UNDER-ICE METHANE ACCUMULATION IN MACKENZIE DELTA LAKES AND POTENTIAL FLUX TO THE ATMOSPHERE AT ICE-OUT

by

Kathryn J. Pipke

B.Ed., Simon Fraser University, 1991
P.B.D. Ed., Simon Fraser University, 1993

THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE

in the Department of Geography

SIMON FRASER UNIVERSITY

July, 1996

ISBN 0-612-17055-1

Title of Thesis/Project/Extended Essay

Under-Ice Methane Accumulation In Mackenzie Delta Lakes And Potential Flux To The Atmosphere At Ice-Out

Author:

(signature)

Kathryn Joanne Pipke
(name)

July 30, 1996
(date)

APPROVAL

Name: Kathryn Joanne Pipke

Degree: Master of Science

Title of Thesis: Under-Ice Methane Accumulation In Mackenzie Delta Lakes And Potential Flux To The Atmosphere At Ice-Out

Examining Committee:

Chair: M.C. Roberts, Professor

L. Lesack, Assistant Professor
Senior Supervisor

R.D. Moore, Associate Professor

K.J. Hall, Professor and Assistant Director
Westwater Research Centre
University of British Columbia
External Examiner

Date Approved: July 30, 1996

Abstract

Under-ice methane accumulations from 76 lakes representing differing frequencies and durations of flooding were determined from among three clusters of lakes distributed over an east-west transect across the central Mackenzie delta. This delta is a lake-rich environment (contains 25,000 lakes) and these 76 lakes represent a stratified sample from 3200 lakes along the east-west transect. Methane accumulation in these lakes is related to the frequency and duration of the spring flooding event. Accumulation in high-closure lakes (not flooded every spring) and low-closure lakes (flooded annually but disconnected from main channels as the summer progresses) was significantly greater (means 451 and 315 μM respectively) than in no-closure lakes (remain connected to main channels throughout open water season) (mean 173 μM). This indicates that the magnitude of methane buildup is strongly related to the flooding and light regimes of the lakes. High-closure lakes are significantly smaller in area than no and low-closure lakes and they also tend to be deeper. A trend for higher under-ice accumulation in the eastern delta compared to the western delta may be related to lower inorganic sedimentation in the eastern delta.

A multiple regression model incorporating chemical indices which are related to primary productivity is able to predict methane accumulation in these lakes with a high degree of precision ($r^2 = 0.88$). Four models which estimate under-ice water volume were used to predict methane fluxes which yielded an area-weighted average ranging from 183 to 2600 mg/m^2 for the set of lakes. Extrapolation of these values to the entire water surface area of the Mackenzie Delta, yields a spring methane pulse of between 0.5 to 12 Gg to the atmosphere. Further extrapolation yields a potential spring pulse of 3 to 109 Gg for Arctic delta lakes on a circumpolar scale.

Best estimates of methane fluxes from the Arctic deltas are probably toward the higher end of the range. An average flux of 2000 mg/m^2 with an average lake surface

area of 35% on all northern deltas would result in a spring pulse of 58 Gg. This estimate represents approximately 0.3% of the annual emissions of methane from northern wetlands.

Acknowledgments

Thanks must first go to my mother, Diana Lifton, for her unquestioning support of my decision to undertake this degree. Even though you knew my financial burden would be great, you foresaw that the rewards of personal gratification would be greater still. I also thank my children, Kristine and Tanya, without whom this whole experience would have been less bright. I thank my brother, Ken, for the friendly competition in the race to graduate first....you won but only by 3 months. Thanks to my other brother, Ted, for your continuing support.

Thanks must also go to Margaret Williams who's life over the past few years has paralleled my own in many ways. Our lives as single parents, struggling to meet the needs of children, employers and our own academic progress, have been made infinitely easier knowing that someone else understands precisely and uncritically why we have no social life as well as the pleasure and scientific insight to be found in a cheap bottle of red wine. Cheers, Peggy! See you at convocation!

I especially thank Professor Lance Lesack for giving me the opportunity to earn this degree and, in the process, to allow me to expand my personal experiences far beyond what I might have accomplished on my own. Thank you for being my senior supervisor, for your academic guidance and generous financial support, and for your patience. Thanks also to Professor Dan Moore for your guidance in writing this thesis and to Professor Ken Hall for being the external examiner at my defence.

Thank you also to Professor Arthur Roberts who first planted in my brain the idea that I might actually be able to be a graduate student. Your encouragement and belief in my abilities was much valued and appreciated. I also thank Professor Mike Roberts for whom I had the immense pleasure of TA'ing for on numerous occasions. Thank you Dr. Leslie Smith for your work on ice-covered alpine lakes which provided the inspiration for this project. Your assistance in collecting and analysing samples during our field season was highly valued. I also thank you for your continued friendship and interest in the development of this thesis over the last two years as well as your suggestions and direction toward relevant literature. Thanks also to Ray Squirrel for your expertise in producing the maps presented in this thesis and to Katja Bach and Dr. P. Marsh for providing additional data used in this thesis.

Special thanks goes out to my peers, Carolyn Teare, Betty Bernoth and Maggie Cobbett. Carolyn, I especially thank you for the uncounted hours you spent helping me to understand statistics and the intricate workings of our computer's programs. Lately I have missed our discussions about current scientific papers, theory, and methodology. The lab became a lot quieter when you left to pursue your career. Thanks to all three of you for sharing the "Inuvik experience" and the ongoing discussions about the frustrations and joys of being grad students.

Finally, special thanks to my many personal friends who have allowed me to be part of their lives and who have given me unconditional support throughout my academic career. May the bonds that have been forged by the university experience remain as strong throughout the rest of our lives.

Table of Contents

List of Tables

List of Figures

Chapter 1
Introduction

The rise in atmospheric concentration of methane, and other, greenhouse gases has raised concern about the potential for increased temperatures due to the possible alteration of the Earth's atmospheric radiation balance. The atmospheric concentration of methane is currently increasing at an annual rate of 0.8 to 1.0%, doubling in the last 200 years (Houghton et al., 1990). To account for current concentrations and increases, annual emissions on the order of 540 Tg (1 Tg = 10^{12} g) are required. In order to intelligently predict changes in concentrations and the subsequent effects on the global budget, it is necessary to develop an understanding of the role individual ecosystems have in the exchange of this radiatively important trace gas between the earth's surface and the atmosphere. To this end, many methane producing systems have been identified and extensive work on quantitatively estimating their inputs to the global budget has been done. Various terrestrial sources contribute approximately 98% of the global atmospheric production (Cicerone and Oremland, 1988). Recent estimates include inputs of approximately 20% from each of wetlands (largest natural source), ruminants and termites, and rice paddies, with the remaining 40% attributed to other human activities. All of these estimates are subject to considerable uncertainties (Fung et al., 1991).

Atmospheric methane measurements taken at Cape Meares on the Oregon coast between 1979 and 1992 indicate a seasonal cycle in atmospheric concentrations in the northern hemisphere with peak tropospheric concentrations occurring in the spring and fall (Khalil et al., 1993). To my knowledge, trace gas studies of northern terrestrial and freshwater ecosystems have focused on open water and vegetation emissions during ice free conditions and potentially address the fall peak in atmospheric methane concentrations. High fall emissions are a result of the decomposition and fermentation of an increased supply of organic material to lake and wetland sediments during the late summer and fall (Hamilton et al., 1994). The spring peak, however, has not yet been adequately addressed and the recognition and confusion surrounding this peak helped spark the interest to undertake this study for it has been postulated that a pulsed release of methane to the atmosphere at the time of ice breakup within lakes may be widespread at high latitudes and may play a role in the observed increase in tropospheric methane concentrations in the northern hemisphere (Smith and Lewis, 1992).

Within this introduction, background information is given on methane flux estimates from northern ecosystems by highlighting two main studies that have taken place within the last 10 years. Controls on methane production and accumulation within under-ice water columns as relevant to the Mackenzie Delta lakes are also discussed. By drawing on this background information and by identifying a potentially significant source of atmospheric methane that has been under-represented in current flux estimates, the two main hypothesis of this thesis, as well as the study objectives, are derived and presented.

Current Methane Flux Estimates from Northern Ecosystems

The contribution of methane to the global budget from northern Canada and the Soviet Union is poorly understood because of the vastness of the area, the logistic difficulties inherent in working in these remote, relatively inaccessible and inhospitable environments, and the heterogeneous nature of the ecosystems contained therein. Recent estimates of methane emissions from high latitude ecosystems of tundra, boreal bogs and fens, and taiga indicate that this area has global significance as an atmospheric methane source. Estimated annual fluxes range from 10 Tg yr^{-1} and 11 Tg yr^{-1} (Matthews and Fung, 1987; Bartlett et al., 1992; Fan et al, 1992) to 22 Tg yr^{-1} (Matthews and Fung, 1987) to 38 Tg yr^{-1} (Whalen and Reeburgh, 1990). The estimates span a wide range due to adoption of different global areas for the estimated flux, the diversity of ecosystem types in any one region, the poor knowledge of the areal extent of any one ecosystem type and various rates and periods for methane emission from each type of vegetation. Also, most global flux estimates do not include Arctic lakes which are important sources of methane, about half the flux in the Yukon-Kuskokwim delta (Fan et al., 1992). The most effective way to obtain more accurate flux estimates is to gather more data from representative northern ecosystems and obtain more accurate estimates of the areal extent of each ecosystem type.

To this end, two major studies, focused on obtaining quantitative estimates of annual methane fluxes from northern ecosystems to the atmosphere, occurred in the late 1980's and early 1990's. Both of these studies used sampling designs which accommodated the heterogeneous distribution of wetland types within the northern ecosystem. Both studies attempted to compare and correlate flux results from aircraft, tower and enclosure sampling methodologies.

The Yukon-Kuskokwim delta in Alaska was intensively studied during a six week period (July 3 to August 10) in 1988. The study obtained estimates of methane flux from three major environments: lakes, wet meadow tundra, and dry upland tundra. Measurements taken from wet meadow tundra yielded values approximately 2 orders of magnitude higher than values obtained from drier upland tundra. It was also found that the highest emissions of methane originated from small delta lakes. Within these lakes, the presence of vegetation significantly enhanced the methane flux compared to open water rates. By extrapolating the values obtained from these observations, Fan et al. (1992) estimated total methane emissions from the global tundra area to be 22 Tg yr^{-1} or about 5% of the annual global methane budget. Without inclusion of lakes, flux estimates decreased to between 11 and 12 Tg yr(Bartlett et al., 1992; Fan et al., 1992) indicating the significance of lakes as methane sources.

The Northern Wetlands Study, undertaken on the Hudson Bay Lowlands, was designed as a multiyear study to determine the importance of northern wetland ecosystems as sources and sinks for a variety of atmospheric gases of which methane was one. Six locations along a 140 km x 40 km transect stretching eastward from North Point on James Bay to Kinosheo Lake plus a second site situated in the subarctic region of the northern Hudson Bay lowland were sampled intensively. Regional flux surveys were also conducted by aircraft between the two main study areas (Glooschenko et al., 1994). Weighted emissions for the Hudson Bay Lowland, using sixteen wetland classes, was estimated at 0.54 Tg yr^{-1}. Extrapolation of flux values to include all northern wetlands yielded an annual flux rate of 17 Tg yr^{-1} or 3 to 4% of the global methane source (Roulet et al., 1994).

Annual flux estimates from these two studies differ mainly because the measured fluxes are extrapolated to vastly different areas. Measured fluxes from the Yukon-Kuskokwim study are used to estimate flux from the entire northern tundra region from 50° N to 80°N (7.3 x 10^6 km^{-2} (Matthews, 1983)) whereas the Hudson Bay Lowland study restricts its estimate to include flux from wetlands only between 40°N and 80°N (2.4 x 10^6 km^2) (Roulet et al., 1994). Therefore, even though the sampling designs allowed for more complete ecosystem representation than previous studies, comparison of estimated annual methane flux is difficult because of the differences in areas that the extrapolations are applied to.

Estimates of methane contribution to the global budget from northern ecosystems, such as cited in the above studies, are based on extrapolations from summer flux values only. There is no indication in the literature that any fluxes were measured immediately after ice-out and incorporated into the total flux calculations. Thus a potentially important contributor to the annual flux could have been omitted from the northern budget estimates. Just how great the buildup of methane may be under ice caps is discussed in the following section.

Under-Ice Accumulation of Methane

In a study of five alpine lakes in the Colorado Rockies, Smith and Lewis (1992) demonstrated that under-ice methane accumulation is considerable in these lakes. Long Lake, for example, had an under-ice methane accumulation of 53 times the summer water column concentrations. This lake is shallow and productive with extensive macrophyte vegetation covering the sediments and, in this way, is similar to the lakes that occupy the deltas and floodplains of the rivers flowing northward into the Arctic Ocean and the Beaufort Sea. Even though rates of decomposition of organic material by microbial organisms slows in response to decreased temperatures, it does not cease. Therefore, the production of methane within anoxic sediments continues through the long winter beneath the thick ice cover that accumulates on these lakes. The ice cover prevents exchange of gases between the lake surface and the atmosphere thus allowing the depletion of oxygen within the water column as well as the accumulation of methane and carbon dioxide. During spring breakup, the ice cover is removed and the wind mixes the water column releasing the accumulated methane in a pulse. Smith and Lewis (1992) postulated that these pulses from lakes could contribute strongly to the spring peak of atmospheric methane.

Following analogous reasoning, a recent study by Lammers and Suess (1995) in the Sea of Okhotsk showed a spring flux at ice-out approximately 4 times greater than that observed in the summer. Lammers and Suess (1995) concluded that the magnitude of the methane flux released during the retreat of the sea ice cover is large enough to contribute to the irregular distribution of atmospheric methane on a regional scale. Even though the flux is not large enough to be a significant influence on the annual variation of atmospheric methane in the northern hemisphere, they conclude that the spring release of methane from parts of the Arctic Ocean combines with and modulates other seasonal active sources in the northern hemisphere and thus may help generate the observed spring peak of atmospheric methane. Without measurements from other representative sources, however, this remains as conjecture.

With under-ice accumulation of methane and subsequent release to the atmosphere during ice-out being observed in both northern oceanic ecosystems and aquatic alpine ecosystems, it follows that other aquatic systems in which ice acts as a barrier to gas exchange could be important contributors to the global methane cycle as well. These systems would include lakes, ponds, and wetlands on the Arctic tundra as well as the organic rich lakes which cover an estimated 20 to 35 percent of the deltas of northward flowing river systems. Of these two ecosystems, the delta lakes may be greater potential contributors of methane to the atmosphere than tundra aquatic ecosystems because they receive a large annual influx of nutrients to their systems with the spring floodwaters. These nutrients promote the high rates of productivity which is characteristic of delta lakes. This, in turn, provides a high carbon flux to the sediments which supplies the substrate upon which the methanogenic bacteria feed.

What is not known is how much methane is actually within the ice-covered lakes on northern deltas and how much will actually be emitted to the atmosphere after the ice has left the lakes. To date, the flux estimates from northern ecosystems rely on summer values only with the only exception being the ice-out flux from the Sea of Okhotsk (Lammers and Suess, 1995). To my knowledge, very few studies report under-ice methane concentrations. Two such studies were done in the Antarctic (Smith et al., 1993; Frazma et al., 1991), one in the Colorado Rockies (Smith and Lewis, 1992), and one study focused on temperate ice-covered lakes in Minnesota (Michmerhuizen and Striegl, 1995). Based on the fact that northern delta lakes are productive ecosystems for which the accumulation of under-ice methane and the subsequent potential flux to the atmosphere during ice-out has not been measured, the objectives for this study include:

(1) Obtaining a quantitative first order estimate of potential methane accumulation in ice-covered Arctic lakes on the Mackenzie River delta.

(2) Estimating subsequent flux to the atmosphere via "lake burping".

(3) Extrapolating flux values for the Mackenzie Delta to estimate flux values for northern delta ecosystems on a circumpolar scale.

(4) Comparing this estimate with present values in the global methane budget to ascertain the significance of these northern delta lakes as methane contributors to the budget. Whether or not the methane pulse to the atmosphere at time of ice-out offers a potential explanation for the atmospheric spring methane peak will also be addressed.

Prior to presenting the hypothesis that guides the study design for this thesis, it is important to provide background information on the Mackenzie Delta lakes in order to draw the link between frequency and duration of spring flooding events and the relative degree of primary productivity within these lakes. Backgound information on established controls of methane production is also necessary as they are inextricably linked to degree of primary productivity in the lakes and the subsequent carbon flux to the sediments.

The Mackenzie Delta:

Background Information

General Description

The headwaters of the largest river system in Canada, the Mackenzie River system, rise in the Rocky Mountains at a distance of 4141 km south of its mouth. The Peace and Athabasca Rivers feed the Slave River which in turn drains into Great Slave Lake (Fig. 1). From Great Slave Lake the Mackenzie River flows north for 1600 km before emptying into the Beaufort Sea. In total, the drainage area of this system is 1.805 million km^2 (Anon, 1975).

Situated in the zone of continuous permafrost, the active delta of the Mackenzie River covers an area of 12,000 km^2 (Fig. 1). Delta sediment accumulation ranges from

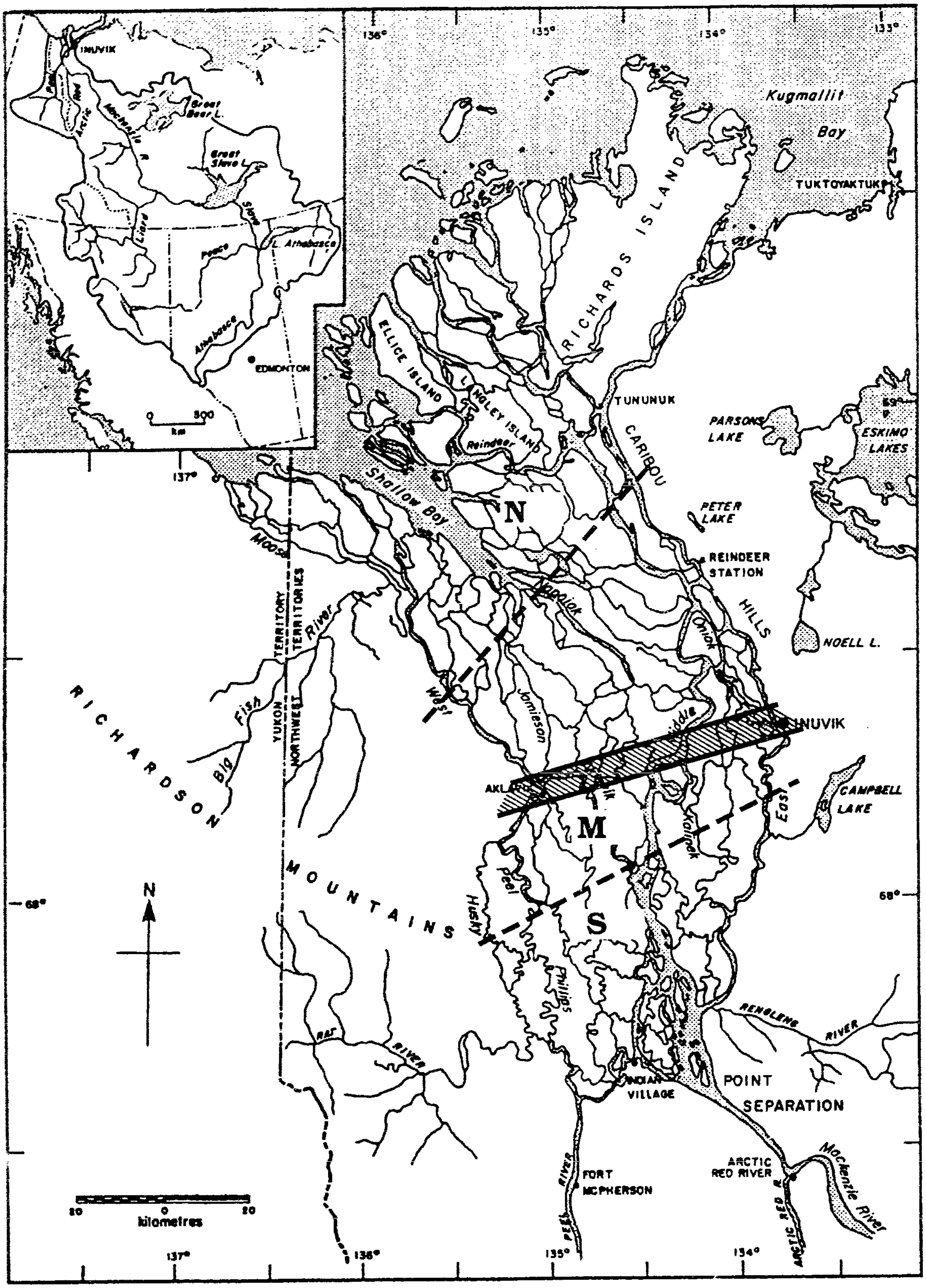
60 to 90 meters thick for a total deposition volume of 1,200 km^3 (Lewis, 1988). An estimated 25,000 lakes interconnected by thousands of kilometers of river channels dominate the delta ecosystem. The mass of water held by the delta leads to the creation of a climatic microcosm with higher mean temperatures enabling the tree line to extend as far north as Shallow Bay (Pearce, 1991). In contrast, the vegetation of the bordering uplands is predominantly scrub tundra from Inuvik northward (Mackay, 1963).

Organic-rich lakes, averaging less than 2 m in depth, cover between 15 and 30% of the area in the southern and northern sections of the delta and between 30 and 50% in the central delta (Mackay, 1963). These three subregions of the delta (Fig. 1), can be recognized either by dominant vegetation type (Gill, 1978) or levee elevation (Mackay, 1963) as both systems of classification are concordant. The southern delta has levee heights greater than 6 m asl and the vegetation on the levees is dominated by spruce and alder. The highest sites, elevated well above the modern flooding and erosional regime by the formation of ice lenses within the substrate, are characterized by thick organic substrates, active layer depths of 30 to 50 cm and luxuriant ground cover of lichens, crowberry, blueberry and other heaths with tundra affinities (Pearce, 1991). In the middle delta levee elevations range between 3 and 6 m asl with spruce and willow being the characteristic vegetation on the land surface. The northern delta has levees less than 3 m asl with willow and small bushes forming the ground cover. The border between the middle and northern delta is the northern extent of the tree line on the delta. Throughout the delta, sedges, horsetails, and pondweeds are common inhabitants of channel and lake shorelines.

Hydrology

Two components of the hydrology of the Mackenzie Delta are of interest to this thesis: (1) the source areas for the flood waters and the subsequent potential effect on the spatial distribution of methane concentration in the delta lakes, and (2) the spring flood

Fig. 1. Location map of the Mackenzie Delta, N.W.T., Canada. The marked section between Inuvik and Aklavik represents the transect containing the sample lakes. Note that the delta has also been subdivided into 3 sections, Northern (N), Middle (M), and Southern (S) which reflect major divisions based upon dominant vegetation and sill elevation regime (Map modified from Marsh and Hey, 1988).


Kugmallit
Bay
TUKTOYAKTUK
RICHARDS ISLAND
ELLICE ISLAND
LANGLEY ISLAND
Reindeer
Shallow Bay
TUNUNUK
CARIBOU
PARSONS LAKE
ESKIMO LAKES
PETER LAKE
REINDEER STATION
HILLS
NOELL L.
N
INUVIK
AKLAVIK
CAMPBELL LAKE
M
S
RICHARDSON
MOUNTAINS
YUKON TERRITORY
NORTHWEST TERRITORIES
Big Fish
Moose
River
West
Jamieson
Middle
Peel
Husky
Phillips
Kalinek
East
Oniak
RENGLENG RIVER
RAT RIVER
POINT SEPARATION
INDIAN VILLAGE
FORT MCPHERSON
PEEL RIVER
ARCTIC RED RIVER
ARCTIC RED R.
Mackenzie River
kilometres
20
0
20
136°
135°
134°
133°
137°
68°
69°
INUVIK
Great Bear L.
Great Slave L.
Arctic
Mackenzie R.
Peace
L. Athabasca
Athabasca
EDMONTON
Liard
Slave
km
500

event, which has considerable control over the ecological characteristics of the delta lakes (Lesack et al., 1996).

The west side of the delta receives 90% of its water from the Peel and Rat Rivers which drain the Mackenzie Mountains and are heavily laden with sediment. The water on the east side of the delta originates almost solely from the Mackenzie River with small contributions from channels draining the Caribou Hills. The eastern tributaries are almost sediment deficient because of geologic controls but the main Mackenzie River is supplied by the silt laden Laird River which is responsible for about 40% of the total sediment load of the Mackenzie River (Marsh and Ferguson, 1988). The waters which feed the mid delta lakes, while containing mainly Mackenzie River water, may also contain 25% Peel River and mountain water.

Spring flooding is maximized because the southern portions of the Mackenzie basin thaw before the northern portions. Ice jamming downstream causes backup of the water with the frequency and duration of flooding increasing in a down-delta direction (Marsh and Hey, 1991). The duration and level of flooding is dependent upon the type of breakup that occurs in the spring (Bigras, 1990). Thermal breakups are the most common type on the Mackenzie delta and result in lower flood levels and shorter duration of the flooding event. With thermal breakups, the northern and central delta lakes are most affected with southern, higher elevation lakes receiving little or no floodwater. Thermal breakups result from high air temperatures, high insolation, reduced albedo, low water flow and an extremely weakened ice cover on the river's main channels. In contrast, mechanical breakups are much more dynamic. They are accompanied by low air temperatures and, with long lasting snow cover over the ice, high albedo. The river therefore has a very strong ice cover which has to be moved and broken up by the force of the spring flood wave. This causes extreme flooding which is high enough to top even the lakes at the higher elevations above the main channel.

As well as a north-south variation in flood water depths, the cross-delta shape of the floodwave is convex probably caused by more extensive ice jamming of the central channel compared to the eastern and western channels (P. Marsh, personal communication). Because extensive data is unavailable at this time for the central and western delta I will assume that this pattern remains consistent from year to year. For the eastern delta, however, over 20 years of data indicates a flood level range between 4.3 to 7.8 m asl with an average mean level of 5.6 m asl occurring on June 3 (Marsh and Ferguson, 1988). After this date, the lake levels fall rapidly in response to falling Mackenzie River levels, with water levels dropping an average of 1.04 m over a 4 day period following the peak. Lower summer floods from precipitation events within the drainage basin also occur but, because their magnitude is much less, their effect on the delta ecosystem is less pronounced.

Lake classification based upon flooding frequency and duration

Delta lakes are linked to nearby lakes or channels by single or multiple breaches in the sill (lowest point on the connecting thalweg). The lakes exist on a continuum of elevations above the main river channels and, as such, frequency and duration of flooding of each lake depends upon the height of the main river flood event. Marsh and Hey (1989) classified Mackenzie Delta lakes as high-closure, low-closure, or no-closure depending upon the duration and frequency of spring floodwaters entering the lake. High-closure lakes have a flood return period of greater than 1 year with a duration period of approximately 14 days. Low closure lakes are flooded annually but become disconnected to the main channel as the summer progresses. No-closure lakes remain connected to the main channel throughout the open water period. Because the sill elevation defines the closure status of the lake, high-sill, low-sill, and no-sill are synonymous with high-closure, low-closure and no-closure. Marsh and Hey (1989) have estimated that high-closure, low-closure, and no-closure lakes constitute approximately 33%, 55%, and 12% respectively of lakes in the Inuvik area of the Mackenzie Delta.

Lesack et al., (1996) have determined that chemical composition of the frequently flooded lakes appears to be relatively stable from year to year. This stability is a result of chemical reinitialization of the water columns by the annual flood event. The composition of high closure lakes which are infrequently flooded are subject to strong biogeochemical controls, but the strength of the effect is proportional to the length of time that the lake has not been flooded. For example, Dishwater Lake went through a period of 8 years where it was not flooded. When reinitialized by floodwater, the chemistry shifted from Ca^{2+} plus SO_4^{2-} dominance to Ca^{2+} plus HCO^{3-}.

Aerial surveys conducted along a 75 km by 5 km mid delta transect (Fig. 1) during the 1992 spring breakup allowed the relation between dates of lake flooding and channel water levels to be examined. The aerial photography showed qualitative variations in lake sediment concentrations, lake ice condition and flooding status. Lakes were considered to be flooded when sediment concentration was constant throughout the lake. When a mixture of concentrations within the lake was noted, the status of the lake was considered to be still flooding. The date and flooding status of each lake was then compared to water level records for each of the three main channels, East, West, and Middle. Lake sill elevation was estimated as being equal to the measured main channel water level on the first day that floodwater was observed to have flooded into a lake. It was from this information, combined with the definition of closure status, that all lakes (approximately 3200) along the transect were classified (Bach, 1994).

Because the elevation of the delta increases from north to south (Marsh and Hey, 1991), the probability of lake flooding decreases in the more elevated southern and upper central regions of the delta (Bigras, 1990). It follows then that, in a southward progression along this transect, the percentage of high-closure lakes ranges from 13%, to 33%, to 44% (Marsh and Hey, 1991). Lake evolution processes explain the differences in sill elevations with channel abandonment and point bar development leading to the formation of low-closure lakes on the delta front. Further south, thermokarst processes dominate and tend to lead to the development of high-closure lakes.

Factors Controlling Methane Production

Methane is a gas emitted in anoxic lake sediments by bacteria which feed on the by products of decomposing organic debris. According to current literature, three main components affect and control the production of methane in lake sediments and the subsequent buildup of this gas in the overlying water column:

1. Substrate availability as derived from the productivity of the lakes
2. pH and redox potential
3. Dissolved oxygen concentration in the water column

Extreme variability in any of these components will cause a significant change in potential methane production and/or accumulation. In this section, a general discussion of each of these three controls will be presented with specific relevance to the Mackenzie Delta lakes.

Substrate availability

There is general agreement in the literature among open water methane emission studies that substrate availability, quality, rate of supply to the sediments, and temperature are major determinants of methane production because they act to control rates of fermentation and subsequent methanogenic activity (Kelly and Chynoweth, 1981; Smith and Lewis, 1992; Valentine, 1994). Kelly and Chynoweth (1981) illustrate the positive relation between *in situ* methane flux rate and sedimentation rate of total organic carbon. However, subsequent studies demonstrated that not only quantity but quality of carbon input affects methane production. Lab studies (Valentine, 1994) demonstrate that carbon with high lignin:N ratios and high carbon:N ratios makes relatively poor methane production substrate as compared with carbon exhibiting low lignin:N and carbon:N ratios. From this relation, it follows that ecosystems with high rates of autochthonous primary productivity would be superior methane producing ecosystems as compared with systems with lower rates of *in situ* primary productivity. This relation has been hypothesized to account for spatial differences in methane flux rates observed between "old" lakes with peaty bottoms and "young" lakes with organic sediments exhibiting lower ratios of carbon:N and lignin:N on the Hudson Bay Lowlands (Valentine, 1994). In relating this correlation to the Mackenzie River delta lakes, it is possible that lakes which characteristically have a high degree of autochthonous production, such as lakes with clear water columns, may provide superior substrate for methanogenic bacteria and thereby prove to be better methane producers than more turbid lakes.

Productivity as related to closure status

Spring flooding is vital to the life of the Mackenzie Delta lakes, for without flooding these lakes would operate with a negative water balance losing more to evaporation each summer than they would gain in direct precipitation and runoff from the surrounding lake basin (Marsh, 1989) In addition to regeneration of water, spring flood waters bring with them nutrients and suspended sediments both of which affect the productivity levels of the lakes. Nutrients can often limit phytoplankton growth when depleted in the surrounding water column. Suspended sediments act to limit light availability to submerged macrophytes.

In the Mackenzie Delta lakes, phytoplankton may become phosphorus limited in high closure-lakes because of their limited connection to the main river channels during the open water season (Hecky et al., 1991). In natural systems, the supply of phosphorus is retained in surrounding terrestrial watersheds by vegetation and by chemical interactions with soil minerals. Thus when sediment moves with the flood waters, phosphorus is delivered to the lake ecosystems. Within the water column a large proportion of the phosphorus is contained in the plankton biomass leaving only a small portion to be found in available form. When the plankton dies, the phosphorus is returned to the sediments. Because of the long period of ice cover for Mackenzie Delta lakes, the water column should become anoxic early in the winter. Phosphorus release from the sediments is at a maximum in anoxic conditions and it is expected that these lakes will yield high values of phosphorus within their under-ice water columns.

High concentrations of nitrogen in the form of ammonium should also be encountered in the delta's anoxic ice-covered lakes. A major source for ammonium for the Mackenzie Delta lakes during winter is from decomposition of organic nitrogen to ammonia and its diffusion into the overlying water. Ammonia combines with water to form ammonium hydroxide which dissociates to form ammonium and hydroxyl ions. Ammonium is the nitrogen source utilized by the methane producing bacteria and thus its spatial distribution is of interest to this study as it is expected to correlate well with methane production.

Unlike phytoplankton populations which depend upon obtaining nutrients from the surrounding water column, macrophytes mine nutrients from the sediments and are therefore unlikely to become nutrient limited. Their growth is, however, affected by light availability. Among the lakes, a strong gradient of light regimes exists (Lesack et al., 1991b). High-closure lakes are only connected to spring flood waters for a short time, if at all, in any given year and are rarely subject to summer flood waters. Their biota is dominated by macrophytes which develop in the clear water columns during the summer months. In contrast, no and low-closure lakes are often too turbid to facilitate submerged vegetation growth and their primary productivity values are often dominated by phytoplankton which can take advantage of the mixing water column to obtain adequate light. Hecky et al. (1991) demonstrated the effects of turbidity on community metabolism and subsequent photosynthetic rates in four delta lakes in which light attenuation was affected by sedimentation in the water column. In the clearest lake, a high sill elevation lake, net photosynthesis of macrophytes per unit area was more than a factor of 20 higher than turbid lakes and accounted for more than 95% of community photosynthesis whereas throughout the four lakes photosynthetic rates of phytoplankton per unit area varied less than two fold. These results are consistent with other studies in northern lakes such as Ramlal et al. (1994) on the Tuktoyaktuk Peninsula and Welch and Kalff (1974) on Char Lake where macrophyte photosynthesis was also important. The most turbid water columns exist in the no and low-closure lakes as they continue to exchange water with the river channel throughout the summer.

Heavy sedimentation of a lake will most likely occur just prior to and immediately following the peak of the river flood. Distance that the suspended sediment travels, or proximity to channel, also determines how much sediment actually enters a lake system. Those lakes closest to the channel will receive heavier sedimentation than those further along the flow path. Once the floods recede somewhat, heavy sedimentation will not affect the whole lake but rather affect only the area near the inflow allowing for a more photosynthetically favorable light regime to exist in the remainder of the lake. Settlement of suspended sediments occurs quickly after connection with the main channel ceases.

Marsh (1995, unpublished), in a study of an 81 lake subset of the 3200 lake transect showed an increasing trend in sedimentation rate from high to no-closure lakes based on the amount of sediment accumulated above a ^{137}Cs peak specific to each lake. From this information it is evident that no and low closure lakes would have more turbid water columns due to higher levels of sediment concentration for a longer duration than the high-closure lakes. The trend in sedimentation rate on a cross-delta basis was also found by Marsh et al. (1995, unpublished) which appears to reflect geological controls although it is unknown how much sediment originates from the erosion of fine grained bank material along the channels.

From the above information, it becomes evident that high-closure lakes have higher rates of primary productivity in the form of aquatic macrophytes than low and no closure lakes. This is a direct result of favorable light regimes (lower sedimentation rates) and adequate nutrient supply. Therefore, in this study, light, as controlled by flooding regimes, may prove to be a controlling factor on methane production through its limitation of primary productivity within the lake ecosystems.

pH and redox potential

Methanogenesis is the anaerobic mineralization of organic matter. Within a typical lake sediment profile, aerobic processes occur near the sediment/water interface. Further down the profile, oxygen disappears and anaerobic processing of organic material begins. As the redox falls lower with depth into the sediments, a sequence of processes occurs by which various bacteria act as catalysts to initiate oxidation of organic material. Methanogenesis is the process which occurs at the lowest redox value.

In freshwater environments, methane production is dominated by acetate splitting:

$$CH_3COOH \rightarrow CO_2 + CH_4 \qquad (1)$$

Methanogenic bacteria can use only certain organic substrates for acetate splitting and sulfate-reducing bacteria are more effective competitors for the same compounds (Schlesinger, 1991). However, sulfate reducers also release acetate which often benefits the acetate fermenting methanogenic bacteria. So even though there is little or no overlap between the zone of methanogenesis and the zone of sulfate reduction in sediments, a dynamic relation exists that responds to the shifting of the redox zones within the sediment profile. As the upper sediments become more anoxic, the redox potential becomes lower at shallower depths in the profile shifting the zones of reduction upward. Therefore, the acetate produced by the sulfate reducers becomes the substrate for the methane producing bacteria.

Methane is also produced by carbon dioxide reduction:

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \qquad (2)$$

where hydrogen is available as a byproduct of fermentation:

$$CH_2O + H_2O \rightarrow 2H_2 + CO_2 \quad (3)$$

Redox potential is closely related to pH by the equation:

$$\log K = pe + pH \quad (4)$$

where: log K = equilibrium constant of the methane reaction

pe = $-\text{Log}[e^-]$ where $[e^-]$ is electron activity in a redox half-reaction.

As the chemical reaction which produces methane is represented by a constant (K), the given relation shows that as redox potential decreases, pH must increase. Methanogenesis requires low redox potentials and thus higher pH values are necessary for high methane production. Hence, both redox potential and pH act as physiological controls over methane production in lake sediments.

Dissolved oxygen concentration

To this point in this section, I have provided an overview of the expected dominant controls on methane production in the Mackenzie Delta lakes. Just as methane production demands an anoxic environment, so does methane accumulation within the water column. Oxidizing bacteria, which can inhabit both the upper lake sediments and/or the overlying water column, use oxygen as an electron acceptor to convert methane to carbon dioxide. Methane oxidation can represent the dominant contributor to the development of total lake anoxia especially in cases where ice cover prevents gas exchange with the atmosphere (Rudd and Hamilton, 1978).

Water column oxygen is also consumed by the metabolic demands of other organisms within the water column and the sediments. The sediments consume oxygen at a rate which is related to lake morphometry and mixing of the water column beneath the ice. As a rule, ice-covered deep lakes with small surface areas take longer to consume oxygen than shallow lakes with larger surface areas (Schindler, 1971; Mathias and Barica, 1980): Even though the Mackenzie Delta lakes are not large in area, they have an average depth of < 2 m and therefore anoxic conditions will develop soon after surface ice formation.

The degree of mixing of the water column under ice cover may be important because of the implications it has for the initial consumption of water column oxygen and hence the accumulation of methane in the under-ice water column. Two scenarios can occur. In the first, the water column mixes completely under the ice as occurs on prairie ice-covered lakes (Mathias and Barica, 1980). In this case, vertical oxygen profiles in the under-ice water column are used as evidence of complete mixing. In the second scenario, a stratified system is set up under the ice cover which prohibits vertical mixing of the column. This could occur via chemical stratification, as occurs in Lake Fryxell (Smith et al., 1993), or by density differences of water layers in response to temperature. For Arctic delta lakes, there is no anticipation that they will become chemically stratified beneath a winter ice cap; however, temperature gradients do exist within the under-ice water columns which would result in density differences between strata of water. These density differences inhibit vertical mixing of the water column. Therefore, there could be a stratification of methane beneath the ice cover with highest values being maintained at the sediment/water interface.

The key to remineralization of carbon materials lies in the flux of carbon to the sediments. The consumption of oxygen by the sediments and the subsequent processing of carbon by anaerobic processes cannot take place unless there is a supply of carbon to the sediments although it is hypothesized that the oxygen uptake rate of sediments reflects a long term integral of sedimented organic matter rather than short term variation (Mathias and Barica, 1980). Thus the long term controlling variables of primary production become important in all estimates of carbon remineralization. Although in general, for lakes that stratify, it has been hypothesized that mid-sized lakes are more productive than small or large lakes (Fee et al., 1992), in the case of the Mackenzie Delta lakes it has been shown that the degree of productivity is related more to channel connectedness and the effects of light limitation than to size. Thus lakes at higher elevations above the river channel (high-closure) are more productive than lakes that are closer in elevation to the river channel (low and no-closure) and therefore should have higher concentrations of methane in their under-ice water columns.

Research Hypotheses

One major aspect of this study has focused on identifying and explaining how sill elevation, through its control on lake flooding regimes, determines nutrient supply and light regimes which act as limiting agents on primary production within delta lakes. Primary production is the main control on methane substrate availability which, in turn, determines the production of methane in the sediments of ice-covered delta lakes. The physiological controls of pH and redox potential are integrated tightly with the controls on substrate availability. There has also been a focus on identifying and explaining the role of water column oxygen concentration and how it will affect the maintenance of methane within the water column of ice-covered lakes.

Previous work has suggested that high-closure lakes are more productive than low and no-closure lakes. Because of their limited connection to the main river channels, they have lower sedimentation rates. These two factors lead to the first hypothesis which guides this thesis:

Hypothesis I: Lake closure (high, low, and no) will have an effect on the spatial distribution of methane and other measured physical and chemical variables.

The second hypothesis focuses on spatial distribution of methane accumulation across the Mackenzie delta. The lakes are fed by three main channels each with it's own chemical signature reflecting differing source areas for the contributing waters. The lakes these waters feed could well reflect these chemical signatures. As well, geologic controls operate to influence the amount and type of sediment in each of the three channels with the western channel being more heavily laden with sediment than the eastern channel. This reasoning leads to the second hypothesis:

Hypothesis II: Lake position on the delta (Inuvik (east), Central, and Aklavik (west)) will have an effect on the spatial distribution of methane and other measured physical and chemical variables.

Chapter 2

Methods

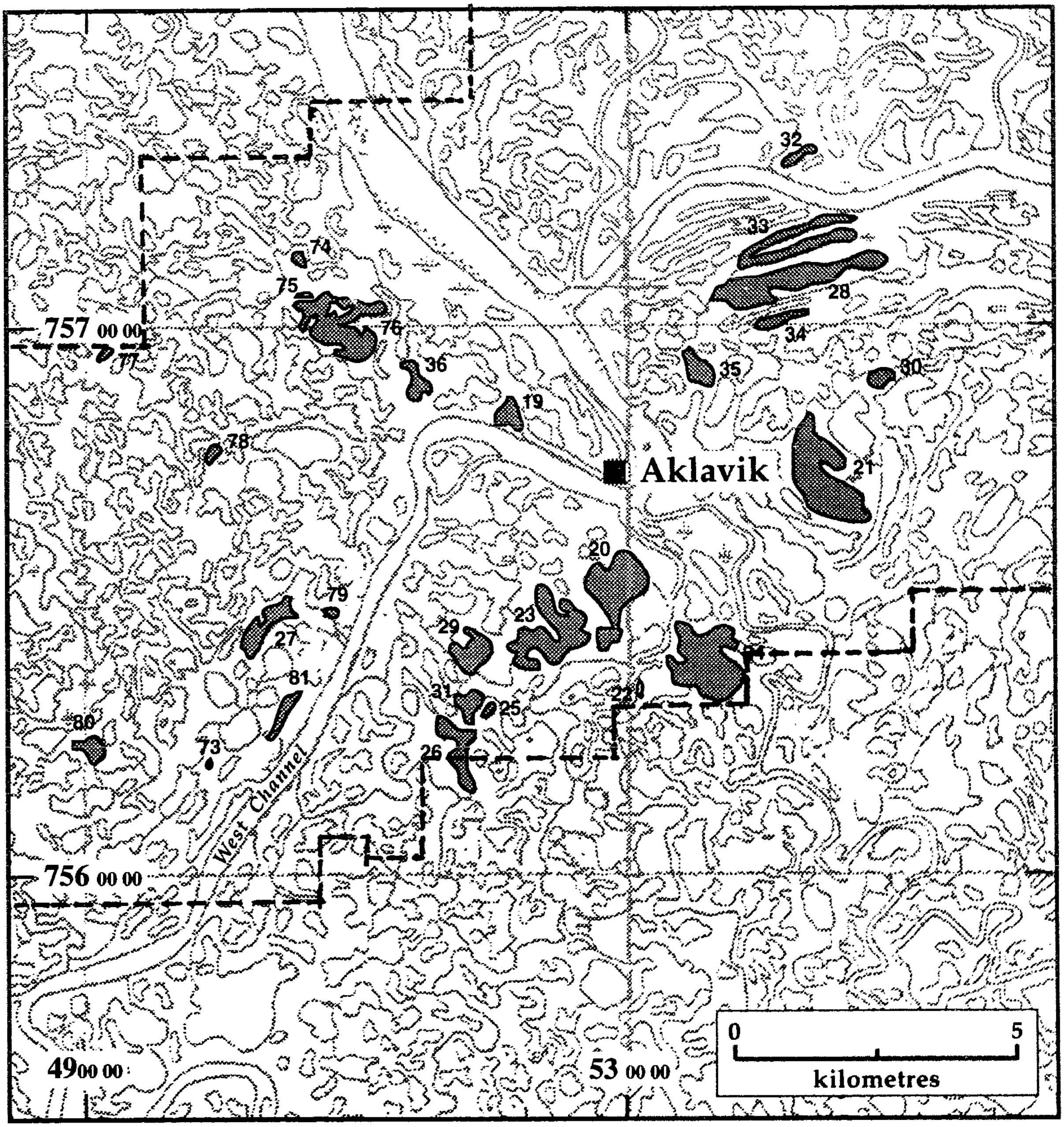
Study Design

The study covered by this thesis is based on an 81 lake subset that was selected (Marsh and Hey, 1989) from a 3200 lake transect between Aklavik and Inuvik. The lakes were chosen to be representative of lakes with differing closure status and location on the delta. The subset focuses on the three main target areas which reflect the differing sources of the floodwaters: (1) western delta near Aklavik (Fig. 2, Table 1), (2) the central delta near Middle Channel (Fig. 3, Table 1) and, (3) the eastern delta near Inuvik (Fig. 4, Table 1). Each area contains 27 lakes of which 9 are high-closure, 9 are low-closure and 9 are no-closure.

Sample Collection and On-Site Measurements

The lakes were sampled three times over two field seasons (spring 1993, summer 1993, spring 1994). Sampling during the spring of 1993 and 1994 was performed over a short period (late April to early May) just prior to ice-out. Sampling during summer 1993 was performed on a single day during late summer (mid August). Sample collection and analytical procedures were consistent across all three data sets. Because the lakes are well mixed during the open water period, water samples for major solute analysis were collected from the subsurface in the middle of the lakes. Under-ice sampling was accomplished by drilling a 20 cm hole through the lake ice with a gas-powered ice auger and withdrawing samples from appropriate points in the water column with a submersible pump. The location of the sampling hole was intended to be at the deepest part of the lake and this location was estimated based on proximity to shore and the degree of bank slumping associated with a particular shoreline. To assist with calculations of lake

Fig. 2. Location map highlighting sampled lakes on the west side of the Mackenzie Delta near Aklavik, N.W.T. Lakes numbered 19 to 27 are classified as no-closure lakes, 28 to 36 are classified as low-closure lakes and 73 to 81 are classified as high-closure lakes (Map modified from Surveys and Mapping Branch, 1974). Dashed lines indicate northern and southern transect boundaries.



757 00 00
756 00 00
49 00 00
53 00 00
Aklavik
West Channel
0
5
kilometres
32
33
28
34
35
30
21
74
75
76
77
36
19
78
20
23
29
79
27
81
31
25
22
24
80
73
26

Table 1. Lake number cross referencing based on lake closure classification scheme for the Mackenzie Delta lake transect

Region	No Closure		Low Closure		High Closure	
	Lake No.	UTM No.	Lake No.	UTM No.	Lake No.	UTM No.
Inuvik	1	NL50508250	46	NL41007840	55	NL49208510
(East)	2	NL47308250	47	NL45407720	56	NL50008480
	4	NL46707860	48	NL50807745	57	NL49007800
	5	NL46207830	49	NL48807870	58	NL49757925
	6	NL45607900	50	NL50757820	59	NL43207945
	8	NL41707640	51	NL47508100	60	NL49007665
	9	NL41657708	52	NL48608060	61	NL47757895
			53	NL45658300	62	NL46357845
			54	NL43658365	63	NL43008055
Central	10	NL29507330	37	NL27157300	64	NL77557865
	11	NL22127040	38	NL15657305	65	NL16707345
	13	NL19856985	39	NL27007950	66	NL16207255
	14	NL20607300	41	NL22907785	67	NL20006888
	15	NL18257250	42	NL26007840	68	NL26057610
	16	NL16586965	43	NL19907675	69	NL21006900
	17	NL16756978	44	NL22157355	70	NL26557750
	18	NL17806770	45	NL24957600	71	NL16257315
					72	NL16557548
Aklavik	19	ML97856830	28	NL03007070	73	ML92356175
(West)	20	NL00006500	29	ML97206380	74	ML93857100
	21	NL03506720	31	ML97206300	75	ML94307045
	22	NL00356335	32	NL03207295	76	ML94557000
	23	ML99006435	33	NL02207105	77	ML90606945
	24	NL01506370	34	NL02957005	78	ML92356760
	25	ML97526285	35	NL01406910	79	ML94856495
	26	ML97006210	36	ML96206890	80	ML90206220
	27	ML93556465			81	ML93546270

Fig. 3. Location map highlighting sampled lakes on the Central Mackenzie Delta, N.W.T. Lakes numbered 10 to 18 are classified as no-closure lakes, 37 to 45 are classified as low-closure lakes and 64 to 72 are classified as high-closure lakes (Map modified from Surveys and Mapping Branch, 1974). The dashed line indicates the southern transect boundary. The northern boundary is located just north of the map margin.

