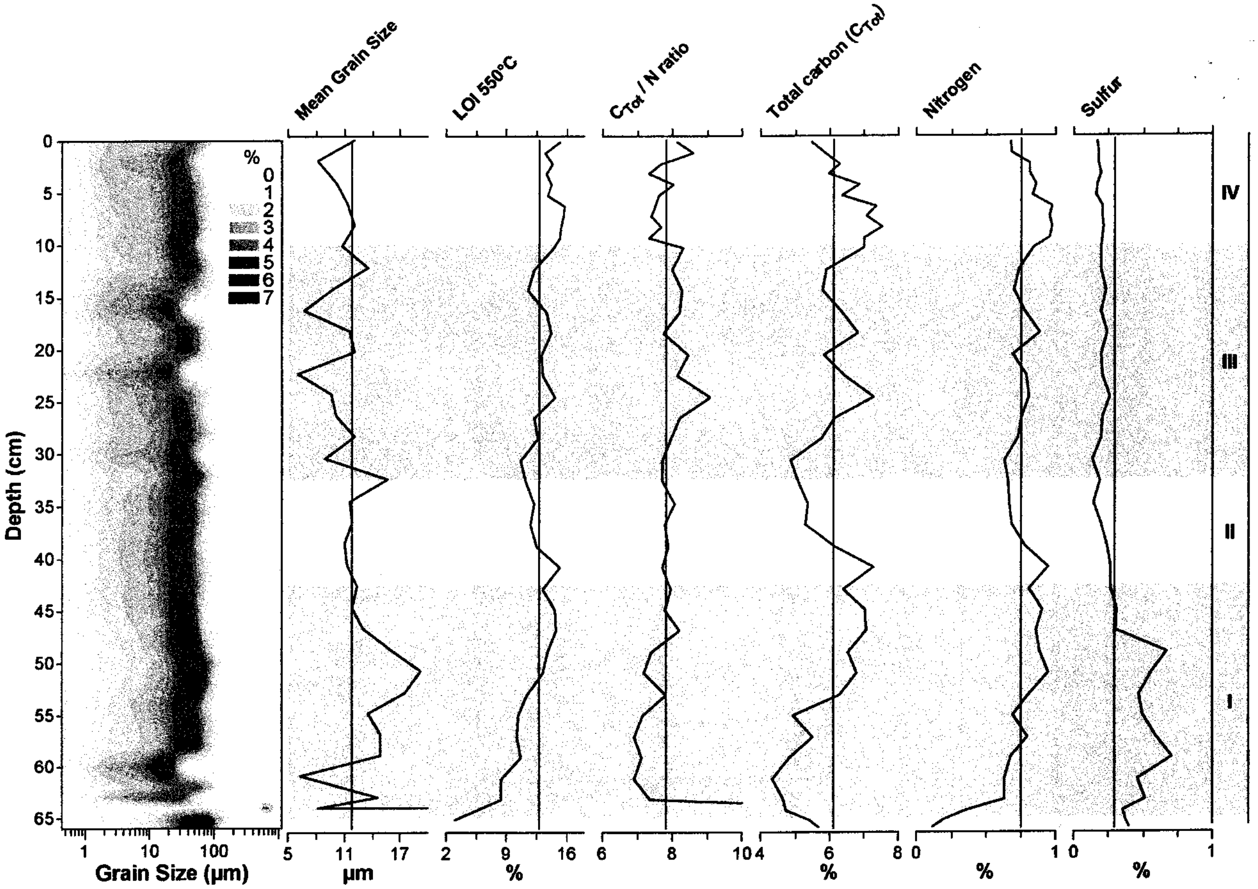

Figure 3.4 Two-dimensional graphic of the grain-size frequency distribution, with frequency values represented along a proportional grey scale from light to dark. Profiles of mean grain size, LOI at 550°C, C_T/N ratio, and total carbon, nitrogen, and sulfur are also provided.

The CNS and LOI analyses (Figure 3.4) provided useful information on the total matter derived from aquatic and terrestrial environments. The total carbon/nitrogen ratio (C_{Tot}/N) fluctuated around a mean value of 7.8, typical for lakes with low inputs of organic matter from vascular plants in arctic tundra settings (Meyers and Lallier-Vergès, 1999). Following the marine/lacustrine transition and until 42 cm, this ratio and the relative contents of total carbon and nitrogen increased as a consequence of higher contributions from vascular plants (carbon) and phytoplankton (nitrogen) to the lake. Between 42 and 32 cm, both total carbon and nitrogen decreased without having any impact on the C_{Tot}/N ratio. Starting at 32 cm, nitrogen increased and stabilized in the upper part of the core around a mean value of 0.75 %, with only a short-lived increase between 10 and 5 cm. By contrast, the total carbon content showed much more variability during that same period, also affecting the C_{Tot}/N ratio. The sulfur content, which is related to lake productivity and biodegradation (Wetzel, 2001), was higher between 64 and 46 cm and then decreased and stabilized in the top part of the core. The LOI followed the same fluctuations as observed in the C_{Tot}/N ratio and remained stable throughout the lake's history.

3.4.3 Midges

Four different stratigraphic zones were obtained using the program ZONE (Figure 3.5). The same zones were obtained with the concentration (Figure 3.5a) and the relative abundance (%) data (Figure 3.5b). Both stratigraphies providing similar information, the concentration diagram will be mainly discussed, unless there are discrepancies between the two graphs.

Results of the DCA analysis are presented on Figure 3.6. The first axis of the DCA explained 79.3 % of the variance in the chironomid assemblages while DCA axis 2 explained 11.6 % of the variance.

Zone I:

This zone was visually divided into two phases: 64-56 cm (Ia), and 56-42 cm (Ib). The first phase corresponded to the establishment of the lake invertebrate community and was dominated by *Corynocera oliveri*-type, *Paracladius,* and *Microspectra radialis*-type. *C. oliveri*-type, a cold-littoral zone dweller, was also found to be abundant during the colonization phase of lakes in the southern Alps, France (Gandouin and Franquet, 2002), Norway (Brooks and Birks, 2000; Velle *et al.*, 2005), Scotland (Brooks *et al.*, 1997), and Sweden (Larocque and Bigler, 2004). Based on previous inference models (e.g. Larocque *et al.*, 2001; 2006), *C. oliveri*-type is a cold-stenotherm with a temperature optimum around 10-11°C. *Paracladius* and *M. radialis*-type were found in the bottom core section of many lakes such as a small Swiss subalpine lake (Heiri *et al.*, 2003) and *Paracladius* commonly occurs in deep and cold arctic tundra lakes (Walker *et al.*, 1997, 2003). Hill's N1 diversity indices (Figure 3.5a) for this phase were lower than 10, but the concentration of chironomid head capsules reached a maximum of ~ 900 head capsules per gram dry sediment.

The second phase was characterized by a rapid increase of Hill's N1 diversity indices with the appearance of the genus *Abiskomyia*, a cold-adapted taxon usually found in shallow arctic lakes and flowing waters (Oliver and Roussel, 1983; Walker, 1990; Olander *et al.*, 1999); *Mesocricotopus*, a taxon of deep, cold, and well oxygenated arctic tundra lakes (Walker *et al.*, 2003); *Sergentia,* a profundal taxon (Francis, 2001); and the *Heterotrissocladius* group, which are adapted to cold waters (Olander *et al.*, 1999) of oligotrophic lakes (Walker and Paterson, 1983). *H. marcidus*-group and *H. brundini*-group had high concentrations but percentages below 20 % in this phase. Their peaks were coincident with decreases of the taxa which first colonized the lake, in particular *C. oliveri*-type. The cold stenotherm (Brooks and Birks, 2001) and acidophilic (Pinder and Morley, 1995) taxa belonging to the *H. grimshawi*-group also reached their maximum abundance during the *C. oliveri*-type decline. This shift also corresponded to an increase of *Parakiefferiella nigra,* a taxon generally related to deep oxygenated lakes (Walker and Mathewes, 1989; Quinlan *et al.*, 1998), and to increases of *Cricotopus* and *Limnophyes*, which are widely distributed in the shallow littoral zones of lakes and on aquatic plants (Oliver and Roussel, 1983). Abundances of initially dominant taxa decreased

(*Paracladius* and *M. radialis*-type) or completely (*C. oliveri*-type) disappeared at 42 cm. The changes in percentages of *M. radialis*-type were less obvious than its changes in abundance. The head-capsule concentrations decreased to ~ 200 per gram dry sediment.

The DCA scores for the first axis (Figure 3.6) were higher during this zone than in any other zone, suggesting unstable lake conditions (Bigler *et al.*, 2002).

Zone II:

This zone was dominated by *Abiskomyia*, a change which is more obvious in the relative abundance (%) diagram. *Pseudodiamesa*, a cold water, high arctic taxon (Walker *et al.*, 1997; Larocque *et al.*, 2006) and often associated to flowing waters (Oliver and Roussel, 1983), appeared with *Zalutschia* sp. B. Both taxa belonging to *Zalutschia* are generally encountered in dystrophic humic waters (Walker *et al.*, 1991) and in productive anoxic environments (*Z.* sp. A, Quinlan and Smol, 2001). *Corynoneura* percentages increased during this zone, as well as *Heterotrissocladius subpilosus*-group. The head-capsule concentrations decreased to ~ 50 head capsules per gram dry sediment at 32 cm. The DCA scores for the first axis (Figure 3.6) steadily decreased up to 32 cm core depth.

Zone III:

This zone is characterized by increased abundance and relative abundances (%) of the *H. subpilosus*-group, which dominated the assemblages together with *Corynoneura*, *H. grimshawi*-group, and *M. radialis*-type. The beginning of this zone (30 cm) was marked by a rapid decline of the Hill's N1 diversity index and of the head-capsule concentration. Starting at 28 cm, these variables returned to their initial values (Hill's N1 index around 10 and head-capsule concentrations around 50 head-capsules per gram dry sediment) and thereafter did not show major variations, except at 16 cm, where they both dropped sharply. *Cricotopus* and *Zalutschia* sp. A were present throughout the whole period. Percentages of *H. grimshawi*-group slightly increased compare to the previous zone. The DCA scores were relatively stable during that zone.

Zone IV:

The chironomid assemblages of this zone were much the same as those encountered in zone III, for they only differed by a higher abundance of *H. subpilosus*-group and the disappearance of Pentaneurini and *Paracladius*. *Psectrocladius sordidellus*-group and *Pseudodiamesa* increased in the top sample. This zone was also characterized by a constant decline of Hill's N1 diversity index, with the possible extinction of less abundant taxa such as *Sergentia* and *Paracladius*. DCA scores ranged between 0 and 0.5.

3.4.4 Temperature reconstruction

The chironomid-based August air temperature (°C) profile is presented on Figure 3.7. All samples had a good-fit to temperature, more than 85% of the fossil taxa were found in the training set and all samples had good-modern analogue situations, suggesting that the temperature optima should be accurate. The climate normal (1971-2000) in August at Coral Harbour is 7.3°C while the inferred temperature in the uppermost sample was 7°C, suggesting that the inference was quite reliable.

Zone I was separated into two phases, as described above. The inferred August air temperature rose rapidly to a maximum of 10 °C, and then decreased to ~ 9.5 °C. The inferred temperatures for the second phase stabilized at ~ 9.5 °C. In zone II, the inferred temperature was, in average, 8.7 °C. This average was pulled down by one cold oscillation (7.8°C) at 38 cm (about 4,200 cal. yrs BP). In zone III, inferred August air temperatures remained relatively stable at ~ 8.6 °C in average, except for a short-lived peak of ~ 10 °C at 16 cm (about 1,900 cal. yrs BP). In the last zone, the average temperature was 8.3°C, with the coldest temperature (7.3°C) recorded in the uppermost sample. The amplitude of average temperature changes between zone I and zone IV was of 1.2°C, which is slightly above the RMSEP. The variation between the warmest (10°C) and the coldest inferences (7.3°C) was 2.7°C.

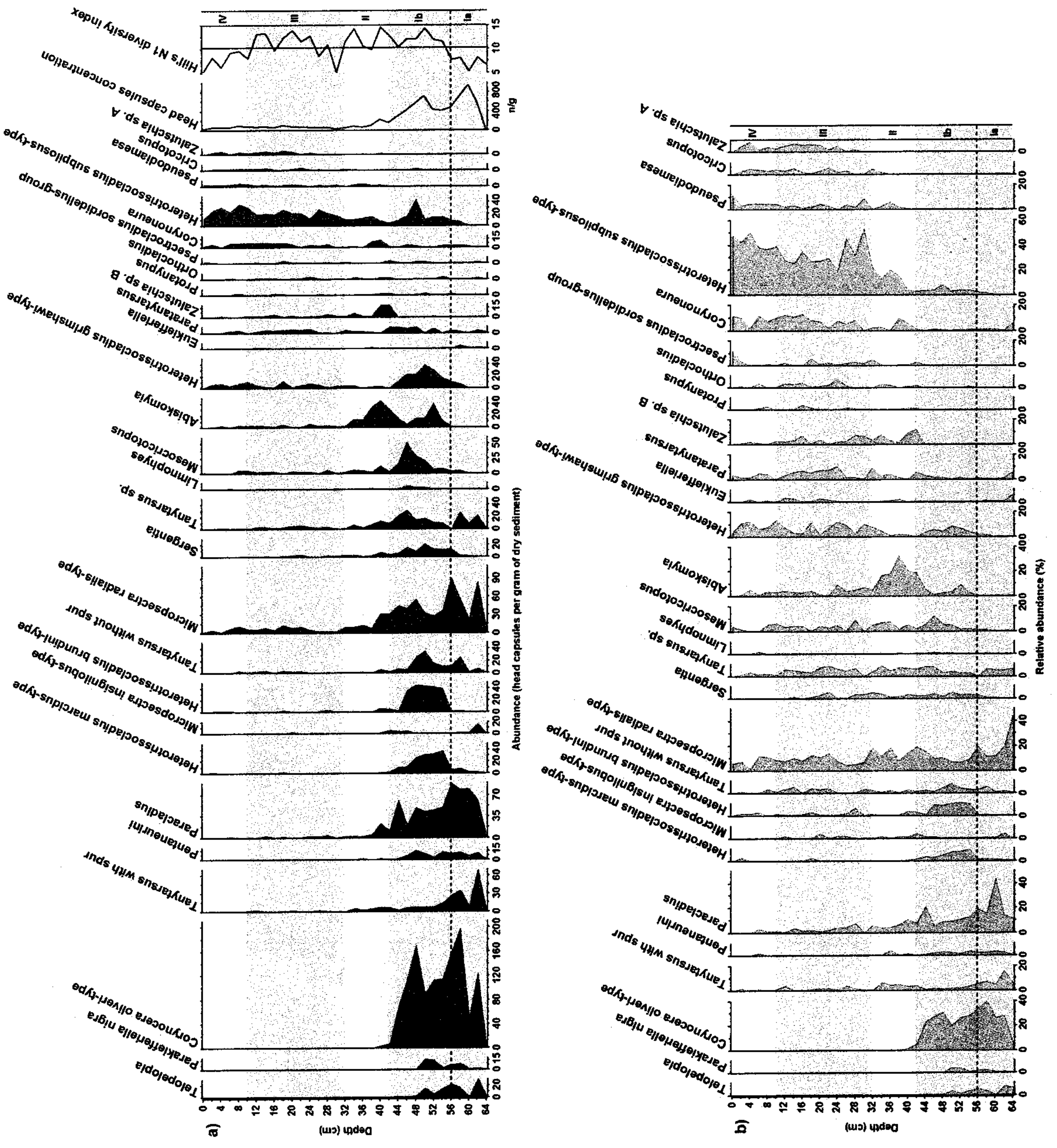

Figure 3.5 Chironomid stratigraphies in abundance per gram of dry sediment (a) and in relative abundance (b) of the sediment core 4P of Caribou Lake. Head-capsule concentration and Hill's N1 diversity index are also provided. The inferred August air temperatures were developed with a calibration data set from the northern part of Québec (Larocque *et al.*, 2006). Zones were calculated by a CONISS cluster analysis.

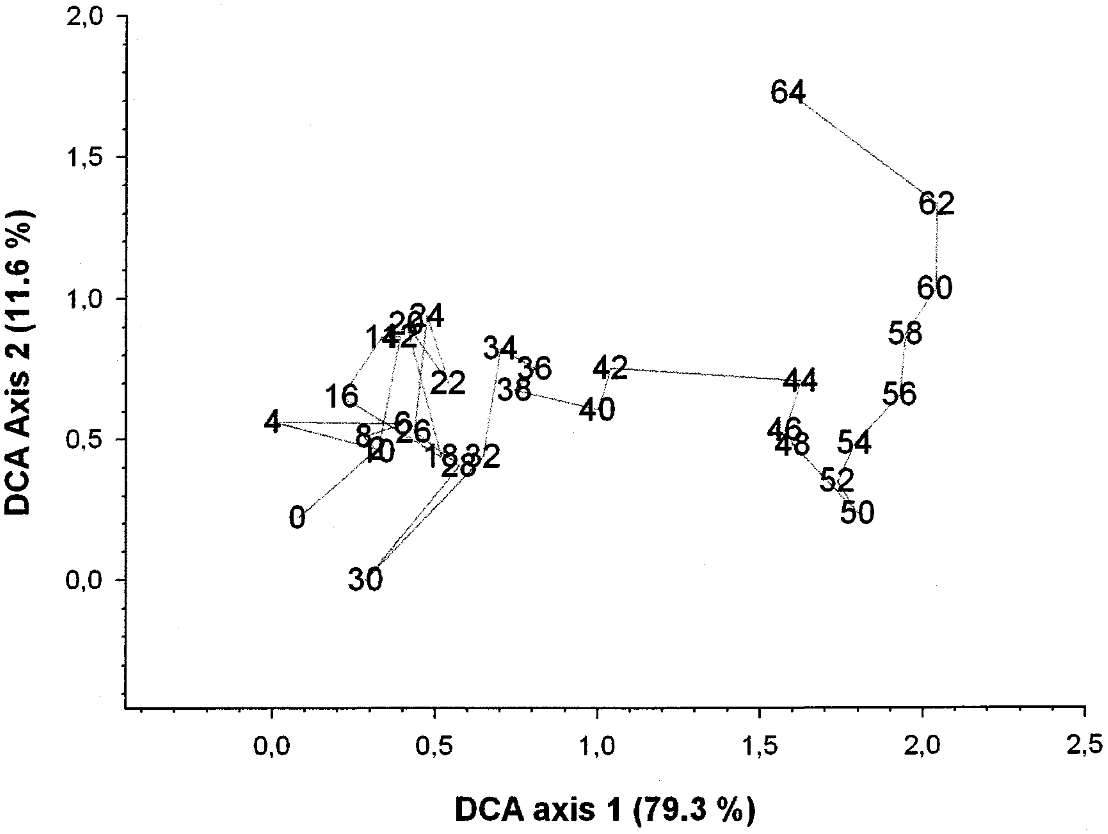

Figure 3.6 Amount of chironomid assemblage turnover as estimated by a Detrended Correspondence Analysis (DCA).

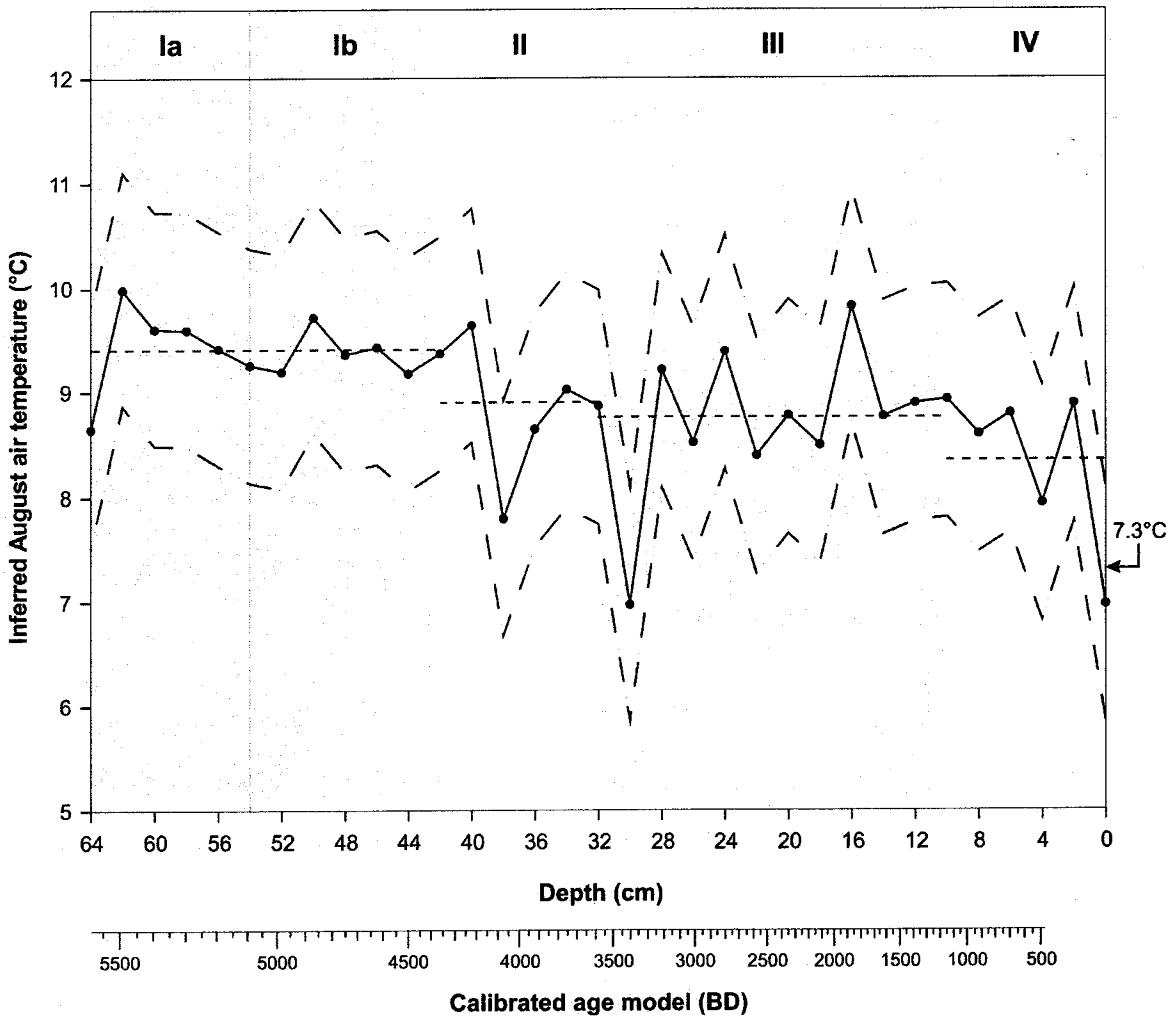

Figure 3.7 Chironomid-based August air temperature (°C). The model root mean square error of prediction (RMSEP) is represented along the profile. The mean inferred temperature for each chironomid-based zone is represented as well as the climate normal (1971-2000) in August at Coral Harbour (7.3°C).

3.5 Discussion

Following the retreat of the Laurentide Ice Sheet around 6600-6900 cal. yrs BP (Dredge, 2001; Rouault, 2006), glacio-isostatic land uplift raised the northern part of Southampton Island which in the Caribou Lake area was still inundated by marine waters. The shift from a marine to a lacustrine environment occurred at about 5570 cal. yrs BP according to our age model and revealed by the presence of dense, clay-rich marine sediments at the bottom of the core. This event also corresponded to an almost instantaneous increase of the sediment porosity and to a rapid decline of the Ca and, to a lesser extent, K concentrations.

3.5.1 Holocene environmental change at Caribou Lake

During the lacustrine phase, the fine grain-size distribution point out for deposition environments of low energy, with little direct influence from the single tributary. These conditions proved to be quite stable during the last 5570 cal. yrs.

Both chironomid-assemblage and DCA data reflect the highly variable environmental conditions between about 5570 and 4360 cal. yrs BP and their relative stability after about 3570 cal. yrs BP. This is also supported by the major chemical elements (Figure 3.3) and the density of the sediment which varied in the first and second zones but stabilized afterwards. Following the creation of the lake, rapid appearances of some chironomid taxa proved their capacity to rapidly colonize lakes on unstable, recently deglaciated landscapes. This instability found its expression in a pre-establishment period (phase one, zone Ia, 64-56 cm) characterized by the highest fossil head-capsule concentrations and by the highest DCA values in the entire core. The dominance of common cold-stenotherm littoral or deep water taxa, such as *Corynocera oliveri*-type, *Paracladius,* and *Microspectra radialis*-type resembles situations recorded from many cores corresponding to early post-deglaciation events (e.g. Heiri *et al.*, 2003; Larocque and Bigler, 2004). This period early in the lake's history is usually described as extremely unstable due to profound modifications of the limnological and landscape states (Korhola *et al.*, 2002; Saulnier-Talbot *et al.*, 2003). Density differences between fresh and saline waters may have also contributed to this instability and created a meromictic-like system shortly after the creation of the lake. Higher salinity in the bottom part of the lake due to trapped seawater might be an explanation for the lower diversity of profundal taxa during this phase, especially at 64-60 cm. However, the most abundant profundal taxa found in this section (*Paracladius* and *Micropsectra radialis*-type) have never previously been associated with saline environments (Walker *et al.*, 1995) but rather with deep and cold arctic tundra lakes (Walker *et al.*, 1997; Pellatt *et al.*, 1998; Brooks and Birks, 2000; Gandouin and Franquet, 2002).

This pre-establishment period was short-lived and was followed in the second phase (zone Ib, 56-42 cm) by the appearance of many new chironomid taxa that may have spread in all the newly available lake habitats The appearance of cold-adapted taxon *Abiskomyia*, usually encountered in the shallow zones of arctic lakes (Oliver and Roussel, 1983), supports this hypothesis. To a lesser extent than in the first phase, chironomid assemblages were still highly variable as expressed by the first DCA axis.

Chironomid assemblages in the second zone of the core (42-32 cm) portrayed a stabilization of the lake ecosystem. The disappearance of almost all the littoral and deep profundal taxa corresponded to a distinct decrease in the scores of the first DCA axis.

The two uppermost zones of the core covered the last 3500 cal. yrs BP and clearly reflected cold oligotrophic conditions with the dominant taxon belonging to *Heterotrissocladius subpilosus*-group. This period was likely the more stable in the lake's history, with a constant decrease in the chironomid assemblages' variability (DCA, Figure 3.6). This relative stability in the chironomid assemblages only changed in the uppermost few centimeters of the core, also shown in changes in the density and some major chemical elements.

3.5.2 Temperature reconstruction and comparison with regional paleoclimatic data

Inferred Holocene August air temperatures at Caribou Lake ranged from 10.0 to 7.0 °C, with the highest inferred values associated with the early lake stages (about 5570-4360 cal. yrs BP) and an obviously more stable period spanning from about 3570 cal. yrs BP until the present-day. The new inference model used to reconstruct air temperatures in this study covered a large geographical and climatic gradient, from southern Québec (Mont-Laurier) to Southampton Island (Larocque *et al.*, 2006). However, this model is lacking mid- and high arctic lakes, which might have reduced its performance on our samples. Also, as described by Larocque and Hall (2004), the large root mean square error of prediction (RMSEP) of the model used for this study (RMSEP = 1.12°C) might limit our interpretation of low (< 1°C) amplitude temperature variations, although it has been shown that small changes in the range of 0.5°C can be adequately inferred by chironomids (Larocque *et al.*, 2003), and that the RMSEP are generally over-conservative and that the average difference between meteorological data and chironomid-inferred temperatures is smaller than 0.7°C (Larocque, submitted). A regional comparison with other lakes is usually used to decrease this uncertainty. However, since our study is the first of its kind completed on this island, we can only refer to data from other study sites located far from Caribou Lake. Despite these restrictions, we can ascertain that our temperature reconstructions are in close agreement with results reported from previous paleolimnological studies in northern Québec and Labrador (Pienitz *et al.*, 2004b). Based on the inference model developed by Walker *et al.* (1997), Fallu *et al.* (2005) inferred surface water temperatures derived from chironomid remains of a shrub-tundra lake in northern Québec. This lake experienced relatively stable paleoclimatic conditions between 4900 and 1500 cal. yrs BP. Using terrestrial pollen remains, Sawada *et al.* (1999) inferred stable August air temperature throughout the Holocene at 4 lake sites (LR1, LB1, BI2, GB2) in northwestern Québec. In the same study, between 5700 to 2000 cal. yrs BP, they obtained similar temperature patterns for the sea-surface temperatures in the southern James Bay area using marine dinocysts. Apart from temperature reconstructions, many studies have already shown this stability during the Holocene. Ponader *et al.* (2002)

studied the fossil diatom assemblages during the late Holocene (last 3000 cal. yrs BP) in a subarctic lake in northwestern Québec. The continued dominance of the taxon *Fragilaria virescens* var. *exigua* confirmed the stable limnological conditions (including dissolved organic carbon content) that prevailed during that time.

In the northern Québec, Labrador, and Baffin Island regions, the Holocene thermal maximum (HTM) was delayed by thousands of years with respect to the early Holocene insolation maximum due to the late decay of Laurentide Ice Sheet remnants (Williams *et al.*, 1995). Quantitative multiproxy studies estimated that the HTM occurred in these regions between 6300 and 3700 cal. yrs BP (Kaufman *et al.*, 2004). This period warmer than today by about 1-2 °C (Kaufman *et al.*, 2004) coincided with changes in vegetation density and a northern advance of the arctic tree line (Payette and Lavoie, 1994). Our results suggest that the HTM in the northern Southampton Island-southern Foxe Basin region ended around 4400 cal. yrs BP and that August air temperatures (9.5°C in average) were about 2.2°C higher than today's climate normal (7.3°C). The average temperature over the last 1,000 cal. yrs BP were, in average, 1.2°C colder than before ca 4,400 cal. yrs BP. The grain-size analysis revealed that the proportion of clay (0-10 μm) particles increased up the core, with the highest values obtained near the water/sediment interface. Cold conditions usually increase the relative proportion of clay because of no high discharge from the watershed. The sedimentological data thus support the temperature reconstruction using chironomids, with colder inferences during the last 1,000 cal. yrs BP.

3.5.3 Chironomid dating

Lake-sediment chronologies are commonly based on AMS ^{14}C radiocarbon dating of plant macrofossils. However, in the unproductive watersheds of arctic tundra lakes with their sparse vegetation cover and thin soils, alternative dating methods must be considered (reviewed in Wolfe *et al.*, 2004), such as humic-acids extracted from bulk sediment and chironomid head capsules. This latter method, which yielded consistently younger ages in Fallu *et al.* (2004), proved to be more reliable as compared to bulk sediment dating at Lake K2 in arctic Québec. In our study, two dates at different levels in the core yielded older dates, with differences of more than 3000 years compared to the dates derived from humic-acids and a marine shell. More than 1200 head capsules were used for each dating. As shown in the stratigraphic diagram (Figure 3.5), these chironomid remains were mainly composed of large head capsules of *Corynocera oliveri*-type, *Paracladius*, and, to a lesser extent, *Microspectra radialis*-type. Although the samples were pre-treated with acid/alkali/acid (44.5-45.5 cm), and acid washes (62 cm), contamination through old carbon trapped inside their capsules might have caused this bias. The chironomid AMS ^{14}C dating method therefore needs further testing and refining in order to evaluate its efficiency in such situations.

3.6 Conclusions and perspectives

Paleoenvironmental reconstructions from Caribou Lake on northeastern Southampton Island showed consistent trends in the different proxies used: unstable conditions after the sea retreated from this site, with inferred temperatures warmer by 2°C compared to today's climate normal, followed by more stable environments and a slight decrease (within the model's RMSEP) of average temperature during the last 1,000 cal. yrs BP. This study, which was mainly based on fossil chironomid interpretations, was supported by sedimentological analyses. No sign of warming was recorded at that site, which is consistent with reconstructions more south in Quebec, but contrasts with reconstructions obtained from the higher arctic. This reconstruction suggests that Southampton Island does not respond to climate change yet. In the future, more paleolimnological studies will have to be initiated in the Foxe Basin region to improve our knowledge of past climates and environments in this area and strengthen our interpretations.

Acknowledgements

This study was made possible through Natural Sciences and Engineering Research Council (NSERC) of Canada funding granted to R. Pienitz, P. Francus and I. Larocque. The Polar Continental Shelf Project (PCSP) provided logistic support (helicopter time) for the fieldwork on Southampton Island. This is PCSP contribution number 011-07.

Logistical and technical supports provided by the local population of Coral Harbour and by professionals at INRS and CEN are greatly appreciated.

Chapitre 4

EVIDENCE FOR A WARMER PERIOD DURING THE 12 AND 13 CENTURY FROM CHIRONOMID ASSEMBLAGES IN SOUTHAMPTON ISLAND (NUNAVUT, CANADA)

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Article à soumettre

Résumé

Cette étude décrit l'évolution durant le dernier millénaire, d'un lac localisé au nord de l'île de Southampton (Nunavut, Canada). Basée sur des indicateurs biologiques (Chironomides) et sédimentaires (XRF, taille des grains et NCS), cette séquence stratigraphique est accompagnée de datations AMS sur des macrofossiles terrestres (feuilles d'éricacées), ainsi que sur des mesures de l'activité du ^{210}Pb dans les couches supérieures de la carotte analysée (0 - 4 cm). Malgré l'apparente stabilité de cet environnement, la bonne concordance entre les indicateurs révèle des changements rapides, mais non permanents, dans cet écosystème lacustre. Les températures inférées par le biais des chironomides, présentent des variations d'amplitude qui concordent avec des changements dans la composition chimique et la densité du sédiment. Les maximums observés dans ces températures coïncident généralement avec une densité du sédiment plus faible, et une diversité et abondance des chironomides plus élevées. Entre ~ AD 1160 et AD 1360, l'une des périodes chaudes inférées correspondrait au maximum thermique durant le médiéval (MWP). Entre ~ AD 1360 et AD 1700, une période froide de cette stratigraphie a été associée à un évènement de petit âge glaciaire (LIA) dans cette région. La mise en évidence de ces événements climatiques permettra d'améliorer notre habilité à modéliser la région du bassin de Foxe, et comprendre l'évolution de ce type d'écosystème sous l'influence des changements anthropiques actuels. De plus, les indicateurs sédimentologiques ont permis de décrire et d'intégrer dans l'interprétation des assemblages de chironomides, les variations dans l'hydrologie et la géochimie du lac afin de mieux comprendre comment ces dernières ont affecté les chironomides au cours de la période de temps couverte par cette étude.

Abstract

This study presents the Late-Holocene (last 1000 years) evolution of a northern Southampton Island (Nunavut, Canada) lake, using fossil chironomids supported by sedimentological evidences (XRF, grain size and CNS). The chronology was based on two calibrated accelerator mass spectrometry (AMS) radiocarbon dates obtained from terrestrial macrofossils (Ericaceae leaves) and also on ^{210}Pb dating of the uppermost 4 cm of the core. All proxies studied in our sediment core revealed a relatively stable environment during the last millennium with short-lived events driving changes in the entire lake ecosystem. The chironomid-based paleotemperatures revealed variations of significant amplitude coincident with changes in the sediment density and chemical composition of the core. Higher temperature intervals were generally correlated to lower sediment density with higher chironomid diversity and capsules concentration per gram of dry sediments. Higher temperatures were recorded from ca. ~ AD 1160 to AD 1360, which may correspond to the so-called Medieval Warming Period (MWP). Between ca. ~ AD 1360 and AD 1700, lower temperatures were probably related to a so-called "Little Ice Age" event. This study presents new information on the timing of known climatic events which will refine our knowledge of the paleoclimate and climatic models of the Foxe Basin region. It also provides a new framework for the evolution of such freshwater ecosystems under the so-called "Anthropocene" and underlines the importance of including sedimentological proxies when interpreting chironomid remains as this combined approach provides an extended overview of the past hydrological and geochemical changes and their impacts on lake biota.

4.1 Introduction

Evidence of rapid climate change at northern latitudes has focussed research efforts on arctic environments. Due to possible feedback mechanisms, such as snow and sea ice extent (albedo), these regions are believed to be particularly sensitive to global warming (Everett and Blair Fitzharris, 1998; IPCC, 2007). Many studies have already shown that some arctic areas have undergone major modifications of their annual thermal budget during the second half of the last century. They specifically showed an increase of surface air temperatures during summer, and a drastic reduction of winter sea ice cover thickness and summer extent (Johannessen *et al.*, 1995; Dickson, 1999; Johannessen *et al.*, 1999; Rothrock *et al.*, 1999; Comiso, 2002). On the other hand, regions surrounding the Foxe Basin, the Hudson Bay, and the Hudson Strait are so far only slightly affected by such global warming effects (Serreze *et al.*, 2000; ACIA, 2005). These contrasting scenarios revealed the necessity to extend our knowledge of past and present environmental conditions in order to be able to refine our ability to model past, present and future environmental changes in the Arctic.

The arctic landscape is covered by thousands of lakes and ponds, from which sediment archives can be retrieved and biological and chemical proxies can be used to reconstruct climate and environmental changes through time. Chironomids (Insecta: Diptera: Chironomidae) are considered to be valuable proxies to infer past environmental variables due to their relatively short response time to environmental forces. These non-biting midges spend most of their life time in the aquatic ecosystem (four larval stages), whereas in their winged-flying adult stage they are directly influenced by the ambient atmospheric conditions (Brodersen and Lindegaard, 1997). Based on the chironomid assemblages from the surface sediments of selected lakes distributed along an ecotonal transect, the development of statistical inference models provided an opportunity to use them specifically to infer water and air temperature (e.g. Walker *et al.*, 1991; Olander *et al.*, 1999; Larocque *et al.*, 2001, 2006). These models were used to reconstruct the Late Glacial period (e.g. Brooks and Birks, 2000; Bedford *et al.*, 2004) and the Holocene (e.g.

Palmer *et al.*, 2002; Heiri *et al.*, 2003; Larocque and Hall, 2004), although the approach can also be limited (e.g. Heinrichs *et al.*, 2005; Velle *et al.*, 2005).

To validate such biological analyses, quantitative reconstructions can be associated with sedimentological studies, such as grain size and geochemical analyses (Rolland *et al.*, accepted). Hydrological conditions and organic input from the surrounding watershed which can be specifically correlated to changes observed in the biological communities are thus useful to understand the ecological factors at play (Ammann *et al.*, 2000).

As part of concerted studies of the Foxe Basin and surrounding regions, a first paleoenvironmental study of the Southampton Island was initiated in 2004. This island occupies a transitional zone because of its central position between northern islands (Ellesmere and Baffin Islands) which already experience major climatic changes (Perren *et al.*, 2003; Antoniades *et al.*, 2005; Smol *et al.*, 2005) and areas in northern Québec and Labrador which do not provide evidence for major significant environmental changes due to non natural climate forces (Ponader, 2002; Saulnier-Talbot *et al.*, 2003; Pienitz *et al.*, 2004b). New data on the postglacial and Holocene history of Southampton Island were already obtained using past inshore marine limit (Rouault, 2006), diatoms (Laperrière, 2006) and chironomids (Rolland *et al.*, accepted). These latter two studies revealed stable climatic conditions for this island during the last 3000 years. However, there results were obtained from a lake basin with low sedimentation accumulation and therefore did not provide high enough temporal resolution for reconstructing recent environmental changes in the region under investigation.

Here we present a higher resolution record from a lake located on northern Southampton Island. Using biological (chironomids) and sedimentological indicators, this study generates new insights into past natural climatic variations of this region over the last millennium.

4.2 Material and methods

4.2.1 Study area

Southampton Island (Nunavut) is located in the northern part of Hudson Bay at the limit of Foxe Basin and at the apex of Hudson Strait (Figure 4.1). Lake 4 (Tasiq Qikitalik, unofficial name; 65°05'70''N, 83°47'49''W) is situated 100 m a.s.l in the northeastern part of the island. This lake has a maximal length and width of 1.6 and 0.75 km, respectively, with a total area covering 0.66 km². The maximum measured depth was 36.5 m, but this might not represent the actual deepest point of the lake as ice still covered two-third of the total lake area at the time of sampling. A large island divides the lake into two physically different basins, the smallest one receiving the inflow of at least two rivers collecting water from a surrounding watershed of about 125.7 km². As water runs out of this basin, it is mainly constrained into a small channel with relatively high water flow that feeds the larger basin. This latter is relatively less turbulent, with a favourable core sampling area located close to the island. The lake is surrounded by low elevation hills (~ 300 m) composed of Precambrian rocks which are part of the Melville plateau and are composed of acid bedrock made of gneiss and granites and covered by typical arctic tundra vegetation such as Ericaceae (*Cassiope tetragona* (L.) D. Don), Rosaceae (*Dryas integrifolia* Vahl), Sphagnum and other peat mosses. Water physical and chemical properties of the lake during sampling are provided in Table 4.1.

4.2.2 Sediment sampling and analyses

In July 2004, a 34-cm long core (core 2G) was retrieved from the deepest reachable point inside the larger basin using a gravity corer (inner diameter = 7 cm) from Aquatic Research. The core was transported intact inside its sampling tube to our laboratory facilities, and kept refrigerated at 4 °C. Another core (core 1G), not described in this paper, but also retrieved at the same location in July 2004, was subsampled at 0.5 cm intervals in the field (Laperrière, 2006). Core 2G was then half-sectioned lengthwise using a rotary tool and a fine iron wire.

A non-destructive geochemical analysis was achieved using an Itrax™ core scanner at the GIRAS laboratory, Institut National de la Recherche Scientifique, Eau-Terre-Environnement (INRS-ETE), in Québec city. This high resolution tool, presented in Croudace *et al.* (2006) and St-Onge *et al.* (in press), used X-ray fluorescence (XRF) to determine the fluctuation in the species and amount of chemical elements along a half-sectioned core. This tool also provides a high resolution x-ray profile of the core and a high definition optical image of its surface. A step size of 100 μm was used for the radiographic profile. This profile is represented as a 2D positive image, with lower and higher X-ray attenuation represented by lighter and darker zones, respectively. For the XRF analysis, a molybdenum X-ray tube was used at a step size of 1000 μm and a 20 sec exposure time.

Table 4.1 Water physical and chemical properties of lake 4 during sampling in July 2004.

Variables	**Depth (m)**		
	0	5	15
Water temperature (°C)	3.64	3.55	3.73
pH (units)	6.34	5.54	5.49
Conductivity (mS.cm^{-1})	0.009	0.009	0.009
Dissolved oxygen (mg.L^{-1})	13.70	12.59	12.14

All measurements were done in July 2004 with a Hydrolab sensor and logger. 15 m was the maximum reachable depth of the analytic instrument.

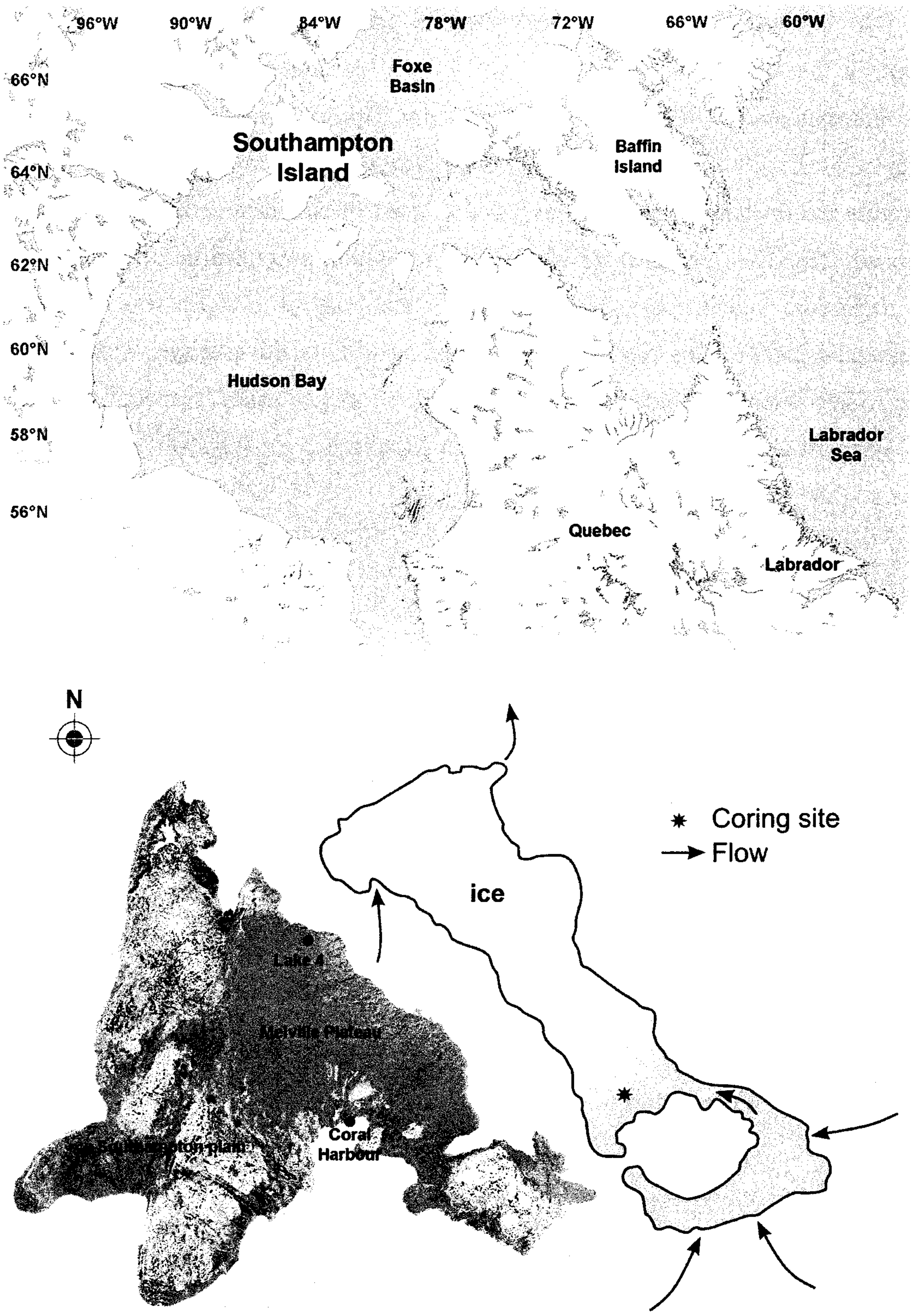

Figure 4.1 Location of Southampton Island and lake 4 with a short diagram of the lake morphology and the core site.

The half-sectioned core used for the ITRAX™ analysis was then subsampled every 0.5 cm and all the subsamples were freeze-dried for 24 h. A grain size analysis was conducted every 1 cm using ~ 0.3 g of dry sediment that were previously treated in a hydrogen peroxide solution (30 % v/v) and in a 1 M sodium hydroxide solution. These treatments were conducted to respectively remove any organic residues and biogenic silicate that may corrupt the particle-size distribution as determined using a Fritch Analysette 22 laser particle sizer. Results were plotted as a two-dimensional contour plot (Beierle *et al.*, 2002) with the boundaries of the particle-size distribution set following Last (2001). Organic matter content in every 1 cm subsample was then estimated on 0.5 g dry sediment subsamples by loss-on-ignition (LOI) at 550 °C during 5 hours following Heiri *et al.* (2001). The total carbon and nitrogen contents (C/N ratio) were also performed using a LECO CHNS-932.

4.2.3 Chironomid analyses

Processing chironomid subfossils followed the most recent methodology: at least 50 chironomid head capsules per sample (Heiri and Lotter, 2001; Larocque, 2001; Quinlan and Smol, 2001) were counted in order to obtain a representative sample of the chironomid assemblages, and more than 1 g of dry sediment was retrieved every 1 cm in the uppermost 10 cm and at 1 or 2 cm intervals for the remaining of the core. The known amount of dry sediment used for each sample allowed the calculation of head capsule concentration per gram for subsequent data analysis. These subsamples were first treated in a hot 10 % KOH solution, and then head capsules were extracted using the kerosene flotation technique (Rolland and Larocque, 2006). Particles collected by the kerosene flotation were then placed in a Bogorov counting tray. Using a stereomicroscope (35-60x), all the chironomid head capsules were picked and mounted ventral side facing upwards on a microscope slide. Identification was done under a microscope at 400x magnification according to different taxonomic guides available at that time (Cranston, 1982; Oliver and Roussel, 1983; Wiederholm, 1983; Larocque and Rolland, 2006; Brooks *et al.*, 2007). Dedicated keys were used to identify Tanytarsini taxa (Brooks *et al.*, 1997; Brooks, unpublished) and Tanypodinae taxa (Rieradevall and Brooks, 2001). The

Tanytarsini and Tanypodinae are now part of Brooks et al. (2007). Identification of *Zalutschia* sp. B followed Barley *et al.* (2006). Fragments with more than half a head capsule were counted as one head capsule, whereas capsules that were exactly half one head capsule were counted as half. All other fragments were disregarded.

4.2.4 Dating

The chronology of this sedimentary sequence (Table 4.2) was based on two calibrated accelerator mass spectrometry (AMS) radiocarbon dates of terrestrial macrofossils (Ericaceae leaves) at 13-14 and 27-27.5 cm in core 2G. Samples were processed by Beta Analytic Laboratories in Miami, Florida, USA. The obtained carbon dates were converted to calendar years Before Present (BP) and Anno Domini (AD) using the program CALIB version 5.0.1 (Stuiver *et al.*, 2005). To increase the age model precision, dates from samples of core 1G on ^{210}Pb and humic-acids were also used. The humic-acids were dated at the Keck Carbon Cycle AMS Facility, Earth Science Department, University of California Irvine, USA.

Table 4.2 AMS radiocarbon dates from lake 4 (humic-acids and macrofossils) and ^{210}Pb dates for the upper part of the core.

Laboratory number	Core ID	Depth (cm)	Material	^{14}C age BP	δ^{13}C	Cal. age BP	
						1 σ (68,3%)	2 σ (95,4%)
UCI-21591	1G	7.0-7.5	Humics	1995 ± 25	-26.0	1902-1987	1889-1994
UCI-21588	1G	11.0-11.5	Humics	2190 ± 25	-25.1	2150-2303	2130-2310
UCI-21590	1G	17.0-17.5	Humics	2280 ± 25	-26.6	2211-2344	2180-2348
Beta-218843	2G	13.0-14.0	Plant material	560 ± 40	-26.4	530-550	510-640
Beta-218844	2G	27.0-27.5	Plant material	1150 ± 40	-25.5	980-1070	960-1160

The age ranges are based on the INTCAL98 calibration using CALIB 5.0.1 (Stuiver *et al.*, 2005). Laboratories were the Keck Carbon Cycle AMS Facility, Earth System Science Department, UC Irvine, USA and Beta Analytic in Miami, Florida, USA.

For the ^{210}Pb dating, eight samples of dry sediment from core 1G were processed at the GEOTOP, Université du Québec, Montréal, Canada. The constant rate of supply (CRS) model was used to calculate these dates (Binford, 1990).

4.2.5 Statistical analyses

Standardization between the X-ray grey profile and the selected chemical element profiles was achieved using a negative exponential smooth method on each profile using SigmaPlot. A principal component analysis (PCA), with square root transformation, was run on these smoothed data in order to detect any trend in the chemical element profiles that may explain the resulting grey profile. The program CANOCO (ter Braak and Šmilauer, 2002) was used for the PCA.

The abundance per gram of selected chironomid taxa was plotted in a stratigraphic diagrams using the program C2 (Juggins, 2003). For each stratigraphic level, a Hill N1 diversity index was calculated using Primer 6 (Clarke and Gorley, 2006). Zonation methods followed the recommendations of Birks and Gordon (1985) and Bennett (1996). Numerical zonation was carried out by optimal partitioning using sum of squares criteria (program ZONE (Version 1.2; Juggins 1992b)) and the number of statistically significant zone limits was determined with the broken-stick model (software BSTICK version 1.0, Bennett, 1996). The relative abundance of chironomid taxa was used to infer mean August air temperatures by a weighted averaging partial least squares (WAPLS) analysis with a leave-one-out cross validation method and a square root transformation. The calibration data set used for this reconstruction was derived from a modified model developed for northern Québec (Larocque *et al.*, 2006) with ten more lakes added north of the previous transect. The correlation coefficient (r^2jack) of this new model is 0.80, the root mean square error of prediction (RMSEP) is 1.26 °C, and the maximum bias is 2.14 °C. Modern analogues and goodness-of-fit to temperature were assessed following methods described in Birks (1998).

4.3 Results

4.3.1 Core chronology

The chronology of the studied core is presented in Figure 4.2. Humic acid dates were systematically older than expected and have therefore been rejected to establish our age model. Compared to the macrofossil date at 13-14 cm, this difference is in the order of 1600 years after calibration. Lead activities obtained on core 1G and macrofossil-derived ^{14}C dates from core 2G were used to develop an age model of this sedimentary sequence (eq. 1). Neither LOI (%) nor water content could be used for core correlation, so this age model might present errors in the upperpart of the core as lead dates were not from the core that provided the macrofossil-derived ^{14}C dates. However, this error should be low considering that compaction was low in both studied core (less that 3 cm for the whole core), and because both cores were sampled at the same date and location.

$$\text{eq. 1 : } y = 2.0979 + 0.0318x - 4.0746.10^{-5}x^2 + 3.1295.10^{-8}x^3$$

4.3.2 Sedimentological analyses

Grey values derived from the X-ray analysis are presented in Figure 4.3, with smoothed data for the XRF profiles of major chemical elements (Fe, Rb, Zr, Sr, Ca, K). This figure also includes the LOI, C/N values and a two-dimensional diagram of the grain size analysis. Sediment grain size distribution is well-sorted, highly dissymmetric, and leptokurtic (higher peak around the mode than the normal distribution) with a single mode at ~ 30 μm, in the very coarse silts range. This distribution was relatively constant through time but with a tendency towards smaller particles in the uppermost and most recent part of the core. LOI and the C/N ratio presented similar trends, with a constant but slow increase through time, and a particularly sharp increase between 16 and 12 cm characterized by the highest values in the entire core.

Sediment relative density was estimated by the grey values derived from the X-ray positive image of the core. Intervals with lighter grey values were observed at 28 and 23 cm and between 16-12 cm and 4-0 cm. The smoothed curve (negative exponential method) derived from these data varied inversely compared with the XRF profiles of major chemical elements. The PCA (Figure 4.4) confirmed this observation as variables were located in the same area along axis 1, but at the opposite end on the axis 2, except for iron (Fe) which did not reveal any signs of influence from the observed grey values.

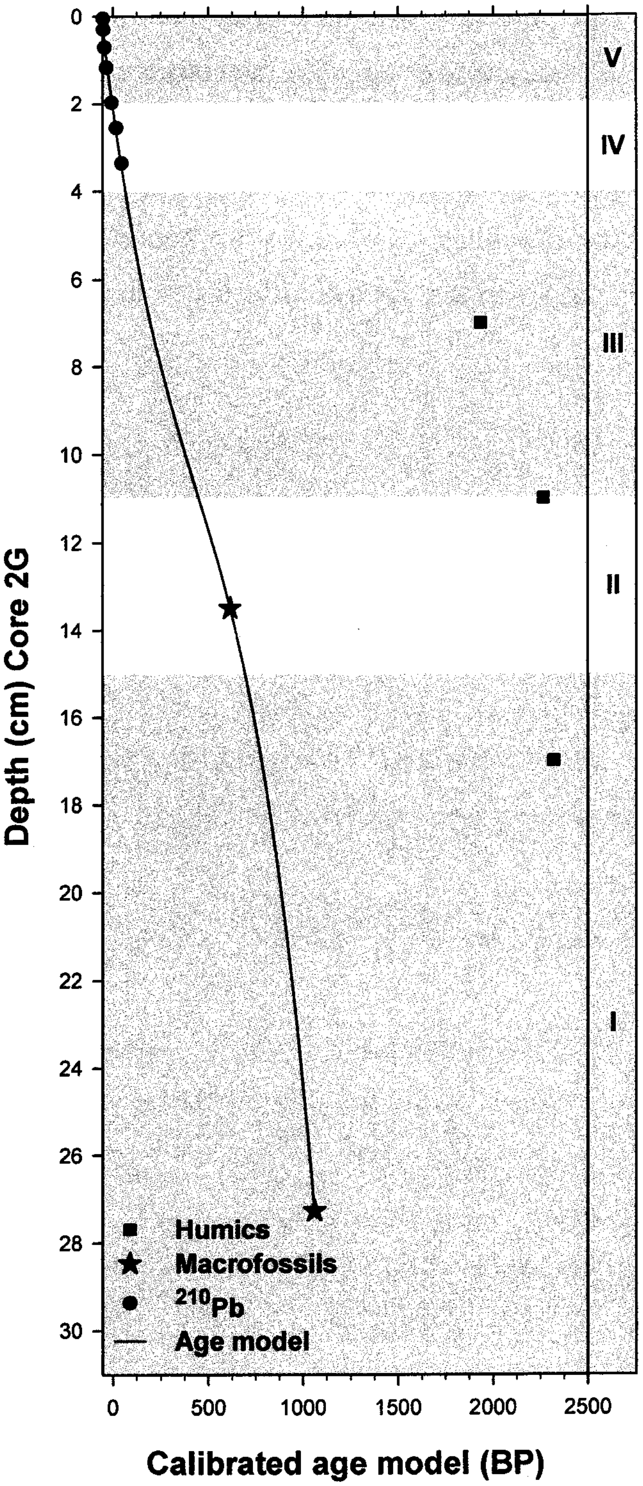

Figure 4.2 Calibrated depth-age model derived from the AMS macrofossils radiocarbon dates and ^{210}Pb dates. Zones are derived from the chironomid analysis.