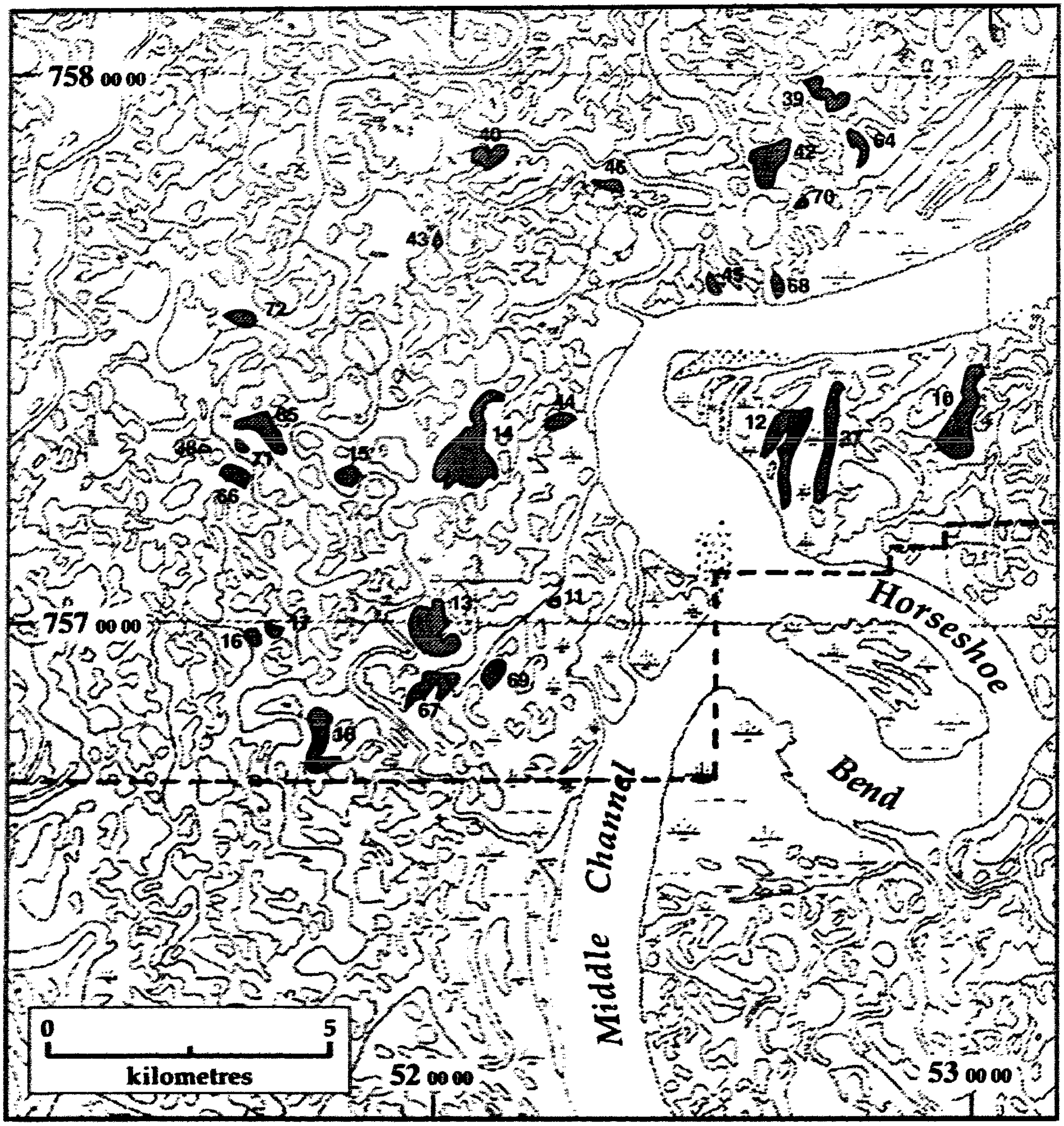
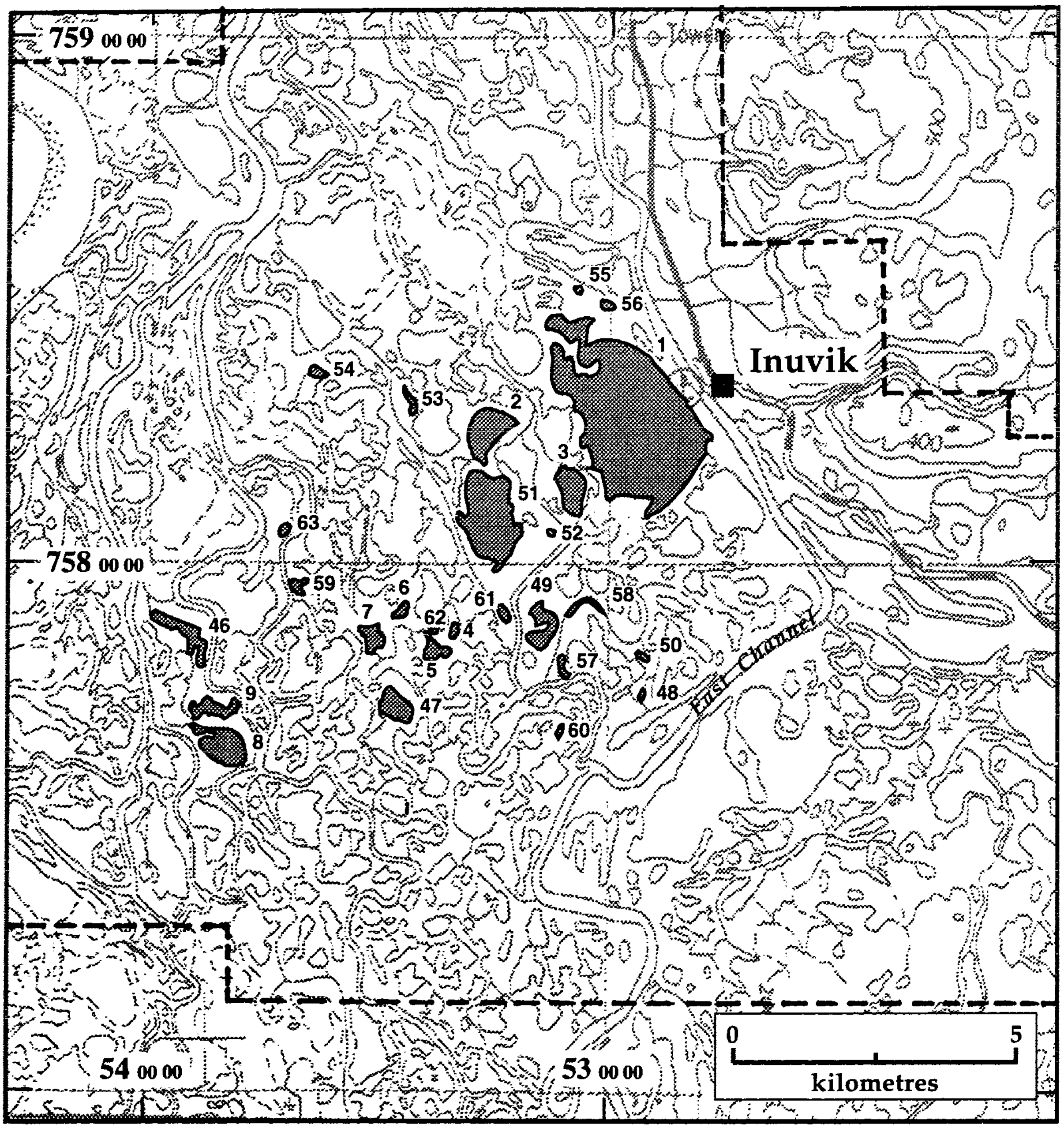

758 00 00
757 00 00
52 00 00
53 00 00
Horseshoe
Bend
Middle Channel
0
5
kilometres

Fig. 4. Location map highlighting sampled lakes on the east side of the Mackenzie Delta near Inuvik, N.W.T. Lakes numbered 1 to 9 are classified as no-closure lakes, 46 to 54 are classified as low-closure lakes and 55 to 63 are classified as high-closure lakes. The dashed lines indicate the northern, southern, and eastern trnasect boundaries.


759 00 00
758 00 00
54 00 00
53 00 00
Inuvik
East Channel
400
0
5
kilometres
1
2
3
4
5
6
7
8
9
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63

volumes and under-ice volumes of water (this thesis, pages 37 to 46), measurements of water column depth, total ice thickness and white ice thickness were obtained at each ice hole. Snow depth was also recorded for each lake. The surface area of each lake was determined by planimetry of 1:50,000 topographic maps.

Gases and Major Solutes

Water samples for CH_4, CO_2, and DIC analysis were collected in evacuated 125 ml serum bottles. Prior to evacuation, 8.9 g of potassium chloride salt (KCl) was added to each bottle as a preservative (Hesslein et al., 1991). The use of KCl as a preservative does not change the CO_2 concentration as it does not affect the pH of the water. The serum bottles were then flushed with ultra high purity nitrogen (UHP N_2) for 2 minutes, sealed with vacutainer rubber septums, and evacuated to 27 inches of mercury using a pump connected to a 18G needle. Bottles prepared in this method have been kept for 6 weeks with no loss of vacuum (Hamilton et al., 1994). In practice, the bottles were prepared within 2 weeks prior to sampling.

The goal at each lake was to obtain duplicate samples which, when analyzed for gas content, would be representative of the entire under-ice water column. Therefore, one of two methods was utilized depending upon the depth of the lake. If the total depth of the lake was less than 1 m the shallow under-ice water column necessitated that duplicate samples be drawn from 5 to 10 cm above the sediment/water interface. If the water column was greater than 1 m deep, a single sample was drawn from approximately 5 to 10 cm above the sediment water interface and another just below the ice/water interface. For these lakes an average of the two samples was assumed representative of the gas content for the entire water column.

It is imperative that the samples drawn from the lake remain anoxic in order to prevent the oxidation of methane contained in the sample. A submersible pump allowed withdrawal of samples from any depth desired with minimal disruption of the water column. The 125 ml serum bottles were submerged into a bottom-filling collecting vessel connected to the pump and the septums were punctured using a 18G needle. Once the flow into the serum bottles stopped, the needle was removed and the bottles were left submerged for 30 seconds to allow the punctured septum to reseal. The KCl within the samples was dissolved by swirling the bottles. In the lab, septums were coated with silicone to ensure tight sealing and the samples were refrigerated.

Using the submersible pump/tygon tubing apparatus, samples for major solute analyses were drawn into clean 1 L plastic bottles (Nalgene HDPE) from just above the sediment water interface. At each lake, conductivity and temperature measurements were taken at 0.5 m intervals in the water column (YSI Model 3000 Temperature Level Conductivity meter). Conductivity values were corrected to 25°C by use of the regression equation:

$$C_c = C(-0.02457 * T + 1.619006) \qquad (5)$$

where C_c = temperature corrected conductivity

C = measured conductivity

T = temperature in °C.

Sediment

In order to determine the relation between the organic carbon, nitrogen, and phosphorus content of the sediments and the potential for under-ice methane production, sediment samples were collected from each lake in the Inuvik and central delta regions. A coring device (ID = 10 cm) was inserted into the sediments with a metal rod. A butterfly sealing valve positioned on top of the tube was open during tube insertion and then closed by releasing the valve after the tube was inserted into the sediments. This resulted in a vacuum being generated within the tube which allowed the sediment to be withdrawn intact. The cores were extruded into a bucket and the top 1 cm of the core was scraped off and stored frozen in whirl-bags.

Analytical Chemistry

Gases and major solutes

Prior to analysis the serum bottles were placed in a warm dark water bath to elevate the sample temperatures quickly to room temperature. The temperature of each sample was recorded. Samples were then shaken by hand for 30 seconds to establish equilibrium between the gas phase and the liquid phases. Duplicate 0.2 ml gas samples were removed using a 0.25 ml pressure lok syringe (Dynatech) and analyzed by gas chromatography (Carle Model AGC-311) using flame ionization and thermal conductance detectors. The gas chromatograph was standardized by injection of six standard mixtures for CH_4 (100 to 250000 ppm, Scotty gases) and three standard mixtures for CO_2 (5000 to 60000 ppm, Scotty gases).

To determine dissolved inorganic carbon (DIC) content, 0.2 ml of phosphoric acid (85%) was added to each sample bottle to drop the pH below 2.5 and the bottles were shaken again for 30 seconds to convert all the DIC to CO_2. Duplicate 0.2 ml sub-samples of headspace gas were again taken from the sample bottles and analyzed as outlined above. The range for the three standard mixtures for CO_2 were increased (10,000 to 300,000 ppm, Scotty gases). During the DIC analysis a double check on methane content was run. HCO_3 concentrations were calculated by subtracting the amount of CO_2 measured for each sample from the total DIC measured for each sample.

To calculate gas content per sample volume, bottle weights were recorded when empty, with the addition of the KCl, with the sample, after the addition of phosphoric acid, and at full weight. To calculate head space, full bottle volumes and sample volumes were measured. Water concentrations of CO_2 and CH_4 were calculated from head space concentrations of these gases using Henry's law and the appropriate solubility coefficients as per Hamilton (1992). Solubility coefficients adjusted for temperature and salinity were obtained from Yamamoto et al. (1976) and Harned and Davis (1943) as per the methodology of Hamilton (1992). Prior to statistical analysis to determine spatial variability or regression correlations with other variables, between bottle concentrations were averaged for the 60 cases where duplicate samples were drawn from the same level of the water column.

Conductivity (YSI Model 32 Conductance meter) and pH (Orion 290A pH/ISE meter) analyses were performed on aliquots of unfiltered sample, while measurements for major solutes were performed on aliquots of sample filtered through thoroughly rinsed Gelman A/E glass fiber filters and an all-plastic filtration apparatus. Conductivity values were standardized to 25° C by use of regression equation (5).

Ammonium was measured by the indophenol blue method and phosphate by the molybdenum blue-ascorbic acid method (Strickland and Parsons, 1972). Sulfate and chloride values were determined via ion chromatography (Dionex) using an IonPac AS4A SC 4mm column. Sodium, magnesium, potassium, and calcium concentrations were obtained via atomic absorption spectroscopy (Varian AA-1275) using an air-acetylene flame. Samples for calcium and magnesium were spiked with lanthanum chloride and potassium and sodium samples were spiked with cesium chloride as per APHA (1989).

Once major ions had been analyzed, theoretical conductivities and per cent charge balances were calculated to ensure that the analysis was complete and that no major analytical errors had been made. Theoretical conductivities were obtained by calculating the equivalent conductance of each major measured cation and anion and summing the results (Golterman and Clymo, 1969):

$$C_T = (Na*50.5)+(Mg*53)+(Ca*60)+(K*74)+(Cl*76.4)+(SO_4*80)+(HCO_3*44.5) \quad (6)$$

where C_T represents the theoretical conductivity

all values of ions are in μM

Per cent charge balance was calculated as:

$$C_b = [C^+ - C^-)/C_t]*100 \qquad (7)$$

where C_b = % charge balance

C^+ = sum of positive charges

C^- = sum of negative charges

C_t = total sum of charges.

Silica values were determined via spectrophotometry using the molybdosilicate method as per APHA (1989). Although silica measurements were performed on filtered water, leaching tests confirmed that the glass fiber filters were not a source of significant leachate in the concentration range in which we were working. Detection limits for gases and major solutes are presented in Appendix E.

Sediments

Prior to analysis, each sample was placed in a pre-weighed 57 mm aluminum dish, weighed and oven dried to a constant weight at 46 °C to ensure no destruction of carbon. Ground replicate sub-samples were placed in capped 20 ml scintillation tubes and stored in a desiccation chamber.

Measurement of sediment phosphorus was performed by using an elevated pressure-temperature microwave dissolution technique revised from Revesz and Hasty (1987) in consultation with a technician from Seigniory Chemical Products. The samples were digested in 10 ml of 1:1 HNO_3:H_2O in closed vessels. Samples were then diluted to 100 ml and filtered through Gelman A/E glass fiber filters. The digested samples were then analyzed after appropriate dilution via spectrophotometry as per the molybdenum blue-ascorbic acid method (Strickland and Parsons, 1972). To ensure reagents did not react with the HNO_3 used in the digestion, 10 ml of a 1 M PO_4 standard was mixed with 10 ml of HNO_3 and then digested along with the samples. After digestion, this standard was diluted with deionized distilled water to form 1, 5, and 10 μM standards and absorbency readings were compared with a control set of 1, 5, and 10 μM PO_4 standards made without being subjected to the addition of HNO_3 or the digestion process. Blanks were also treated in this manner.

Sediment carbon and nitrogen concentrations were obtained via CHN analysis done at the Freshwater Institute, Saskatoon (Stainton et al., 1977).

Statistical Analysis of Data

Determining the effect of closure and/or position on the spatial distribution of measured variables

An important goal for the statistical analyses of the data sets is to determine if the spatial variability of the physical and chemical variables is defined by lake closure and/or position on the delta. Testing for variability between level means can therefore be accommodated by using a Model 1, two factor analysis of variance as follows:

Factor	**Level**
Closure classification	High, Low, No
Delta position	Aklavik, Central, Inuvik

If significant variation between the level means of the variable was identified by the two-way ANOVA a subsequent one-way ANOVA combined with a post-hoc TUKEY HSD test was run on the category to determine exactly which levels of the category contained significant variation between the means.

Prior to performing the ANOVAs, transformations of the data were carried out to obtain the most normal distribution possible for each variable. To help identify the transformation that best fit the normal distribution, the Lilliefors test for normality was performed on various transformations of each variable and the transformation that yielded the highest p-value was used in subsequent statistical analyses.

Predicting Under-Ice Methane Concentrations

Multiple regression was used to predict under-ice methane concentration from measured water chemistry and sediment variables. Residual plots were examined to verify the linear fit of the model as well as to identify outliers. Transformation of the dependent variable, as well as many of the independent variables, was necessary to avoid violating the assumption of model linearity. Checks for collinearity of independent variables were performed in order to stabilize estimates of regression coefficients which can be adversely affected by strong linear relationships among explanatory variables (Chatterjee and Price, 1990).

Determination of Total Lake Volume and Under-ice Volume

A major objective of this study is to obtain a quantitative first-order estimate of potential methane accumulation in ice-covered Arctic lakes on the Mackenzie River delta and then to extrapolate these values to give an estimated flux value for northern delta ecosystems on a circumpolar scale. To do this, whole lake methane content had to first be determined for each lake based upon the concentration of methane found in the samples multiplied by under-ice water volume. A challenge became to determine total lake volume and under-ice water volume from known lake surface area, ice column depth, lake depth at point of sampling and ion concentrations from the summer 1993 data set and the under-ice data set from the spring of 1994. In this section two models are presented, Model 1 and Model 2, each of which determine total lake volume. Under-ice volumes are then estimated for each model using two methods, Method A and Method B. Thus 4 models are generated to determine under-ice volume:

Model 1, Method A

Model 1, Method B

Model 2, Method A

Model 2, Method B

Model 1 includes two inherent assumptions: (1) that the point we sampled was the deepest point of the lake; (2) that the bathymetry of NRC Lake is indeed a representative model for all the lakes in the Mackenzie Delta and therefore the relations between % depth with % area are also representative. This model takes advantage of the excellent spatial information available for NRC lake. A hypsometric curve was generated for NRC lake (Fig. 5) and a seven degree polynomial equation was fit to the data to enable % area to be estimated for each lake from known % depth values ($r^2 = 0.998$). Using this relation, total lake volumes can be estimated from the measured surface area of the lakes and the measured depth at the sampling sites. By calculating areas of strata at 5 cm depth intervals, determining the volumes of each strata section, and then summing the volumes, the total lake volume can be estimated (Fig. 6).

Model 2 assumes that the sampling point was representative of the average depth of the lake (D_l in Fig. 6). Total lake volume is hence obtained from the product of the lake surface area and depth at the sampling point:

$$V_t = D_l * A \qquad (8)$$

where V_t = Total volume of the lake (m^3)

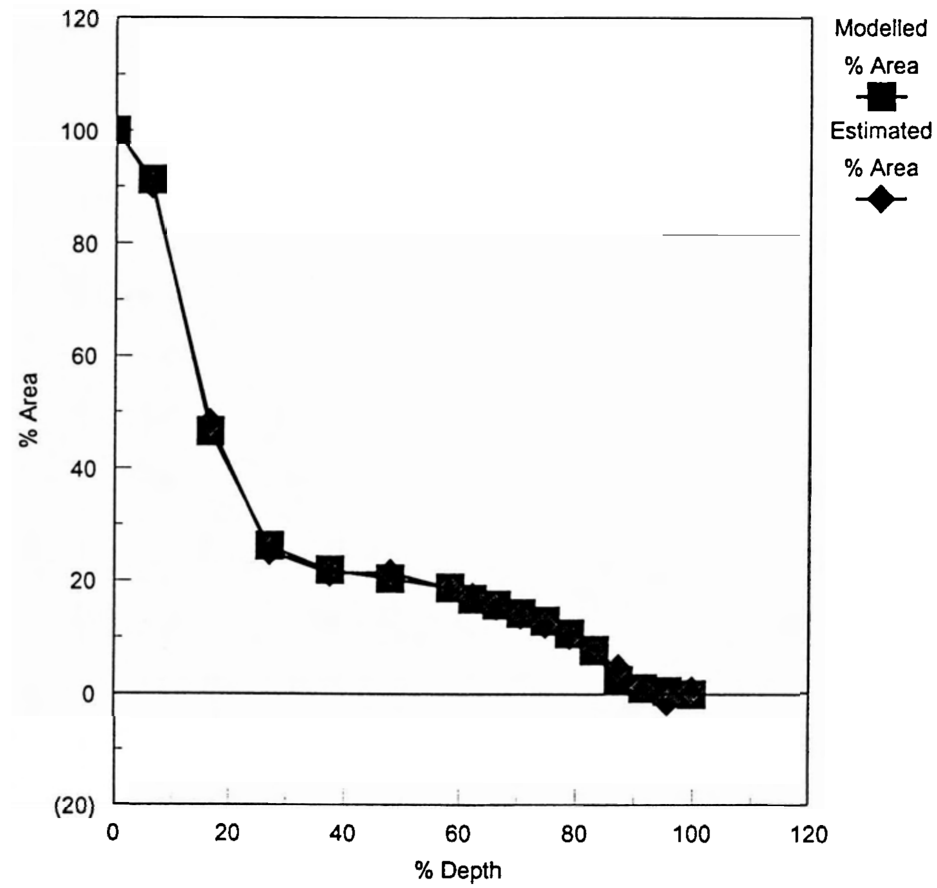
D_l = Depth of lake (m) at sampling point

A = Area of lake (m^2)

Individual volumes for the sampled lakes as determined by both Model 1 and Model 2 are presented in Appendix D (Table D1).

Under-ice volume for both models was calculated by two methods. The first method (A) involves identifying the depth at which the ice/water interface occurs. Model 1 under-ice volumes (Fig 6) can then be determined by summing the volumes of the strata

Fig. 5. Hypsometric curve of NRC Lake. A 7 degree polynomial equation for best fit line generates an r^2 value of 0.998. This model is used to calculate unknown areas at known depths for lakes sampled on the Mackenzie Delta lake transect in the spring of 1994.

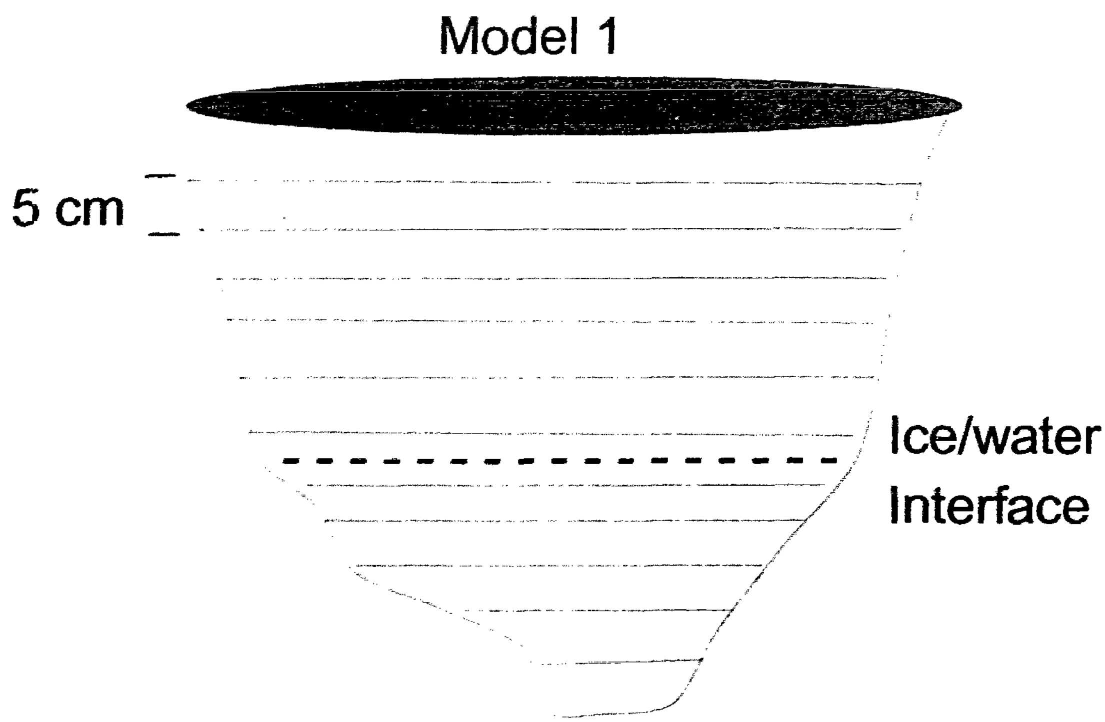


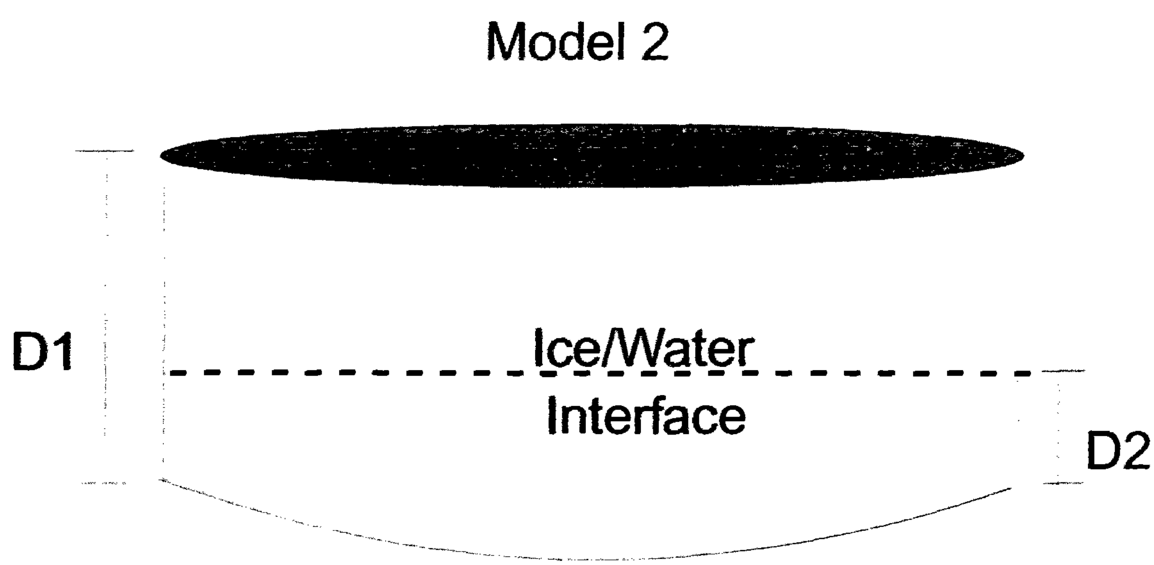
120
100
80
60
40
20
0
(20)
% Area
0
20
40
60
80
100
120
% Depth
Modelled
% Area
Estimated
% Area

Fig. 6 Total lake volume as determined by Model 1 and Model 2. Model 1 assumes that the sampling point was the deepest point of the lake and that the bathymetry of NRC Lake is representative of average lake-basin shape. Total lake volume is obtained by using the surface area of the lake and depth at the sampling point to estimate areas at 5 cm depth intervals and then summing the volumes associated with each strata.

Model 2 assumes that the sampling point was representative of the average depth of the lake (D_1). Total lake volume is hence obtained from the product of the lake surface area and depth at the sampling point.

Dashed lines on each diagram indicate a hypothesized ice/water interface. Determination of under-ice volume by Method A uses the measured ice thickness on each lake. Model 1A adds together the strata volumes beneath the ice/water interface. Model 2A assumes that the depth of unfrozen water at the sampling point was representative of the average depth of unfrozen water beneath the lake-ice (D_2). Under-ice water volume is hence obtained from the product of the lake surface area and depth of unfrozen water at the sampling point.


Model 1
5 cm
Ice/water
Interface


Model 2
D1
Ice/Water
Interface
D2

below the ice water interface. Model 2 (Fig 6) uses method A to calculate under-ice volume by:

$$V_u = D_2 * A \qquad (9)$$

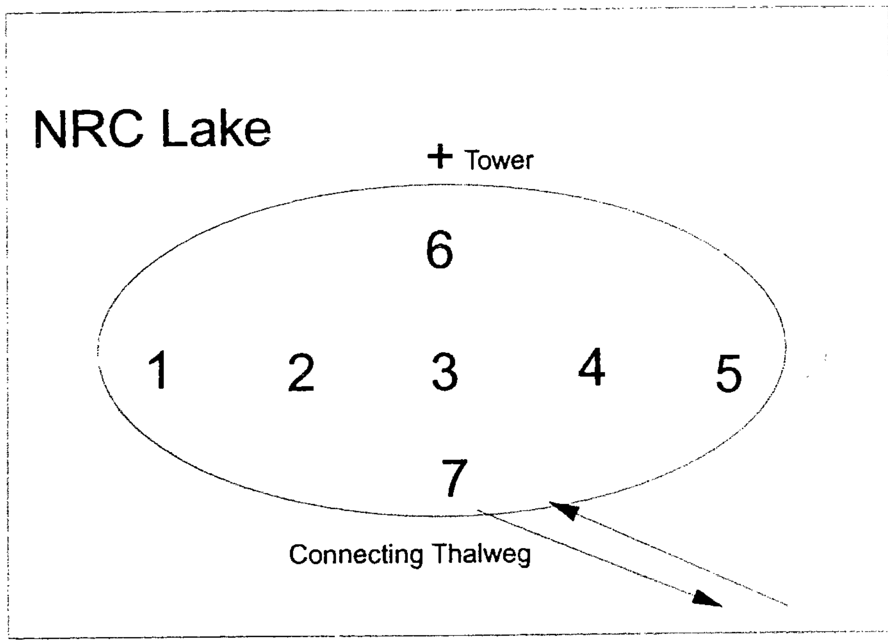
where V_u = Under-ice volume of the lake (m^3)

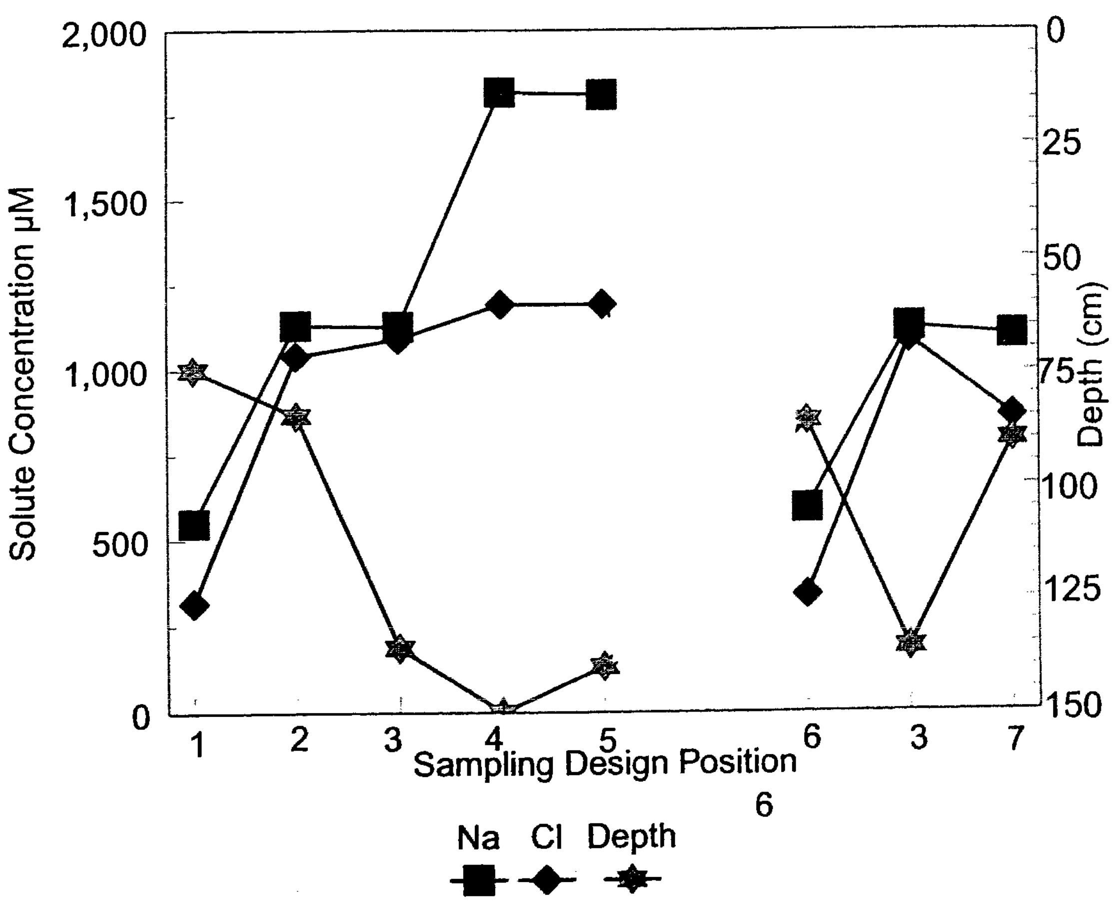
D_2 = Depth of under-ice water column (m) at sampling point

Method B assumes that there is no loss or addition of water beneath the ice front, and that solute exclusion is complete during ice formation. This method involves using an ion concentration factor to determine under-ice volume. Chloride and sodium concentrations are available for the summer 1993 field season and the spring 1994 field season and enabled the determination of an ion concentration factor for a subset of 47 of the sampled lakes. Linear regression of the chloride concentration factor against the sodium concentration factor for each lake yielded an r^2 value of 0.57. This correlation is within the range expected as spatial variation of solute concentration occurs in the water column beneath the winter ice cover which inhibits mixing due to isolation from wind. Higher solute concentrations characteristically occur at the deeper parts of the lake (Fig. 7). When looking at the under-ice spatial distribution of sodium and chloride in relation to depth for NRC lake (spring 1994 field season) it can be seen that sodium concentrations appear to respond more dramatically to depth changes whereas chloride has a relatively more consistent distribution. Consequently, determination of a concentration factor for sodium and chloride from a single bore hole for each of the delta transect lakes could result in some variation. Averaging the two concentration factors may give a more representative value. Therefore, the ion concentration factor was calculated by averaging the chloride and sodium concentration factors determined for each lake by:

$$C_{cf} = C_{sp94}/C_{su93} \qquad (10)$$

Fig 7. Spatial sampling design for the spring 1994 field season for NRC Lake. The top figure illustrates the relative points at which samples were drawn from beneath the ice of NRC Lake. The bottom graph gives solute concentrations and depth measurements in relation to the sampling points. Note the tendency for solutes concentrations to be higher at the deeper points of the lake and lower at the shallower points.


NRC Lake
Tower
6
1
2
3
4
5
7
Connecting Thalweg


2,000
1,500
1,000
500
0
Solute Concentration µM
0
25
50
75
100
125
150
Depth (cm)
1
2
3
4
5
6
3
7
Sampling Design Position
6
Na
Cl
Depth

$$N_{cf} = N_{sp94}/N_{su93} \quad (11)$$

$$I_{cf} = (C_{cf}+N_{cf})/2 \quad (12)$$

where C_{cf} = the chloride concentration factor for each lake

C_{sp94} = the concentration of chloride in the spring 1994 sample

C_{su93} = the concentration of chloride in the summer 1993 sample

N_{cf} = the sodium concentration factor for each lake

N_{sp94} = the concentration of sodium in the spring 1994 sample

N_{su93} = the concentration of sodium in the summer 1993 sample

I_{cf} = the ion (average of the sodium and chloride) concentration factor

The volume of the unfrozen water column can then be estimated by dividing the total water volume of each lake as calculated by both Model 1 and Model 2 by the ion concentration factor specific to each lake. Under-ice water volumes calculated for each lake by methods A and B are given in Appendix D (Table D1).

To test the degree of agreement between the two methods for determining under-ice volumes the under-ice volume for NRC Lake was calculated. The bathymetry information available for NRC Lake enabled accurate estimation of water volume below the ice depth as measured in the spring of 1994. Under-ice chloride and sodium concentration values were obtained from seven sites during the spring 1994 field season as illustrated in Fig. 7. Because of the good spatial representation inherent in the sampling design, the averaging of these values can be considered representative of a total lake concentration for each ion. Open water concentrations of sodium and chloride are also available (Lesack et al., 1996). Under-ice volumes calculated via both methods resulted in a difference of less than 5% at the time of sampling (spring 1994). These results establish that Method B should work reasonably well, at least in cases where the chemistry is well characterized.

Circumpolar Delta/Wetland Areas

Literature searches provided areas for several of the circumpolar deltas that are of interest to this thesis. To complement information, planimetry on operational navigation charts (scale 1:1,000,000) was used to define the area of major river deltas and associated wetlands

Chapter 3
Results

Methane accumulation in the water column of ice-covered lakes is the product of physical, chemical, and biological variables. It is necessary to evaluate quantitatively the most obvious of these variables in order to come to an initial understanding of the relations that exist between them and methane production and retention within the water column.

This chapter is divided into four main sections:

(1) Physical Data Analyses

(2) Sediment Content Data Analyses

(3) Gases and Major Solute Data Analyses

(4) Methane Prediction and Spatial Modeling

The two-way analysis of variance, chosen to determine statistical significance for the first three of these sections, tests the two research hypotheses: The fourth section of this chapter deals specifically with methane. In this section the results from the multiple regression model used to predict under-ice methane concentrations are given. As well, the four models used to calculate under-ice volumes are applied to methane concentrations and used to calculate whole lake methane content as well as total Mackenzie delta methane emissions at ice-out. Emissions from northern delta lakes are then calculated using these same four models.

This set of 81 lakes has been sampled during 3 consecutive field seasons: the spring of 1993, the summer of 1993, and the spring of 1994. Therefore the data sets generated from these field seasons represent two under-ice sets and one open water set. A complete set of variables for which samples were collected for each of the field seasons is summarized in Table 2. Data from all three of these field seasons has been

Table 2. Variables measured for the spring 1993 under-ice data set, the summer 1993 open water data set, and the spring 1994 under-ice data set denoted by "X".

Variables	Spring 1993 Under-ice Aklavik, Central, & Inuvik lakes	Summer 1993 Open water Aklavik & Central Lakes	Spring 1994 Under-ice Aklavik, Central, & Inuvik lakes
Physical			
Lake area	-	-	X
Lake depth	-	X	X
Secchi depth	-	X	-
Snow depth	-	-	X
White ice thickness	-	-	X
Total ice thickness	-	-	X
Temperature	-	X	X
	-	-	-
Gases			
Methane			X
Carbon dioxide			X
Dissolved inorganic carbon			X
Major solutes			
pH	X	X	X
Conductivity	X	X	X
Chloride	X	X	X
Sulfate	X	X	X
Sodium	X	X	X
Magnessium	X	X	X
Potassium	X	X	X
Calcium	X	X	X
Silica	X	X	X
Bicarbonate	-	-	X
Phosphate	-	-	X
Ammonium	-	-	X
Sediment			Central & Inuvik lakes
Carbon content	-	-	X
Nitrogen content	-	-	X
Phosphate content	-	-	X
Sedimentation rate	X	-	-

quantitatively analyzed and synthesized for use in this thesis. Conductivity, pH, and major ions were analyzed for all three data sets. The spring 1994 under-ice data set is the most extensive and it includes analyses of methane and carbon dioxide, dissolved inorganic carbon and bicarbonate, phosphate and ammonium as well as physical measurements relating to ice thickness, snow depth, and lake areas. Also, as sediment samples were taken from each lake during the spring 1994 field season for the Inuvik and Central delta regions, carbon, phosphate, and nitrogen content of the sediments was determined. Sedimentation rate was determined from a separate data set obtained from NHRI in Saskatoon (Marsh, 1995 unpublished data). The summer 1993 open water data set was collected from Aklavik and Central delta lakes only and includes variables of secchi depth, lake depth and temperature as well as analyses of major solutes that are specific to that sampling period. The spring 1993 data set is the smallest and includes analyses of major solutes.

Results for Lake 21 indicated abnormally high conductivity (1317μS), calcium, sodium, and chloride values (4644, 3398, and 6859 μM respectively). These values are two to three times the conductivity values for other lakes in the data set, six times the next highest chloride value, three times the next highest sodium value and 25% higher than the next highest calcium value. Possible contamination of sample bottles was eliminated as a source for this error as data from both summer 1993 and spring 1993 also indicate abnormally high values of these variables for this lake. Charge balances were within 10% and theoretical conductivity values calculated from measured cation and anion concentrations (equation 2) fell within 2% of the measured conductivity values taken on site and within 7% of the conductivity value as measured in the lab. Therefore I accepted the water chemistry analyses as being accurate but omitted Lake 21 from the data set for the analysis performed on these four variables due to suspicions that human interference with the lake was causing abnormally high readings for ions.

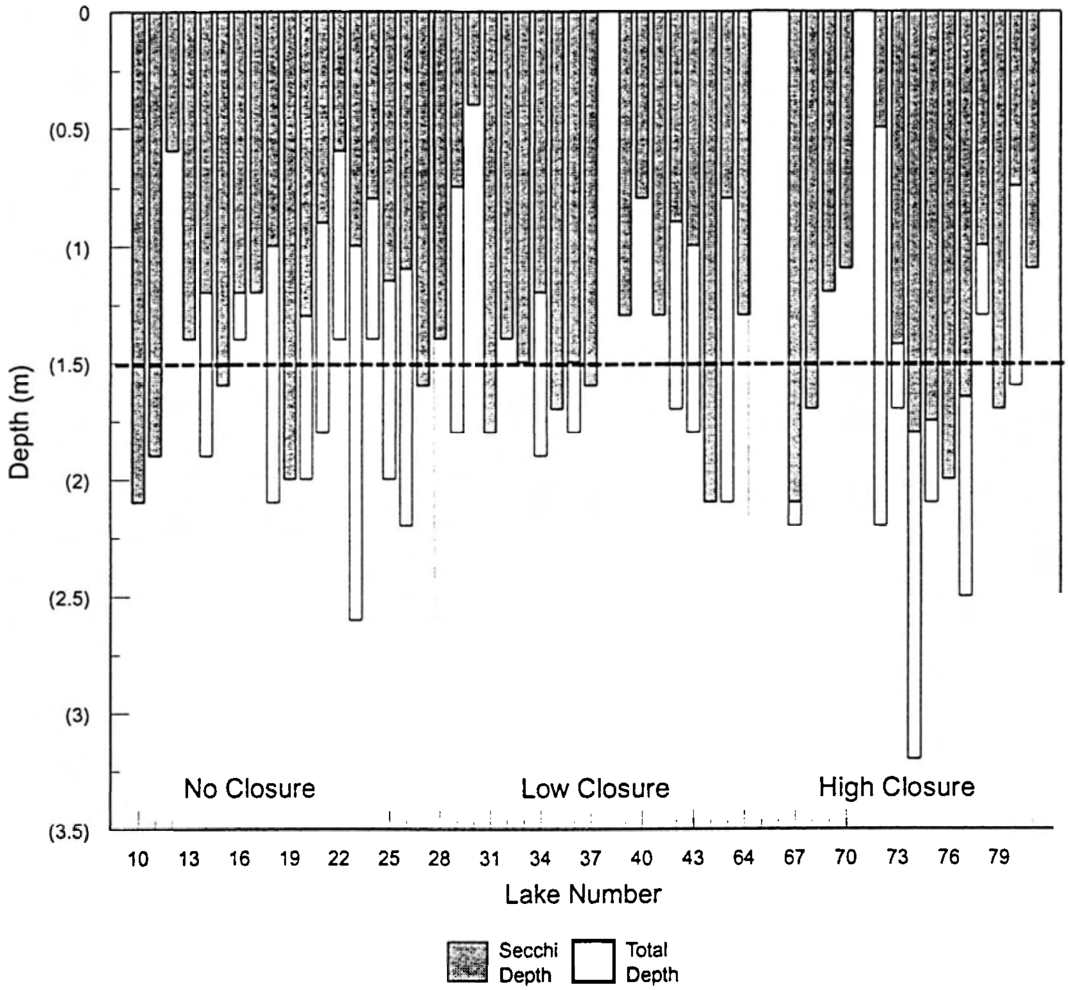
Physical Data

Physical data on the lakes are available for the summer 1993 data set as well as the spring 1994 data set. The entire physical data set includes variables of lake depth, secchi depth, and temperature for the summer field season and lake depth, temperature, total ice thickness, white ice thickness and snow depth for the spring field season (Table 2). Analysis of lake area is also included in this section.

Although several relations between variables of the physical data set became apparent during the analyses, this data set becomes most useful when estimating lake volume. Volume is an essential component of the models developed in this thesis to calculate individual lake methane content as well as in estimating total Mackenzie delta lake methane content and then extrapolating to circumpolar delta lake methane content.

Before discussing the spatial distribution of these variables, there are two relations that stand out when first viewing the data. Fig. 8 highlights the relation between water column depth and secchi depth for the summer 1993 data set. To analyse this relation, I considered only those lakes with depths $\geq$ 1.5 m.. Within each closure class, the lakes were divided into 2 groups: 1 with secchi depths < 1.5 m and 1 with secchi depths $\geq$ 1.5 m. The use of a chi-square statistic indicated that there is no relation between secchi depth and lake closure ($p > 0.25$). From this information it could be concluded that light is not a major limiting factor for primary productivity in any of these delta lake ecosystems. However, it must be remembered that the secchi depth observations represent a snap-shot in time. On occasions of rapid inflow into the lakes, such as during and after river rise, turbidity may well be much higher. As no and low-closure lakes remain connected to the main channels for significantly longer time periods than the high-closure lakes it seems plausible that high-closure lakes would be more conducive to rooted macrophyte growth as their water columns are clearer. Three of the lakes (12, 30, and 40) included in this data set could not be sampled in the spring of 1994 as unfrozen

Fig. 8. Secchi depth in relation to total lake depth for lakes in the Aklavik and Central Delta regions ($N = 50$). Although statistically there is no relation between secchi depth and closure status (chi-square statistic, $p > 0.25$) this represents a snap-shot in time and it is likely that the photic zone would decrease in times of rapid inflow into the lakes..


0
(0.5)
(1)
(1.5)
(2)
(2.5)
(3)
(3.5)
Depth (m)
No Closure
Low Closure
High Closure
10 13 16 19 22 25 28 31 34 37 40 43 64 67 70 73 76 79
Lake Number
Secchi Depth
Total Depth

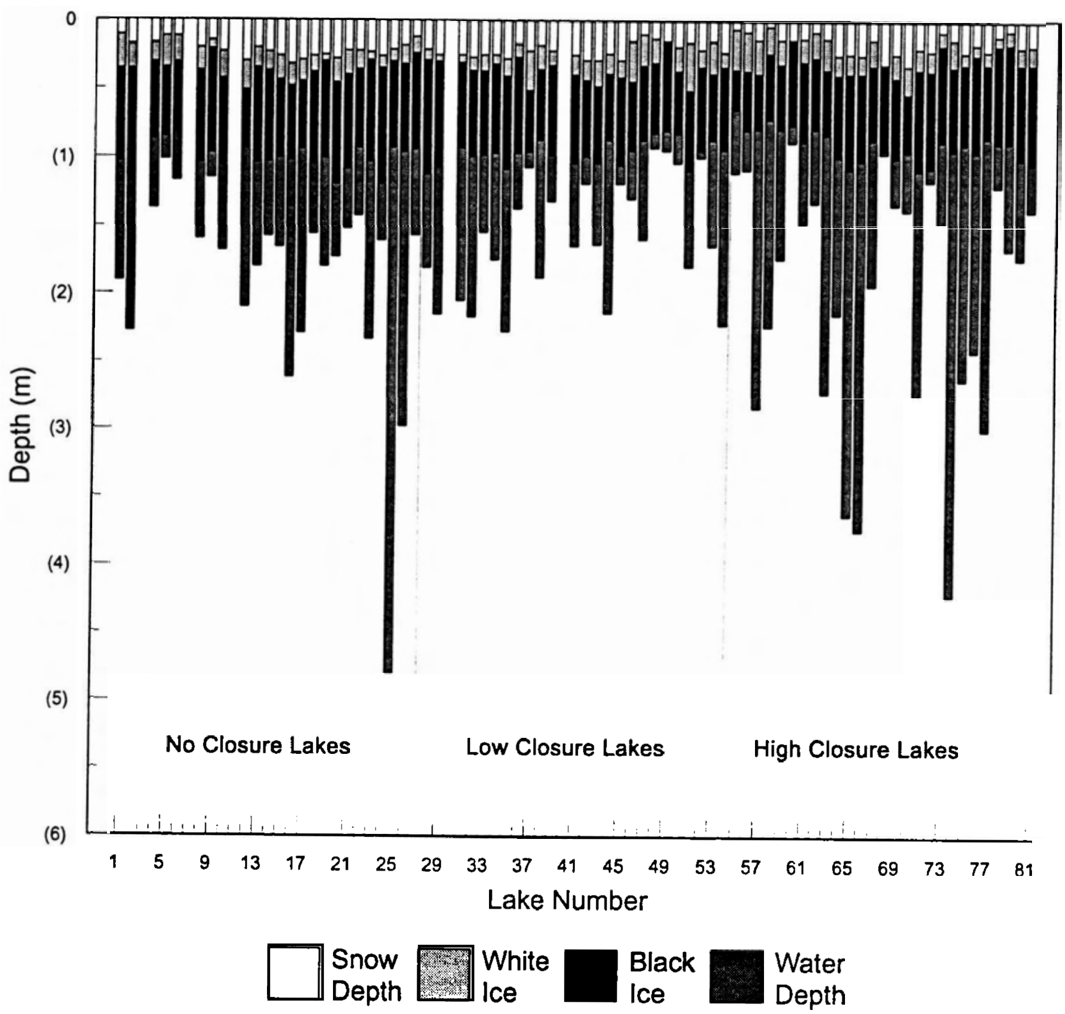
water was not found. Two other lakes (3 and 7) not a part of the summer data set could not be sampled as unfrozen water was not found.

The other relation between physical variables that is interesting involves variables in the spring 1994 data set. The ratio of white ice thickness to black ice thickness was approximately 1:3 for the entire data set, which is consistent with the results found by Bigras (1990) (Fig. 9). White ice is formed when snow accumulation on top of a thickening black ice column is sufficient to depress the surface of the black ice column below the hydrostatic water level forcing water up through cracks in the ice and around the edges of the lake (Adams and Lasenby, 1985). This depression of the ice column usually occurs when the snow cover equals approximately 50% of the depth of the ice column below. The escaping water saturates the snow cover to the hydrostatic water level and freezes forming the white ice layer.

Spatial variability

Because of the distance included in the sampling area and the dominant lake forming processes characteristic of each closure level, spatial variability within the data set for physical variables is likely. For example, high-closure lakes proved to be significantly smaller in area that either the low or no-closure lakes (Table 3). Snow depth on the high-closure lakes is significantly less than either the no or low-closure lakes. As total ice depth and white ice accumulation show no significant variation between level means for this category, less snow coverage could lead to more favorable light regimes in the early spring thereby encouraging earlier photosynthetic activity in the under-ice water columns of these lakes. It is somewhat surprising that the snow cover on these lakes is less than the low and no-closure lakes. The high-closure lakes are significantly smaller in area than either of the other two levels and therefore one would expect relatively less redistribution of snow by wind on these lakes which would lead to higher accumulations of snow on their ice surfaces. One possible explanation for the lower snow

Fig. 9. Snow, ice and unfrozen water measurements for the Mackenzie Delta lakes, spring 1994. White ice to black ice formation exists at a ratio of approximately 1:3. Note the tendency for high-closure lakes to be deeper than the low and no-closure lakes.



0
(1)
(2)
(3)
(4)
(5)
(6)
Depth (m)
No Closure Lakes
Low Closure Lakes
High Closure Lakes
1
5
9
13
17
21
25
29
33
37
41
45
49
53
57
61
65
69
73
77
81
Lake Number
Snow Depth
White Ice
Black Ice
Water Depth

Table 3. Summary for the Two Way ANOVAs and TUKEY HSD tests performed on the physical variables for the summer 1993 and spring 1994 Mackenzie Delta transect lakes. p values are reported for all Two-Way ANOVAs. p values < 0.051 are reported for TUKEY HSD tests run on One-Way ANOVAs. Dashes indicate insignificant variation between level means whereas blank cells indicate testing not applicable for these variables

	Two-Way ANOVA Summer 1993 p values	One-Way ANOVA Summer 1993 p values			Two-Way ANOVA Spring 1994 p values	One-Way ANOVA Spring 1994 p values		
	Closure	High/No	High/Low	Low/No	Closure	High/No	High/Low	Low/No
Depth	0.809	-	-	-	0.095	-	-	-
Secchi Depth	0.757	-	-	-				
Temperature	0.625	-	-	-				
Total Ice Depth					0.089	-	-	-
White Ice Depth					0.508	-	-	-
Snow Depth					<.001	0.039	0.027	-
Area					0.002	0.002	0.020	-

	Two-Way ANOVA Summer 1993 p values	One-Way ANOVA Summer 1993 p values			Two-Way ANOVA Spring 1994 p values	One-Way ANOVA Spring 1994 p values		
	Position	Aklavik/Inuvik	Aklavik/Central	Central/Inuvik	Position	Aklavik/Inuvik	Aklavik/Central	Central/Inuvik
Depth	0.102	No data	-	No data	0.017	0.014	-	-
Secchi Depth	0.615	No data	-	No data				
Temperature	0.971	No data	-	No data				
Total Ice Depth					0.035	0.020	-	-
White Ice Depth					<.001	<.001	<.001	0.020
Snow Depth					<.001	<.001	0.004	<.001
Area					0.282	-	-	-

Note: Data for the Inuvik region are not available for the summer 1993 data set and therefore statistical testing for significant variation between level means for the position category is limited to Aklavik/Central levels.

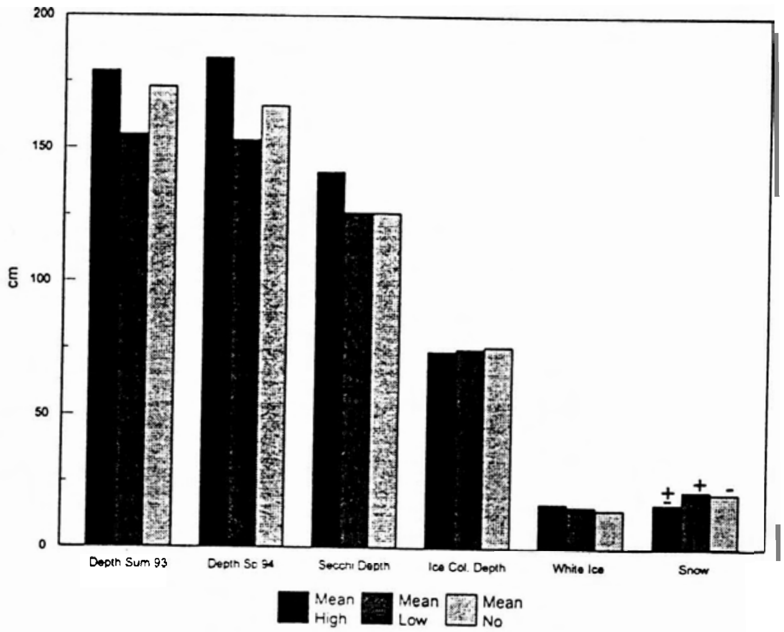
accumulations is that the surrounding coniferous vegetation is more likely to trap the snow before it can settle on the small ice surfaces.

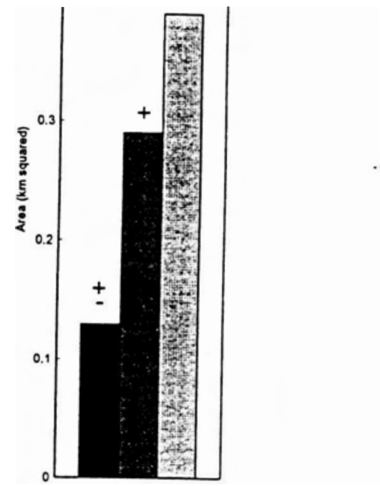
When examining variation within the position category, Aklavik lakes prove to be significantly deeper at our point of sampling and also have significantly thicker ice columns than the Inuvik or Central delta lakes (Table 3, Fig 10). Even though the total ice column is thicker, the portion composed of white ice is significantly less than either the Inuvik or Central delta lakes. This is a logical relation when you consider the importance of deeper snow cover in the formation of white ice. If the ice column grows rapidly, it would become thick enough that it would be less likely to be submerged by snow cover and therefore these lakes would attain a thinner white ice layer.

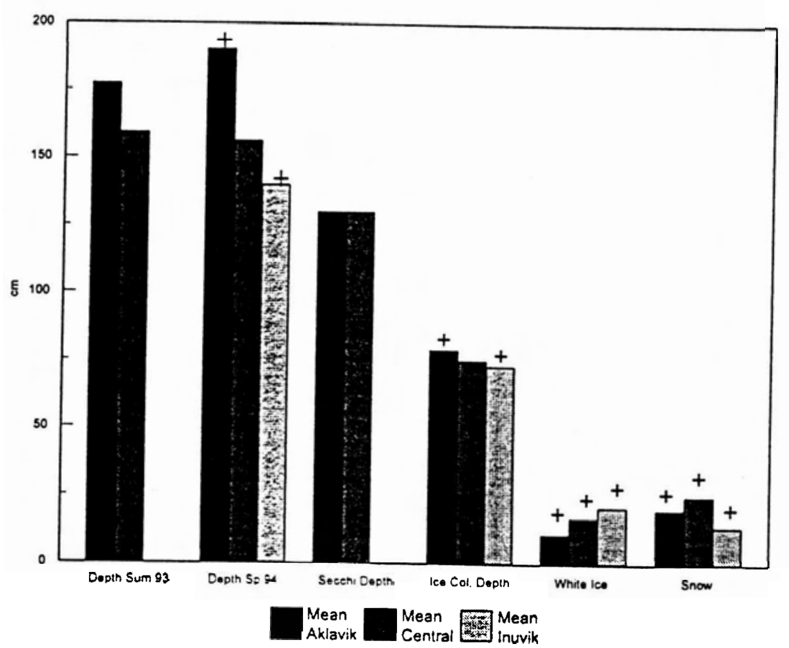
High-closure lakes tend to be deeper than the no-closure lakes with the low-closure lakes being the shallowest ($p = .095$) (Fig. 10). As both the summer and the spring data sets follow the same pattern for the depth variable some confidence in this trend can be held. Therefore, even though lake area is the smallest for the high-closure lakes, they are also the deepest. For the position category, not only are Aklavik lakes significantly larger in area than the Inuvik lakes but they also appear to be deeper on average with thicker total ice columns and less white ice accumulation (Fig 10).

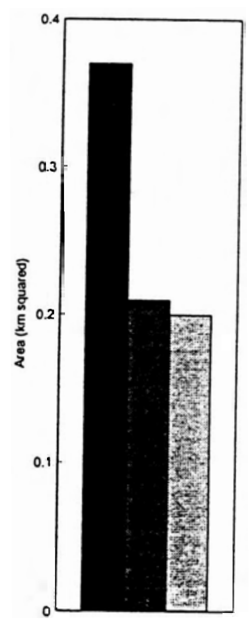
Summer water column temperature attained a mean value of 17.9 °C with a range from 14.8 °C to 22.3 °C and a standard deviation of 1.73. Because of the shallow nature of these lakes, they are constantly mixed by wind and do not stratify. It can therefore be assumed that the single temperature reading taken is representative of the entire water column. The mean of the under-ice spring water column temperature was 1.3 °C with a standard deviation of 0.87. The temperature profiles of each lake for the spring 1994 data set are given in Appendix B alongside the conductivity profiles.

Fig. 10. Physical variable means of depth, secchi depth, ice column depth, white ice thickness, snow depth and lake area for the summer 1993 (Sum 93) and spring 1994 (Sp 94) data sets for the Mackenzie Delta lake transect. The top two graphs report arithmetic means for the category of closure while the bottom two graphs offer arithmetic means for the position category. Matching symbols above bars indicate significant variation between level means ($p < 0.05$).


200
150
100
50
0
cm
Depth Sum 93
Depth Sp 94
Secchi Depth
Ice Col. Depth
White Ice
Snow
Mean High
Mean Low
Mean No


Area (km squared)
0.3
0.2
0.1
0


200
150
100
50
0
cm
Depth Sum 93
Depth Sp 94
Secchi Depth
Ice Col. Depth
White Ice
Snow
Mean Aklavik
Mean Central
Mean Inuvik


0.4
0.3
0.2
0.1
0
Area (km squared)

Sediment Content Data

It is apparent that sediment accumulation within the Mackenzie delta lakes is related to lake closure with no-closure lakes having higher annual sedimentation rates than low-closure lakes which, in turn, have higher sedimentation rates than high-closure lakes (Marsh, 1995, unpublished data). To determine sedimentation rates, a ^{137}Cs marker bed was identified in sediment cores obtained from each of the transect lakes. Knowing the closure classification of each of the lakes enabled sedimentation rates to be related to lake closure.

As no-closure lakes receive sediment laden river water throughout the summer season and high-closure lakes are only connected to the main channels for a short time, sediment accumulation rates for high-closure lakes should be more dependent upon autochthonous primary production than either low or no-closure lakes. Hence, the sediments of high-closure lakes should contain a higher percentage of carbon than the other lake closure types. As carbon is the substrate that methanogenic bacteria feed on, it is no surprise that sediment carbon content has been found to be well correlated with methane emissions from wetland ecosystems (Kelly and Chynoweth, 1981; Smith and Lewis, 1992; Valentine, 1994).

Spatial variability

Sediments were analyzed for carbon, nitrogen and phosphate content. Also included in the statistical analysis for this data set is sedimentation rate. Significant variation between level means for sediment carbon content between the high and no-closure lakes and high and low-closure lakes exists (Table 4). Sedimentation rate also shows significant variation between high and no-closure lakes. Sedimentation rate declines from no-closure, through low-closure, and into the higher closure lakes while sediment carbon content shows an inverse relation to this pattern (Fig. 11). This is the

Table 4. Summary for the Two Way ANOVAs and TUKEY HSD tests performed on the sediment content and sedimentation rate for the spring 1994 Mackenzie Delta transect lakes. p values are reported for all Two Way ANOVAs. p values < 0.051 reported for TUKEY HSD tests run on One Way ANOVAs.

	Two-Way ANOVA p values	One Way ANOVA p values		
	Closure	High/No	High/Low	Low/No
Carbon	0.013	0.021	0.064	-
Nitrogen	0.050	-	-	-
Phosphate	0.667	-	-	-
Sed. Rate	0.056	0.038	-	-

	Two-Way ANOVA p values	One Way ANOVA p values		
	Position	Aklavik/Inuvik	Aklavik/Central	Central/Inuvik
Carbon	0.265	No data	No data	-
Nitrogen	0.004	No data	No data	0.005
Phosphate	0.003	No data	No data	0.002
Sed. Rate	0.338	-	-	-

Note: Data for the Aklavik region are not available for this data set and therefore statistical testing for significant variation between level means for the position category is limited to Central/Inuvik levels.

to this pattern (Fig. 11). This is the relation that is expected as no and low-closure lakes receive sediments from longer interaction with floodwaters than the high-closure lakes do. The resultant clearer water columns, on the other hand tend to favor macrophyte growth in the high-closure lakes which results in enhanced flux of carbon to the sediments.

For the category of position, the nitrogen content of the sediments is significantly higher for the Inuvik lakes than for the Central delta lakes with phosphate showing an inverse relation to this (Table 4 and Fig. 11). Sediment carbon content, like nitrogen, appears higher in the Inuvik sediments than the Aklavik sediments. Sedimentation rate appears lower on the eastern side of the delta than the western side with highest rates occurring in the central delta. This possibly reflects the geologic controls on sedimentation as outlined earlier.

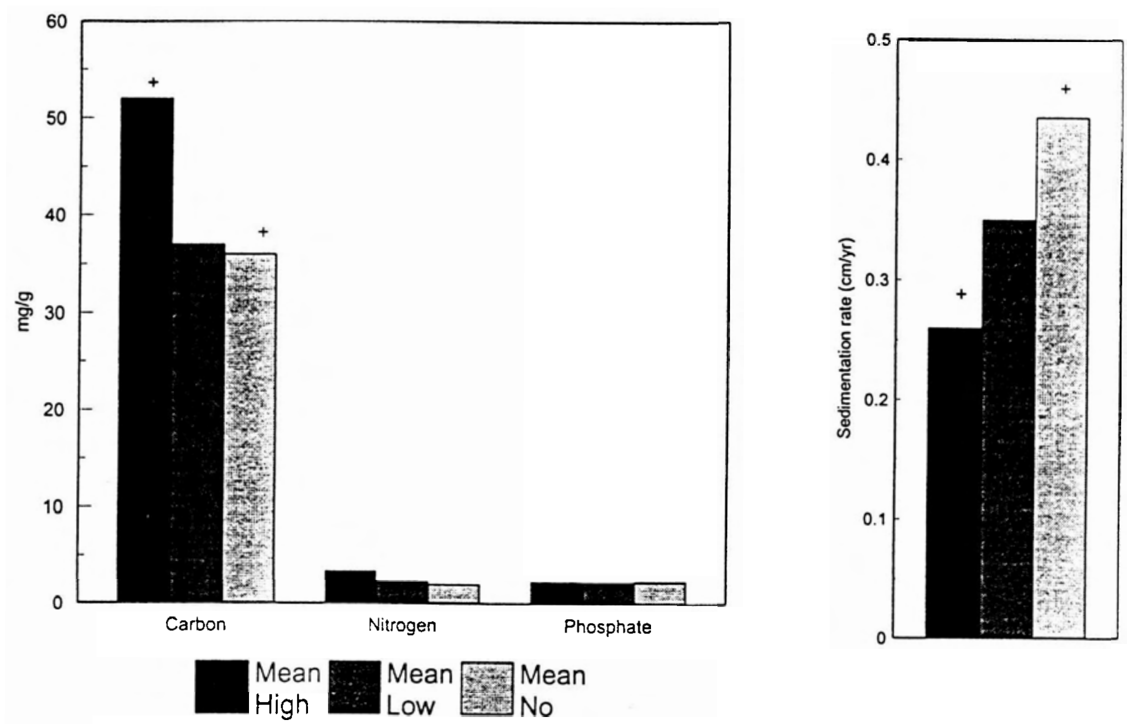
Gases and Major Solutes

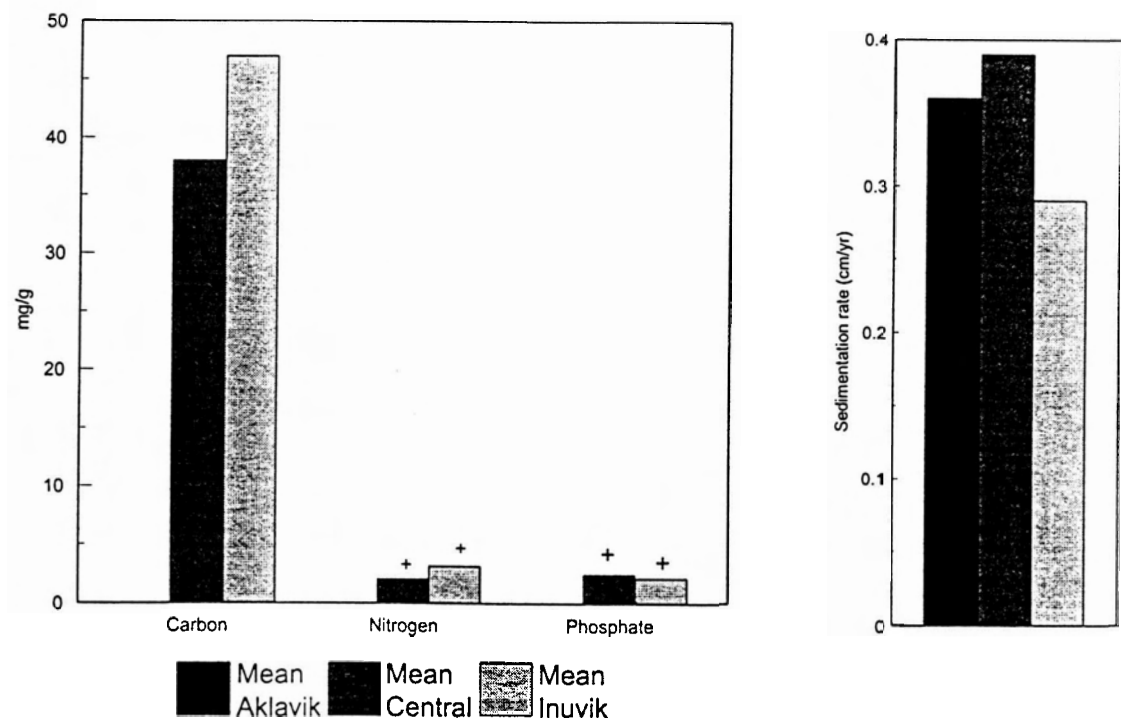
Although the hypotheses guiding this thesis focus on methane and its spatial distribution among lakes on the Mackenzie Delta, the rationale that supports these hypotheses generally holds true for the variables of gases and major solutes. If the flooding regime of these lakes is a major control on their biological compositions through the delivery of nutrients and sediments, it should also prove to be a major control on the chemical composition of the lake water.

Spatial variability of gases

Initially the non-parametric distribution free Kruskal-Wallis test was performed on transformed methane values. This test is not concerned with specific parameters (such as level means as in ANOVA) but with the distribution of the variates. Results of Kruskal-Wallis test rejected the null hypothesis that the groups do not differ in terms of closure ($p = .002$). However, because the design of this study is to determine the role that

Fig. 11. Mean values for the sediment content and sedimentation rate data sets for the Mackenzie Delta lake transect. The top two graphs report arithmetic means for the category of closure while the bottom two graphs offer arithmetic means for the position category. Matching symbols above bars indicate significant variation between level means (p value < 0.051).


mg/g
Carbon
Nitrogen
Phosphate
Sedimentation rate (cm/yr)
Mean High
Mean Low
Mean No


mg/g
Carbon
Nitrogen
Phosphate
Sedimentation rate (cm/yr)
Mean Aklavik
Mean Central
Mean Inuvik

lake closure has on the spatial distribution of methane and testing between levels in the closure category is not possible with this non-parametric test, a Two-Way ANOVA was again used.

Methane shows significantly higher concentrations in high and low-closure lakes than in no-closure lakes verifying that closure is indeed a major control on the spatial variation of methane concentrations in under-ice water columns of Mackenzie Delta lakes (Table 5). Mean values range from 477 μM for high-closure lakes to 315 μM for low-closure lakes down to 173 μM for no-closure lakes (Fig. 12). As previously stated, sediment carbon content is an important variable in methane production and the sediments of the high-closure lakes in this study have proven to contain significantly higher concentrations of carbon than the no-closure lakes (Fig. 11). It is not surprising therefore that the sediments of the high-closure lakes produce more methane than the low and no-closure lakes.

An increasing trend in lake methane concentration appears to exist as one moves east across the delta ($p = .066$, Table 6) with Inuvik lakes attaining a mean concentration of 402 μM, Central delta lakes having an average of 366 μM and Aklavik lakes containing the least methane with a mean of 213 μM (Fig. 12). Again, when considering that a trend of increased sediment carbon content exists in the Inuvik lakes compared to the Central delta lakes (Fig. 8) it logically follows that these eastern lakes should be better methane producers than the central lakes.

In studying the interaction between closure and position, Inuvik high-closure lakes were significantly higher in methane concentration than both Aklavik and central no-closure lakes (p values < 0.001 and 0.041 respectively). Aklavik no-closure lakes had extremely low methane concentrations (56 μM) and were significantly lower than central low and high-closure lakes as well as the Inuvik high-closure lakes.

Table 5A. Summary for the Two-way ANOVAs and TUKEY HSD tests performed on the gases and major solute variables from the spring 1993 (5A), summer 1993 (5B) and spring 1994 (5C) data sets for the category of closure. p-values are given for all Two-way ANOVAs. p-values < 0.10 are given for TUKEY HSD tests run on One-way ANOVAs. Dashes indicate insignificant variation between level means.

	Two-Way ANOVA Spring 1993 p value	'One-Way ANOVA Spring 1993 p value		
	Closure	High/No	High/Low	Low/No
Gases				
Methane	No data	No data	No data	No data
Carbon Dioxide	No data	No data	No data	No data
DIC	No data	No data	No data	No data
Major Solutes				
pH	0.330	-	-	-
Conductivity	0.007	-	0.010	-
Calcium	0.009	0.051	0.015	-
Magnesium	0.106	-	-	-
Potassium	0.293	-	-	-
Sodium	0.012	-	0.017	-
Ammonium	No data	No data	No data	No data
Chloride	<.001	-	,004	-
Sulfate	0.004	0.013	-	-
Bicarbonate	No data	No data	No data	No data
Phosphate	No data	No data	No data	No data
Silica	<.001	0.008	0.001	-

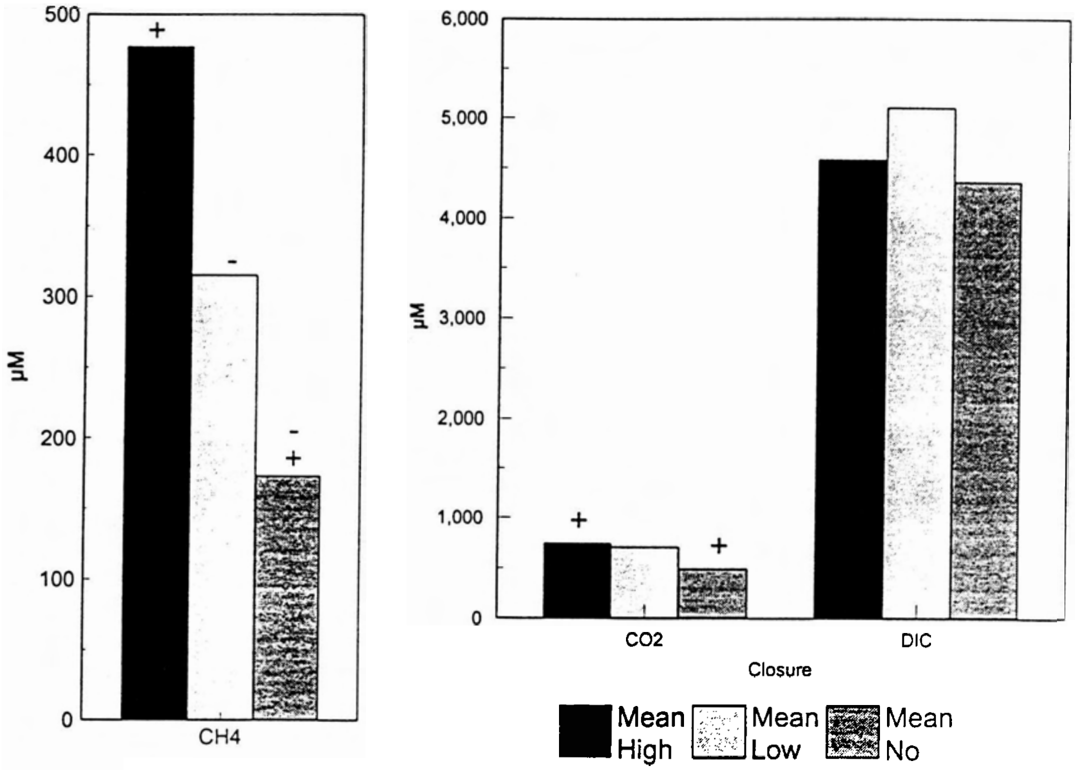
Table 5B.

	Two-Way ANOVA Summer 1993 p value	'One-Way ANOVA Summer 1993 p value		
	Closure	High/No	High/Low	Low/No
Gases				
Methane	No data	No data	No data	No data
Carbon Dioxide	No data	No data	No data	No data
DIC	No data	No data	No data	No data
Major Solutes				
pH	0.053	-	-	0.072
Conductivity	0.028	0.033	-	-
Calcium	0.040	-	-	-
Magnesium	0.107	-	-	-
Potassium	0.206	-	-	-
Sodium	0.169	-	-	-
Ammonium	No Data	No data	No data	No data
Chloride	0.002	-	0.023	-
Sulfate	0.026	0.086	0.055	-
Bicarbonate	No data	No data	No data	No data
Phosphate	No data	No data	No data	No data
Silica	0.285	-	-	-

Table 5C.

	Two-Way ANOVA Spring 1994 p value	One-Way ANOVA Spring 1994 p value		
	Closure	High/No	High/Low	Low/No
Gases				
Methane	<.001	<.001	-	0.056
Carbon Dioxide	0.012	0.028	-	-
DIC	0.102	-	-	-
Major Solutes				
pH	0.005	-	0.041	-
Conductivity	0.005	-	0.018	0.057
Calcium	0.030	-	0.047	-
Magnesium	0.033	-	0.048	-
Potassium	0.018	0.037	-	0.046
Sodium	0.010	-	0.041	0.049
Ammonium	<.001	0.003	-	0.001
Chloride	0.001	-	0.016	0.028
Sulfate	0.001	0.002	0.027	-
Bicarbonate	0.027	-	-	-
Phosphate	0.623	-	-	-
Silica	0.030	-	0.029	0.098

Fig. 12. Mean concentrations for gases for the spring 1994 under-ice data set for the Mackenzie Delta lake transect. The top two graphs indicate arithmetic means for the category of closure while the bottom two graphs indicate arithmetic means for the position category. Matching symbols above bars indicate significant variation (p value < 0.051).


500
400
300
200
100
0
µM
+
-
-
+
CH4
6,000
5,000
4,000
3,000
2,000
1,000
0
µM
+
+
CO2
DIC
Closure
Mean High
Mean Low
Mean No

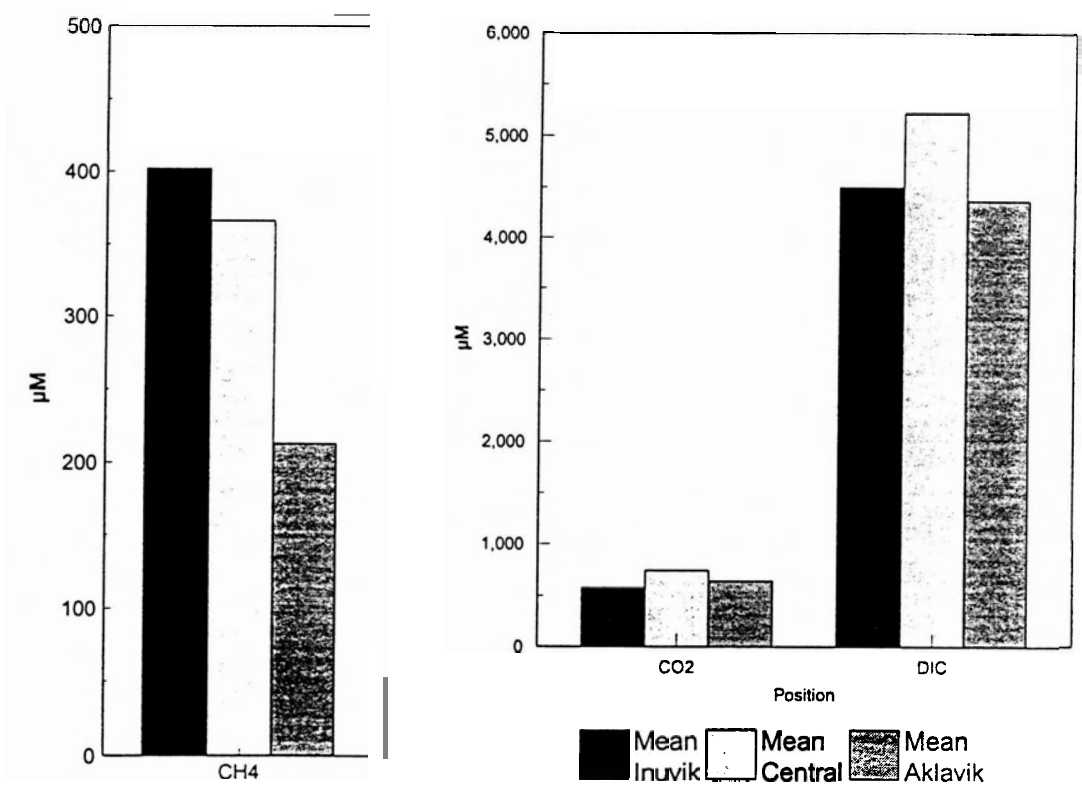

500
400
300
200
100
0
µM
CH4
6,000
5,000
4,000
3,000
2,000
1,000
0
µM
CO2
DIC
Position
Mean Inuvik
Mean Central
Mean Aklavik

Table 6A. Summary for the Two-way ANOVAs and TUKEY HSD tests performed on the gases and major solute variables from the spring 1993 (6A), summer 1993 (6B), and spring 1994 (6C) data sets for the category of position. p-values are given for all Two-way ANOVAs. p-values < 0.10 are given for TUKEY HSD tests run on One-way ANOVAs. Dashes indicate insignificant variation between level means.

	Two-Way ANOVA Spring 1993 p value	One-Way ANOVA Spring 1993 p value		
	Position	Aklavik/inuvik	Aklavik/Central	Central/Inuvik
Gases				
Methane	No data	No data	No data	No data
Carbon Dioxide	No data	No data	No data	No data
DIC	No data	No data	No data	No data
Major Solutes				
pH	0.068	-	-	-
Conductivity	0.097	-	-	-
Calcium	0.085	-	-	-
Magnesium	0.019	-	0.023	-
Potassium	0.022	-	0.030	-
Sodium	0.002	0.010	-	0.014
Ammonium	No data	No data	No data	No data
Chloride	<.001	<.001	0.031	0.001
Sulfate	0.001	0.002	0.057	-
Bicarbonate	No data	No data	No data	No data
Phosphate	No data	No data	No data	No data
Silica	0.060	-	-	-

Note: Data for the Inuvik region is not available for the summer 1993 data set and therefore statistical testing for significant variation between level means for the position category is limited to Central/Aklavik levels.

Table 6B.

	One-Way ANOVA Summer 1993 p value Aklavik/Central
Gases	
Methane	No data
Carbon Dioxide	No data
DIC	No data
Major Solutes	
pH	0.118
Conductivity	0.314
Calcium	0.205
Magnesium	0.033
Potassium	0.051
Sodium	<.001
Ammonium	No data
Chloride	<.001
Sulfate	0.260
Bicarbonate	No data
Phosphate	No data
Silica	0.256

Table 6C.

	Two-Way ANOVA Spring 1994 p value	One-Way ANOVA Spring 1994 p value		
	Position	Aklavik/Inuvik	Aklavik/Central	Central/Inuvik
Gases				
Methane	0.066	0.099	-	-
Carbon Dioxide	0.063	-	-	-
DIC	0.041	-	-	-
Major Solutes				
pH	<.001	0.037	-	</001
Conductivity	0.848	-	-	-
Calcium	0.480	-	-	-
Magnesium	0.344	-	-	-
Potassium	0.559	-	-	-
Sodium	<.001	<.001	0.003	-
Ammonium	0.008	0.015	0.076	-
Chloride	<.001	<.001	<.001	0.021
Sulfate	0.021	0.033	0.090	-
Bicarbonate	0.053	-	-	-
Phosphate	0.002	-	0.063	-
Silica	0.129	-	-	-

Carbon dioxide also shows significantly higher concentrations in the under-ice water column of high-closure lakes than no-closure lakes (Table 5). As both methane and carbon dioxide are products of methanogenesis, a close correlation between these two variables was expected and subsequent regression analysis yielded an r^2 value of 0.44. The average lake concentration of methane is 310 μM and the average concentration of carbon dioxide is 650 μM. By assuming that a net stoichiometry of 1 mole of carbon dioxide is produced for every mole of methane, it can be calculated that approximately 50% of the carbon dioxide present at the time of sampling was produced by methanogenesis. As per Fig. 12. which reports the mean concentration of these gases in each closure level, it can be interpreted that 65% of the carbon dioxide in the high-closure lakes was produced by methanogenesis, 45% in the low-closure lakes and 33% in the no-closure lakes. As well as the under-ice content of both methane and carbon dioxide decreasing from high to no-closure lakes, the amount of carbon dioxide produced by methanogenic activity also decreases. If dissolved inorganic carbon concentration is representative of total carbon remineralization, methanogenesis is responsible for 10% in the high-closure lakes, 6% in low-closure lakes and 4% in no-closure lakes (Fig. 12) for an average of 7% for all the sampled lakes. Using the above presented percentages as indication of the importance of methane producing bacteria as agents of carbon remineralization, it can be seen that the bacteria are twice as important in the high-closure lakes than in the no-closure lakes for this purpose.

The remainder of the carbon dioxide present in these lakes is a product of respiration and would have been present in the water column prior to, and after, the development of an ice cover on these lakes. Carbon dioxide would have been excluded into the water column during ice formation. Carbon dioxide is also generated during methane oxidation processes which often occur at the sediment water interface until the supply of oxygen is consumed.

Central low-closure lakes had the highest concentrations of dissolved inorganic carbon and were significantly higher than Inuvik no-closure lakes ($p = 0.002$). This difference was paralleled in the concentration of carbon dioxide in the under-ice water column ($p = 0.002$).

For the sixteen lakes that had under-ice water columns greater than 1 m deep, thereby allowing for two water column sample locations, methane concentrations were highest at the sediment/water interface in all but two cases (Appendix C). In the two cases where there were lower concentrations at the sediment/water interface (Lakes 29 and 31) the values were very low (< 0.5 μM) and the difference between the upper and lower readings was slight (< 0.3 μM). This consistent pattern of higher concentrations of methane at the sediment/water interface suggests that the methane is not being mixed uniformly through the under-ice water column but rather is staying close to its source and follows the pattern observed for Lake Fryxell, a permanently ice-covered lake in the Antarctic (Smith et al., 1993). The pattern for carbon dioxide and dissolved inorganic carbon generally followed the same trend as methane (See also Appendix C for profiles).

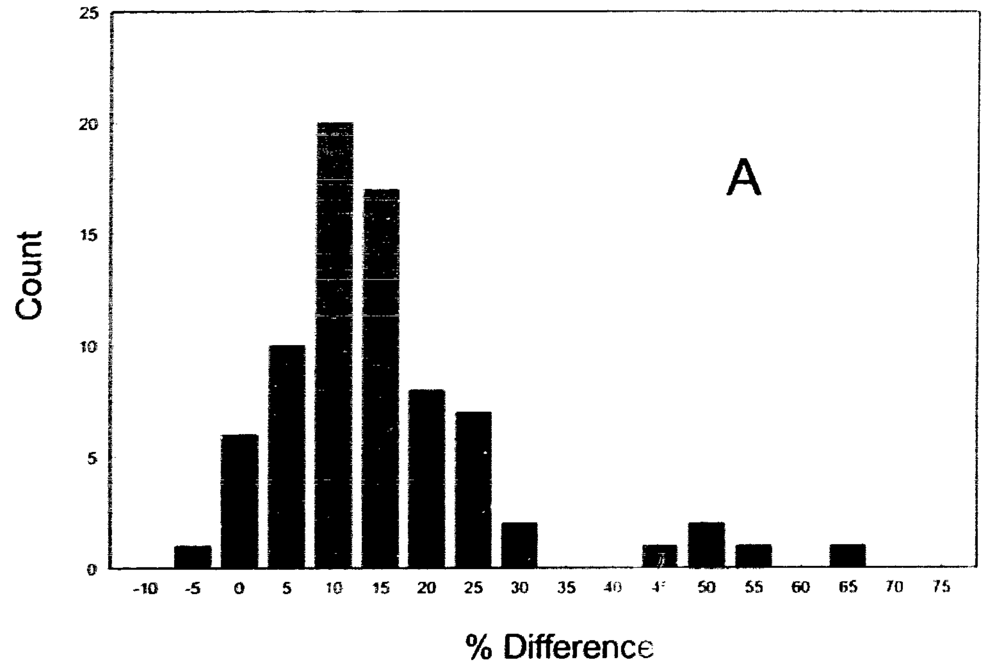
Spatial variability of major solutes

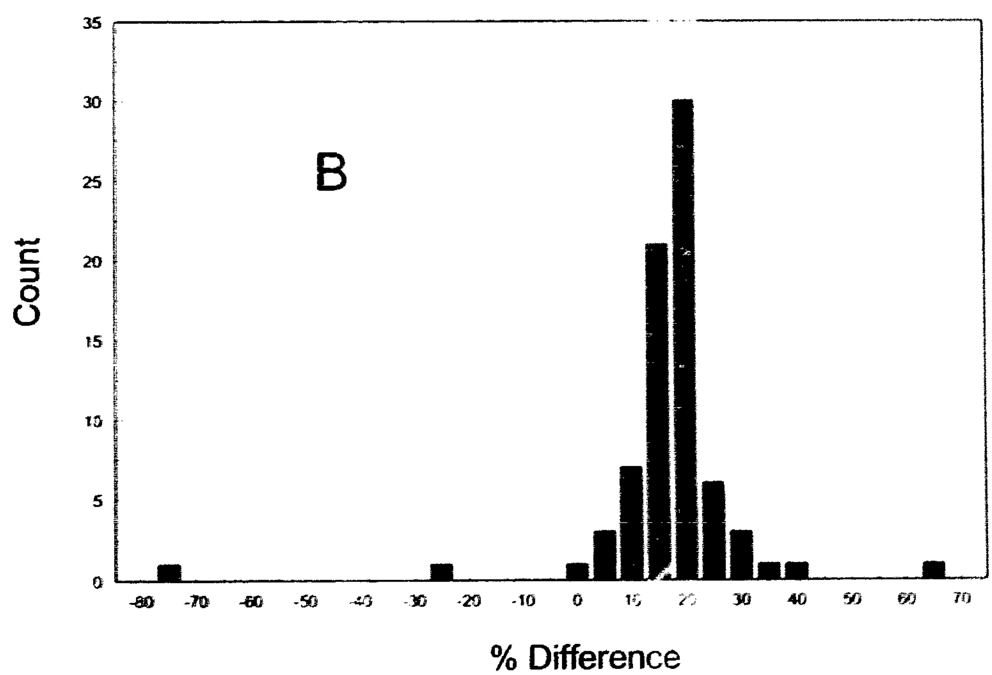
The importance of the influence of frequency and duration of flooding on the nutrient chemistry of the delta lakes as dictated by lake closure has been addressed (Lesack et al., 1991b). Based on summer water chemistry obtained from 42 Inuvik lakes, chemical signatures were tentatively assigned to lake closure levels. It is hoped, by broadening the data set to include lakes from the Central delta and Aklavik areas, as well as to include data sets from under-ice samples, that delta wide trends will become apparent that will allow lake classification on a more general scale of chemical signatures. As it has previously been determined in this thesis that lake closure is a significant determinant of methane production, it would be of value to be able to classify lakes as to their level of closure and therefore their ability to produce methane based upon their more readily obtainable water chemistry.

Conductivity, a measure of total dissolved ions in the water column, seems a logical place to start looking for spatial variation based on lake closure and position. Conductivities were obtained both in the field and in the lab for each lake. Simple linear regression between lab conductivities and *in situ* conductivities yielded a strong, positive correlation ($r^2 = 0.72$, $N = 76$) giving confidence that no major recording errors were made during data collection.

Measured conductivities can also be used as a check to ensure that all major ions have been accurately accounted for by comparing them to theoretical conductivities. By calculating and summing the equivalent conductance for each ion on a per lake basis (equation 6), it becomes evident that the conductivities measured in the field give closer representation to the theoretical conductivities than the conductivities measured in the lab (Fig 13). The % difference for *in situ* lake conductivities peak over the 5 - 10 interval while the lab conductivities peak over the 15 - 20 interval indicating that, while both variables generally read higher than theoretical conductivities, lab conductivities are approximately 10% higher than the lake conductivities. *In situ* conductivities reflect the under-ice environment where gas exchange between the water column and the atmosphere has been inhibited. During sample collection we observed degassing of carbon dioxide from the water as a state of equilibrium between the water sample and the atmosphere was establishing. As a response to the newly established equilibrium, pH values would rise and a higher percentage of the dissolved inorganic carbon contained in the sample would be present as the bicarbonate ion. This increase in anion concentration would result in higher lab conductivities. This same argument can be used to explain why the theoretical conductivities are lower than both the lab and lake conductivities. Some of the variation between theoretical and measured conductivities is also likely due

Fig. 13. Conductivity difference of (A) lake versus theoretical conductivity and (B) lab versus theoretical conductivity. Percent difference of lake versus theoretical conductivities peak over the 5 - 10% interval indicating that lake conductivities are generally higher than theoretical conductivities by 5 - 10%. Percent difference of lab versus theoretical conductivities peak over the 15 - 20% interval indicating that lab conductivities are even higher than the lake conductivities.


A
Count
0
5
10
15
20
25
-10
-5
0
5
10
15
20
25
30
35
50
55
60
65
70
75
% Difference


B
Count
0
5
10
15
20
25
30
35
-80
-70
-60
-50
-20
-10
0
30
40
50
60
70
% Difference

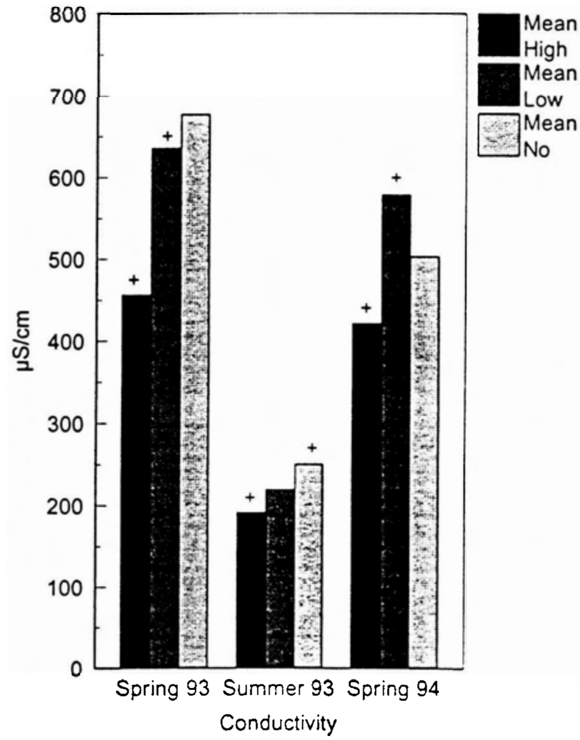
to the fact that organic acids, which could potentially add sufficient anions to lower the variance between measured and theoretical conductance, were not measured.