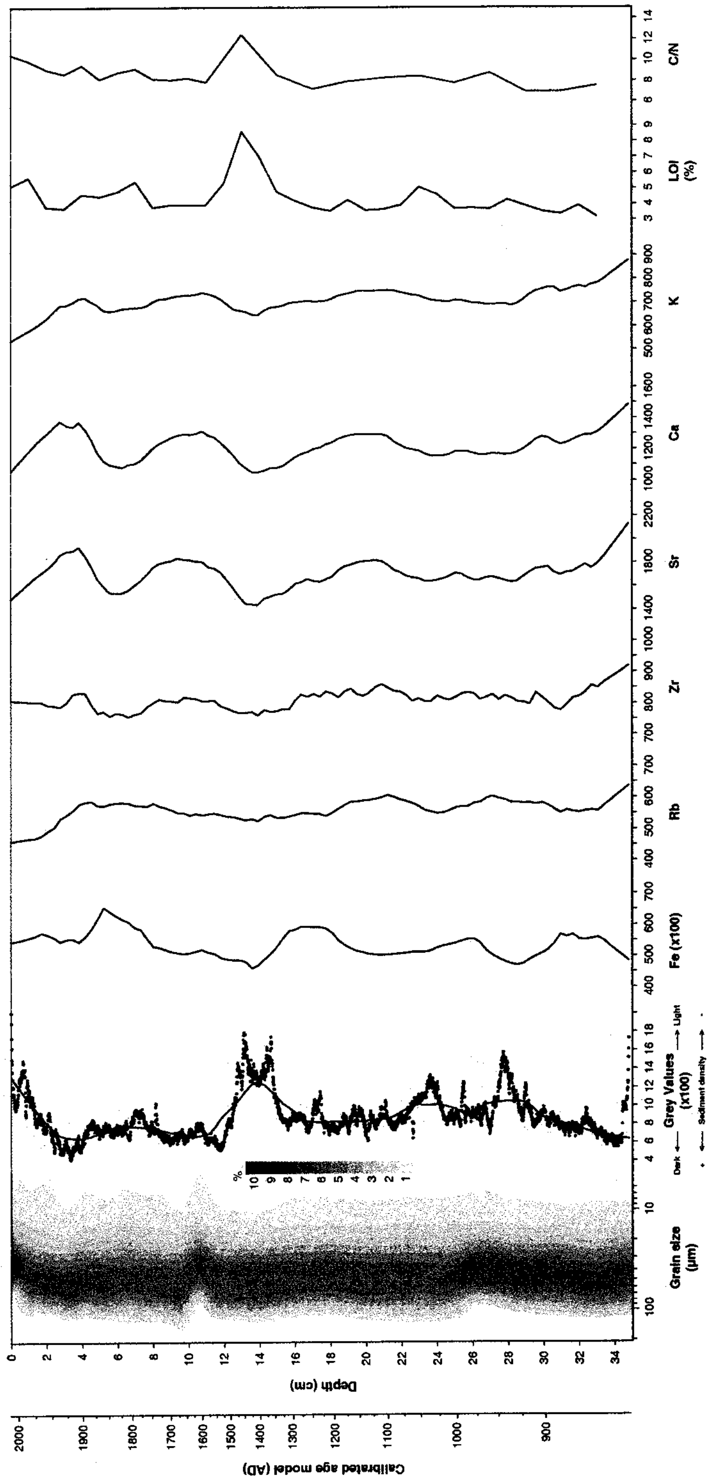

Figure 4.3 Variations of the grey values derived from the X-ray analysis of the core. High and low values corresponded to light greys (low sediment density) and dark greys (high sediment density) respectively. Also provided, XRF profiles of major chemical elements and a two dimensional graphic of the grain size frequency distribution (%), with frequencies represented along a proportional grey scale from light (low %) to dark (high %), LOI (550°C) and C/N ratio.

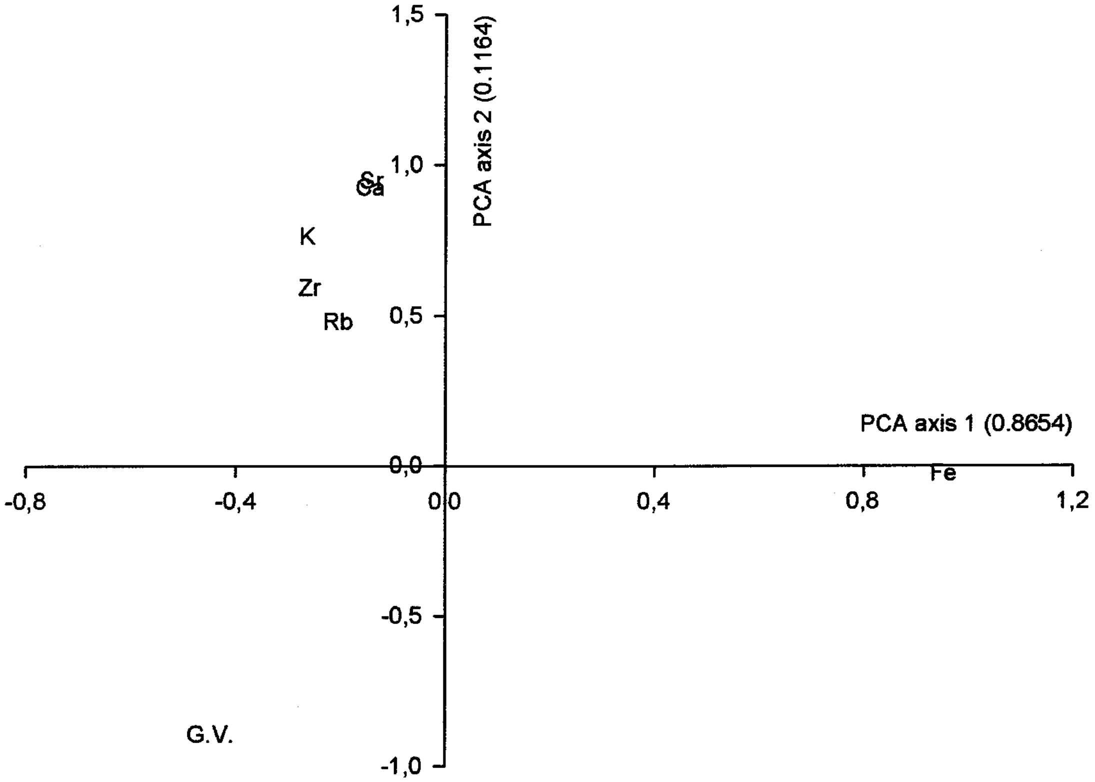

Figure 4.4 PCA analysis of the grey values (G.V.) derived from the X-ray analysis and of the major chemical elements measured by the XRF analysis.

4.3.3 Chironomid stratigraphy

The stratigraphic distribution of selected midges are presented on Figure 4.5. Based on the program ZONE, the succession of chironomid assemblages was divided into five zones. This analysis especially revealed one major event (Zone II), where initially rare taxa with low abundance developed rapidly and dominated the chironomid population. The mean value of the chironomid head capsule concentration (HC) was ~ 50 head capsules per gram of dry sediment in the entire core. The 43 identified taxa were mainly cold-adapted specimens. *Heterotrissocladius subpilosus*-group, widely encountered in arctic oligotrophic lakes (Walker and Paterson, 1983; Olander *et al.*, 1999), was regularly represented and its constant abundance of ~ 10 specimens per gram of dry sediment represented more than 20 % of the chironomids picked throughout the core. The Hill N1 diversity index along the core had a mean value of ~ 11.

Chironomid zone I covered half of the core from 31 to 15 cm core depth (ca ~ 1100-700 cal. yrs BP). This zone was mainly dominated by *H. subpilosus*-group. Although not statistically significant to create a zone, changes in the chironomid assemblages occurred at 27 cm (ca ~ 1050 cal. yrs BP) and at 23 cm (ca ~ 970 cal. yrs BP). At 27 cm, HC concentrations and Hill N1 diversity index increased due to an increase of *Corynoneura*, typically encountered in the littoral zone of shallow tundra lakes and on aquatic plants (Oliver and Roussel, 1983; Schmäh, 1993; Walker and McDonald, 1995). This event also corresponded to an increase of *Cricotopus*, *H. subpilosus*-group, *Tanytarsus* with and without spur and *Sergentia*, a mesotrophic (Merilaïnen *et al.*, 2000) and profundal taxon (Francis, 2001). At 23 cm, the Hill N1 diversity index was just slightly higher than the average but the HC concentration almost reached its peak. At that depth, taxa found at 27 cm depth (*Corynoneura*, *H. subpilosus*, *Tanytarsus* with and without spur) increased again, but with the addition of *H. grimshawi*-group, a cold-stenotherm (Brooks and Birks, 2001), acidophilic (Pinder and Morley, 1995), oligotrophic (Brodin, 1986), high-alpine (Heiri *et al.*, 2003) taxon, *Mesocricotopus*, a cold-stenotherm and oligotrophic taxon (Levesque *et al.*, 1996, Walker *et al.*, 1997), *M. radialis*-type, a high alpine (Heiri *et al.*, 2003) cold indicator (Brooks and Birks, 2000) and *Orthocladius*, found in medium to large arctic lakes (Oliver and Roussel, 1983).

The lower part of chironomid Zone II, between 15 and 13 cm (ca ~ 700-585 cal. yrs BP), was characterized by a rise of the abundance of almost all the identified taxa, and an increase in the HC concentration and the Hill N1 diversity index. The most abundant taxa (>20 HC/g) were *Corynoneura* and *Micropsectra radialis*-type. The other abundant taxa (up to 20 HC/g) were *Orthocladius* and *Cricotopus*, which are often associated with the littoral zone, aquatic plants and more productive environments (Oliver and Roussel, 1983; Simola *et al.*, 1996). This event also corresponded to a short appearance of *Diamesa* which lives in running/lotic waters but is also known to feed on algae in lakes (Oliver and Roussel, 1983). Two other taxa, *Limnophyes* and *Zalutschia* sp., were also identified in this zone, but with relatively low concentration (~ 4 HC/g). They are often associated with the littoral zone, aquatic plants and more productive environments (Oliver and Roussel, 1983; Quinlan and Smol, 2002). In the upper part of this zone (13-11 cm, ca ~ 585-450 cal. yrs BP), the abundance of most taxa decreased, as well as the HC concentrations and the Hill N1 diversity index.

Chironomid zone III (11-4 cm, ca ~ 450-65 cal. yrs BP), closely reflected the same trends observed in Zone I, namely that *H. subpilosus*-group dominated the assemblages and the Hill N1 diversity indexes was below or just above the average.

In chironomid zone IV (4-2 cm, ca ~ 65-0 cal. yrs BP), *H. grimshawi*-group and *H. subpilosus*-group had HC concentrations lower than 10 per gram of dry sediment, whereas *Corynoneura* and *Cricotopus* dominated the assemblages. The Hill N1 diversity index was slightly higher than the average but increased towards the upper end of the zone. HC concentration was low at ca. 25 HC/g. *H. grimshawi*-group and *H. subpilosus*-group increased again in zone V, with an increase in *H. brundini*-group, *Mesocricotopus*, *Tanytarsus* sp. and *Tanytarsus* with spur. *Corynoneura* and *Cricotopus* were also present with concentration at 10 ca. HC/g. Hill N1 diversity index was slightly higher than in the previous zone and the HC concentration almost doubled (from 25 to 50 HC/g).

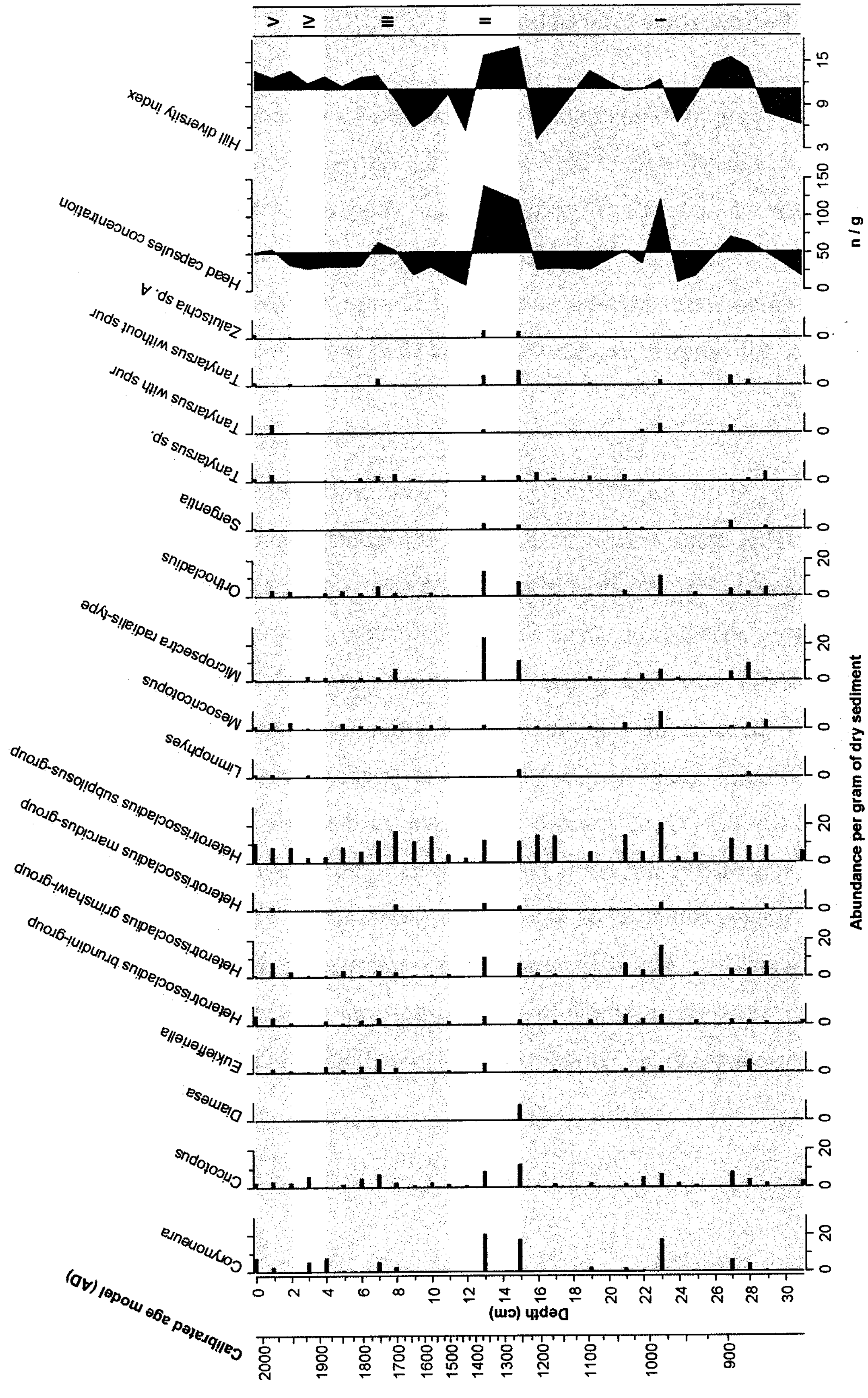

Figure 4.5 Chironomid stratigraphy (in abundance per gram of dry sediment). Head capsules concentration and Hill diversity index are also provided.

4.3.4 Temperature inferences

The inferred August air temperatures are presented on Figure 4.6, with the RMSEP limit of the model and the five zones derived from the chironomid analysis. The inferred values varied between 6.5 and 10.1 °C around a mean value of 8.4 °C. Taking into account the RMSEP of the model (1.26 °C), this temperature range showed significant variations of the inferred temperatures between the highest (2 cm core depth) and lowest (17 cm core depth) values. All samples except one (16 cm) had good modern analogues and good-fit to temperature.

Zone I (31-15 cm) showed mainly low amplitude variations of the inferred temperature. This main trend was however interrupted by two high magnitude cooler events at 31 and 17 cm, which corresponded to the coldest values inferred for the whole core with lowest values more than 1.5 °C colder than the average. Inferred temperatures in zone II (15-11 cm) were above the average except at 11 cm were they remained slightly lower. In zone III, the variability of inferred-temperature increased with colder than average temperatures (by 0.7-1.2 °C) at 9 and 8 cm and warmer than average temperatures (by 0.9 °C) at 7 and 6 cm. Based on the RMSEP limit, these values were however not statistically different. In zone IV the inferred temperatures rapidly increased above the average, and reached the highest value (10.1 °C) at 2 cm core depth. The inferred temperature then decreased to the average in zone V, with the inferred temperature in the surface sample (8.4 °C) being close to the mean inferred value and the summer temperature climate normal (8.3°C; 1971-2000) (Environment Canada, 2002).

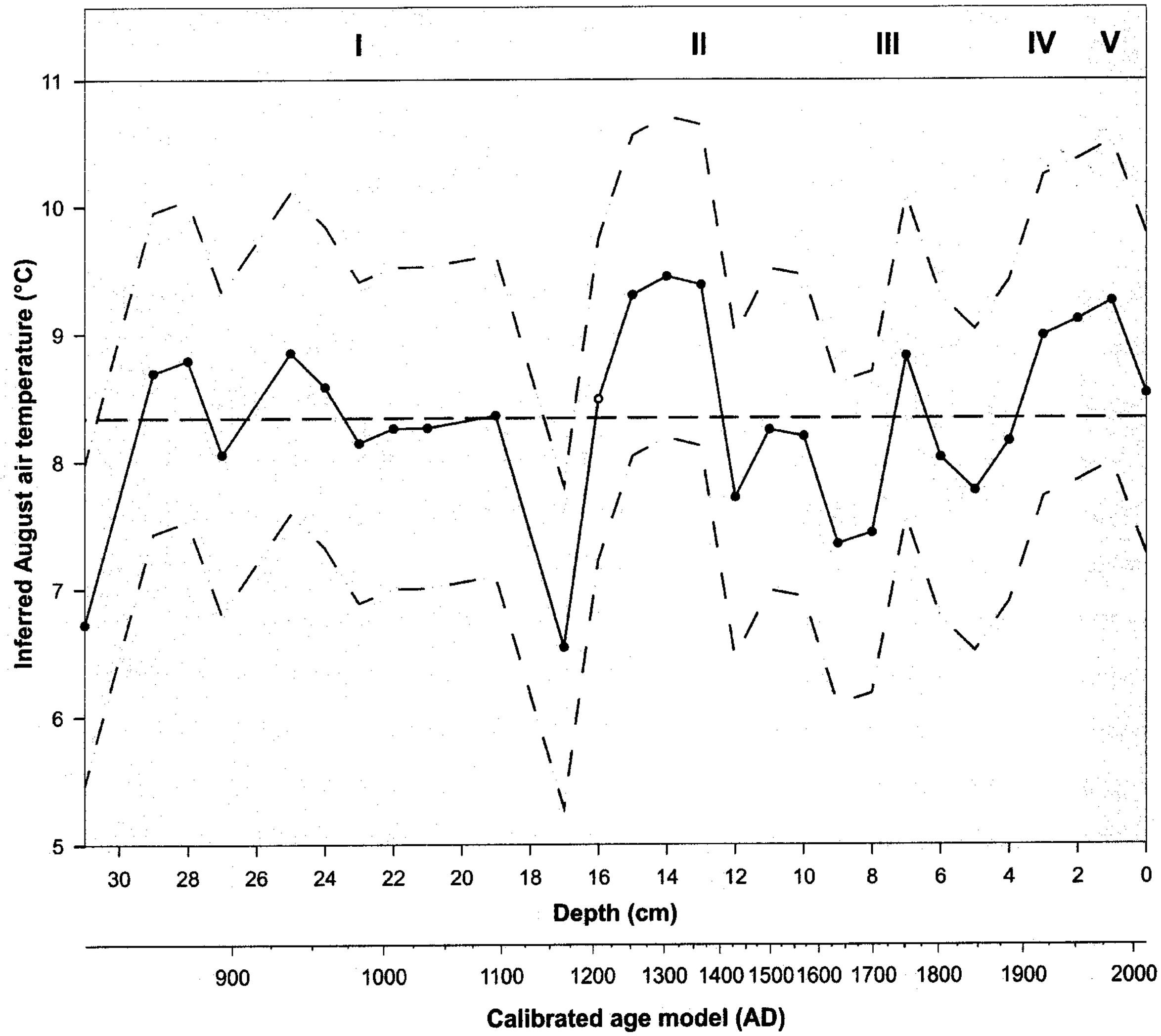

Figure 4.6 Chironomid-based August air temperature (°C). All samples except one (16 cm) had good modern analogues and good-fit to temperature. The model root mean square error of prediction (RMSEP) and the mean inferred temperature for the whole core are represented as long dash/dot/dash and short dash lines respectively. Zones are derived from the chironomid analysis.

4.4 Discussion

This study presented the environmental portrait of a northern Southampton Island lake during the last millennium. Both biological and sedimentological analyses revealed that this geographical area was perturbed by short-lived environmental changes in the lake ecosystem.

4.4.1 Sedimentary processes through the late Holocene

The sedimentological information of this study was used as a complement to better understand the biological diversity and succession of the chironomid assemblages over time. Grain size is usually highly affected by changes in the hydrological regime of a lake, which includes precipitation rates and the amount of water inputs during snow melt periods (Last, 2001). In Lake 4, the grain size analysis did not present any major shifts in sediment textural properties and grain population though the entire core. Although the analytical resolution was set at 1 cm intervals, this revealed that, on a long term perspective, the hydrological input of the lake were almost constant during the studied period of time. On the contrary, the variations observed in the grey values of the radiographic profile clearly revealed that the sediment density was variable. Sediment density reflected the amount of detrital and organic input within the lake ecosystem. The observed increase of grey values at 28, 23 cm, 16-12 cm and 4-0 cm, characterized higher organic sediment content, with higher porosity to X-rays. Taking into account the constant amount and size of grain particles entering the lake, the higher organic content might have originated mainly from the lake itself (autochthonus) or from an enrichment of terrestrial organic matter, as seen with the increase of the C/N ratio. The ITRAX results strengthen this hypothesis as all the selected chemical elements (except Fe) were negatively correlated to the grey values (Figure 4.4). A constant input of particles would have, in theory, provided a constant amount of detritic material inside the lake basin and hence constant detrital elements (PCA2) concentrations. However, we observe a decrease of the elements concomitant with lower density values. This suggests that detrital sedimentary input remained constant but has been diluted by higher organic matter fluxes.

4.4.2 Chironomids

The fossil assemblages were mainly composed of cold oligotrophic chironomid taxa. The latter were commonly found in the Canadian Arctic and northern Europe (Walker *et al.*, 1997; Larocque *et al.*, 2001). The most abundant, *H. subpilosus*-group, was also abundantly found in another lake on Southampton Island (Rolland *et al.*, accepted). This strictly profundal (Simola *et al.*, 1996) lake dweller had a more or less constant concentration throughout the core. Physiologically, chironomids depends on their living substrata, which must be suitable for their biological requirements (Armitage *et al.*, 1995). Combined with the stable grain size profile, the regular presence of *H. subpilosus*-group means that its habitat and/or its physiological needs did not change significantly during the period covered by this sedimentary sequence. By contrast, all the identified taxa with increased concentrations in zone II, such as *Corynoneura*, *Orthocladius*, *Limnophyes* and *Zalutschia* sp. A, are related to aquatic plants, the littoral zone and more productive environments (Oliver and Roussel, 1983; Quinlan and Smol, 2002). Their presence and the lower sediment density (as measured by X-rays) undoubtedly characterized changes in the littoral zone and trophic state of the lake. Arctic lakes are highly influenced by their winter ice cover which determines the timing and duration of the primary production period (Rühland *et al.*, 2003; Smol *et al.*, 2005). Although ice algae may develop under a thin ice cover and feed part of the trophic network (and by extrapolation chironomids) of a lake, a reduced ice-free season might not be sufficient to provide food and habitats to the littoral chironomid community. Therefore, the increased chironomid head capsule concentrations in zone II were probably the results of a longer ice-free season, which might have started earlier or ended later during the summer period.

Based on *in situ* lake water column measurements (Table 4.1), the high occurrence of taxa belonging to the *Heterotrissocladius*-group and especially *H. grimshawi*-group (Pinder and Morley, 1995), revealed that the lake was mainly acid throughout the reconstructed period of time. This chemical state of the lake was confirmed by the fossil diatom assemblages identified along core 1G (Laperrière, 2006). This acidity is mainly derived from the surrounding watershed. This relatively low pH might have restricted the development of other chironomid taxa, as Walker *et al.* (2003) revealed that pH was an important variable explaining the distribution of freshwater midges in lakes from the Yukon and Northwest Territories.

4.4.3 Temperature inferences and comparison with regional paleoclimate data

The paleotemperature record from this northern Southampton Island lake revealed a close match between modern inferred temperatures and average summer temperatures reported for this area between 1971 and 2000. This profile also presented several short-lived departures from this average. The interpretation of every inferred variable is always dependent on the RMSEP of the model used in its reconstruction (Lepš and Šmilauer, 2003). In this study, almost all inferences were constrained within the limit of the model which, in theory, means that all the observed variations cannot be statistically differentiated. However, in the case of temperature changes exceeding 1 °C in this core, chironomid-based inferred temperatures should provide reliable scenarios of paleoclimate at this site (Larocque and Hall, 2004). Based on the variations in the abundance of the *H. subpilosus*-group, the inference model used for this paleotemperature seemed to have been strongly influenced by this taxon which has the lowest temperature optimum in the training set (Larocque *et al.*, 2006). The relatively Low and High-Arctic lakes in this transfer function might explain the overriding influence of this taxon on the temperature reconstruction and might have biased the high amplitude events by giving more emphasis to the lowest but also less emphasis on highest inferred values. Taking into account these limitations, only a general portrait of the lake conditions can be provided, but our general interpretations were supported by other paleolimnological data from the mid- and eastern High-Arctic.

Indeed, the significant 1°C temperature increase between ~ cal. yrs AD 1164-1364 may correspond to the one found in the study of varved sediments from Donard Lake, west of Baffin Island, Moore *et al.* (2001). They found a rapid increase of the inferred summer temperatures between cal. yrs AD 1195 and 1220 followed by an extended warmer period until cal. yrs AD 1375. Based on this high resolution record, the authors associated this warmer period with the Medieval Warming Period (MWP) which was about 0.5 °C warmer than their average inferred summer temperature before cal. yrs AD 1195. Despite the low number of samples analysed in our core for this period, the inferred records observed in Lake 4, with about 1 °C warmer than average temperatures, presented the same tendencies as in Donard Lake and might also correspond to a MWP. Archaeological and anthropological studies of Thule, also named Sadlirmiut on Southampton Island, revealed that this tribe took advantage of the MWP to migrate from northern Alaska to the eastern Canadian Arctic (Coltrain *et al.*, 2004). Southampton Island has a rich archaeological site in Native Point, where high numbers of bowhead whale skeletal remains from the Thule era were dated between cal. yrs AD 1000 and 1350 (Coltrain *et al.*, 2004). Coltrain *et al.* (2004) suggested that the high number of bowhead whale skeletal remains corresponded to longer ice-free seasons in the Hudson Bay that promoted whale hunting by the Thule. Such longer ice-free seasons might also have existed in freshwater ecosystems on this island and may have controlled the sedimentological and biological processes in our study site during this period. The presence of this native tribe and the changes in our temperature reconstruction, clearly suggest that the Southampton Island experienced a warmer period during the 13th century.

Although the inferred temperatures in zone III between ~ cal. yrs AD 1364 and AD 1695 were lower but not statistically different from the ones observed in zone II, they reflected a shift to a cooler environment over approximately 300 years. The so called "Little Ice Age (LIA)" was reported from pollen analyses in northern Quebec and Labrador between AD 1570 and 1870 (Gajewski and Atkinson, 2003). In their study of Donard Lake, Moore *et al.* (2001) concluded that the LIA occurred between cal. yrs AD 1375 and AD 1800 and was characterized by a rapid decrease of ~ 0.7 °C in the summer temperatures compared to the MWP. Our record from Southampton Island presented a similar trend, with a minimum inferred value ca. 2 °C colder than the maximum observed during the MWP but this cooler event ended earlier (~cal. yrs AD 1695) and was followed by a second warm period between ~ cal. yrs AD 1751 and AD 1800. The three minima registered in Donard lake during the LIA, with the coolest period being around cal. yrs AD 1645-1715 (possibly corresponding to the Maunder Minimum), agrees with our results. This cooling was still described as modest, being less than 1 °C (Bradley and Jones, 1993; Jones *et al.*, 1998; Mann *et al.*, 1999). Here, an excursion of about 1 °C from the average was inferred using chironomids, and the similarity in the climate patterns suggest that this cooling episode corresponded to the LIA.

The LIA was described as the coldest period of the last millennium (Mann *et al.*, 1998; Jones *et al.*, 1998). This was not the case at our site. Another cold event at ca. cal. yrs AD 1175 was identified in our record when the inferred temperature was almost 2 °C colder than the average. A pre-medieval cold period has been described elsewhere (Cowling *et al.*, 2001), although the amplitude of the temperature decrease was slightly smaller than that of the LIA.

In the two upper zones, the increase in the inferred temperatures might reveal recent changes that are due to non-natural forces. Although sediments were usually less compact near the water/sediment interface, our results revealed that both variables are close but not as high as the ones observed during the MWP. Similar results were observed in Europe with inferred summer MWP temperatures that were the same as those measured into the last quarter of the 20th century (Goosse *et al.*, 2006). The record from Southampton Island does not reveal such high amplitude climate changes as observed elsewhere in the Canadian High Arctic, but undoubtedly this island is actually experiencing environmental changes that have already existed in its history. Although the MWP mainly resulted from natural climate forces, the recent lacustrine changes might be the result of increasing greenhouse warming and subsequent changes in the physical environment such as longer ice-free seasons. Based on the reconstructed lake state during the MWP, such warming should positively affect the lake community and productivity and, in a long-term perspective, will shift the lake to a mesotrophic state. Such situations underlined the importance of long-term monitoring programs in this remote area and the development of new frameworks that focus on the way this environment will be affected by global warming.

4.5 Conclusions and perspectives

The paleolimnological study of this northern Southampton Island lake provides information on the timing of known northern hemisphere climatic events (Medieval Warming Period and Little Ice Age) in the Foxe Basin region. Similarities with those climatic events and the recent changes observed in the physiological and biological properties of the lake sediments provided an opportunity to develop new frameworks on the evolution of such freshwater ecosystems under the now called "Anthropocene". In the present study, the information extracted based on the biological indicators (chironomids) was supported by a large range of sedimentological analyses. Such results confirm the importance of including sedimentological proxies when interpreting chironomid analysis as they provided an extended overview of the past hydrological and geochemical status of the lake which has affected its biological community.

The high number of lakes covering the arctic landscape provides a real opportunity to improve our knowledge of past natural climates in still poorly studied arctic regions. The convergence of many proxies combined with higher resolution records will be a key feature of future paleoclimatic analyses in those regions.

Acknowledgement

This study was made possible through Natural Sciences and Engineering Research Council (NSERC) of Canada funding granted to R. Pienitz, P. Francus and I. Larocque. The Polar Continental Shelf Project (PCSP) provided logistic support (helicopter time) to R. Pienitz (contract # 627-04) for the fieldwork on Southampton Island. Thanks to the local population of Coral Harbour who provided invaluable information and logistic support when on the field. Professionals at INRS and CEN who provided technical support are also acknowledged.

Chapitre 5

CONCLUSIONS

The sciences do not try to explain, they hardly even try to interpret, they mainly make models. By a model is meant a mathematical construct which, with the addition of certain verbal interpretations, describes observed phenomena. The justification of such a mathematical construct is solely and precisely that it is expected to work.

John von Neumann

5.1 Conclusions générales

Cette thèse de doctorat est la première à présenter l'histoire paléoclimatique de l'île de Southampton (Nanavut) durant l'Holocène, soit dans le cas d'un des lacs étudiés, les 6000 dernières années (Chapitre 3) et dans le cas du deuxième lac, le dernier millénaire (Chapitre 4). L'originalité de cette étude repose principalement sur l'utilisation de différents indicateurs sédimentaires dans le but d'accompagner l'interprétation des résultats obtenus à l'aide des chironomides fossiles. Ces indicateurs biologiques possèdent d'excellentes capacités de reconstructions des conditions environnementales passées des milieux aquatiques terrestres. Leur capacité à modéliser la température de l'air et, par conséquent, à reconstruire les variations climatiques qui ont influencé le bassin étudié, a notamment été mise à contribution avec succès dans cette étude. L'apport de l'information sédimentaire, qui correspond à la fois à une signature intra et extra lacustre, s'est révélée importante dans la compréhension des trajectoires prises au cours du temps par les assemblages de chironomides dans chacun des lacs. Les différentes signatures physiques et chimiques du sédiment des deux lacs étudiés, ont notamment permis de lier l'apparition de certains taxons de chironomides avec des conditions limnologiques, telles qu'une productivité interne plus importante ou une influence directe du bassin versant. L'interprétation parfois hypothétique donnée aux profils stratigraphiques de chironomides a donc été grandement améliorée par cette information sédimentaire, particulièrement dans le chapitre 4.

Ces deux études paléoclimatiques apportent de nouvelles informations climatiques indispensables à l'élaboration des modèles climatiques futurs, ainsi qu'aux tests des modèles actuels. La capacité de ces derniers à reconstruire les conditions environnementales passées, donnera davantage de crédibilité à leurs prédictions futures et requiert pour se faire une multiplication d'études paléoclimatiques à moyennes et hautes résolutions temporelles. La région d'étude, juste que là représentée dans les modèles climatiques via l'extrapolation des données prédites pour les régions avoisinantes, pourra être mieux modélisée à l'avenir. De plus, l'étude des conditions environnementales passées et leur comparaison avec l'état actuel des milieux aquatiques de cette région, permettra d'envisager la direction que prendra cet écosystème dans un futur proche.

En parallèle à cette étude paléoclimatique, cette thèse a permis le développement de trois outils qui s'avéreront indispensables aux futures recherches paléoclimatiques impliquant les chironomides en Arctique, mais aussi dans d'autres régions du monde. L'utilisation des chironomides est toujours problématique lorsque vient le temps de les prélever au travers la multitude de résidus et particules qui composent chaque couche sédimentaire d'un bassin aquatique. Le temps nécessaire à cette étape représente souvent une très grande partie du temps alloué à chaque étude, ce qui limite le nombre d'échantillons analysables et par le fait même, la résolution temporelle de chaque étude. Devant cette problématique, une étude (Chapitre 2) a permis de confirmer l'utilité du kérosène pour séparer les capsules de chironomides d'une matrice sédimentaire. Cette étude, une première dans le domaine, apporte une preuve tangible de la rapidité avec laquelle cette méthode permet de récupérer ces capsules, sans pour autant diminuer la représentativité de la population de chironomides. De plus, d'un point de vue statistique, cette méthode permet de connaître rapidement la concentration en capsules des échantillons ainsi traités. Des comparaisons quantitatives entre chaque échantillon peuvent donc être réalisées lors de l'analyse des résultats.

Le développement d'une nouvelle fonction de transfert pour l'est Canadien, marque un pas important dans l'élargissement de l'utilisation des chironomides dans cette région (Annexe A). L'expansion des modèles climatiques et l'importance de multiplier des reconstructions paléoclimatiques seront supportées par de tels modèles d'inférence. Par le biais de la création de cette nouvelle fonction de transfert, cette thèse a également permis de développer un nouveau guide taxonomique axé sur les espèces de chironomides de l'est canadien (Annexe B). De part sa simplicité et son format, ce guide facilitera les futures études basées sur les chironomides dans cette région mais aussi, grâce à la grande similitude entre ces milieux, dans d'autres régions du Canada et de l'Europe. Ce guide contraste radicalement avec les guides déjà disponibles dans le domaine. Cependant, il se complète parfaitement avec eux sans reprendre inutilement l'information déjà présentées dans ces derniers.

5.2 Limites de la présente étude et travaux futurs

Cette thèse, comme toutes les études paléoenvironnementales impliquant des indicateurs biologiques, repose sur diverses prémices, dont la principale est basée sur l'actualisme et l'uniformitarisme (Alley, 2001). Ces principes sont malheureusement contraires à la théorie d'évolution de Darwin, puisque l'utilisation des conditions présentes pour reconstruire celles du passé suppose que, dans le cas des chironomides, le lien étroit entre les taxons et des conditions climatiques précises n'a pas évolué au cours du temps. L'évolution est rythmée par le temps et la capacité des organismes à réagir aux changements environnementaux. Dans le cas d'études multidisciplinaires basées sur différents indicateurs biologiques n'ayant pas tous les mêmes exigences physiologiques (p. ex. les chironomides, les diatomées, le pollen), il a cependant été démontré que même si les valeurs inférées peuvent différer, les tendances observées concordent généralement très bien entre ces indicateurs (Lotter *et al.*, 2000; Schmidt *et al.*, 2002). Cette concordance est principalement bonne pour les périodes couvrant les 10000 dernières années, soit depuis la fin de la dernière déglaciation. Il est donc tout à fait valable de penser que même si l'évolution ne s'est pas arrêtée depuis cette importante étape géologique, les différents indicateurs utilisés en paléolimnologie n'ont pas ou peu évolué au cours du temps et sont globalement toujours associés aux mêmes conditions environnementales.

La capacité des chironomides à remanier les particules sédimentaires de surface, mais aussi en profondeur par le biais de tubes, pose beaucoup de problèmes quand à la viabilité même des études paléoclimatiques. L'abondance de chironomides peut probablement remodeler les couches de sédiments de surface, et par conséquent biaiser le lien entre les indicateurs identifiés dans ces couches sédimentaires et les conditions environnementales au moment de leur dépôt. Cette problématique a été soulevée dans la présente thèse au chapitre 3 pour expliquer l'écart des dates obtenues par les capsules de chironomides et le modèle établit par les autres méthodes de datations. Plusieurs études ont fait état de l'activité verticale des chironomides dans les sédiments et de leur capacité à construire des tubes (Charbonneau *et al.*, 1997; Stribling *et al.*, 1998), cependant il semble que seul le sédiment de surface soit utilisé pour la fabrication de ces tubes, limitant ainsi le remaniement de sédiment sur de grandes profondeurs (Olafsson et Paterson, 2004). Ce problème est néanmoins encore peu étudié et mériterait des études plus approfondies pour déterminer avec exactitude l'impact réel des chironomides sur les couches sédimentaires.

Comme mentionné par le Dr John Von Neumann, mathématicien de renom, la science repose sur des modèles pour résoudre des problèmes de plus en plus complexes. Devant l'inquiétude grandissante des changements climatiques, l'importance accordée à ces modèles se doit cependant d'être tempérée par une prise de conscience de leurs faiblesses et de l'importance de coupler leur utilisation à des analyses qualitatives. Dans le cadre de cette thèse, un modèle de reconstruction de la température de l'air au mois d'août a été réalisé à l'aide des chironomides. La viabilité de ce modèle repose essentiellement sur la base de données qui le compose. Cependant, les hautes latitudes arctiques sont relativement peu représentées dans cette base de données. Le modèle est donc probablement limité dans sa capacité à reconstruire adéquatement des extrêmes de températures. L'élargissement du gradient thermique représenté par ce modèle permettra d'accroître sa résolution ainsi que son utilisation dans plusieurs régions du Haut Arctique Canadien.

Les profils des éléments chimiques, déterminés par le scanner à microfluorescence-X, ont mis en évidence les changements globaux dans l'abondance de ces éléments, mais n'ont pas permis de relier précisément leurs variations à des événements environnementaux. Des rapports (p. ex. Fe/Mn) peuvent permettre d'évaluer des changements dans les états trophiques et chimiques des bassins étudiés, cependant seule une connaissance approfondie de la géologie du bassin versant permettra d'exploiter pleinement cette source de données. Cette étude a donc du se limiter à une interprétation qualitative de ces données. Cependant, l'utilisation de cette information pour corroborer des interprétations biologiques ne requière pas une quantification de ces variables. Dans le futur, une analyse géochimique plus exhaustive du bassin versant permettra d'améliorer l'interprétation des données de micro-fluorescence-X.

Pour conclure, de telles études devront être étendues à d'autres régions arctiques pour accroître davantage notre connaissance historique de ces régions et mieux comprendre comment elles réagiront dans le futur.

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Troisième Partie

Appendices

Liste des appendices

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Appendice B : Larocque I, Rolland N (2006) A Visual Guide to Sub-fossil Chironomids from Québec to Ellesmere Island. Rapport de recherche R-900. Institut National de la Recherche Scientifique, Québec, Canada, 116 pp

Appendice A

FACTORS INFLUENCING THE DISTRIBUTION OF CHIRONOMIDS IN LAKES DISTRIBUTED ALONG A LATITUDINAL GRADIENT IN NORTHWESTERN QUEBEC, CANADA

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Article publié dans *Canadian Journal of Fisheries and Aquatic Sciences* 63:1286-1297

Résumé

L'effet de 33 variables environnementales sur la distribution des chironomides dans 60 lacs du nord-ouest du Quebec (Canada) a été étudié. Une relation linéaire dans les assemblages de chironomides a été démontrée par une analyse canonique des correspondances redressée. Une analyse de redondance a donc été utilisée pour identifier les variables influençant les communautés de chironomides. La profondeur du lac, le carbone organique dissous (COD), la température moyenne de l'air en août et la température de l'eau en surface sont les quatre variables qui expliquent le mieux la distribution. Une analyse partielle des moindres carrés a été utilisée pour développer des modèles d'inférence. Le modèle qui prédit la température moyenne de l'air en août a le plus haut coefficient de détermination ($r^2_{jack} = 0,67$) et l'erreur quadratique moyenne de prédiction (= 1,17 °C) la plus faible. Les variations de certains taxons (type *Heterotrissocladius brundini*, type *Heterotrissocladius subpilosus*, type *Heterotrissocladius grimshawi*, type *Micropsectra radialis*, type *Tanytarsus lugens* et *Microtendipes*) peuvent être attribuées aux variations de la profondeur du lac et (ou) de la température. Les changements de *Heterotanytarsus*, *Dicrotendipes*, *Cryptotendipes* et *Cryptochironomus* peuvent être associés aux variations de température et de COD. Les effets combinés de la température, du COD et de la profondeur du lac sur les assemblages de chironomides devraient être étudiés selon un schéma de « néo-écologie » pour dissocier leurs influences respectives.

Abstract

The effect of 33 environmental variables on the distribution of chironomids was studied in 60 lakes of northwestern Quebec (Canada). A detrended canonical correspondence analysis detected linearity in the chironomid assemblages, thus redundancy analysis was used to identify the variables affecting the chironomid communities. Lake depth, dissolved organic carbon (DOC), mean August air temperature, and surface water temperature were the four variables that best explained the distribution of chironomids. Partial least squares analysis was used to develop new inference models. Among models, the one for mean August air temperature had the highest coefficient of determination ($r^2_{jack} = 0.67$) and the lowest root mean square error of prediction (= 1.17 °C). The results indicated that for downcore temperature reconstructions, it might be hard to dissociate the combined effects of temperature, DOC, and depth. Changes in taxa such as *Heterotrissocladius brundini*-type, *Heterotrissocladius subpilosus*-type, *Heterotrissocladius grimshawi*-type, *Micropsectra radialis*-type, *Tanytarsus lugens*-type, and *Microtendipes* can be attributed to changes in lake depth and (or) temperature. Changes in *Heterotanytarsus*, *Dicrotendipes*, *Cryptotendipes*, and *Cryptochironomus* might be attributed to shifts in temperature and DOC. Relationships among temperature, DOC, and lake depth should be studied in a "neo-ecology" design to better understand their impact on chironomid assemblage composition.

A.1 Introduction

Numerous chironomid transfer functions have been created since the early 1990s to quantitatively reconstruct air and water temperatures (e.g., Walker *et al.*, 1997; Larocque *et al.*, 2001; Porinchu *et al.*, 2002), oxygen availability (Quinlan *et al.*, 1998), water depth (Korhola *et al.*, 2000), and chlorophyll a (Brodersen and Lindegaard, 1999) from lake sediment sequences. These training sets are still limited geographically (Scandinavia, Switzerland, western Canada, eastern Canada, and the USA (Colorado and Maine)), and uncertainties remain regarding the applicability of a training set from one region to reconstruct temperature from lakes located outside of the geographical range of the training set (I. Larocque, unpublished data). Thus, it is still useful to develop new transfer functions that encompass the geographical range of the lakes to be used for paleoclimate (or any other variable) reconstructions. Training sets are useful to identify the environmental factors influencing the distribution of chironomids in lakes over a large geographical transect (more than 1000 km), thereby contributing to a better understanding of their ecology and biogeographical distribution.

Northwestern Quebec (from Abitibi-Temiscamingue to northern Nunavik) covers a vast territory where rivers have been damned and where hydroelectricity plays a key role for the energy supply of industrial centers and communities in southern Quebec. It would be important to determine the effect of climate on future lake water levels and river discharge for the management and regulation of these aquatic ecosystems for the production of hydroelectricity. Although global climate models have shown that a substantial warming will occur in northern environments, regional to local predictions are needed to better manage the northern Quebec facilities. Climate data are thus necessary at regional to local scales. Meteorological data are available only at six locations in northwestern Quebec and data have been recorded only since 1993 (i.e., by Environment Canada). Only paleoarchives can provide longer temporal series of temperature inferences in areas where meteorological data are scarce. Here, we lay the foundations for future climate reconstructions along a south-north transect in northern Quebec by (i) determining those factors that statistically exert the strongest influence on the distribution of chironomids in the surface sediments of 60 lakes in northwestern Quebec and (ii) developing an inference model for the quantitative reconstruction of temperature based on fossil chironomid assemblages.

A.2 Materials and methods

A.2.1 Study area

Sixty lakes were sampled in August 1995, which resulted in the development of a dissolved organic carbon (DOC) diatom transfer function (Fallu and Pienitz, 1999). These lakes were located at the northern and southern part of the tree limit in northern Quebec (Figure A.1). The transect covers 1100 km, between 49°48′N to 59°32′N and 75°43′W to 78°78′W. Three eco-climatic zones are covered by this transect: the high boreal, the subarctic, and the low arctic (Environment Canada, 1989). The mean annual temperature and precipitation vary from -0.1 °C and 920 mm in Matagami (49°45′N, 77°38′W) to -6.8 °C and 418 mm in Inukjuak (58°27′N, 78°07′W) (Environnement Canada, 1993). These three eco-climatic zones are characterized by different vegetation types. The high boreal is composed mainly of spruce trees (*Picea mariana* and *Picea glauca*), with lichen cover (Payette, 1983). In this paper, this zone will be referred to as the Boreal Forest. The subarctic has sporadic forest cover (spruce krummholz) and will be referred to as Forest-Tundra. This zone ends with the northern limit of trees. The last ecozone is described as Tundra with no krummholz and low ground vegetation. The southern zone is composed of granites and gneisses while the northern zone (starting at about 55° N) is composed of metamorphic rocks (Landry and Mercier, 1992).

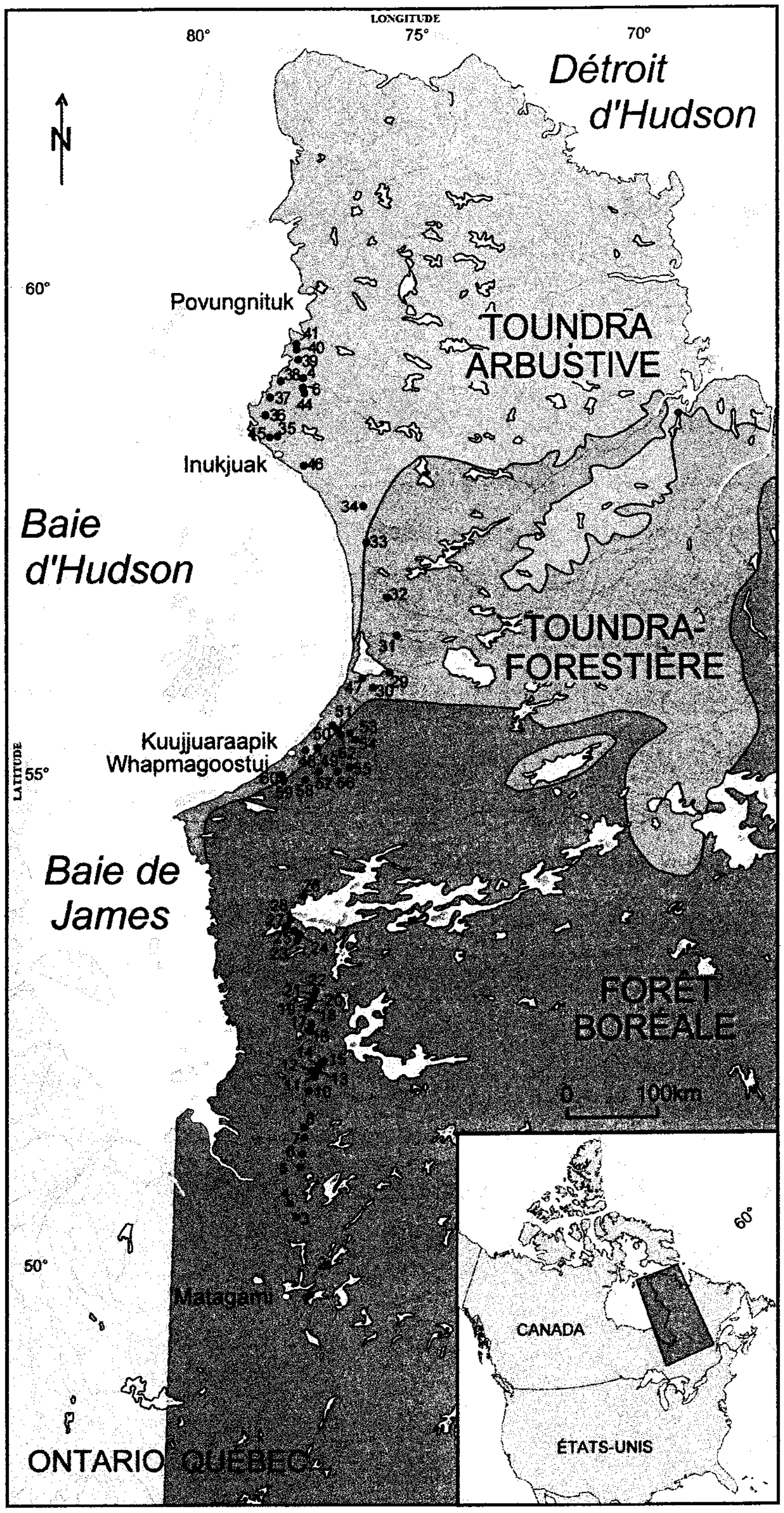

Figure A.1 Location of the 60 sampled lakes in northern Quebec, Canada. Modified from Fallu and Pienitz (1999).

A.2.2 Study sites

Most of the 60 lakes had no affluent. The sampling procedures are described in Fallu and Pienitz (1999). Sediment cores were extracted with a modified Kajak-Brinkhurst or Glew gravity corer (Glew, 1991) at the deepest part of the lake. The surface sediment (top 1 cm) was extracted and kept in a refrigerator at 4 °C. This centimeter likely represents the last 3-5 years of sedimentation (Richard *et al.*, 1982; Larocque and Hall, 2003). Some physical and limnological parameters were measured on site, while water samples were taken at 40 cm depth and brought back for chemical analysis at the National Water Research Institute in Burlington, Ontario. Salinity, conductivity, and water temperature (WT) were measured in situ with a Yellow Spring Instrument 33 meter at a depth of 50 cm; transparency was measured with a Secchi disk; and pH was measured in the sampled water bottle at the Centre d'Études Nordiques research station in Kuujjuaraapik-Whapmagoostui. Altitude, area, and distance from the forest were measured on topographic maps (Fallu and Pienitz, 1999). All parameters are summarized in Table A.1. Meteorological data were available from Environment Canada at six sites: Matagami (49°45′N, 77°38′W), Radisson (LG2; 53°63′N, 77°07′W), Kuujjuaraapik (55°28′N, 77°75′W), Umiujak (56°53′N, 76°52′W), and Inukjuak (58°27′N, 78°07′W). Air temperature data at each site were plotted against latitude, and a model was developed to extrapolate temperature at each studied lake. In other training set studies, July air temperature was one of the major factors controlling the distribution of chironomids (e.g., Lotter *et al.*, 1997; Larocque *et al.*, 2001), and in the present study we wanted to test if (i) air temperature was also important in explaining the distribution of chironomids in our training set and (ii) July air temperature (compared with June or August) was the important climate variable explaining the distribution of chironomids.

Table A.1 Minimum, maximum, mean, and standard deviation (SD) of the environmental characteristics of the 52 studied lakes.

Lake characteristic	Min.	Max.	Mean	SD
TNP (µg·L^{-1})	1.0	48.9	11.6	7.8
TFP (µg·L^{-1})	0.6	10.6	3.9	2.3
PRS (µg·L^{-1})	0.4	7.7	1.9	1.5
TNK (µg·L^{-1})	32.0	396.0	233.5	83.9
NO$_2$ (µg·L^{-1})	0.0	8.0	2.5	1.8
DIC (mg·L^{-1})	0.2	4.8	1.3	1.1
DOC (mg·L^{-1})	2.3	19.4	8.1	4.3
Mg (mg·L^{-1})	0.2	4.3	0.7	0.6
Ca (mg·L^{-1})	0.3	6.2	1.9	1.3
Na (mg·L^{-1})	0.6	28.3	3.0	3.9
K (mg·L^{-1})	0.0	1.4	0.3	0.2
Cl (mg·L^{-1})	1.0	54.6	5.1	7.4
SO$_4$ (mg·L^{-1})	1.4	8.9	3.5	1.6
SiO$_2$ (mg·L^{-1})	0.1	5.5	1.5	1.5
CHLaN (µg·L^{-1})	0.4	17.7	3.7	2.7
CHLaC (µg·L^{-1})	0.0	13.1	2.6	2.1
POC (mg·L^{-1})	0.0	12.7	1.0	1.7
PON (mg·L^{-1})	0.0	1.4	0.1	0.2
Al (µg·L^{-1})	0.0	1000.0	142.8	191.6
Ba (µg·L^{-1})	0.8	11.1	3.2	2.3
Fe (µg·L^{-1})	5.0	1100.0	280.3	267.8
Mn (µg·L^{-1})	1.6	33.0	8.3	6.9
Sr (µg·L^{-1})	2.9	48.6	12.4	8.5
Altitude (m)	13.0	292.6	167.0	75.9
Area (ha)	4.5	292.6	80.2	162.7
Depth (m)	1.0	18.5	3.9	3.6
Transparency (Secchi)	0.5	6.6	2.2	1.6
Water temperature (°C)	13.0	23.6	18.4	3.2
Conductivity (µS·cm^{-1})	10.0	170.0	28.7	22.6

Note: TNP, total nonfilterd phoshorus; TFP, total filtered phosphorous; PRS, soluble phosphorous; NKT, total Kjedahl nitrogen; DIC, dissolved inorganic carbon; DOC, dissolved organic carbon; CHLaN, noncorrected chlorophyll *a*; CHLaC, chlorophyll *a* corrected for pheophytins; POC, particulated organic carbon; PON, particulated organic nitrogen.

A.2.3 Chironomid analysis

All the sediment remaining after diatom analysis (Fallu and Pienitz, 1999) in the top centimetre was used to extract chironomid head capsules. KOH (10 %) was added overnight and the samples were sieved through a 100 µm mesh. The remaining solution was placed in a Bogorov counting tray and examined under a stereomicroscope at × 35 magnification. Head capsules were picked, one by one, and fixed in Hydromatrix mounting medium on a microscope slide. Head capsules were identified using a Van Guard light microscope at × 400 or × 1000. The taxonomy mainly followed Wiederholm (1983) and Oliver and Roussel (1983). Specific keys were used to separate the Tanytarsini subtribe (Brooks *et al.*, 1997; S. Brooks, National History Museum, Cromwell Road, London SW7 5BD, UK, unpublished data). The Tanytarsini who could not be placed into taxonomic groups were separated following the presence (Tanytarsini with) or absence (Tanytarsini without) of a spur on the antenna pedicel. Tanypodinae groups were separated using the position of the setae following Rieradevall and Brooks (2001).