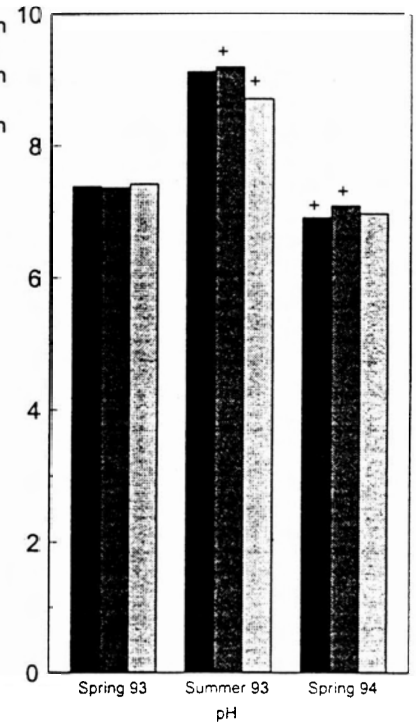
Even though the graph (Fig 13) showing the difference between lake and theoretical conductance shows a normal distribution for the most part, 5 lakes appear to have significantly higher in situ measurements of conductivities than is expected when calculating the theoretical conductivities. The theoretical conductivity for these five lakes (Lakes 5, 17, 48, 50, and 73) is actually closer to the measured lab conductivity than the in situ conductivity. One possible explanation for the discrepancies of these five lakes is that as the in situ conductivities are consistently much higher than the theoretical conductivities and the lab conductivities, it is possible that the in situ conductivity measurement was taken closer to the sediment/water interface and the sample was actually obtained further up in the water column than was recorded.

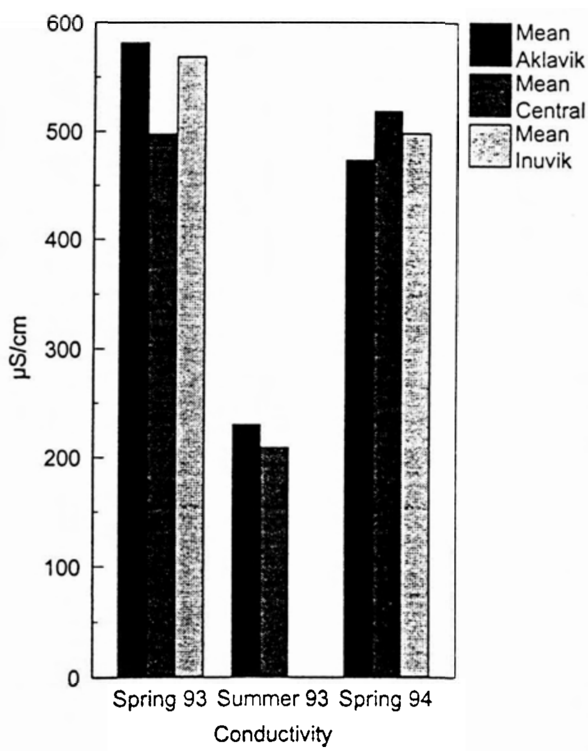
For both the under-ice data sets, high-closure lakes had significantly lower conductivity readings than low-closure lakes (Table 5). If you consider that high-closure lakes also have the lowest summer conductivity values (Fig 14) and that their under-ice water columns are the deepest, relatively low conductivities are expected. For the spring 1993 under-ice data set, the lowest conductivities were found in the central high-closure lakes. These lakes had an average conductivity significantly lower than the Inuvik and Aklavik no-closure lakes as well as the central low-closure lakes ($p = 0.005$, 0.001, and 0.023 respectively). For the spring 1994 under-ice data set, the central low-closure lakes had the highest conductivity values. These lakes had an average conductivity significantly higher than central and Inuvik no-closure lakes as well as Aklavik high-closure lakes ($p = 0.044$, 0.028, and 0.040 respectively).

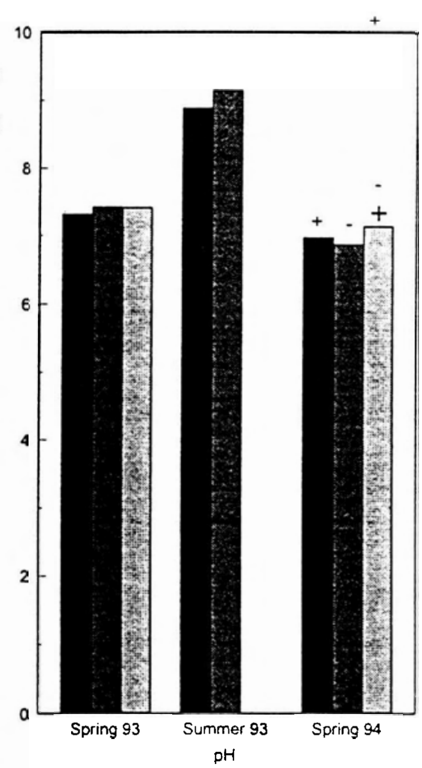
Variation between conductivity level means is not significant for the category of position for the three data sets indicating that location on the delta is not a determinant factor for lake conductivity (Fig. 14, Table 6). Conductivities for the summer data set are significantly lower than for the two under-ice data sets. The process of salt exclusion into

Fig. 14. Mean values for conductivity and pH for the spring 1993, summer 1993, and spring 1994 data sets for the Mackenzie Delta lake transect. The top two graphs report arithmetic means for the category of closure while the bottom two graphs offer arithmetic means for the position category. Matching symbols above bars indicate significant variation between level means (p value < 0.051).


800
700
600
500
400
300
200
100
0
µS/cm
Mean High
Mean Low
Mean No
Spring 93
Summer 93
Spring 94
Conductivity


10
8
6
4
2
0
Spring 93
Summer 93
Spring 94
pH


600
500
400
300
200
100
0
µS/cm
Mean Aklavik
Mean Central
Mean Inuvik
Spring 93
Summer 93
Spring 94
Conductivity


10
8
6
4
2
0
Spring 93
Summer 93
Spring 94
pH

the water column during ice growth resulting in concentration of ions is the primary reason for this.

Conductivity/temperature profiles for each of the 76 lakes from the spring 1994 data set (Appendix B) exhibit the same pattern as the 16 gas profiles (Appendix C) with highest concentrations evident at the sediment/water interface. Plotted on each conductivity profile is the ice/water interface depth indicating the thickness of the ice for each lake and the depth of the water column below. Either slightly above or below this ice/water interface, the conductivity line takes a sharp positive bend and continues in this manner to the sediments. The conductivity of the water within the drill hole reflects the conductivity of the water that was immediately below the ice prior to the hole being drilled and therefore would represent the conductivity of the water near the water/ice interface (Adams and Lasenby, 1985). The general trend of the temperature profiles tends to replicate the conductivity readings in the majority of cases (See also Appendix B)

For the spring 1994 data set, central no-closure lakes had an average pH value which was significantly lower than all other lake groups with the exception of Aklavik and central high-closure lakes (p values range from < 0.001 to 0.003). For both under-ice data sets, Aklavik high-closure lakes had significantly lower pH values than Inuvik no-closure lakes ($p = 0.001$ (spring 1994); $p = 0.012$ (spring 1993)). In general, though, along with lower conductivities, high-closure lakes had significantly lower pH values than low-closure lakes for both under-ice data sets (Table 5, Fig. 14).

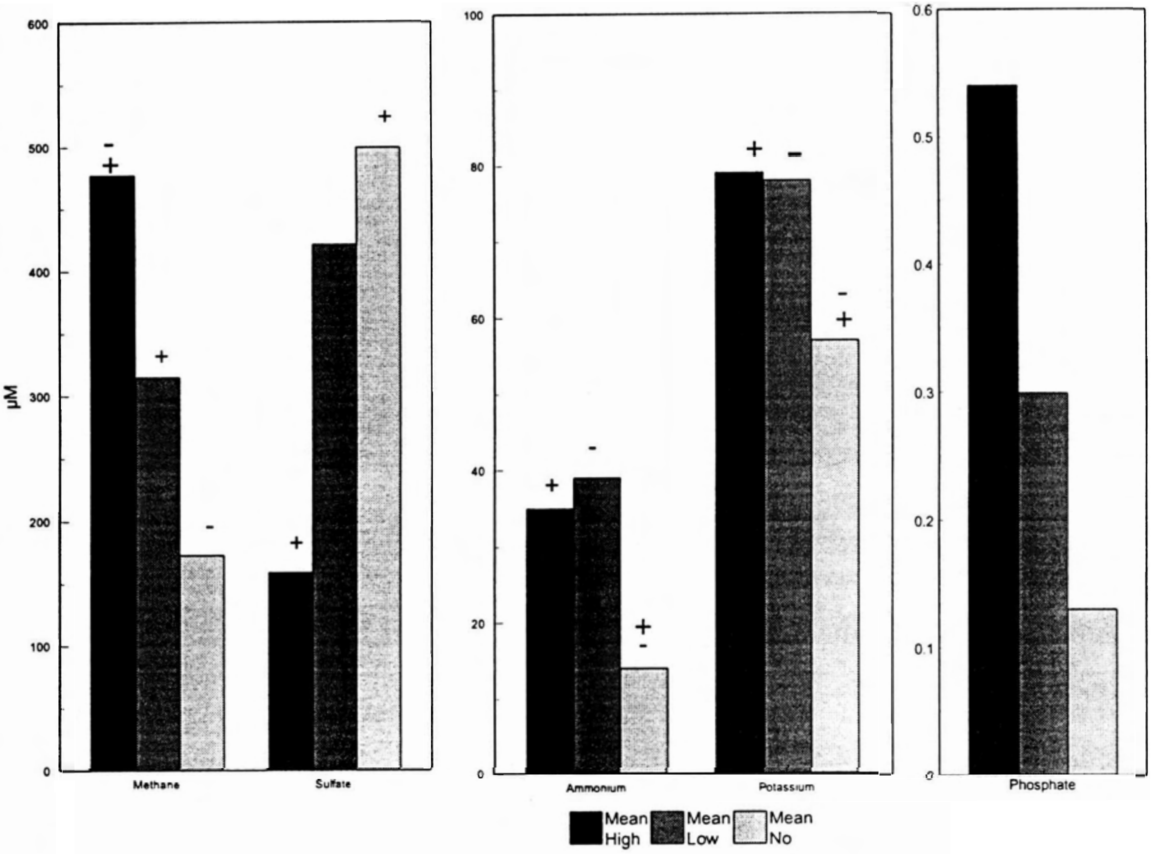
pH values in the summer were much higher for all levels of both categories but showed the most dramatic increase in the high and low-closure lakes. This is most likely a result of high levels of primary productivity in these lakes during the summer which drives the pH up through enhanced photosynthetic demands for free carbon dioxide. For the position category, Inuvik lakes had significantly higher pH values than both central and Aklavik lakes for the spring 1994 data set (Table 6, Fig. 14).

Analyses of the spring 1994 data set indicates that high-closure lakes appear to contain lower than average concentrations for all the major ions with the exception of potassium, ammonium, and phosphate (Figs. 15 and 16). These three ions are indicators of levels of primary productivity and should also be indicators of methanogenesis. For the most part, the spatial distribution throughout the categories parallels the distribution of methane.

Ammonium, the form of nitrogen utilized by the methanogenic bacteria, is also present in significantly higher concentrations in high and low-closure lakes than in no-closure lakes with phosphate concentrations tending to be higher in high-closure lakes as well (Table 5, Fig. 15). High levels of primary productivity demand high levels of these nutrients. Ammonium and phosphate would be rapidly recycled during the spring and summer growth periods resulting in low concentrations in the water. Over winter when light limits primary productivity in these lakes and respiration dominates biological functions in the system, ammonium and phosphate would be released from the decomposing organic matter.

The spring 1994 data set illustrates a strong inverse relation between methane and sulfate exists in the water columns of the Mackenzie delta lakes with sulfate being significantly higher in no-closure lakes than in high-closure lakes (Fig. 15). This inverse relation is also evident in the position category of the data set with Inuvik lakes containing significantly lower concentrations of sulfate than Aklavik lakes (Table 6) while tending to contain higher concentrations of methane (Fig. 15). Sulfate reducing bacteria are active at a redox potential just above that necessary for the production of methane. Therefore, in lakes exhibiting high concentrations of methane, sulfate reducers have used up a large percentage of the sulfate during the production of hydrogen sulfide gas. Often we could smell the gas during sample collection which gave little doubt as to the anoxic conditions of the under-ice water columns. Examination of the data for the

Fig. 15. Mean values for methane, sulfate, ammonium and phosphate for the spring 1994 data set for the Mackenzie Delta lake transect. The top two graphs give arithmetic means for the category of closure while the bottom two graphs indicate arithmetic means for the position category. Matching symbols above bars indicate significant variation (p value $<$ 0.051). Note the positive relation between methane, ammonium, potassium and phosphate and the strong negative relation between methane and sulfate for both categories.


µM
Methane
Sulfate
Ammonium
Potassium
Phosphate
Mean High
Mean Low
Mean No

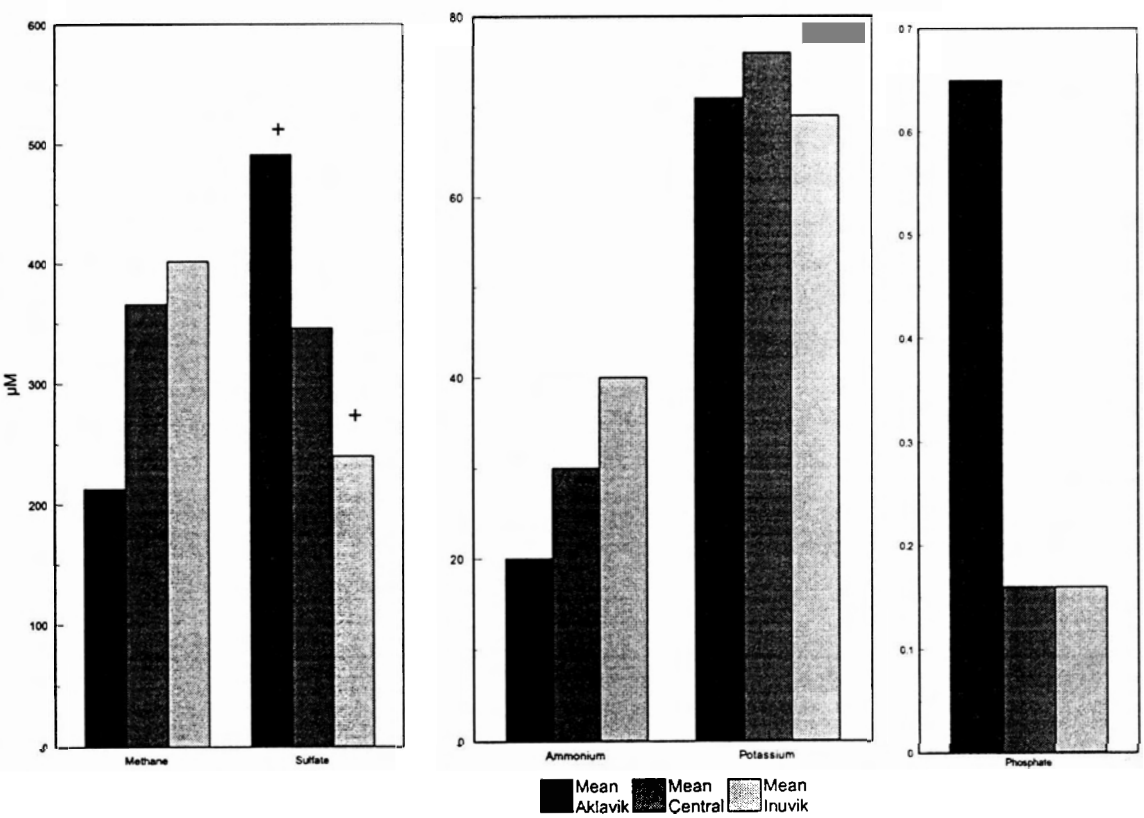
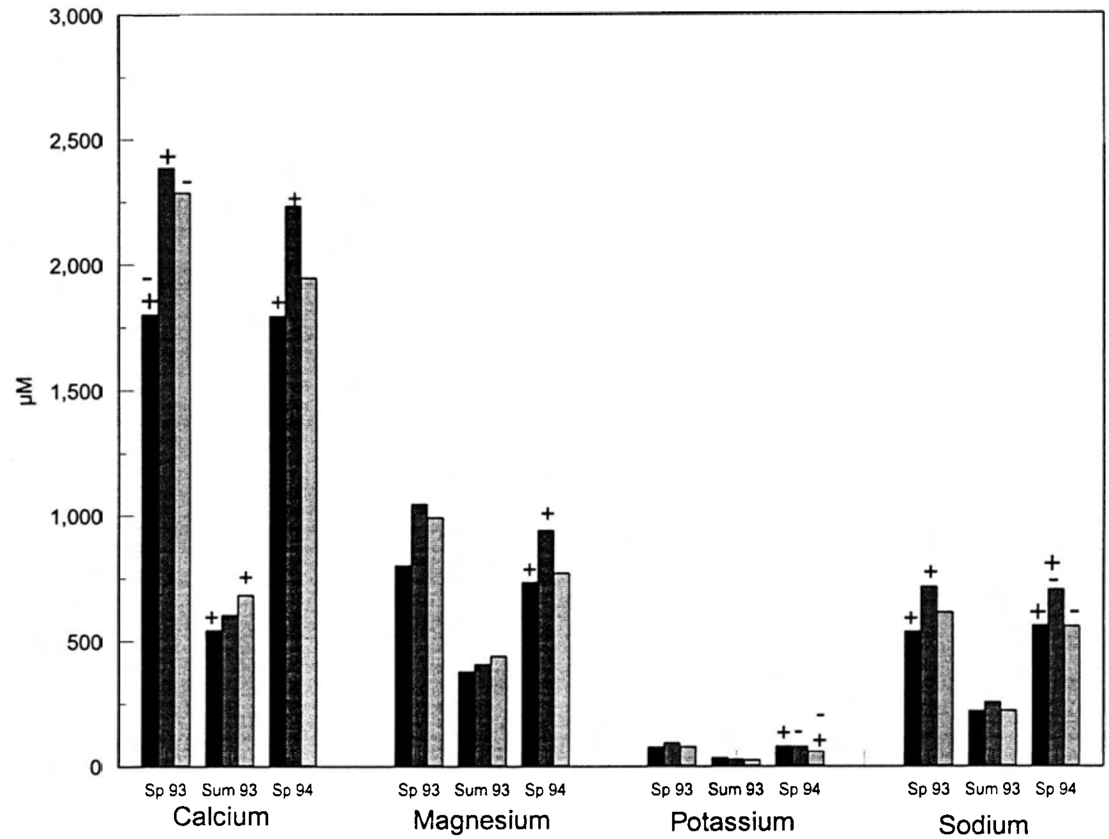
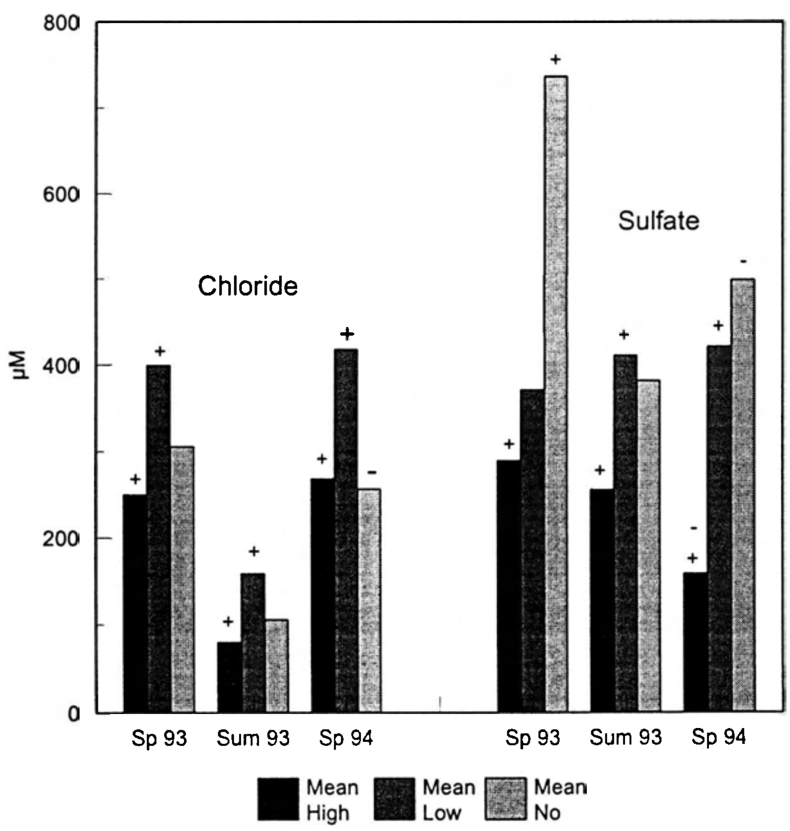

µM
Methane
Sulfate
Ammonium
Potassium
Phosphate
Mean Aklavik
Mean Central
Mean Inuvik

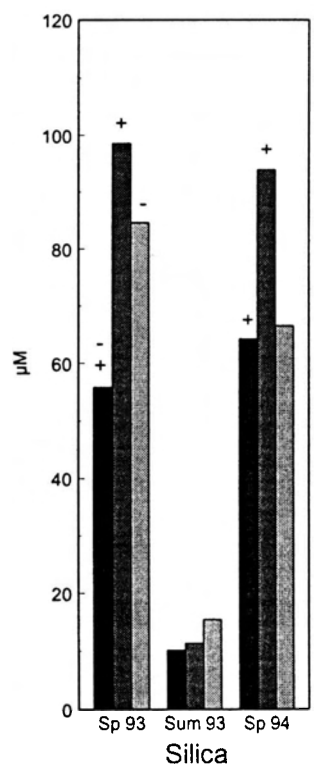
Fig. 16. Mean values for the major solutes for the spring 1993 (Sp 93), summer 1993 (Sum 93), and spring 1994 (Sp 94) data sets for the Mackenzie Delta lake transect for the category of closure. Matching symbols above bars indicate significant variation between level means (p value < 0.051).



3,000
2,500
2,000
1,500
1,000
500
0
µM
Sp 93 Sum 93 Sp 94
Calcium
Sp 93 Sum 93 Sp 94
Magnesium
Sp 93 Sum 93 Sp 94
Potassium
Sp 93 Sum 93 Sp 94
Sodium



800
600
400
200
0
µM
Chloride
Sulfate
Sp 93 Sum 93 Sp 94
Sp 93 Sum 93 Sp 94
Mean High
Mean Low
Mean No



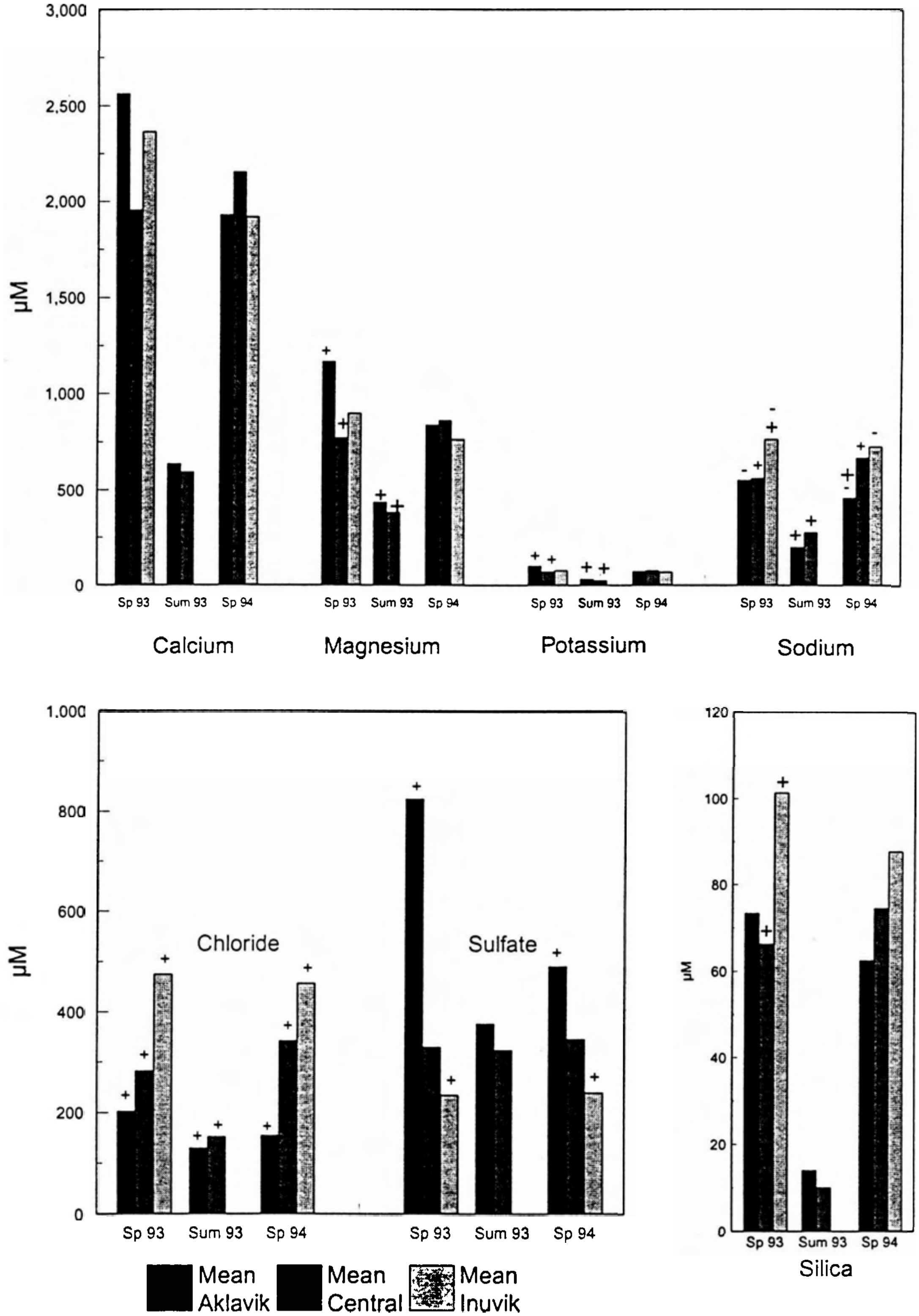
120
100
80
60
40
20
0
µM
Sp 93 Sum 93 Sp 94
Silica

position category verifies the tendency toward a positive relation between the concentration pattern set by methane and ammonium, potassium, and phosphate.

To this point in the results, it has been established that closure does play a significant role in the spatial distribution of methane with an increasing gradient in concentration from no, through low and into high-closure lakes. Paralleling this pattern for the spring 1994 data set is sedimentary carbon content, and water column carbon dioxide, ammonium, potassium, and phosphate concentrations with water column sulfate concentrations exhibiting an inverse relation with these variables. These positive and negative relations are also present in the position category and therefore should prove useful for predicting methane concentrations from known water and sediment chemistry.

Confidence is gained in the significance of the spatial distribution patterns when viewing the results for the three data sets simultaneously (Figs. 16 and17). Since measurements were made in two consecutive years for under-ice samples as well as the summer between, both annual variation and interannual variability between data set means of the water chemistry can be tested by means of one-way and two-way ANOVAs for each variable measured. None of the variables in the two under-ice data sets show significant variation in the means. However, summer values for all major ions as well as for conductivity were significantly lower in the summer data sets than the spring data sets while pH was significantly higher in the summer than the spring. Regression of conductivity versus chloride concentration factor (summer 1993 chloride concentration/spring 1994 chloride concentration) determines that about 13% of this variance is due to solutes being excluded from the freezing front into the unfrozen water beneath the ice ($r^2 = 0.13$, $N = 41$, $p = 0.021$). Chloride is a conservative ion which is excluded into the under-ice water column during ice growth. It can therefore can be used to determine the approximate percentage of solute increase in under-ice water columns due to salt exclusion into a decreasing volume of water resulting from ice growth.

Fig. 17. Mean values for the major solutes for the spring 1993 (Sp 93), summer 1993 (Sum 93), and spring 1994 (Sp 94) data sets for the Mackenzie Delta lake transect for the category of position. Matching symbols above bars indicate significant variation between level means. (p value < 0.051).



3,000
2,500
2,000
1,500
1,000
500
0
µM
Sp 93 Sum 93 Sp 94
Calcium
Magnesium
Potassium
Sodium
1,000
800
600
400
200
0
µM
Chloride
Sulfate
Mean Aklavik
Mean Central
Mean Inuvik
120
100
80
60
40
20
0
µM
Silica

Although absolute means are different, the patterns between levels are consistent in the majority of cases with low-closure lakes attaining maximum concentrations of calcium, magnesium, sodium, chloride and silica irregardless of the season or the year. Significant variation, where it exists, occurs most often between high and low-closure lakes for these variables (Fig. 16).

For position, the distribution patterns of each variable are not quite as consistent in their trends except in cases where significant variance between level means is noted (Fig 17). For example, while Aklavik lakes tend to have low chloride and sodium concentrations and high sulfate concentrations with Inuvik lakes exhibiting the opposite pattern, calcium and magnesium concentrations tend to fluctuate in their spatial distribution for the two spring data sets.

Dissolved silica is of interest to this thesis for two main reasons. First, dissolved silica is used by diatom populations for synthesis of their cell walls. Therefore, the availability of silica can have a marked effect on the population dynamics of algae species inhabiting delta lakes. Conversely, diatom populations also regulate the flux of silica in these lakes. Because of this dynamic interaction between silica availability and algae populations, the availability of silica can have an effect on the productivity of each lake.

Secondly, as the recycling rate through the diatom species for silica is very low, new inputs to the lakes via floodwaters are required to replenish supplies. Weathering of feldspar crystals (a main component of granite rock) is the dominant source for silica with a small amount being released from anoxic sediments. Although the source area mountains for the Mackenzie and other contributing rivers are predominantly composed of sedimentary rocks, it would still be expected that the flooding regime of these lakes would be a major control over silica availability.

High-closure lakes contain significantly lower concentrations of silica in their water columns than low-closure lakes for both the under-ice data sets (Fig 16). Based upon these results, it is likely that diatoms do not play as important a role in the composition of phytoplankton populations of high-closure lakes. As silica is mainly provided to the lakes via flooding, it is probable that the lower concentrations of silica in these lakes is a result of the limited exposure that these lakes have to flood waters. There is the same pattern of summer drawdown of silica in the low-closure lakes as was apparent for calcium. It could therefore be conjectured that diatoms play a major role in the structuring of the phytoplankton assemblage in low-closure lakes. Although significant only at the 90% confidence level, there seems to be a decreasing trend in silica concentration as one moves westward across the delta (Fig 17). Whether or not source area differences is a causal factor for this trend is questionable but perhaps offers a potential explanation.

Methane Prediction and Spatial Modeling

To put the results determined by the methane data analyses into a broader, more useful context, five models have been generated. The first model is designed to predict methane accumulation in Arctic delta lakes from measured water column chemistry and sediment content variables. A model of this type enables calculation of methane accumulation in an ice-covered delta lake without the expense and time constraints inherent in establishing a specialized sampling routine designed to preserve methane samples. The other four models are designed to give first-order quantitative estimates of total methane flux to the atmosphere on a per lake basis during ice-out from the Mackenzie Delta lakes. The results from these models can then be extrapolated to yield flux values for northern delta ecosystems on a circumpolar scale. Comparison of these estimates with present flux estimates from northern ecosystems will ascertain the significance of Arctic lakes as methane contributors to the global methane budget.

Methane and predictor variables

Methane production is a direct result of several interacting sedimentary and water column variables and therefore it should be feasible to predict the amount of methane likely to be contained in the under-ice water column of a lake from known quantities of variables which exhibit a strong correlation with methane. It has already been demonstrated in this thesis that lake closure is a significant determinant of methane production and accumulation within the under-ice water column of Mackenzie Delta lakes. It has also been shown that other variables which play major roles in the metabolism of methanogenic bacteria have a spatial distribution contingent upon lake closure as well and that this distribution parallels or exists in an inverse relation to methane concentrations. Seven of these variables meet the criteria: under-ice carbon dioxide, sulfate, ammonium, and potassium; summer calcium, sediment carbon content and sedimentation rate (Fig 18). Therefore it makes sense that prediction of methane concentrations from these variables is possible.

Prediction of methane concentration in the under-ice water column of Mackenzie Delta lakes was facilitated using various combinations of the seven identified variables (Table 7). When using only variables from the under-ice data set, the highest adjusted r^2 value that can be obtained is 0.846 (Table 7, Fig 19A). It is doubtful that the use of this model would be valuable in its present state for ammonium is a variable that is not commonly measured or reported. Although it is the source of nitrogen used by the methanogenic bacteria as well as being an important nitrogen source for other bacteria, algae and larger aquatic plants, its concentrations commonly are low and the content in water samples can change quickly and markedly. If ammonium is dropped from the equation, the adjusted r^2 value drops to 0.831 (Fig. 19B) and the corresponding standard error of the estimate rises from 3.8 to 4.1.

Fig. 18. The relation between water column mean methane concentration and variables used for prediction of methane concentration versus lake closure status. Note the positive relation between methane and carbon dioxide, ammonium, potassium, and sediment carbon content and the negative relation between methane and sulfate and summer calcium concentrations. (All variables except calcium represent under-ice values from the spring 1994 data set).

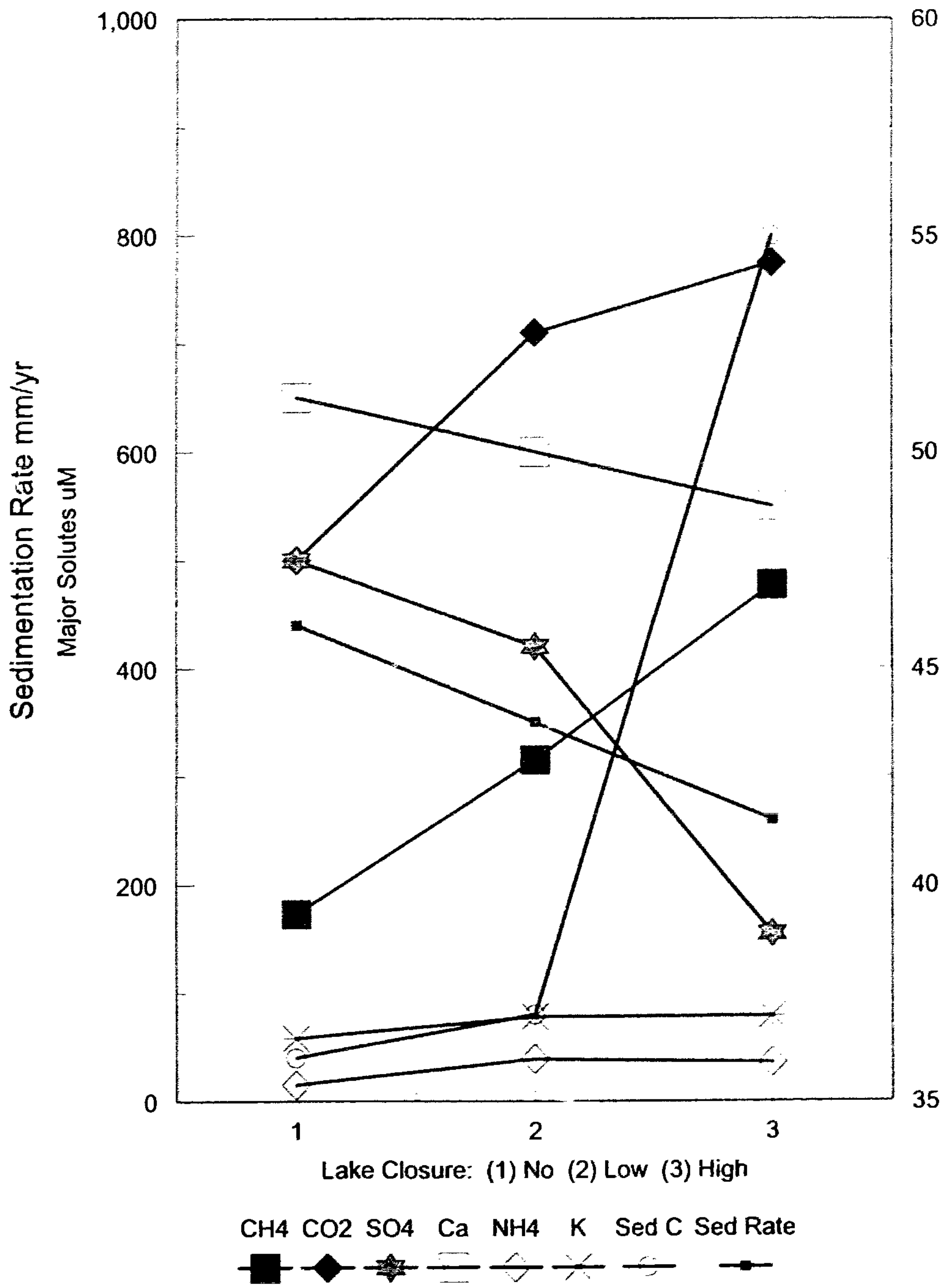
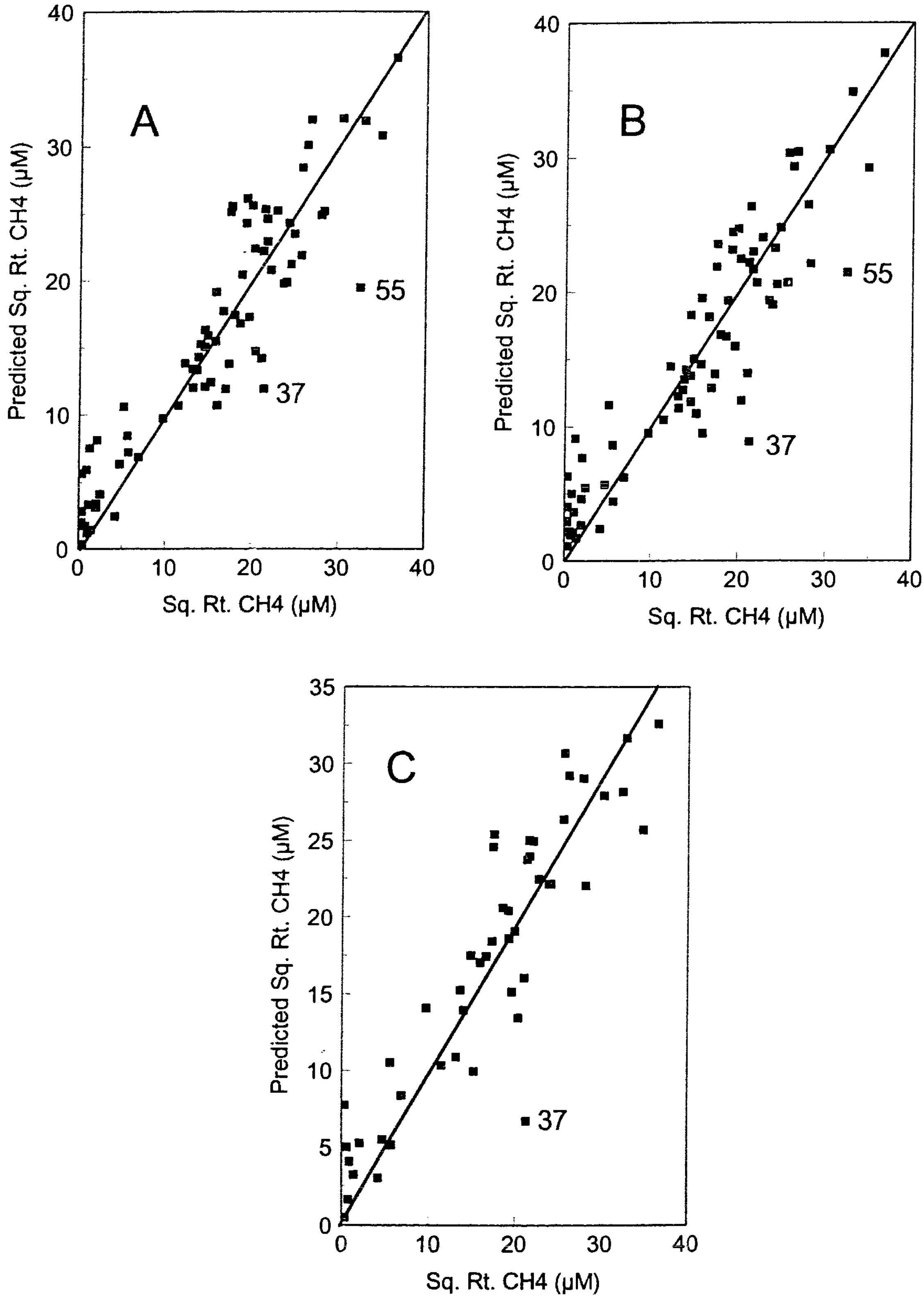

Sedimentation Rate mm/yr
Major Solutes uM
1,000
800
600
400
200
0
60
55
50
45
40
35
Sed. C mg/g
1
2
3
Lake Closure: (1) No (2) Low (3) High
CH4 CO2 SO4 Ca NH4 K Sed C Sed Rate

Table 7 Multiple regression models which predict the square root of methane concentration (µM) in the under-ice water column of Mackenzie Delta lakes lakes from combinations of under-ice water chemistry (µM), summer water chemistry (µM), sedimentation rate (cm/yr) and sediment carbon content (mg/g).

Model		Constant	Log Sulfate	Sq. Root Carbon Dioxide	Potassium	Sq. Root Ammonium	1/ Sediment Carbon	Sedimentation Rate	Summer Calcium	Adjusted R squared	Standard Error of Estimate	N
A	Coefficient	18.76	-8.4	0.28	0.07	0.65				0.846	3.852	76
	p-value		< 0.001	0.002	0.002	0.006						
B	Coefficient	22.10	-9.59	0.3	0.09					0.831	4.035	76
	p-value		< 0.001	< 0.001	< 0.001							
C	Coefficient	32.59	-7.77		0.12		-331.98			0.808	4.359	49
	p-value		< 0.001		< 0.001		0.001					
D	Coefficient	34.84	-7.54		0.10				-.02	0.876	3.369	46
	p-value		< 0.001		< 0.001				0.001			
E	Coefficient	48.94						-6.79	-0.05	0.739	4.861	41
	p-value							0.080	< 0.001			

Fig. 19. Methane prediction from spring 1994 under-ice water column data sets. "A" represents the best possible prediction equation using only water column variables and includes sulfate, ammonium, potassium, and carbon dioxide as predictor variables. Lakes 55 and 37 are identified as outliers (studentized residuals 4.1 and 2.9 respectively). Removal of these two points increases the r^2 value to 0.89 and decreases the standard error of estimate to 3.3. "B" includes sulfate, potassium and carbon dioxide only. Lakes 55 and 37 are again identified as outliers (studentized residuals 3.0 and 3.5 respectively). Removal of outliers increases the r^2 value to .89 and decreases the standard error of estimate to 3.5. "C" includes sulfate, potassium and sediment carbon content. Lake 37 has a large studentized residual (4.0) and removal of this lake from the data set increases the r^2 value to .86 and decreases the standard error of estimate to 3.7. 1:1 lines are indicated.


A
B
C
55
37
Predicted Sq. Rt. CH4 (μM)
Sq. Rt. CH4 (μM)

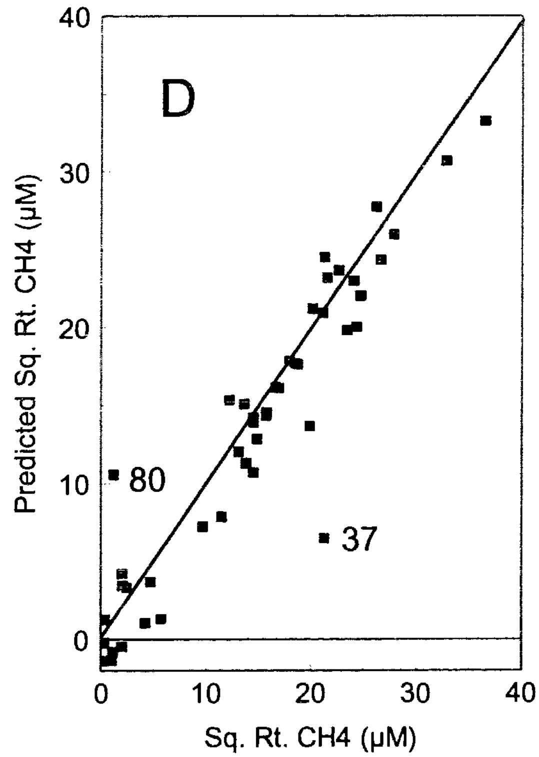
If the sediment carbon variable is included in the predictive equation and carbon dioxide is dropped, the adjusted r^2 value drops to 0.808 and the standard error of estimate rises to 4.4. Time is saved, however, in terms of sample preparation and analysis (Table 7, Fig. 19C). The sample size is decreased to 49 because sediment cores could not be obtained from the Aklavik lakes during the sampling period.

The best predictive equation obtainable from my data sets includes water column variables from both the summer 1993 (calcium) and winter 1994 (sulfate and potassium) data sets. Equation E (Table 7, Fig. 20D) yields an adjusted r^2 value of 0.876 with a standard error of estimate of 3.4. Using this equation, two lakes are identified by the statistics program as outliers because of the large studentized residuals associated with the observations (Lakes 37 and 80). Removal of these outliers from the data set increases the r^2 value to 0.953 and decreases the standard error of estimate of 2.06 which is quite significant. In general, I have avoided removing "identified" outliers from the data sets because these are biological data sets and, as such, can be expected to have anomalies associated with them. For reader information, however, I have identified outliers on Figs 19 and 20 (by Lake number) and given the studentized residual associated with them in the figure caption.

Under-Ice Volume

In order to determine potential methane content in the under-ice water columns of Mackenzie Delta lakes, four models were developed to calculate under-ice volumes (presented in the Methods section of this thesis). Fig. 21 compares under-ice volumes derived from each of these models. For Model 1 (based on maximum depth) method B, under-ice volumes are approximately 2 times greater than for method A. For Model 2 (based on mean depth) the under-ice volumes are within 5% of each other regardless of the method used to calculate them. What is also evident from Fig. 21 is that the mean depth model (Model 2) yields higher under-ice estimates by about 4 to 8 times over the

Fig. 20. Methane prediction from summer 1993 and spring 1994 water column data sets. "D" includes under-ice sulfate and potassium as well as summer calcium. Removal of lakes 37 and 80 (studentized residuals 5.5 and -3.8 respectively) increases the r^2 valus to 0.96 and reduces the standard error of estimate to 2.1. "E" uses summer calcium and sedimentation rate to predict under-ice methane accumulation. Again, Lake 80 is identified as an outlier (studentized residual -3.2). Removal of this data point increases the r^2 value to 0.79 and reduces the standard error of estimate to 4.3. 1:1 lines are indicated.