A.2.4 Statistical analysis

We used samples with at least 50 head capsules following the methods outlined in Quinlan and Smol (2000), Heiri and Lotter (2001), and Larocque (2001). Taxa with an abundance of at least 2 % in two lakes were kept for statistical analyses.

A detrended correspondence analysis (DCA) and a detrended canonical correspondence analysis (DCCA) were used to determine the unimodality or linearity in the chironomid data. A redundancy analysis (RDA) was used to determine those environmental variables that explained most of the variance in the distribution and composition of chironomid assemblages (ter Braak and Šmilauer, 2002; Lepš and Šmilauer, 2003). The CANOCO program (ter Braak and Šmilauer, 2002) was used for all ordinations. The chironomid inference models were developed using partial least squares (PLS) methods using the program C2 (Juggins, 2003).

A.3 Results

A.3.1 Chironomid distribution

Of the 60 lake sediment samples analysed, 52 contained enough chironomid head capsules (>50) to be used for statistical analyses. A total of 97 different chironomid taxa were identified in the surface sediments from the 52 lakes. Of those taxa, 64 had abundances of 2 % and more in two lakes (Table A.2) and were therefore used in statistical analyses. *Tanytarsus* without, *Tanytarsus* sp. B., *Procladius*, and the *Psectrocladius sordidellus* group were found in more than 40 of the 52 lakes. The *Heterotrissocladius grimshawi* group had the highest percentage (46 %) in one lake (lake 29) followed by *Tanytarsus* without (42 %), the *Psectrocladius sordidellus* group (30 %), *Zalutschia lingulata pauca* (28 %), *Sergentia* (27 %), and *Procladius* (26 %). Fourty-eight of the other taxa had maximum percentages of less than 10 %.

The taxa presented in Figure A.2 are those showing the most variations with latitude and vegetation zones. *Cryptochironomus*, *Polypedilum* IIIC (fig. IIIC in Wiederholm 1983), and *Zalutschia zalutschicola* were found only in lakes located in the Boreal Forest zone. *Glyptotendipes*, *Chironomus plumosus*-type, *Paracladopelma*, *Heterotanytarsus*, *Pagastiella*, and *Cryptotendipes* were mainly restricted to the boreal zone, with some sporadic (<2) occurrences in lakes located in the two other zones. *Dicrotendipes* had higher percentages in low latitude lakes located in the boreal zone and was absent in the higher latitude lakes. *Tanytarsus lugens*-type and *Cladopelma* were absent in lakes located in the Forest-Tundra zone, but were sporadically present in the Boreal Forest and the Tundra zones. *Microtendipes* had higher percentages in the higher latitude lakes in the Boreal Forest zone, but decreased with latitude in the Forest-Tundra zone and disappeared in lakes of the Tundra zone. *Heterotrissocladius grimshawi*-type and *Heterotrissocladius marcidus*-type had higher abundances in the lakes of the Forest-

Tundra zone. *Heterotrissocladius subpilosus*-type was found mainly in lakes of the Forest-Tundra and Tundra zones. The *Psectrocladius sordidellus* group percentages were higher in Tundra lakes, although the taxon was present in most lakes. *Corynocera ambigua* was present only in some Tundra lakes, usually at low percentages (<7 %).

A.3.2 Relationship with environmental factors

We provide all the meteorological data that were tested in an RDA to determine the ones explaining the best the distribution of chironomids (Table A.3). Mean August air temperature in 1993 and 1994 was the air temperature variable that best explained the distribution of chironomids and was added to the 32 other environmental variables for statistical analysis.

Table A.2 Chironomid taxa with percentage of 2 % in at least two lakes.

No.	Taxa	No. of lakes	Max. %
1	*Chironomus anthracinus*-type	14	8.4
2	*Chironomus plumosus*-type	12	8.7
3	*Cladopelma*	20	8.1
4	*Constempellina brevicosta*	21	6.9
5	*Cryptochironomus*	17	5.4
6	*Cryptotendipes*	12	10.2
7	*Dicrotendipes*	39	19.7
8	*Einfeldia*	8	7.2
9	*Endochironomus impar*-type	5	9.5
10	*Glyptotendipes*	10	3.7
11	*Microtendipes*	38	25.9
12	*Omisus*	7	4.1
13	*Pagastiella*	23	7.0
14	*Parachironomus*	5	2.2
15	*Paracladopelma*	12	4.6
16	*Polypedilum*	7	5.7
17	*Polypedilum* III C	12	16.8
18	*Sergentia*	19	27.3
19	*Stempellinella*	24	17.5
20	*Micropsectra bidentata*-type	12	6.9
21	*Micropsectra insignilobus*-type	13	13.1
22	*Micropsectra radialis*-type	19	20.0
23	*Cladotanytarsus*	18	7.0
24	*Paratanytarsus*	26	15.3
25	*Tanytarsus* without	51	43.0
26	*Tanytarsus* with	13	3.2
27	*Tanytarsus chinyensis*-type	9	6.9
28	*Tanytarsus* sp. B	44	19.8
29	*Tanytarsus* sp. C	6	4.3
30	*Tanytarsus lugens*-type	14	5.7
31	*Tanytarsus pallidicornis*-type	19	9.3
32	*Allopsectrocladius*	15	5.7
33	*Corynocera ambigua*	3	3.4
34	*Corynocera oliveri*	24	7.6
35	*Corynoneura*	5	3.0
36	*Cricotopus*	8	4.4
37	*Cricotopus* sp. A	16	6.0
38	*Cricotopus* sp. B	8	5.6
39	*Cricotopus sylvestris*	7	3.2
40	*Cricotopus cylindricus*	6	4.3
41	*Georthocladius*	2	2.5
42	*Heterotrissocladius grimshawi*-type	30	46.2
43	*Heterotrissocladius marcidus*-type	33	12.8
44	*Heterotrissocladius brundini*-type	7	7.1
45	*Heterotrissocladius subpilosus*	19	10.3
46	*Heterotanytarsus*	22	5.1
47	*Limnophyes*	6	3.0
48	*Mesocricotopus*	6	9.6
49	*Nanocladius*	8	3.4
50	*Orthocladius* sp. A	16	4.3
51	*Orthocladius* sp. D	7	2.8
52	*Paracricotopus*	8	3.2
53	*Parakiefferiella*	9	8.7
54	*Paraphaenocladius*	4	5.2
55	*Protanypus*	17	10.3
56	*Psectrocladius septentrionalis*-group	29	16.8
57	*Psectrocladius sordidellus*-group	49	30.0
58	*Smittia*	3	4.3
59	*Zalutschia lingulata pauca*	35	28.6
60	*Zalutschia zalutschicola*	15	10.4
61	*Ablabesmyia*	15	3.7
62	*Telopelopia*	22	5.6
63	*Pentaneurini*	34	7.4
64	*Procladius*	48	26.3

Note: The number of lakes indicates where the taxa was found; Max. % shows the percentage of the lakes where 2% of the taxa are found.

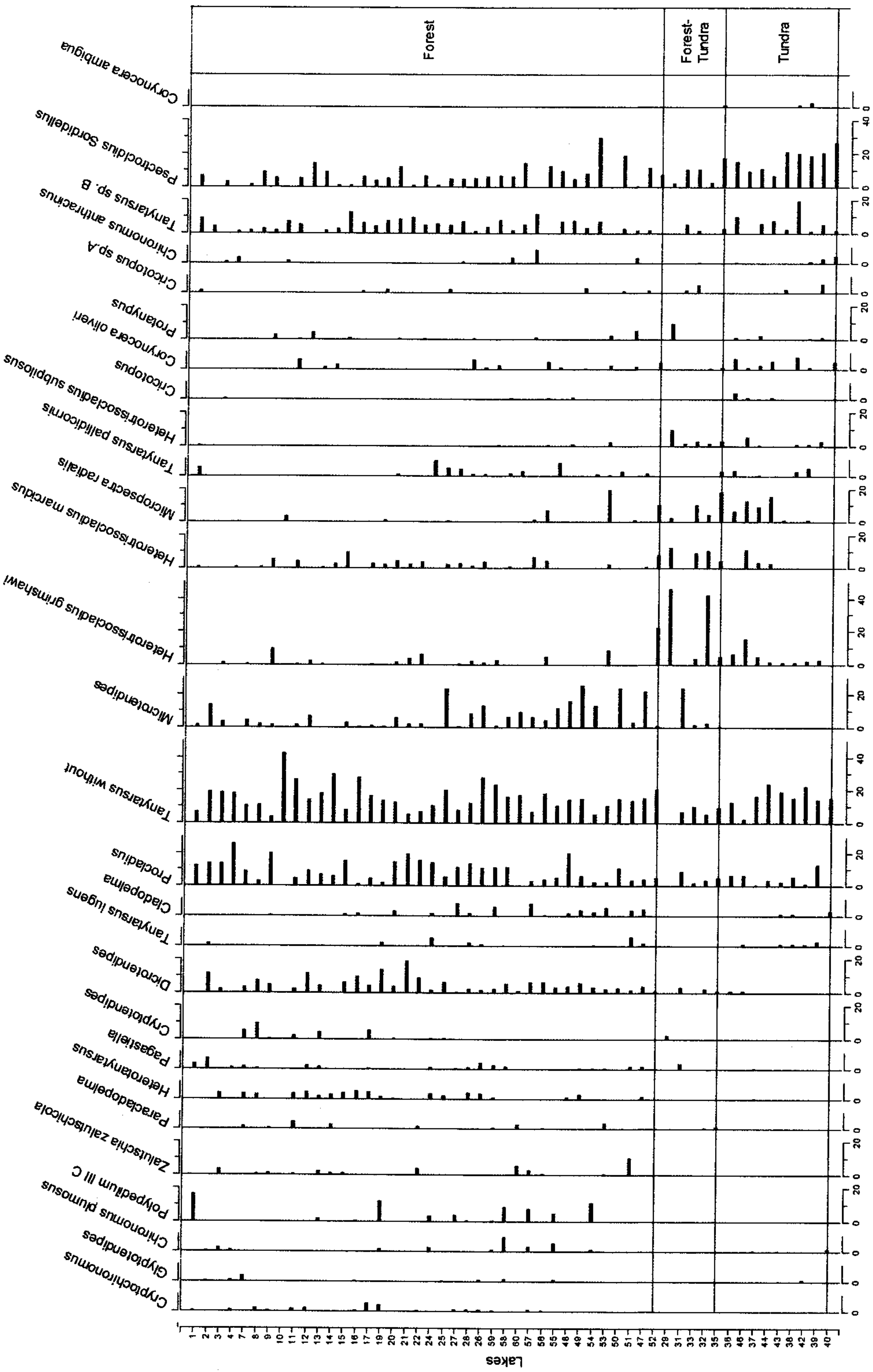

Figure A.2 Chironomid percentages in the training set lakes. Lakes are listed in order of decreasing latitude (°N). The zones indicate the limit of the three major vegetation types.

Latitude, vegetation zones, and distance from the forest were highly correlated with temperature, so they were removed from statistical analyses. Two types of analyses can determine the unimodality of taxa: a DCA (ter Braak and Šmilauer, 2002) or a DCCA (Lepš and Šmilauer, 2003). In both cases, the gradient length expressed as standard deviation (SD) units is the measure of unimodality. The gradient length should be higher than 3 to indicate unimodality (Lepš and Šmilauer, 2003). In the DCA, the gradient lengths for the first four axes were 2.01, 1.98, 1.44, and 1.99, indicating that chironomids had a linear distribution. The gradient lengths of the DCCA with all variables were 1.97, 1.95, 1.57, and 1.21. In a DCCA with WT as the sole variable, the gradient lengths were 1.139, 2.056, 1.718, and 1.486. Gradient lengths were longer in a DCCA with August temperature (1.537, 2.296, 2.229, and 1.692). Since all gradient lengths were <3, most chironomid taxa showed a linear relationship with surface water and mean August air temperature.

Table A.3 Meteorological data analysed in a redundancy analysis.

Variable	Variance explained (%)
All variables	27
June 1993	—
July 1993	4
August 1993	—
Mean summer 1993	—
June 1994	4
July 1994	—
August 1994	—
Mean summer 1994	—
June 1995	—
July 1995	—
August 1995	—
Mean summer 1995	—
June 1993–1994	—
July 1993–1994	—
August 1993–1994	9
Mean summer 1993–1994	—
June 1993–1995	—
July 1993–1995	—
August 1993–1995	—
Mean summer 1993–1995	—

An RDA with 999 Monte Carlo permutations and forward selection of variables was used to determine the relationship between chironomid distributions in the 52 lakes and the 33 environmental data. All variables combined explained 84 % of the variance in the chironomid assemblages. The first and second RDA axes explained 38 % and 22 %, respectively, of the variance. In general, the separation between the chironomid assemblages in Tundra lakes compared with those of the Boreal Forest lakes was clear (Figure A.3a), although 5 of the 37 Forest lakes had chironomid assemblages that resembled those found in Forest-Tundra or Tundra lakes. Seven variables (DOC, depth, area, WT, soluble phosphorus (PRS), dissolved inorganic carbon (DIC), and mean August air temperature) explained 33 % of the variance in the distribution of chironomids in the 52 lakes. The variance explained by each environmental variable was estimated in partial RDAs. The variance explained, from highest to lowest, was DOC (9.2 %) > depth (9.0 %) > mean August air temperature (8.7 %) > WT (8.5 %) > PRS (6.9 %) > DIC (4.4 %) > area (3.7 %). High $\lambda1/\lambda2$ ratios were obtained for depth (0.78), DOC (0.72), WT (0.71), and mean August air temperature (0.63), indicating that inference models could be created for these variables (Fallu and Pienitz, 1999; ter Braak and Smilauer, 2002).

Heterotrissocladius marcidus-type, *H. grimshawi*-type, *H. subpilosus*-type, *Micropsectra radialis*-type, *Protanypus*, and *Heterotrissocladius brundini*-type are taxa that were most influenced by depth (Figure A.3b). *Heterotanytarsus*, *Dicrotendipes*, *Cryptotendipes*, and *Cryptochironomus* seemed to be mostly influenced by WT, mean August air temperature, and DOC.

A.3.3 Transfer functions

Models for WT and mean August air temperature were developed using PLS. The coefficient of determination between mean August air temperature and chironomid percentages was higher ($r^2 = 0.67$) and the root mean square error of prediction (RMSEP) much lower (1.17 °C) than those for WT ($r^2 = 0.59$, RMSEP = 2.24 °C). When inferring WT, lakes with temperature lower than 16 °C were located further away from the 1:1 line of prediction (Figure A.4a), indicating that colder lakes were not so well predicted. In mean August predictions, the temperature in warmer lakes was generally underestimated, and the residuals for these lakes were more important (Figure A.4b).

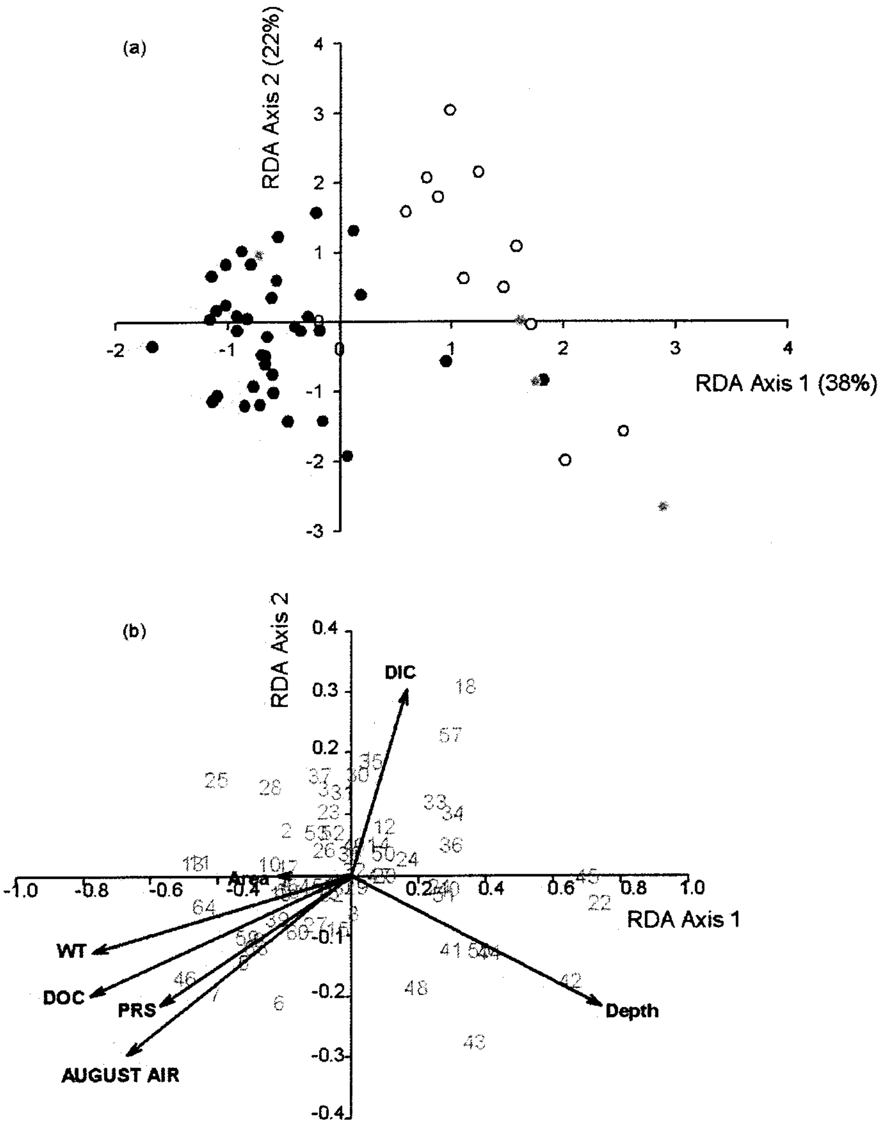

Figure A.3 (a) Redundancy analysis (RDA) of lake data. Solid circles are lakes located in the Boreal Forest zone, shaded circles represent lakes located in the Forest-Tundra ecotone, and open circles represent lakes within the Tundra zone. (b) RDA analysis of taxa. The numbers are associated to taxon names in Table 3.2. The arrows represent the vectors of the seven environmental data explaining the distribution of chironomids in the 52 lakes. DIC, dissolved inorganic carbon; Area, area of lakes; WT, water temperature; DOC, dissolved organic carbon; PRS, soluble reactive phosphorus; AUGUST AIR, mean August air temperature in 1993 and 1994; Depth, maximum lake depth.

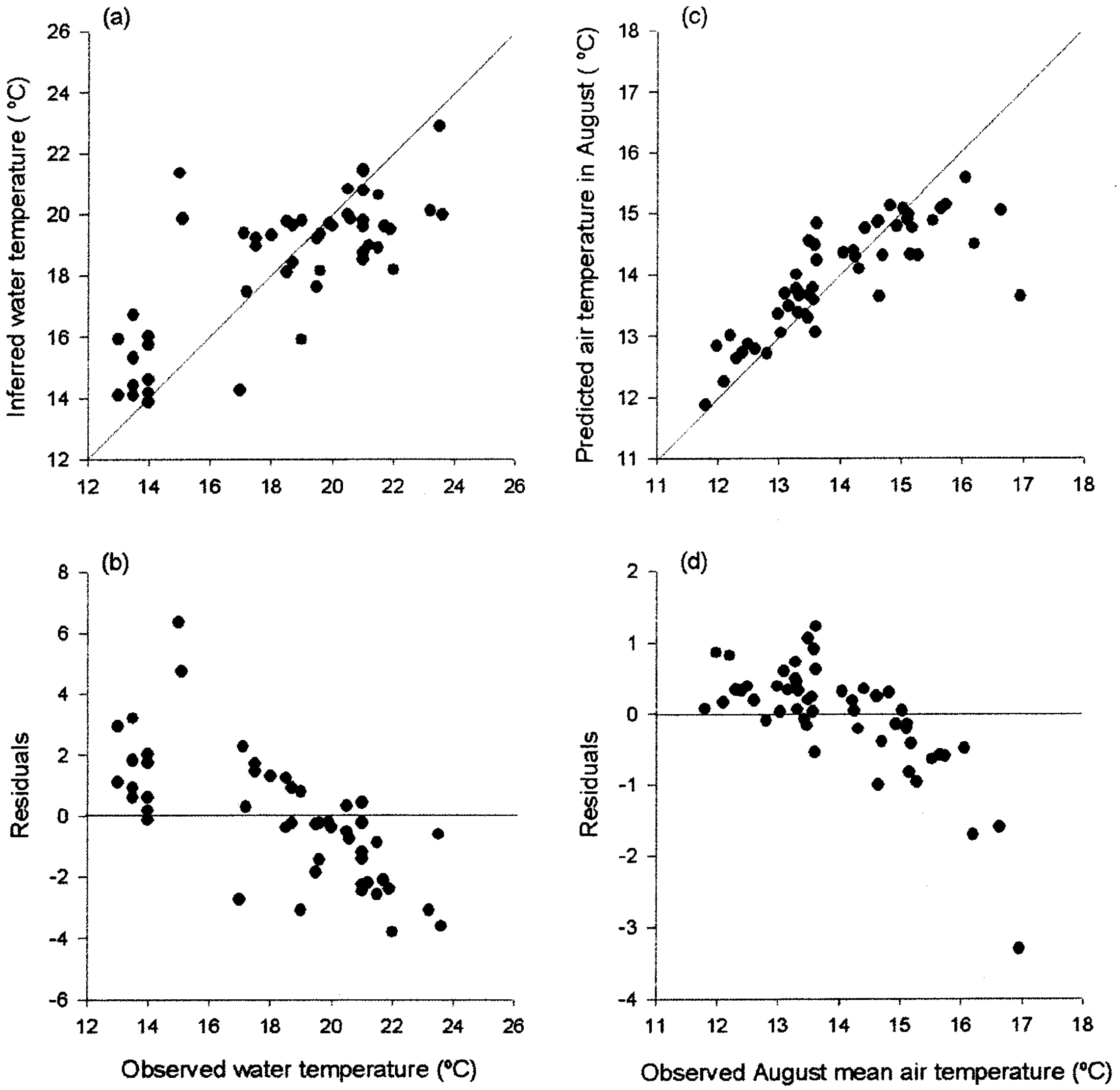

Figure A.4 (a) Relationship between observed and inferred water temperature. The solid line represents the 1:1 relationship. (b) Observed water temperature versus residuals. (c) Relationship between observed and inferred mean August air temperature. The solid line represents the 1:1 relationship. (d) Observed water temperature versus residuals.

Although our goal was to create chironomid transfer functions for temperature, models for DOC and depth were also attempted using PLS. While the transfer function for DOC had relatively good statistics (r^2 = 0.62, RMSEP = 2.78 mg.L^{-1}), the model for depth had a low coefficient of correlation (r^2 = 0.40, RMSEP = 2.84 m).

A.4 Discussion

The chironomid distribution in our 52 lakes from northwestern Quebec was mainly influenced by four parameters: depth, DOC, WT, and mean August air temperature. The goal of this paper was to create a transfer function for temperature, and the model performance data showed that it was coherent to do so. Although the r^2 (0.67) was lower than that of the Eastern Canadian training set for WT (0.88; Walker *et al.*, 1997), the RMSEP (1.17 °C) was lower (RMSEP Eastern Canadian = 2.26 °C). The better correlation in the Eastern Canadian training set might be explained by the fact that its 39 lakes were distributed over 3000 km and over a larger temperature gradient (20 °C). Our 52 lakes, however, were located within 1100 km in a temperature gradient of 10 °C. Similar results were obtained in Norway, where the first developed training set comprised only 44 lakes in a temperature gradient of 8.3 °C with r^2 = 0.69 (Brooks and Birks, 2000), and the second training set comprised 153 lakes in Norway and Svalbard in a temperature gradient of 12.5 °C and an r^2 of 0.90 (S. Brooks, National History Museum, Cromwell Road, London SW7 5BD, UK; and H.J.B. Birks, Botanical Institute, University of Bergen, N-5007 Bergen, Norway, unpublished data). In general, training sets with longer temperature gradients have better r^2 (table 6 in Larocque *et al.*, 2001). These results suggest that to obtain a better r^2, our training set should be extended, although training sets with lower r^2 also perform in general quite well. For example, inferences based on a Swedish training set with an r^2 of 0.65 were quite similar to meteorological data (Larocque and Hall, 2003). It seems evident that the r^2 is not the only statistical parameter that is important for the relevance of the temperature inferences.

The lower RMSEP of our training set might result from higher taxonomic resolution. Here, we separated many of the taxa that were combined in the Eastern Canadian training set (especially the Tanytarsina), and we think we obtained better temperature optima for each taxon, thereby decreasing the error of temperature estimates. Similar results were obtained in Norway; increasing the taxonomic level probably decreased the error of temperature estimates in the 153-lake training set (S. Brooks, Natural History Museum, Cromwell Road, London SW7 5BD, UK, personal communication).

The PLS coefficients for each taxa (Table A.4) identified the *Psectrocladius sordidellus* group, *Sergentia*, *Micropsectra radialis*-type, *Corynocera oliveri*, and *Heterotrissocladius subpilosus*-type as the coldest indicators. A review of temperature optima from four training sets is presented in Bennike *et al.* (2004) and is used for comparison with our results. The *Psectrocladius sordidellus* group was not considered as a cold indicator in northern Sweden (optimum = 11.6 °C), but *Psectrocladius* were the most abundant taxon in the cold early Holocene in a shrub-tundra lake in northern Quebec (Fallu *et al.*, 2005). The species name *Psectrocladius sordidellus* is given to a group with similar characteristics of the head capsule but might comprise species with potentially different temperature optima. Here, the *Psectrocladius sordidellus* group is also located along the DIC vector in the RDA analysis and could be influenced by this factor more than by temperature. While *Sergentia* has a cold optimum in eastern Canada (6 °C) and is a cold indicator in our training set, it had higher temperature optima (15 °C) in northern Finland and northern Sweden (Bennike *et al.*, 2004). These contradictory results indicate that the taxa called "*Sergentia*" might not comprise the same species in Canada and in northern Europe. A special taxonomic effort could be given to this taxon to try to separate it into taxonomic groups. *Micropsectra radialis*-type, *Corynocera oliveri*, and *Heterotrissocladius* are cold indicators (optimum <7 °C) in the Canadian and in the North European training sets. *Dicrotendipes*, *Cryptochironomus*, and *Zalutschia* were identified as warm indicators in this training set and in the Eastern Canada and Northern Europe training sets (Bennike *et al.*, 2004). Other taxa have contradictory results. *Cladotanytarsus* and *Cladopelma* were considered here as colder indicators, while they were warm indicators in other training sets; *Heterotanytarsus* is an intermediate taxon in other training sets, while it is a warmer indicator here. These differences might be attributed to the fact that we had linear relationships between the chironomid taxa and the temperature. By increasing the training set north and south, we might get a better distribution of all taxa and be able to calculate optima with unimodal techniques.

Although temperature was an important factor explaining the distribution of chironomids, other parameters obviously also had an influence on larval distribution. Depth and DOC effects on the chironomid distribution are further discussed below.

Table A.4 Partial least square (PLS) coefficients of each taxon.

Taxa	PLS
Psectrocladius sordidellus-group	–0.331
Sergentia	–0.301
Micropsectra radialis-type	–0.177
Corynocera oliveri	–0.163
Heterotrissocladius subpilosus-type	–0.142
Cladopelma	–0.116
Heterotrissocladius grimshawi-type	–0.085
Tanytarsus pallidicornis-type	–0.083
Cladotanytarsus	–0.083
Tanytarsus lugens-type	–0.080
Tanytarsus sp. B	–0.075
Microtendipes	–0.072
Cricotopus sp. A	–0.067
Cricotopus	–0.061
Omisus	–0.058
Paracricotopus	–0.052
Orthocladius sp. A	–0.044
Chironomus anthracinus-type	–0.044
Corynocera ambigua	–0.044
Telopelopia	–0.032
Orthocladius sp. D	–0.029
Parachironomus	–0.026
Cricotopus cylindricus	–0.024
Chironomus plumosus-type	–0.023
Heterotrissocladius brundini-type	–0.020
Ablabesmyia	–0.014
Limnophyes	–0.008
Protanypus	–0.004
Parakiefferiella	–0.004
Paratanytarsus	–0.003
Micropsectra bidentata-type	–0.002
Micropsectra insignilobus-type	0.002
Nanocladius	0.002
Tanytarsus with	0.006
Georthocladius	0.008
Polypedilum	0.011
Einfeldia	0.018
Corynoneura scutellata	0.024
Psectrocladius septentrionalis-group	0.026
Allopsectrocladius	0.027
Glyptotendipes	0.029
Constempellina	0.035
Smittia	0.039
Heterotrissocladius marcidus-type	0.042
Tanytarsus without	0.044
Cricotopus sp. B	0.046
Paracladopelma	0.048
Tanytarsus sp. C	0.051
Paraphaenocladius	0.053
Cricotopus laricomalis	0.060
Polypedilum III C	0.069
Mesocricotopus	0.070
Pagastiella	0.074
Zalutschia lingulata pauca	0.086
Zalutschia zalutschicola	0.095
Tanytarsus chinyensis-type	0.112
Dicrotendipes	0.119
Endochironomus impar-type	0.131
Cryptochironomus	0.132
Cryptotendipes	0.136
Procladius	0.143
Heterotanytarsus	0.150
Stempellinella	0.151
Pentaneurini	0.192

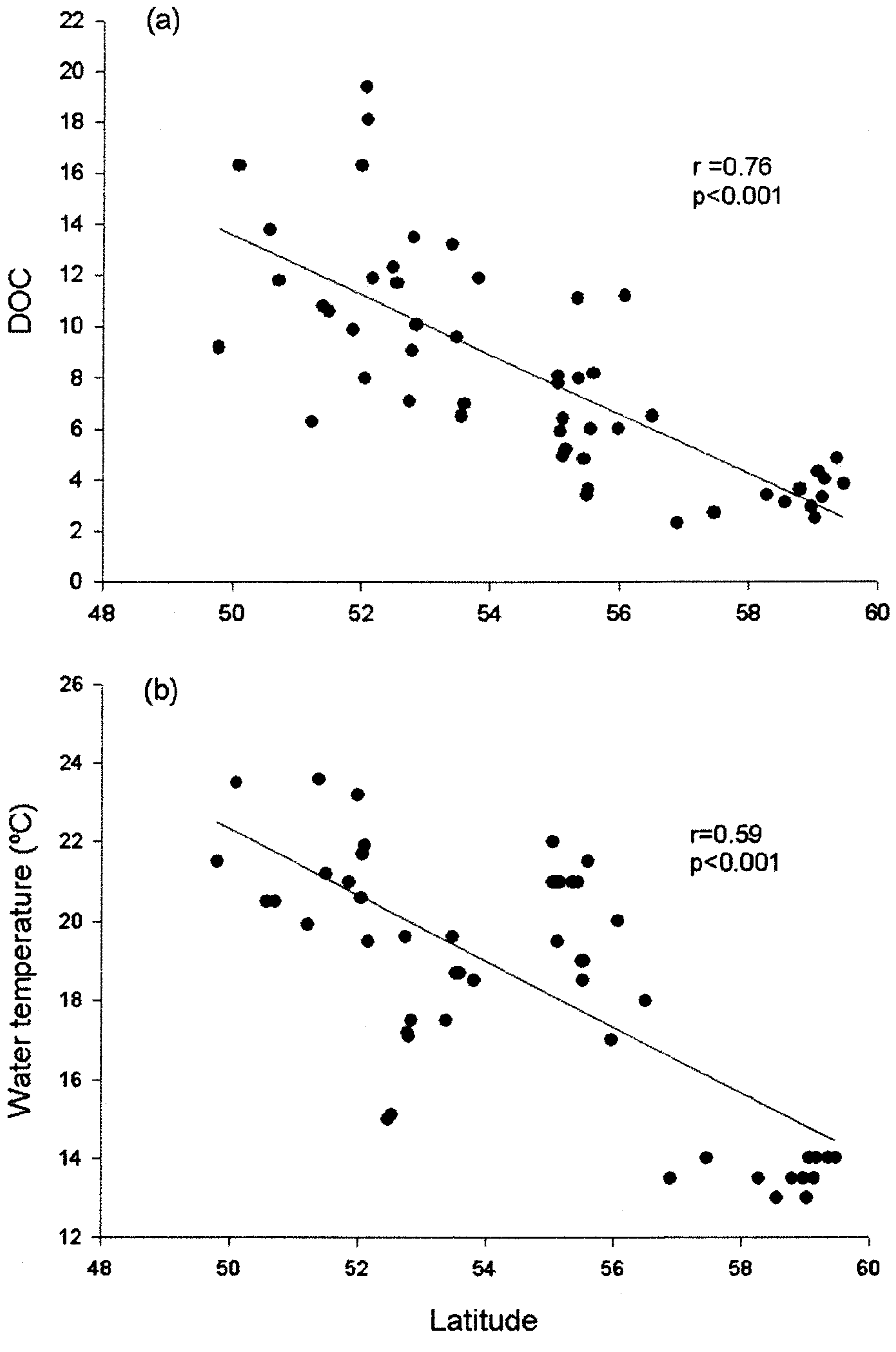

Figure A.5 Relationships between latitude and (a) dissolved organic carbon (DOC) and (b) water temperature. The solid line is the regression

A.4.1 Depth

Depth has been identified as an important factor explaining the distribution of chironomids in many other training sets (e.g., Olander *et al.*, 1997; Quinlan *et al.*, 1998; Porinchu *et al.*, 2002). Taxa such as *Micropsectra*, *Heterotrissocladius subpilosus*, and *H. brundini* are restricted to deep lakes or to the profundal zones (Walker, 1990; Walker and MacDonald, 1995; Simola *et al.*, 1996). These taxa were also found in deeper lakes in our training set. Most *Tanytarsus*, *Tanytarsus lugens*, and *Microtendipes* prefer the littoral zone (Schmäh, 1993; Walker and MacDonald, 1995; Heiri *et al.*, 2003). In the RDA ordination, these taxa were located at the opposite end of the depth vector, indicating that they prefer shallow lakes. Although an inference model has been built for the reconstruction of depth (Korhola *et al.*, 2000), the low coefficient of determination we obtained here does not indicate that the model would be significant. The importance of depth in explaining the distribution of chironomids should be taken into account when interpreting temperature reconstructions, especially if the community changes involve changes in taxa such as *Micropsectra*, *H. subpilosus*-type and *H. brundini*-type, *Tanytarsus*, *Tanytarsus lugens*-type, and *Microtendipes*.

A.4.2 DOC

DOC was not an important parameter explaining the distribution of chironomids in most other training sets either because it was not measured as such (e.g., Walker *et al.*, 1991; Olander *et al.*, 1997 (total organic carbon, (TOC)); Porinchu *et al.*, 2002 (particulate organic carbon) or the DOC gradient along the transect was weak (e.g., Larocque *et al.*, 2001). Lotter *et al.* (1997) found a relationship between DOC and the chironomid distribution in Swiss lakes, but DOC did not solely explain a high proportion of the variance in the species data. In Finland, TOC was an important factor explaining the distribution of chironomids; high TOC lakes were surrounded by peatlands (Nyman *et al.*, 2005).

In our study sites, DOC derives mainly from allochthonous sources (Fallu and Pienitz, 1999). This has been shown also in other high latitude areas (e.g., Labrador, Engstrom, 1987; Alaska, Kling *et al.*, 1991; Yukon, Pienitz *et al.*, 1997a; Northwest Territories, Pienitz *et al.*, 1997b; Mackenzie Delta, Ramlal *et al.*, 1994). The relationship between latitude and DOC is relatively important (Figure A.5); DOC is generally higher in lakes located in the Boreal Forest (average 9.8 $mg.L^{-1}$) and lower in Tundra lakes (average 4.8 $mg.L^{-1}$) (Fallu and Pienitz, 1999). Similar results were obtained in northern Canada (Pienitz *et al.*, 1997a, 1997b), in Siberia (Laing *et al.*, 1999), and in Europe (Kingston and Birks, 1990; Stevenson *et al.*, 1991). The feeding habits of chironomid larvae vary, but many are detritivores and (or) filter-feeders, while others graze on bacteria (Walker, 2001). These are feeding habits that involve DOC absorption. Binkley *et al.* (2005) showed that although DOC was thought to come primarily from bacteria degradation, *Chironomus* utilized DOC derived from terrestrial sources. Labile carbon was added to a stream in North Carolina, USA, and lead to a threefold increase in growth rate of chironomid larvae (Wilcox *et al.*, 2005).

DOC can influence aquatic communities by attenuating light penetration (Vincent and Roy, 1993) and by changing the thermal stratification of lakes (Scully, 1998). In the RDA, DOC and temperature were represented by vectors that pointed in the same direction, indicating that separation of DOC and temperature effects on chironomid distribution might be difficult, although the relationship between WT and DOC was weak (Figure A.5).

The DOC-diatom transfer function elaborated from the same set of lakes seems to be more relevant ($r^2 = 0.90$, RMSEP = 1.23 $mg.L^{-1}$) (Fallu and Pienitz, 1999), and we therefore do not suggest to use the DOC-chironomid transfer function developed here.

A.4.3 Water, air, and August temperature

Based on other published transfer functions (e.g., Lotter *et al.*, 1997; Brooks and Birks, 2000; Larocque *et al.*, 2001), it is not surprising that air temperature is better predicted with chironomids than with WT. This relationship is not entirely due to chironomid ecology and life cycle, although hatching of adults and reproduction might be related to air temperature (Armitage *et al.*, 1995). It is mainly due to the fact that meteorological data have been sampled more frequently than WT. The air temperature data set is thus more representative than the punctual WT measurements.

Mean August air temperature 2 years prior to the sampling year is a better predictor of chironomid distribution than July air temperature of the sampling year, generally considered in other transfer functions (e.g., Brooks and Birks, 2000; Larocque *et al.*, 2001). Chironomid assemblages in surface sediment integrate several years (likely 2-5 years), and larvae might take more than 1 year to become fourth instar, especially in colder lakes (Armitage *et al.*, 1995). August is the month when emergence was highest in temperate zone streams (Pinder, 1974), and voltinism (number of annual generations per species in a habitat) decreases with latitude (Armitage *et al.*, 1995). At high latitude sites, one generation per species is generally recorded every 2-3 years, and the adults of certain species (*H. grimshawi*, *Psectrocladius limbatellus*, *Rheocricotopus effusus*, and *Paracladopelma nigritula*) mainly emerge between mid-July and September (Welch, 1976). These studies highlight the need for a better understanding of chironomid larval ecology when trying to explain the stronger impact of August (in this case) rather than July, mean June, or mean summer temperatures on the distribution of chironomids.

In conclusion, our results indicate that the northern Quebec lake training set should be extended to (i) get a unimodal response of taxa to better calculate optima of temperature and (ii) to better predict temperature in colder and warmer lakes. By extending the training set, we hope to achieve a better correlation (r^2) between temperature and chironomids. However, statistical analysis should not be the only approach for climate reconstruction. Understanding the relationship between temperature and chironomid larval life strategies (e.g., timing and duration of larval development, emergence) is still a research challenge for paleoecological studies using fossil chironomids. We plan to study more lakes along our transect with weekly sampling intervals to determine which taxa might be better indicators of temperature and to further refine the relationship between chironomids and lake DOC.

Acknowledgements

The environmental data were obtained through research funding obtained by R. Pienitz from the Natural Sciences and Engineering Research Council of Canada (NSERC) and Fonds de recherche sur la nature et les technologies (FQRNT). Thanks go to N. Allaire, M.-A. Fallu, and P. Tremblay who helped with field work.

Appendice B

A Visual Guide to Sub-fossil Chironomids from Quebec to Ellesmere Island

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Eau, Terre et Environnement

www.chironomids.com

Résumé

Ce guide a pour but d'illustrer les différents taxons de chironomides sub-fossiles recueillis à la surface des sédiments de plusieurs lacs, entre Mont-Laurier (Québec) et l'île d'Ellesmere, lors de l'établissement d'une fonction de transfert (Larocque *et al.*, 2006). Au total 90 taxons ont été retenus et sont représentés dans cet appendice. Ce guide ne veut en aucun cas éclipser les quelques guides taxonomiques déjà disponibles pour le Canada et l'Europe. Son objectif est d'apporter un nouveau support d'identification tirant parti presque exclusivement du sens visuel des utilisateurs, ce qui n'a jamais été fait auparavant. Le guide ne comporte donc aucune clef d'identification.

Chaque fiche d'identification se compose de photos digitales retouchées principalement pour isoler les parties d'intérêt et augmenter la profondeur de champ de chaque image (unique à ce jour pour un guide taxonomique). Un court texte accompagne l'utilisateur sur les points importants à observer, et l'informe des caractéristiques écologiques de chaque taxon. Les taxons présentés provenant d'une fonction de transfert, des cartes contenant des marqueurs où ils ont été retrouvés sont incluses avec pour chacun leur optimum de température. La fonction de transfert étant en constant développement, au fur et à mesure que de nouveaux taxons seront trouvés, ils seront ajoutés à ce guide. De plus, l'observation de taxons déjà inclus, mais permettant d'obtenir de meilleures photos haute résolution, améliorera davantage l'aspect visuel du guide. Un site web, www.chironomids.com, accompagnera prochainement ce guide dans le but de le rendre disponible à un très grand nombre de personnes. Pour le rendre universel, le guide a donc été rédigé en anglais. Cette thèse ne comporte que le chapitre 4 du guide, soit les fiches d'identification.

B.1 Introduction

The taxonomy presented here is based on various sources including published keys (e.g., Wiederholm 1983; Oliver and Roussel 1983; Moller Pilot 1984 a,b, Epler 1995; Rieradevall and Brooks 2001), information gathered at various workshops attended in Europe and North America (e.g., unpublished keys developed by Steve Brooks on Tanytarsini), Oliver Heiri's website on Tanytarsisni www.bio.uu.nl/~palaeo/Chironomids /Tanytarsini/intro.htm) and personal observations and classifications of different taxa.

This guide is not complete, it only concerns the taxa found in the training set lakes. For complete guides, please consult the sources enumerated above. A complete guide for subfossil taxonomy by Brooks, Langdon and Heiri should be available soon. The taxonomy section of this guide is separated into Tribe and subtribes, based primarily on parts that are preserved and are present in sub-fossils: the mentum and the ventromental plates.

The Chironominae have elongated fan-shaped ventromental plates. They are divided into two subtribes: the Chironomini, with wide ventromental plates (Figure B.1) and the Tanytarsisni, with thin bar-shaped ventromental plates (Figure B.2). The shape of the ventromental plates and the shape of the teeth on the mentum are used to differentiate the taxa.

Figure B.1 Ventromental plates and mentum of Chironomini

The taxonomy of Tanytarsini is based on Steve Brooks' unpublished key. The presence and shape of the spur on the antenna, the number of teeth on the mandible and the shape of the occipital plates are characteristics used to separate the different taxa.

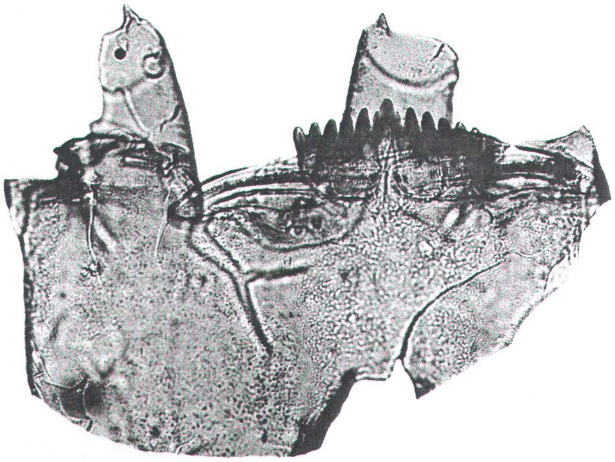

Figure B.2 Ventromental plates and mentum of Tanytarsini

The Orthocladiinae have thin ventromental plates which follow the mentum and are often hard to see (Figure B.3). The shape of the ventromental plates, the shape of the median teeth/tooth, the shape and number of lateral teeth are characteristics used to differentiate the taxa.

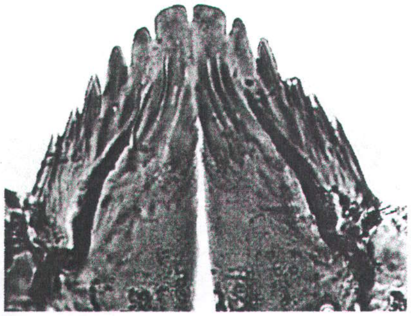

Figure B.3 Ventromental plates and mentum of Orthocladiinae

The Diamesinae are distinguished by a high number (>6) of lateral teeth on the mentum. The shape and number of teeth on the mentum are used to differentiate the taxa (Figure B.4).

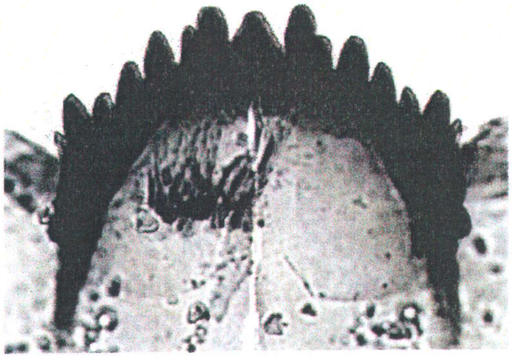

Figure B.4 Ventromental plates and mentum Pseudodiamesa

The Tanypodinae have elongated headcapsules, they do not have a mentum but a ligula. Taxonomy is based on Rieradevall and Brooks (2001) where setae pores are used. The ventromental pore is oval (A), the setae pores are round and look double-lined (B-C) (Figure B.5).

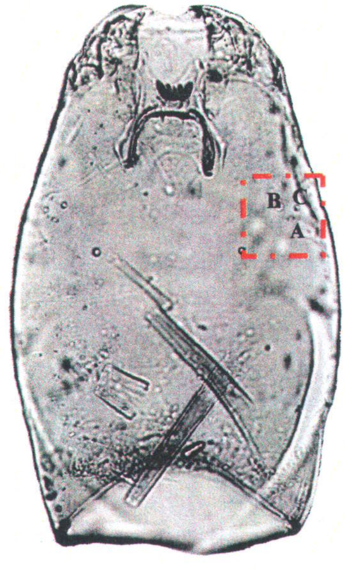

Figure B.5 Telopelopia headcapsule

B.2 Chironomini

The visual guide
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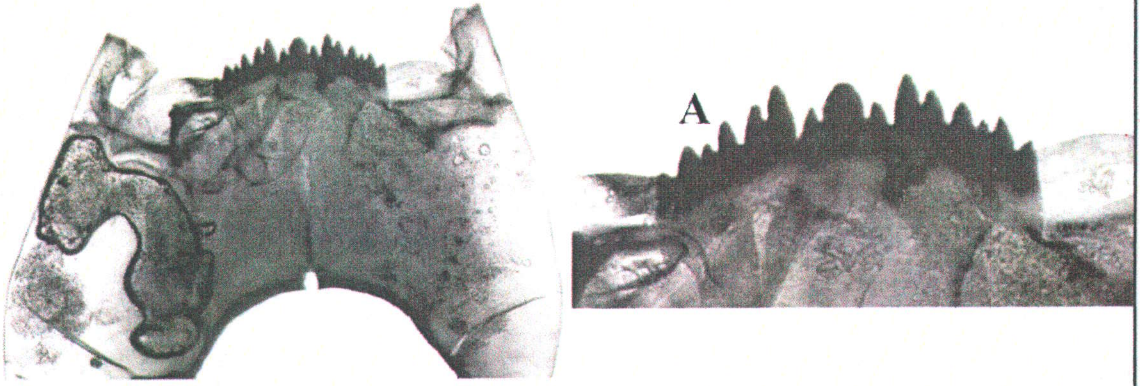
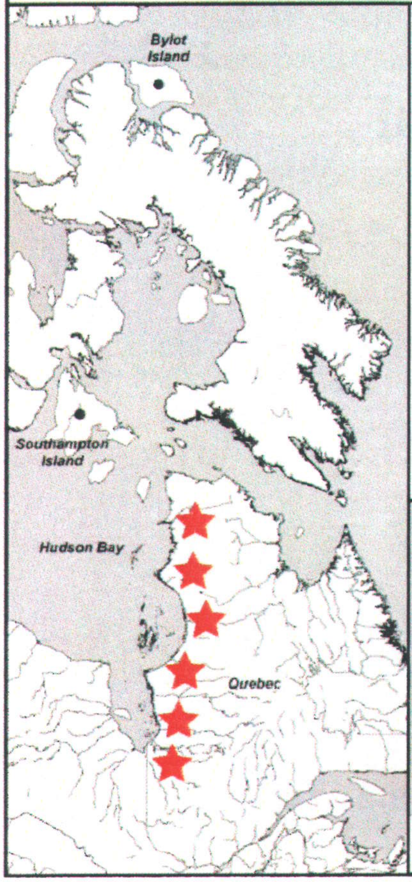
chironomid analysis

Genera: Chironomus anthracinus-type
Tribe: Chironominae



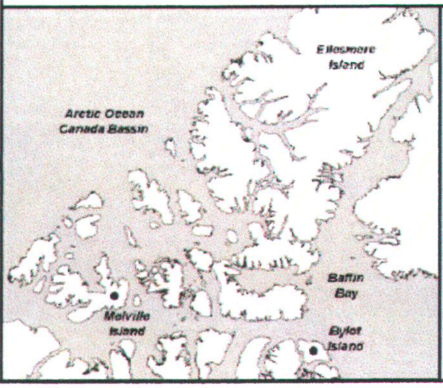


Description:

Differentiated from *C. plumosus*-type by a shorter lateral tooth (A)

Ecology:

Found in productive lakes (1), in the profundal zone (2, 3)



Temperature optimum (°C):

11.0

The visual guide
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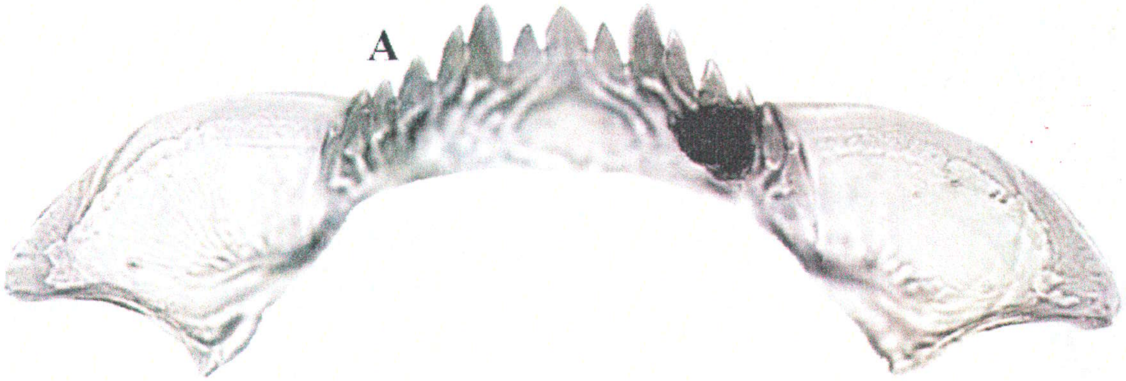
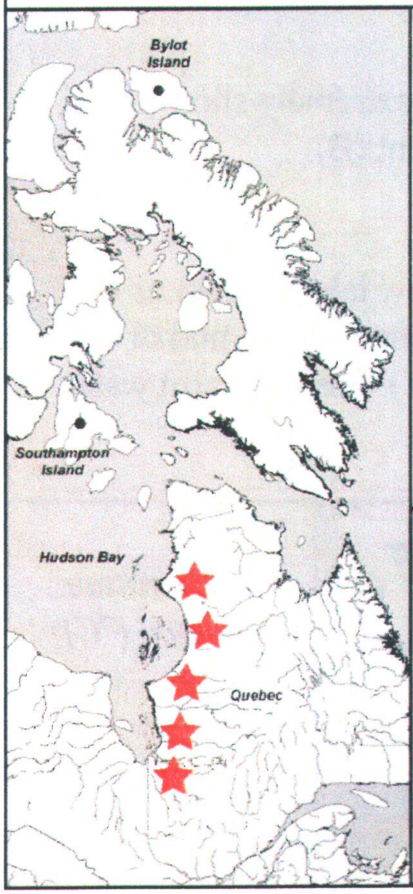
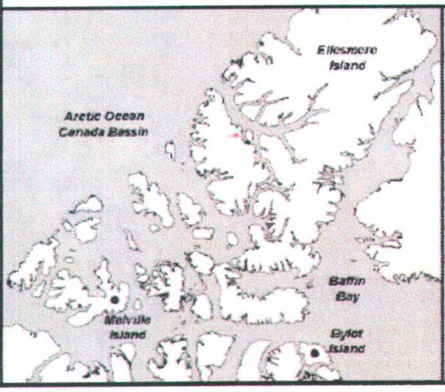
chironomid analysis

Genera: Chironomus plumosus-type
Tribe: Chironominae





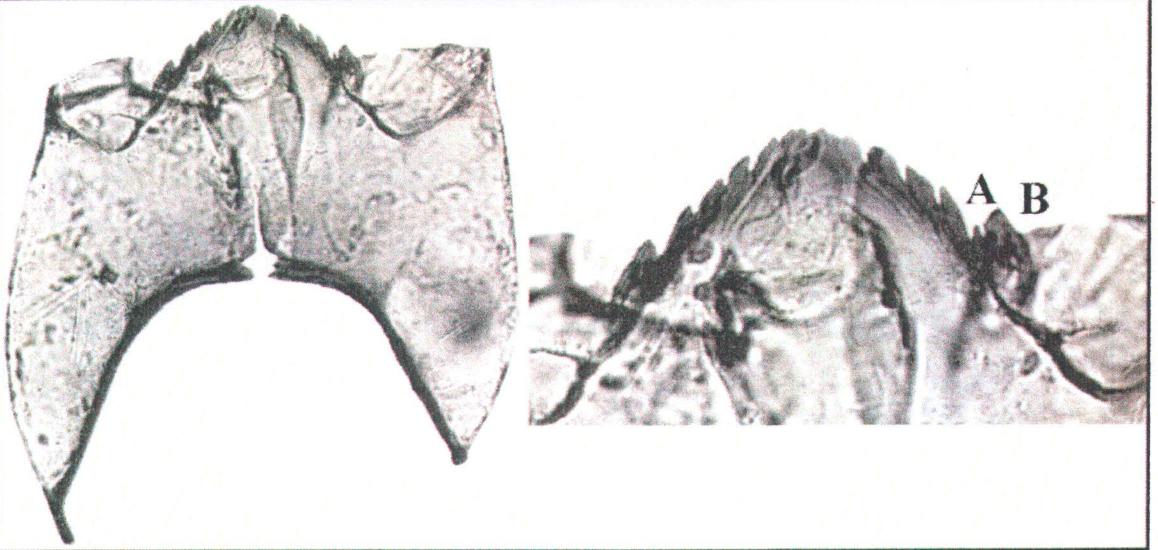
Description:
4th lateral teeth as long as the others (A)
Ecology:
Found in productive lakes, with low pH, in the profundal zone and increase with eutrophication (4). Found in warm and humic waters (5,6), in eutrophic lakes (7,8) and in the profundal zone of lakes with low oxygen (8).

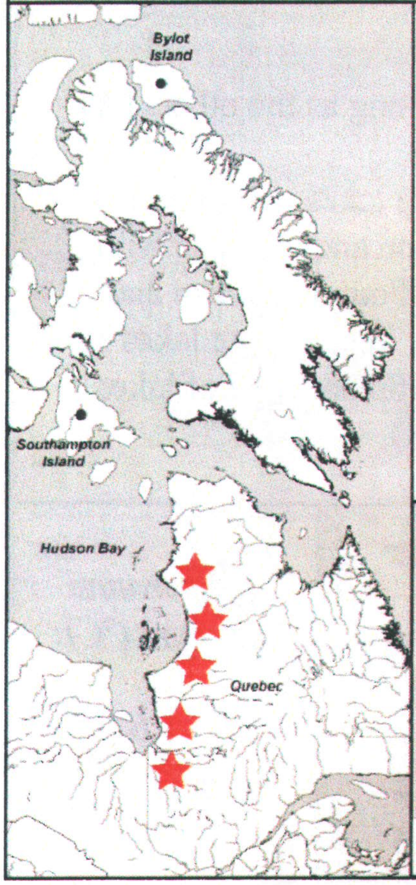


Temperature optimum (°C):

11.6

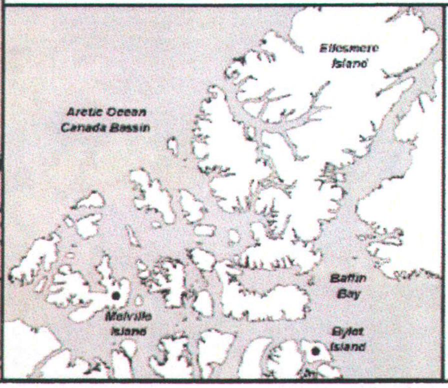
Genera: Cladopelma
Tribe: Chironominae, Chironomini





Description:
Second last lateral extremely short (A), last lateral prominent (B).