D
Predicted Sq. Rt. CH4 (µM)
Sq. Rt. CH4 (µM)
80
37
0
10
20
30
40

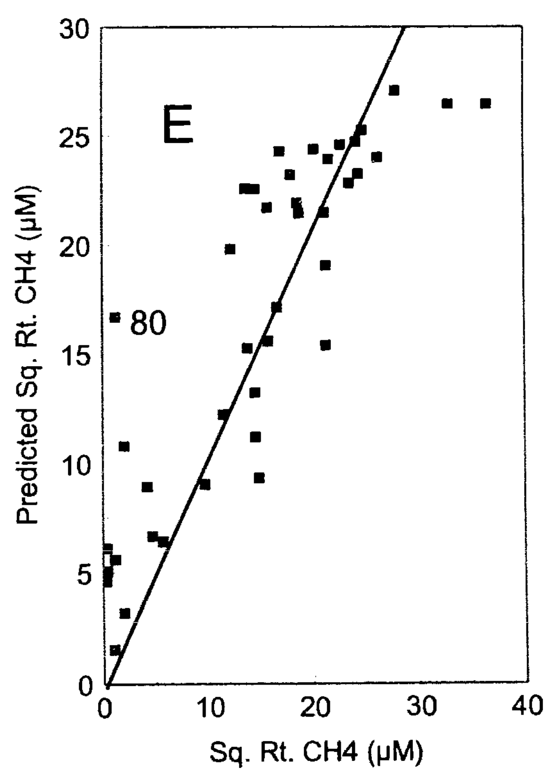
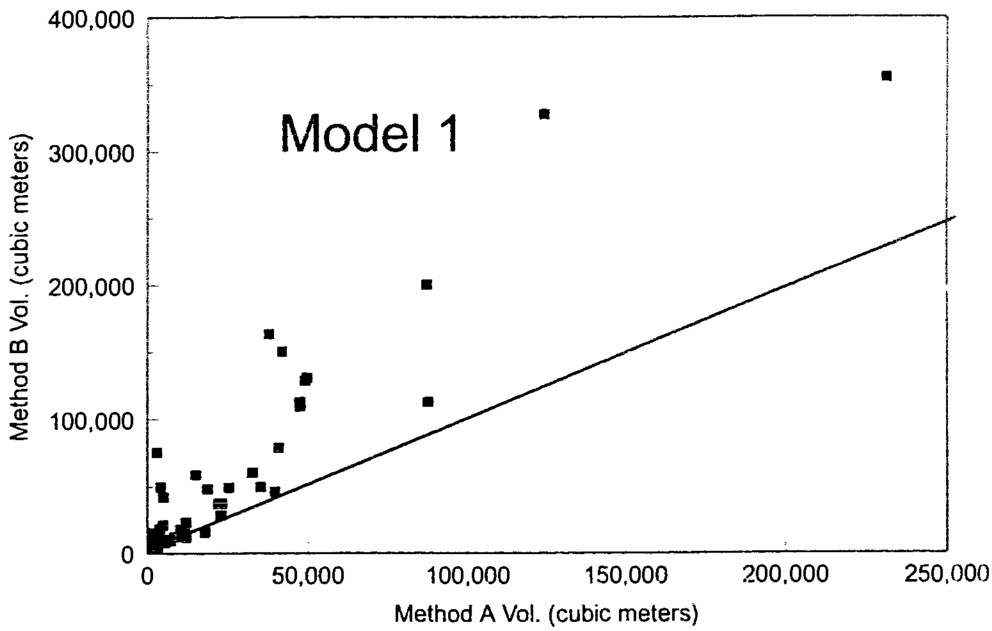
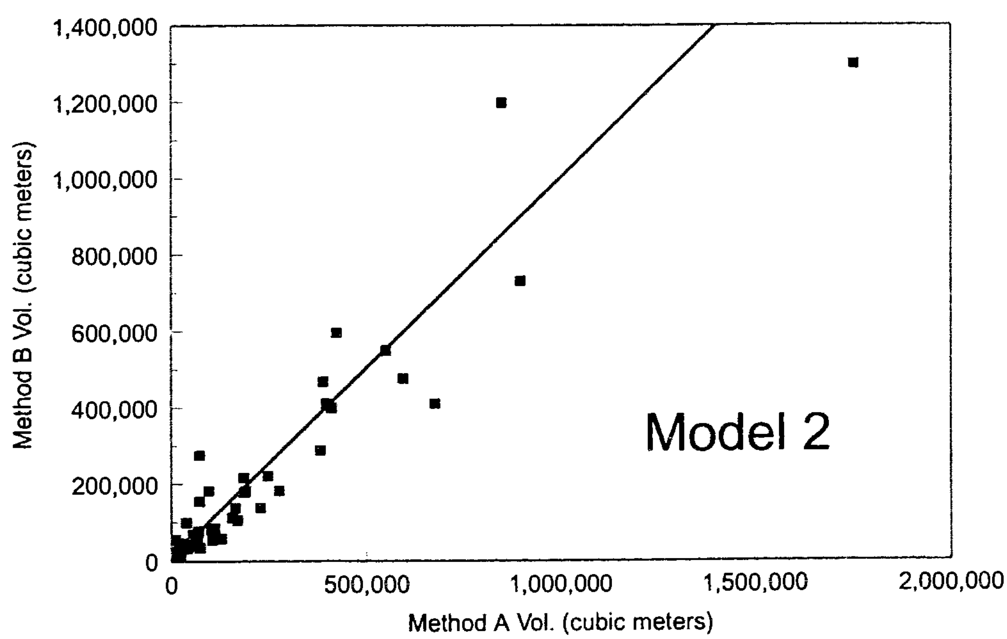

E
Predicted Sq. Rt. CH4 (µM)
Sq. Rt. CH4 (µM)
80
0
5
10
15
20
25
30
40

Fig. 21. Comparison of under-ice volumes derived from Method A and Method B for each of Model 1 and Model 2 (N = 47). For Model 1 (based on maximum depth), method B estimates under-ice volumes at approximately 2 times that of method A. Model 2 estimates for under-ice volumes are within 5% of each other regardless of the method used to calculate them. Model 2 estimates under-ice volume at between 4 and 8 times greater than Model 1. 1:1 lines are indicated.


Model 1
Method B Vol. (cubic meters)
400,000
300,000
200,000
100,000
0
0
50,000
100,000
150,000
200,000
250,000
Method A Vol. (cubic meters)


Model 2
Method B Vol. (cubic meters)
1,400,000
1,200,000
1,000,000
800,000
600,000
400,000
200,000
0
0
500,000
1,000,000
1,500,000
2,000,000
Method A Vol. (cubic meters)

maximum depth model (Model 1). In order for the smaller values calculated via Method 1A to be correct, the ion concentration factors would have to be significantly higher than they are. Given that changes in ionic concentration can give good estimates of under-ice volumes as indicated by the results obtained for NRC Lake, an implication may be that the shape of NRC Lake is not well representative of the lakes in the transect and that the mean depth model (Model 2) may provide a better estimate of under-ice volumes.

The results from the four models indicate that the sampling point for each of the lakes may be representative of an average depth rather than the deepest point of the lake. Therefore it is likely that the under-ice volumes derived from Model 2 are closer to the "true" under-ice volumes of the lakes than the estimates from Model 1. However, the under-ice volumes from all four models will be used to estimate methane fluxes on a per lake basis in the following section.

Whole lake methane content modeling

All four models assume homogeneous methane concentration throughout the water column of the lakes. For the 16 lakes where two values of methane were determined (one just above the sediment/water interface and one just below the ice/water interface), the two values were averaged. The two sampling depths were chosen to capture potential gradients of methane concentration between lower and upper layers of the water column. By averaging the two values a representative value for the entire water column should have been obtained. For the remaining 60 lakes which had a shallow under-ice water column, the single sample depth value was assumed to be representative of the water column. Total lake methane content was calculated using each of the four water volumes as:

$$M_T = M_s * V_u \qquad (13)$$

Where M_T = total lake methane content (moles)

M_s = methane concentration in the sample (moles/m^3)

V_u = Under-ice volume of the lake (m^3)

Once the methane content was calculated for each lake using the four methods, estimates of "potential" methane flux was obtained by dividing lake methane content by surface area. In plotting the methane flux against area on a per lake basis, it is evident that a strong curvilinear relation exists in which lakes with small surface areas tend to have a greater potential flux per unit area than lakes with large surface areas (Fig. 22).

As lake closure has been shown to be a primary control on the spatial distribution of methane accumulation in ice-covered delta lakes, average flux values for high, low, and no-closure lakes were calculated using each of the methods. Because of the observed relation between potential methane flux and lake surface area, both arithmetic means and area-weighted means were calculated (Fig. 23). The arithmetic means were within 10% of the area-weighted means for all four methods for high and low-closure lakes (Table 8, Fig. 24). However, for the no-closure lakes, arithmetic means were consistently higher by a factor of approximately 3 (Table 8, Fig. 23). This is due to the tendency for no-closure lakes to have very low methane accumulation and significantly larger surface areas than the low and high-closure lakes. Given these results, the area-weighted means may be a more realistic estimate of average potential methane fluxes from the no, low, and high-closure lakes. Also, because of the closeness of the results obtained by Methods 2A and 2B using the reduced data set, confidence is gained in the results from Method 2A in the larger data set. Therefore, the average potential fluxes at ice-out may range from 36 to 400 mg m^{-2} for no-closure lakes, 300 to 3000 mg m^{-2} for low-closure lakes and from 700 to 5500 mg m^{-2} for high-closure lakes (Table 8).

Mackenzie Delta methane flux prediction

Using the range of fluxes generated in the previous section and the estimated areas of lake surface in the northern, middle and southern delta, a range of total methane flux

Fig. 22. Estimated methane flux per unit area versus lake area on a per lake basis. The relation suggests that high methane fluxes are generated from lakes with small surface areas and that low methane fluxes are emitted from lakes with large surface areas. Lake 1 is not plotted because of its extremely large surface area (8.13 km^2). Its estimated flux value of 0.47 mg m^{-2} for Method 1A and 4.7 mg m^{-2} for Method 2A reinforces this pattern. Note that both the Method B graphs have a reduced data set (N = 47) as under-ice volumes could not be calculated using the ion concentration factor for the Inuvik lakes.

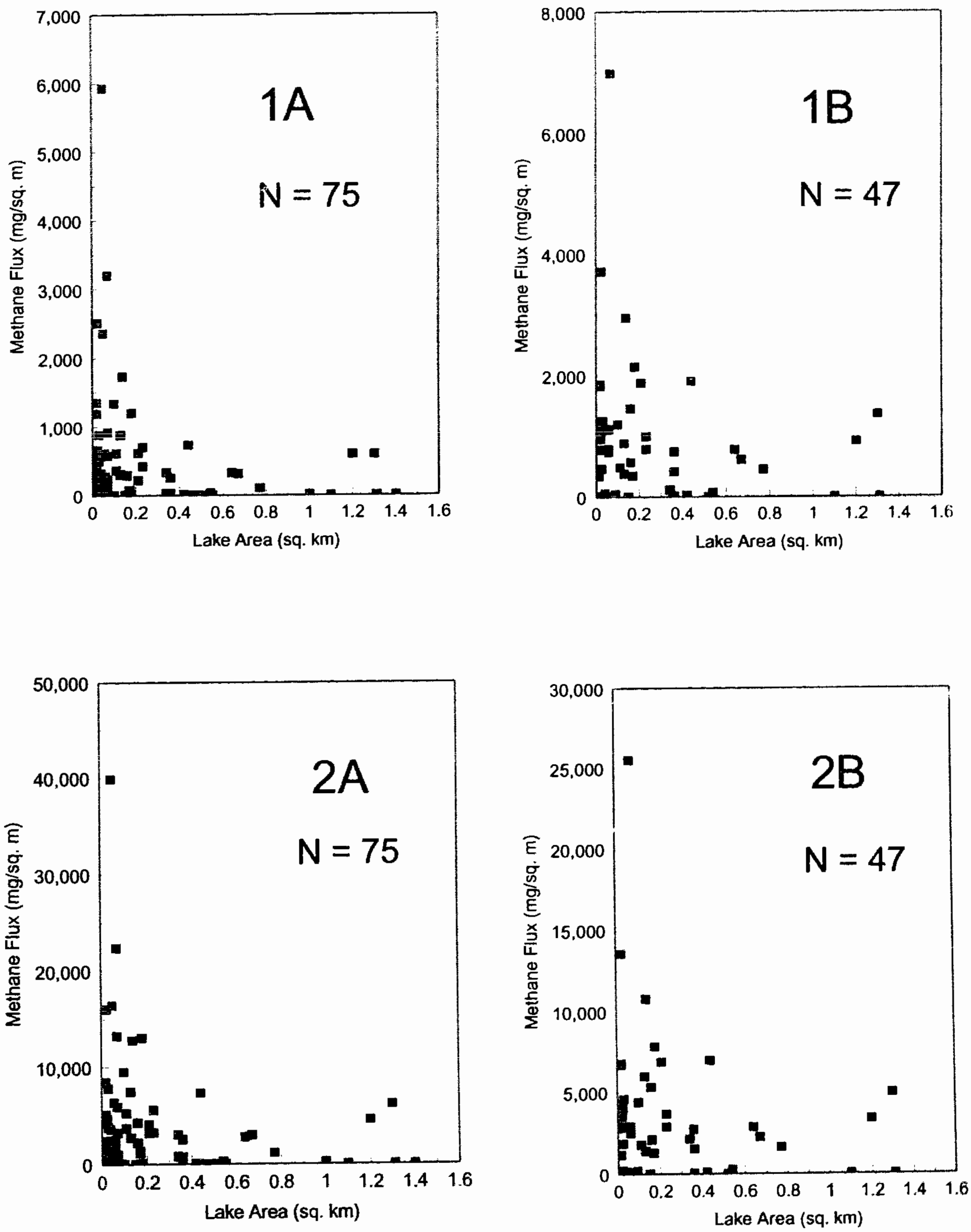
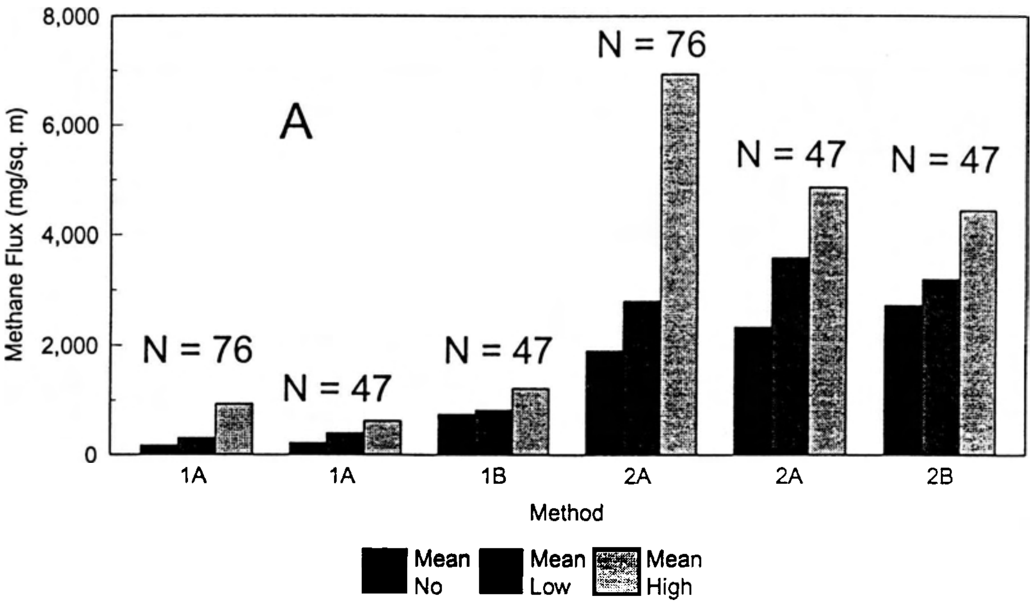

1A
N = 75
1B
N = 47
2A
N = 75
2B
N = 47
Methane Flux (mg/sq. m)
Lake Area (sq. km)

Fig. 23. Mean methane flux for high, low and no-closure lakes as derived from the four water volume models. Graph A shows the arithmetic means for the data set whereas graph B shows the area-weighted means of the methane flux. Note that both the Method B graphs have a reduced data set (N = 47) as under-ice volumes could not be calculated using the ion concentration factor for the Inuvik lakes.


8,000
6,000
4,000
2,000
0
Methane Flux (mg/sq. m)
A
N = 76
N = 47
N = 47
N = 76
N = 47
N = 47
1A
1A
1B
2A
2A
2B
Method
Mean No
Mean Low
Mean High

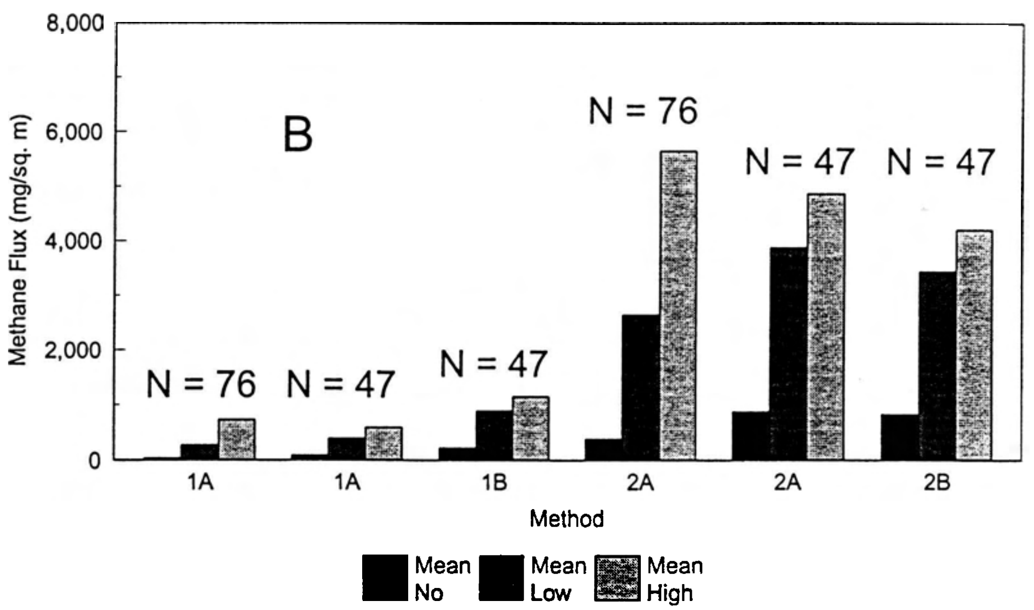

8,000
6,000
4,000
2,000
0
Methane Flux (mg/sq. m)
B
N = 76
N = 47
N = 47
N = 76
N = 47
N = 47
1A
1A
1B
2A
2A
2B
Method
Mean No
Mean Low
Mean High

Table 8. Estimated methane fluxes (mg/sq. m) from no, low, and high closure lakes as determined by arithmetic and area-weighted means. Inuvik lakes are not represented in Method B and therefore the data set is reduced. Method A reflects this by presenting 2 means; 1 for the full data set of 76 and one for the reduced data set.

	Average Lake Area (sq. km)	Method 1A N = 76	Method 1A N = 46	Method 1B N = 46	Method 2A N = 76	Method 2A N = 46	Method 2B N = 46
Arithmetic Mean							
High		936	635	1224	6937	4869	4463
Low		310	405	828	2804	3593	3210
No		173	221	748	1907	2336	2738
Overall Mean		489	416	927	3990	3570	3450
Area Weighted Mean							
High	0.13	729	590	1154	5659	4873	4215
Low	0.29	270	395	892	2650	3884	3449
No	0.39	36	86	262	382	878	957
Overall Mean		183	286	643	1632	2646	2412

from the Mackenzie Delta at ice-out can be estimated (Table 9). As previously discussed in relation to Fig. 1, the Mackenzie Delta can be divided into three sections in which the southern portion of the delta constitutes approximately 20% of the total delta (2400 km^2) with the middle and northern portions of the delta comprising approximately 40% (4800 km^2) each. Mackay (1963) estimated that 15 to 30% of the southern and northern portion of the delta is covered by lakes and 30 to 50% of the middle delta is water covered. Therefore, estimates of lake surface for the southern delta range from 360 to 720 km^2, from 1440 to 2400 km^2 for the middle delta, and 720 to 1440 km^2 for the northern delta for a total area of lake surface of 2520 to 4560 km^2 in the delta. These areas of total lake surface were multiplied by the average area-weighted methane flux derived from Methods 1A and 2B (Table 8) to determine a range of potential methane flux from the Mackenzie Delta during ice-out of between 0.5 and 12 Gg (Table 9).

Because of the short flooding duration of high-closure lakes, it is most probable that the methane in these lakes enters the atmosphere rather than becoming oxidized by mixing with oxygen rich floodwaters. It can be estimated that the lake surface area represented by high closure lakes is approximately 12% of the total lake surface area on the middle delta. This estimate is arrived at by dividing the lake surface area of the sampled high-closure lakes by the lake surface area of all the sampled lakes. It can therefore be crudely estimated that high closure lakes would have a delta wide surface area from 300 to 550 km^2. Based upon this lake surface area and average methane concentrations, potential methane flux for high-closure lakes on the Mackenzie Delta is estimated at between 0.18 to 3.11 Gg (Table 10) or approximately 35% of the total potential methane flux from the Mackenzie Delta at ice-out (Table 9).

Potential methane flux from northern deltas

The Mackenzie River is not the only northward flowing river in the northern hemisphere to have built a large delta studded with organic-rich lakes. Several such

Table 9. Total potential flux of methane from the Mackenzie Delta at ice-out as estimated by Methods 1A and 2B. Inuvik lakes are not represented in Method B and consequently the data set is smaller (N = 47). Della lake surface area based on minimum and maximum estimates for northern, middle, and southern sections of the delta (see page 108 in text).

Method	Delta Lake Surface Area (square km)	Average Methane Concentration (µM)	Average Lake Surface Area (square km)	Average Under-Ice Volume (cubic m)	Area Weighted Methane Flux (mg/sq. m)	Total Delta Flux (Gg)
1A (N = 76)	2520	315	0.37	32379	183	0.46
	4560	315	0.37	32379	183	0.83
2B (N = 47)	2520	295	0.29	223677	2600	6.55
	4560	295	0.29	223677	2600	11.86

Table 10 Total potential flux of methane from the Mackenzie Delta high-closure lakes at ice-out as estimated by Methods 1A and 2B Inuvik lakes are not represented in Method 1A and consequently the data set is smaller (N = 15).

Method	High-Closure Lake Surface Area (square km)	Average Methane Concentration (μM)	Area Weighted Methane Flux (mg/sq. m)	Total Delta Flux (Gg)
1A (N = 15)	300	380	590	0.18
	550	380	590	0.32
2A (N = 27)	300	451	5660	1.70
	550	451	5660	3.11

deltas exist on the Eurasian continent as well as in North America (Fig. 24). In fact, the delta built by the Lena River which covers an area of 30,000 km^2 (Telang et al., 1991) is two and a half times the size of the Mackenzie Delta (Table 11). Assuming that thermal and mechanical breakup patterns are alike on all northward flowing rivers and have similar impacts in terms of controlling nutrient and sediment regimes in the delta lakes, and assuming methane fluxes are similar to those estimated for the Mackenzie Delta, extrapolation of the fluxes presented in Table 9 to the estimated lake surface areas of each of the northern deltas will give a gross estimate of circumpolar methane flux at spring ice-out.

I assumed a range of lake area coverage from 20 to 50% for each delta. Bartlett et al. (1992) estimated water coverage of the Yukon-Kuskokwim Delta at 15% using 1984 Landsat imagery. The vast area of land (> 120,000 km^2) includes the active deltas of the Kuskowim and the Yukon Rivers as well as the inactive delta between them. Because of the closer proximity to main river channels and lower elevations associated with active deltas, they tend to have greater water coverage than the abandoned deltas that border them. The estimate for the Yukon-Kuskokwim Delta plus Mackay's (1963) lower estimate of 15% lake coverage for the northern and southern portions of the Mackenzie Delta dictated my choice of 20% to represent the low end of my range for lake coverage of northern deltas. The high end of Mackay's (1963) range for lake coverage on the middle of the Mackenzie Delta serves as the high end of my range of surface water cover.

The potential total contribution to the atmospheric methane from these northern delta lake during the spring ice-out ranges between 3 and 43 Gg if using the conservative 20% lake coverage figure, and from 8 to 109 Gg using 50% as an estimate for delta lake coverage (Table 11).

Fig. 24. Location of northward draining rivers in the circumpolar region of the northern hemisphere. These rivers have built large deltas scattered with highly productive lakes (Figure reprinted from Telang, et. al, 1991).

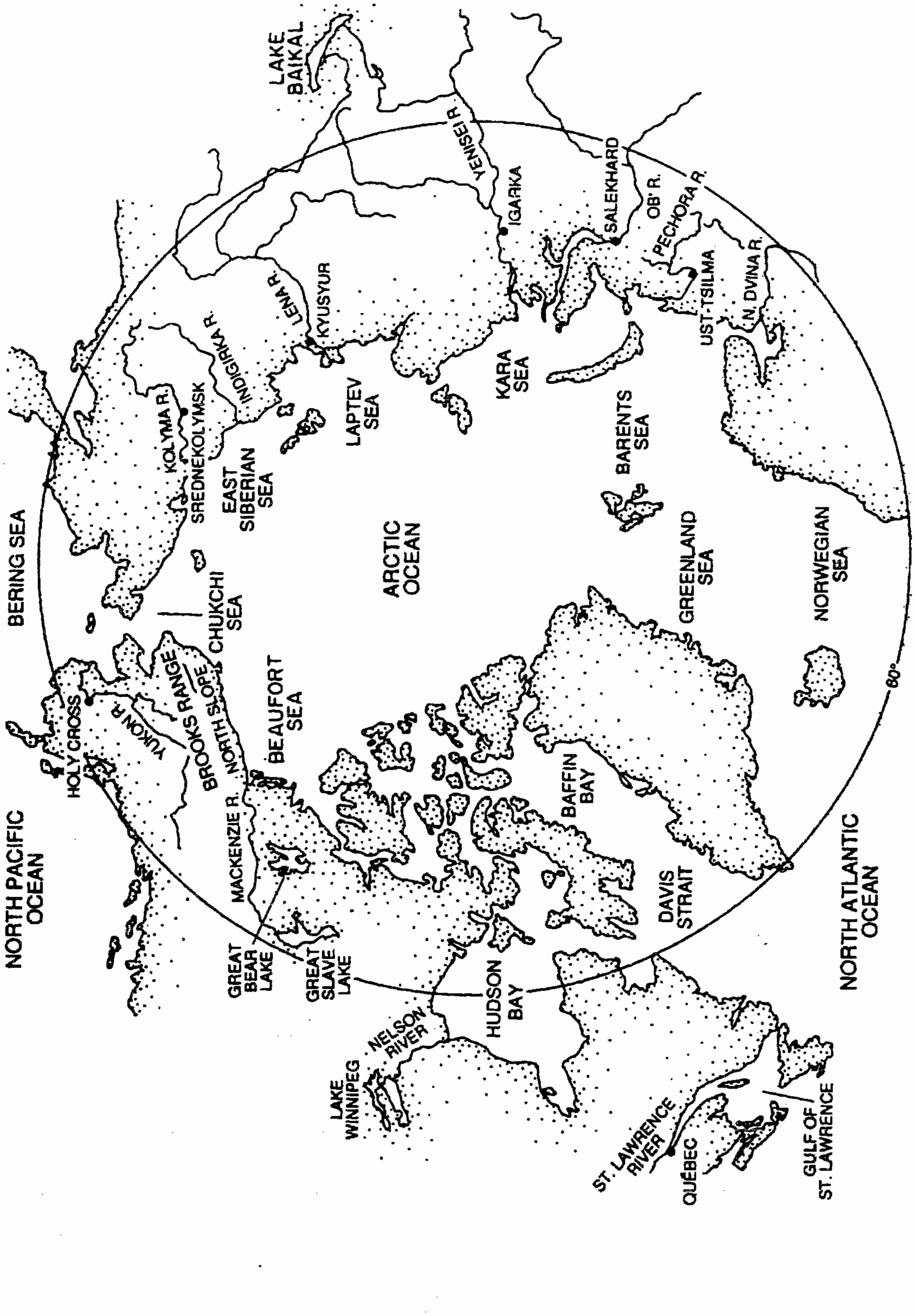

NORTH PACIFIC OCEAN
BERING SEA
HOLY CROSS
YUKON R.
BROOKS RANGE
NORTH SLOPE
CHUKCHI SEA
BEAUFORT SEA
MACKENZIE R.
GREAT BEAR LAKE
GREAT SLAVE LAKE
LAKE WINNIPEG
NELSON RIVER
HUDSON BAY
ST. LAWRENCE RIVER
QUÉBEC
GULF OF ST. LAWRENCE
NORTH ATLANTIC OCEAN
DAVIS STRAIT
BAFFIN BAY
ARCTIC OCEAN
EAST SIBERIAN SEA
SREDNEKOLYMSK
KOLYMA R.
INDIGIRKA R.
LENA R.
KYUSYUR
LAPTEV SEA
KARA SEA
BARENTS SEA
GREENLAND SEA
NORWEGIAN SEA
60°
LAKE BAIKAL
YENISEI R.
IGARKA
SALEKHARD
OB' R.
PECHORA R.
UST-TSILMA
N. DVINA R.

Table 11. Total methane flux estimates at ice out of circumpolar delta lakes as estimated by Methods 1A and 2B. Two flux estimates are given for each of these *methods for each delta reflecting the estimated range of lake surface area.*

Delta Name	Active Delta Area (sq. km)	References for Delta Areas	Lake Surface Area (20% Total Area) (sq. km)	Lake Surface Area (50% Total Area) (sq. km)	Area-Weighted Methane Flux (mg/sq. m)	Delta Methane Flux Method 1A (Gg)	Area-Weighted Methane Flux (mg/sq. m)	Delta Methane Flux Method 2B (Gg)
Mackenzie	12000	(Lewis, 1991)	2400	6000	186	0.44 to 1.1	2600	6.29 to 15.63
Yukon	3600	(Bartlett et al, 1992) + planimetr	720	1800	186	0.13 to 0.33	2600	1.88 to 4.69
Slave	8300	(Vanderburg & Smith, 1987)	1660	4150	186	0.30 to 0.76	2600	4.32 to 10.81
Colville	600	Planimetry	120	300	186	0.02 to 0.05	2600	0.31 to 0.78
Kuskokwim	200	(Bartlett et al, 1992) + planimetr	40	100	186	0.01 to 0.02	2600	0.11 to 0.26
Albany	350	Planimetry	70	175	186	0.01 to 0.03	2600	0.18 to 0.45
Subtotal	25050		5010	12525		0.91 to 2.29		13.04 to 32.62
Lena	30000	(Telang et al., 1991)	6000	15000	186	1.10 to 2.75	2600	15.63 to 39.07
Ob	4614	(Telang et al., 1991) + planimetr	923	2307	186	0.17 to 0.42	2600	2.41 to 6.00
Indigerka	8053	Planimetry	1610	4026.5	186	0.29 to 0.74	2600	4.19 to 10.49
Kolyma	3900	Planimetry	780	1950	186	0.14 to 0.36	2600	2.03 to 5.08
Pechora	2880	Planimetry	576	1440	186	0.11 to 0.26	2600	1.50 to 3.75
Sev Dvina	980	Planimetry	196	490	186	0.04 to 0.09	2600	0.51 to 1.27
Yenisei	6530	Planimetry	1306	3265	186	0.24 to 0.60	2600	3.40 to 8.51
Messoyaka	500	Planimetry	100	250	186	0.02 to 0.05	2600	0.26 to 0.65
Taz	917	Planimetry	183	458.5	186	0.03 to 0.08	2600	0.48 to 1.20
Subtotal	58374		11674	29187		2.14 to 5.34		30.40 to 76.03
Total	83424		16684	41712		3.05 to 7.63		43.48 to 108.65

Chapter 4
Discussion

Distribution of Methane Among Mackenzie Delta Lakes

The distribution of methane concentration among Mackenzie Delta lakes is consistent with expectations for the flooding frequency of the lakes, and with chemical indices of productivity of the lakes. It was expected that high-closure lakes would contain the highest concentrations of methane. As light is not a limiting factor in the high-closure lakes, macrophyte vegetation dominates primary production which results in the sediments being composed of a relatively high percentage of carbon. In low and no-closure lakes, where turbidity limits light penetration of the water column, the importance of macrophyte growth to the lake productivity is reduced. Phytoplankton populations in high-closure lakes, which suffer from nutrient limitation as the summer progresses, play a more important role in low and no-closure lakes. Carbon flux to the sediments in the low and no-closure lakes is subsequently lower than in the high-closure lakes. Low carbon flux, in combination with sediment laden river water entering the lakes for longer periods of time, results in the sediments of the low and no-closure lakes containing a lower percentage of carbon.

Other indices of relative rates of primary productivity are also reflected in the variables used to predict under-ice methane concentrations. Potassium, which plays a minor role in phytoplankton growth and metabolism, is present in larger quantities inside the cells of macrophytes than in the surrounding water (Goldman and Horne 1983). As under-ice decomposition of organic material occurs, potassium is released to the overlying water column. If high-closure lakes are recognized as containing greater quantities of aquatic vegetation than no and low-closure lakes (Hecky et al. 1991), it follows that the under-ice water columns of these lakes should contain the highest concentrations of potassium as the quantity of organic material available for decomposition is greater.

Summer calcium concentrations can also indicate relative rates of primary productivity among lakes. There appears to be a large summer drawdown of calcium which is most enhanced in the low-closure lakes. This is a good indication of high rates of primary productivity as calcium carbonate will precipitate out in high pH situations such as occurs in the summer low and high-closure lakes (Fig. 14). pH is driven up by high rates of primary productivity. Therefore, the more productive a lake is, the higher the pH rises and the more calcium carbonate is precipitated out of the water column.

Equations to predict methane concentrations use the above discussed variables which are expected to represent indices of productivity for the lakes. High rates of primary productivity result in enhanced carbon flux to the sediments which results in increased substrate availability. Using the above reasoning, the link between primary production, substrate availability, and methane production is forged.

Sulfate, another variable that appears to be important in methane concentration prediction, shows an inverse relation with methane that is characteristic of wetland ecosystems. The zone of sulfate reduction in lake sediments is underlain by the zone in which methanogenic bacteria are active. Therefore, if sulfate concentrations are low, the zone of sulfate reduction will be shallow and methanogenesis will dominate. The strong, positivie relation between carbon dioxide and methane has been discussed previously and the inclusion of this variable in predictive equations is obvious.

Although an independent set of data was not used to test the equations, the high adjusted r^2 values give confidence of their predictive capabilities. Predictive ability really becomes a matter of available data and/or choice of variables. I would suggest that model "D" (Table 7, Fig. 20) which uses summer calcium, under-ice summer calcium along with under-ice potassium and sulfate to predict under-ice methane concentrations holds the most promise for this purpose.

Representativeness of Methane Fluxes

Comparisons with other studies

Under-ice methane concentrations in the 76 lakes sampled for this study ranged from 0.09 to 1334 μM. This range of values is higher than other studies which used a similar methodology to obtain under-ice methane samples. This is undoubtedly due to the high productivity of the Mackenzie Delta lakes. For the five Colorado Rocky lakes studied by Smith and Lewis (1992), methane concentrations ranged from 0.5 to 80 μM just prior to ice-out. Methane concentrations throughout the water column of Lake Fryxell in Antarctica show a gradient beginning at < 1 μM in the aerobic region of the water column and increasing exponentially to approximately 1000 μM at the sediment/water interface (Smith et al., 1993).

Potential fluxes from this study are consistent with the spring pulse range estimated for temperate ice-covered lakes containing organic rich sediments (Michmerhuizen et al., 1995) (Table 12). The range magnitude is also consistent with other ranges reported in the literature (Harriss and Sebacher, 1981; Michmerhuizen et al., 1995; Whalen and Reeburgh, 1992;) (Table 12). In a study of 19 lakes in four geographic locations in northern Minnesota and Wisconsin, Michmerhuizen et al. (1995) found that the magnitude of the potential spring pulse of methane was dependent upon the nature of the lake sediments and the extent of the littoral zone. Lakes with extensive littoral zones and soft, organic sediments were likely to be more productive and therefore more likely to produce high concentrations of methane in their under-ice water columns. Lakes with greater surface areas and non-organic sediments produced lower methane concentrations in the under-ice water columns and therefore had a lower potential emission at ice-out. Potential methane emission from the lakes with organic-rich sediment ranged from 145 to 3000 mg/m^2 whereas potential emission from lakes with non-organic sediments ranged

Table 12. Methane fluxes from a variety of temperate, subarctic, and arctic aquatic ecosystems. Calculated spring melt pulses contrast with open water averaged fluxes for several systems.

Ecosystem Type	Mean mg/sq. m/day	Range mg/sq. m/day	N	Sampling Period	No. of Sites	Source
Spring melt pulse:						
Arctic delta lakes		180 - 2600			76	This study (Extrapolation to delta)
Temperate lakes (organic rich sediments)		145 - 3000			19	Michmerhuizen et al., in prep, 1995
Temperate lakes (non-organic rich sediments)		0.69 - 300			19	Michmerhuizen et al., in prep, 1995
Temperate alpine lakes	128		1		1	Smith and Lewis, 1992
Northern ocean	9		6		6	Lammers and Suess, 1995
Summer Open Water						
Arctic lakes	3.1		16	3 weeks		Morrissey and Livingston, 1992
Arctic lakes	77		64	6 weeks		Bartlet et al., 1992
Arctic lakes	125.5		238	4 months	6 sites (5 - 15 ponds @ each site)	Roulet et al., 1994
Arctic lakes (small)	21	5 - 131	6	1 month		Whalen and Reeburgh, 1990
Subarctic Lakes	57		-	1 month		Fan et al., 1992
Subarctic fen pools	163	15 - 770	62	4 months		Roulet et al., 1994
Subarctic bog pools	110	1 - 930	39	4 months		Roulet et al., 1994
Subarctic coastal fen	160		160	4 months	10	Hamilton and Kelly, 1994
Subarctic interior fen	180		80	4 months	5	Hamilton and Kelly, 1994
Subarctic bog	110		96	4 months	6	Hamilton and Kelly, 1994
Subarctic interior pond	24		30	3 months	1	Rouse et al., 1995 (Site 1, 1989)
Subarctic interior pond	114		60	3 months	1	Rouse et al., 1995 (Site 1, 1990)
Subarctic coastal pond	120		39	4 months	1	Rouse et al., 1995 (Site 2, 1989)
Subarctic coastal pond	88		60	4 months	1	Rouse et al., 1995 (Site 2, 1990)
Arctic (Pond margins with carex)	37		27	1 month	1	Christensen, 1993 (Site 1)
Arctic (Pond margins with carex)	373		27	1 month	1	Christensen, 1993 (Site 2)
Arctic (Pond margins with carex)	39		27	1 month	1	Christensen, 1993 (Site 3)
Arctic lakes with macrophytes	80		14	3 weeks		Morrissey and Livingston, 1992
Temperate lakes with macrophytes	350		-	2 weeks	1	Dacey and Klug, 1979
Temperate wild rice bed	493	127 - 883	51	1 month	4	Harriss et al., 1985
Temperate shoreline fen	165	151 - 171	51	1 month	2	Harriss et al., 1985
Temperate swamp		5 - 68	16	-	4	Harriss and Sebacher, 1981
Low boreal beaver ponds	-	30 - 90	186	6 months	3	Roulet et al., 1992
Temperate beaver pond	22		24	6 months	1	Ford and Naimon, 1988
Temperate beaver pond	19		24	6 months	1	Ford and Naimon, 1988
Northern ocean	2.4		12	1 month	12	Lammers and Suess, 1995
All seasons						
Temperate swamp		1 - 20	36	17 months		Harriss and Sebacher, 1982
Temperate beaver pond	302	1 - 1400	124	22 months	3	Yavitt et al., 1990
Temperate lakes with macrophytes	208		12	15 months	1	Smith and Lewis, 1992
Temperate alpine lakes	26		60	15 months	4	Smith and Lewis, 1992
Temperate freshwater estuary		39 - 425	76	15 months	10	Chanton et al., 1989
Temperate lakes	160		16	24 months	1	Miller and Oremland, 1988

from 0.64 to 298 mg/m^2. When extrapolating fluxes from the sampled lakes to a regional scale (Minnesota N. of 45°), the potential emission at ice-out ranged from 0.9 Gg assuming no lakes have organic-rich sediments to 7.1 Gg assuming all lakes have organic-rich sediments. When assuming that the mix of lakes was the same as the sample, a spring flux of 2.4 Gg was estimated. The land surface area covered by this extrapolation is approximately 2/3 of the state of Minnesota which is large when compared with the Mackenzie Delta, and this difference must be considered when comparing the regional fluxes from the two systems. Therefore, even though the high estimate from the Minnesota study is within the range of the high potential flux of the Mackenzie Delta (Table 9), the flux is from a much larger area which emphasizes the potential importance of northern deltaic ecosystems sources of methane.

In comparing the pulse results from Michmerhuizen et al. (1995) and this study with other systems, it can be seen that the values are similar to open water fluxes associated with Arctic pond and lake margins with carex, temperate beaver ponds, and temperate wild rice beds (Table 12). Because these delta lakes often contain extensive macrophyte coverage it is not surprising that the methane pulse generated by the models is more representative of aquatic systems containing extensive macrophyte populations.

Uncertainties associated with extrapolations

Mackenzie Delta lakes yielded potential methane fluxes at ice-out ranging from 180 mg/m^2 to 2600 mg/m^2 (Table 11) for a total spring pulse from the Mackenzie Delta of 0.5 to 11 Gg (Table 8). This range represents the highest and the lowest flux values generated by use of the four methods used to calculate under-ice lake volumes (Table 7). This flux estimate have a wide range because of uncertainties associated with:

(1) Under-ice volumes.

(2) Total area of lake surface on the delta.

(3) Potential spatial variation of ion concentration in the under-ice water columns of the sampled lakes.

(4) Potential spatial variation of methane concentration in the under-ice water columns of the sampled lakes.

Three other sources of uncertainty, although probably of less importance, include:

(1) Loss of ionic solutes from beneath the ice cover due to the formation of white ice.

(2) The assumption that exclusion of solutes is complete during the growth of black ice.

(3) Potential exchange of water with talik zones which may connect lakes with other water bodies.

I expect that the "true" emission of methane from these lakes at ice-out may be towards the high end of the calculated flux range. The strong correlation between Methods 2A and 2B provides evidence that the average depth model (Model 2) may be more representative of under-ice volumes than the maximum depth model (Model 1). I was also able to establish that the ion concentration factor is capable of predicting under-ice volumes reasonably well (within 5% of actual measured volume in the case of NRC lake). Based on this reasoning, I judge that the best estimate of methane flux from Mackenzie Delta lakes at ice-out may be about 2000 $mg/m^2/d$. I also judge (by taking the mid-point of Mackay's (1963) estimates) that the best estimate of actual lake coverage of the Mackenzie Delta to be closer to 35%. This would give a water surface area of 4200 km^2 on the delta for a spring pulse of 8.4 Gg.

Does all the methane escape at ice-out?

There are three pathways by which methane reaches the atmosphere from the sediments: (1) diffusion through the water column, (2) ebullition, and, (3) through rooted aquatic plants. Although it is well established in the literature that methane flux is enhanced in areas with aquatic macrophytes because of the ability of the plant lacunae to act as a gas exchange vehicle between lake sediments and the atmosphere (Dacey and Klug, 1979, Smith and Lewis, 1991, Sebacher et al., 1985) , this thesis is concerned with water column methane accumulation and its potential release to the atmosphere at spring turnover and thus macrophytes are unlikely to be an important mode of transport for this event. Likewise, ebullition, or bubble formation, which occurs most frequently in peaty or less compacted organic sediments having pore spaces large enough to let large bubbles escape, may be a major transport process during the open water season but is unlikely to be dominant during spring turnover. More likely, diffusion, a random, chaotic movement of gas through water as it spreads from zones of high concentrations to areas of lower concentration, is the dominant method by which the methane reaches the atmosphere at ice-out.

Methane has very limited solubility in water and, due to the steep concentration gradient which exists between the methane in the under-ice water column and the atmosphere, it is likely that rapid degassing will occur once enough of the lake surface is exposed so that the wind can mix the water column fully. In the Colorado lake study, Smith and Lewis (1992) observed methane concentrations in the water column of one lake fall from a high of 99.9 to 2.2 μM over a 24 hour period immediately following spring turn-over. They concluded that loss of methane from the water column was essentially equal to loss to the atmosphere. Methane losses to oxidation processes were deemed to be comparatively small because of the low water temperatures associated with ice melt and the rapid nature of the degassing event.

There are two scenarios most likely describe the fate of the methane trapped beneath the winter ice cover. The first scenario is that all the methane contained in the under-ice water column will be released to the atmosphere at spring ice-out. The second scenario is that a portion of the methane becomes oxidized prior to being emitted at the lake surface. Which scenario dominates each lake becomes dependent upon the duration of the spring flooding event.

While methane is produced and maintained in an anoxic environment under the ice-cover of lakes in the Mackenzie Delta, the floodwaters that invade these lakes for varying durations each spring are highly oxygenated. The anoxic lake water becomes concentrated as solutes from the water are excluded into the underlying water column during ice cap growth. When the floodwater enters the lake, it often comes in on top of the ice cover. The ice then cracks around the edges of the lake or releases its hold on the sediments and floats to the surface forming an intact cap over the lake. This cap effectively protects the water column from wind. In order for the methane to become oxidized the floodwater would have to mix with the lake water beneath the ice cover. Lesack et al. (1991a) have shown that, without exposure to the wind, the denser lake water remains separated from the floodwater and, when the floodwaters recede, most of the lake water may remain behind. After the ice cover has melted, the first significant wind will mix the entire water column which, theoretically, would allow the methane to escape into the atmosphere.

In a study on NRC Lake which was designed to look at the probability of the Mackenzie Delta lake waters mixing with the flood waters at spring ice-out time, Lesack *et al.* (1991b) concluded that the high-closure lakes of the middle delta (approximately 1/3 of all the lakes) are flooded for a sufficiently short time that the ice cap would remain intact and the water column would remain unmixed until after the flood levels had receded. The remaining 2/3 of the lakes are exposed to wind before the flood waters have receded and the stability of their water columns is too weak to resist mixing. Therefore, it is likely for the low and no-closure lakes that the influx of oxygen into the water column may cause some of the methane to be converted to carbon dioxide before it has a chance to cross the water/air interface. For the high-closure lakes, however, such methane oxidation may be negligible. How much of the methane is affected in this manner will be investigated in the future.

Importance of Northern Circumpolar Deltas

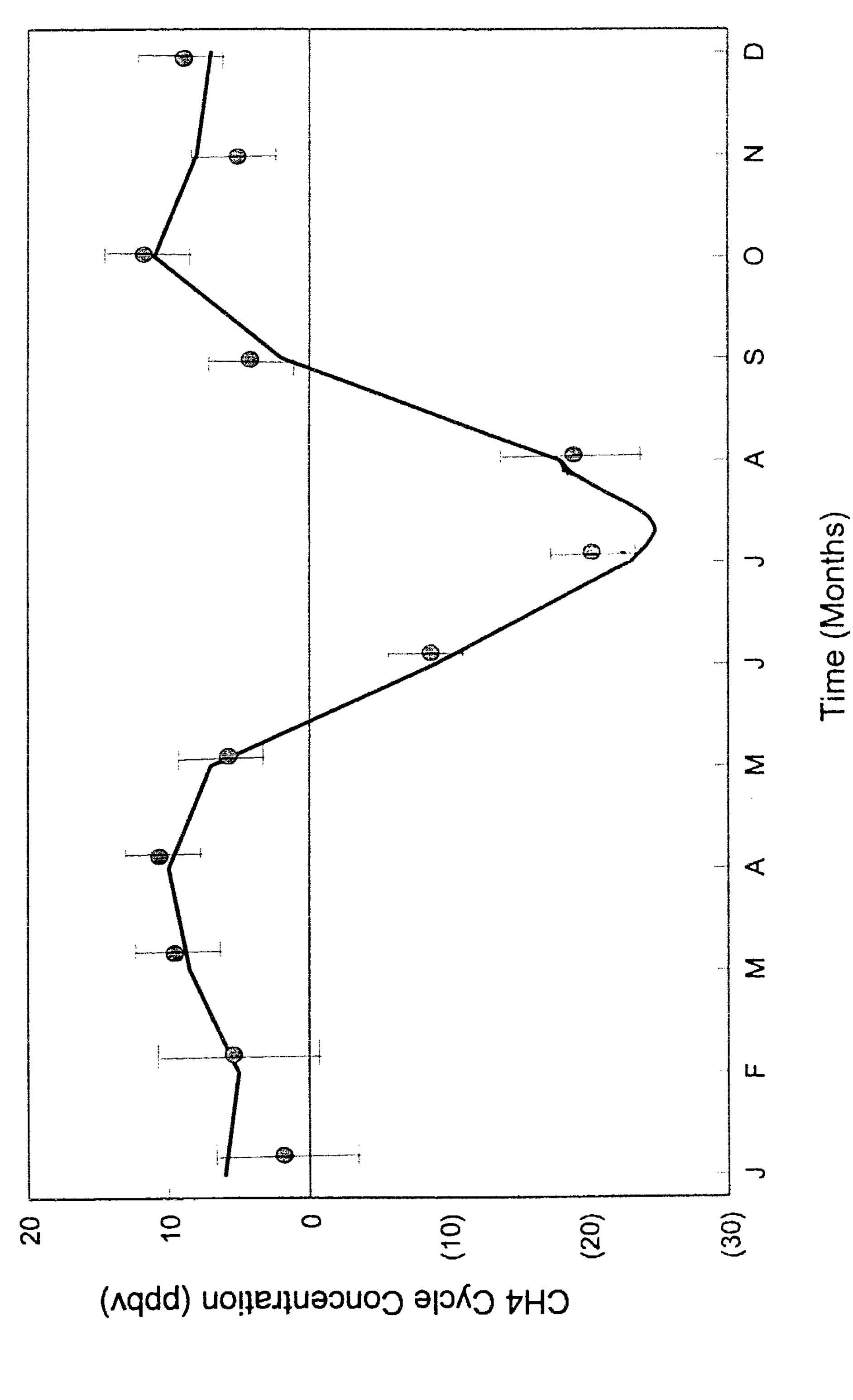
The potential contribution of methane to the atmosphere from lakes on active deltas in the northern circumpolar region ranges from 3 to 100 Gg (Table 10). This range is generated by using differing estimates of surface water cover and differing averages of potential methane flux. Using my best estimates of potential flux per unit area (2000 mg/m^2) and lake surface coverage for all major northern deltas (35%), the methane pulse to the atmosphere at ice-out would be about 58 Gg. With the lowest recent estimate of annual methane flux from northern wetlands being 17 Tg, the single episode flux at ice-out from lakes in all the major northern deltas represents 0.3% of the total annual flux from northern wetlands. Considering that the majority of the annual flux takes place over approximately 150 days, average daily flux from the tundra approximates 113 Gg d^{-1}. Therefore, the pulsed emissions from the northern delta lakes alone, comprising less than 1% of the landmass, would be about 51% of the average daily emission of methane from the entire norther wetlands north of 40°.

It is not possible that all lakes experience ice-out and mixing of the water column at the same time throughout the northern hemisphere. The freezing and breaking up of rivers always has a zonal character which is dependent upon climate, proximity and numbers of lakes, permafrost distribution, subsurface temperature and proximity of glaciers (Telang et al. 1991). The rivers of the European part of the Arctic Basin (Pechora and N. Dvina) experience ice-out in April and May (Fig. 20). The upper reaches of the Ob become ice free in April but the lower reaches are still ice-covered until June. The Asian rivers (Lower Lena, Kolyma, Indigirka, etc.) become ice free in May or June which is similar to the Mackenzie, Colville and Yukon. Breakup can often take place over a period of three months for many of these northern rivers as the mechanics of these northward flowing rivers involves thawing in their headwaters with extensive ice jamming in the northern portions. The warmer waters associated with river flooding enters the delta lakes and aids in the melting of the lake ice caps. Ice-out on the lakes follows shortly after the river channels are clear of ice. Overall, ice-out on the lakes corresponds to the timing of increased spring temperatures along a latitudinal gradient progressing from the southern Arctic northward.

Kahlil et al. (1993) conclude that the spring atmospheric methane cycle has a remarkable stability associated with the cycle length from year to year (Fig. 25). While the days in mid July on which the minimum concentrations occur are very precisely defined in the data the maxima are not. The fact that lakes would degas along a latitudinal gradient from April to June as ice-out progresses northward may offer a potential explanation to the lack of definition of the methane maxima.

Although the spring pulse associated with ice-out may be small relative to the annual flux from the northern circumpolar region, methane flux from these lakes will continue through the summer. Even though the lakes do not stratify, and therefore remain oxygen rich throughout their water columns, they also contain extensive macrophyte coverage and methane flux from anoxic lake sediments through macrophyte vegetation should continue at a rate equivalent to those exhibited for other systems in similar environments. Open water fluxes for Arctic pond and lake margins with carex stands have mean fluxes of 300 to 600 $mg/m^2/d$ (Christensen, 1993; Whalen and Reeburg, 1992) and other systems such as the Hudson Bay lowlands and the Yukon-Kuskokwim Delta report fluxes between 20 to 200 $mg/m^2/d$ (Table 12). Therefore it is not unreasonable to estimate that the Mackenzie delta lakes which are organic-rich and dominated by macrophyte vegetation would have methane fluxes close to the upper limits of lakes in similar systems and may represent an important component of the Arctic methane budget.

Fig. 25. The seasonal cycle of methane concentrations based on monthly averaged concentrations. 90% confidence limits have been added to the monthly indices (points). The line is from the Fourier decomposition using the three most prominent frequencies (12, 6, and 4 month cycles) (graph redrawn from Kahlil et al, 1995).



CH4 Cycle Concentration (ppbv)
20
10
0
(10)
(20)
(30)
J
F
M
A
M
J
J
A
S
O
N
D
Time (Months)

Chapter 5
Conclusions

Summary of Main Findings

The results from this study are consistent with the accepted controls on substrate availability for production of methane and the relation between pH and redox potential on methane production. Lakes with higher relative rates of primary productivity, as indicated by various chemical indices, contained higher concentrations of methane in their under-ice water columns. Under-ice concentrations of methane can be predicted quite precisely from measurement of chemical indices which are related to primary productivity.

Frequency and duration of flooding has a significant effect on under-ice methane accumulation among Mackenzie Delta lakes. High-closure lakes have significantly higher methane concentrations than low-closure lakes which, in turn, have significantly higher concentrations of methane than no-closure lakes. High-closure lakes also have high carbon content in their sediments, which is associated with aquatic macrophyte populations that dominate primary productivity in the summer growth season. No-closure lakes, on the other hand, are turbid environments and have a lower percentage of carbon in their sediments. Low-closure lakes also have a water chemistry conducive to high rates of primary productivity but the carbon content in their sediments is modified by the mineral sediments delivered to these lakes by the Mackenzie River which make them not as conducive to methane production as the high-closure lakes.

Within the sampled lakes, position across the delta has no significant effect on the distribution of methane among lakes although a trend exists that shows an increase in methane accumulation in an eastward direction across the delta. The trend for higher methane accumulation on the Inuvik side of the delta corresponds with decreased sedimentation rates and higher sediment carbon content as well as with low sulfate values for these eastern lakes.

On average, spring methane pulse on a per lake basis ranges from about 180 to 2600 mg/m^2/d which translates to a Mackenzie Delta pulse of 0.5 to 12 Gg assuming that all the methane produced in the lakes is emitted to the atmosphere. My best estimate for a spring pulse contribution of methane to the atmosphere from all major northern deltas is about 58 Gg which represents approximately 0.3% of the annual emissions of methane from northern wetlands. Although the spring pulse of methane associated with these delta lakes is small relative to the annual methane budget for the northern wetlands, methane emissions which continue through the open-water season have not bet been measured. The combined flux from the pulse at ice-out and continued emissions during open-water may be a significant component of the tundra methane budget.

Suggestions for Future Research

In order to further refine this research several avenues should be followed:

(1) In order to determine how much of the methane actually enters the atmosphere as a spring pulse from these ice-covered lakes, it is necessary to measure flux rates directly from the water to the atmosphere. Chambers placed on the lake surfaces could be used for this purpose. They could be set up on a subset of lakes that represent the three closure categories to determine if connection to the main channels has an effect on methane oxidation through mixing of the water column prior to ice-out. Initial water column values of methane would also have to be determined prior to ice-out.

(2) The models developed to estimate under-ice volumes should be refined to give more accurate representation of "true" volumes.

(3) Spatial modeling of methane concentrations within lakes would be beneficial in determining how representative single bore hole measurements are at representing whole lake methane content.

(4) More accurate estimates of lake area coverage throughout the delta would be an asset when calculating potential flux from the Mackenzie Delta.

(5) More accurate estimates of delta areas in circumpolar regions would be helpful in determining the spring methane pulse from northern delta.

(5) Accurate estimates of per cent lake coverage of all the circumpolar deltas would be an asset when calculating potential flux from Arctic delta ecosystems.

(6) Cross delta transects representing northern and southern sections of the delta should be sampled in a manner similar to that performed for this study to see if the same controls on methane production and accumulation operate throughout the delta and to see if the methane concentration values are indeed representative of high, low, and no-closure lakes on a delta wide basis.

(7) Tundra lakes in the vicinity of the delta should be sampled for methane in order to obtain representative values from these ecosystems.

References

Adams, W.P. and D.C. Lasenby. 1985. The roles of snow, lake ice and lake water in the distribution of major ions in the ice cover of a lake. International Glaciological Society 702-707.

Anon. 1985 Canada Drainage Basins. The National Atlas of Canada, 5th edn, Energy, Mines and Resources Canada, Ottawa.

APHA.. 1989. Standard Methods for the Examination of Water and Wastewater. American Public Health Association, Washington, DC.

Aselmann, I. and P.J. Crutzen. 1989. Global distribution of natural freshwater wetlands and rice paddies, their net primary productivity, seasonality and possible methane emissions. J. Atmos. Chem. 8:307-358.

Bach, K. 1994. Unpublished manuscript. Classification scheme for the Mackenzie Delta Lakes. Report to the Department of Geography, Simon Fraser University, Burnaby, B.C., Canada.

Bartlett, K.B., P.M. Crill, R.L. Sass, R.C. Harriss, and N.B. Dise. 1992. Methane emissions from tundra environments in the Yukon-Kuskokwim Delta, Alaska. J. Geophys. Res. 97(D15):16,645-16,660.

Bartlett, K.B. and R.C. Harriss. 1992. Review and assessment of methane emissions from wetlands. Chemosphere,

Bigras, S.C. 1990. Hydrological regime of lakes in the Mackenzie Delta, Northwest Territories, Canada. Arctic and Alpine Res. 22(2):163-174.

Burn, C.R. 1991. Recharge of Mackenzie delta lakes during winter. p.1-8, In P. Marsh and C.S.L. Ommanney (Eds.), The Mackenzie Delta: Environmental Interactions and Implications of Development. Environ. Can., NHRI Symp. No. 4, Oct. 1989, Saskatoon.

Chanton, J.P., C.S. Martens and C.A. Kelley. 1989. Gas transport from methane-saturated, tidal freshwater and wetland sediments. Limnol. Oceanogr. 34(5):807-819.

Chanton, J.P., C.S. Martens, C.A. Kelley, P.M. Crill, and W.J. Showers. 1992. Methane transport mechanisms and isotopic fractionation in emergent macrophytes of an Alaskan tundra lake. J. Geophys. Res. 97(D15):16,681-16,688.

Chatterjee, S. and B. Price. 1991. Regression Analysis by Example. John Wiley and Sons, Inc. 278pp.

Christensen, T.R. 1993. Methane emission from Arctic tundra. Biogeochemistry 21:117-139.

Cicerone, R.J. and R.S. Oremland. 1988. Biogeochemical aspects of atmospheric methane. Global Biogeochem. Cycles 2:299-327.

Dacey, J.W.H. and M.J. Klug. 1979. Methane efflux from lake sediments through water lilies. Science 203:1253-1255.

Fan, S.M., S.C. Wofsy, P.S. Bakwin, D.J. Jacob, S.M. Anderson, P.L. Kebabian, J.B. McManus, and C.E. Kolb. 1992. Micrometeorological measurements of CH_4 and CO_2 exchange between the atmosphere and subarctic tundra. J. Geophysical Res. 97(D15):16627-16643.

Fee, E.J., J.A. Shearer, E.R. DeBrivn, and E.U. Schindler. 1992. Effects of lake size on phytoplankton photosynthesis. Can. J. Fish. Aquat. Sci. 49:2445-2459.

Ford, T.E. and R.J. Naimon. 1988. Alteration of carbon cycling by beaver: Methane evasion rates from boreal forest streams and rivers. Can. J. Zool. 66:529-533.

Franzmann, P.D., N.J. Roberts, C.A. Mancuso, H.R. Burton, and T.A. McMeekin. 1991. Methane production in meromictic Ace Lake, Antarctica. Kluwer Academic Publishers, Dordrecht. 191-201.

Fung, I., J. John, J. Lerner, E. Matthews, M. Prather, L.P. Steele, and P.J. Fraser. 1991. Three dimensional model synthesis of the global methane cycle. J. Geophys. Res. 96:13033 - 13065.

Gill, D. 1978. Biophysical Environment of the Mackenzie River Delta. Guide for Field Trip No. 3, Lower Mackenzie Valley, Third International Conference on Permafrost. 14 - 23 July.

Glooschenko, W.A., N.T. Roulet, L.A. Barrie, H.I. Schiff, and H.G. McAdie. 1994. The Northern Wetlands study (NOWES): An overview. J. Geophys. Res. 99(D1): 1423-1428.

Goldman, C.R. and A.J. Horne. 1983. Limnology. McGraw-Hill Publishing Co., New York. 464 pp

Golterman, H.L. and R.S. Clymo. 1969. Methods for Chemical Analysis of Fresh Waters. Published for the International Biological Programme by Blackwell Scientific, Oxford, Edinburgh.

Hamilton, J.D., 1992. Methane and carbon dioxide flux from small ponds and lakes of the Hudson Bay Lowland. MSc thesis. Univ. of Manitoba, Winnipeg. 281pp.

Hamilton, J.D., C.A. Kelly, J.W.M. Rudd, R.H. Hesslein, and N.T. Roulet. 1994. Flux to the atmosphere of CH4 and CO2 from wetland ponds on the Hudson Bay Lowlands (HBLs). J. Geophys. Res. 99(D1):1495-1510.

Harned, H.S. and R. Davis, 1943. The ionization constant of carbonic acid in water and the solubility of carbon dioxide in water and aqueous salt solutions from 0°C to 50°C. Am. Chem. Soc. J. 65:2030-2037.

Harriss, R.C., E. Gorham, D.I. Sebacher, K.B. Bartlett, and P.A. Flebbe. 1985. Methane flux from nothern peatlands. Nature 315(20):652-653.

Harriss, R.C. and D.I. Sebacher. 1981. Methane flux in forested freshwater swamps of the southeastern United States. Geophys.Res. Letters 8(9):1002-1004.

Harriss, R.C. and D.I. Sebacher. 1982. Methane flux in the Great Dismal Swamp. Nature 297(5868):673-674.

Hecky, R.E., R.H. Hesslein and P.S. Ramlal, 1991. Net community photosynthesis in Mackenzie Delta lakes near Inuvik, N.W.T. p. 69, In P. Marsh and C.S.L. Ommanney (Eds.), The Mackenzie Delta: Environmental Interactions and Implications of Development. Environ. Can., NHRI Symp. No. 4, Oct. 1989, Saskatoon.

Hesslein, R.H., J.W.M. Rudd, C. Kelly, P. Ramlal, and K.A. Hallard. 1991. Carbon dioxide partial pressure in the surface waters of lakes in Northwestern, Ontario and the MacKenzie Delta region, Canada. In Air-S.C. Wiehelms and J.S. Gulliver (Eds.), Water Mass Transfer.

Houghton, J.T., G.J. Jenkins, and J.J. Ephraums (Eds.). 1990 Climate Change: The IPCC Scientific Assessment. Cambridge University Press, New York

Kahlil, M.A.K., R.A. Rasmussen, and F. Moraes. 1993. Atmospheric methane at Cape Meares: Analysis of a high-resolution data base and its environmental implications. J. Geophys. Res. 98(D8):14753-14770.

Kelly, C.A. and D.P. Chynoweth. 1981. The contributions of temperature and of the input of organic matter in controlling rates of sediment methanogensis. Limnol. Oceanogr. 26(5):891-897.

Koroleff, F. 1976. Determination of nutrients. p127-133, In K.Grasshoff (Ed), Methods of Seawater Analysis. Verlag Chemie, Weinheim.

Lammers, S. and E. Suess. 1995. Variations of atmospheric methane supply from the Sea of Okhotsk induced by the seasonal ice cover. Global Biogeochem. Cycle 9(3):351-358.

Lesack, L.F.W., P. Marsh, and R.E. Hecky. 1996 in prep. Spatial and temporal dynamics of major solute chemistry among Mackenzie Delta lakes. Submitted to Limnol. Oceanogr.

Lesack, L.F.W., P. Marsh, and R.E. Hecky. 1991a. Ice-cover growth and freeze-out of solutes in a Mackenzie Delta lake. p. 219-237, In T.D. Prowse and C.S.L. Ommanney (Eds.), Northern Hydrology: Selected Perspectives. Environ. Can., NHRI Symp. No. 6, July 1990, Saskatoon.

Lesack, L.F.W., R.E. Hecky, and P. Marsh. 1991b. The influence of frequency and duration of flooding on the nutrient chemistry of Mackenzie Delta lakes. p. 19-36, In P. Marsh and C.S.L. Ommanney (Eds.), The Mackenzie Delta: Environmental Interactions and Implications of Development. Environ. Can., NHRI Symp. No. 4, Oct. 1989, Saskatoon.

Lewis, C.P. 1988 Unpublished manuscript. Sedimentary environments and processes on the modern Mackenzie Delta. Report to Inland Waters Directorate, Environ.t Can., Ottawa.

Mackay, J.R. 1963. The Mackenzie Delta Area, N.W.T. Geographical Branch, Mines and Technical Surveys, Ottawa. 202pp.

Marsh, P.. 1995 Unpublished data. Mean sedimentation rates for 81 Mackenzie Delta lakes grouped into three closure categories. National Hydrology Research Institute, Saskatoon.

Marsh, P. 1989. Hydrology of Mackenzie Delta lakes. p. 43-55, In W.C. Mackay (Ed.), Northern Lakes and Rivers. Boreal Institute for Northern Studies, Edmonton.

Marsh, P. and M. Ferguson. 1988. Sediment regime of lakes in the Mackenzie Delta. NOGAP Project C.11A, NHRI Contribution No. 88016

Marsh, P and M. Hey. 1991. Spatial variations in the spring flooding of Mackenzie Delta lakes. p. 9-18, In P. Marsh and C.S.L. Ommanney (Eds.), The Mackenzie Delta: Environmental Interactions and Implications of Development. Environ. Can., NHRI Symp. No. 4, Oct. 1989, Saskatoon.

Marsh, P. and M. Hey. 1989. The flooding hydrology of Mackenzie Delta lakes near Inuvik, N.W.T., Canada. Arctic 42(1):41-49.

Marsh, P. and M. Hey. 1988. Mackenzie River water levels and the flooding of delta lakes. Hational Hydrology Research Institute, Environ. Can., Saskatoon,

Mathias, J.A. and J. Barica. 1980. Factors controlling oxygen depletion in ice-covered lakes. Can. J. Fish. Aquat. Sci. 35:185-194.

Matthews, E. 1983. Global vegetation and land use: new high resolution data bases for climate studies. J. Chim. Appl. Meteorol. 22:474-487.

Matthews, E. and I. Fung. 1987. Methane emission from natural wetlands: Global distribution, area, and environmental characteristics of sources. Global Biogeochem. Cycles 1:61-86.

Michmerhuizen, C.M. and R.G. Striegl. 1995 in prep. Methane emission from north temperate lakes following ice melt. Submitted to Limnol.Oceanogr.

Miller, L.G. and R.S. Oremland. 1988. Methane efflux from the pelagic regions of four lakes. Global Biogeochem. Cycles 2:269-277.

Morrissey, LA. and G.P. Livingston. 1992. Methane emissions from Alaska arctic tundra: An assessment of local spatial variability. J. Geophysical Res. 97(D15): 16661-16670.

Pearce, C.M. 1991. Monitoring white spruce communities on the Mackenzie Delta with satellites. p. 107-120, In P. Marsh and C.S.L. Ommanney (Eds.), The Mackenzie Delta: Environmental Interactions and Implications of Development. Environ. Can., NHRI Symp. No. 4, Oct. 1989, Saskatoon.

Ramlal, P.S., R.H. Hesslein, R.E. Hecky, E.J. Fee, J.W.M. Rudd, and S.J. Guidford. 1994. The organic carbon budget of a shallow Arctic tundra lake on the Tuktoyaktuk Penninsula, N.W.T., Canada. Biogeochem. 24:145-172.

Revesz, R. and E. Hasty. 1987. Recovery study using an elevated pressure microwave dissolution technique. CEM Corp. Matthews, N. Carolina. March 1987.

Roulet, N.T., R. Ash and T.R. Moore. 1992. Low boreal wetlands as a source of atmospheric methane. J. Geophysical Res. 97(D4):3739-3749.

Roulet, N.T., A. Jano, C.A. Kelly, L.F. Klinger, T.R. Moore, R. Protz, J.A. Ritter, and W.R. Rouse. 1994. The role of the Hudson Bay lowland as a source of atmospheric methane. J. Geophys. Res. 99(D1):1439-1454.

Rouse, W.R., S. Holland, and T.R. Moore. 1995. Variability in Methane emissions from wetlands at northern treeline near Churchill, Manitoba, Canada. Arctic and Alpine Res. 27(2):146-156.

Rudd, J.W.M. and R.D. Hamilton. 1978. Methane cycling in a eutrophic shield lake and its effects on whole lake metabolism. Limnol. Oceanogr. 23:337-348.

Schindler, D.W. 1971. A hypothesis to explain differences and similarities among lakes in the Experimental Lakes Area, northwestern Ontario. J. Fish. Res. Board Can. 28:157-169.

Schindler, D.W. 1978. Factors regulating phytoplankton production and standing crop in the world's freshwaters. Limnol. Oceanogr. 23:478-486.

Schlesinger, W.H. 1991. Biogeochemistry: An Analysis of Global Change. Academic Press, Inc. Harcourt Brace Jovanovich. 443 pp.

Sebacher, D.I., R.C. Harris, and K.B.Bartlett. 1985. Methane emissions to the atmosphere through aquatic plants. J. Environ. Qual. 14(1):40-46.

Smith, M.W. 1976. Permafrost in the Mackenzie Delta, Northwest Territories. Geological Survey Paper 75-28. Canada Geological Survey. 33pp.

Smith, L. and W.M. Lewis. 1992. Seasonality of methane emissions from five lakes and associated wetlands of the Colorado Rockies. Global Biogeochem. Cycles 6(4): 323-338.

Smith, R.L., L.G. Miller, and B.L. Howes. 1993. The geochemistry of methane in Lake Fryxell, an amictic, permanently ice-covered, Antarctic lake. Biogeochem. 21:95-115.

Stainton, M.P., M.J. Capel, and F.A.J. Armstrong, 1977. The chemical analysis of freshwater, 2nd ed. Can. Fish. Mar. Serv. Misc. Spec. Publ. 25. 180pp.

Strickland, J.D., and T.R. Parsons. 1972. A practical handbook of seawater analysis, 2nd ed. Bull. Fish. Res. Board Can. 167pp.

Surveys and Mapping Branch. 1974. Aklavik, Northwest Territories, District of Mackenzie. Department of Mines and Technical Surveys, Ottawa. Map sheet 107B, 1:250,000.

Telang, S.A., R. Pocklington, A.S. Naidu, E.A. Romankevich, I.I. Gitelson, and M.I. Gladyshev. 1991. Carbon and mineral transport in major North American, Russian Arctic, and Siberian Rivers: The St. Lawrence, the Mackenzie, the Yukon, the Arctic Alaskan rivers, the Arctic Basin rivers in the Soviet Union, and the Yenisei. p. 75-104, In E.T. Degens, S. Kempe, and J.E. Richey (Eds.), Biogeochemistry of Major World Rivers: Scope 42. John Wiley and Sons, New York.

Valentine, D.W. 1994. Ecosystem and physiological controls over methane production in northern wetlands. J. Geophys. Res. 99(D1):1563-1571.

Vanderburgh, S. and D.G. Smith. 1987. Slave River delta: Geomorphology, sedimentology, and Holocene reconstruction. Can. J. Earth Sci., 25:1990-2004.

Welch, H.E. and J. Kalff. 1974. Benthic photosynthesis and respiration in Char Lake. J. Fish. Res. Board Can. 31:609-620.

Whalen, S.C. and W.S. Reeburgh. 1990. A methane flux transect along the trans-Alaska pipeline haul road. Tellus 42B:237-249.

Whalen, S.C. and W.S. Reeburgh. 1992. Interannual variations in tundra methane emission: A 4-year time series at fixed sites. Global Biogeochem. Cycles 6: 139-159.

Yamamoto, S., J.B. Alcanskas, and T.E. Crozier. 1976. Solubility of methane in distilled water and seawater. J. Chem. Eng. Data 21:72-80.

Appendix A - Data Tables and Statistical Summary Tables

This section includes raw data tables and statistical summaries for the two-way and one-way ANOVA tests performed on the three main data sets of spring 1993, summer 1993 and spring 1994. The tables are presented in the following order:

Table A.1	Spring 1993 major solutes data
Table A.2	Spring 1993 Two-Way ANOVA summary statistics
Table A.3	Spring 1993 One-Way ANOVA summary statistics
Table A.4	Summer 1993 major solutes data
Table A.5	Summer 1993 Two-Way ANOVA summary statistics
Table A.6	Summer 1993 One-Way ANOVA summary statistics
Table A.7	Spring 1994 major solutes, gases, physical measurements, and sediment data
Table A.8	Spring 1994 Two-Way ANOVA summary statistics for major solutes
Table A.9	Spring 1994 One-Way ANOVA summary statistics for major solutes
Table A.10	Spring 1994 Two-Way ANOVA summary statistics for gases
Table A.11	Spring 1994 One-Way ANOVA summary statistics for gases
Table A.12	Spring 1994 Two-Way ANOVA summary statistics for physical measurement variables
Table A.13	Spring 1994 One-Way ANOVA summary statistics for physical measurement variables
Table A.14	Spring 1994 Two-Way ANOVA summary statistics for sediment data
Table A.15	Spring 1994 One-Way ANOVA summary statistics for sediment data

Table A.16 Summary sstatistics for Two-Way and One-Way ANOVAs for between data set variation

Table A.1 Spring 1993 Major Solutes Data

Lake	K μM	Na μM	Mg μM	Ca μM	Cl μM	SO4 μM	Si μM
1	27.2	603.4	324.3	1216.2	387.4	401.2	63.7
2	37.1	699.1	397.1	1679.8	348.8	513.0	89.8
3	27.6	497.8	348.4	1369.5	440.9	404.6	66.4
4	57.5	444.2	620.5	1215.8	230.9	172.2	47.4
5	104.3	871.7	844.1	2146.0	604.4	20.1	197.4
6	117.1	869.0	622.3	2055.9	267.3	120.9	23.3
7	80.2	1015.0	1600.0	3757.3	611.6	803.4	158.2
8	46.9	473.0	412.4	1671.9	435.0	527.2	72.0
9	105.3	856.8	950.5	1999.6	432.0	32.1	100.6
10	89.6	555.2	637.1	1959.6	341.1	111.1	80.3
11	50.4	378.9	524.7	1473.5	148.2	85.8	31.3
13	58.8	470.1	834.1	2341.5	258.2	650.7	53.5
14	62.7	639.3	662.0	2357.0	287.6	458.5	102.9
15	97.3	520.6	888.6	2167.1	253.9	322.7	63.4
16	67.7	470.2	484.7	1877.3	202.5	242.0	55.2
17	70.5	559.6	617.9	1463.2	214.6	91.3	42.3
18	80.5	760.1	1446.0	3728.5	469.8	955.1	113.0
19	107.8	754.8	2086.5	3502.0	154.8	1021.9	71.7
20	91.2	893.8	909.1	3414.0	317.3	3155.5	81.9
21	179.3	8124.1	4582.1	7461.7	16353.3	2355.6	199.5
22	60.5	448.3	579.2	2195.4	189.5	1456.5	68.4
23	92.1	515.3	681.4	2421.6	191.0	1310.9	107.4
24	28.5	425.5	1039.9	2206.7	276.1	1054.9	72.0
25	96.4	708.7	1617.5	4392.2	357.6	1660.1	103.3
26	47.4	208.8	623.1	1662.5	64.7	437.6	45.4
27	142.4	709.5	1443.6	2898.8	132.7	801.0	88.4
28	130.1	711.2	637.1	2087.6	329.4	60.1	66.1
29	24.9	393.1	904.0	2159.1	189.3	958.7	72.2
30	134.3	859.0	1337.5	2434.4	470.6	24.1	81.8
31	53.7	440.3	1141.0	2942.0	148.0	1272.0	90.1
32	58.9	394.6	562.5	1632.5	164.8	236.1	24.4
33	131.4	686.3	940.2	2077.5	439.5	35.3	120.5
34	79.1	579.1	725.3	1594.7	268.0	67.2	67.3
35	87.8	468.4	818.3	1969.0	226.8	110.2	48.3
36	119.4	502.8	1512.4	2963.3	158.0	506.0	76.5
37	119.0	859.0	1446.8	2933.5	437.3	1031.9	104.8
38	33.5	449.5	631.9	1454.4	144.0	178.4	29.7
39	85.6	653.4	744.4	1805.0	295.1	38.9	75.6
40	169.4	1055.2	1820.5	4184.4	549.7	137.0	142.4
41	118.5	686.1	897.5	2051.2	351.7	25.4	71.8
42	69.7	925.8	1249.7	2860.1	551.4	945.5	99.9

Lake	K µM	Na µM	Mg µM	Ca µM	Cl µM	SO4 µM	Si µM
43	73.0	506.8	817.9	2283.0	366.0	665.0	86.4
44	72.9	407.5	737.5	1515.5	175.6	115.2	50.4
45	117.4	989.1	803.3	1739.7	453.9	793.3	137.8
46	35.3	785.5	695.6	1723.0	440.1	557.1	86.7
48	172.6	1717.3	2467.2	3782.3	1109.9	22.4	240.2
49	122.4	1030.0	1479.5	3963.5	851.6	88.9	225.2
50	166.0	970.8	1823.8	4336.8	626.7	15.7	170.6
51	51.4	805.6	767.1	2070.6	489.5	665.6	117.2
53	61.2	487.4	653.3	1826.8	332.0	298.6	106.6
54	28.2	512.8	499.3	1270.1	394.8	414.2	70.7
55	112.4	991.3	996.5	2403.5	571.4	156.9	71.2
57	30.1	409.5	493.2	900.0	146.0	130.3	13.9
58	50.6	357.6	573.8	1451.8	227.2	11.4	39.6
59	48.8	751.9	824.6	1797.7	378.7	100.0	57.2
60	131.5	1163.0	1831.9	4046.0	714.2	20.8	208.0
61	97.9	834.9	896.0	1887.0	532.4	63.3	63.8
62	85.7	711.8	695.0	1780.3	448.3	28.6	92.3
63	54.9	507.3	756.5	1585.9	378.9	61.2	50.9
64	84.0	471.5	773.9	1785.1	260.4	51.3	47.9
65	27.1	285.3	405.0	1230.3	106.0	241.6	33.3
66	29.3	282.7	249.6	1208.7	121.6	270.7	47.7
67	30.3	287.1	336.7	1181.4	123.6	156.8	14.8
68	21.2	344.9	544.1	1116.8	141.8	278.6	22.8
69	67.9	455.1	760.5	1768.5	230.9	24.1	80.4
70	78.3	731.0	852.8	1774.1	323.7	16.7	55.4
71	29.7	327.6	413.2	1298.8	142.9	248.7	17.6
72	28.1	481.2	442.3	1244.1	385.3	441.5	60.8
73	132.4	652.2	1370.1	2317.4	97.4	541.1	98.7
74	73.9	353.1	424.5	1451.8	77.9	424.4	29.5
75	83.8	304.3	691.0	1605.2	80.3	387.4	38.9
76	110.9	448.4	1263.7	2717.3	189.7	452.2	77.2
78	106.3	442.1	825.7	1483.8	112.2	286.1	48.1
79	120.9	341.1	880.7	2051.0	101.4	278.9	61.6
80	154.0	1102.5	1645.3	3145.8	230.7	2420.8	4.4
81	123.8	398.8	1047.5	1820.5	91.3	136.4	59.7

Table A.2. Summary for Descriptive Statistics and Two Way ANOVAs performed on water chemistry for Spring 1993 Under-Ice Samples, Mackenzie Delta Lake transect.

	Log Ca	Log Mg	K	Log Na	Log Cl	Log SO4	Log Si	Log Cond	pH
N	75	76	76	75	75	76	76	71	71
Mean	3.30	2.91	82.30	2.76	2.42	2.34	1.82	2.71	7.38
Stand. Dev.	0.16	0.23	40.68	0.18	0.27	0.60	0.29	0.17	0.18
Minimum	2.95	2.40	21.17	2.32	1.81	1.06	0.64	2.37	7.06
Maximum	3.64	3.66	179.32	3.24	3.05	3.50	2.38	3.14	7.87
Skewness	0.37	0.46	0.40	0.08	-0.20	-0.29	-1.00	0.25	0.63
Lilliefors	0.22	0.04	0.51	0.06	0.26	0.08	0.01	0.51	0.04
Closure									
Anova p =	0.01	0.11	0.29	0.01	<.001	0.004	<.001	0.01	0.33
:F =	5.07	2.32	1.25	4.76	0.57	5.88	8.63	5.42	1.13
High									
LS Mean	3.23	2.86	77.90	2.69	2.30	2.15	1.65	2.63	7.38
S.E.	0.03	0.04	7.58	0.03	0.04	0.10	0.05	0.03	0.03
Low									
LS Mean	3.36	2.98	92.50	2.83	2.55	2.24	1.95	2.77	7.36
S.E.	0.03	0.04	7.63	0.03	0.04	0.10	0.05	0.03	0.03
No									
LS Mean	3.34	2.90	77.72	2.76	2.43	2.61	1.87	2.73	0.74
S.E.	0.03	0.04	7.44	0.03	0.04	0.10	0.05	0.03	0.03
Position									
Anova p =	0.09	0.02	0.02	0.00	< .001	0.001	0.06	0.10	0.07
F =	2.56	4.21	4.03	6.77	26.92	8.40	2.93	2.42	2.84
Inuvik									
LS Mean	3.30	2.90	78.17	2.86	2.64	2.06	1.93	2.71	7.42
S.E.	0.03	0.04	7.77	0.03	0.04	0.10	0.06	0.03	0.03
Central									
LS Mean	3.27	2.84	70.53	2.72	2.40	2.28	1.75	2.66	7.42
S.E.	0.03	0.04	7.44	0.03	0.04	0.20	0.05	0.03	0.03
Aklavik									
LS Mean	3.36	3.00	99.41	2.71	2.24	2.64	1.79	2.76	7.32
S.E.	0.03	0.04	7.44	0.03	0.04	0.10	0.05	0.03	0.03
Closure * Position									
Anova p =	0.09	0.026	0.073	0.403	0.675	0.05	0.404	0.027	0.009
F =	2.109	2.962	2.244	1.021	0.641	2.506	1.02	2.939	3.725
Outliers									
Lake Number	57	21		26, 80	26		56, 79		47
Student. Resid.	2.69	3.25		-2.95, 2.69	-2.66		-2.753, -4.517		2.85

Table A.3. Summary for One Way ANOVA's and TUKEY HSD tests performed on Major Ions for Spring 1993 Under-ice samples, Mackenzie Delta Lake transect.

	One Way ANOVA Results						TUKEY			Outliers	
	Mean High (Standard Errorj)	Mean Low (Standard Errorj)	Mean No (Standard Errorj)	N	p	F	High/No p	High/Low p	Low/No p	Lake No.	Student. Resid.
Log SO4	2.14 (.12)	2.24 (.12)	2.61 (.11)	76	0.01	4.74	0.01	0.81	0.06		
Log Ca	3.23 (.03)	3.35 (.03)	3.33 (.05)	75	0.01	4.69	0.05	0.02	0.89	57	2.65
Log Cl	2.30 (.05)	2.54 (.05)	2.44 (.05)	75	0.01	5.64	0.15	0.00	0.32		
Log Na	2.68 (.03)	2.82 (.03)	2.76 (.03)	75	0.02	3.98	0.25	0.02	0.46	26	-2.81
Log Si	1.64 (.05)	1.94 (.05)	1.88 (.05)	76	0.00	8.44	0.01	0.001	0.69		
Log Cond	2.63 (.03)	2.77 (.03)	2.73 (.04)	71	0.01	4.77	0.10	0.01			
	Mean Aklavik (Standard Error)	Mean Central (Standard Error)	Mean Inuvik (Standard Error)	N	p	F	Akl./Inuv. p	Alk./Cent. p	ent./Inuv. p		
K	98.88 (7.71)	70.47 (7.71)	77.17 (8.02)	76	0.03	3.70	0.13	0.03	0.82	40	2.67
Log SO4	2.64 (.11)	2.28 (.11)	2.06 (.12)	76	0.002	6.82	0.002	0.06	0.38		
Log Cl	2.24 (.04)	2.40 (.04)	2.64 (.04)	75	< .001	20.39	< .001	0.03	0.001		
Log Mg	3.01 (.04)	2.84 (.04)	2.89 (.04)	76	0.03	3.87	0.15	0.02	0.74	21	3.28
Log Na	2.71 (.03)	2.72 (.03)	2.85 (.03)	75	0.01	5.80	0.01	0.99	0.01		

Table A.4 Summer 1993 water chemistry, lake depth, secchi depth and temperature data

Lake No	Cl µM	SO4 µM	K µM	Na µM	Ca µM	Mg µM	Si µM	pH	Cond µS	Depth (m)	Secchi (m)	Temp °C
10	168.4	303.2	27.0	273.5	611.8	327.8	4.2	9.1	195	2.1	2.1	18.1
11	99.6	159.8	25.3	193.6	518.5	318.5	3.1	8.5	170	1.9	1.9	20.6
12	118.3	63.6	6.5	341.7	833.6	592.3	3.7	8.1	310	0.6	0.6	15.6
13	163.4	387.5	24.1	260.0	732.8	346.7	17.4			1.4	1.4	
14	164.5	330.7	26.1	262.8	690.6	345.2	20.1	8.6	227	1.9	1.2	17.3
15	77.2	158.2	14.4	179.5	435.8	269.5	3.7	9.6	145	1.6	1.6	19.8
16	179.1	361.6	49.6	287.0	773.4	417.8	6.9	8.0	278	1.4	1.2	17.2
17	183.4	267.4	17.4	312.4	430.2	473.2	4.5	9.9	183	1.2	1.2	18.8
18	170.6	423.6	37.4	275.7	804.5	353.3	20.6	8.5	284	2.1	1	18.2
19	26.7	325.3	2.0	158.3	432.8	504.2	4.8	9.8	174	2	2	17.1
20	66.1	676.2	24.7	180.2	835.2	597.4	33.2	8.6	333	2	1.3	18.5
21	1307.9	335.4						8.8	340	1.8	0.9	19.4
22	56.4	725.1	20.7	182.9	836.6	605.2	37.4	8.0	323	1.4	0.6	15.3
23	90.5	483.6	35.8	186.7	795.7	466.0	28.2	8.5	294	2.6	1	20.3
24	100.2	593.9	24.8	189.4	823.5	531.3	31.0	8.6	305	1.4	0.8	16.8
25	64.0	497.4	28.9	173.9	774.1	495.4	22.2	7.5	280	2	1.15	22.3
26	50.8	371.7	26.5	145.6	701.4	360.9	17.3	8.2	220	2.2	1.1	16.9
27	22.9	420.6	27.0	165.1	537.8	496.5	3.3	9.7	192	1.6	1.6	17.3
28	109.3	237.5	26.9	192.2	447.5	273.9	3.7	9.4	156	1.4	1.4	18.9
29	63.0	691.6	23.8	190.6	843.4	610.4	44.0	8.4	321	1.8	0.75	20.5
30	653.0	578.6	47.2	591.9	781.3		4.3	9.0	336	0.4	0.4	17.9
31	61.8	592.3	26.9	182.6	825.4	545.4	34.3	8.5	296	1.8	1.8	15.5
32	86.6	147.0	21.4	172.9	548.6	284.3	6.3	8.3	166	1.4	1.4	16.1
33	122.9	373.4	25.0	247.2	480.6	410.5	2.7	9.4	185	1.5	1.5	19.1
34	112.8	281.7	28.9	238.6	507.1	414.1	2.6	9.2	170	1.9	1.2	15.9
35	75.4	175.4	14.8	177.8	418.4	278.0	2.8	9.7	136	1.7	1.7	17.3
36	47.5	339.1	29.3	157.2	561.4	403.5	3.4	9.3		1.8	1.5	17.2
37	196.1	810.8	21.0	336.3	582.3	444.1	5.0	9.9	238	1.6	1.6	20
39	144.6	274.7	20.8	267.1	423.0	304.8	6.5	9.8	166	1.3	1.3	16.5
40	219.5	633.2	34.1	358.5	571.5	522.1	5.9	9.5	243	0.8	0.8	18.4
41	139.5	200.7	11.8	276.4	388.3	294.2	4.7	9.9	148	1.3	1.3	16.1

Table A.4 Cont'd

Lake No	Cl µM	SO4 µM	K µM	Na µM	Ca µM	Mg µM	Si µM	pH	Cond µS	Depth (m)	Secchi (m)	Temp °C
42	188.3	423.7	29.2	281.3	744.9	368.6	31.7	8.7	265	1.7	0.9	20.3
43	194.4	464.5	29.9	290.7	816.6	449.0	19.2			1.8	1	
44	120.2	259.1	19.4	203.0	493.3	343.8	3.2	9.4	162	2.1	2.1	16
45	160.4	499.4	33.6	260.2	828.0	470.1	12.4	8.7	303	2.1	0.8	15.8
64	132.3	224.9	35.9	407.7	455.1	356.3	3.8	9.5	165	1.3	1.3	18.8
67	101.2	124.3	26.2	188.5	493.3	270.0	3.5	8.8	156	2.2	2.1	21.9
68	88.9	273.8	1.9	199.3	421.7	358.6	5.3	9.9	157	1.7	1.7	17.2
69	115.2	189.1	11.6	260.6	412.5	316.0	7.6	9.6	157	1.2	1.2	14.8
70	202.1	208.9	30.2	330.4	415.5	458.9	6.2	9.7	177	1.1	1.1	16.8
72	178.0	420.7	27.6	273.4	766.2	319.8	42.2	8.5	265	2.2	0.5	18
73	32.2	293.1	38.0	166.8	633.1	450.9	17.2	8.7	198	1.7	1.425	18.6
74	54.5	294.8	38.1	179.8	670.3	367.0	3.6	8.4	220	3.2	1.8	19.5
75	49.5	129.0	40.9	170.0	729.9	471.1	10.2	8.6	247	2.1	1.75	17.8
76	47.7	265.7	30.3	148.1	616.4	293.1	2.7	9.3	192	2	2	17.4
77	53.7	88.4	60.9	247.8	603.3	480.5	14.1	8.4	218	2.5	1.65	19.9
78	45.2	296.1	35.3	183.4	515.6	410.5	2.6	9.4	177	1.3	1	17.6
79	23.3	149.3	22.1	128.9	484.2	360.9	8.7	10.0	157	1.7	1.7	17.2
80	48.7	520.5	59.2	251.3	587.9	323.1	21.8	8.6	197	1.6	0.75	17.4
81	21.4	350.5	39.2	149.1	505.5	417.8	2.5	9.6	176	1.1	1.1	16.5

Table A.5. Summary for Descriptive Statistics and Two Way ANOVAs performed on the summer 1993 open water data set, Mackenzie Delta Lake transect.

	Ca	K	Log Mg	Log Na	Log Cl	Sq Rt SO4	Log Si	1/Cond*100	pH	Log Depth	Log Secchi	Temp
N	49	49	48	49	49	50	49	47	48	50	50	48
Mean	615.12	27.75	2.39	2.35	1.96	18.22	0.91	0.49	9.00	0.21	0.09	17.93
Stand. Dev.	153.03	12.03	0.10	0.14	0.30	4.75	0.40	0.13	0.64	0.15	0.17	1.73
Min	388.33	1.92	2.43	2.11	1.33	7.98	0.39	0.74	7.47	-0.40	-0.40	14.80
Max	843.42	60.86	2.79	2.77	2.82	28.48	1.64	0.29	9.96	0.51	0.32	22.30
Skewness	0.15	0.42	0.09	0.69	-0.08	0.09	0.44	-0.00	-0.14	-1.67	-0.79	0.49
Lilliefors	0.03	0.002	0.06	0.23	0.43	1.00	0.01	0.08		0.02	0.20	0.09
Closure												
Anova p =	0.04	0.21	0.11	0.17	0.002	0.03	0.29	0.03	0.05	0.81	0.76	0.63
F =	3.48	1.64	2.36	1.85	6.99	3.98	1.29	3.94	3.17	0.21	0.28	0.48
Hi												
LS Mean	544.03	31.34	2.56	2.34	1.86	15.52	0.84	0.55	9.15	0.23	0.11	17.95
S.E.	38.90	2.86	0.03	0.03	0.04	1.11	0.10	0.03	0.16	0.03	0.04	0.48
Lo												
LS Mean	603.78	26.06	2.59	2.39	2.07	19.43	0.85	0.51	9.22	0.20	0.10	17.57
S.E.	35.86	2.64	0.02	0.03	0.04	1.04	0.10	0.03	0.16	0.03	0.04	0.47
No												
LS Mean	682.53	24.56	2.64	2.33	1.94	19.01	1.04	0.43	8.71	0.23	0.07	18.21
S.E.	35.86	2.64	0.02	0.03	0.04	0.98	0.10	0.03	0.15	0.03	0.04	0.45
Position												
Anova p =	0.21	0.05	0.03	<.001	< .001	0.26	0.26	0.31	0.12	0.10	0.62	0.97
F =	1.66	4.01	4.84	24.30	85.52	1.30	0.41	1.04	2.55	2.80	0.26	0.00
Central												
LS Mean	582.67	24.18	2.57	2.43	2.16	17.30	0.86	0.52	9.17	0.19	0.08	17.90
S.E.	31.23	2.30	0.02	0.02	0.03	0.88	0.16	0.03	0.14	0.03	0.03	0.40
Aklavik												
LS Mean	637.56	30.46	2.63	2.27	1.75	18.68	0.95	0.48	8.88	0.25	0.11	17.92
S.E.	28.99	2.13	0.02	0.02	0.03	0.82	0.13	0.02	0.12	0.03	0.03	0.36
Clos*Pos												
Anova p =	0.59	0.04	0.14	0.57	0.22	0.19	0.15	0.26	0.85	0.86	0.35	1.00
F =	0.53	3.56	2.10	0.57	1.60	4.34	2.01	1.38	0.16	0.16	1.07	0.003
Outliers												
Lake No.				20	27					12	72	
Student. Resid				5.38	=2.72					-3.73	-2.89	

Table A.6 . Summary for One Way ANOVA's and TUKEY HSD tests performed on Summer 1993 open water data set, Mackenzie Delta Lake trasect.