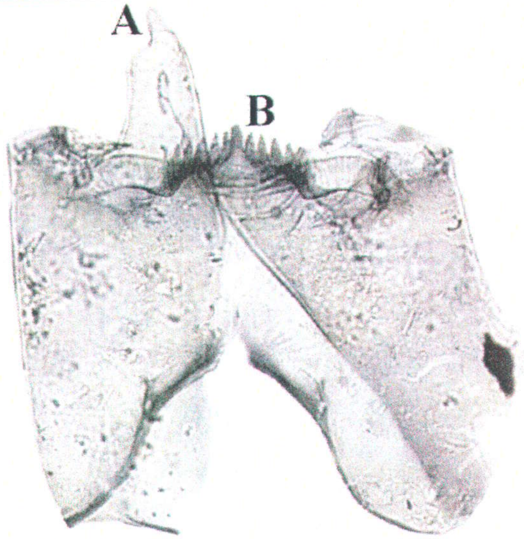
Ecology:
Restricted to shallow lakes (9), on or in the bottom sediments (10), in mud of gravel substrate (11). Prefers warm water (12,13).

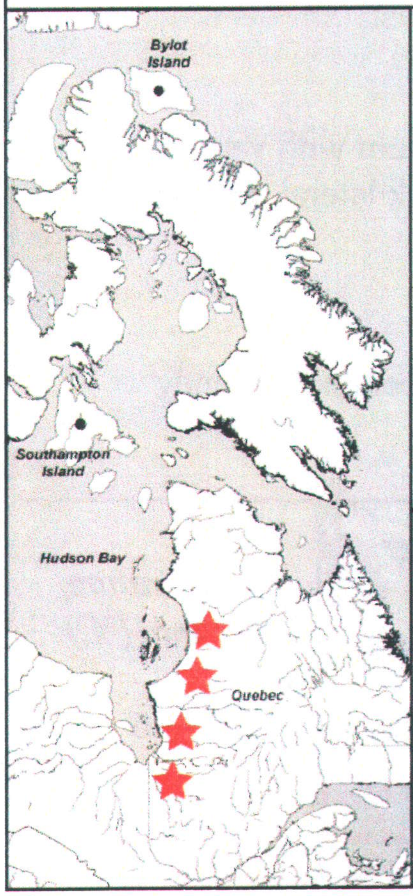


Temperature optimum (°C):

9.5

Genera: Constempellina
Tribe: Chironominae, Chironomini



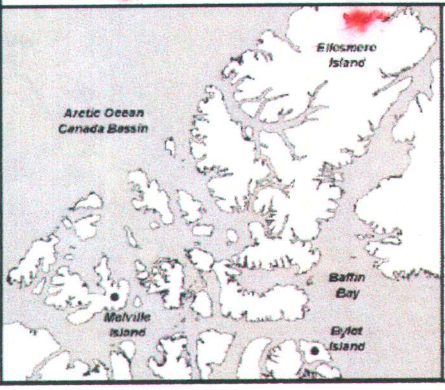


Description:

Spur on each antenna (A). Spur shorter than Stempellinella. Lateral teeth (B) are thin and curved compared to Stempellinella

Ecology:

Stream dwellers (10)

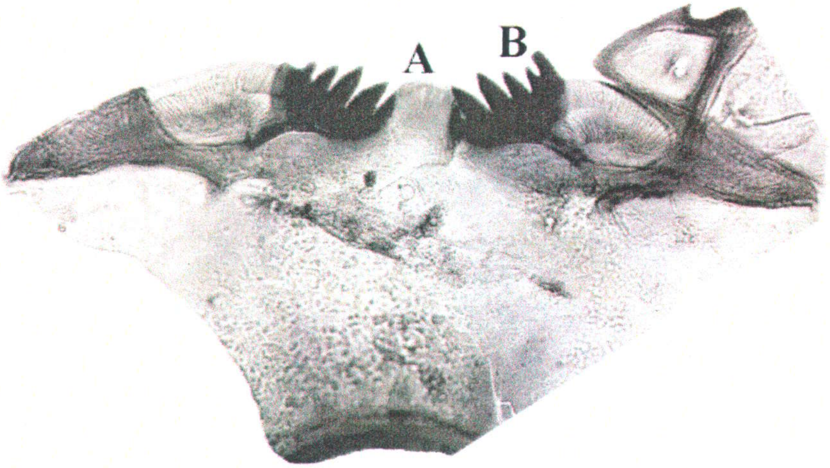


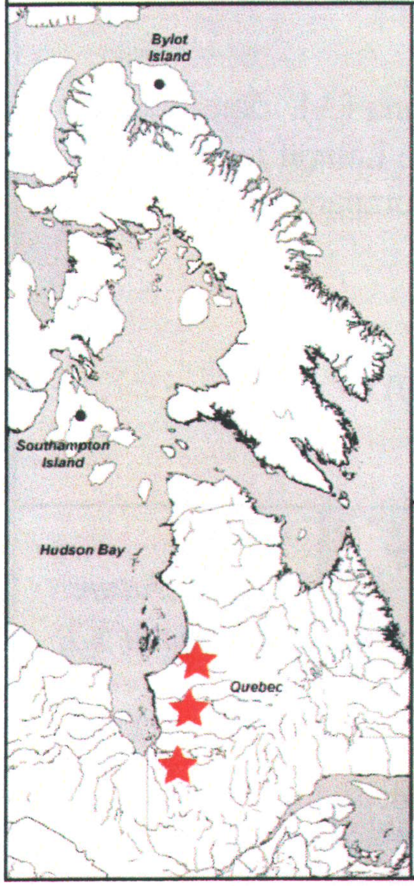
Temperature optimum (°C):

21.2

The visual guide to subfossil chironomid analysis

Genera: Cryptochironomus
Tribe: Chironominae, Chironomini



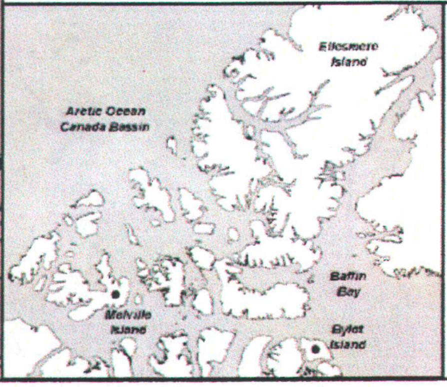


Description:

Characteristic mentum with very large median (A) and dark lateral teeth (B).

Ecology:

Larvae are mostly benthic on sandy substrata (10).



Temperature optimum (°C):

21.6

The visual guide
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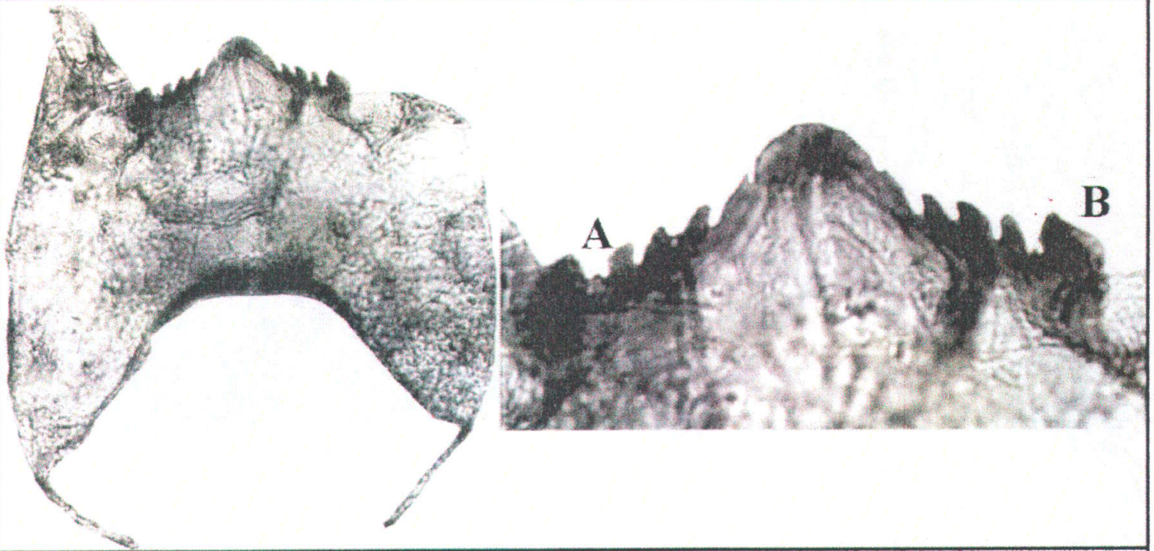
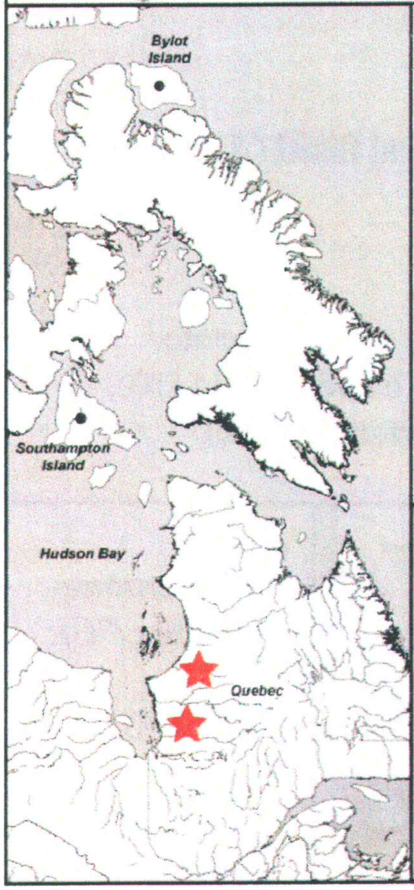
chironomid analysis

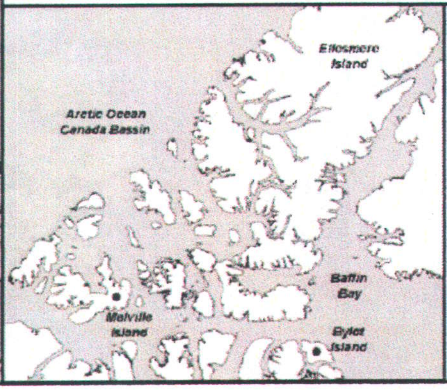
Genera: Cryptotendipes
Tribe: Chironominae, Chironomini





Description:
Fifth lateral suppressed (A), 6th lateral prominent (B).

Ecology:
Lotic or lentic taxa, benthic and tolerate enriched lakes (10), oligo to mesothrophic (32).

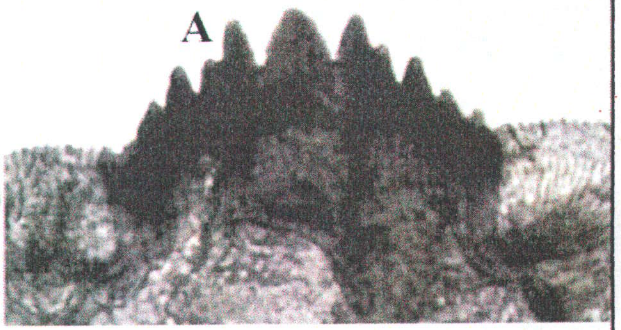


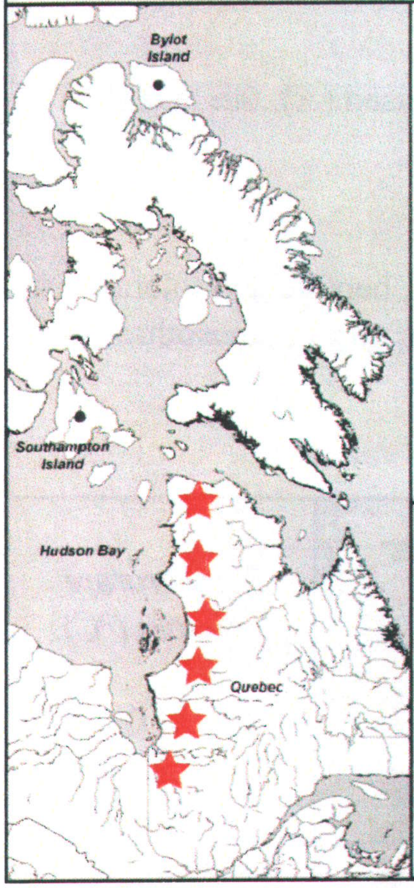
Temperature optimum (°C):

24.0

The visual guide
to subfossil
chironomid analysis

Genera: Dicrotendipes
Tribe: Chironominae, Chironomini



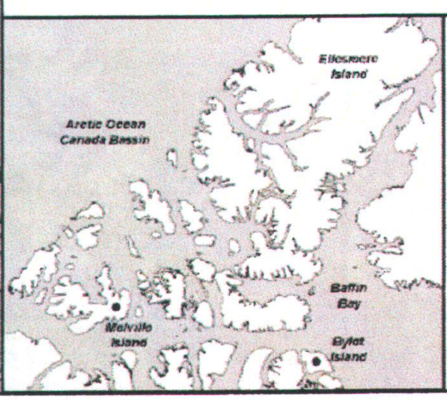


Description:

1st and second lateral fused (A).

Ecology:

Eutrophic taxa (14, 15) in vegetated ponds (11, 16, 17), on vegetation (10), decrease with deforestation (14).

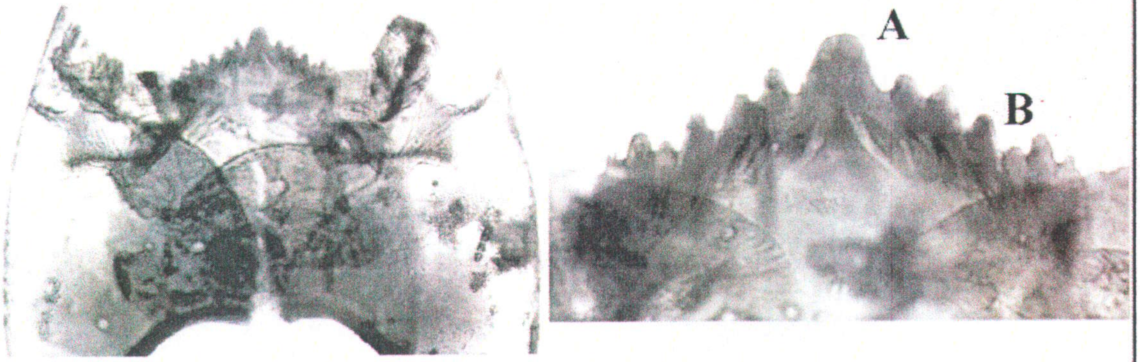


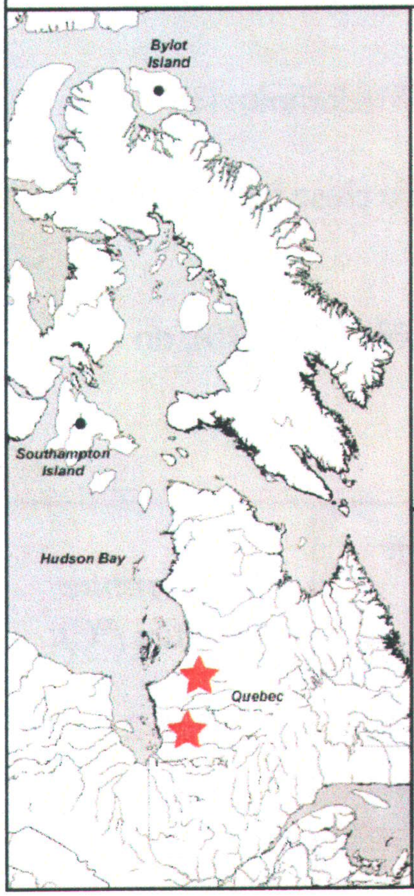
Temperature optimum (°C):

16.0

The visual guide to subfossil chironomid analysis

Genera: Einfeldia
Tribe: Chironominae, Chironomini



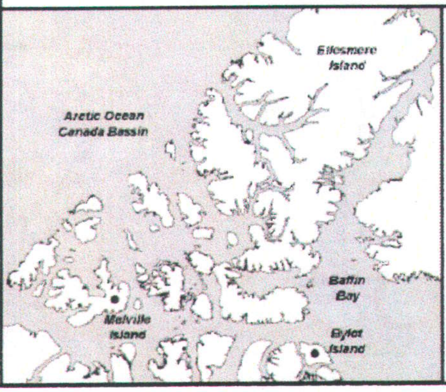


Description:

Round and prominent median (A), 4th lateral smaller (B).

Ecology:

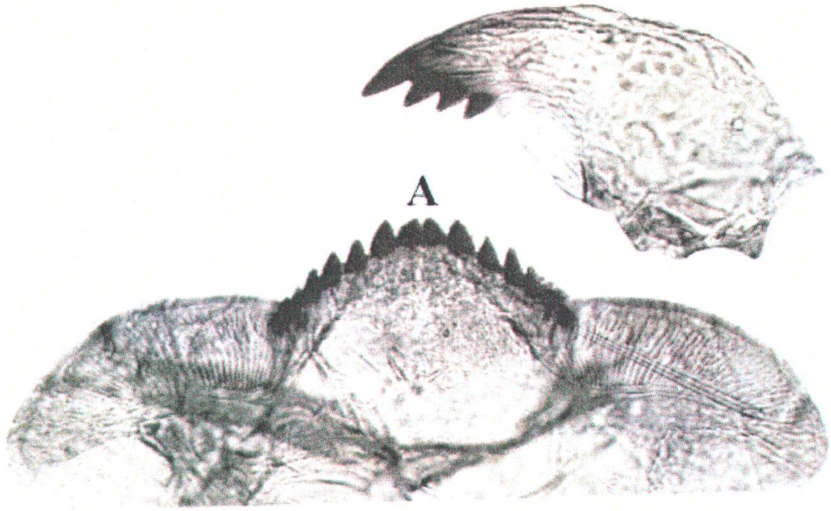
In eutrophic (10) and/or small lakes (4).

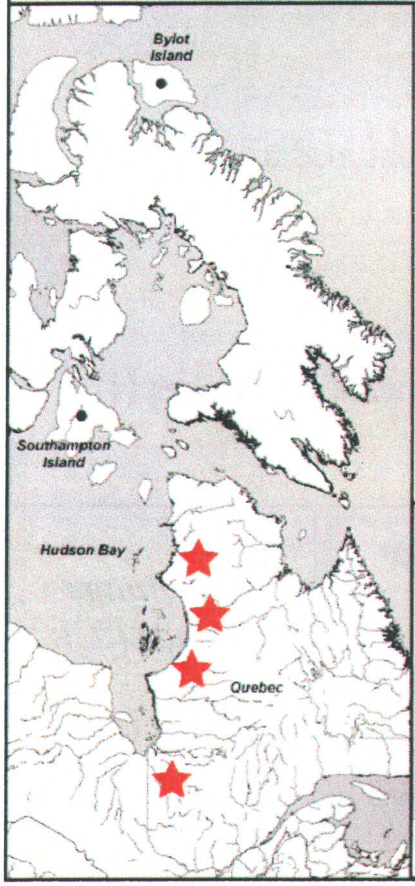


Temperature optimum (°C):

16.1

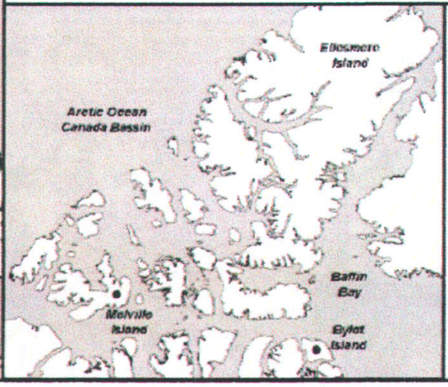
Genera: Endochironomus albipennis
Tribe: Chironominae, Chironomini





Description:
Named following Wiederholm (1983) *fig.* 10.24
First two median are close together (A).

Ecology:
Moderate to eutrophic lakes (10), on vegetation (4).

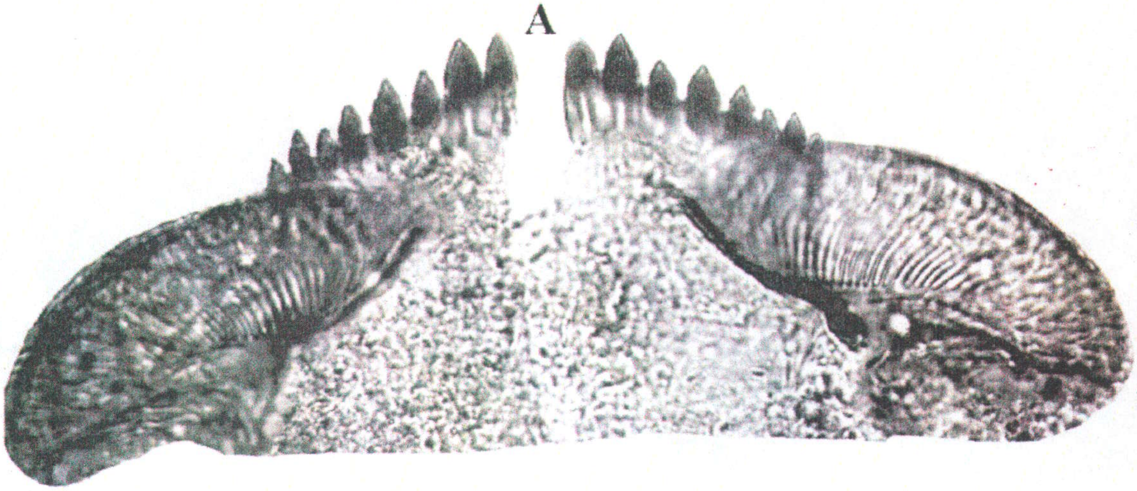


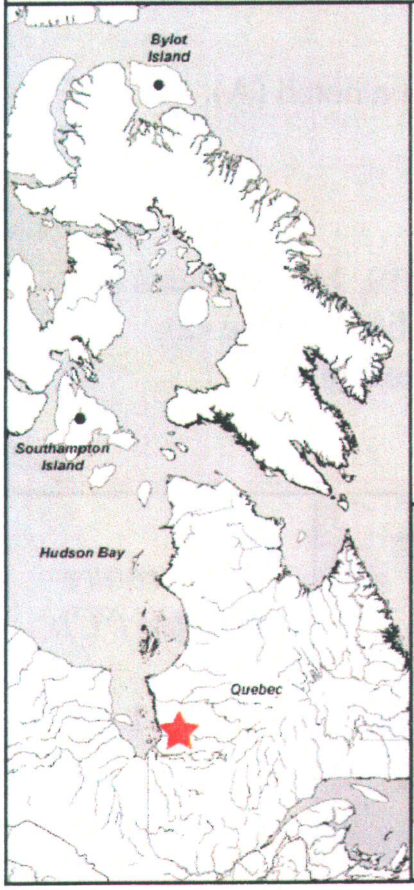
Temperature optimum (°C):

13.2

The visual guide
to subfossil
chironomid analysis

Genera: Endochironomus impar
Tribe: Chironominae, Chironomini

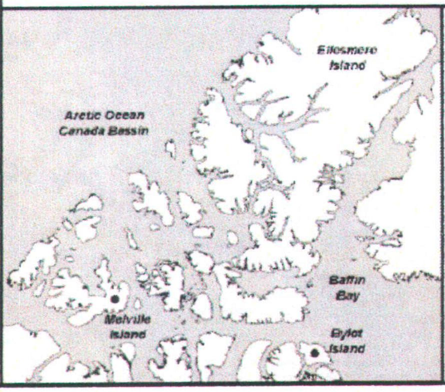




Description:

Named following Wiederholm (1983)
fig. 10.26B.
Four Median (A).
Same as Endochironomus dispar ?

Ecology:

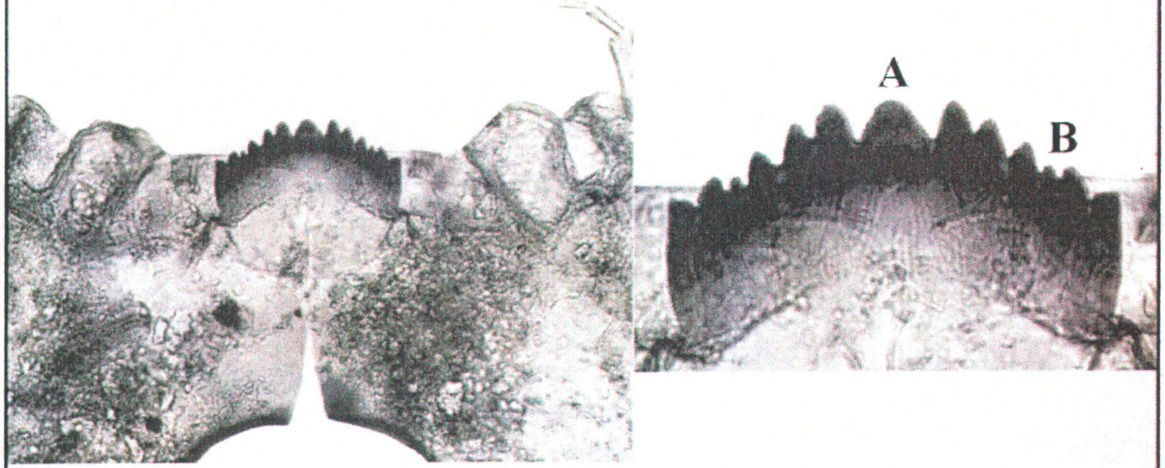


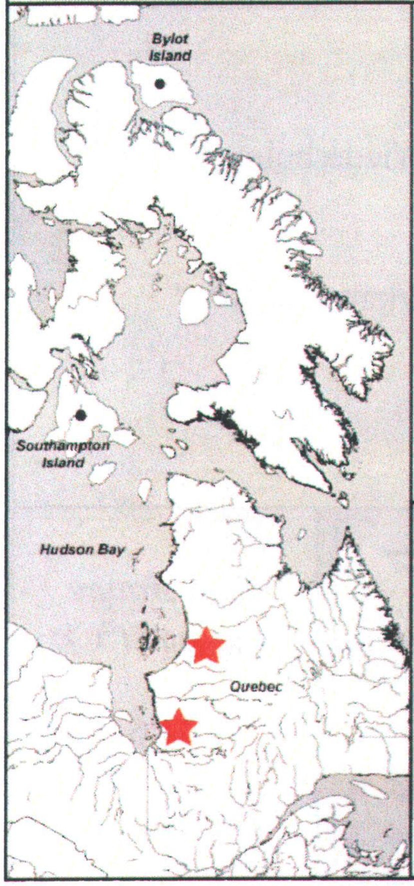
Temperature optimum (°C):

28.6

The visual guide to subfossil chironomid analysis

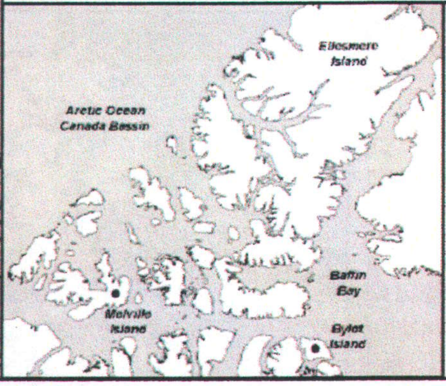
Genera: Glyptotendipes
Tribe: Chironominae, Chironomini





Description:
Round median with a notch (A), 4th lateral smaller (B)

Ecology:
In eutrophic lakes (10, 14), on plants (4, 10), exclusively in littoral zone (2), decrease with deforestation (14).

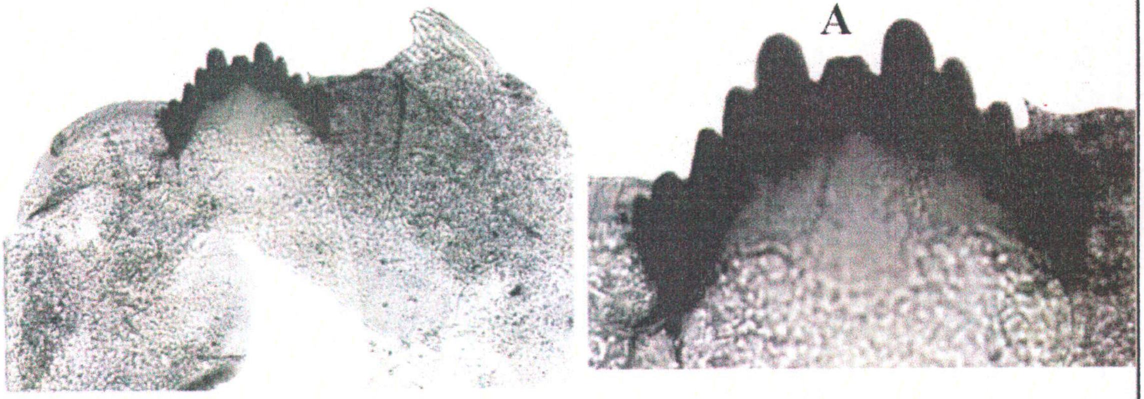


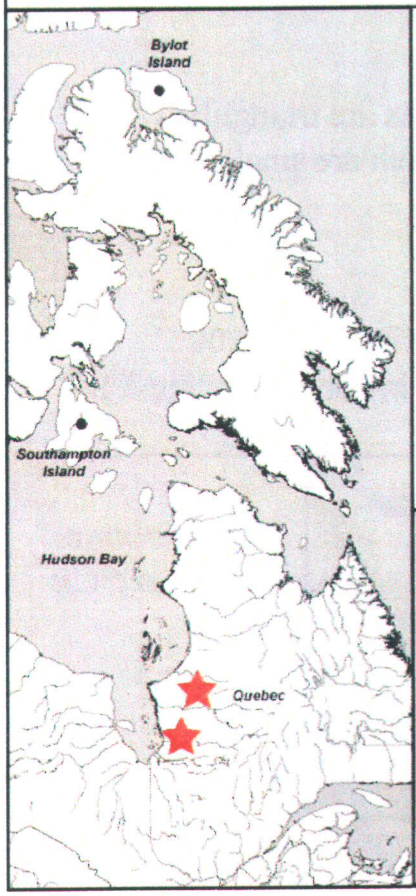
Temperature optimum (°C):

17.1

The visual guide
to subfossil
chironomid analysis

Genera: Glyptotendipes type 2
Tribe: Chironominae, Chironomini

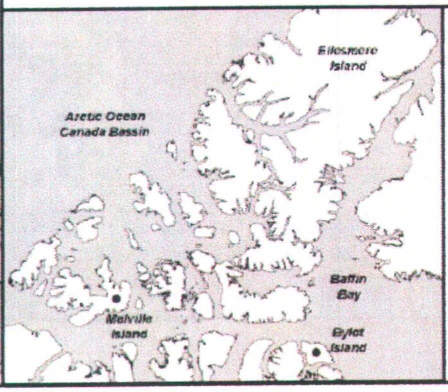




Description:

Named following Wiederholm (1983) *fig.*10.30.
Glyptotendipes II (severini ?)
Three median elevated with the middle tooth smaller (A) and a dark mentum.

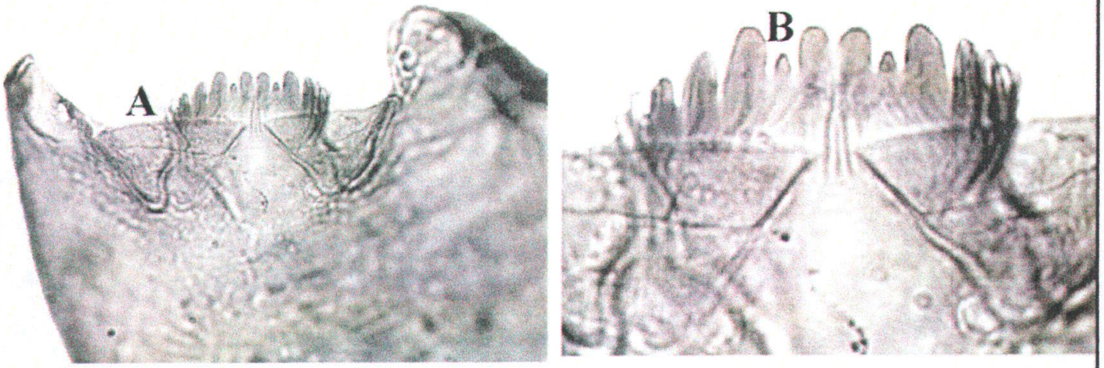
Ecology:

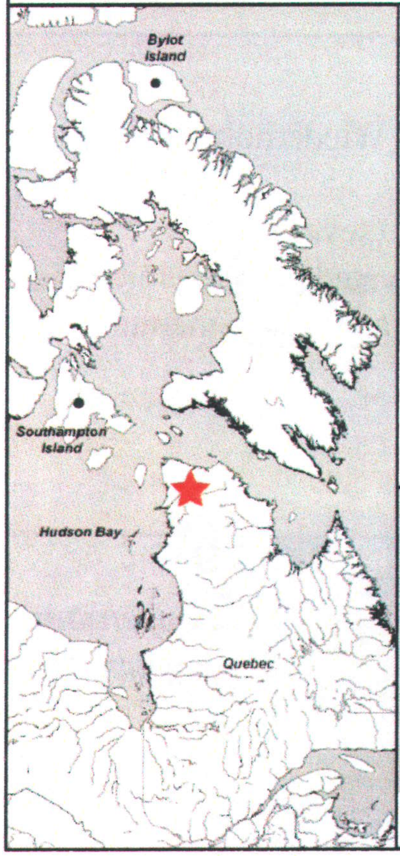


Temperature optimum (°C):

34.7

Genera: Lauterborniella
Tribe: Chironominae, Chironomini



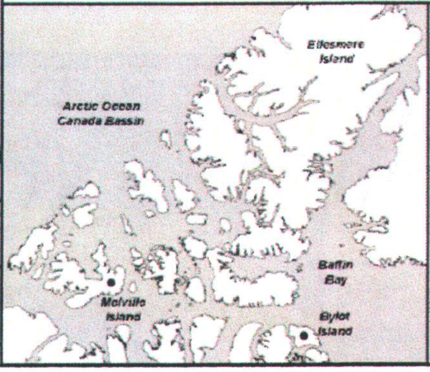


Description:

Ventromental plates are triangular (A).
The first lateral teeth are smaller (B).

Ecology:

Among vegetation in ponds (10).
Note: Found only in one lake in the T.S.



Temperature optimum (°C):

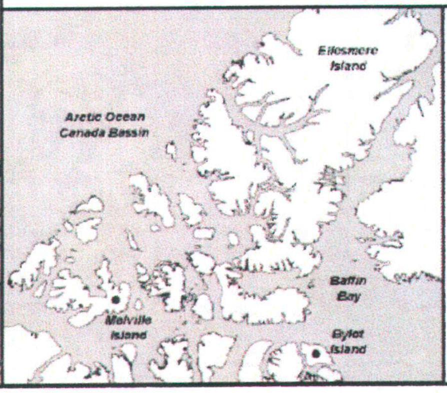
n.a

The visual guide
to subfossil
chironomid analysis

Genera: Microtendipes
Tribe: Chironominae, Chironomini

Description:
Second lateral and third are fused. The second is smaller (A). The median are often paler (B) than other teeth.

Ecology:
In warm and humic waters (5), small, shallow lakes (9), low to mid-elevation (18).

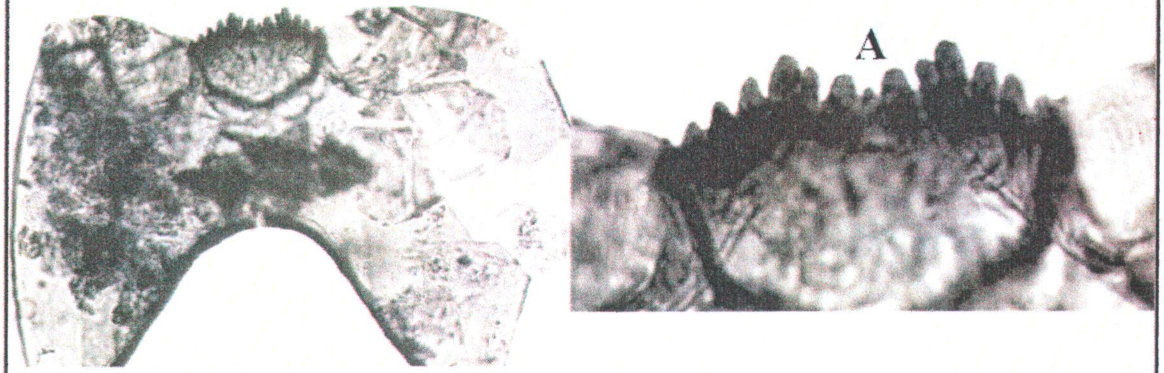


Temperature optimum (°C):

12.6

The visual guide
to subfossil
chironomid analysis

Genera: Microtendipes rydalensis
Tribe: Chironominae, Chironomini

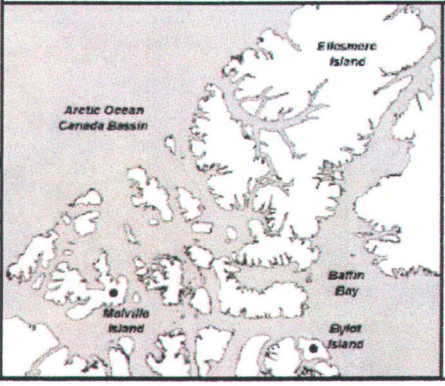


Description:

Three median teeth (A).

Ecology:

Not included in the T.S.

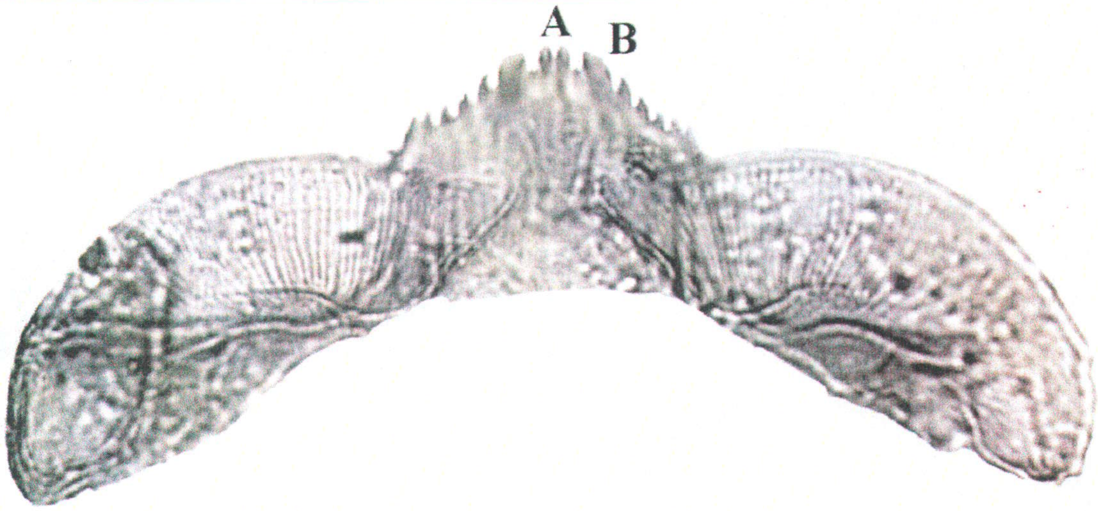


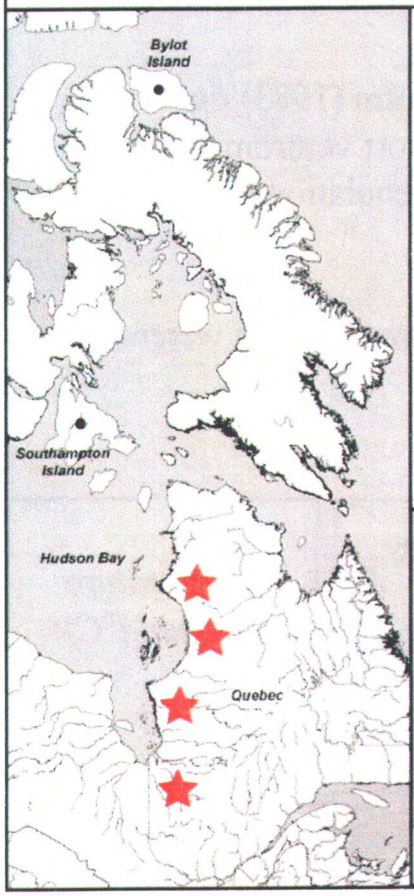
Temperature optimum (°C):

n.a

The visual guide to subfossil chironomid analysis

Genera: Pagastiella
Tribe: Chironominae, Chironomini



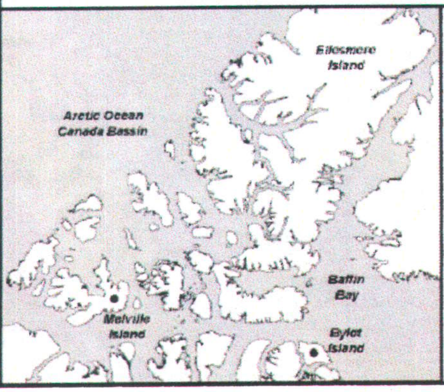


Description:

Two thin median (A) followed by small lateral. The third lateral is wider (B).

Ecology:

In littoral zone (10), oligotrophic (34), acid-sensitive (35).

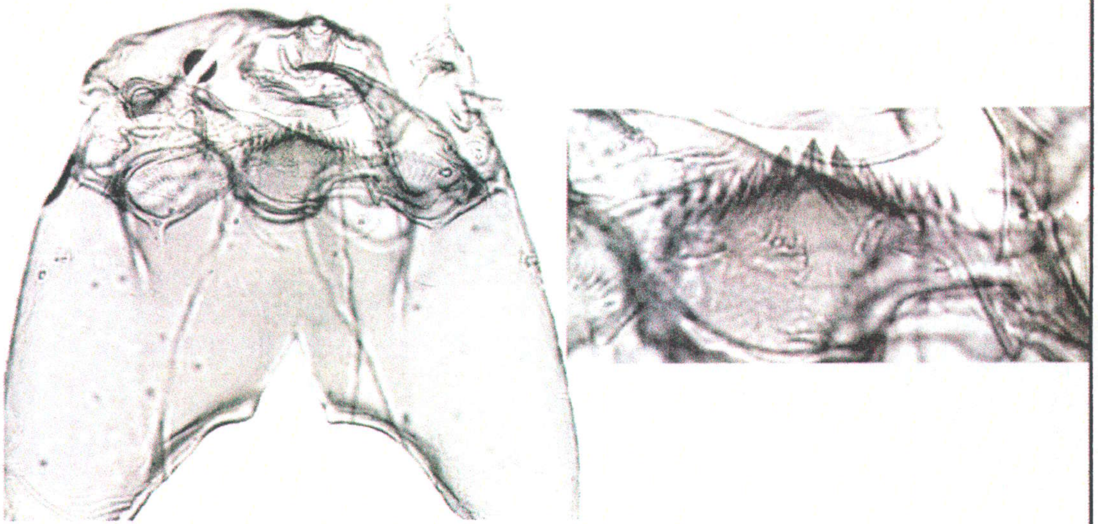


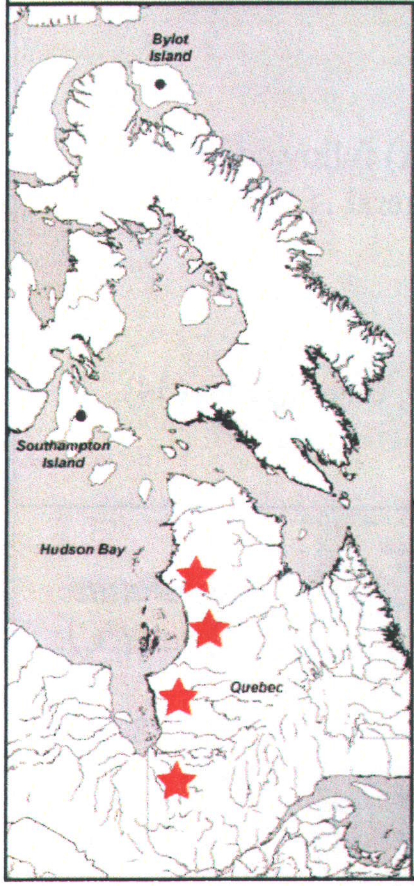
Temperature optimum (°C):

17.8

The visual guide
to subfossil
chironomid analysis

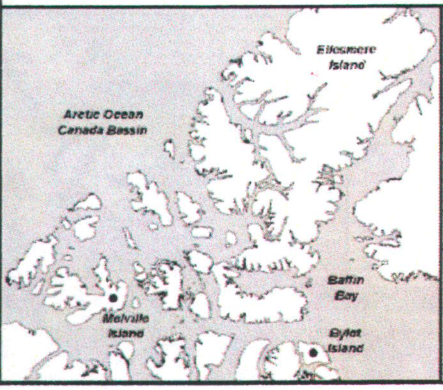
Genera: Parachironomus
Tribe: Chironominae, Chironomini





Description:
Type C in Wiederholm (1983) *fig.* 10.51
Triangular teeth, short ventromental plates with large crenulations.

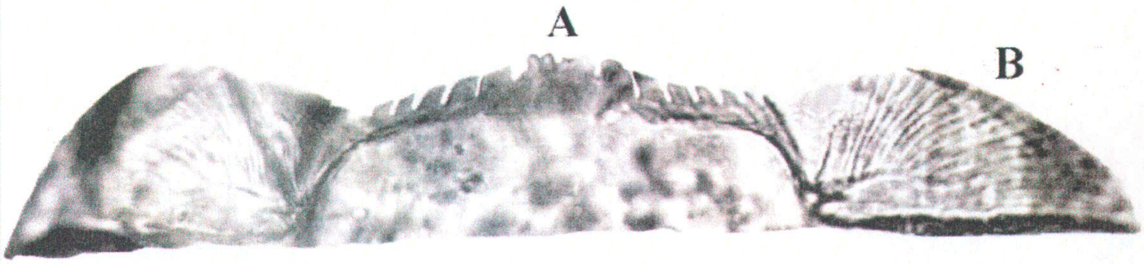
Ecology:
Ponds, lakes and slow flowing waters (4).

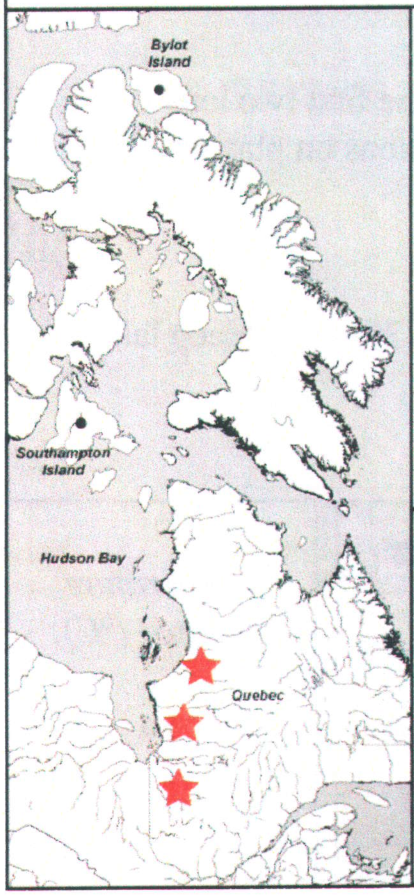


Temperature optimum (°C):

5.7

Genera: Paracladopelma
Tribe: Chironominae, Chironomini



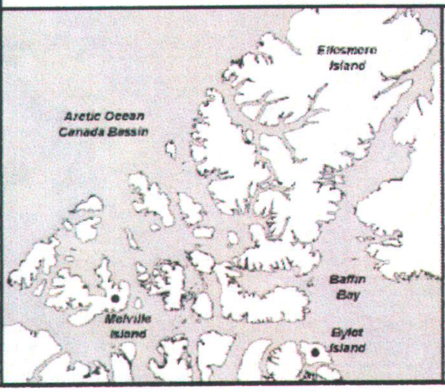


Description:

Square teeth (A), ventromental plates with wide crenulations (B).

Ecology:

In oligotrophic (8, 32) and profundal (32) lakes.

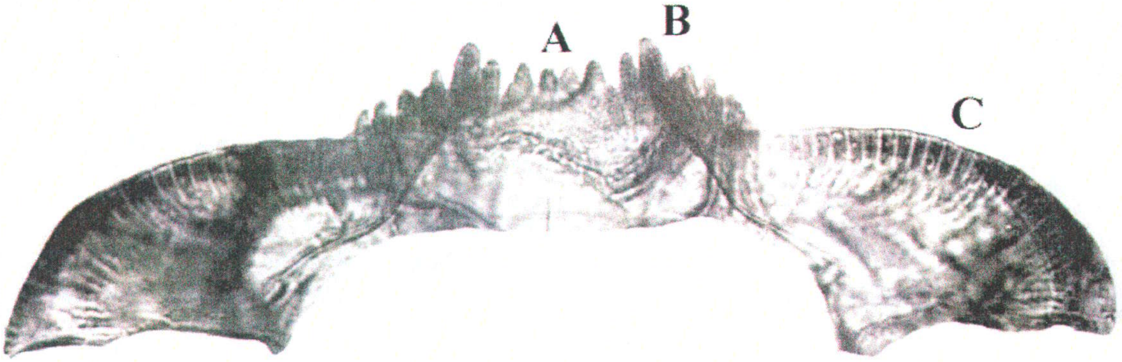


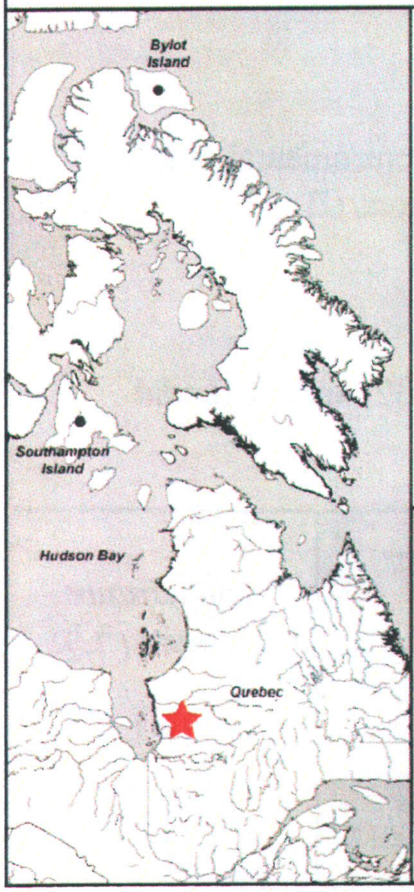
Temperature optimum (°C):

18.1

The visual guide to subfossil chironomid analysis

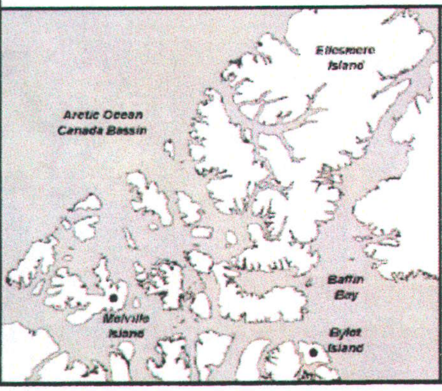
Genera: Paratendipes albimanus
Tribe: Chironominae, Chironomini





Description:
Four median (A), the first two lateral are fused (B). Crenulations on plates well defined (C).

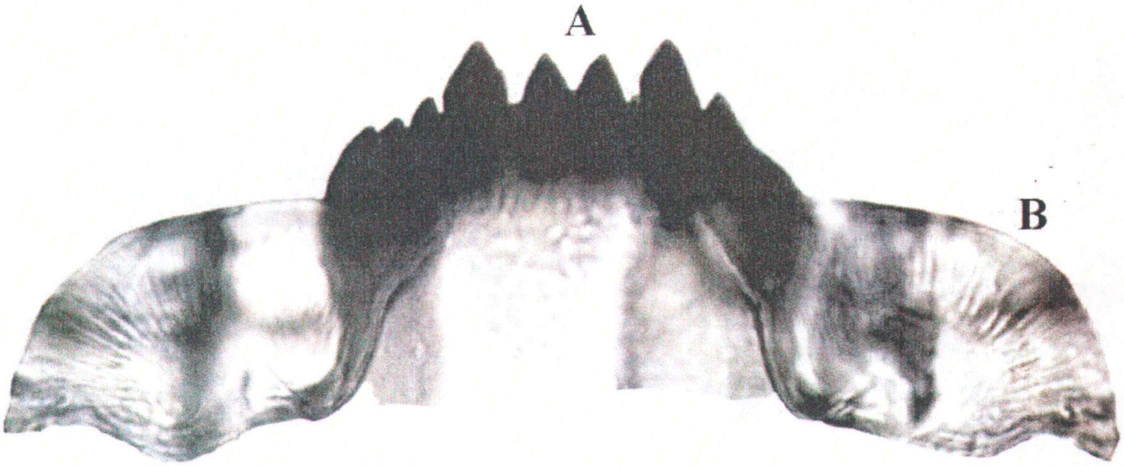
Ecology:
Stream detritivore (36), large deep lakes with high pH (37).

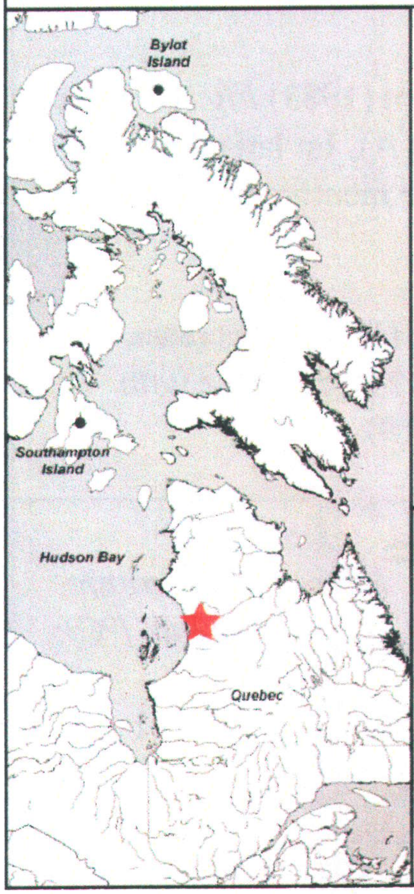


Temperature optimum (°C):

n.a

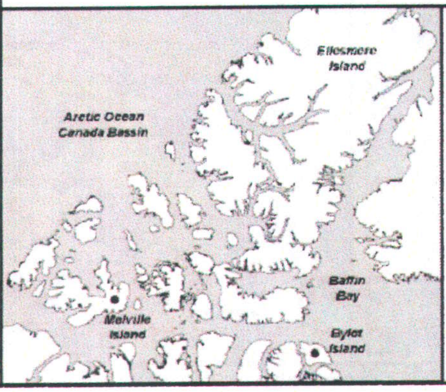
Genera: Phaenopsectra
Tribe: Chironominae, Chironomini





Description:
Four median teeth prominent (A), dark mentum, small crenulation on the margin of the ventromental plates (B).

Ecology:
Either in streams (10) or in the profundal of cold lakes (4).