	One Way ANOVA Results						TUKEY			Outliers	
	Mean High (Standard Error)	Mean Low (Standard Error)	Mean No (Standard Error)	N	p	F	High/No p	High/Low p	Low/No p	Lake No.	Student. Resid.
Ca	554.09 (37.94)	603.64 (35.64)	680.49 (35.64)	49	0.06	3.03					
Log Cl	1.81 (.07)	2.07 (.07)	1.95 (.06)	48	0.03	3.78	0.27	0.02	0.44		
Sq. Rt. SO4	15.58 (1.16)	19.43 (1.12)	19.01 (1.06)	49	0.04	3.42	0.09	0.06	0.96	12	-2.69
1/Cond*100	0.54 (.03)	.51 (.03)	0.43 (.03)	46	0.03	3.77	0.03	0.84	0.13		
pH	9.12 (.16)	9.20 (.16)	8.71 (.15)	47	0.06	3.00	0.15	0.93	0.07		
	Mean Aklavik (Standard Error)	Mean Central (Standard Error)	Mean Inuvik (Standard Error)	N	p	F					
Log Cl	1.74 (.04)	2.17 (.04)		48	< .001	69.00					
Log Na	2.27 (0.02)	2.43 (0.02)		49	<.001	24.30					

Table A.7 Spring 1994 Under Ice Data Set: Mackenzie Delta Lake Transect

Lake	Na µM	Mg µM	Ca µM	K µM .	Cl µM	SO4 µM	HCO3 µM	CH4 µM	CO2 µM	DIC µM
1	650.0	426.6	1236.2	28.3	384.6	416.9	2044.2	0.3	79.9	2124.3
2	713.9	588.8	1901.2	41.0	385.6	691.8	2903.5	0.1	213.1	3117.0
4	614.7	588.8	1643.9	62.7	358.3	128.8	3292.8	443.1	460.1	3752.8
5	233.5	524.8	495.8	14.8	170.1	50.1	1604.3	31.0	25.7	1629.7
6	676.4	631.0	1900.9	89.1	353.1	66.1	3892.8	570.3	453.3	4346.8
8	719.6	537.0	1483.8	31.6	427.9	524.8	2393.9	0.5	105.1	2505.0
9	821.0	758.6	1947.6	87.1	458.6	43.7	5109.4	467.4	619.1	5729.0
10	646.6	616.6	2175.1	87.8	361.7	104.7	4330.4	276.2	629.4	4960.4
11	427.8	457.1	1350.6	63.2	171.3	6.8	3487.3	455.4	474.8	3962.7
13	637.6	724.4	2096.6	49.3	305.5	691.8	4157.5	22.0	455.9	4614.5
14	513.1	501.2	1842.2	54.9	251.2	295.1	4458.1	131.8	569.8	5028.2
15	765.3	1122.0	2714.1	99.5	349.8	275.4	5704.2	344.8	906.7	6611.3
16	595.0	660.7	1924.1	75.7	263.1	407.4	3441.2	94.1	353.5	3849.0
17	187.2	660.7	568.6	19.0	81.0	6.5	2790.3	612.6	852.7	4985.8
18	680.9	724.4	2158.6	61.8	316.6	707.9	4415.2	4.2	602.6	6218.9
19	513.3	1230.3	2400.0	69.3	114.3	354.8	4482.6	211.1	701.8	5185.4
20	607.3	1513.6	3484.8	48.8	218.9	1698.2	4385.9	1.0	485.1	4872.0
21	3997.6	2187.8	4643.7	110.4	6857.5	1202.3	4653.1	26.2	923.7	5577.1
22	515.3	1202.3	2858.4	47.1	137.0	1230.3	4028.4	3.9	396.1	4424.9
23	553.7	1174.9	2729.0	54.8	211.5	1174.9	4204.4	0.1	459.6	4777.6
24	656.1	871.0	2462.0	39.1	297.4	1148.2	4505.0	1.3	603.6	5109.4
25	325.6	501.2	1412.2	41.0	90.4	467.7	4580.6	5.9	309.0	2940.9
26	285.9	602.6	1548.4	39.1	85.9	524.8	2550.1	4.0	288.3	2879.4
27	509.3	1174.9	2458.7	104.7	103.5	478.6	4823.3	247.4	859.7	5683.7
28	528.9	794.3	1842.5	93.9	321.3	112.2	4053.6	552.3	801.9	4855.3

Table A.7

Lake	Na µM	Mg µM	Ca µM	K µM .	Cl µM	SO4 µM	HCO3 µM	CH4 µM	CO2 µM	DIC µM
29	555.7	1122.0	2608.6	34.3	249.2	1047.1	3442.9	0.2	266.3	3514.1
31	466.5	1000.0	2478.2	40.0	158.7	977.2	3466.6	0.1	392.6	3872.6
32	345.0	407.4	931.9	52.0	118.9	66.1	2727.8	149.1	294.2	3082.5
33	752.8	1148.2	2572.7	116.8	369.1	338.8	5415.9	322.6	798.3	6215.7
34	561.1	831.8	1934.3	83.6	274.6	53.7	3894.9	593.9	636.6	4419.6
35	487.7	676.1	1565.1	57.5	174.6	138.0	3324.2	287.0	412.7	3736.9
36	458.3	871.0	1911.8	81.1	110.1	407.4	4336.1	171.9	687.8	4981.5
37	767.2	1380.4	3367.2	56.3	689.5	912.0	6219.2	454.1	1139.5	7133.5
38	454.0	549.5	1454.6	37.7	208.7	147.9	3046.4	231.0	437.6	3484.5
39	797.2	758.6	2037.3	81.4	398.0	33.9	4326.0	582.3	806.4	5132.3
41	945.8	1230.3	3094.4	154.5	587.9	17.0	6716.3	1333.7	2029.5	8467.7
42	659.8	1071.5	2939.8	150.6	388.2	871.0	5446.4	220.5	637.1	6084.0
43	1052.3	1000.0	2491.7	71.7	758.7	1698.2	4558.0	32.5	523.7	5082.3
44	659.7	912.0	2008.7	112.8	391.7	53.7	4626.7	466.6	598.4	5028.2
45	1071.2	1737.8	3566.4	91.8	81.5	67.6	7623.7	396.8	1569.3	9194.9
46	1123.7	1445.4	2800.4	73.8	1110.9	1621.8	3735.8	1.9	155.6	3891.3
47	744.1	724.4	1690.8	77.3	391.1	354.8	3768.2	254.4	268.1	4037.3
48	624.3	602.6	1634.6	61.9	371.7	25.7	3990.3	368.6	898.3	4606.3
49	1006.1	1047.1	1983.1	86.5	866.0	22.9	4746.5	307.0	501.7	5249.0
50	370.2	1047.1	2622.3	75.3	478.1	77.6	6518.0	370.9	2094.0	8613.7
51	847.2	758.6	2183.4	54.0	504.5	758.6	3599.6	0.8	358.1	3957.7
52	1061.5	1174.9	2301.7	105.8	607.8	47.9	4389.6	303.5	447.3	4837.2
53	770.4	691.8	2172.7	65.2	426.8	251.2	4411.1	414.1	539.9	4951.9
54	696.0	489.8	1631.2	46.6	424.4	436.5	2909.8	47.3	308.8	3218.3
55	1006.1	933.3	2458.0	111.8	674.8	89.1	4741.0	1053.7	713.2	5455.3
56	459.0	457.1	1343.8	38.4	192.5	53.7	3071.5	299.6	269.0	3340.8

Table A.7

Lake	Na µM	Mg µM	Ca µM	K µM .	Cl µM	SO4 µM	HCO3 µM	CH4 µM	CO2 µM	DIC µM
57	366.8	416.9	1368.4	75.8	183.0	7.9	2740.6	1213.1	895.4	4334.9
58	474.5	512.9	1566.7	79.0	247.3	5.6	3684.5	918.1	822.7	4394.4
59	704.7	933.3	2443.5	70.0	460.1	147.9	4422.0	384.9	781.5	5204.2
60	827.8	1174.9	2750.0	102.6	466.4	17.0	5693.0	659.5	1298.4	6992.3
61	1001.0	1047.1	2158.6	76.8	549.7	43.7	4909.4	654.8	616.6	5526.4
62	929.2	955.0	2093.7	96.0	496.9	66.1	4709.0	486.2	614.9	5324.6
63	724.2	724.4	2155.4	78.2	438.5	38.0	4137.2	794.1	738.4	5227.3
64	594.9	758.6	2052.0	112.1	320.7	16.6	4911.5	687.5	872.9	5785.1
65	292.3	398.1	1286.7	43.5	122.1	67.6	2822.6	196.6	365.8	3259.3
66	351.7	436.5	1276.6	36.8	142.0	251.2	2426.3	0.1	173.4	2566.4
67	379.2	398.1	1033.2	49.7	176.4	93.3	2388.4	186.3	282.8	2670.8
68	823.8	1202.3	2967.3	98.6	461.6	46.8	5992.0	515.7	923.4	6915.6
69	686.9	831.8	1903.4	85.0	289.7	16.2	3977.2	777.3	780.0	4758.2
70	925.4	1258.9	2389.3	126.7	489.0	13.5	5332.2	1081.1	1659.7	6992.3
71	479.7	575.4	1293.2	37.8	203.0	166.0	2968.7	173.7	571.4	3367.5
72	828.3	1000.0	2867.3	44.6	503.7	1096.5	4005.0	17.6	329.3	4334.9
73	313.8	549.5	1239.9	76.6	66.4	107.2	3332.2	249.0	1114.2	5479.0
74	314.4	524.8	1292.5	60.2	73.6	166.0	2685.7	210.8	630.5	3517.7
75	290.3	537.0	1225.1	76.8	72.3	66.1	3240.7	210.8	501.8	3648.2
76	288.8	478.6	1603.4	74.2	105.5	295.1	2815.4	190.7	785.1	3566.5
77	416.5	602.6	1034.9	91.1	73.6	10.0	3275.8	710.2	1054.3	4312.5
78	426.7	724.4	1565.2	89.2	102.1	125.9	4044.2	352.3	974.2	4503.8
79	296.8	741.3	1499.2	89.4	86.1	51.3	3855.8	407.6	843.8	4700.5
80	631.8	891.3	1736.4	106.5	144.6	1174.9	2349.6	1.5	528.6	2878.3
81	287.2	758.6	1833.3	100.0	86.6	67.6	3941.8	448.6	831.2	4756.9

Table A.7

Lake	Si µM	NH4 µM	PO4 µM	pH	Cond µS	Sediment C mg/g	Sediment N mg/g	Sediment PO4 mg/g	Sedimentation Rate cm/yr
1	66.1	0.59	0.23	7.3	328.1	31.3	1.0	1.8	1.03
2	112.2	2.22	0.16	7.4	470.4	22.2	1.7	2.3	0.18
4	46.8	18.49	0.05	7.1	398.4	43.5	3.2	2.0	0.45
5	30.2	5.52	0.01	7.4	151.4	31.3	2.3	2.4	0.32
6	53.7	41.99	0.10	7.4	471.2	47.6	3.4	1.8	0.18
8	79.4	1.28	0.44	7.2	399.4	24.4	1.3	2.4	0.32
9	97.7	56.70	0.35	7.0	554.2	52.6	3.7	2.2	0.18
10	93.3	18.15	0.05	6.7	507.4	33.3	2.2	1.9	0.18
11	40.7	21.53	0.14	6.8	335.3	33.3	1.7	2.4	0.58
13	61.7	9.80	0.13	6.2	528.4	30.3	1.1	2.4	0.83
14	66.1	11.09	0.09	6.3	412.7	34.5	1.9	2.9	0.32
15	75.9	23.62	0.19	6.8	321.8	66.7	0.7	2.6	0.77
16	58.9	13.10	0.01	6.8	472.6	45.5	2.2	2.1	0.18
17	18.6	9.86	0.02	6.4	166.6				0.32
18	102.3	10.69	0.19	6.7	528.9	26.3	1.6	3.0	
19	49.0	14.52	0.17	7.1	554.8				0.7
20	67.6	0.00	0.02	7.0	769.2				0.83
21	107.2	5.24	0.72	7.0	1213.8				0.03
22	53.7	5.02	0.11	6.9	648.4				0.58
23	53.7	0.00	0.11	7.0	617.8				0.45
24	102.3	1.00	0.09	7.1	674.2				0.32
25	38.0	0.00	0.05	7.3	357.7				
26	32.4	0.00	0.06	7.3	363.6				0.45
27	70.8	32.26	0.24	7.1	609.5				0.05
28	56.2	33.18	0.08	6.9	495.4				0.55

Table A.7

Lake	Si µM	NH4 µM	PO4 µM	pH	Cond µS	Sediment C mg/g	Sediment N mg/g	Sediment PO4 mg/g	Sedimentation Rate cm/yr
29	74.1	0.00	0.10	7.1	578.7				0.25
31	72.4	0.00	0.14	6.9	563.4				0.45
32	24.0	8.76	0.16	6.7	248.1				0.25
33	91.2	35.05	0.13	7.0	653.4				0.25
34	79.4	39.31	1.00	7.2	450.6				0.05
35	26.3	4.80	1.00	7.0	390.1				0.55
36	49.0	30.03	0.21	7.1	480.1				
37	114.8	51.12	0.06	7.1	965.0	34.5	1.1	2.0	0.65
38	34.7	27.25	0.37	7.1	366.2	32.3	0.9	2.5	0.65
39	79.4	53.88	0.21	7.0	493.4	40.0	2.9		0.45
41	112.2	52.71	0.03	6.9	745.2	37.0	1.1	2.4	0.45
42	131.8	42.25	0.02	7.1	898.6	32.3	1.0	2.5	0.35
43	158.5	41.34	0.02	7.1	672.7	30.3	2.6	3.2	0.25
44	72.4	75.52	1.00	7.4	467.6	43.5	3.1	2.8	0.05
45	109.6	52.27	0.06	7.0	971.3	32.3	1.0	1.8	
46	190.5	2.31	0.02	7.4	780.3	25.0	1.7	2.3	
47	58.9	27.04	0.12	7.5	445.5	66.7	5.0	2.3	0
48	91.2	51.41	0.20	7.1	415.4	38.5	2.1	2.4	0.25
49	158.5	82.26	1.00	6.8	618.7	47.6	3.2	1.9	0.45
50	50.1	63.68	0.29	7.0	870.9	40.0	2.3	2.2	0.83
51	128.8	12.60	0.03	7.4	596.8	26.3	2.3	2.4	0.15
52	97.7	121.00	0.08	7.3	633.1	43.5	1.7	2.1	0.45
53	162.2	60.53	0.58	7.1	529.3	40.0	3.2	2.3	
54	97.7	10.63	0.06	7.2	420.7	35.7	2.9	2.4	0.15
55	46.8	7.67	0.42	7.0	632.0	125.0	6.5	1.8	0.05
56	24.5	12.39	0.05	7.1	373.3	62.5	3.6	2.0	0.42

Table A.7

Lake	Si µM	NH4 µM	PO4 µM	pH	Cond µS	Sediment C mg/g	Sediment N mg/g	Sediment PO4 mg/g	Sedimentation Rate cm/yr
57	95.5	83.72	0.03	7.1	283.6	37.0	1.9	2.5	0.32
58	70.8	87.05	0.02	7.0	392.0	40.0	2.4	2.2	0.05
59	44.7	38.44	0.04	6.8	542.7	37.0	1.3	2.2	0.05
60	117.5	17.81	0.03	6.8	642.6	71.4	4.6	1.5	
61	69.2	49.56	0.05	7.0	547.5	125.0	9.3	1.8	0.25
62	91.2	31.81	0.05	7.1	569.3	66.7	3.6	2.1	0.05
63	83.2	103.84	0.62	7.0	444.5	43.5	3.4	2.6	0.25
64	63.1	71.23	0.09	6.9	533.9	45.5	3.5	2.7	0.32
65	43.7	28.52	0.44	7.1	294.2	34.5	3.0	2.7	
66	43.7	1.51	1.00	7.1	280.1	31.3	1.6	2.5	0.38
67	19.1	20.16	0.03	7.1	266.1	41.7	3.0	2.5	0.25
68	75.9	61.47	0.08	6.9	681.5	37.0	1.5	2.4	0.48
69	79.4	15.21	0.04	6.7	481.4	76.9	5.6	2.3	0.18
70	70.8	13.32	0.04	6.6	631.9	45.5	2.3	2.4	0.25
71	25.7	15.60	0.08	6.8	341.8	37.0	1.3	2.3	0.48
72	89.1	2.43	0.04	6.8	663.9	29.4	1.4	2.2	0.25
73	41.7	17.56	0.49	6.5	320.5				0.25
74	46.8	32.83	3.16	6.6	669.5				0.32
75	28.2	3.46	0.11	6.8	333.4				0.18
76	134.9	25.10	2.45	7.0	402.6				0.42
77	109.6	90.44	1.51	6.7	340.0				
78	53.7	44.89	1.05	7.2	382.4				0.25
79	52.5	30.80	0.17	7.0	385.4				0.05
80	30.2	1.12	1.00	7.0	446.6				0.42
81	63.1	33.18	3.55	6.7	447.1				0.32

Table A.7

Lake	Lake Area (km^2)	Ice Thickness (cm)	White Ice (cm)	Snow Depth (cm)	Total Depth (cm)
1	8.13	92	25	11	180
2	0.55	73	18	18	210
4	0.04	70	14	17	120
5	0.18	73	23	12	90
6	0.07	70	19	12	105
8	0.46	84	17	20	140
9	0.17	82	6	15	100
10	0.64	83	20	23	145
11	0.02	64	21	30	180
13	0.54	84	15	20	160
14	0.77	80	14	23	135
15	0.11	74	18	26	140
16	0.03	70	16	32	230
17	0.07		16	29	135
18	0.36	79	12	26	130
19	0.13	75	5	25	155
20	1.10	91	18	28	145
21	1.00	86	18	22	130
22	0.05	71	14	22	120
23	0.52	80	6	23	210
24	1.31	93	9	26	135
25	0.04	72	9	21	460
26	0.42	78	14	18	280
27	0.36	82	12	12	145
28	1.30	91	8	21	160

Table A.7

Lake	Lake Area (km^2)	Ice Thickness (cm)	White Ice (cm)	Snow Depth (cm)	Total Depth (cm)
29	0.36	82	5	25	190
31	0.15	68	6	25	180
32	0.16	72	10	27	190
33	0.67	73	12	25	130
34	0.13	72	7	25	150
35	0.23	80	13	28	200
36	0.17	80	10	17	120
37	0.34	74	29	22	85
38	0.03	69	18	18	170
39	0.21	76	11	22	110
41	0.18	79	15	25	140
42	0.36	70	15	29	90
43	0.02	75	19	29	135
44	0.10	63	15	24	190
45	0.06	76	13	29	90
46	0.48	80	30	15	115
47	0.34	77	23	10	150
48	0.01	69	18	13	80
49	0.35	65		15	80
50	0.04	63	18	19	85
51	1.40	93	35	16	164
52	0.04	74	13	21	70
53	0.11	72	24	15	150
54	0.07	71	11	23	200
55	0.03	59	30	6	105
56	0.06	72	29	8	101

Table A.7

Lake	Lake Area (km^2)	Ice Thickness (cm)	White Ice (cm)	Snow Depth (cm)	Total Depth (cm)
57	0.05	65	25	14	270
58	0.07	68	20	4	220
59	0.07	65	18	14	160
60	0.03	62		14	75
61	0.06	75	17	13	135
62	0.02	71	19	8	125
63	0.05	70	23	13	260
64	0.14	74	15	25	190
65	0.21	84	15	24	340
66	0.10	77	14	25	350
67	0.23	73	19	14	180
68	0.01	63		32	65
69	0.16	76	18	24	110
70	0.44	63	21	33	105
71	0.03	89	16	20	255
72	0.09	85	15	22	95
73	0.02	80	10	8	140
74	0.02	81	20	14	410
75	0.03	67	9	23	240
76	1.20	79	8	17	225
77	0.03	63	10	22	280
78	0.06	78	7	11	110
79	0.02	82	10	7	160
80	0.15	82	13	19	155
81	0.06	86	14	18	120

Table A.8 Summary for descriptive statistics and Two-Way ANOVAs performed on major solutes for Spring 1994 under-ice samples, Mackenzie Delta Lake transect.

	Sq Rt Ca	Log Mg	K	Na	Sq Rt Cl	Log SO4	Sq Rt HCO3	Log Si	Sq Rt NH4	Log PO4	Sq Rt Cond	pH
N	75	76	76	75	75	76	76	76	76	76	75	76
Mean	43.95	2.89	72.49	610.36	16.83	2.15	62.61	1.82	4.66	-0.93	22.10	6.98
Stand. Dev	7.55	0.17	28.69	230.19	5.64	0.67	9.01	0.23	2.77	0.58	3.83	0.25
Min	22.28	2.60	14.77	187.22	8.15	0.75	40.05	1.27	0.00	-2.00	12.30	6.22
Max	59.72	3.34	154.52	1123.70	33.33	3.23	87.31	2.29	11.00	0.55	31.17	7.47
Skewness	-0.31	0.21	0.44	0.29	0.35	-0.21	0.14	-0.37	0.10	0.58	0.06	-0.64
Lilliesfor Val.	0.83	0.41	0.64	0.69	0.36	0.24	0.72	0.63	0.88	0.21	0.85	0.06
Closure												
Anova p=	0.03	0.03	0.02	0.01	0.001	0.001	0.03	0.03	<.001	0.62	0.005	0.005
F=	0.46	0.46	4.26	4.92	8.15	7.20	3.83	3.70	9.34	0.48		
Hi												
LS Mean	41.85	2.84	78.78	560.05	15.37	1.80	61.06	1.76	5 33	-0.85	21.14	6.91
S.E.	1.31	0.03	5.34	36.92	0.76	0.12	1.57	0.04	0.45	0.11	0.66	0.04
Lo												
LS Mean	46.84	2.95	78.77	708.41	19.42	2.26	66.19	1.91	5.61	-0.95	23.98	7.08
S.E.	1.36	0.03	5.56	38.43	0.79	0.12	1.63	0.04	0.47	0.11	0.69	0.04
No												
LS Mean	43.10	2.87	58.72	561.74	15.67	2.41	60.32	1.79	2.96	-0.95	21.12	6.98
S.E.	1.42	0.03	5.69	40.08	0.83	0.12	1.67	0.04	0.48	0.11	0.72	0.04
Position												
Anova p=	0.46	0.34	0.56	<.001	<.001	0.02	0.05	0.13	0.01	0.00	0.85	<.001
F=	0.79	1.08	0.57	12.28	30.56	4.11	3.08	2.11	5.15	3.03		
Inuvik												
LS Mean	42.95	2.87	67.81	719.67	20.77	1.99	61.18	1.88	5.39	-1.00	21.91	7.14
S.E.	1.37	0.03	5.59	38.64	0.80	0.12	1.64	0.04	0.47	0.11	0.69	0.04
Central												
LS Mean	45.28	2.95	76.34	651.40	17.62	2.06	65.80	1.82	5.08	-1.07	22.40	6.86
S.E.	1.36	0.03	5.56	38.43	0.79	0.12	1.63	0.04	0.47	0.11	0.69	0.04
Aklavik												
LS Mean	43.56	2.84	72.11	459.40	12.08	2.43	60.59	1.76	3.43	-0.72	21.93	6.97
S.E.	1.36	0.03	5.45	38.43	0.79	0.12	1.60	0.04	0.46	0.11	0.69	0.04
Clos*Pos												
Anova p=	0.004	0.01	0.27	0.36	0.63	0.38	0.02	0.21	0.16	0.04	0.01	<.001
F=	4.23	3.84	1.32	1.11	0.66	1.06	3.05	1.50	1.71	2.62		
Outliers												
Lake No.	5, 17				45, 46						21	
Student. Resid.	-2.66, -3.08				-3.19, 2.7							

Table A.9. Summary for One Way ANOVA's and TUKEY HSD tests performed on major ions for spring 1994 under-ice samples, Mackenzie Delta Lake transect.

	One Way ANOVA Results						TUKEY			Outliers	
	Mean High (Standard Error)	Mean Low (Standard Error)	Mean No (Standard Error)	N	p	F	High/No p	High/Low p	Low/No p	Lake No.	Student. Resid.
Na	560.05 (42.62)	712.27 (44.25)	558.65 (46.10)	75	0.02	3.97	1.00	0.04	0.05		
Log Mg	2.84 (.03)	2.95 (.03)	2.88 (.03)	76	0.06	2.95	0.65	0.05	0.31	21	3.03
Sq. Rt. Ca	41.85 (1.41)	46.79 (1.47)	43.31 (1.53)	75	0.05	3.06	0.77	0.05	0.24	5, 17	-3.1, -2.84
K	78.78 (5.35)	78.49 (5.56)	59.18 (5.67)	76	0.02	4.03	0.04	1.00	0.05	41, 42	2.93, 2.77
Sq. Rt. NH4	5.33 (.48)	5.64 (.50)	2.89 (.51)	76	<.001	8.789	0.003	0.90	0.001		
Sq. Rt. Cl	15.37 (1.03)	19.59 (1.07)	15.53 (1.12)	75	0.01	4.99	0.99	0.02	0.03	46	2.73
Log SO4	1.80 (.12)	2.26 (.12)	2.44 (.13)	76	0.002	7.11	0.002	0.03	0.59	11, 17	-2.75, -2.79
Sq. Rt. HCO3	61.06 (1.69)	66.13 (1.75)	60.69 (1.79)	76	0.06	3.01	0.99	0.10	0.08		
Log Si	1.78 (.04)	1.92 (.04)	1.78 (.04)	76	0.03	3.83	0.98	0.03	0.10		
pH	6.91 (.05)	7.08 (.05)	6.97 (.05)	76	0.03	3.55	0.64	0.03	0.23		
Sq. Rt. Cond.	21.14 (.70)	23.98 (.73)	21.53 (.75)	76	0.02	4.51	0.92	0.02	0.06		

	Mean Aklavik (Standard Error)	Mean Central (Standard Error)	Mean Inuvik (Standard Error)	N	p	F	Akl./Inuv. p	Alk./Cent. p	Cent./Inuv. p		
Na	455.54 (40.46)	648.91 (40.46)	726.63 (40.46)	75	<.001	11.90	<.001	0.003	0.37		
Sq. Rt. NH4	3.42 (.52)	5.06 (.53)	5.55 (.53)	76	0.01	4.54	0.02	0.08	0.79		
Sq. Rt. Cl	11.98 (.86)	17.58 (.86)	20.92 (.86)	75	<.001	27.62	<.001	<.001	0.02	46	3.12
Log SO4	2.43 (.13)	2.05 (.13)	1.97 (.13)	76	0.03	3.79	0.03	0.09	0.91		
Log PO4	-.71 (.11)	-1.07 (.11)	-1.01 (.11)	76	0.06	3.03	0.14	0.06	0.92		
pH	6.97 (.04)	6.86 (.05)	7.13 (.05)	76	<.001	8.66	0.04	0.230	<.001		

Table A.10 Summary for descriptive statistics and Two-Way ANOVAs performed on gases for Spring 1994 under-ice samples, Mackenzie Delta Lakes.

	Sq Rt CH4	Sq Rt CO2	Sq Rt DIC
N	76	76	76
Mean	15.00	24.41	67.69
Stand. Dev	9.80	7.40	10.91
Min	0.30	5.07	40.37
Max	36.50	45.76	95.89
Skewness	-0.05	0.32	0.17
Lilliesfor Val.	0.02	0.12	0.36
Closure			
Anova p=	<,001	0.01	0.10
F=		4.74	2.37
High			
LS Mean	19.92	26.51	67.10
S.E.	1.62	1.29	1.82
Lo			
LS Mean	15.57	25.28	70.70
S.E.	1.69	1.35	1.90
No			
LS Mean	9.70	20.92	64.84
S.E.	1.73	1.38	1.95
Position			
Anova p =	0.05	0.06	0.04
F=	3.24	2.89	0.01
Inuvik			
LS Mean	17.14	21.75	65.40
S.E.	1.70	1.35	1.91
Central			
LS Mean	16.93	26.27	70.13
S.E.	1.69	1.35	1.81
Aklavik			
LS Mean	11.60	24.69	65.69
S.E.	1.65	1.32	1.87
Clos*Pos			
Anova p=	0.07	0.04	0.02
F=	2.29	2.77	3.33
Outliers			
Lake No.		50, 70	50
Student. Resid.		3.95, 1.70	2.82

Table A.11 . Summary for One Way ANOVA's and TUKEY HSD tests performed on gases for spring 1994 under-ice samples, Mackenzie Delta Lake transect.

	One Way ANOVA Results						TUKEY			Outliers	
	Mean High (Standard Error)	Mean Low (Standard Error)	Mean No Standard Error)	N	p	F	High/No p	High/Low p	Low/No p	Lake No.	Student. Resid.
Sq. Rt. CH4	19.92 (1.72)	15.47 (1.79)	9.47 (1.83)	76	<.001	8.67	<.001	0.18	0.06		
Sq. Rt. CO2	26.51 (1.38)	25.19 (1.44)	21.25 (1.46)	76	.03	3.66	0.03	0.79	0.14	41, 50	2.99, 3.11
	Mean Aklavik (Standard Error)	Mean Central (Standard Error)	Mean Inuvik Standard Error)	N	p	F	Akl./Inuv. p	Alk./Cent. p	Cent./Inuv. p		
Sq. Rt. CH4	11.53 (1.88)	16.94 (1.92)	17.14 (1.92)	76	0.07	2.83	0.10	0.12	1.00		

Table A.12 Summary for descriptive statistics and Two-Way ANOVAs performed on physical measurements for Spring 1994 under-ice samples, Mackenzie Delta Lake transect.

	Ice Thick cm	Log Area km squ'd	1/Log Depth (m)	Snow Dep cm	White Ice cm
N	75	76	76	76	73
Mean	75.45	-912.00	0.46	19.75	15.78
Stand. Dev	8.07	0.56	0.04	6.81	6.41
Min	59.00	-2.00	0.55	4.00	5.00
Max	94.00	0.15	0.38	33.00	35.00
Skewness	0.22	0.11	0.02	-0.23	0.61
Lilliesfor Val.	0.57	0.09	0.76	0.04	0.14
Closure					
Anova p =	0.09	0.002	0.10	<.001	0.51
F=	2.51	6.96	2.44	9.37	0.69
Hi					
LS Mean	73.67	-1.21	0.46	16.74	16.82
S.E.	1.46	0.10	0.01	0.87	0.99
Lo					
LS Mean	74.59	-0.81	0.48	21.74	15.75
S.E.	1.52	0.10	0.01	0.90	1.01
No					
LS Mean	78.30	-0.61	0.46	21.01	15.20
S.E.	1.59	0.11	0.01	0.92	1.01
Position					
Anova p=	0.04	0.28	0.02	<.001	<.001
F=	3.53	1.29	4.34	38.33	25.25
Inuvik					
LS Mean	72.98	-1.01	0.48	13.93	20.52
S.E.	1.53	0.11	0.01	0.91	1.03
Central					
LS Mean	75.01	-0.92	0.47	25.07	16.67
S.E.	1.56	0.10	0.01	0.90	1.01
Aklavik					
LS Mean	78.57	-0.78	0.45	20.49	10.59
S.E.	1.49	0.10	0.01	0.88	0.97
Clos*Pos					
Anova p=	0.30	0.30	0.89	0.13	0.31
F=	1.25	1.24	0.23	1.87	1.23
Outliers					
Lake No.	51	76	88		37, 51
Student. Resid.	2.83	2.96	2.89		-2.76, -3.11

Table A13. Summary for One Way ANOVAs and TUKEY HSD tests performed on physical measurements for spring 1994 under-ice samples, Mackenzie Delta Lake transect.

	One Way ANOVA Results						TUKEY			Outliers	
	Mean High (Standard Error)	Mean Low (Standard Error)	Mean No (Standard Error)	N	p	F	High/No p	High/Low p	Low/No p	Lake No.	Student. Resid.
Log Area	-1.21 (.10)	-.81 (.10)	-.68 (.11)	75	0.001	7.16	0.002	0.02	0.66		
1/Log Depth	.45 (.01)	.48 (.01)	.45 (.01)	76	0.09	2.55	0.94	0.09	0.20	68	2.79
Snow Depth	16.74 (1.25)	21.52 (1.30)	21.29 (1.25)	76	0.02	4.48	0.04	0.03	0.99	70	2.65
Total Ice Thick	73.67 (1.52)	74.56 (1.58)	78.52 (1.65)	75	0.08	2.58	0.09	0.91	0.20		
	Mean Aklavik (Standard Error)	Mean Central (Standard Error)	Mean Inuvik (Standard Error)	N	p	F	Akl./Inuv. p	Alk./Cent. p	Cent./Inuv. p		
1/Log Depth	.45 (.01)	.47 (.01)	.48 (.01)	76	0.02	4.42	0.01	0.12	0.66		
Snow Depth	20.35 (1.00)	25.04 (1.02)	13.84 (1.02)	76	<.001	30.49	<.001	0.004	<.001		
White Ice	10.65 (.97)	16.67 (1.01)	20.65 (1.03)	73	<.001	25.57	<.001	<.001	0.02	9, 37, 51	-3.23, 2.66, 3.15
Total Ice Thick	78.62 (1.53)	75.00 (1.59)	72.60 (1.56)	75	0.03	3.87	0.02	0.24	0.53	1, 51	2.65, 2.80

Table A.14 Summary for descriptive statistics and Two-Way ANOVAs performed on sediment data for Spring 1994 under-ice samples, Mackenzie Delta Lake transect.

	1/Sed C	Log S N	Log S PO4	Sed Rate
N	49	49	48	67
Mean	0.03	0.34	0.36	0.34
Stand. Dev	0.01	0.24	0.06	0.22
Min	0.01	-0.15	0.18	0
Max	0.05	0.97	0.50	1.03
Skewness	-0.11	0.21	-0.28	0.80
Lilliesfor Val.	0.48	0.65	0.56	0.00
Closure				
Anova p=	0.01	0.03	0.78	0.06
F=	4.83	3.78	0.25	3.03
Hi				
LS Mean	0.02	0.45	0.35	0.26
S.E.	0.002	0.05	0.02	0.05
Lo				
LS Mean	0.03	0.29	0.37	0.36
S.E.	0.002	0.05	0.02	0.05
No				
LS Mean	0.03	0.26	0.36	0.42
S.E.	0.002	0.06	0.02	0.05
Position				
Anova p=	0.27	0.004	0.003	0.34
F=	1.28	9.18	0.69	1.11
Inuvik				
LS Mean	0.03	0.43	0.33	0.30
S.E.	0.002	0.04	0.01	0.05
Central				
LS Mean	0.03	0.24	0.39	0.40
S.E.	0.002	0.04	0.01	0.05
Aklavik				
LS Mean				0.35
S.E.				0.05
Clos*Pos				
Anova p=	0.18	0.86	0.62	0.98
F=	1.18	0.15	0.48	0.10
Outliers				
Lake No.				1
Student. Resid.				3.44

Table A.15. Summary for One Way ANOV's and TUKEY HSD tests performed on sediment data for spring 1994, Mackenzie Delta Lake transect.

	One Way ANOVA Results						TUKEY			Outliers	
	Mean High (Standard Error)	Mean Low (Standard Error)	Mean No (Standard Error)	N	p	F	High/No p	High/Low p	Low/No p	Lake No.	Student. Resid.
1/Sed C	.02 (.002)	.03 (.002)	.03 (.002)	49	0.02	4.57	0.02	0.06	0.83		
Sed Rate	.26 (.04)	.36 (.05)	.42 (.05)	67	0.05	3.21	0.04	0.30	0.60	1	3.07
Log Sed N	.45 (.05)	.31 (.06)	.26 (.06)	49	0.05						

	Mean Central (Standard Error)	Mean Inuvik (Standard Error)	N	p	F
Log Sed N	.24 (.05)	.43 (.04)	49	0.005	8.62
Log Sed PO4	1.11 (.01)	1.05 (.01)	48	0.002	10.69

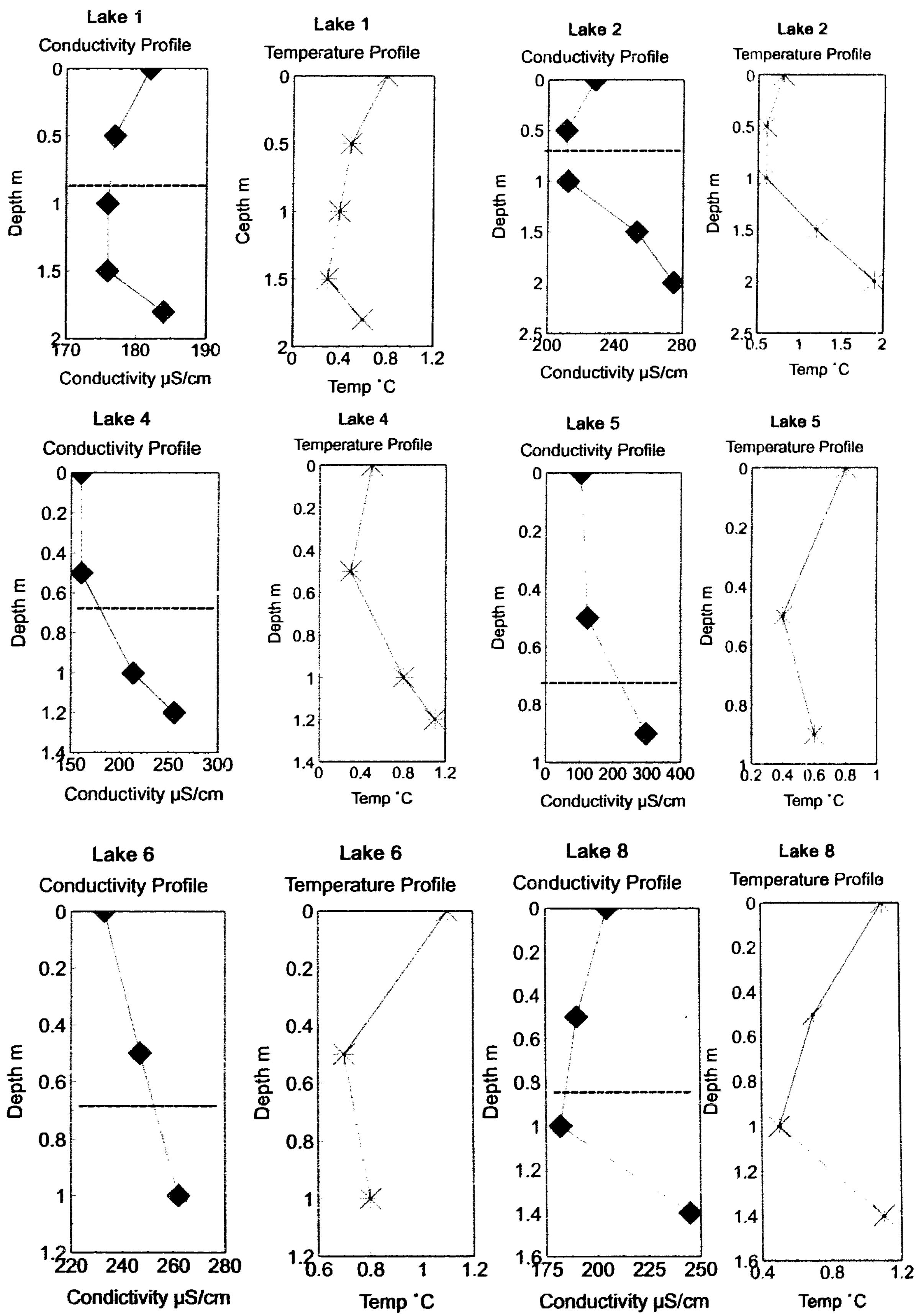
Table A16. Summary for One Way ANOVAs, Two Way ANOVAs and TUKEY HSD tests performed on (1) Spring 1994, (2) Spring 1993, and (3) Summer 1993 data sets

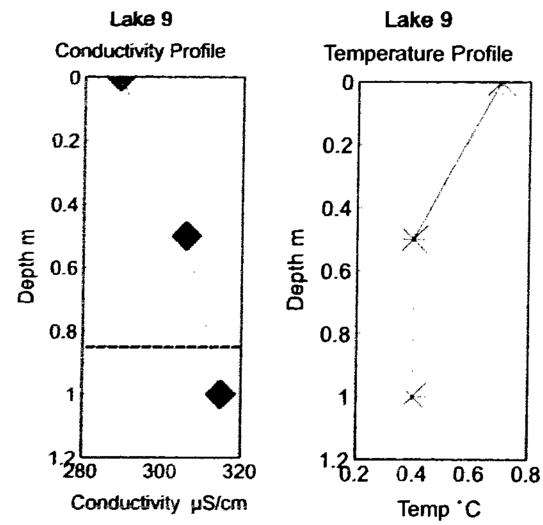
	1/Log Ca	1/Log Mg	K	1/Log Na	log SO4	Log Cl	SqRt HCO3	Log Si	pH	Log Cond
Data Sets	1, 2	1, 2	1, 2	1, 2	1, 2, 3	1, 2, 3	1, 2	1, 2	1, 2, 3	1, 2, 3
Anova p =	0.21	0.57	0.09	0.81	0.005	<.001	<.001	0.99	<.001	<.001
F =	1.56	0.33	2.94	0.06	5.46	44.57	24.32	<.001	466.25	44.57
N =	150	0.152	152	150	202	199	152	152	196	199
Spring 1094 mean	0.31	0.35	72.49	0.37	2.15	2.40	62.61	1.82	6.98	2.40
S.E.	0.002	0.003	4.05	0.003	0.07	0.03	1.69	0.03	0.04	0.03
N	75	76	76	75	76	75	76	76	76	75
Spring 1993 mean	0.30	0.35	82.30	0.36	2.34	2.42	74.41	1.82	7.38	2.42
S.E.	0.002	0.003	4.05	0.003	0.07	0.03	1.69	0.03	0.04	0.03
N	75	76	76	75	76	75	76	76	72	75
Summer 1993 mean					2.49	1.96			9.00	1.96
S.E.					0.08	0.04			0.05	0.04
N					50	49			48	49
Data Sets					1, 3	1, 3			1, 2	1, 3
Tukey p =					0.003	<.001			<.001	<.001
Data Sets						2,3			1, 3	2. 3
Tukey p =						<.001			<.001	<.001
Data Sets									2, 3	
Tukey p =									<.001	
Outliers										
Data Set/Lake No.	1/5	2/21	2/21	1/17		3/30	2/21	2/57	3/16	3/30
Student. Residual	4.55	-3.19	2.83	3.26		3.03	7.29	-2.65	-2.93	3.03
Data Set/Lake No.	1/17	2/66	2.48	2/26			2/48	2/80	3/22	
Student. Residual	3.92	3.18	2.63	2.89			2.84	-4.83	-2.73	
Data Set/Lake No.							2/50		3/25	
Student. Residual							2.69		-4.39	
Data Set/Lake No.									3/37	
Student. Residual									2.61	
Data Set/Lake No.									3/68	
Student. Residual									2.6	
Data Set/Lake No.									3/79	
Student. Residual									2.69	

Appendix B - Temperature and Conductivity Profiles

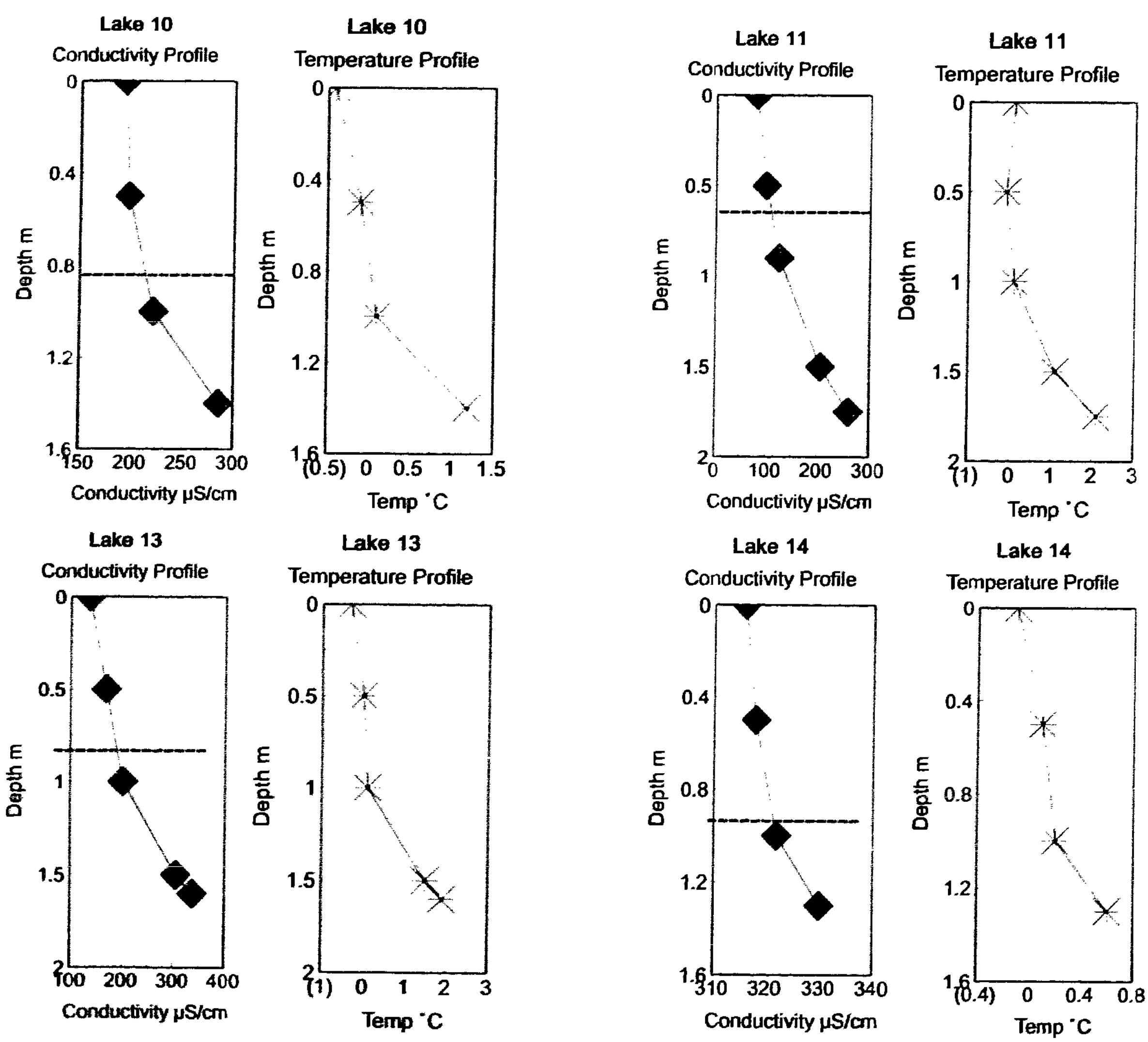
This section includes temperature and conductivity profiles for each of the sampled lakes. They are presented sequentially and are subtitled reflecting their position on the delta and their closure status. Plotted on each of the conductivity profiles is a dashed line that indicates the location of the ice/water interface at the time of sampling.