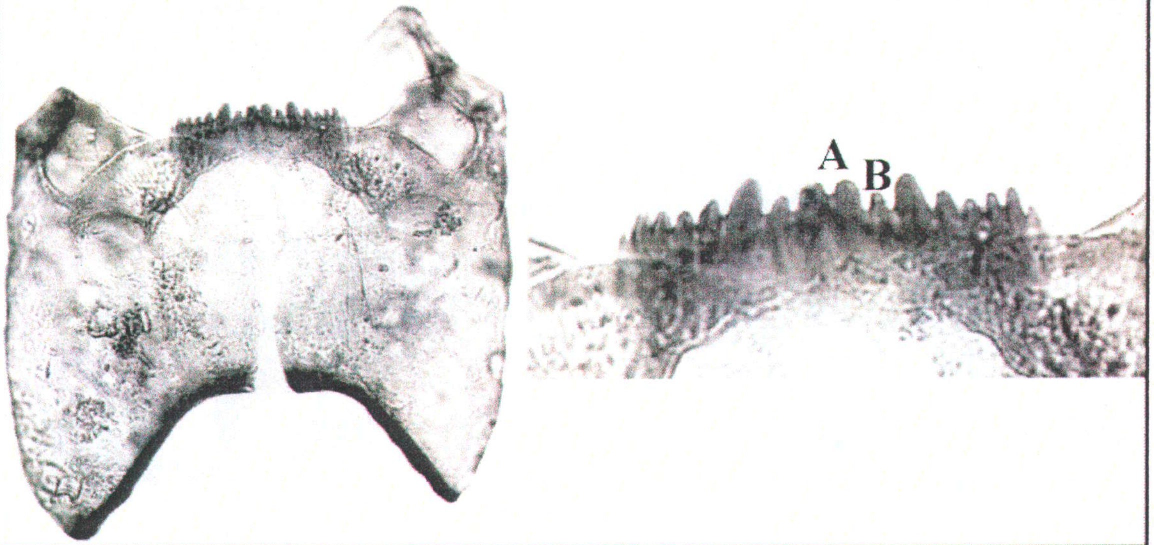


Temperature optimum (°C):

n.a

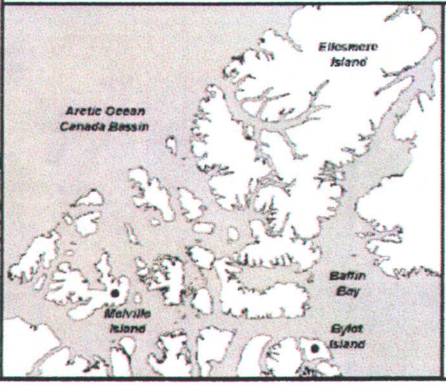
The visual guide to subfossil chironomid analysis

Genera: Polypedilum nubeculosum
Tribe: Chironominae, Chironomini



Description:
Follows Wiederholm (1983) *Fig.* 10.59. Two median fused (A), 1st lateral small (B), the teeth on the mentum are round.

Ecology:
In eutrophic waters (13, 15), increase with deforestation (14), decrease with oxygen depletion (19).

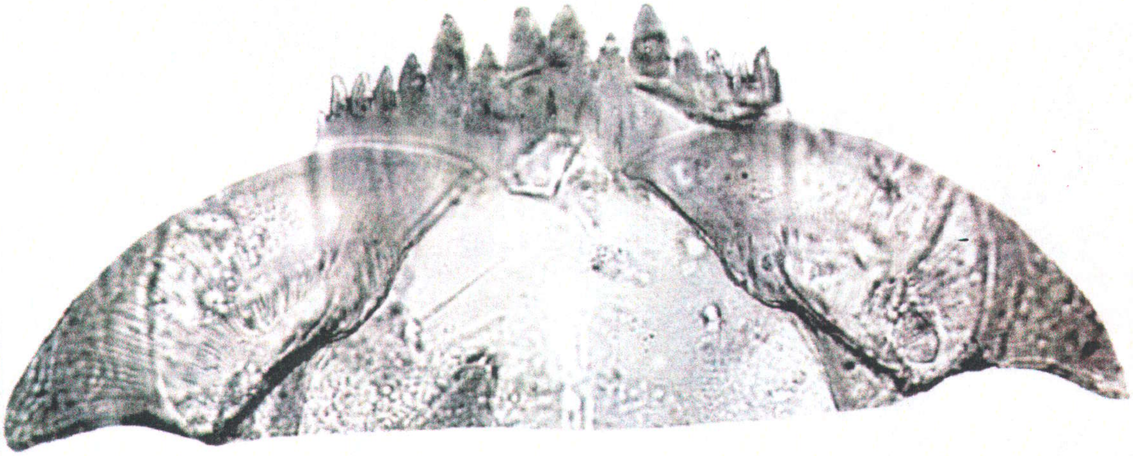


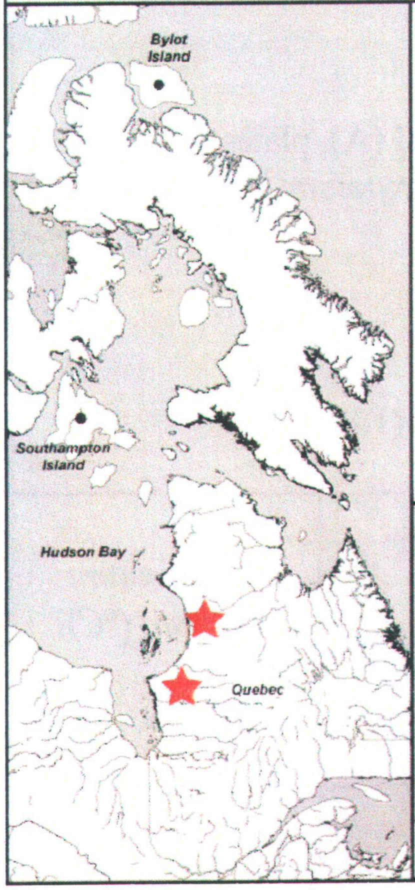
Temperature optimum (°C):

15.1

The visual guide
to subfossil
chironomid analysis

Genera: Polypedilum type IIIc
Tribe: Chironominae, Chironomini

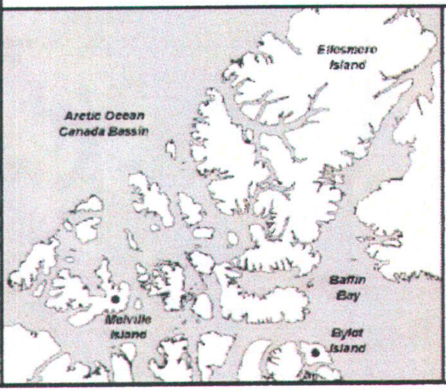




Description:

Follows Wiederholm (1983) *Fig.* 10.61c. Teeth on the mentum are triangular not round like P. nebeculosum.

Ecology:

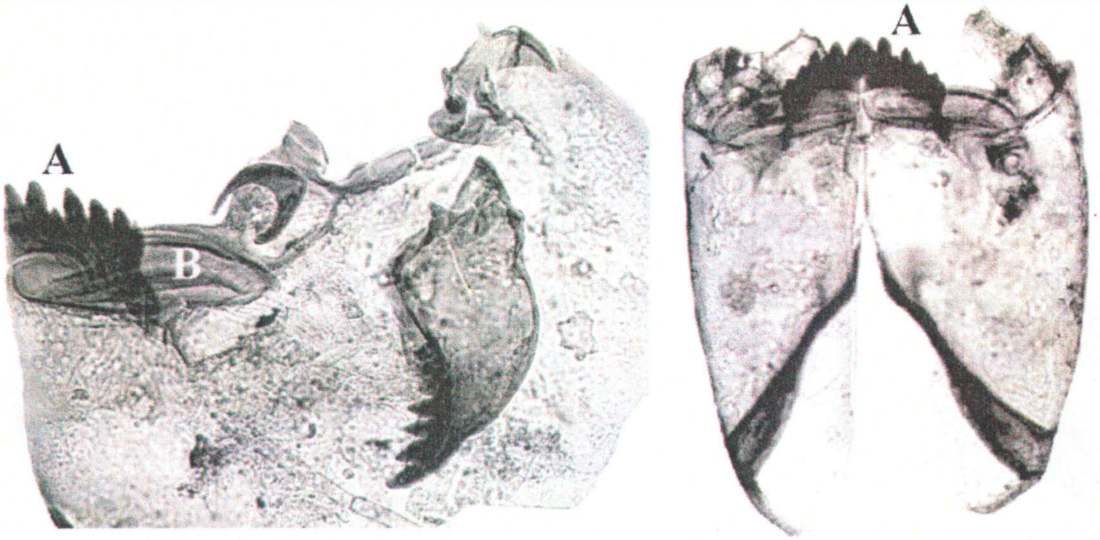


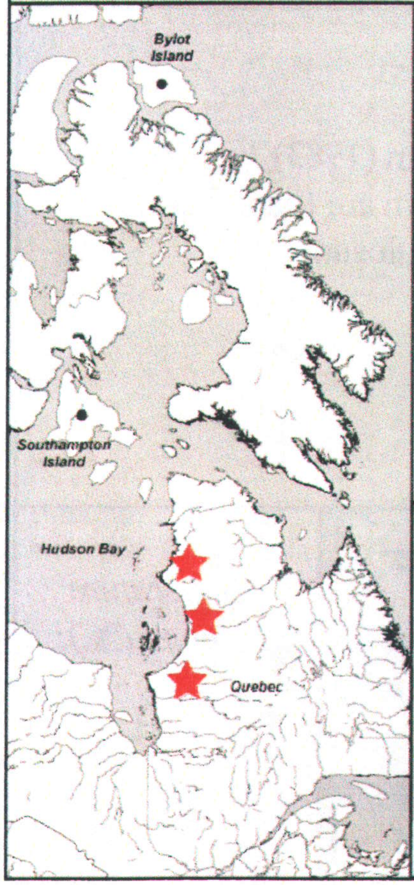
Temperature optimum (°C):

15.4

The visual guide
to subfossil
chironomid analysis

Genera: Pseudochironomus
Tribe: Chironominae, Chironomini



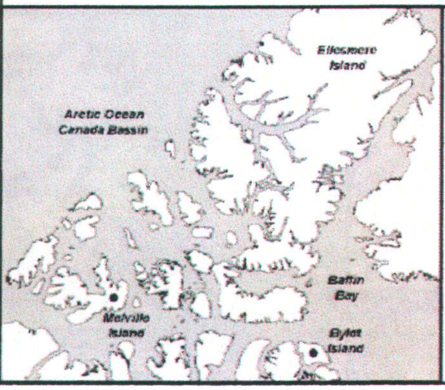


Description:

Small second lateral (A), plates with a similar shape as Tanytarsini but wider (B).

Ecology:

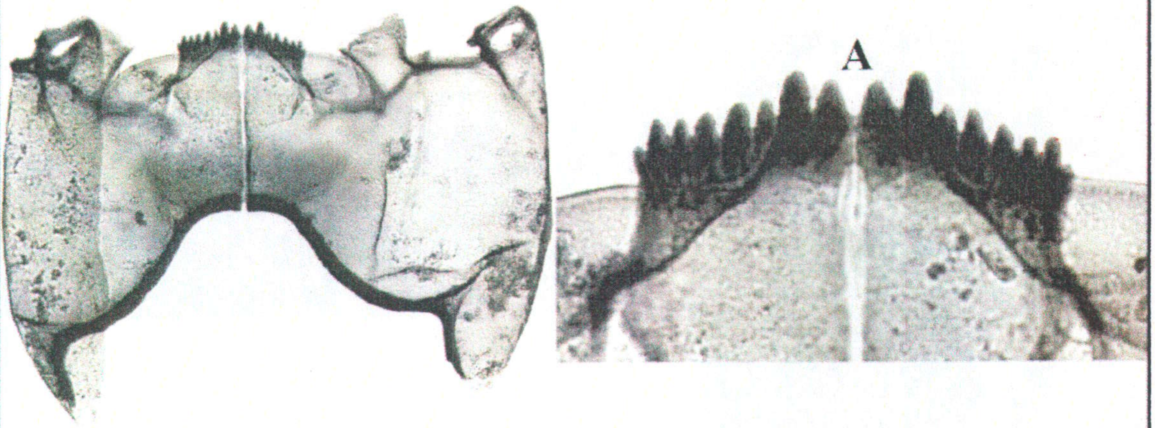
On sandy substrate (10).

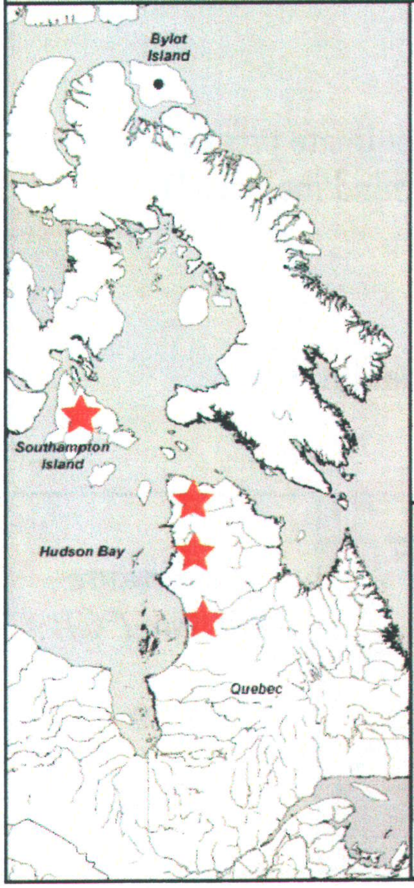


Temperature optimum (°C):

5.3

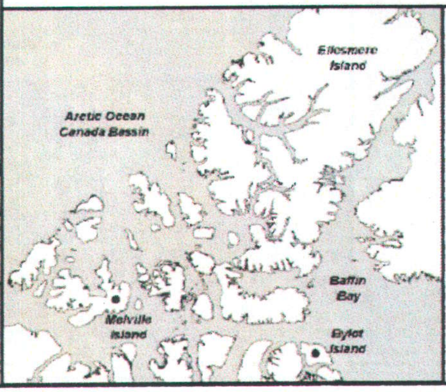
Genera: Sergentia coracina-type
Tribe: Chironominae, Chironomini





Description:
Four median (A), the ventromental plate starts at the fourth median, the crenulations are weaker than on S. longiventris.

Ecology:
Mesotrophic (8), profundal (20).

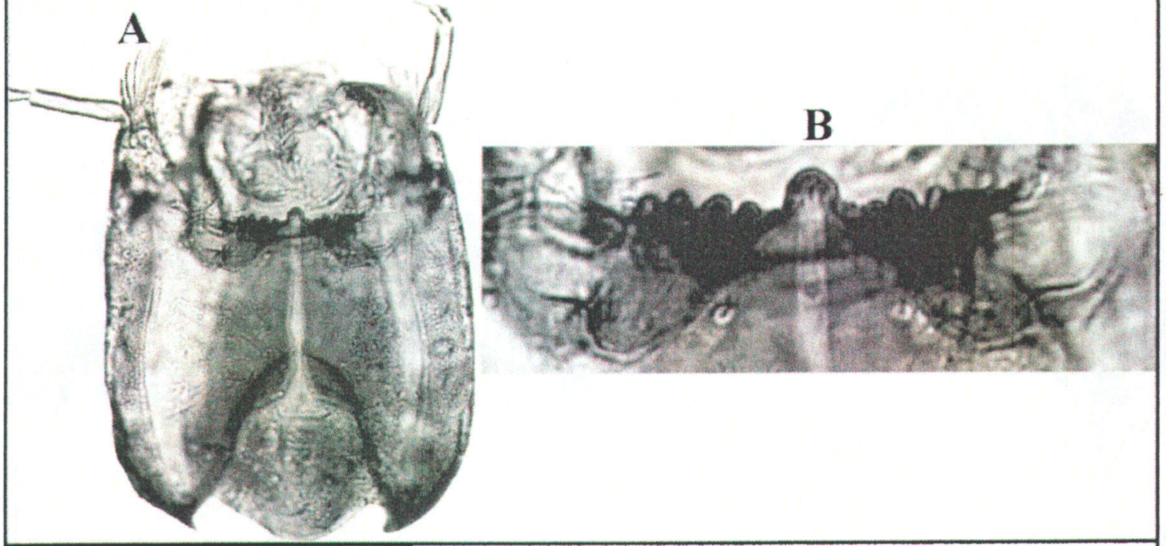


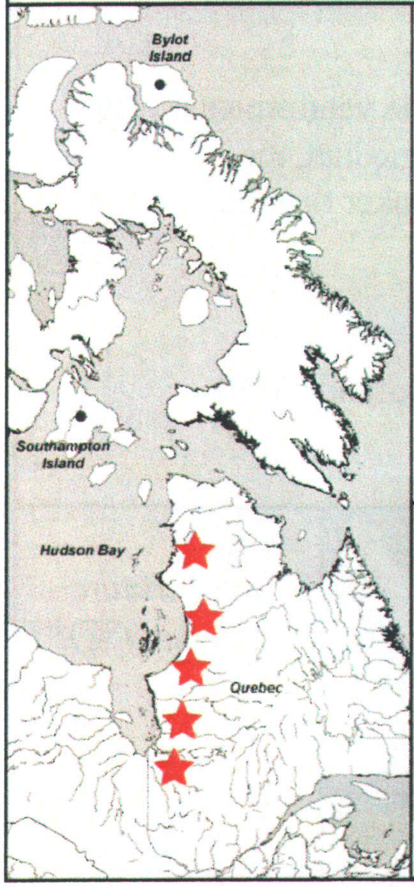
Temperature optimum (°C):

1.1

The visual guide to subfossil chironomid analysis

Genera: Stempellina
Tribe: Chironominae, Chironomini



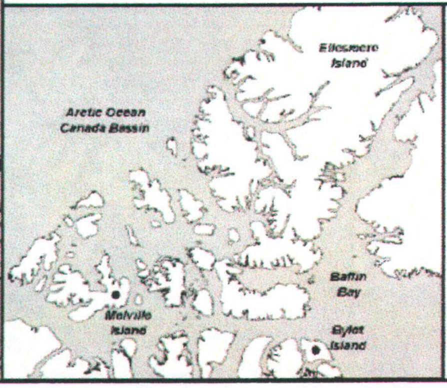


Description:

Many projections (palmate process) on each antenna (A), round median (B).

Ecology:

Lotic and lentic situations (10).

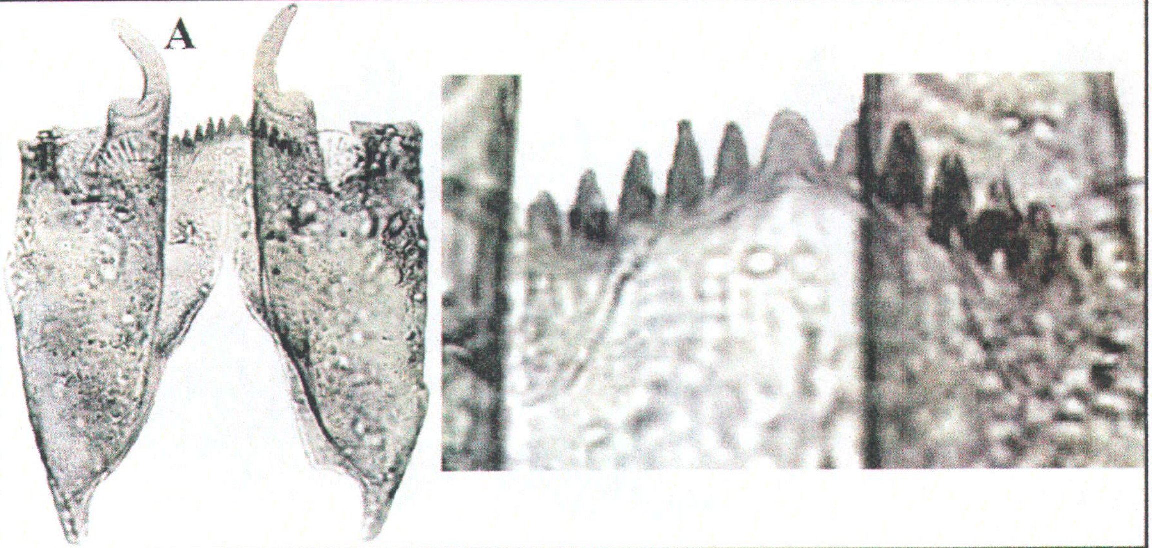


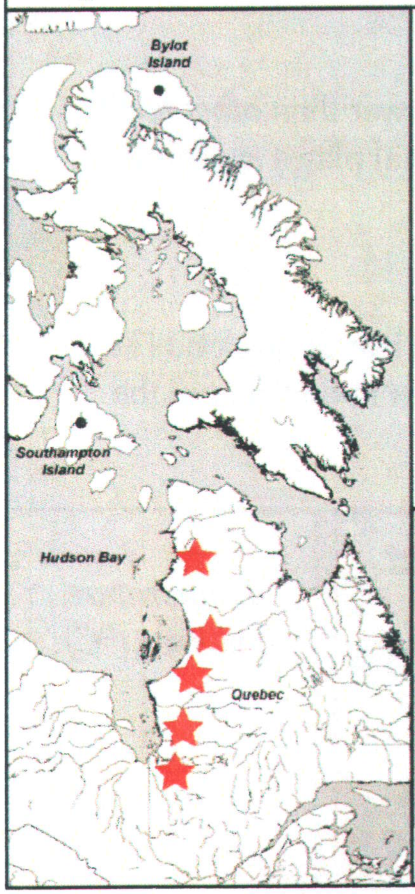
Temperature optimum (°C):

17.9

The visual guide to subfossil chironomid analysis

Genera: Stempellinella
Tribe: Chironominae, Chironomini



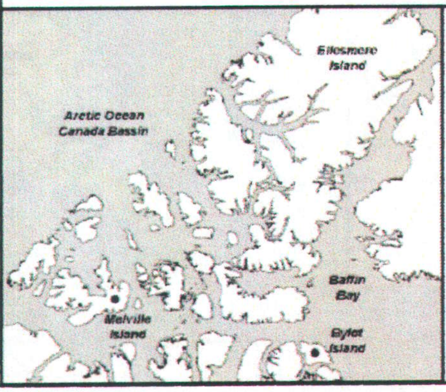


Description:

Long spur on each antenna (A).

Ecology:

Spring, streams and river but also in lakes (10).

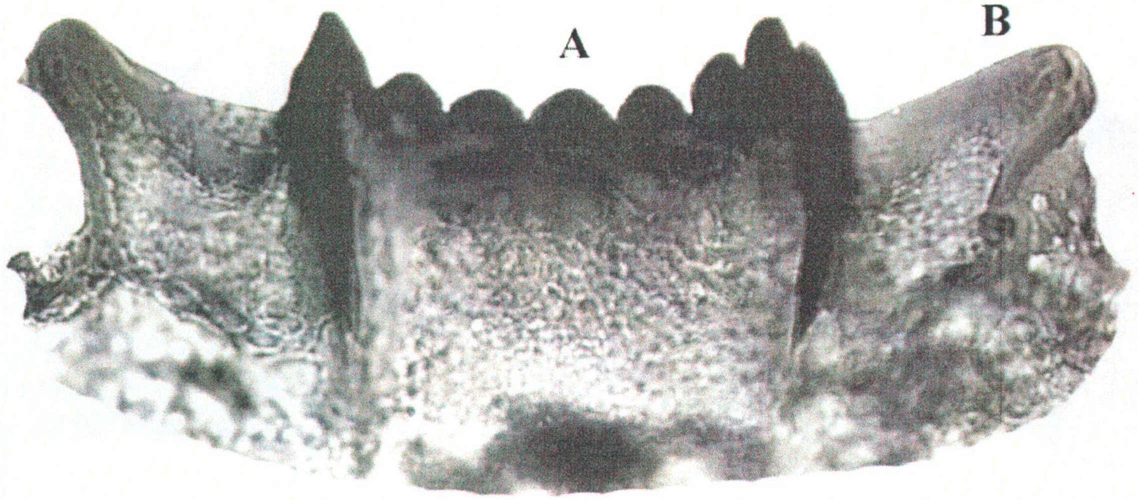


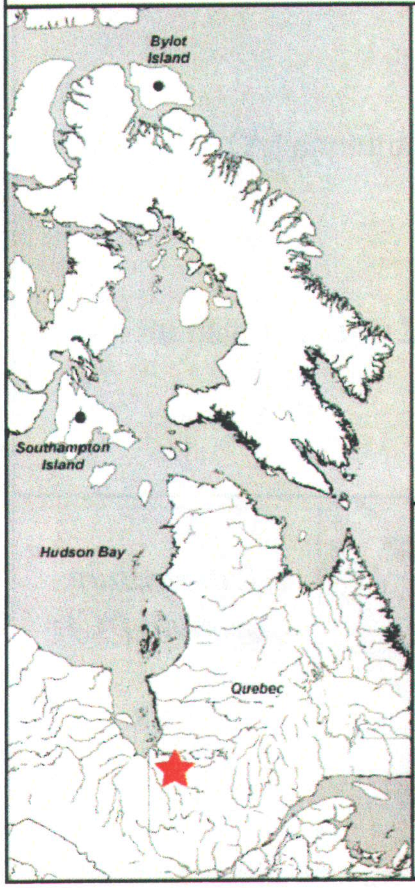
Temperature optimum (°C):

13.8

The visual guide to subfossil chironomid analysis

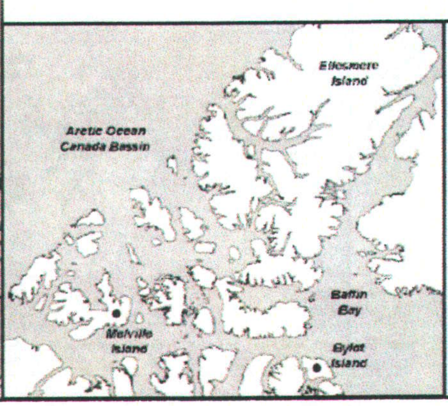
Genera: Stenochironomus
Tribe: Chironominae, Chironomini





Description:
Median teeth are lower than other teeth (A), the ventromental plates are large (B).

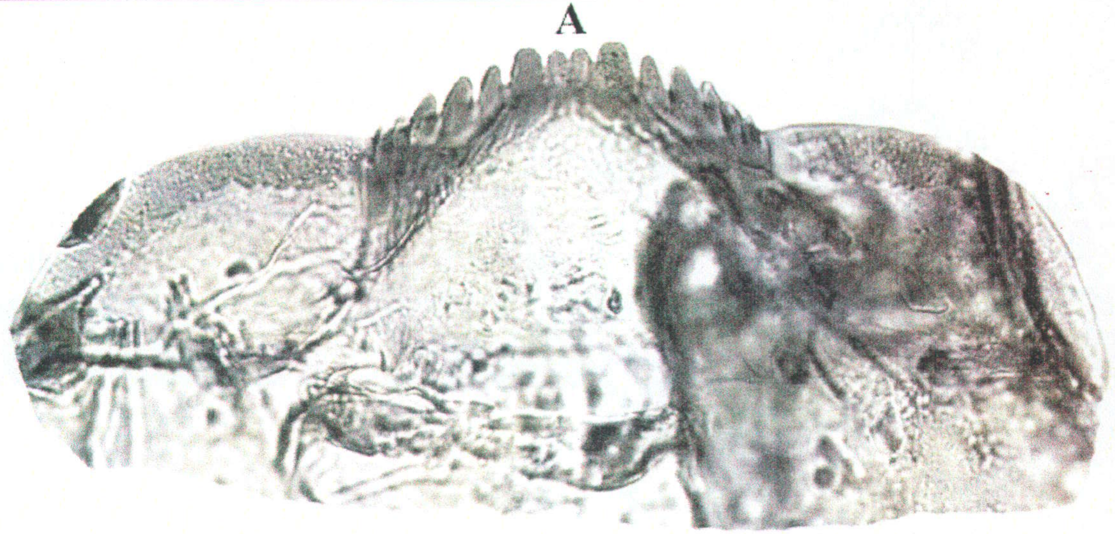
Ecology:
In dead submerged leaves or wood (10).
Note: One specimen in one lake in the T.S.

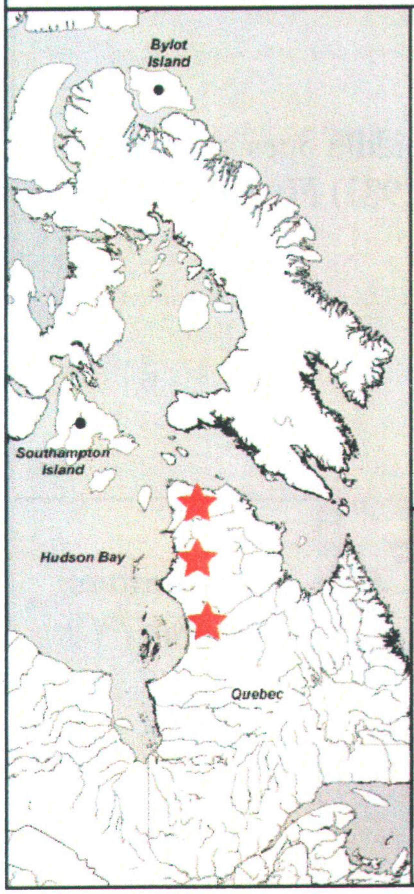


Temperature optimum (°C):

n.a

Genera: Stictochironomus
Tribe: Chironominae, Chironomini



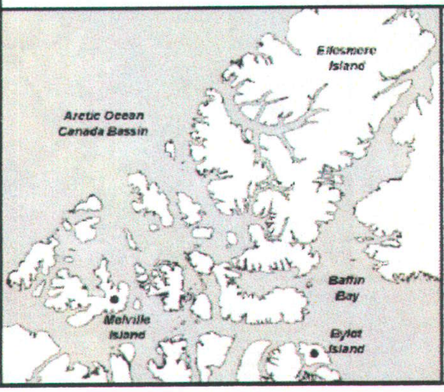


Description:

Four median, the middle ones are small (A).

Ecology:

Profundal taxa (20), sandy sediment of streams, rivers and lakes (10).

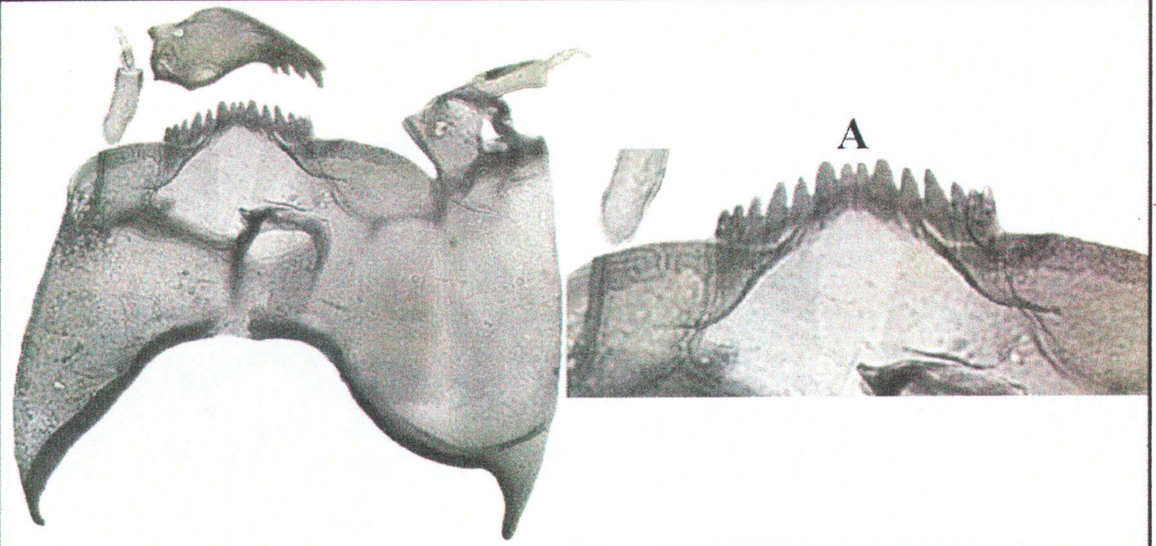


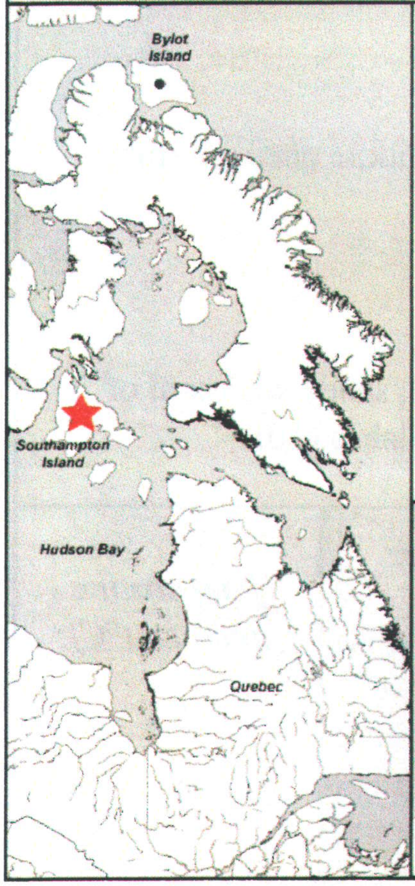
Temperature optimum (°C):

9.4

The visual guide to subfossil chironomid analysis

Genera: Stictochironomus type B
Tribe: Chironominae, Chironomini

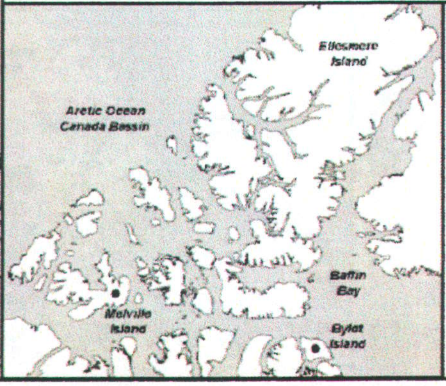




Description:

Four median, the middle ones are small (A). Wiederholm (1983) *Fig.* 10.74 B

Ecology:



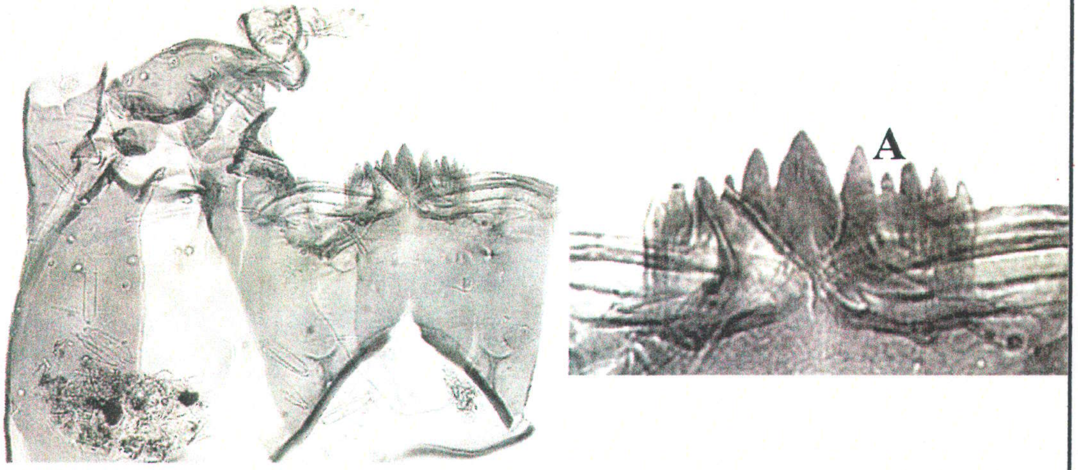
Temperature optimum (°C):

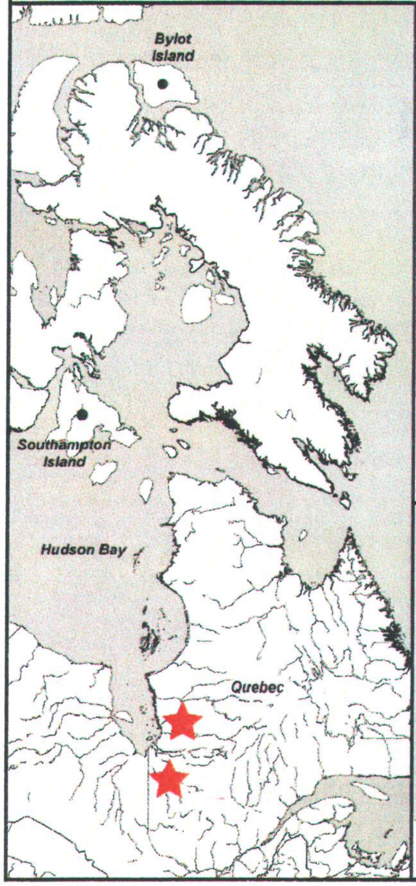
n.a

B.3 Tanytarsini

The visual guide to subfossil chironomid analysis

Genera: Cladotanytarsus mancus-type
Tribe: Chironominae, Tanytarsini



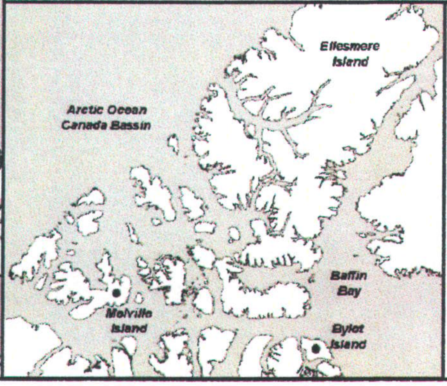


Description:

Second lateral shorter than other teeth (A).

Ecology:

Exclusively littoral (2), in warm and humic waters (4)

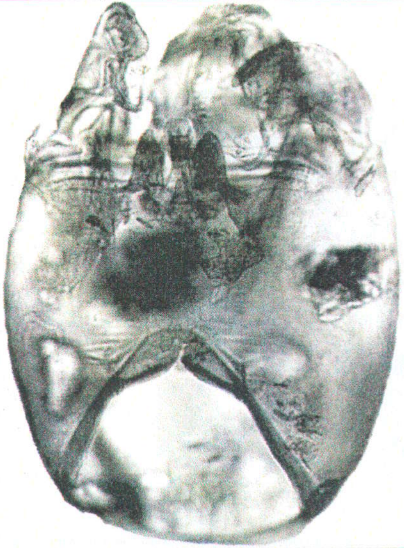


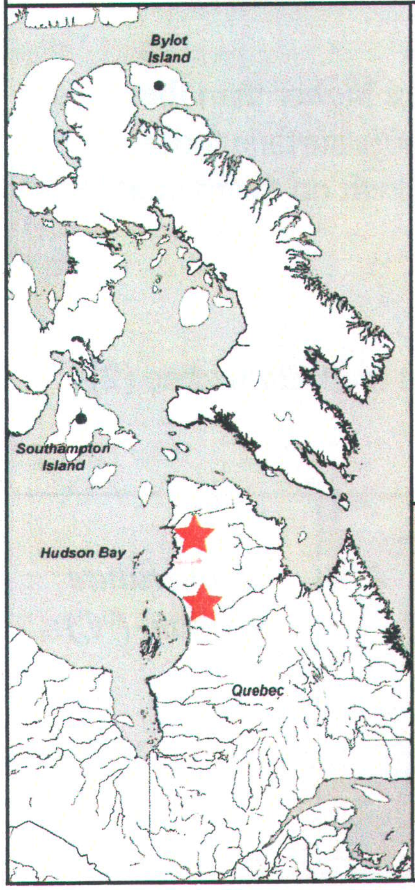
Temperature optimum (°C):

17.9

The visual guide
to subfossil
chironomid analysis

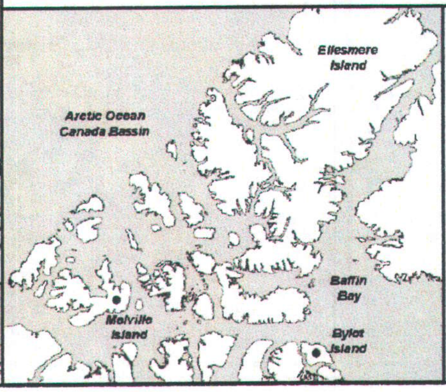
Genera: Corynocera ambigua
Tribe: Chironominae, Tanytarsini





Description:
Three pale teeth on the back and two very dark ones on front.

Ecology:
In shallow tundra lakes (9), oligothrophic, associated with Chara sp. (40).

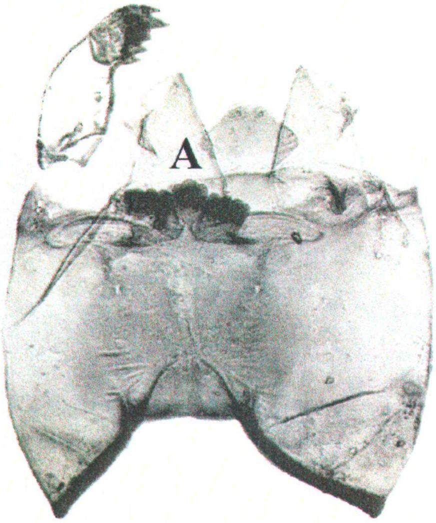


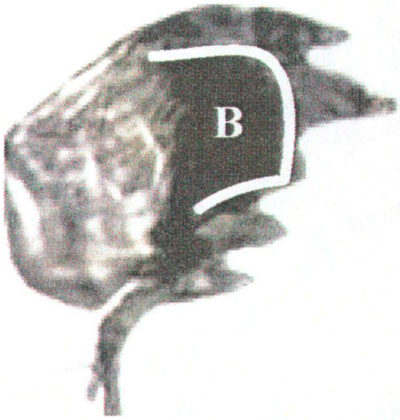
Temperature optimum (°C):

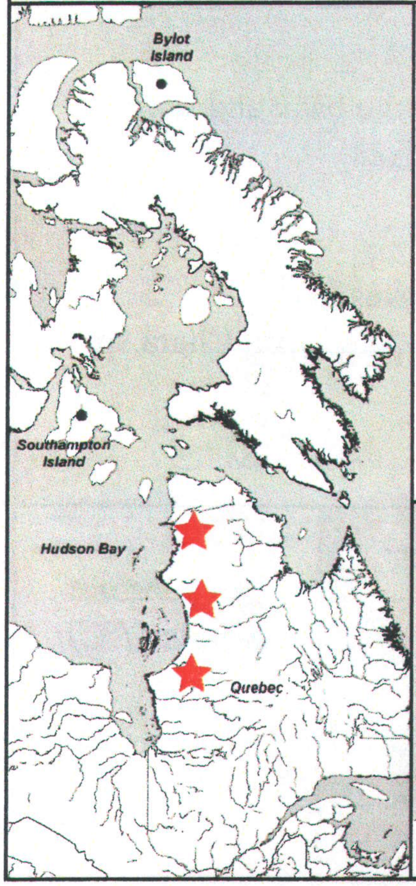
1.2

The visual guide to subfossil chironomid analysis

Genera: Corynocera oliveri
Tribe: Chironominae, Tanytarsini

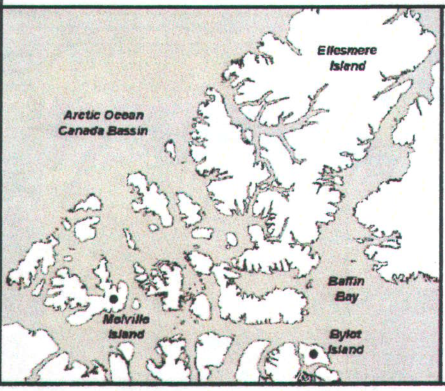






Description:
Median teeth (A) are higher than the lateral teeth. One large surface tooth covering the inner teeth on the mandible (B).

Ecology:
In cold water (5), in the littoral zone (2).

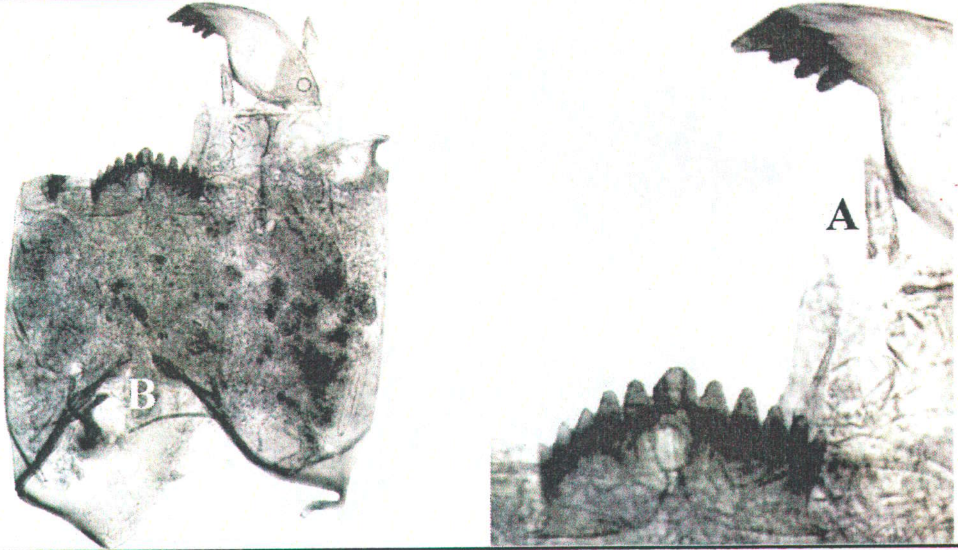


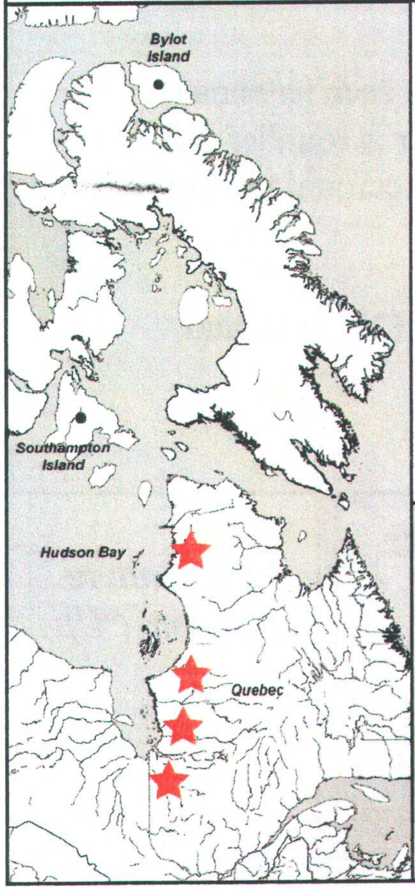
Temperature optimum (°C):

5.9

The visual guide
to subfossil
chironomid analysis

Genera: Micropsectra bidentata-type
Tribe: Chironominae, Tanytarsini



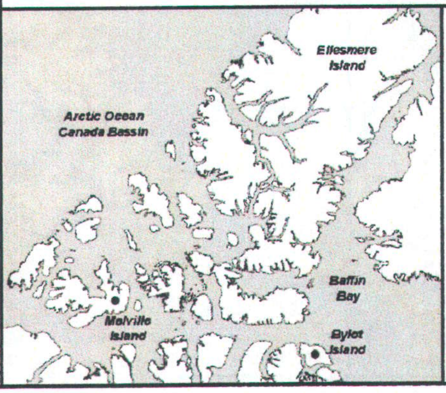


Description:

Long spur on each antenna (A). The spur is wider than on T. chinyensis. Large occipital plates (B).

Ecology:

In streams (41), temporary pools (42).

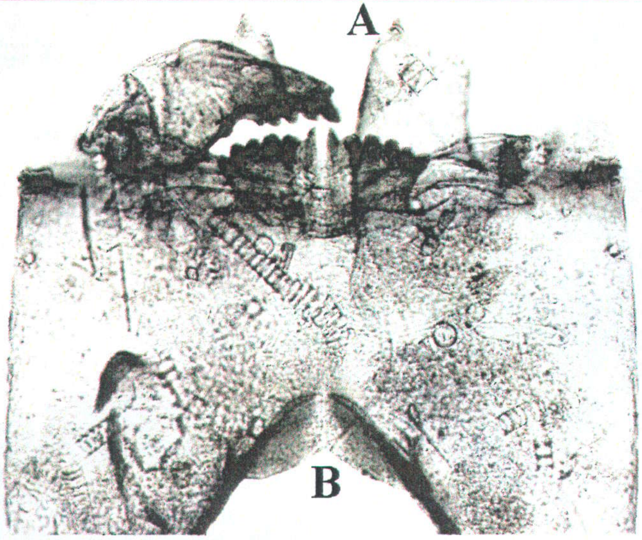


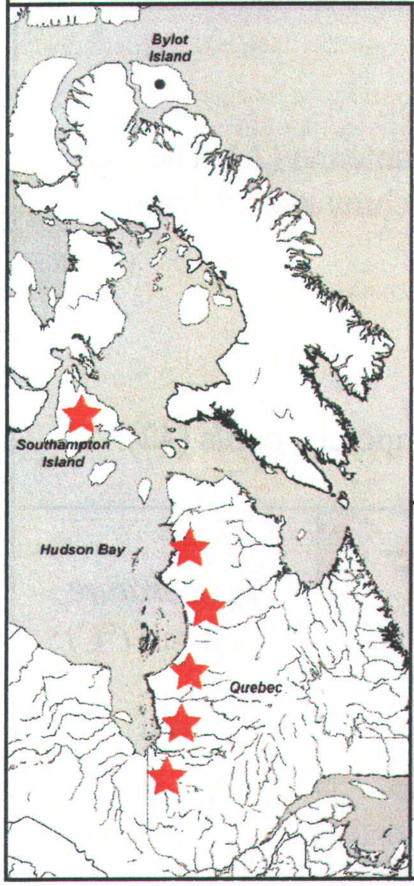
Temperature optimum (°C):

9.9

The visual guide to subfossil chironomid analysis

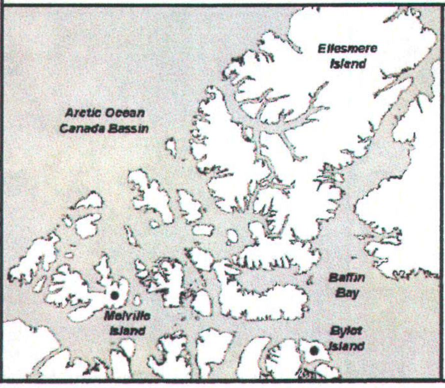
Genera: Micropsectra insignilobus-type
Tribe: Chironominae, Tanytarsini





Description:
Short sharp spur on each antenna (A). One side of the spur is rounder than on M. radialis. Large occipital plates (B).

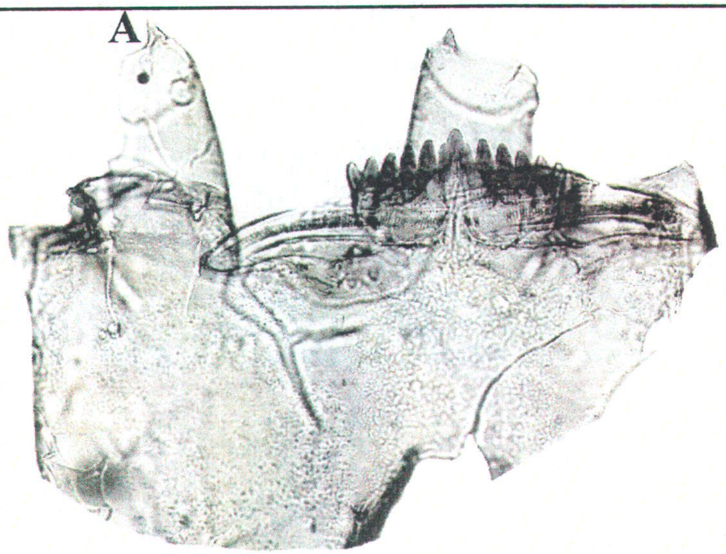
Ecology:
Oligotrophic taxon (21), cold and acidophilic (43).

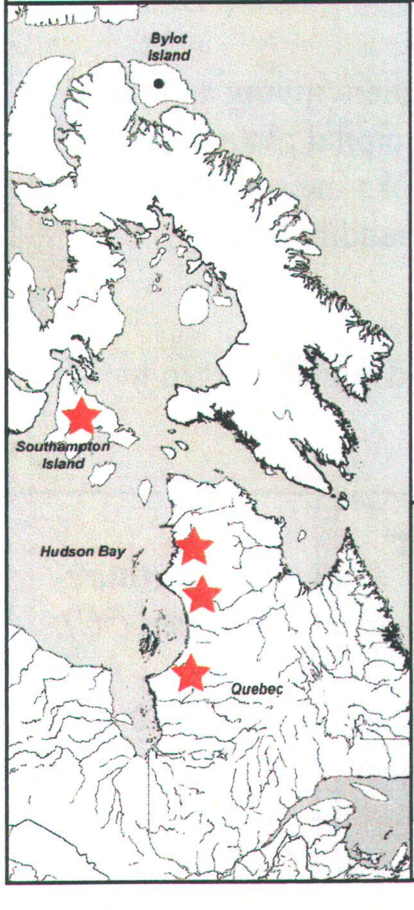


Temperature optimum (°C):

9.5

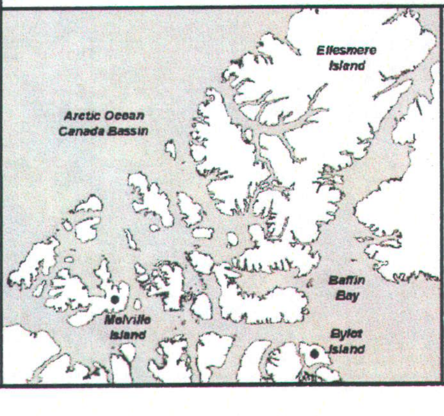
Genera: Micropsectra radialis-type
Tribe: Chironominae, Tanytarsini





Description:
Short and pointy spur on each antenna (A). The spur is sharper than on M. radialis.

Ecology:
High alpine lakes (22), cold indicator (44).

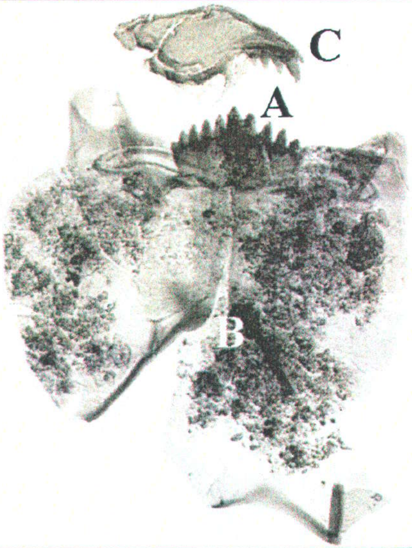


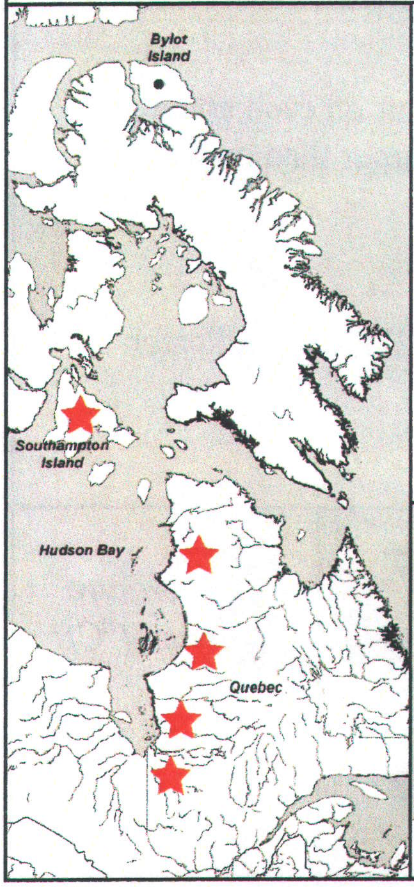
Temperature optimum (°C):

4.4

The visual guide to subfossil chironomid analysis

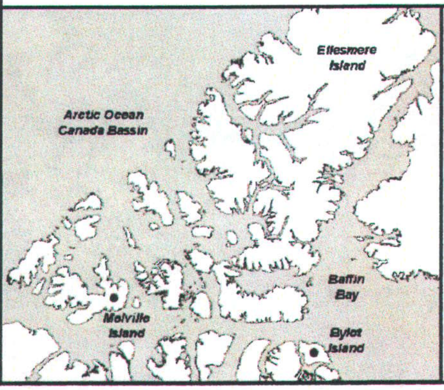
Genera: Paratanytarsus austriacus-type
Tribe: Chironominae, Tanytarsini





Description:
Median teeth prominent giving an arched mentum (A). No occipital plate present, the head capsule looks incised (B). Three inner teeth on the mandibule (C).

Ecology:
Most ubiquitous and abundant taxa in the Alps (45).

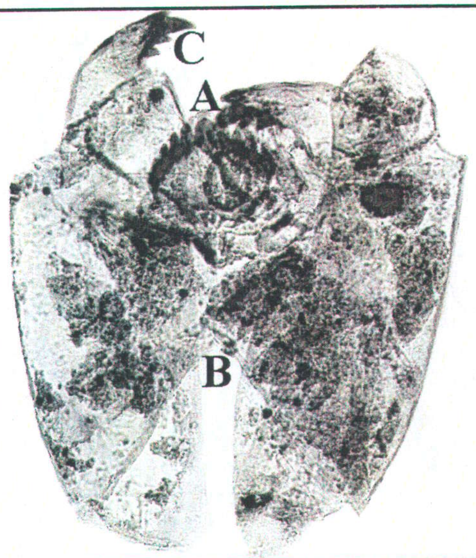


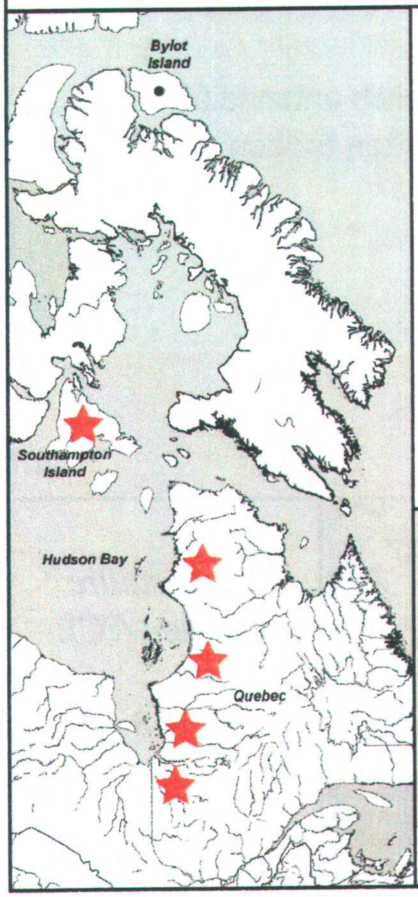
Temperature optimum (°C):

10.0

The visual guide
to subfossil
chironomid analysis

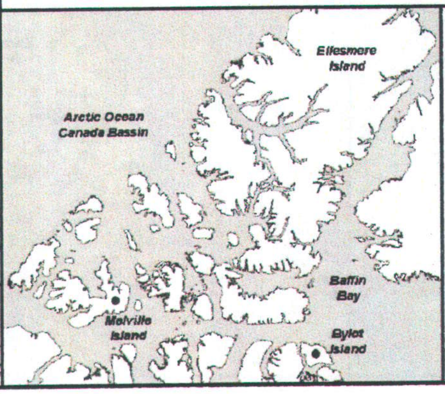
Genera: Paratanytarsus penicillatus-type
Tribe: Chironominae, Tanytarsini





Description:
Median teeth prominent giving an arched mentum (A). No occipital plate present, the head capsule looks incised (B). Two inner teeth on the mandibule (C).

Ecology:
Oligotrophic (21), cool and clean water lakes (46).

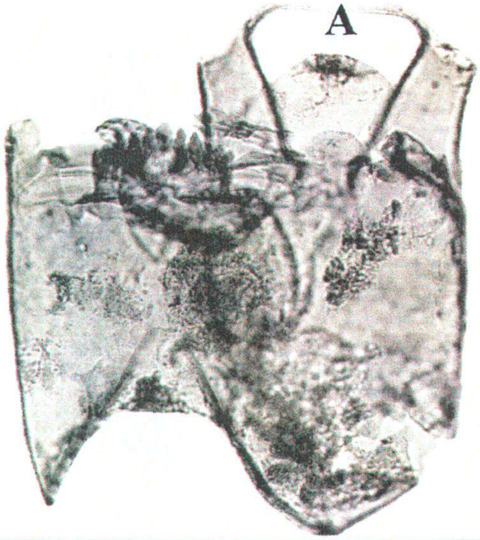


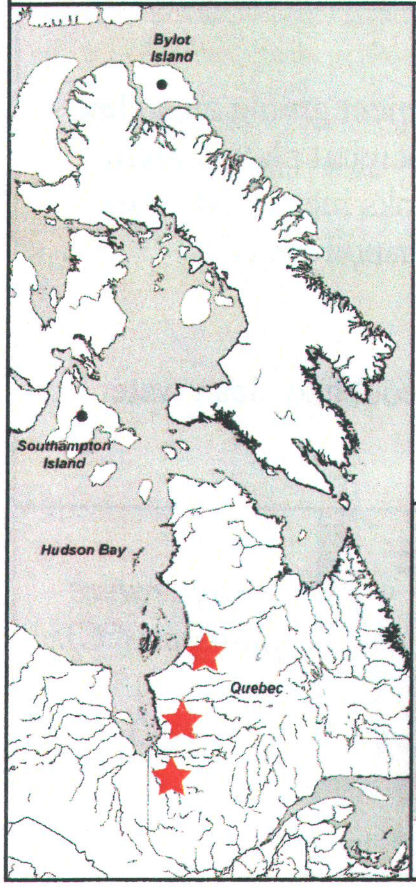
Temperature optimum (°C):

10.0

The visual guide to subfossil chironomid analysis

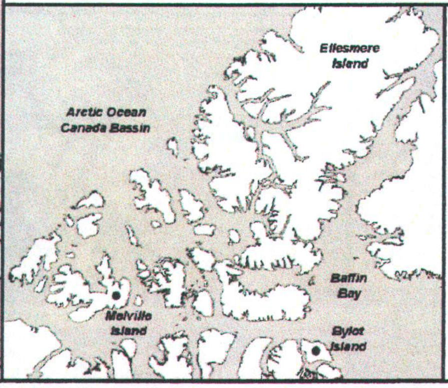
Genera: Tanytarsus chinyensis-type
Tribe: Chironominae, Tanytarsini





Description:
Very long spur on each antenna (A).
They are thin and often broken.

Ecology:

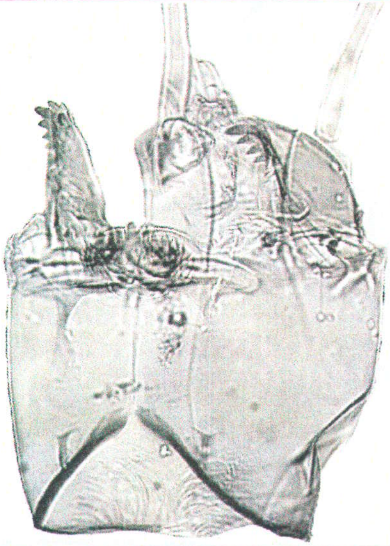


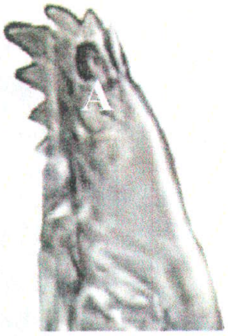
Temperature optimum (°C):

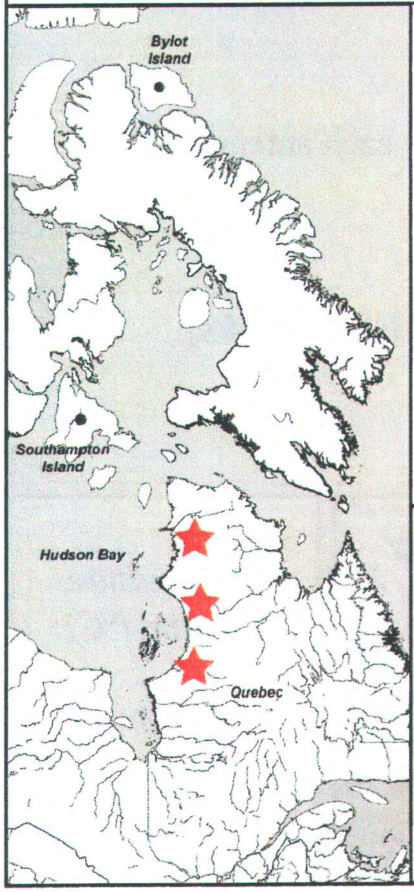
23.8

The visual guide
to subfossil
chironomid analysis

Genera: Tanytarsus lugens-type
Tribe: Chironominae, Tanytarsini

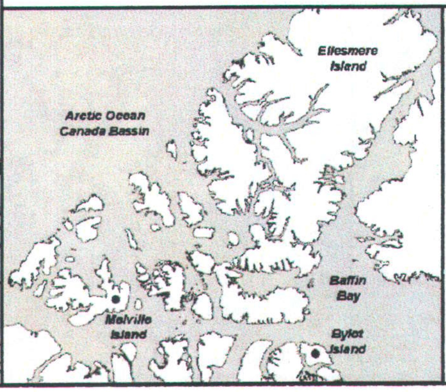






Description:
One large surface tooth on the mandible (A).

Ecology:
Cold stenotherm (13), in shallow lakes (22), increase following human impact (1).

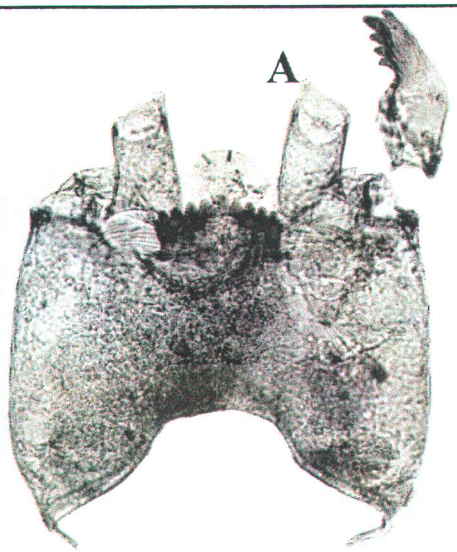


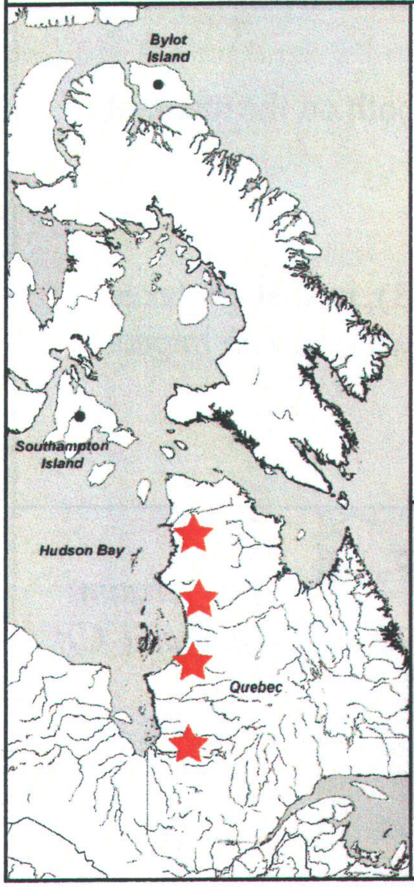
Temperature optimum (°C):

9.5

The visual guide to subfossil chironomid analysis

Genera: Tanytarsus pallidicornis-type
Tribe: Chironominae, Tanytarsini



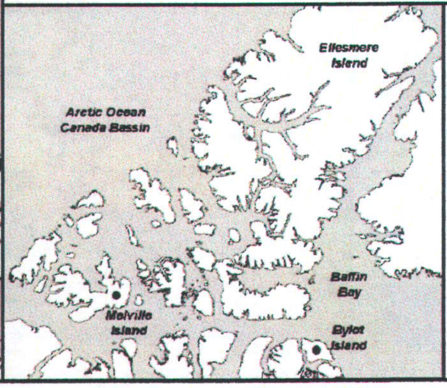


Description:

Small blunt spur on each antenna (A).

Ecology:

Temperate lowland lakes (47, 48).

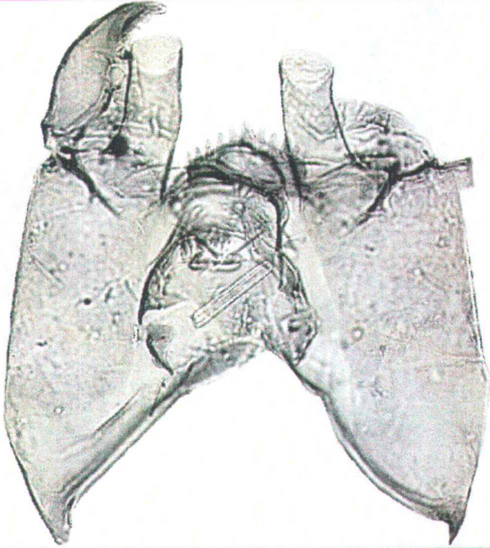


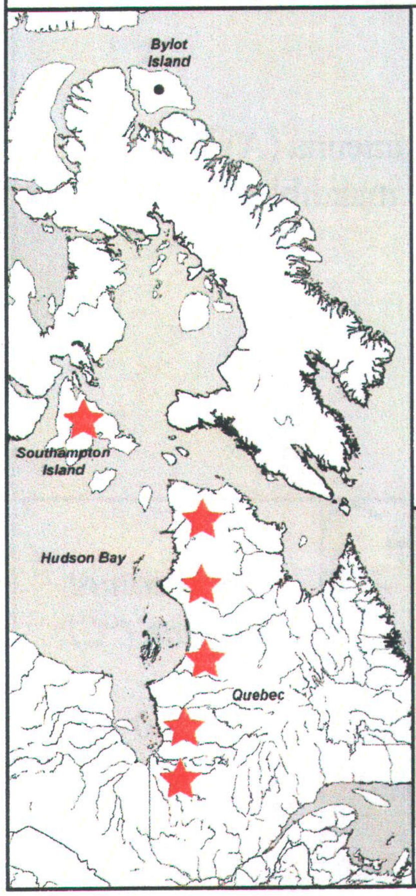
Temperature optimum (°C):

8.6

The visual guide to subfossil chironomid analysis

Genera: Tanytarsus sp. B.
Tribe: Chironominae, Tanytarsini

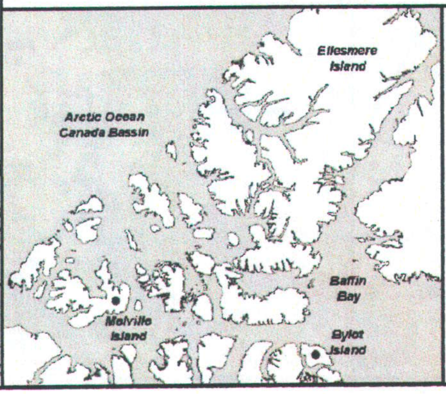




Description:

No specific characteristic.

Ecology:

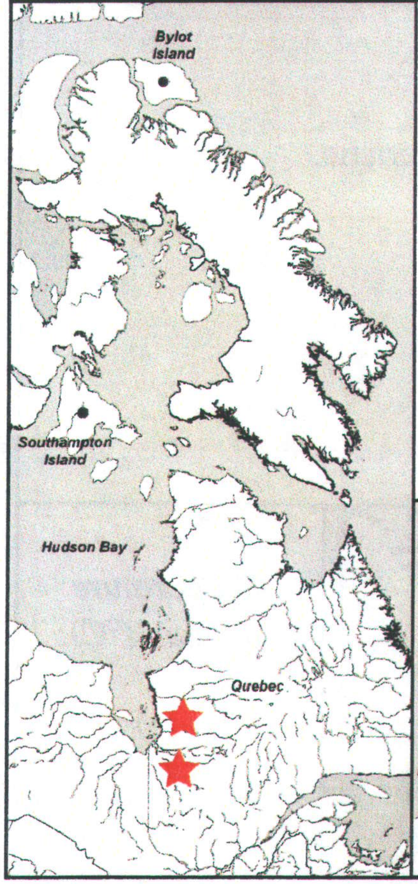


Temperature optimum (°C):

11.9

The visual guide
to subfossil
chironomid analysis

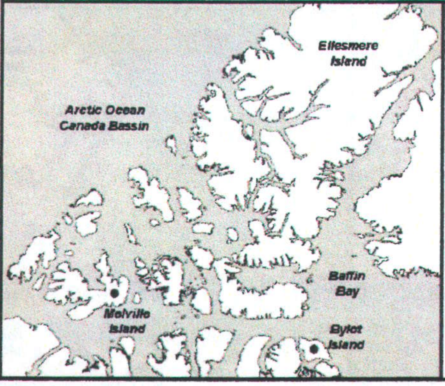
Genera: Tanytarsus sp. C.
Tribe: Chironominae, Tanytarsini



Description:

Short spur on each antenna (A). Two surface teeth on the mandible (B).

Ecology:



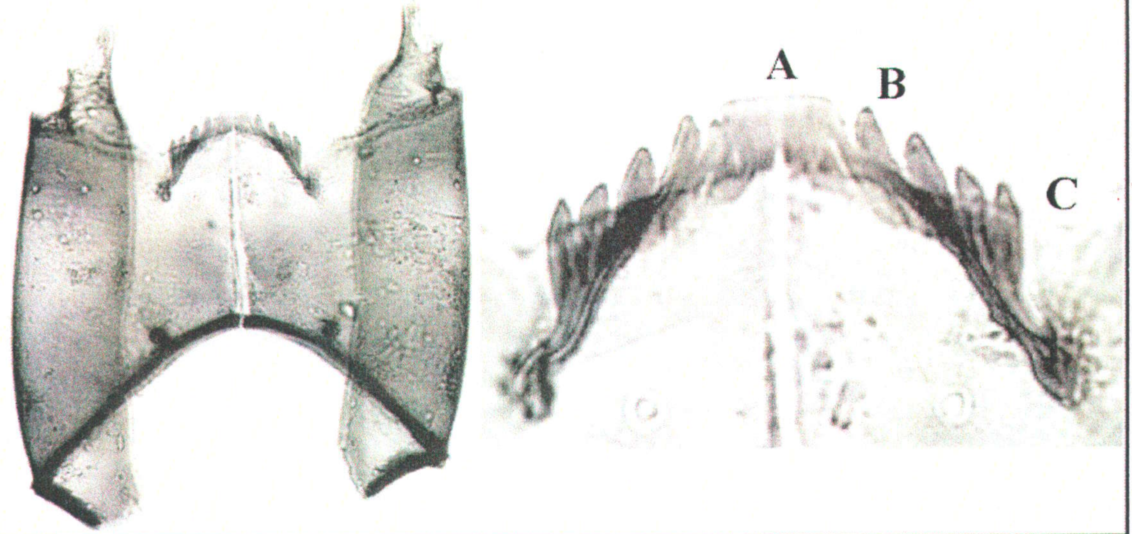
Temperature optimum (°C):

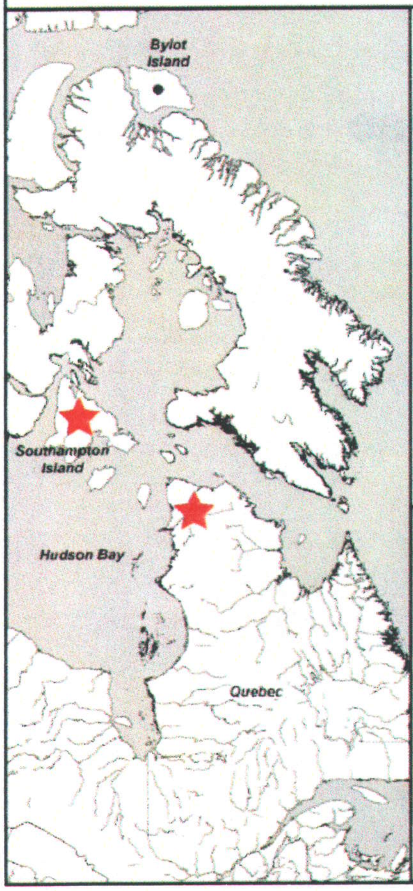
19.0

B.4 Orthocladiinae

The visual guide to subfossil chironomid analysis

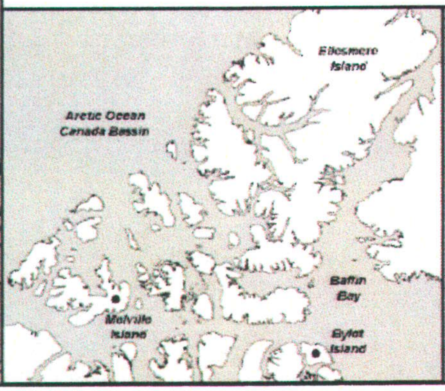
Genera: Abiskomya
Tribe: Orthocladiinae





Description:
Median teeth plate-like (A), four lateral, the 1st one is long and thin (B). Large ventromental plates (C).

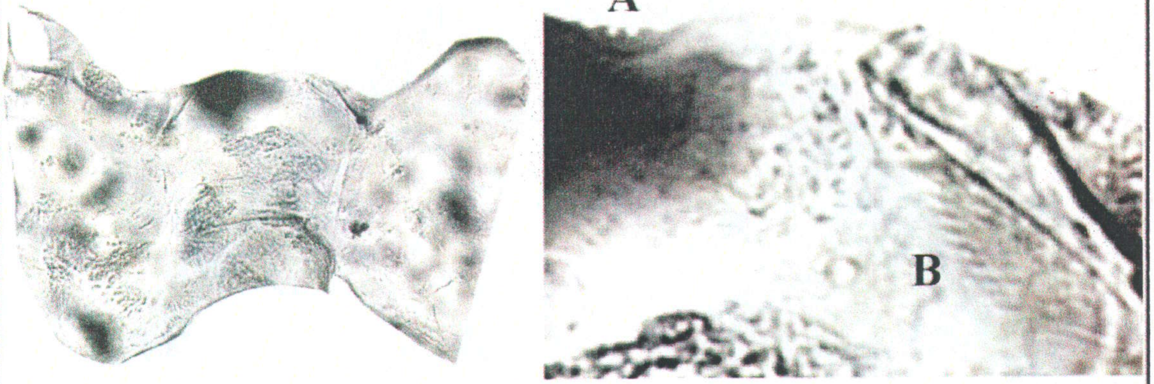
Ecology:
Cold-adapted, in shallow arctic lakes (4, 5).

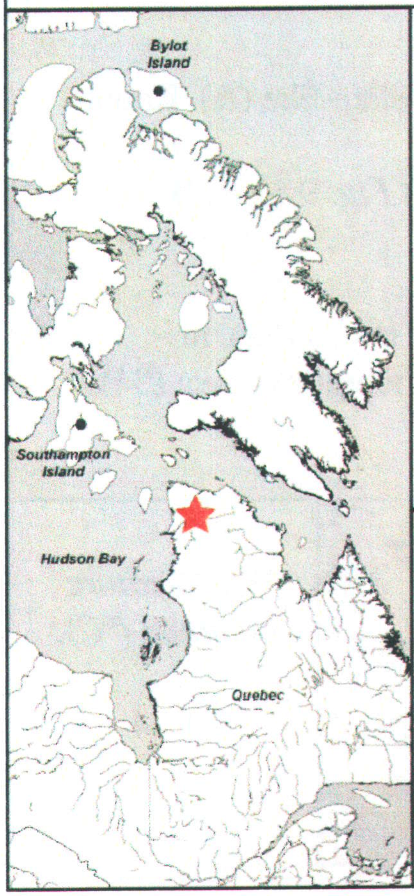


Temperature optimum (°C):

5.9

Genera: Acamptocladius
Tribe: Orthocladiinae

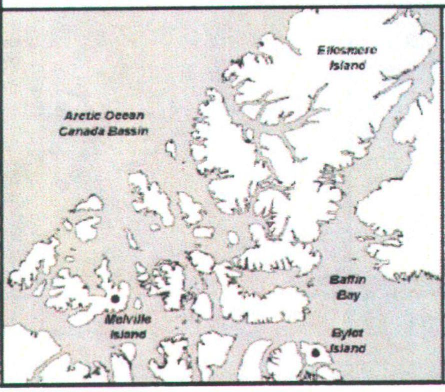




Description:

Small teeth in the middle of the mentum (A), plates with sharp teeth (B).

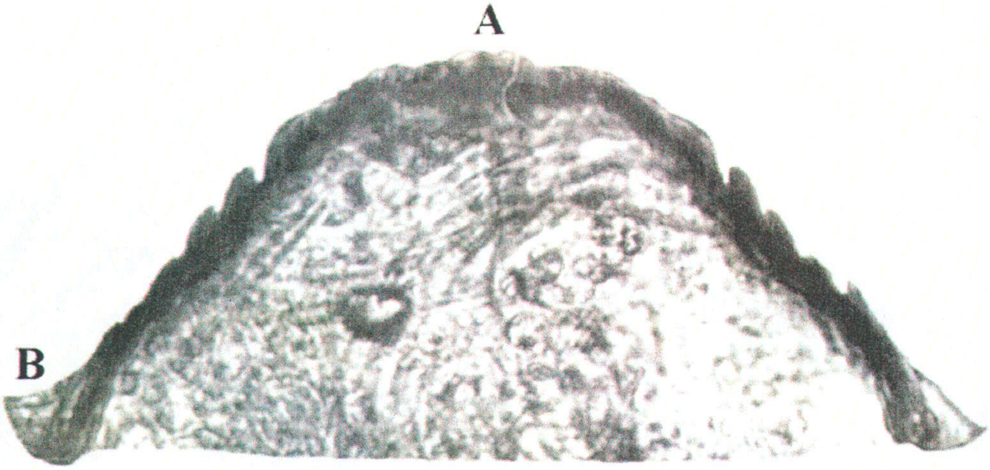
Ecology:

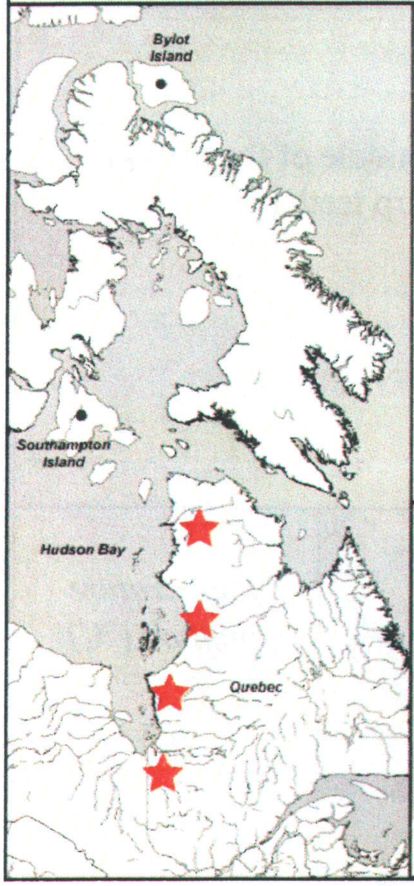


Temperature optimum (°C):

n.a

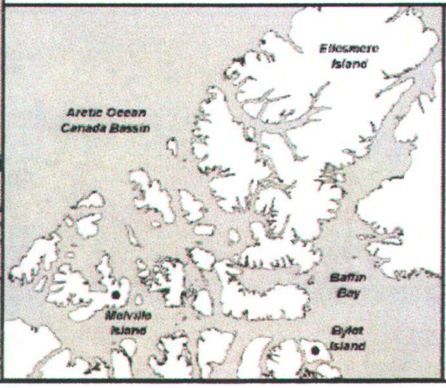
Genera: Allopsectrocladius-group
Tribe: Orthocladiinae





Description:
Two large median, plate-like (A). Round plate (B).
Wiederholm (1983) *Fig.* 9.61 A, B.

Ecology:
In high oxygenated ponds (52), in shallow lakes (53), temperate taxa (54).

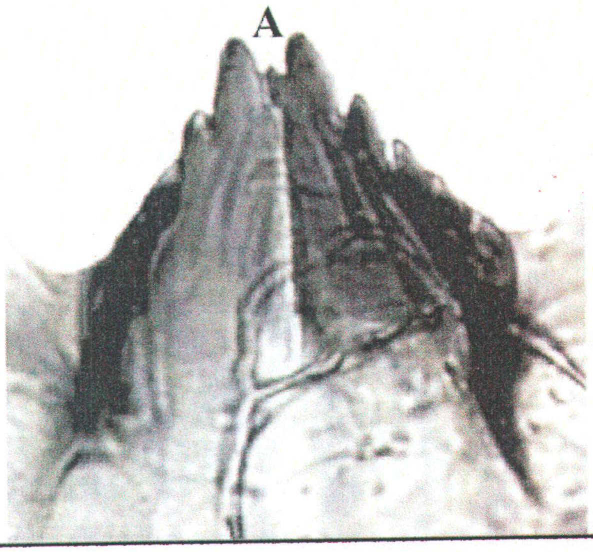


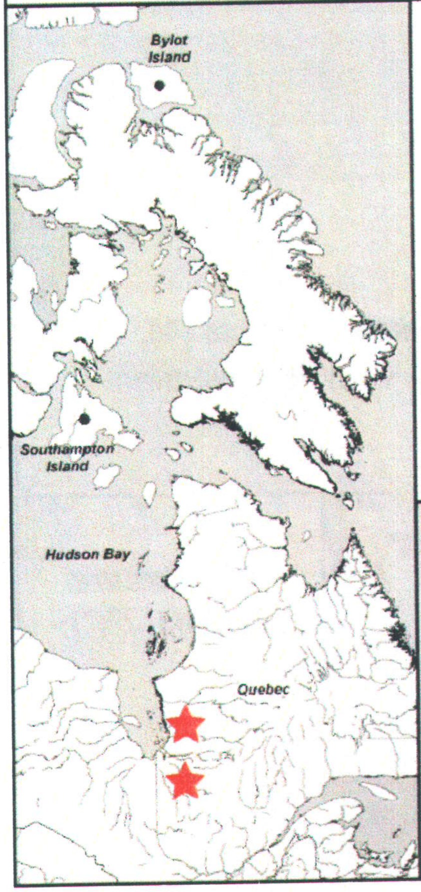
Temperature optimum (°C):

15.4

The visual guide
to subfossil
chironomid analysis

Genera: Brillia
Tribe: Orthocladiinae



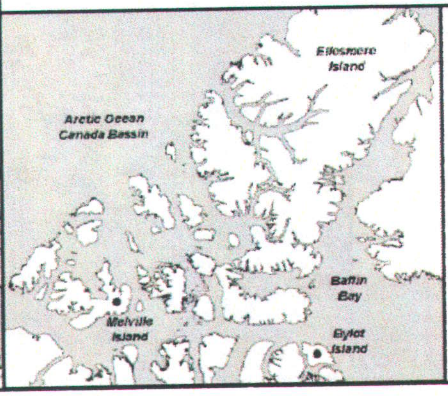


Description:

Three elevated median, one is very small (A). Five lateral teeth, the last two are compressed together.

Ecology:

Flowing waters (23, 24).

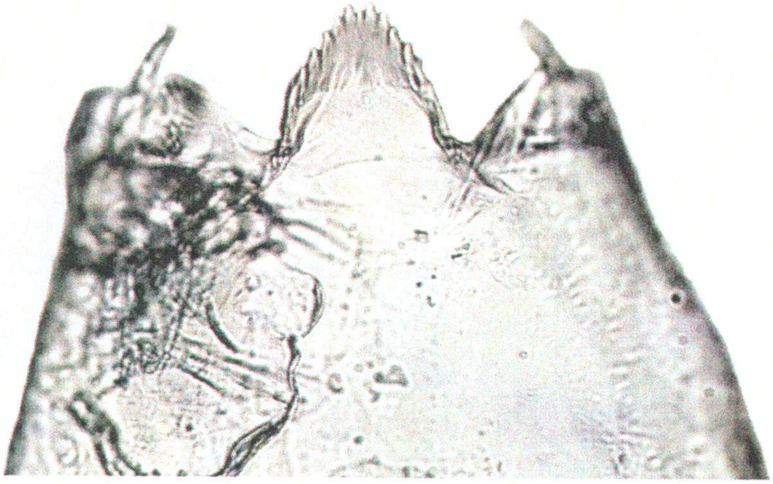


Temperature optimum (°C):

27.6

The visual guide
to subfossil
chironomid analysis

Genera: Corynoneura
Tribe: Orthocladiinae

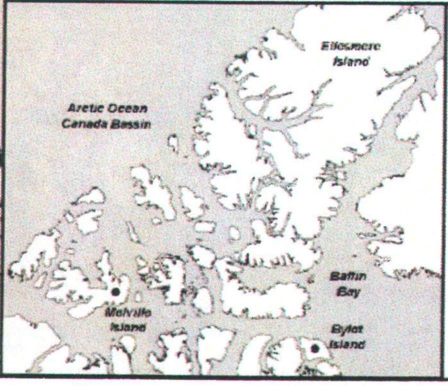


Description:

Triangular mentum.

Ecology:

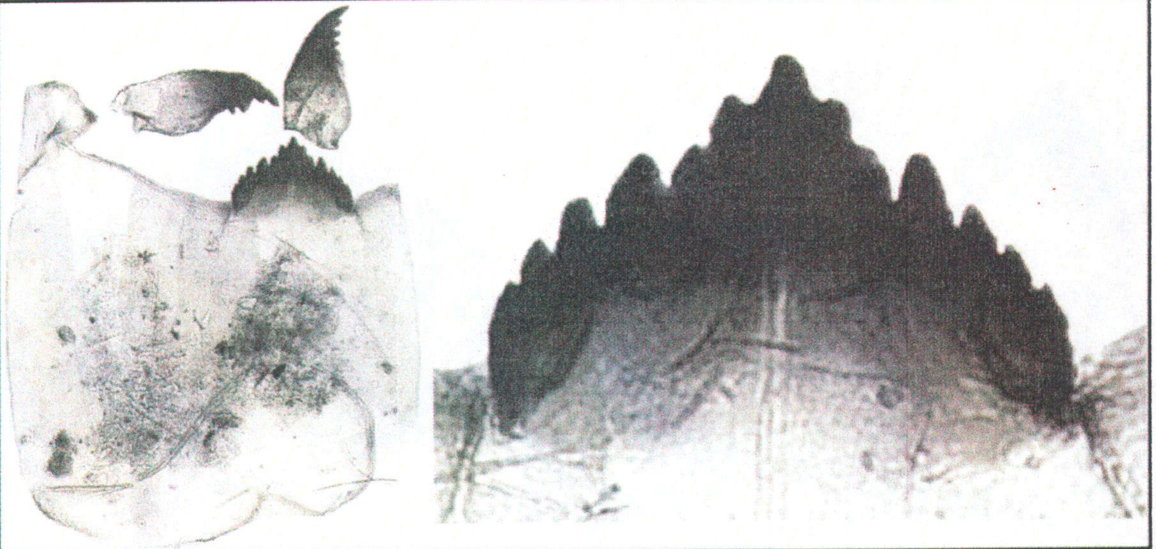
Standing water on aquatic plants (4), littoral (2), increase with deforestation (14).

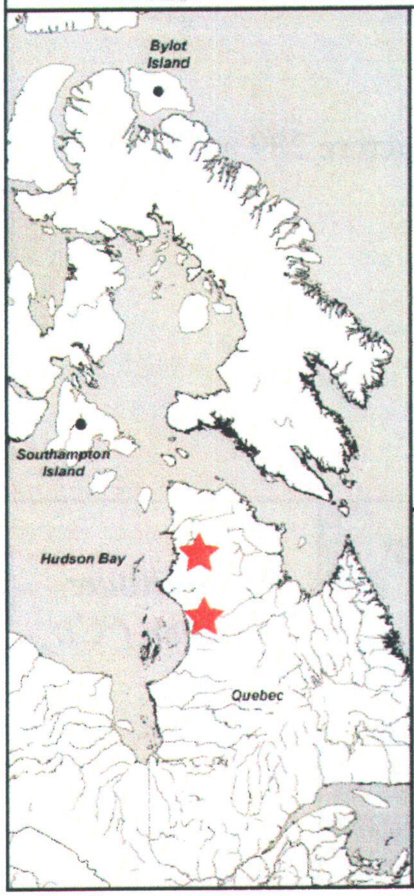


Temperature optimum (°C):

1.0

Genera: Cricotopus 285
Tribe: Orthocladiinae

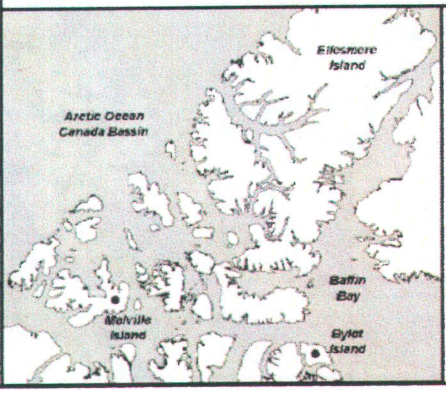




Description:

Named following picture 285 in Oliver and Roussel (1983).

Ecology:

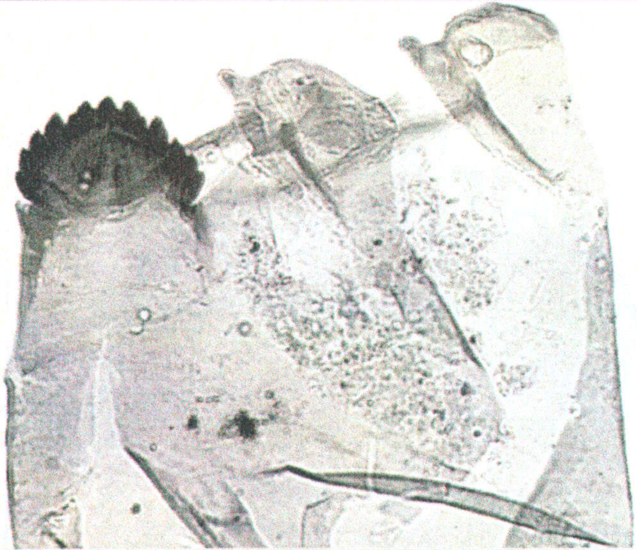


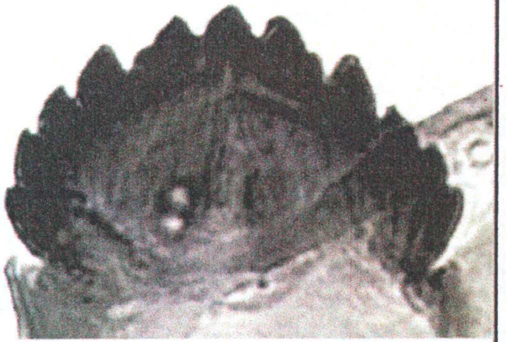
Temperature optimum (°C):

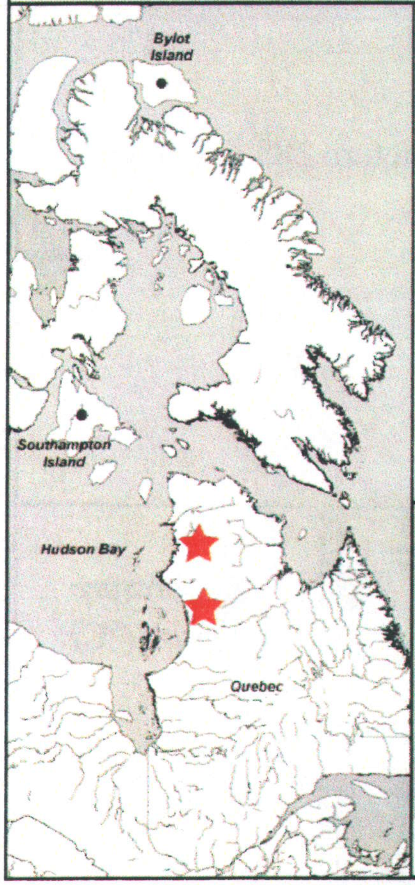
n.a

The visual guide to subfossil chironomid analysis

Genera: Cricotopus 289
Tribe: Orthocladiinae



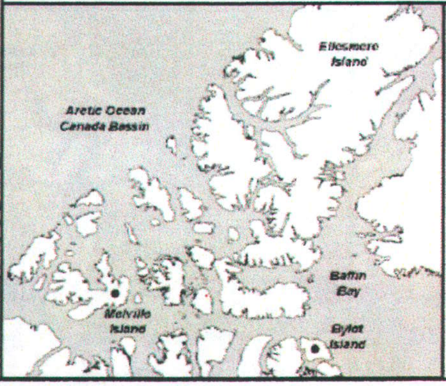




Description:

Named following picture 289 in Oliver and Roussel (1983).

Ecology:

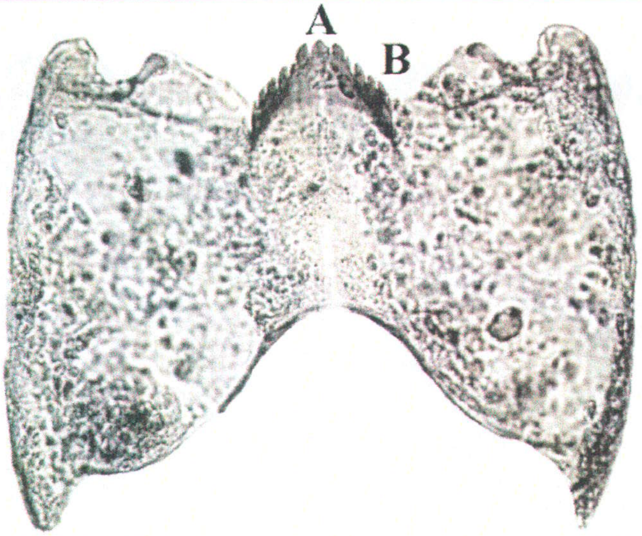


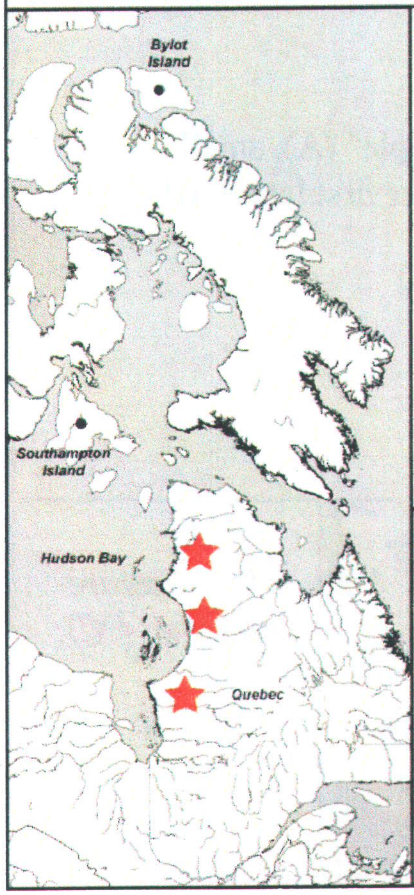
Temperature optimum (°C):

n.a

The visual guide
to subfossil
chironomid analysis

Genera: Cricotopus B
Tribe: Orthocladiinae

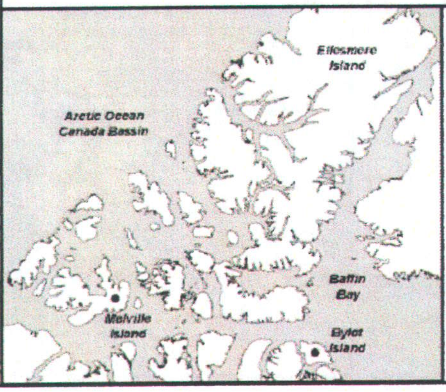




Description:

Described by Steve Brooks.
Three median are round and of equal length (A). The lateral are round and decreased in size (B).

Ecology:

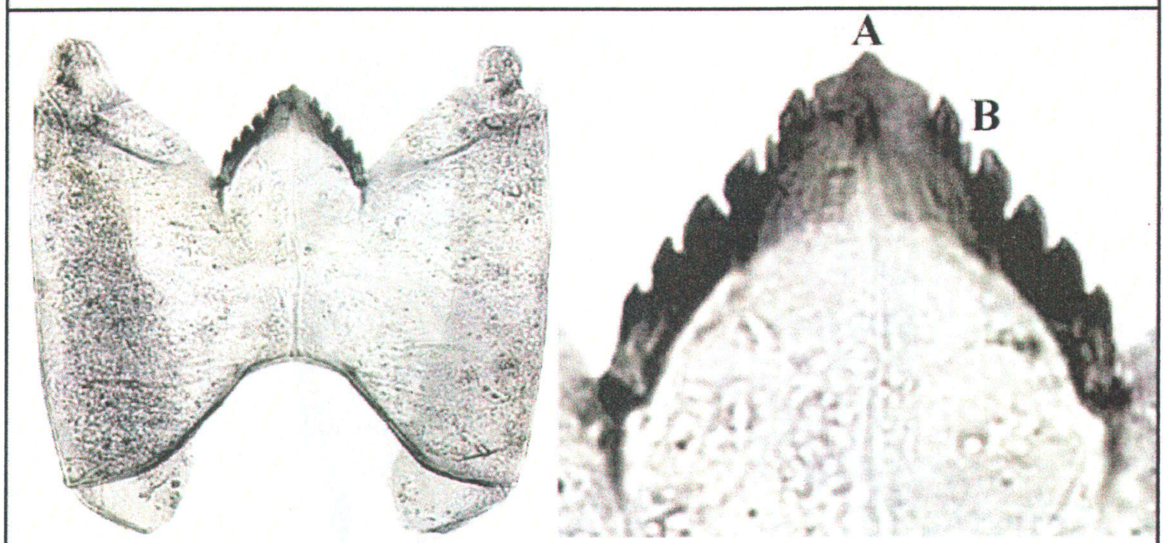


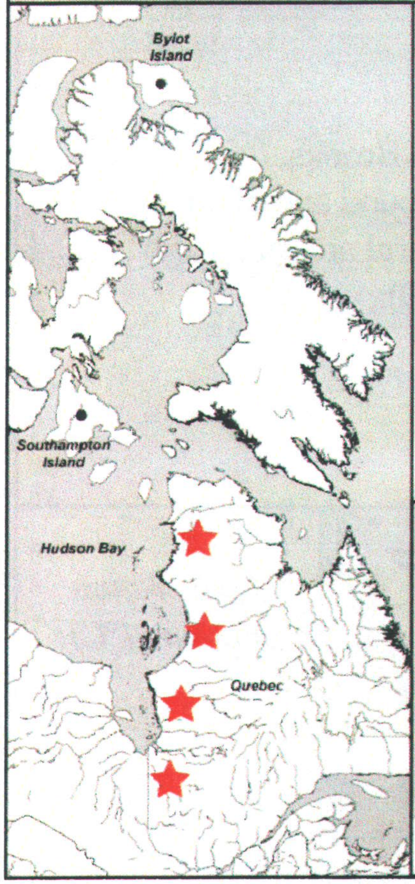
Temperature optimum (°C):

n.a

The visual guide to subfossil chironomid analysis

Genera: Cricotopus cylindraceus-type
Tribe: Orthocladiinae

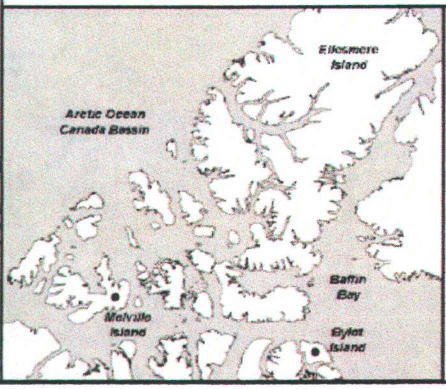




Description:

Median with a "nipple" (A), small accessory tooth after first lateral (B).

Ecology:

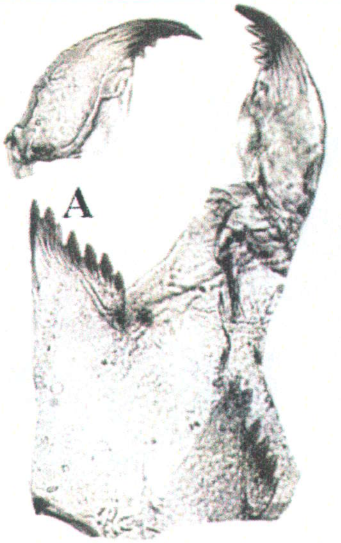


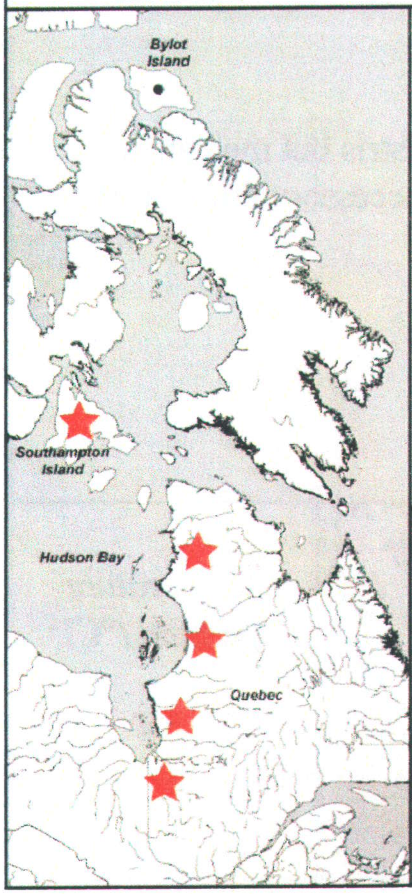
Temperature optimum (°C):

n.a

The visual guide
to subfossil
chironomid analysis

Genera: Cricotopus laricomalis
Tribe: Orthocladiinae

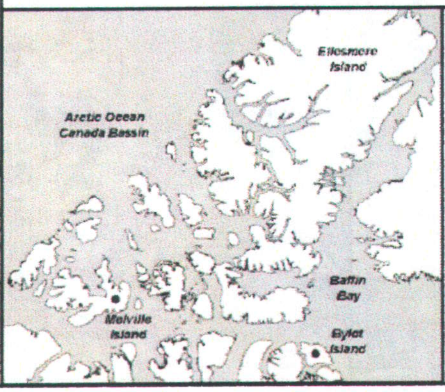




Description:

Accessory tooth on the 1st lateral (A).

Ecology:

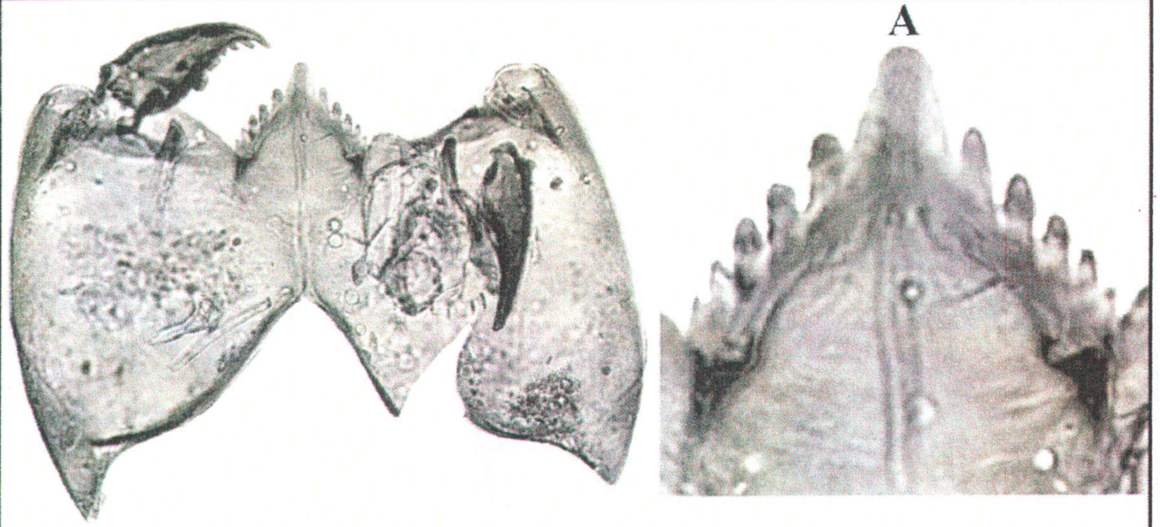


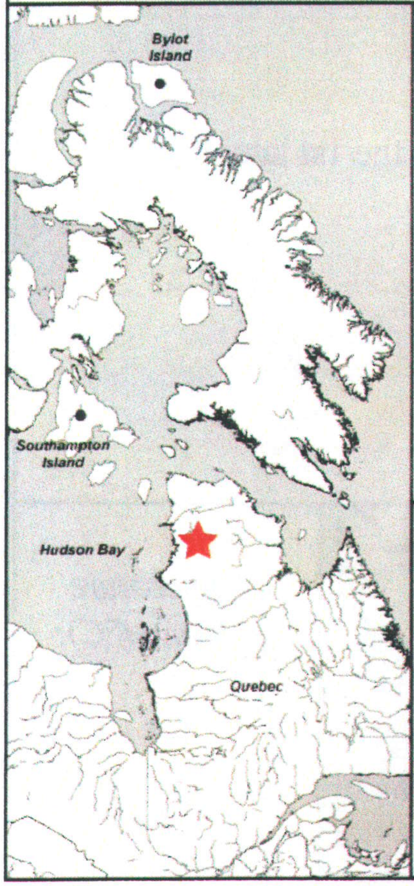
Temperature optimum (°C):

n.a

The visual guide to subfossil chironomid analysis

Genera: Cricotopus mlm
Tribe: Orthocladiinae

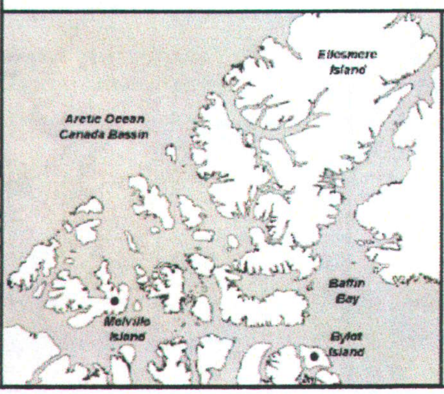




Description:

Looks like C. sylvestris but median is longer (A) and no accessory tooth on the 1st lateral.

Ecology:

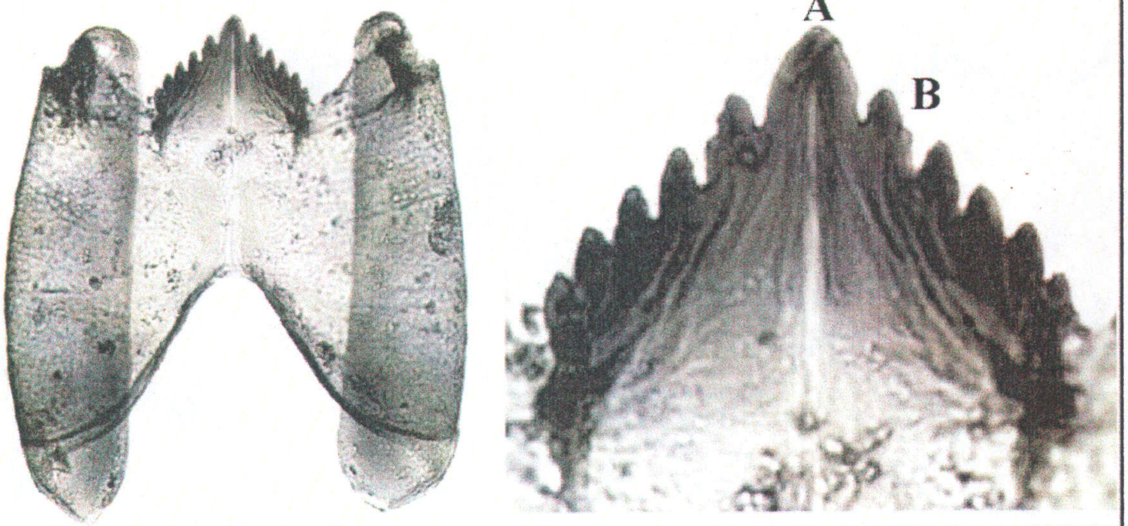


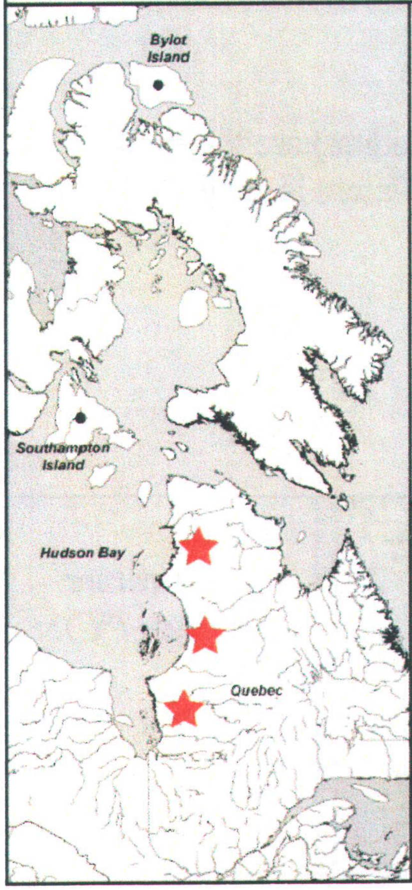
Temperature optimum (°C):

n.a

The visual guide to subfossil chironomid analysis

Genera: Cricotopus sylvestris-type
Tribe: Orthocladiinae

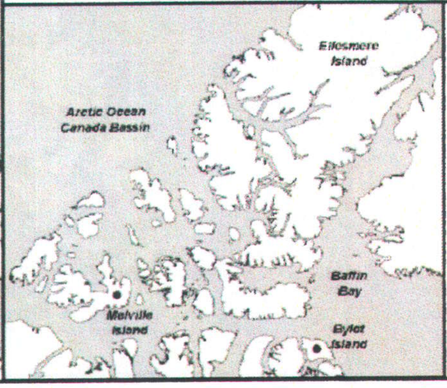




Description:

Long rounded median (A), small accessory tooth on 1st lateral (B).

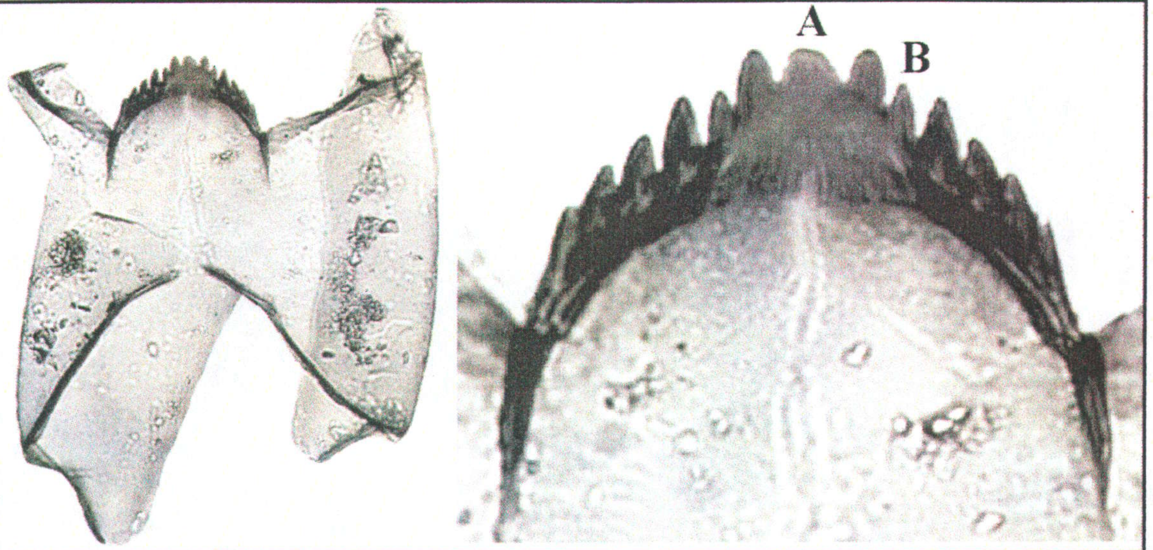
Ecology:

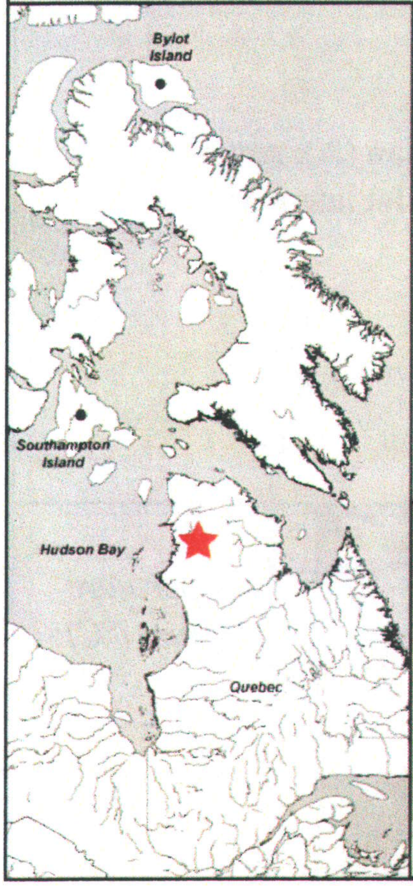


Temperature optimum (°C):

n.a

Genera: Cricotopus tremulus-type
Tribe: Orthocladiinae

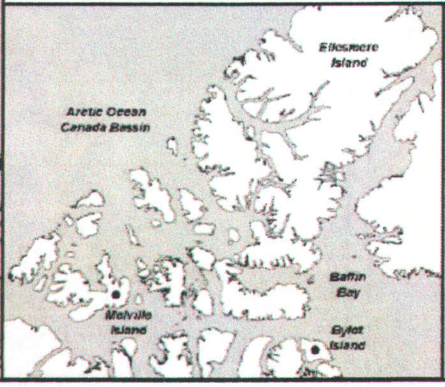




Description:

First three teeth (median) are the same lenght (A). Second latera is smaller (B).

Ecology:

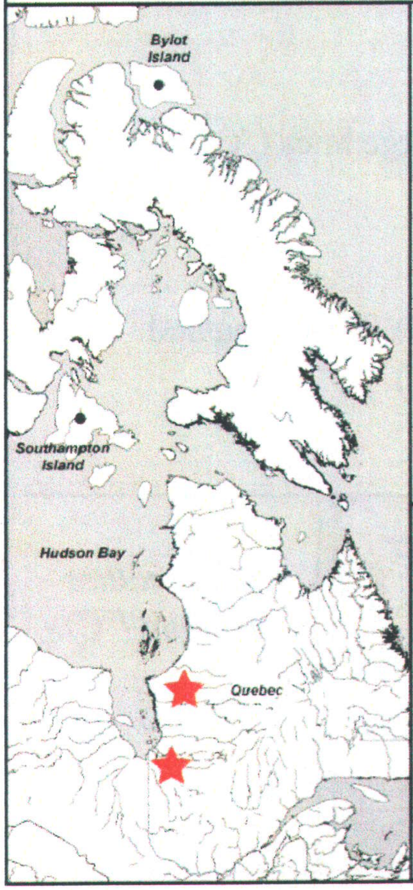


Temperature optimum (°C):

n.a

The visual guide to subfossil chironomid analysis

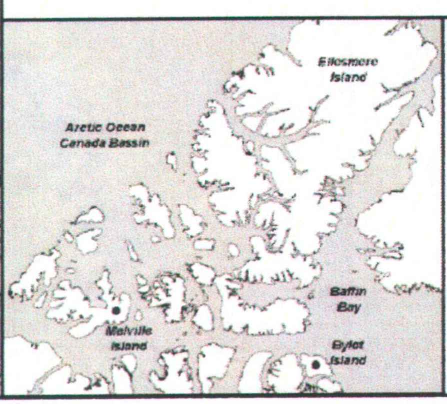
Genera: Cricotopus trifasciata-type
Tribe: Orthocladiinae



Description:

Oliver and Roussel (1983) Fig. 277.

Ecology:

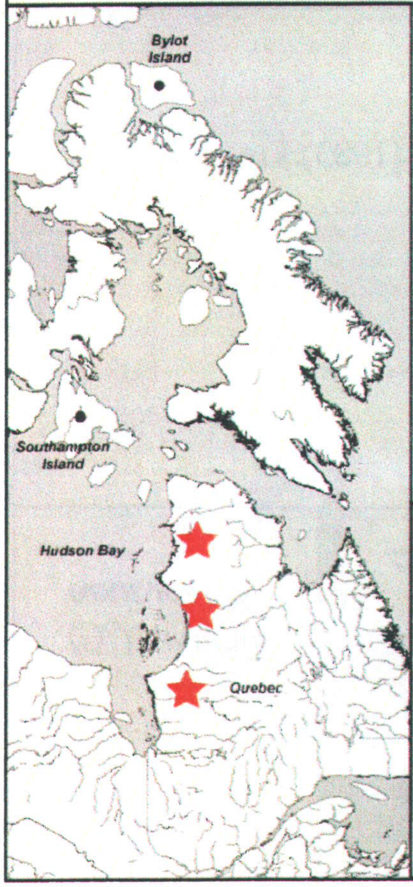


Temperature optimum (°C):

n.a

The visual guide
to subfossil
chironomid analysis

Genera: Eukieferiella
Tribe: Orthocladiinae

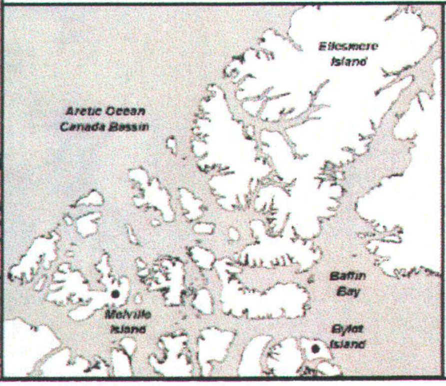


Description:

The mentum has large lines (A).

Ecology:

North of treeline (4), in running and polluted waters (10).

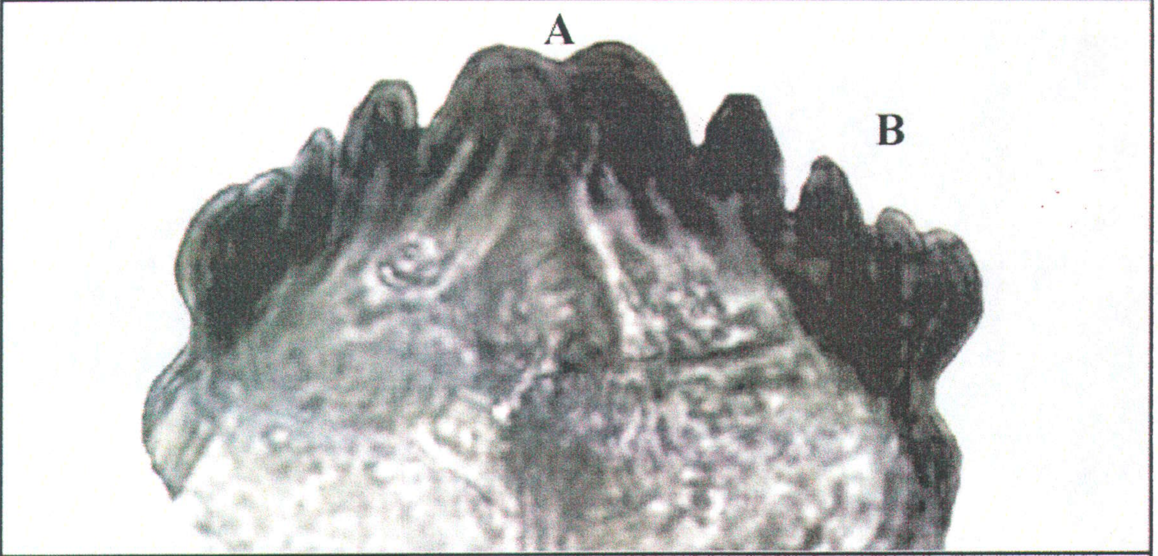


Temperature optimum (°C):

1.0

The visual guide
to subfossil
chironomid analysis

Genera: Georthocladius
Tribe: Orthocladiinae

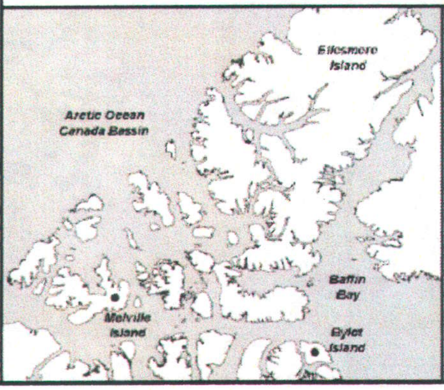


Description:

Two median (A), four lateral teeth (B).

Ecology:

Semi-terrestrial (63).

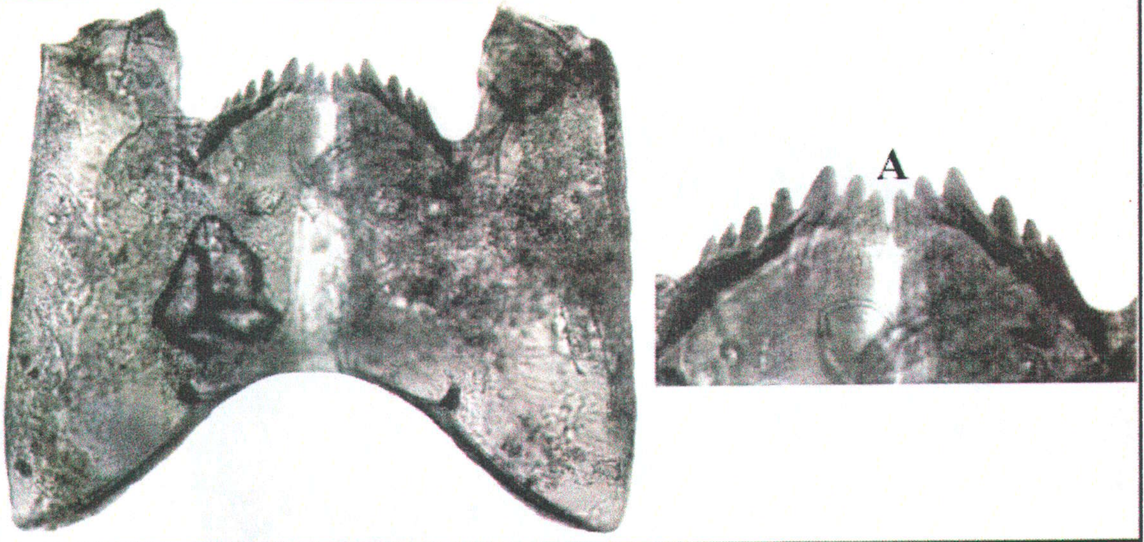


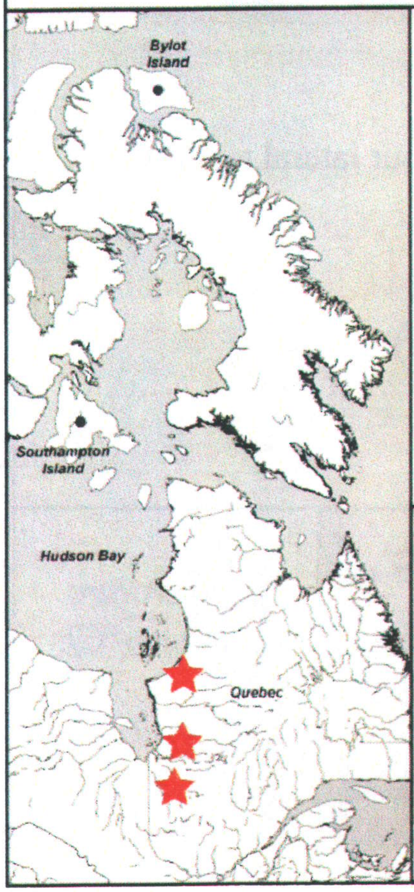
Temperature optimum (°C):

17.7

The visual guide
to subfossil
chironomid analysis

Genera: Heterotanytarsus
Tribe: Orthocladiinae



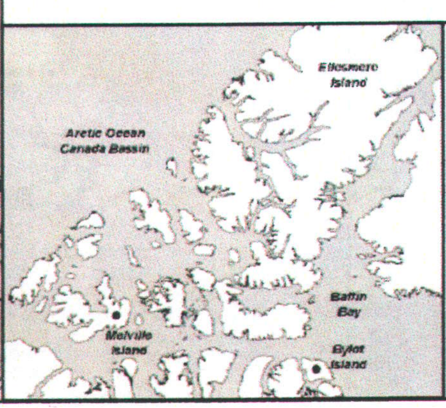


Description:

Median teeth are lower than the lateral teeth (A).

Ecology:

In humic waters (13), small lakes (4), littoral taxon (55).

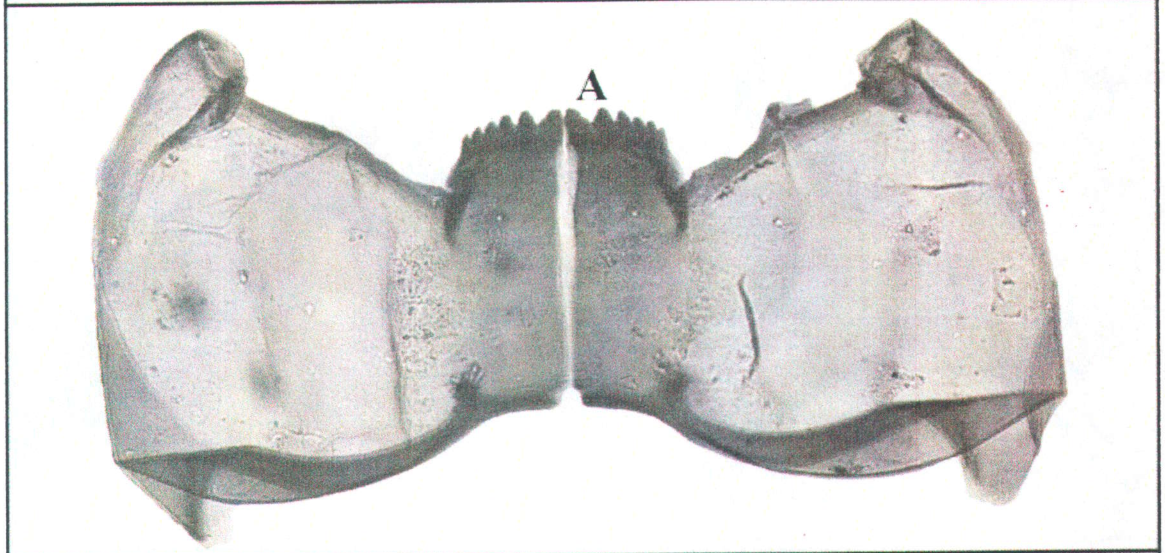


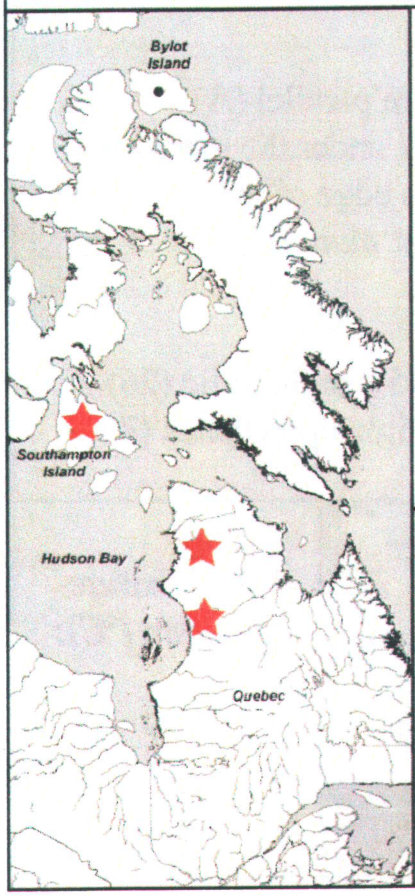
Temperature optimum (°C):

19.1

The visual guide to subfossil chironomid analysis

Genera: Heterotrissocladius brundini-type
Tribe: Orthocladiinae



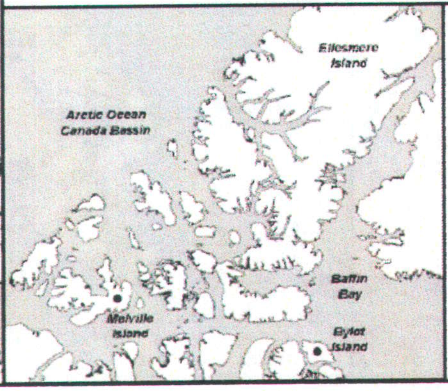


Description:

Large gap between the median and the 1st lateral (A). Post mentum dark.

Ecology:

Strickly profundal (3), cold stenothermic oligotroph (43).

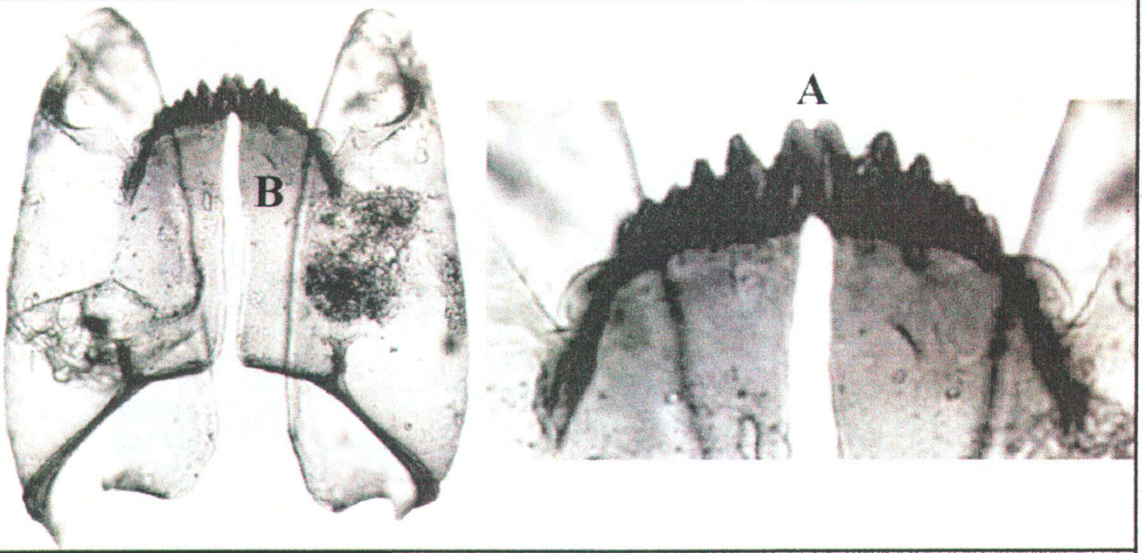


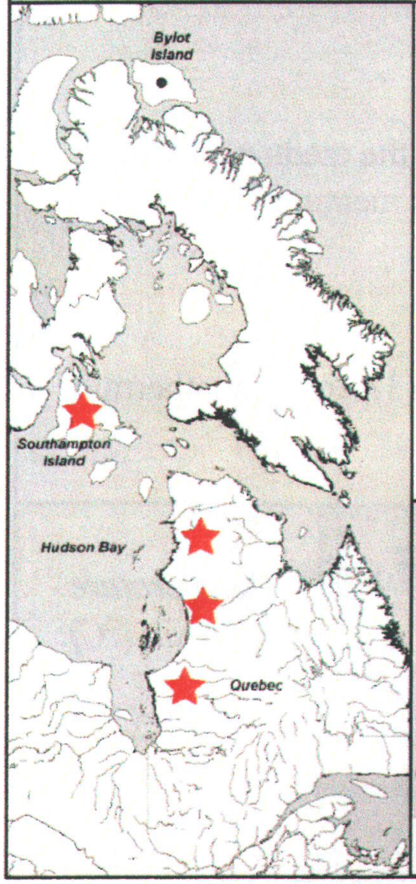
Temperature optimum (°C):

12.2

The visual guide to subfossil chironomid analysis

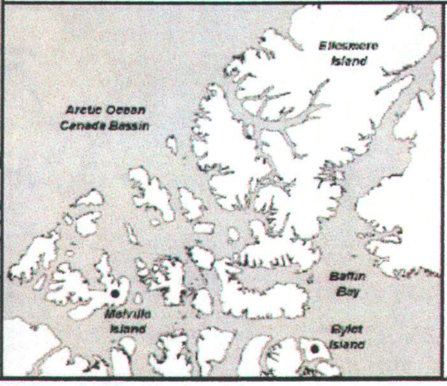
Genera: Heterotrissocladius grimshawi-type
Tribe: Orthocladiinae





Description:
The median teeth are parallel (A). Headcapsule is dark under the mentum (B) but not until the edge of the postmentum as in *H. marcidus*.

Ecology:
Cold-stenotherm (15), acidophilic (26), oligotrophic (27), high alpine lakes (22).

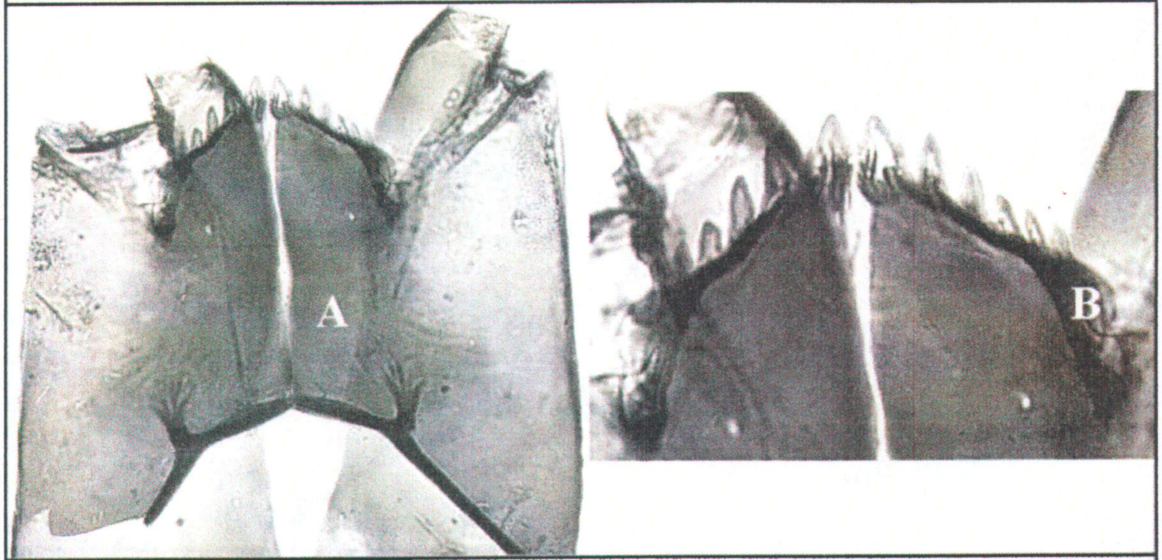


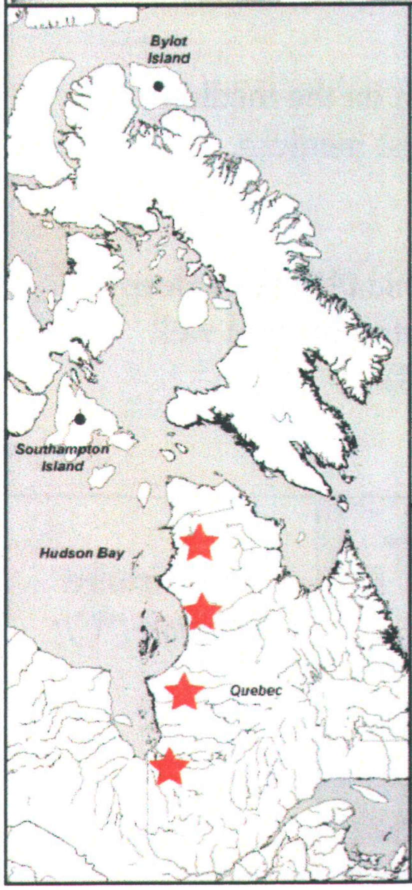
Temperature optimum (°C):

9.9

The visual guide to subfossil chironomid analysis

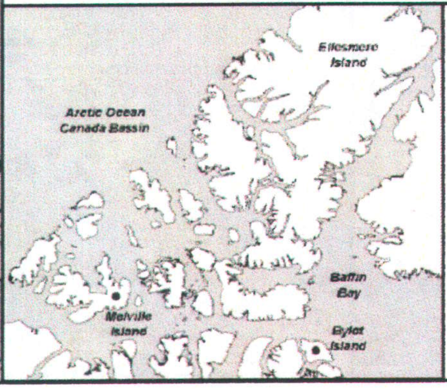
Genera: Heterotrissocladius marcidus-type
Tribe: Orthocladiinae





Description:
Post mentum dark until the end of the headcapsule (A).
Ventromental plate has large shoulders (B).

Ecology:
Oligotrophic (21), mesotrophic (32).

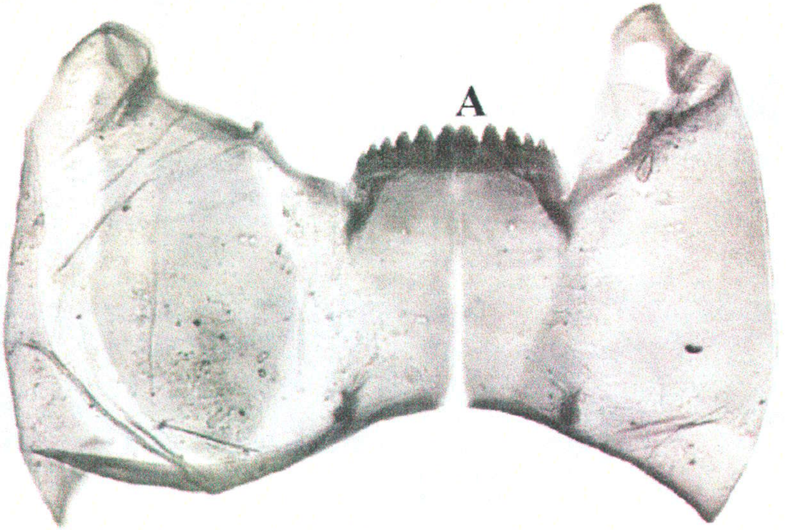


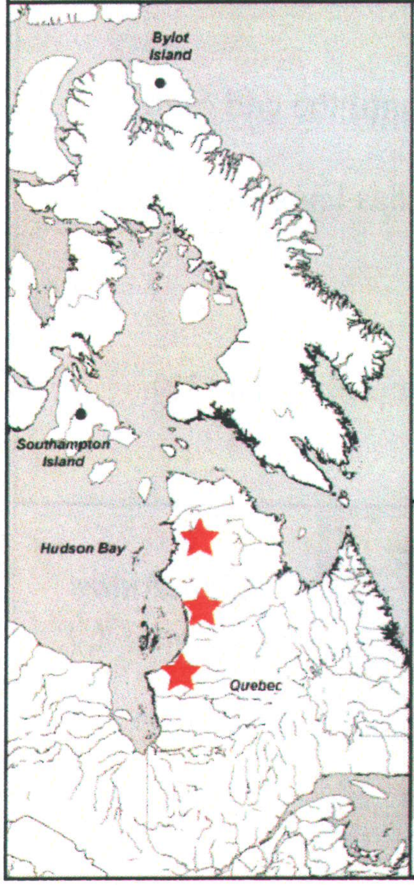
Temperature optimum (°C):

12.2

The visual guide to subfossil chironomid analysis

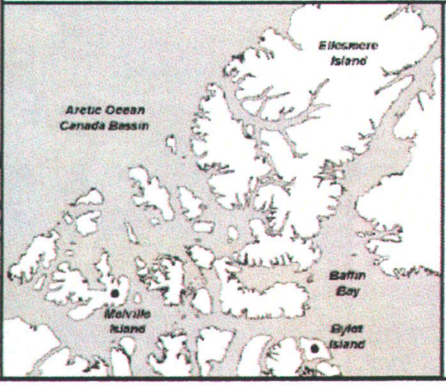
Genera: Heterotrissocladius subpilosus-type
Tribe: Orthocladiinae





Description:
One accessory tooth on the median (A). Dark teeth, clear post mentum.

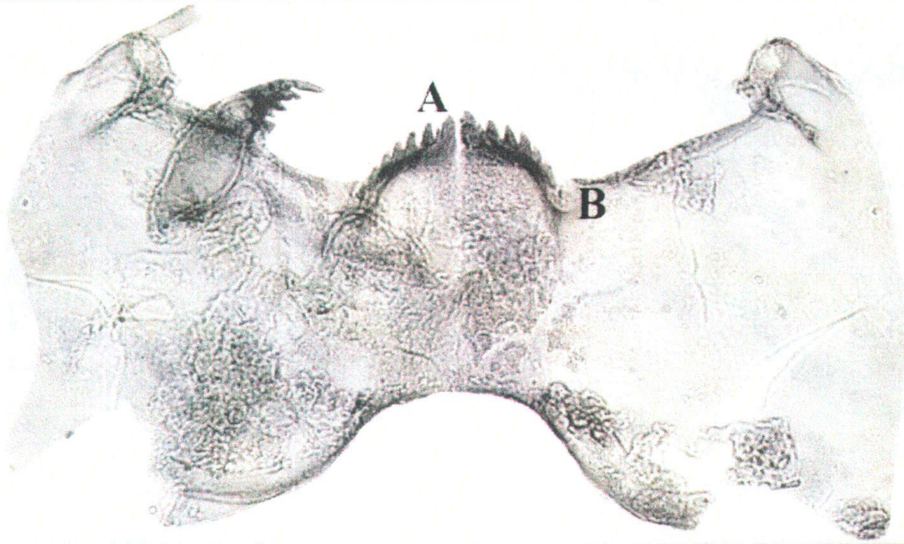
Ecology:
Cold and oligotrophic (18),large deep lakes (9), ultraoligotrophic and well oxygenated lakes (8).

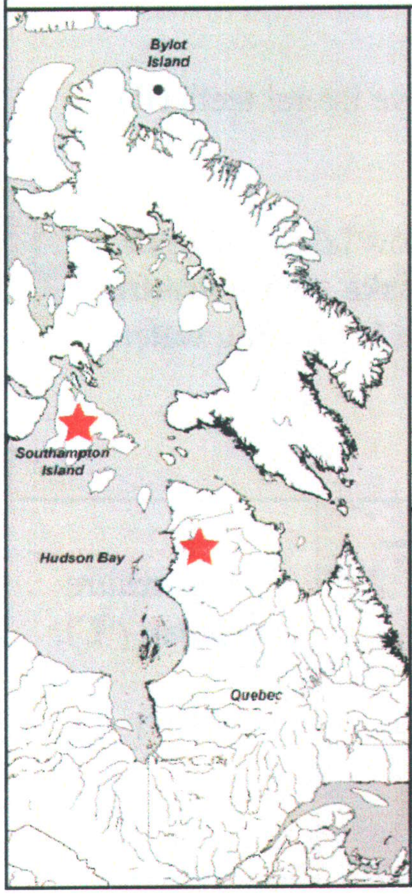


Temperature optimum (°C):

4.2

Genera: Hydrobaenus
Tribe: Orthocladiinae



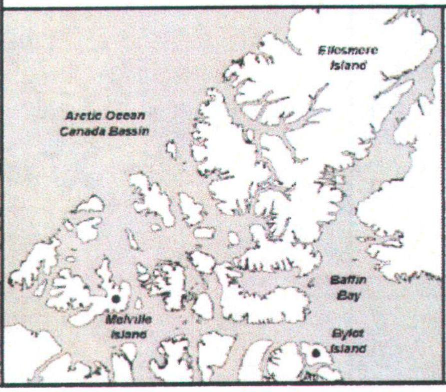


Description:

Small accessory tooth (A), large plate round at the end (B).

Ecology:

Cold adapted, littoral (25).

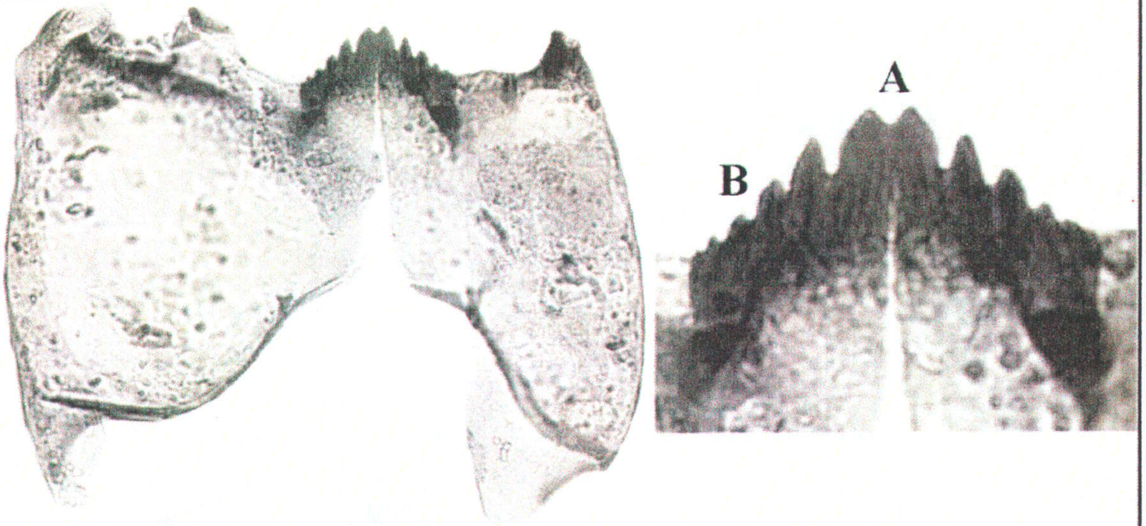


Temperature optimum (°C):

n.a

The visual guide to subfossil chironomid analysis

Genera: Limnophyes
Tribe: Orthocladiinae

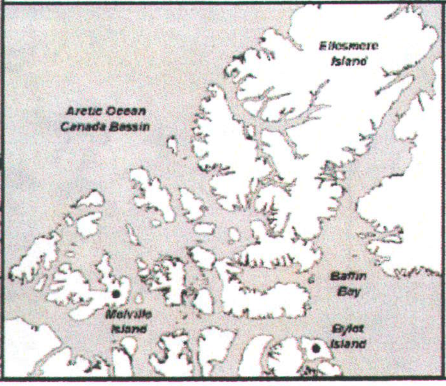


Description:

Two median (A), five lateral teeth (B).

Ecology:

At margins of shallow lakes, on aquatic plants (4), edge-of-lake, semi-terrestrial or stream habitants (1), running waters (28).

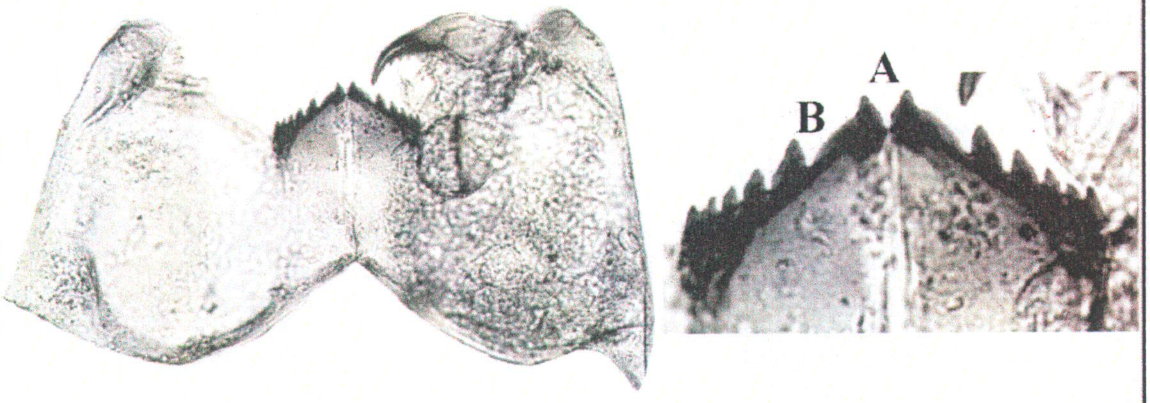


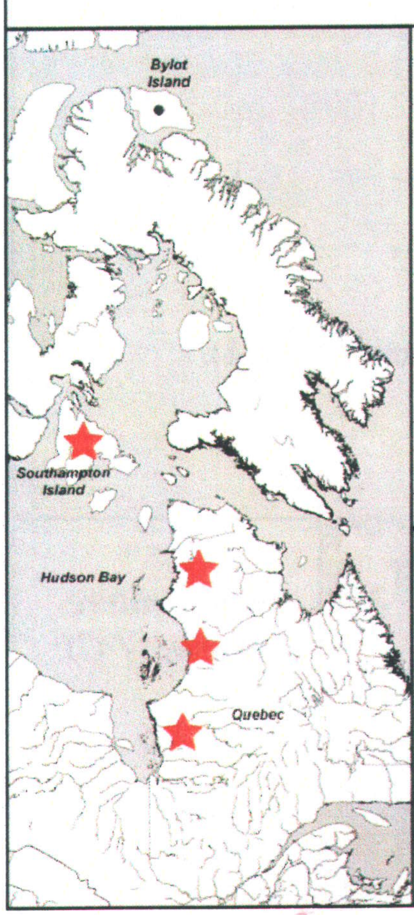
Temperature optimum (°C):

11.1

The visual guide
to subfossil
chironomid analysis

Genera: Mesocricotopus
Tribe: Orthocladiinae



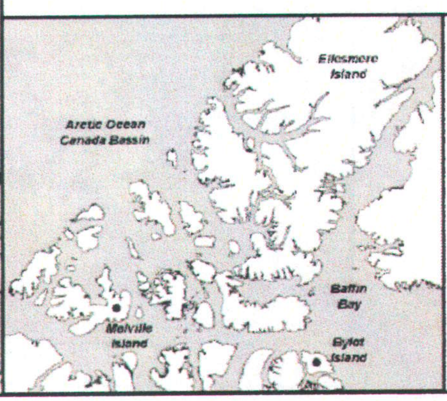


Description:

Median curved outwards (A). Gap between median and 1st lateral (B).

Ecology:

Cold-stenotherm (60), oligotrophic and cold (61).

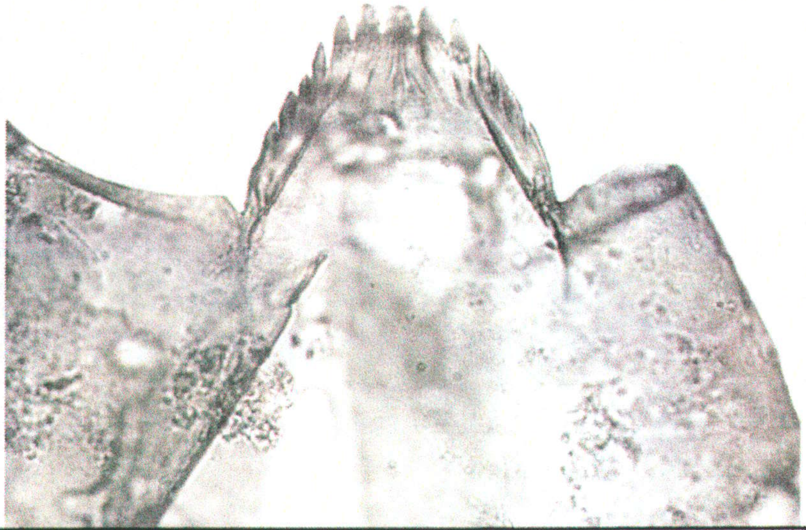


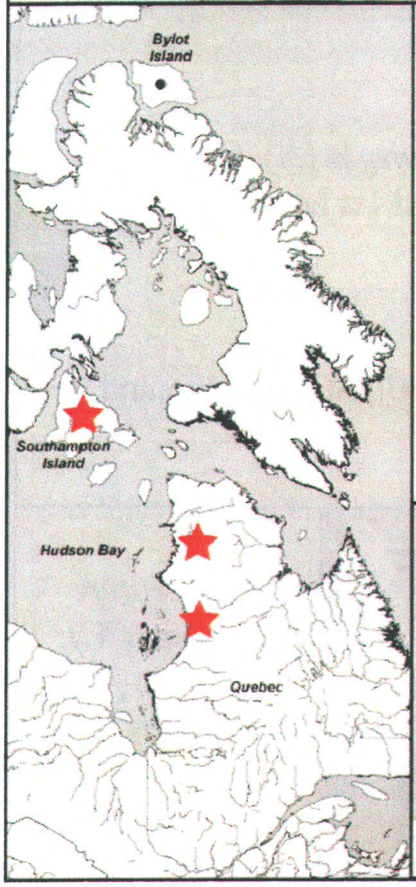
Temperature optimum (°C):

16.6

The visual guide to subfossil chironomid analysis

Genera: Orthocladius
Tribe: Orthocladiinae



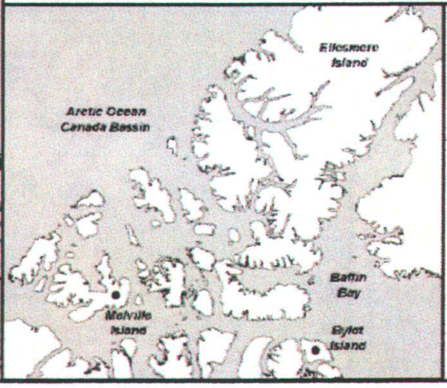


Description:

6 lateral teeth.

Ecology:

Medium to large arctic lakes (4).

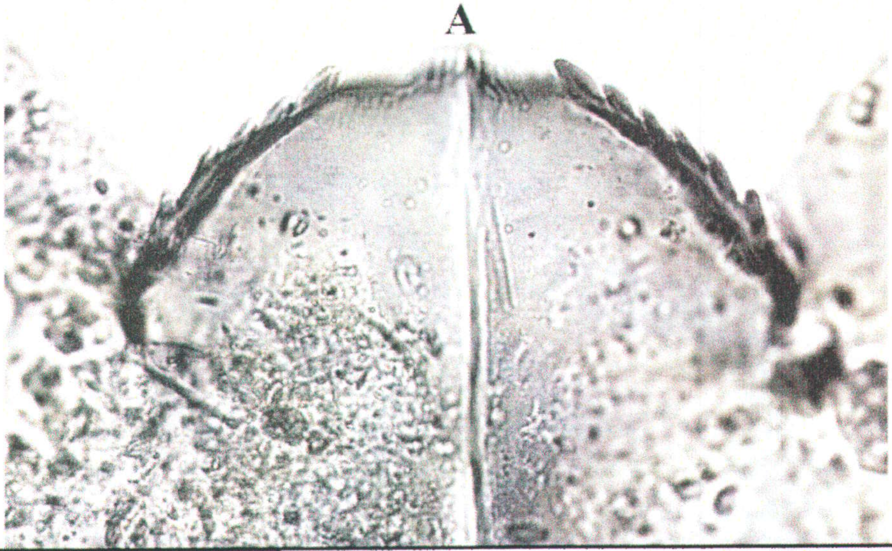


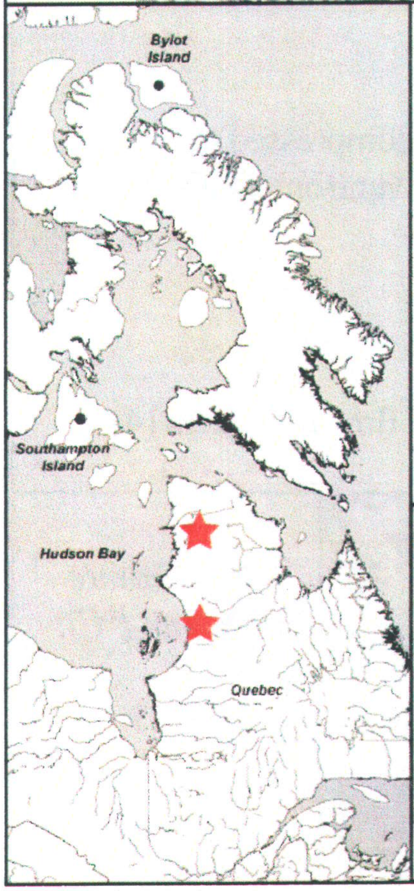
Temperature optimum (°C):

9.9

The visual guide
to subfossil
chironomid analysis

Genera: Paracladius
Tribe: Orthocladiinae



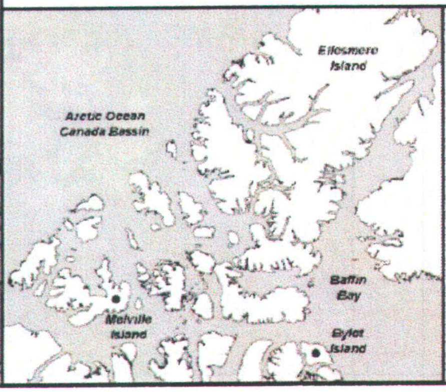


Description:

Large median, plate-like (A).

Ecology:

Strongly cold-stenotherm (17, 29, 30).

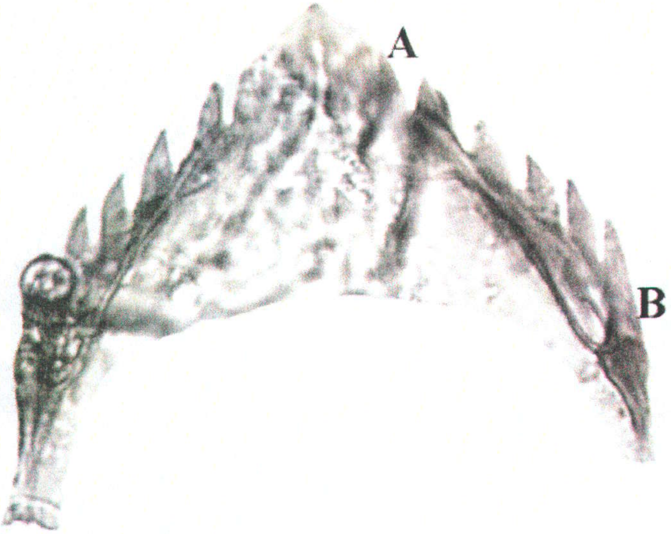


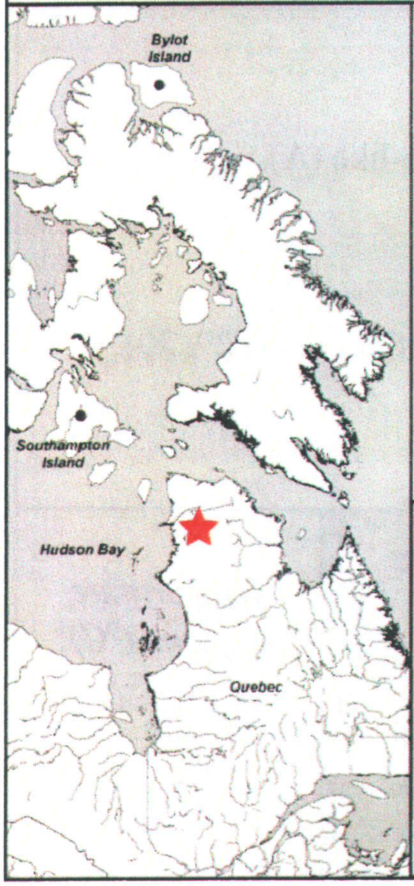
Temperature optimum (°C):

4.4

The visual guide to subfossil chironomid analysis

Genera: Parakieferiella
Tribe: Orthocladiinae



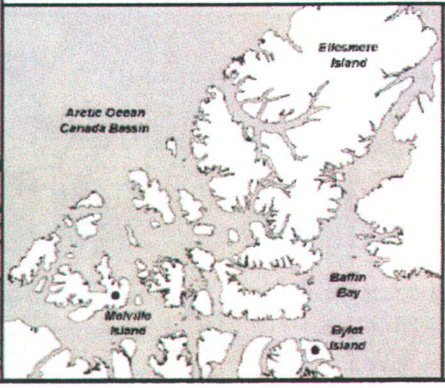


Description:

Small lateral tooth compressed to median (A), end of ventromental plate round (B).

Ecology:

Still water, some in flowing waters (4).

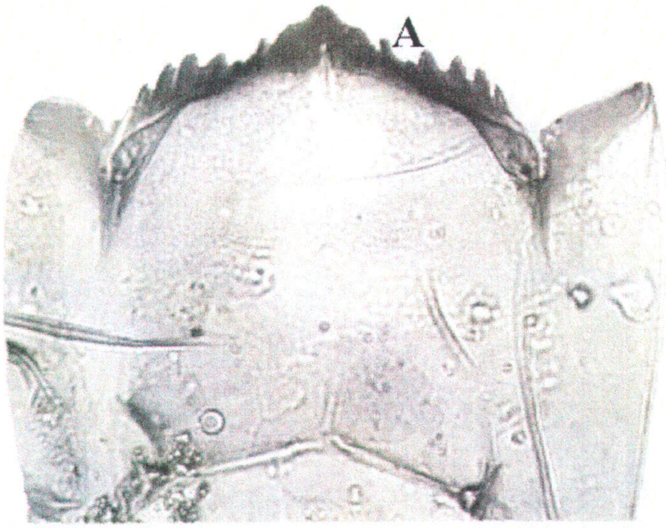


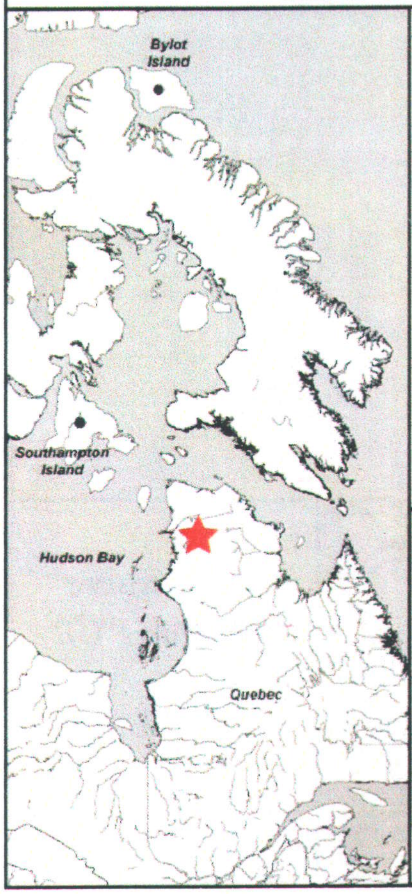
Temperature optimum (°C):

12.5

The visual guide
to subfossil
chironomid analysis

Genera: Parakieferiella sp 368
Tribe: Orthocladiinae

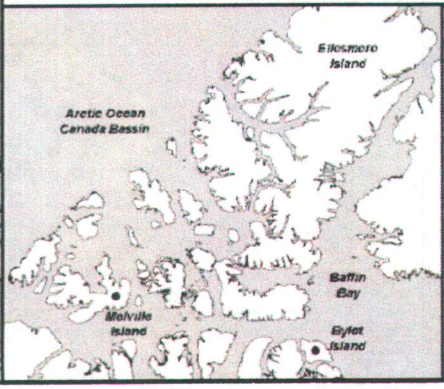




Description:

Oliver and Roussel (1983) *Fig.* 368. Small lateral tooth (A), median with "nipple".

Ecology:

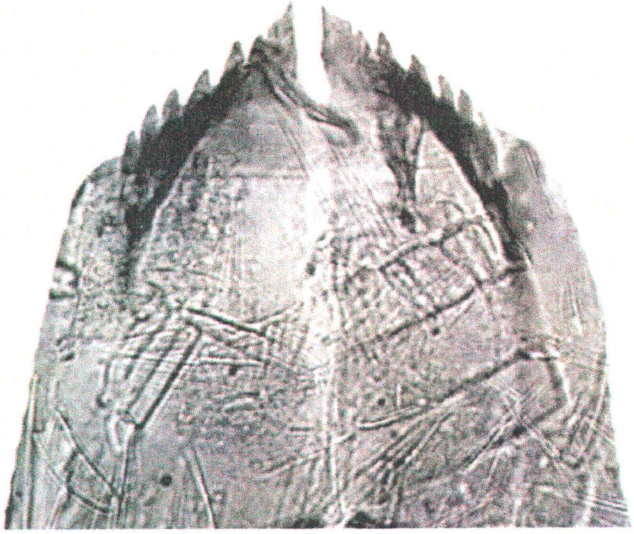


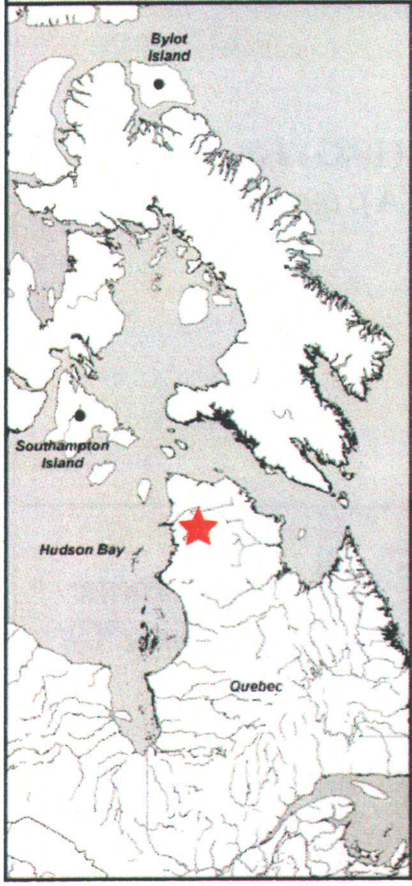
Temperature optimum (°C):

n.a

The visual guide to subfossil chironomid analysis

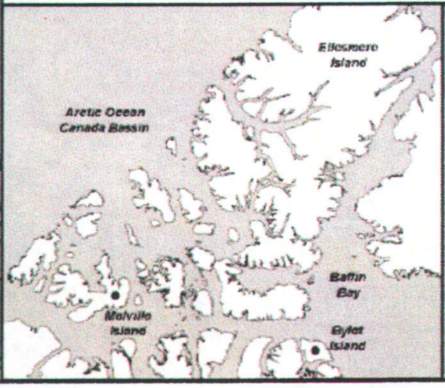
Genera: Parakieferiella bathophila
Tribe: Orthocladiinae





Description:

Ecology:

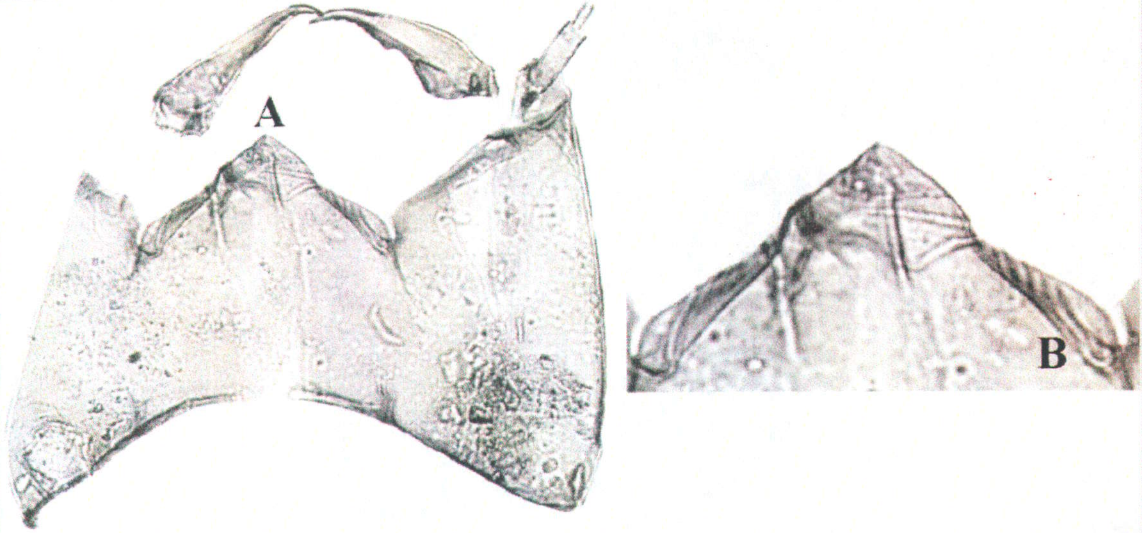


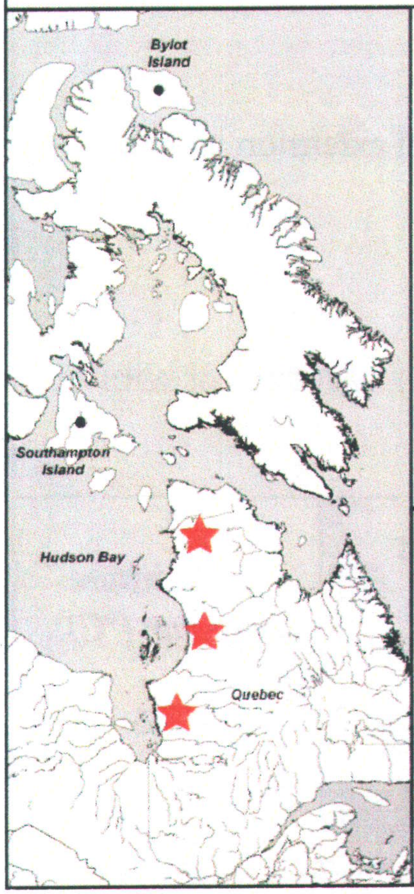
Temperature optimum (°C):

n.a

The visual guide to subfossil chironomid analysis

Genera: Parakieferiella fennica
Tribe: Orthocladiinae

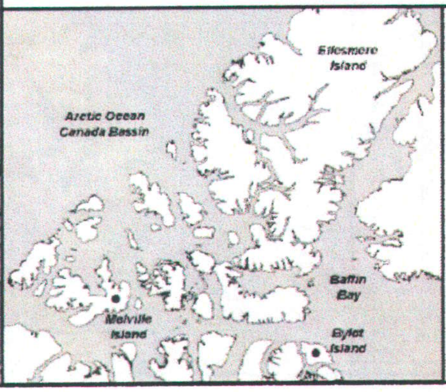




Description:

Large triangular median (A), large plates (B).

Ecology:

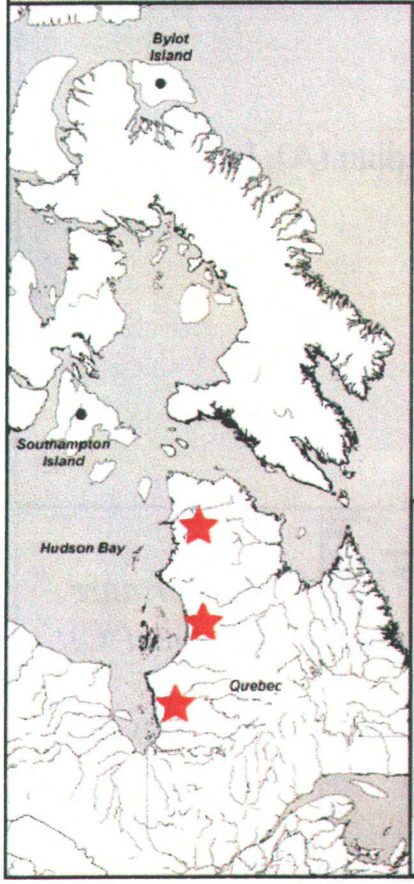


Temperature optimum (°C):

16.0

The visual guide to subfossil chironomid analysis

Genera: Paraphaenocladius
Tribe: Orthocladiinae

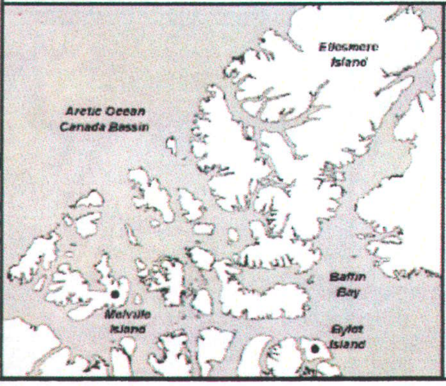


Description:

Round plate with an extension inwards (A).

Ecology:

North of treeline (4), terrestrial or semi-terrestrial (59).

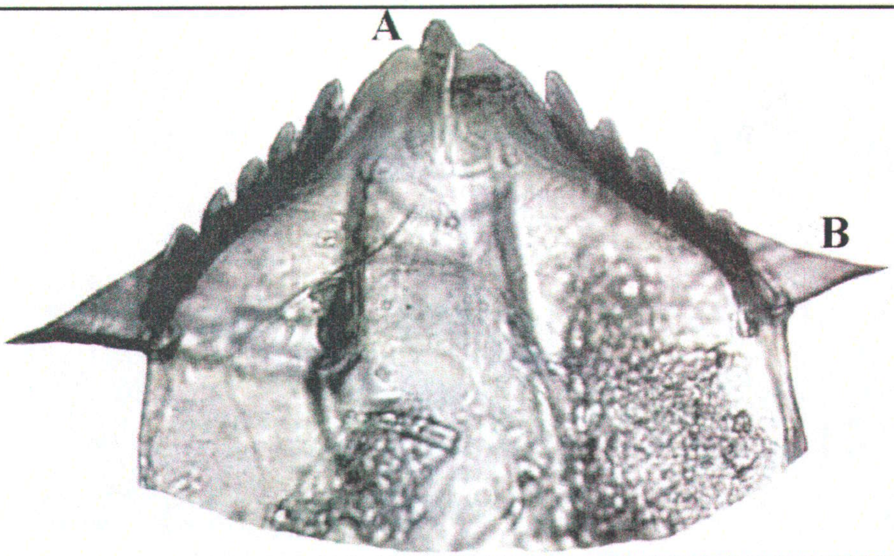


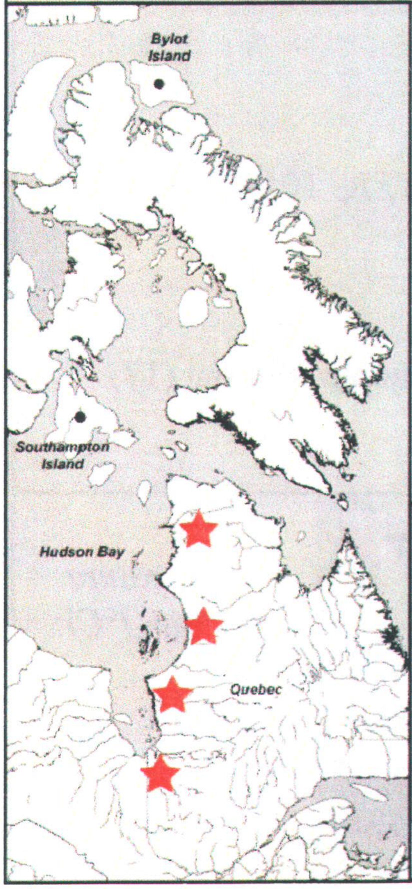
Temperature optimum (°C):

20.6

The visual guide
to subfossil
chironomid analysis

Genera: Psectrocladius septentrionalis-gr
Tribe: Orthocladiinae



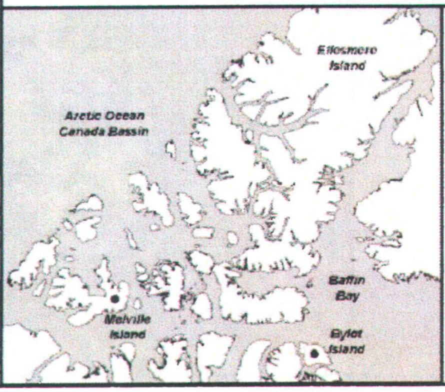


Description:

Median large with a "nipple" (A). Plates are triangular and extended (B). Wiederholm (1983) *Fig.* 9.61 C,D.

Ecology:

Temperate (16, 50, 51), cold taxa (49).

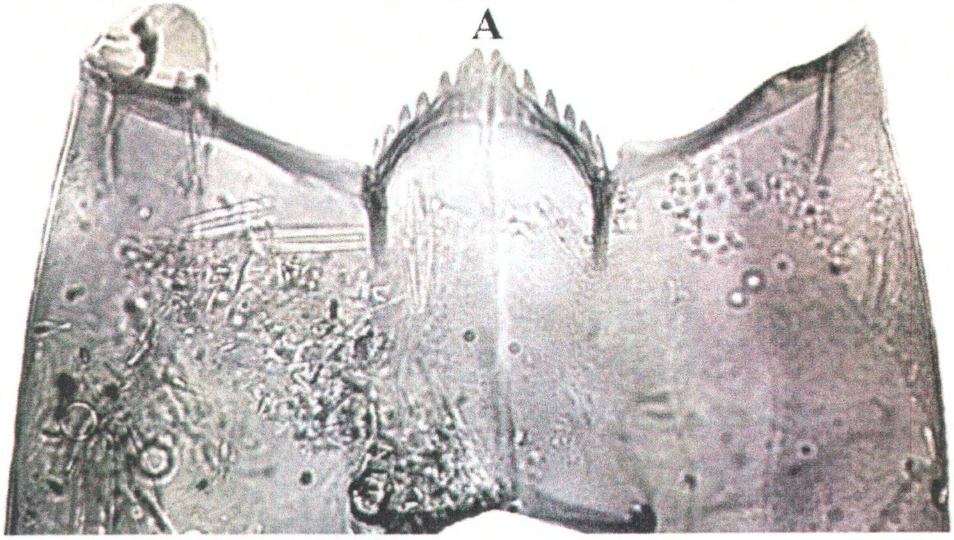


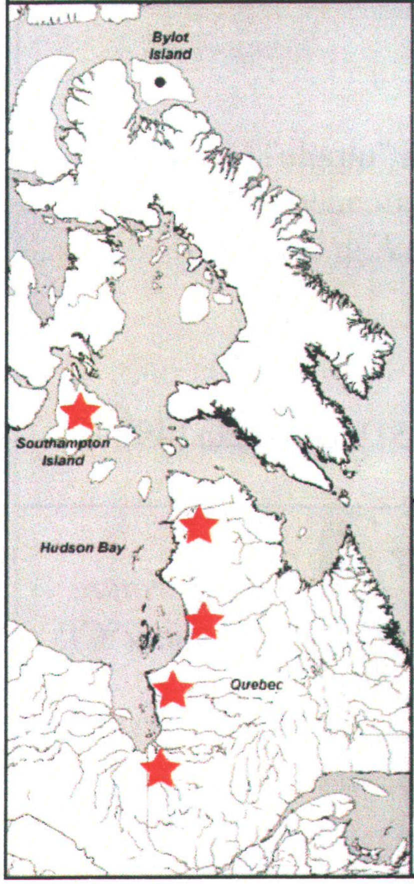
Temperature optimum (°C):

14.0

The visual guide to subfossil chironomid analysis

Genera: Psectrocladius sordidellus-gr
Tribe: Orthocladiinae



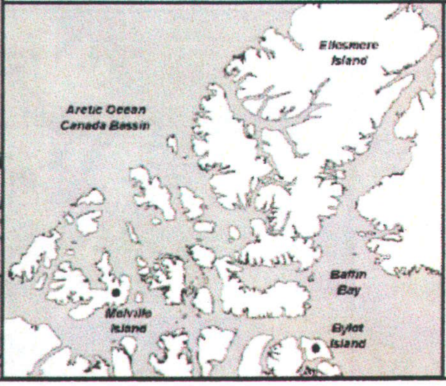


Description:

Two median (A).
Wiederholm (1983) *Fig.* 10.64 E, F.

Ecology:

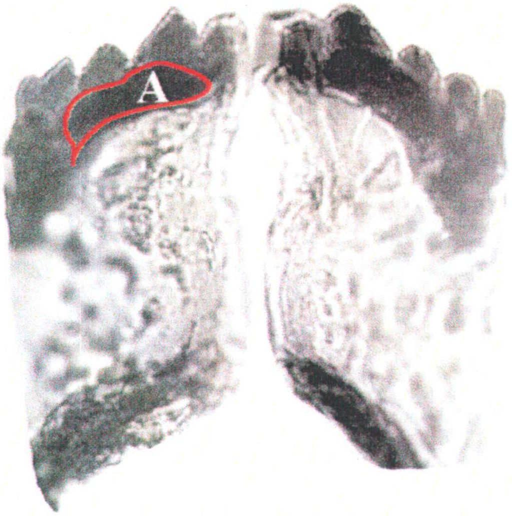
In acidophilic and humic material (13).

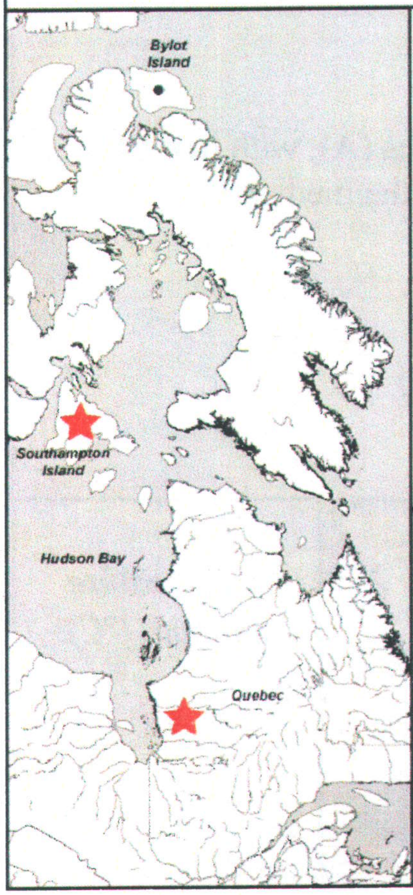


Temperature optimum (°C):

8.1

Genera: Pseudosmittia
Tribe: Orthocladiinae



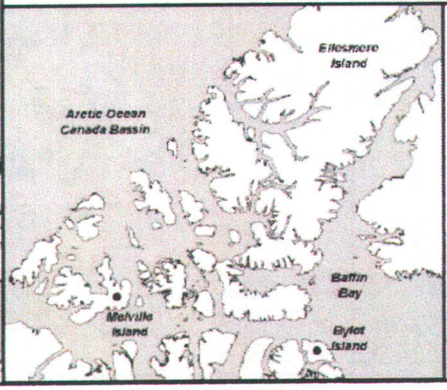


Description:

Ventromental plate large, short and dark like a cat nail (A).

Ecology:

Terrestrial, semi-aquatic habitats, associated with wetland areas (4).

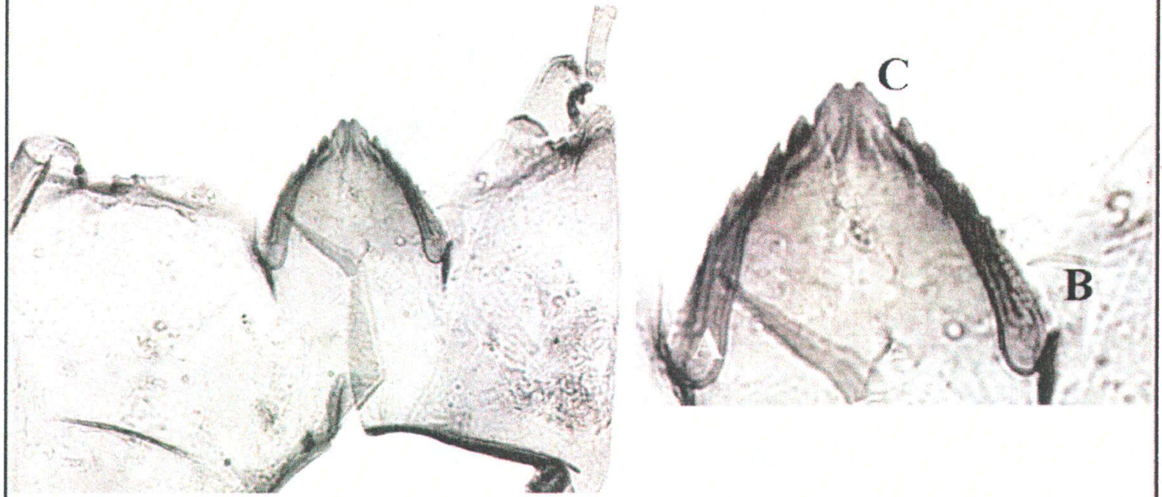


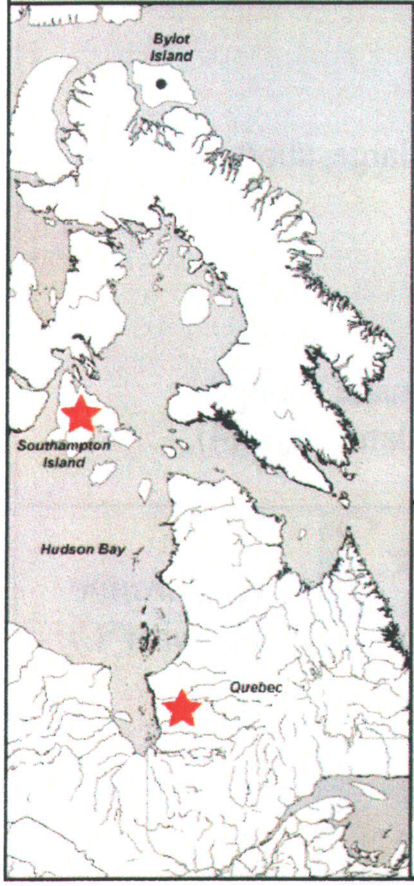
Temperature optimum (°C):

n.a

The visual guide to subfossil chironomid analysis

Genera: Rheocricotopus
Tribe: Orthocladiinae



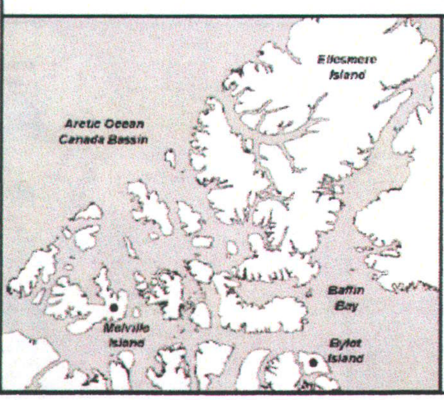


Description:

Large rounded plates (A), with hair (B), accessory tooth on the median (C).

Ecology:

North ot treeline (4).

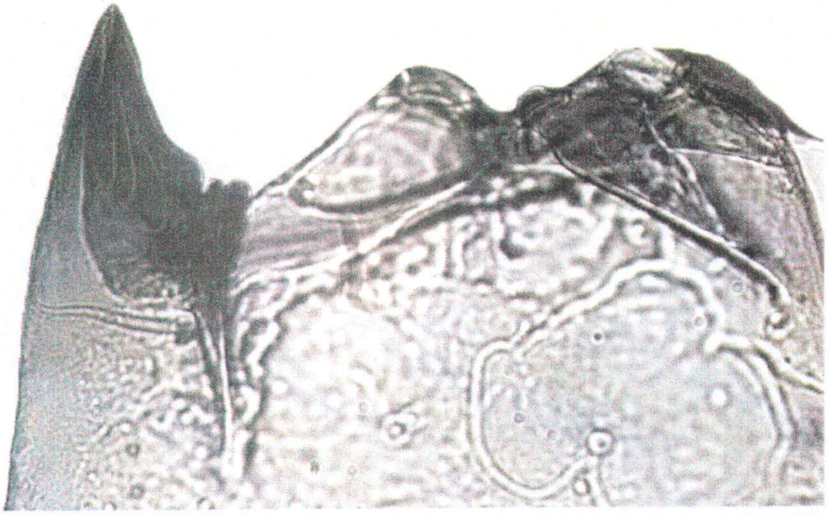


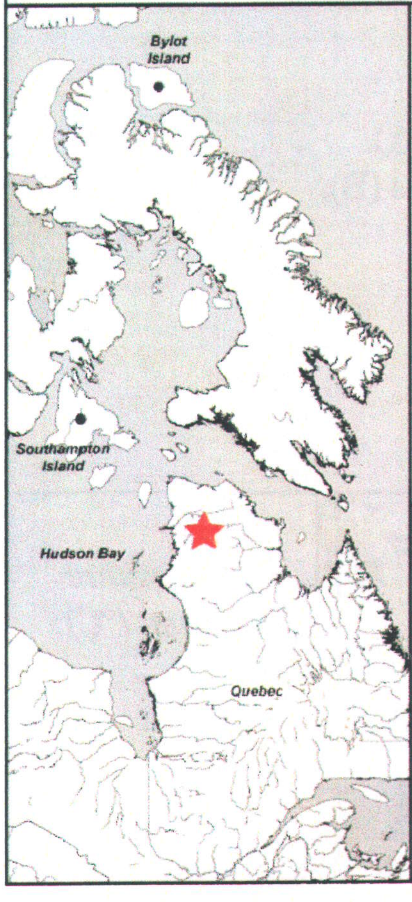
Temperature optimum (°C):

n.a

The visual guide to subfossil chironomid analysis

Genera: Symbiocladius
Tribe: Orthocladiinae





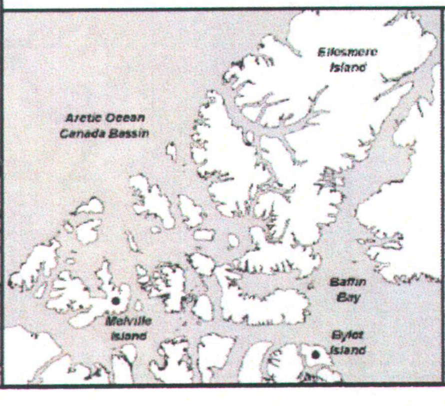
Description:

Extremely long median.

Ecology:

Parasitic on mayfly nymphs (4).

Note: only found in one lake.

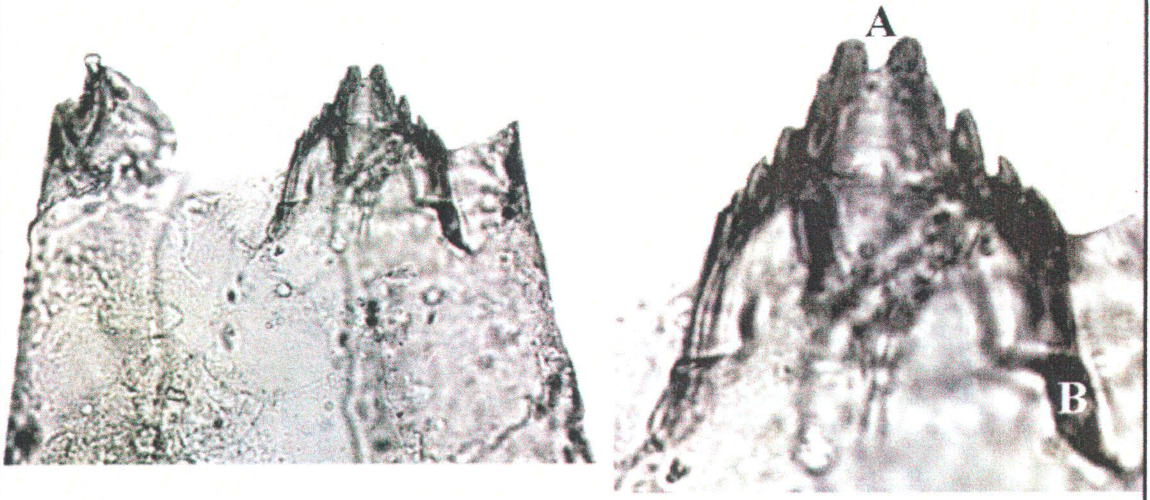


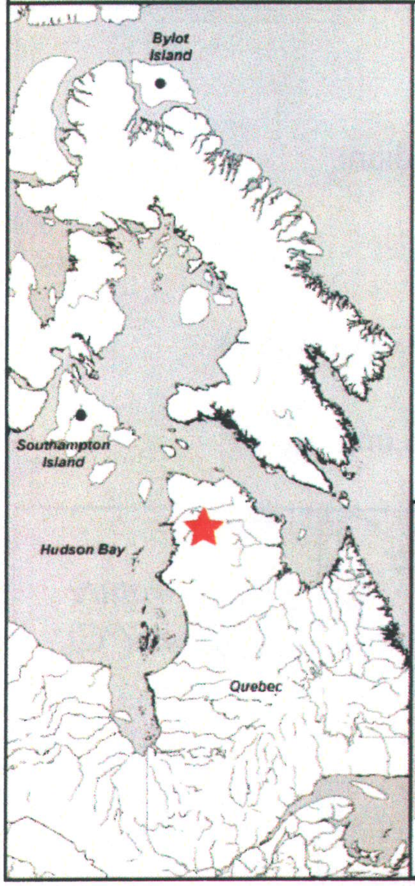
Temperature optimum (°C):

n.a

The visual guide to subfossil chironomid analysis

Genera: Synorthocladius
Tribe: Orthocladiinae



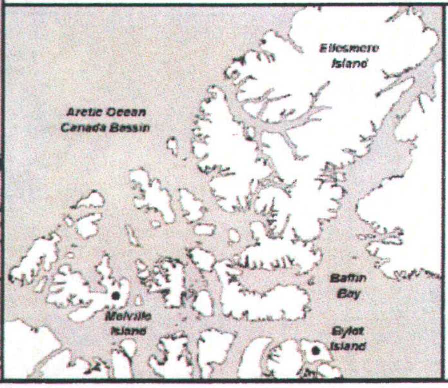


Description:

Two long median (A).
Long and thin plates (B).

Ecology:

Flowing waters (4).

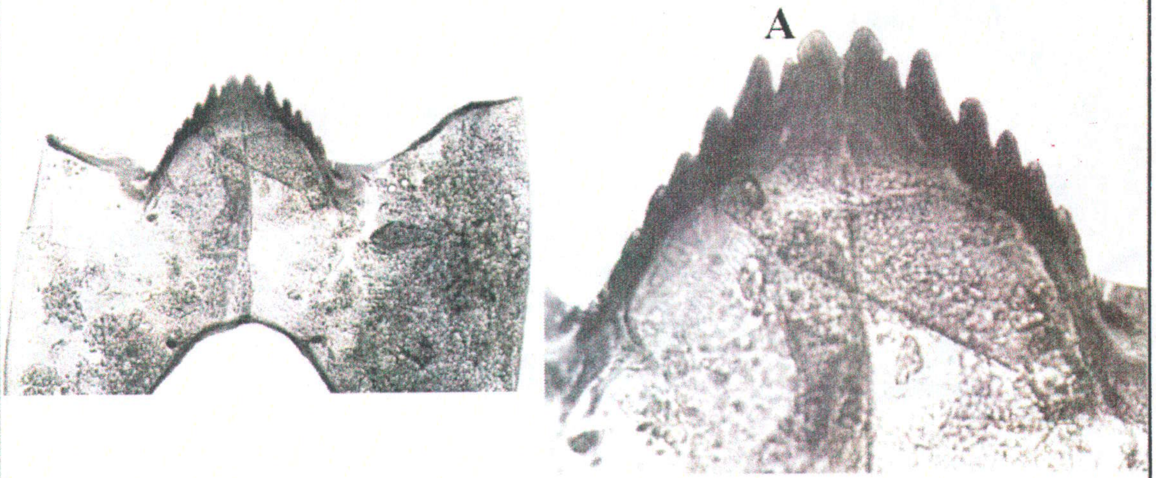


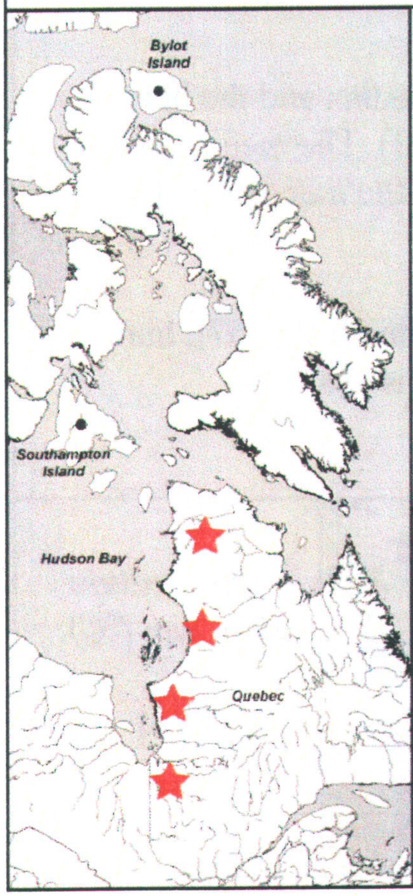
Temperature optimum (°C):

n.a

The visual guide
to subfossil
chironomid analysis

Genera: Zalutschia lingulata pauca
Tribe: Orthocladiinae



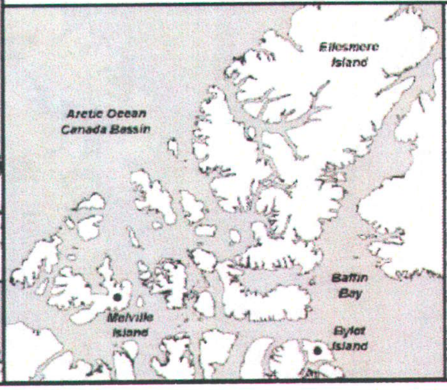


Description:

One small accessory tooth after the median (A).

Ecology:

Productive and anoxic conditions (56).

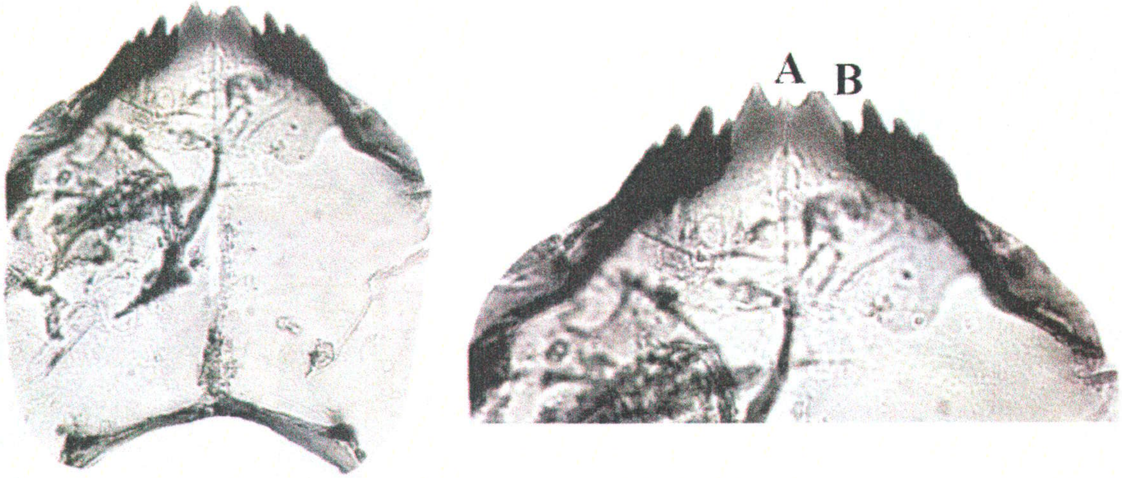


Temperature optimum (°C):

12.9

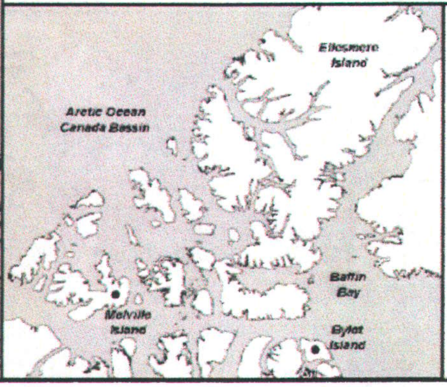
The visual guide
to subfossil
chironomid analysis

Genera: Zalutschia zalutschicola
Tribe: Orthocladiinae



Description:
Gap between the median and the lateral (A). Small lateral (B). The median are pale and the rest of the mentum is dark.

Ecology:
Forest tundra, forested lakes (57), humic and acidic conditions (58).



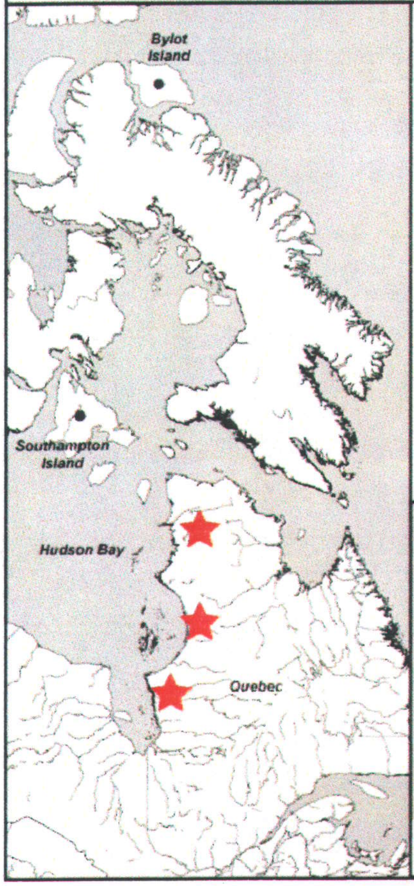
Temperature optimum (°C):

20.1

B.5 Diamesinae

The visual guide to subfossil chironomid analysis

Genera: Protanypus
Tribe: Diamesinae

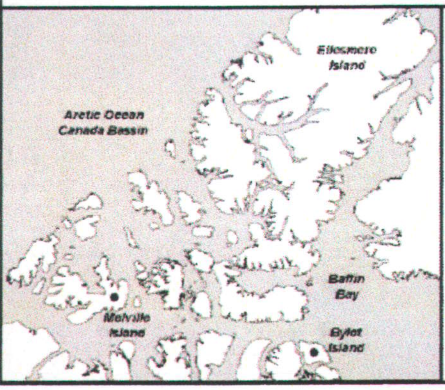


Description:

Large median, plate-like (A). Pointy last laterals (B).

Ecology:

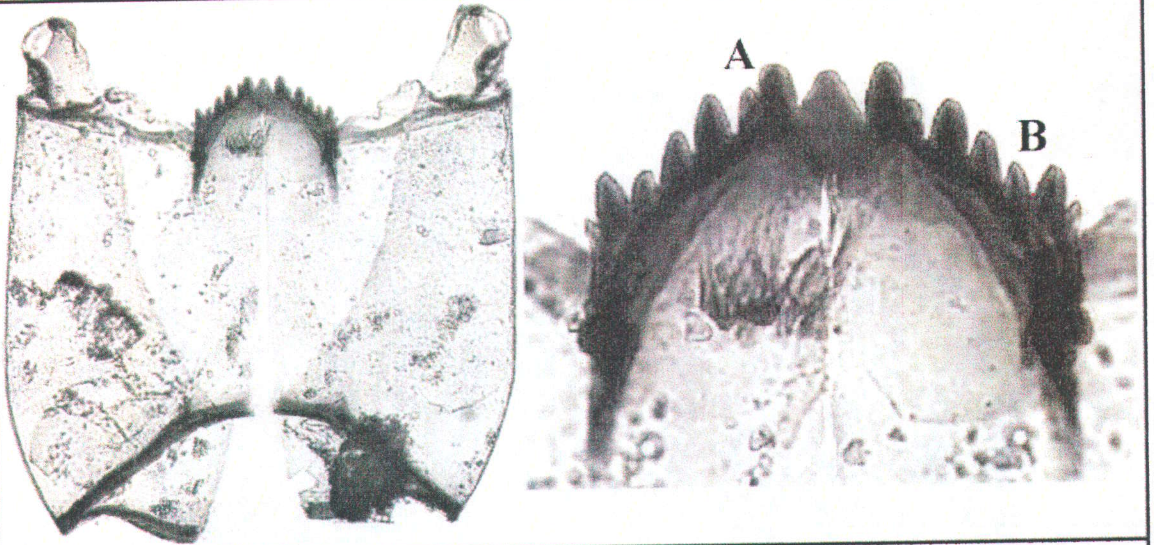
Deep, cold lakes (4).

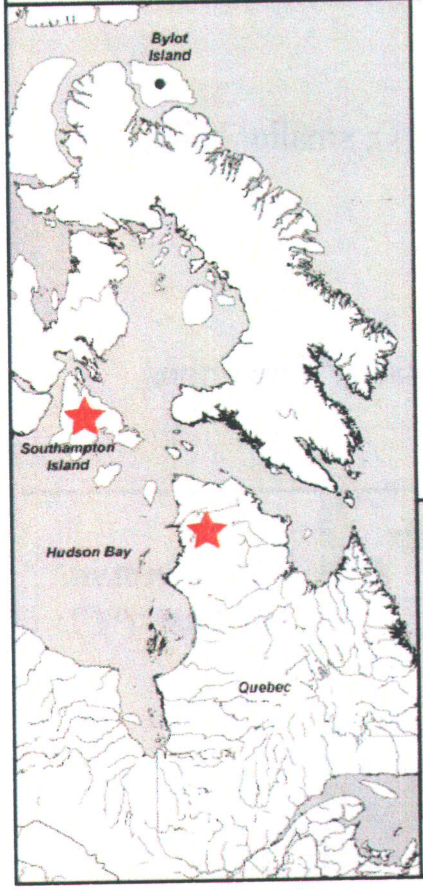


Temperature optimum (°C):

13.3

Genera: Pseudodiamesa
Tribe: Diamesinae



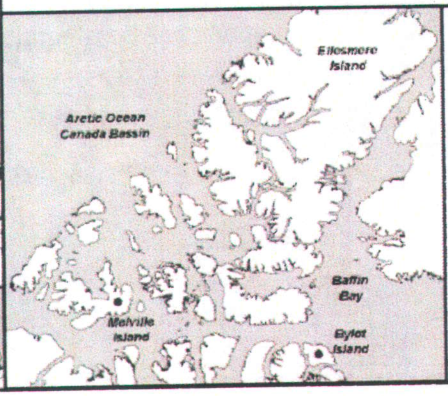


Description:

Second lateral (A) and second last lateral (B) short.

Ecology:

Flowing water and deep still lakes (4).

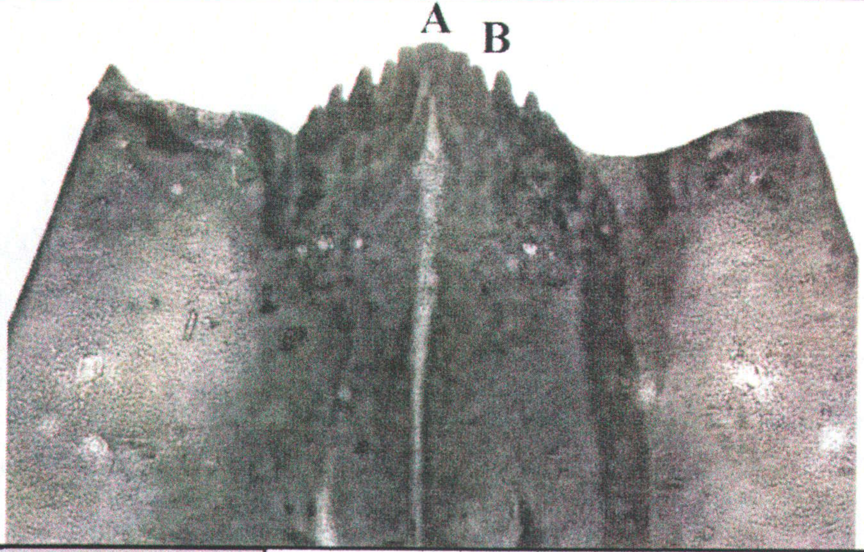


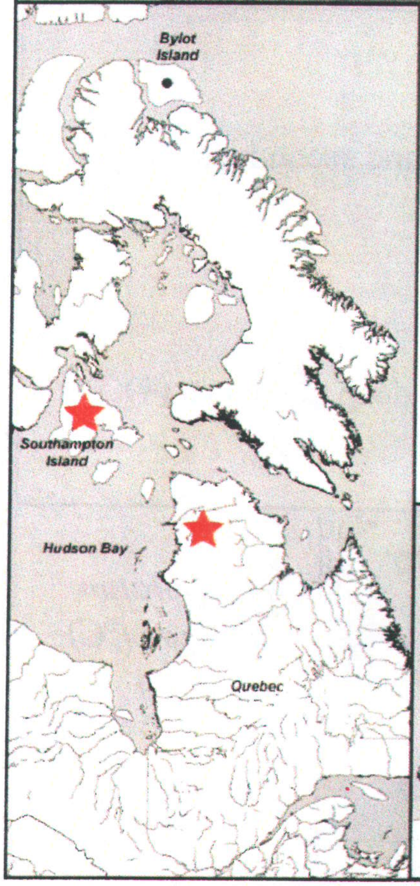
Temperature optimum (°C):

4.9

The visual guide to subfossil chironomid analysis

Genera: Pseudokieferiella
Tribe: Diamesinae



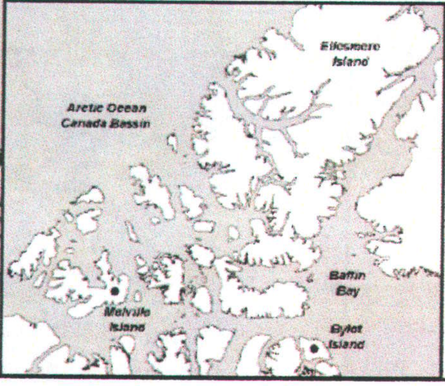


Description:

Plate-like median (A), smaller lateral tooth (B).

Ecology:

Associated with "glacial" conditions (62).



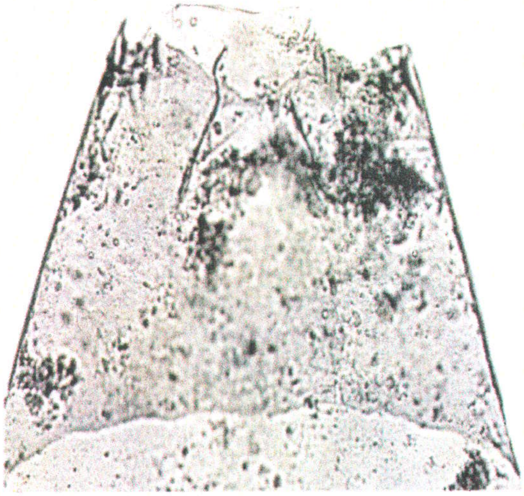
Temperature optimum (°C):

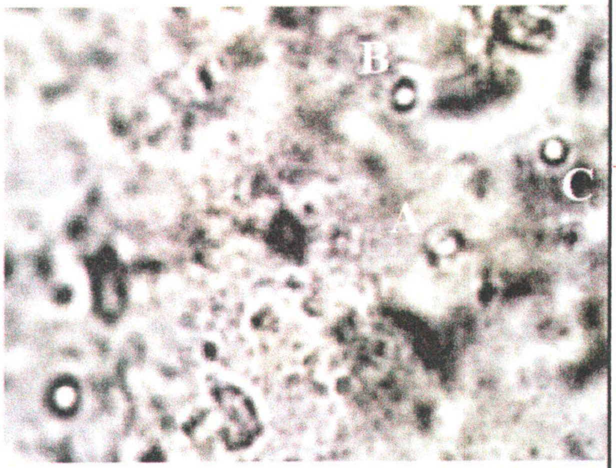
n.a

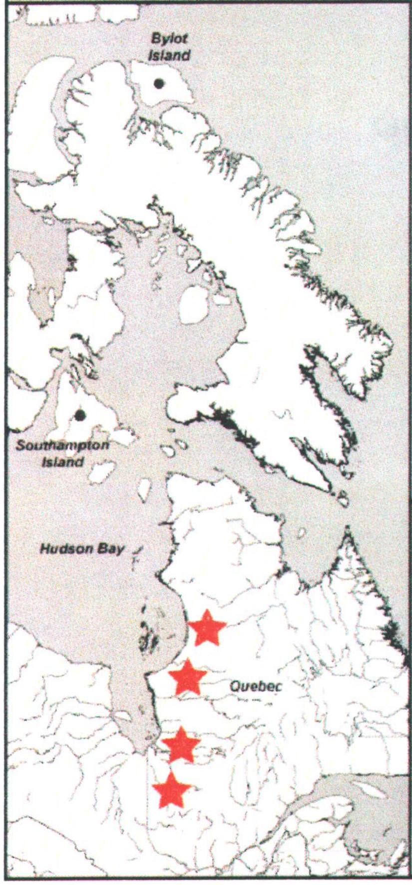
B.6 Tanypodinae

The visual guide to subfossil chironomid analysis

Genera: Ablabesmiyia
Tribe: Tanypodinae, Pentaneurini





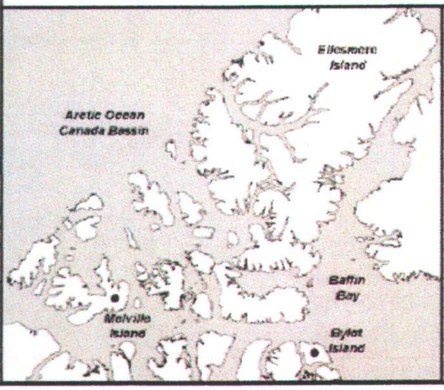


Description:

Pores are in a diagonal.

Ecology:

Warm, shallow lakes, on soft substrate (4)

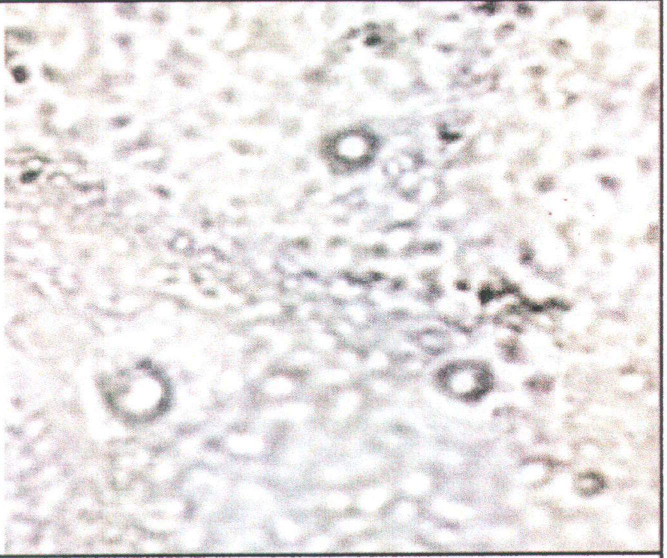


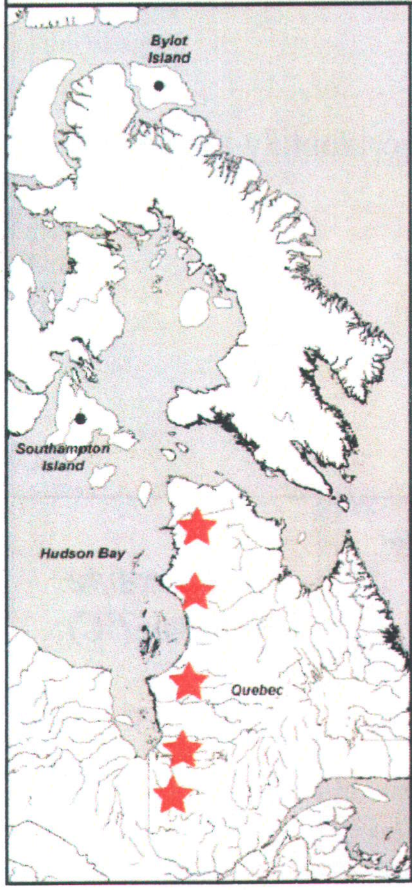
Temperature optimum (°C):

12.4

The visual guide
to subfossil
chironomid analysis

Genera: Procladius
Tribe: Tanypodinae



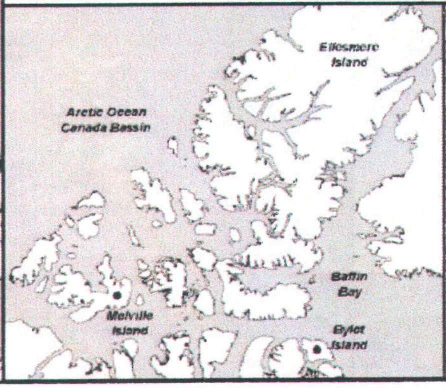


Description:

Paralabial teeth present (A), tip of the mandible is dark (B). note: pores are from the left side of the headcapsule.

Ecology:

Profundal (14), low abundance in fish

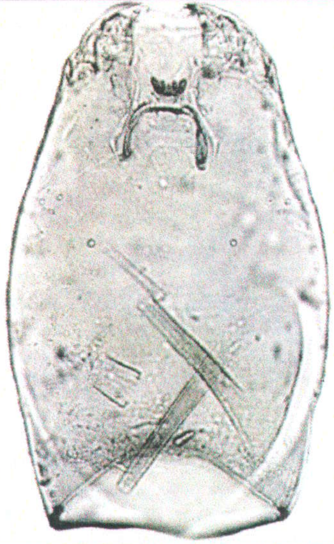


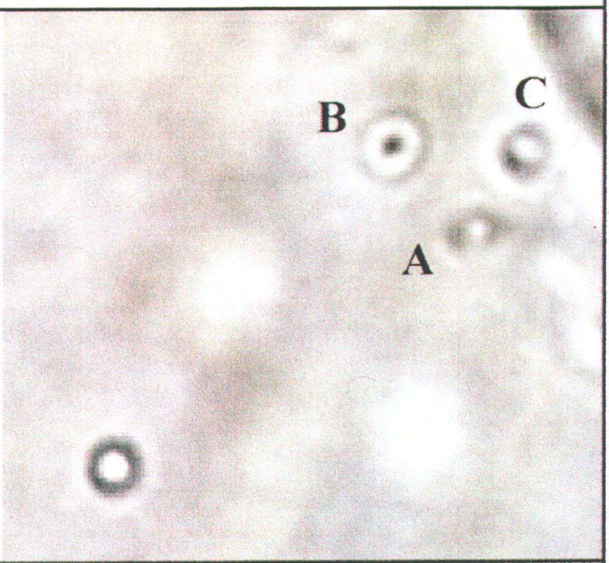
Temperature optimum (°C):

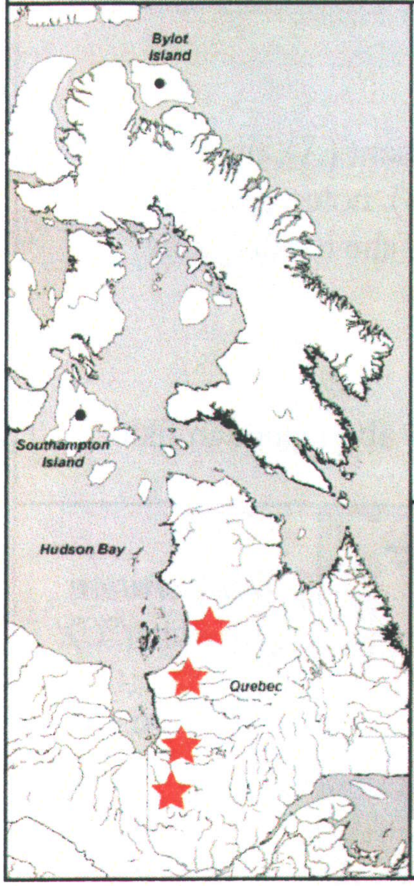
14.9

The visual guide
to subfossil
chironomid analysis

Genera: Telopelopia
Tribe: Tanypodinae, Pentaneurini



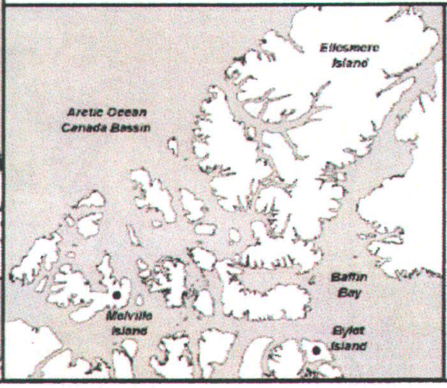




Description:

The two pores are horizontaly aligned (B - C)

Ecology:

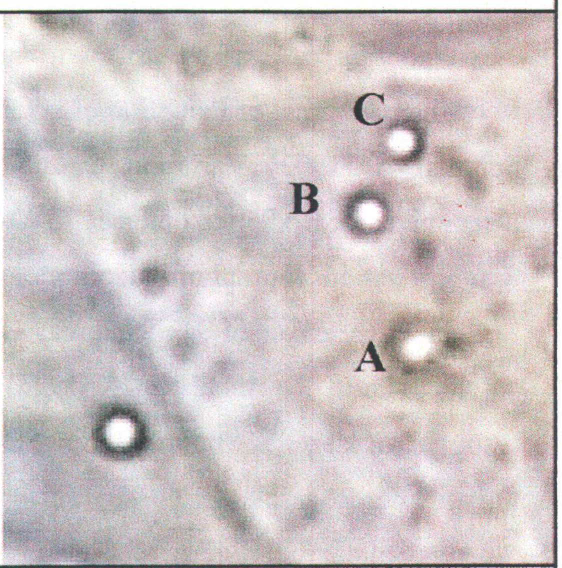


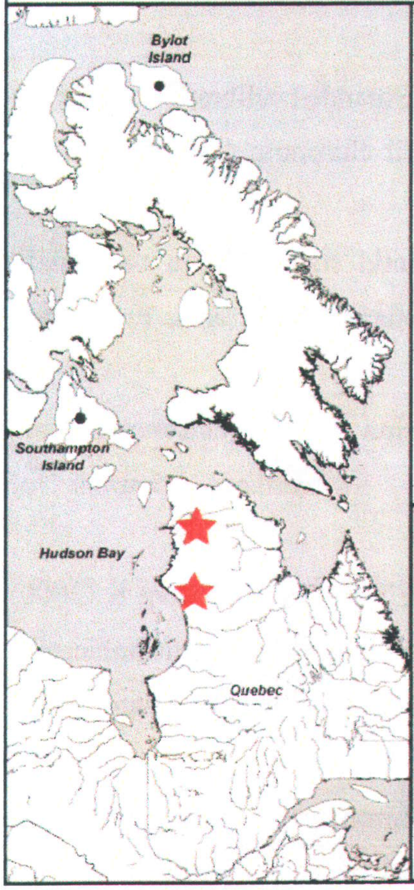
Temperature optimum (°C):

11.3

The visual guide to subfossil chironomid analysis

Genera: Thiennemanimyia
Tribe: Tanypodinae, Pentaneurini



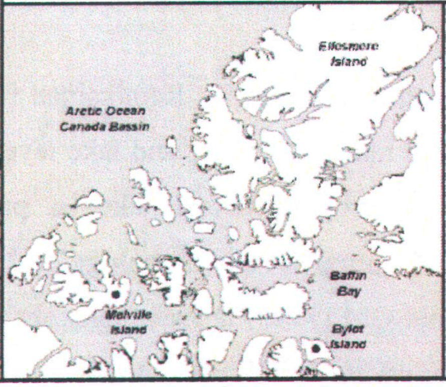


Description:

Two pores are close but in diagonal (B-C)

Ecology:

Cool-adapted, well oxygenated habitats (4), in rivers (28)



Temperature optimum (°C):

1.0

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