Inuvik No-Closure Lakes

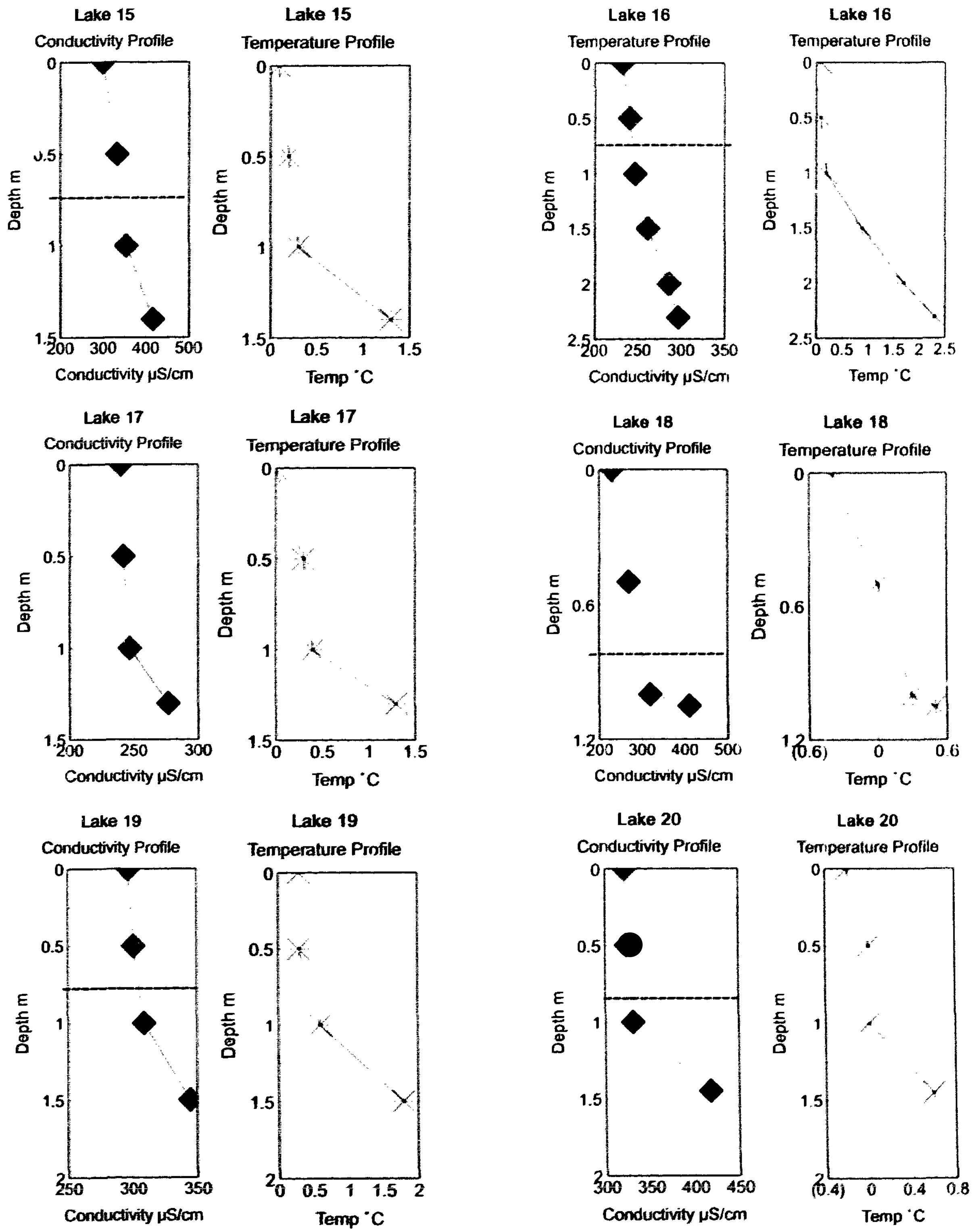




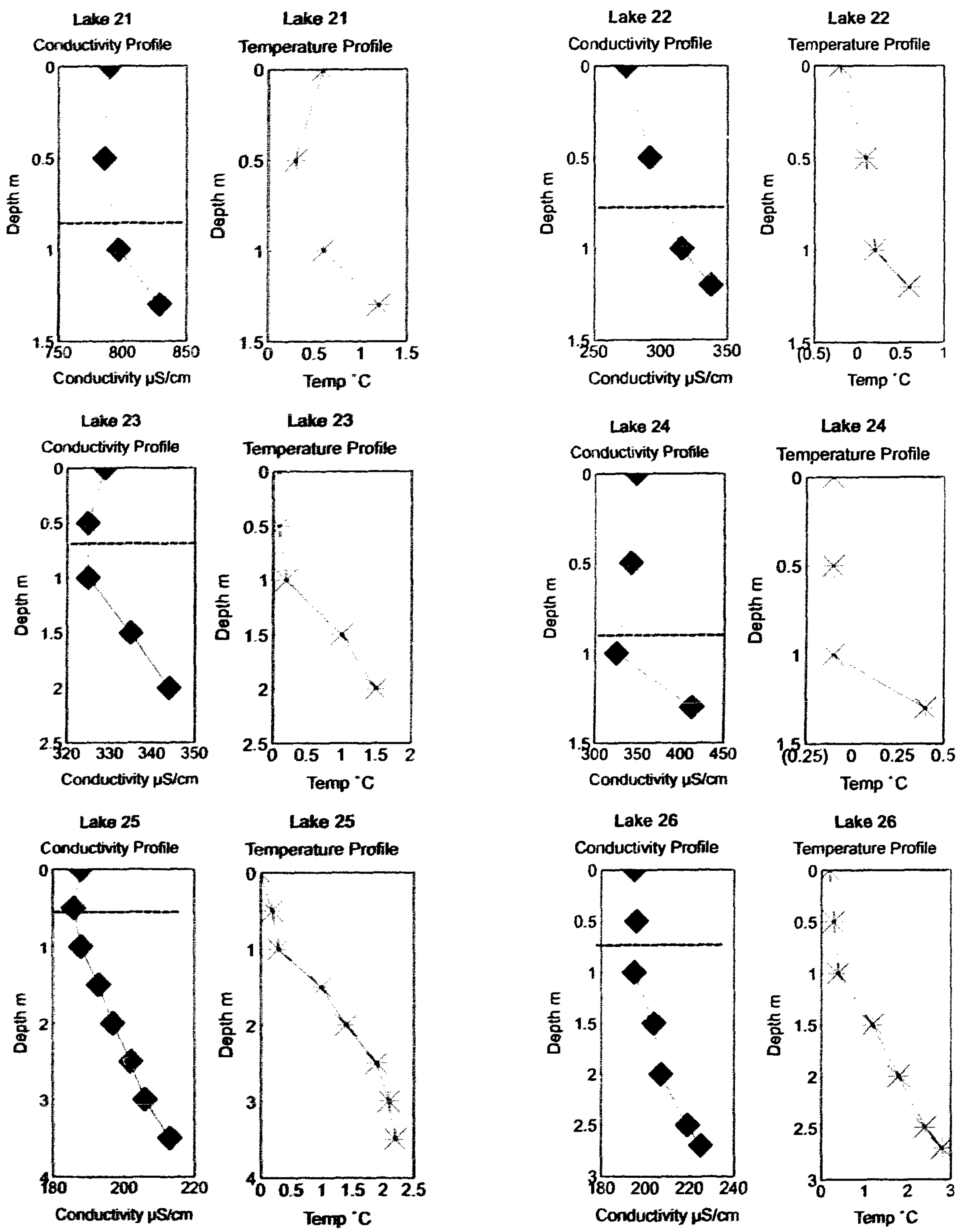
Central No-Closure Lakes

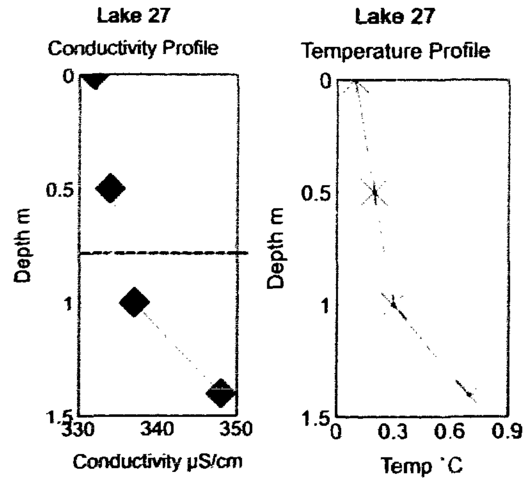


Central No-Closure Lakes

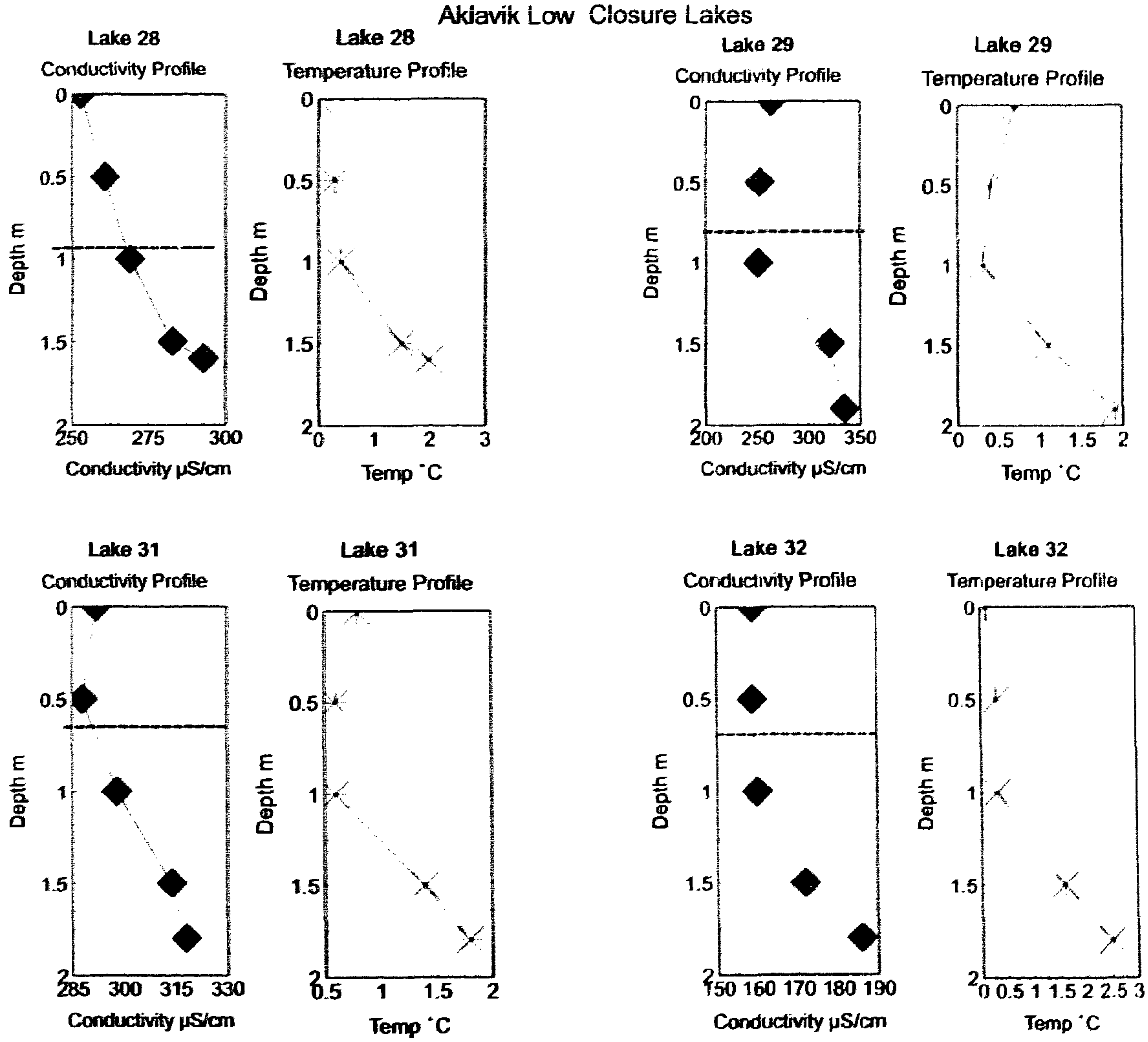


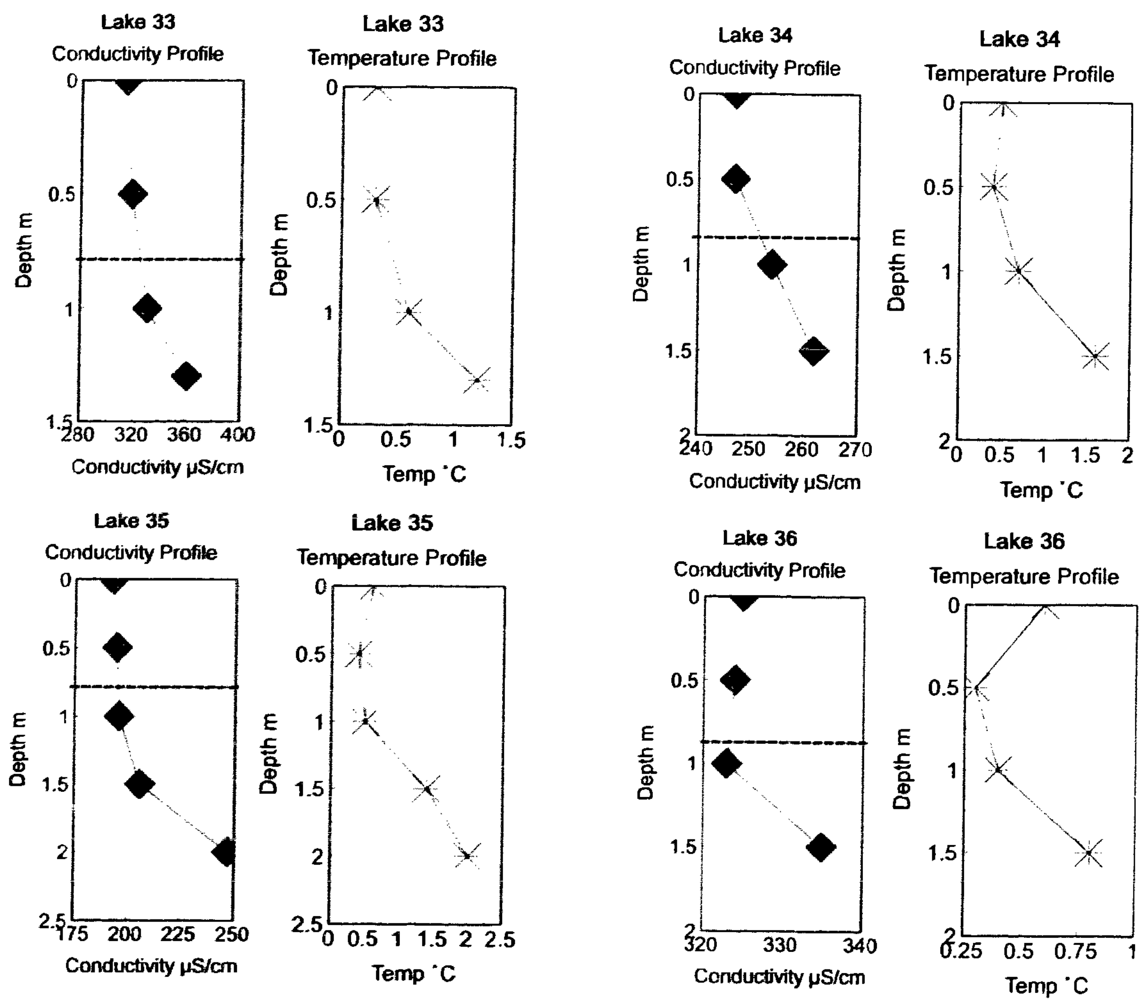
Aklavik No Closure Lakes



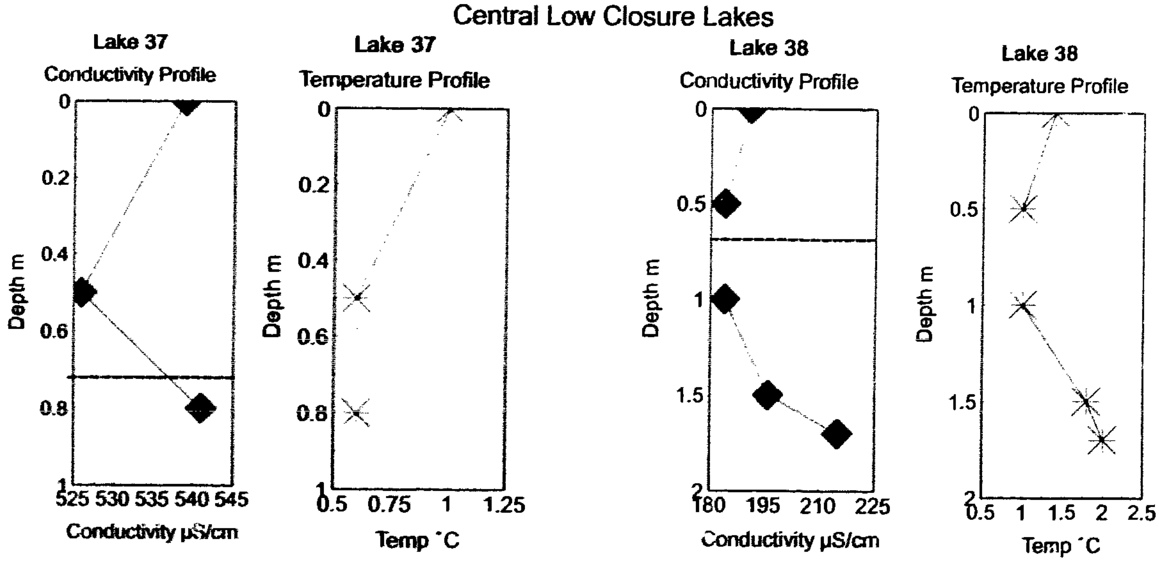


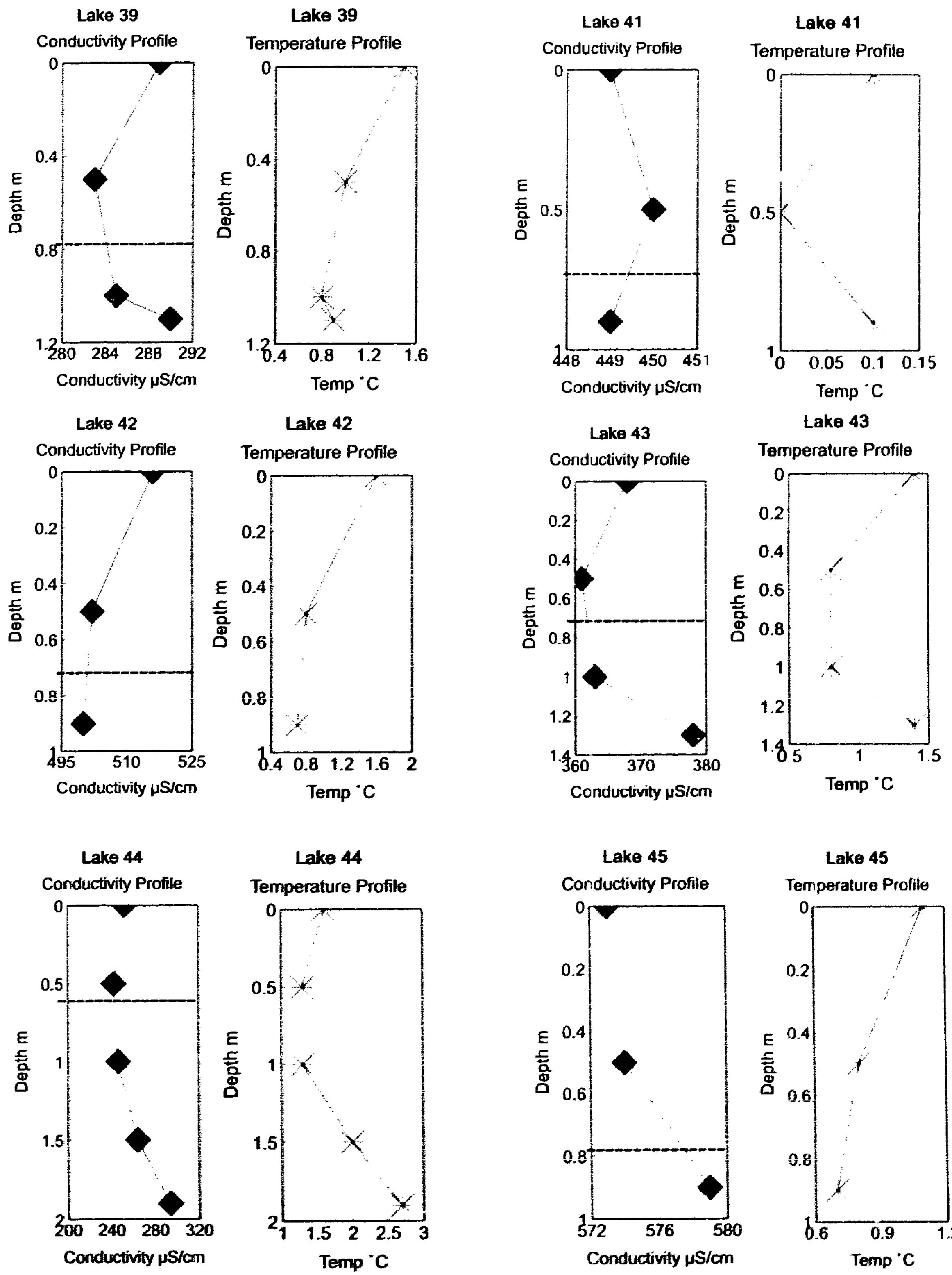
Aklavik Low Closure Lakes





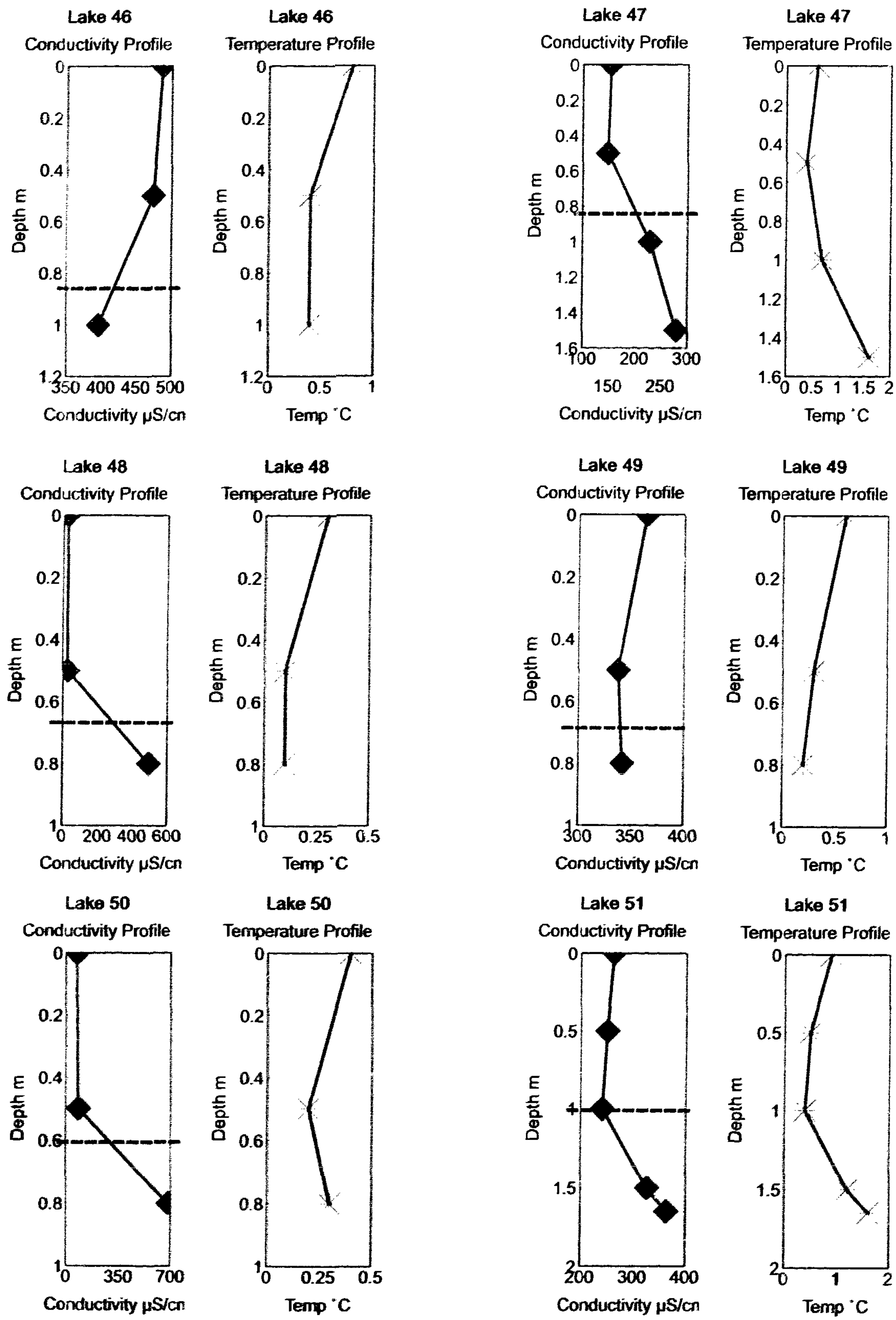
Central Low Closure Lakes

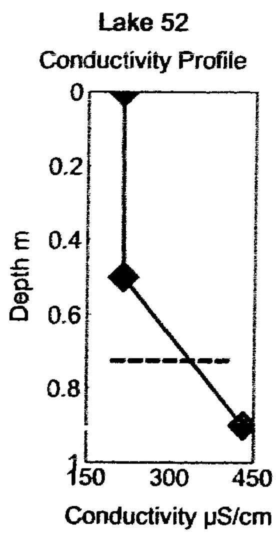


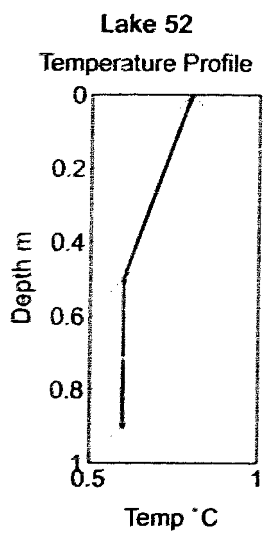


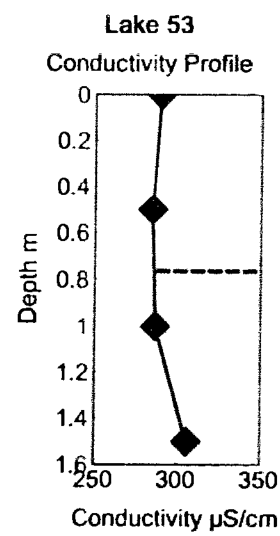
Lake 39
Conductivity Profile
Depth m
Conductivity µS/cm
Lake 39
Temperature Profile
Depth m
Temp ˚C
Lake 41
Conductivity Profile
Depth m
Conductivity µS/cm
Lake 41
Temperature Profile
Depth m
Temp ˚C
Lake 42
Conductivity Profile
Depth m
Conductivity µS/cm
Lake 42
Temperature Profile
Depth m
Temp ˚C
Lake 43
Conductivity Profile
Depth m
Conductivity µS/cm
Lake 43
Temperature Profile
Depth m
Temp ˚C
Lake 44
Conductivity Profile
Depth m
Conductivity µS/cm
Lake 44
Temperature Profile
Depth m
Temp ˚C
Lake 45
Conductivity Profile
Depth m
Conductivity µS/cm
Lake 45
Temperature Profile
Depth m
Temp ˚C

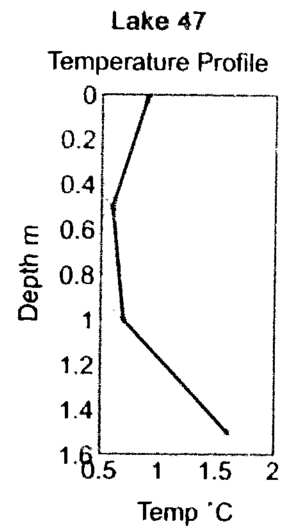
Inuvik Low-Closure Lakes

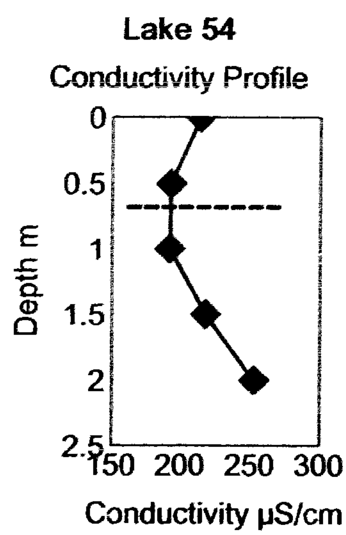


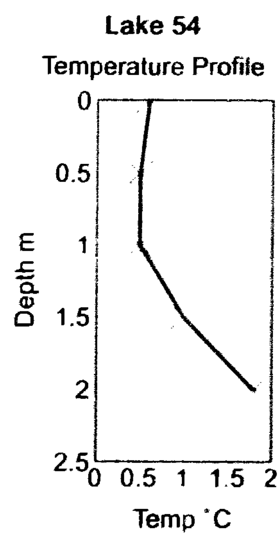




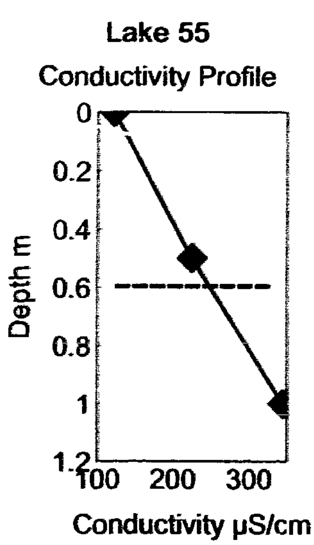


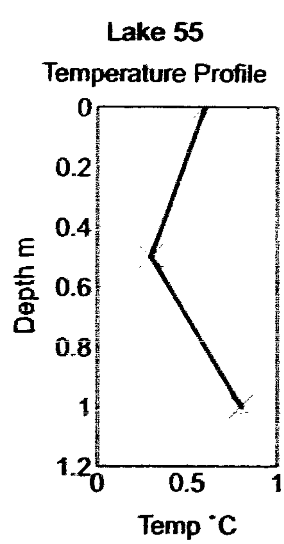


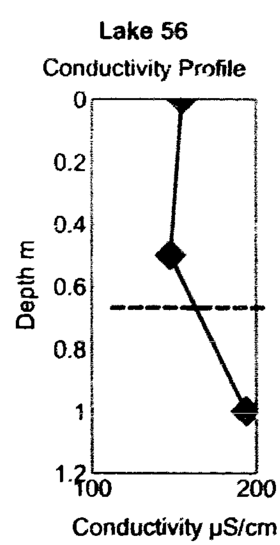


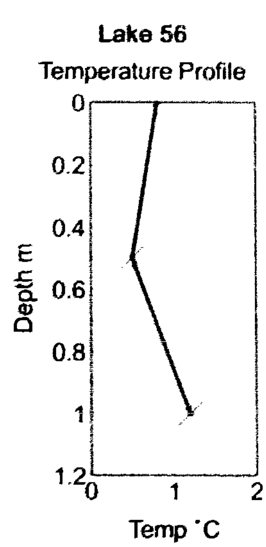


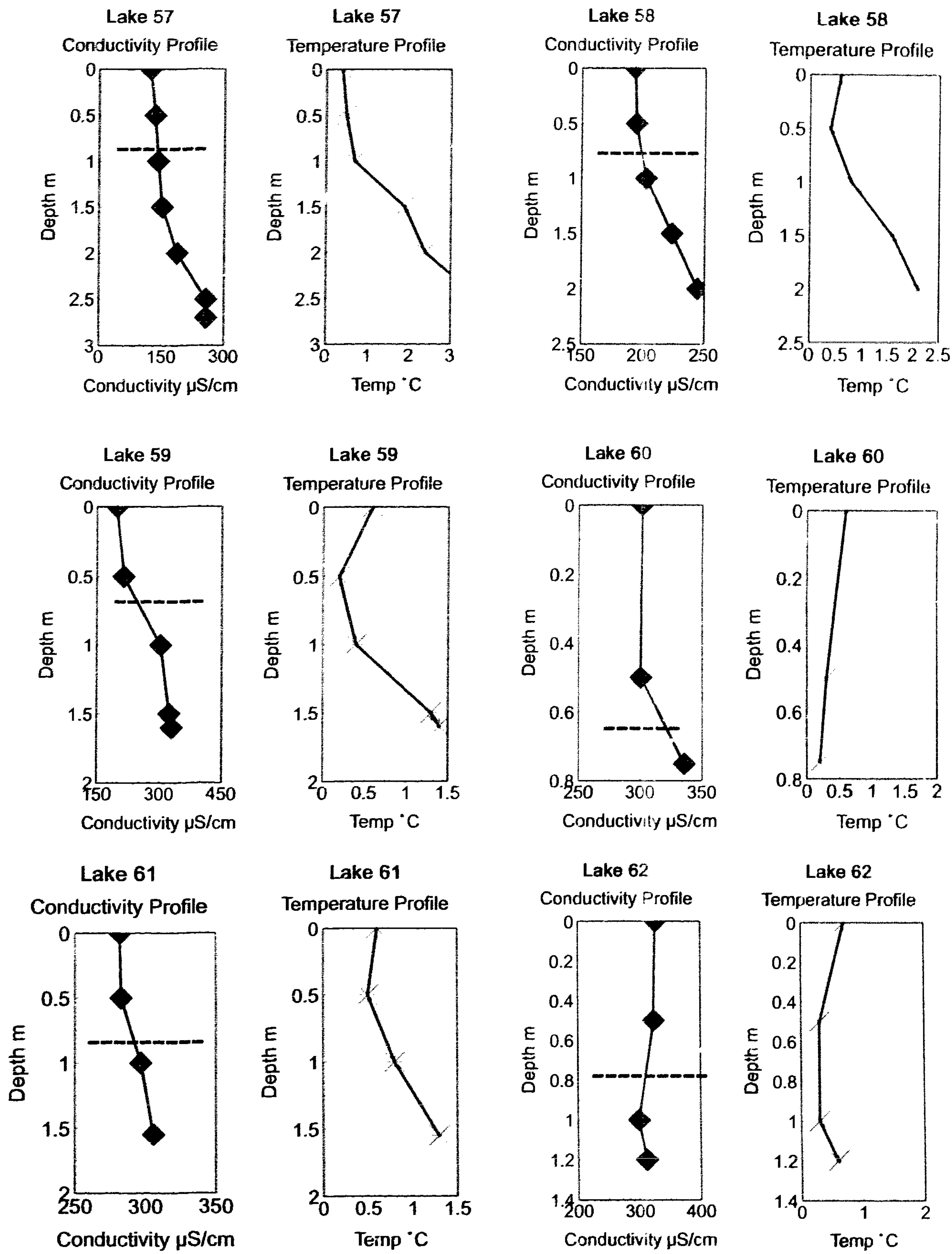
Inuvik High-Closure Lakes



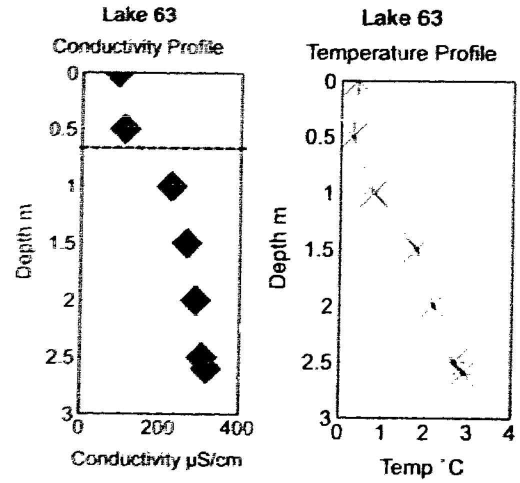




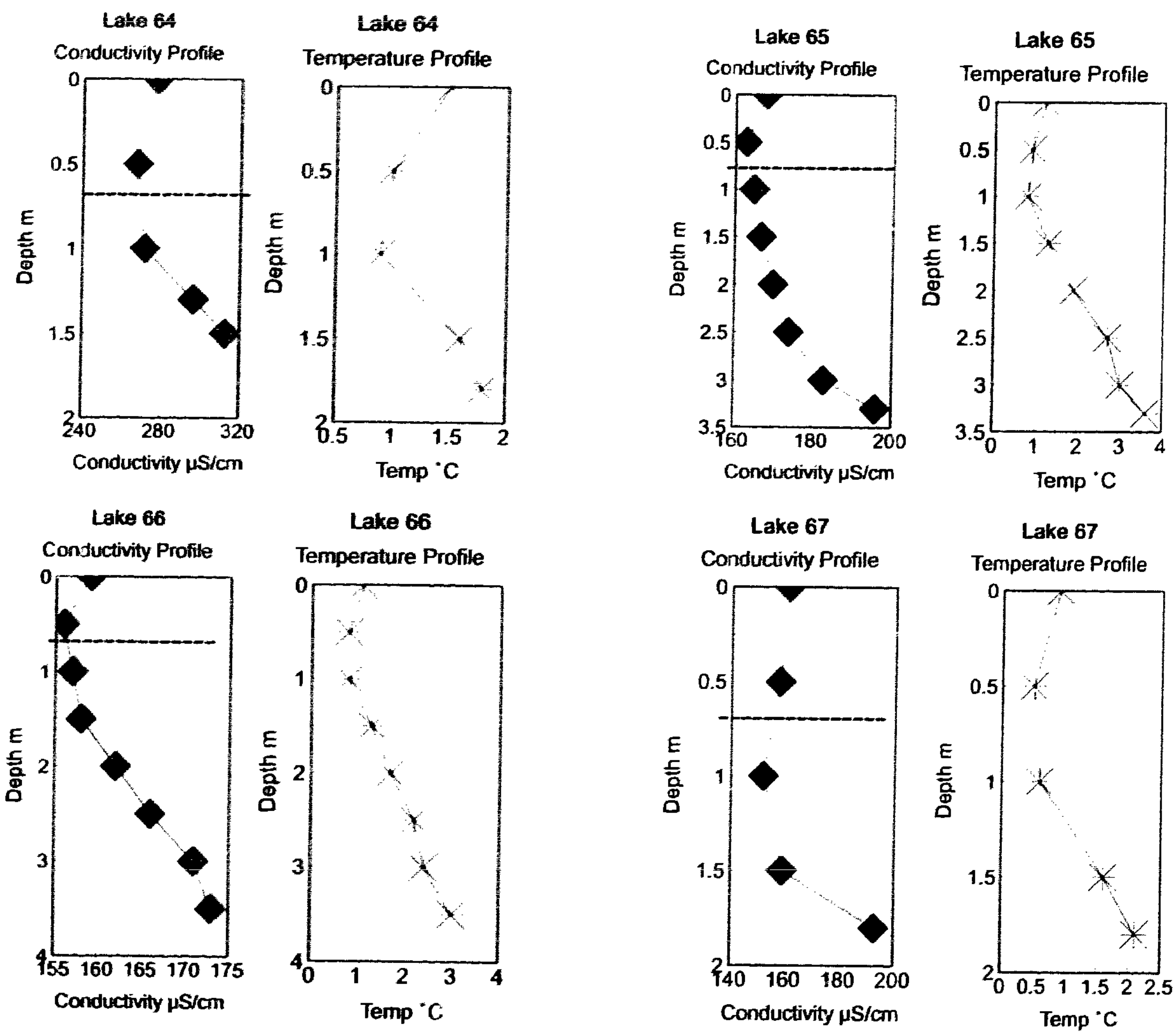


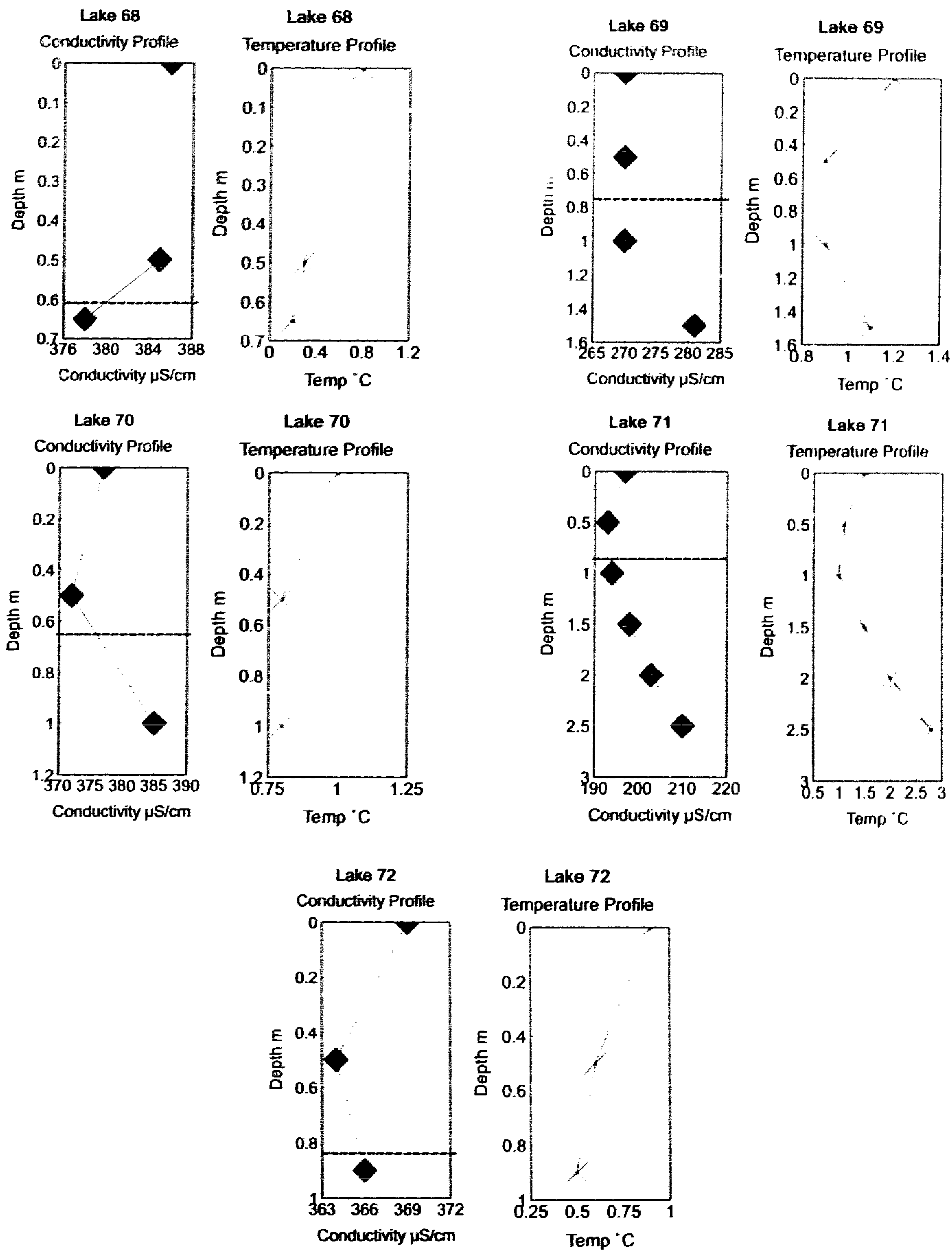


Lake 57
Conductivity Profile
Depth m
Conductivity µS/cm
Lake 57
Temperature Profile
Depth m
Temp °C
Lake 58
Conductivity Profile
Depth m
Conductivity µS/cm
Lake 58
Temperature Profile
Depth m
Temp °C
Lake 59
Conductivity Profile
Depth m
Conductivity µS/cm
Lake 59
Temperature Profile
Depth m
Temp °C
Lake 60
Conductivity Profile
Depth m
Conductivity µS/cm
Lake 60
Temperature Profile
Depth m
Temp °C
Lake 61
Conductivity Profile
Depth m
Conductivity µS/cm
Lake 61
Temperature Profile
Depth m
Temp °C
Lake 62
Conductivity Profile
Depth m
Conductivity µS/cm
Lake 62
Temperature Profile
Depth m
Temp °C

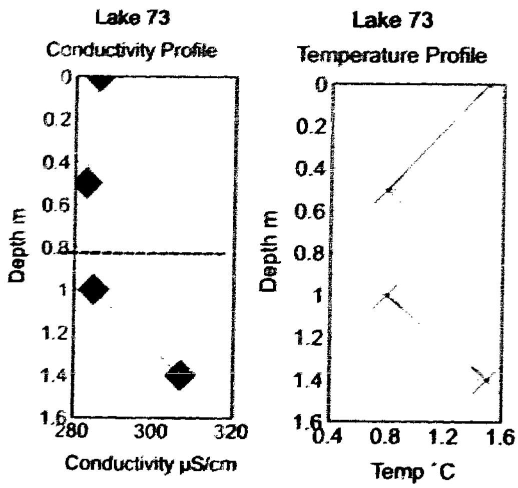


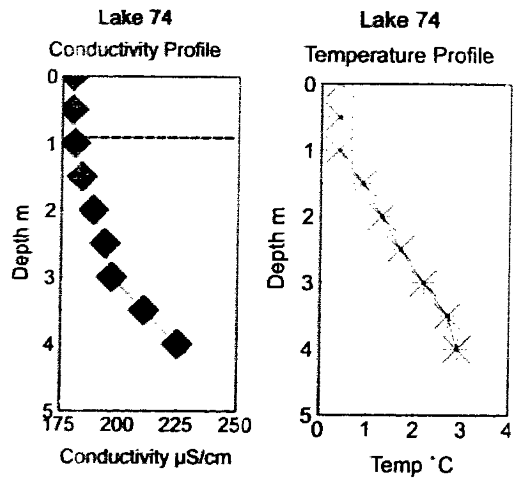
Central High-Closure Lakes

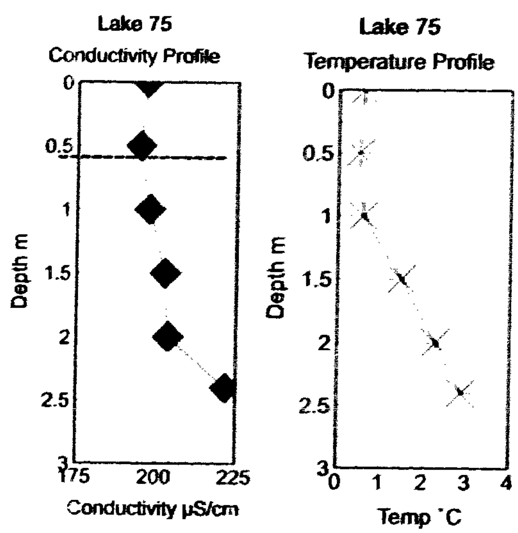


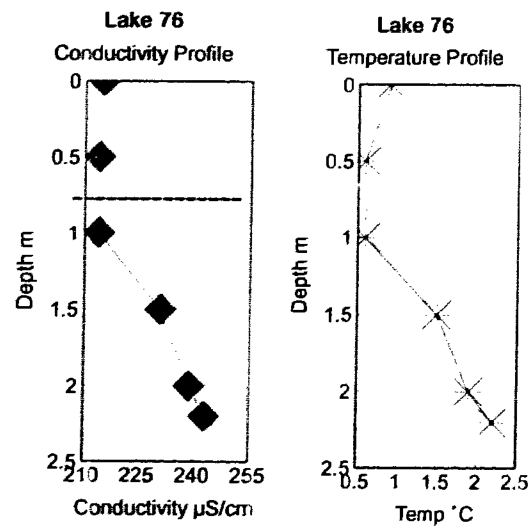

Lake 68
Conductivity Profile
Depth m
Conductivity µS/cm
Lake 68
Temperature Profile
Depth m
Temp °C
Lake 69
Conductivity Profile
Depth m
Conductivity µS/cm
Lake 69
Temperature Profile
Depth m
Temp °C
Lake 70
Conductivity Profile
Depth m
Conductivity µS/cm
Lake 70
Temperature Profile
Depth m
Temp °C
Lake 71
Conductivity Profile
Depth m
Conductivity µS/cm
Lake 71
Temperature Profile
Depth m
Temp °C
Lake 72
Conductivity Profile
Depth m
Conductivity µS/cm
Lake 72
Temperature Profile
Depth m
Temp °C

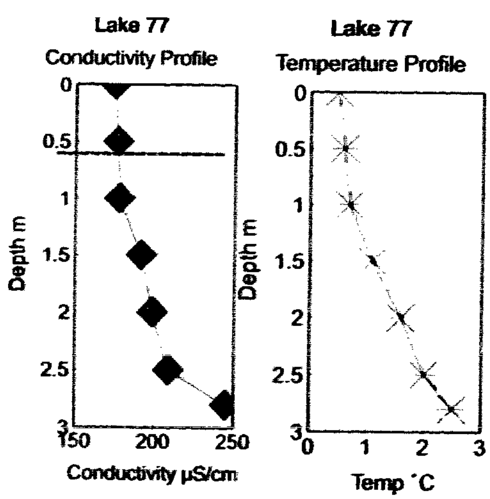
Alkavvik High-Closure Lakes

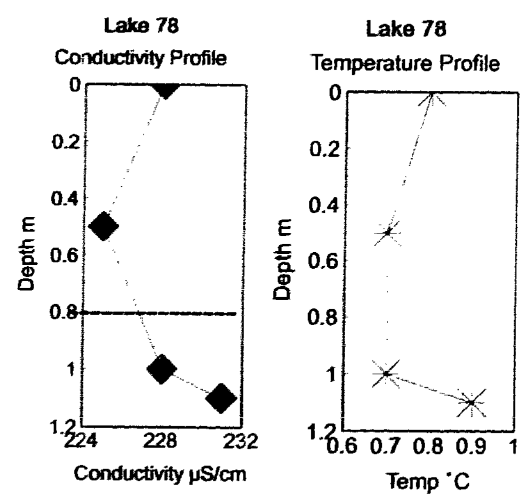


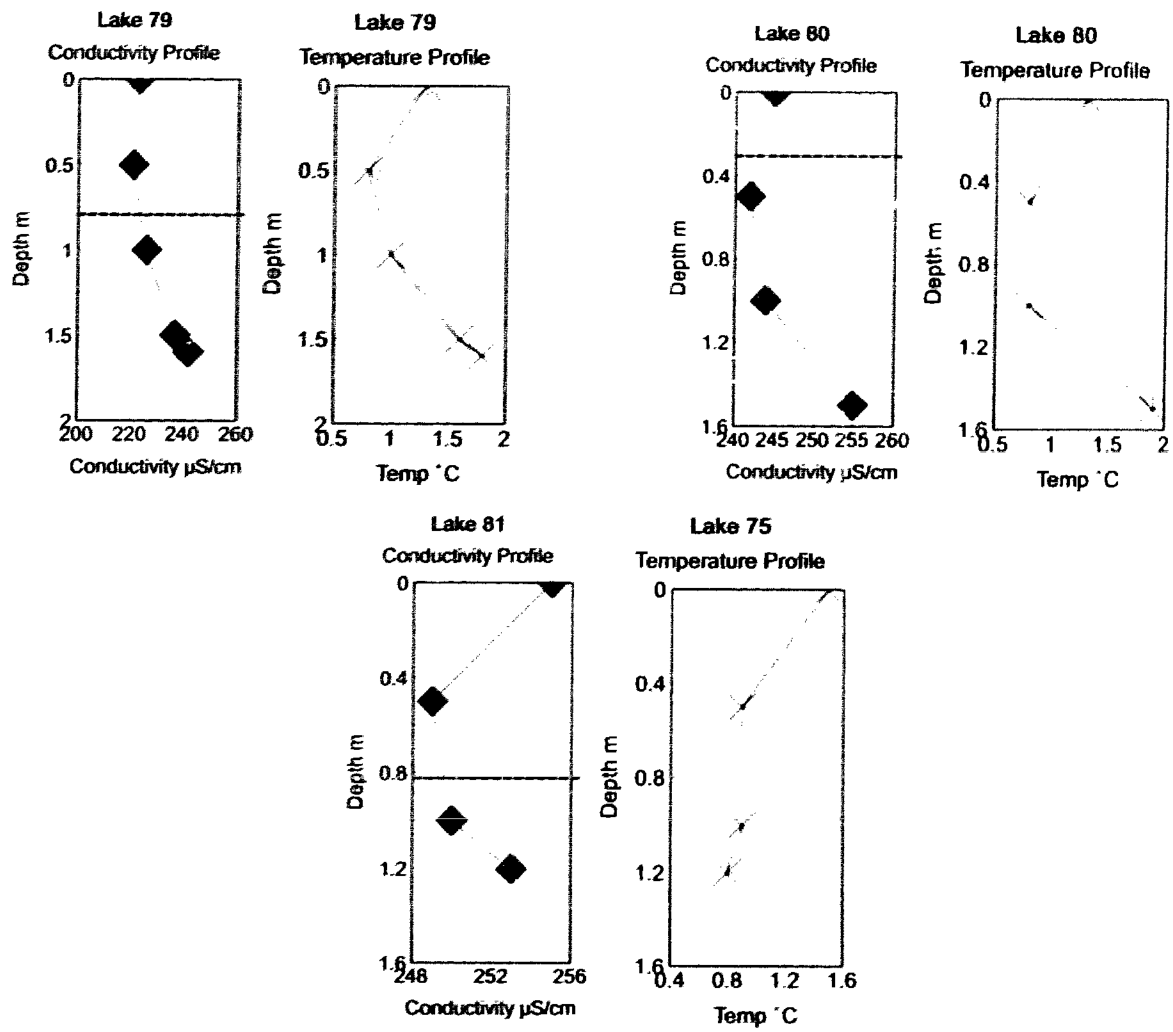








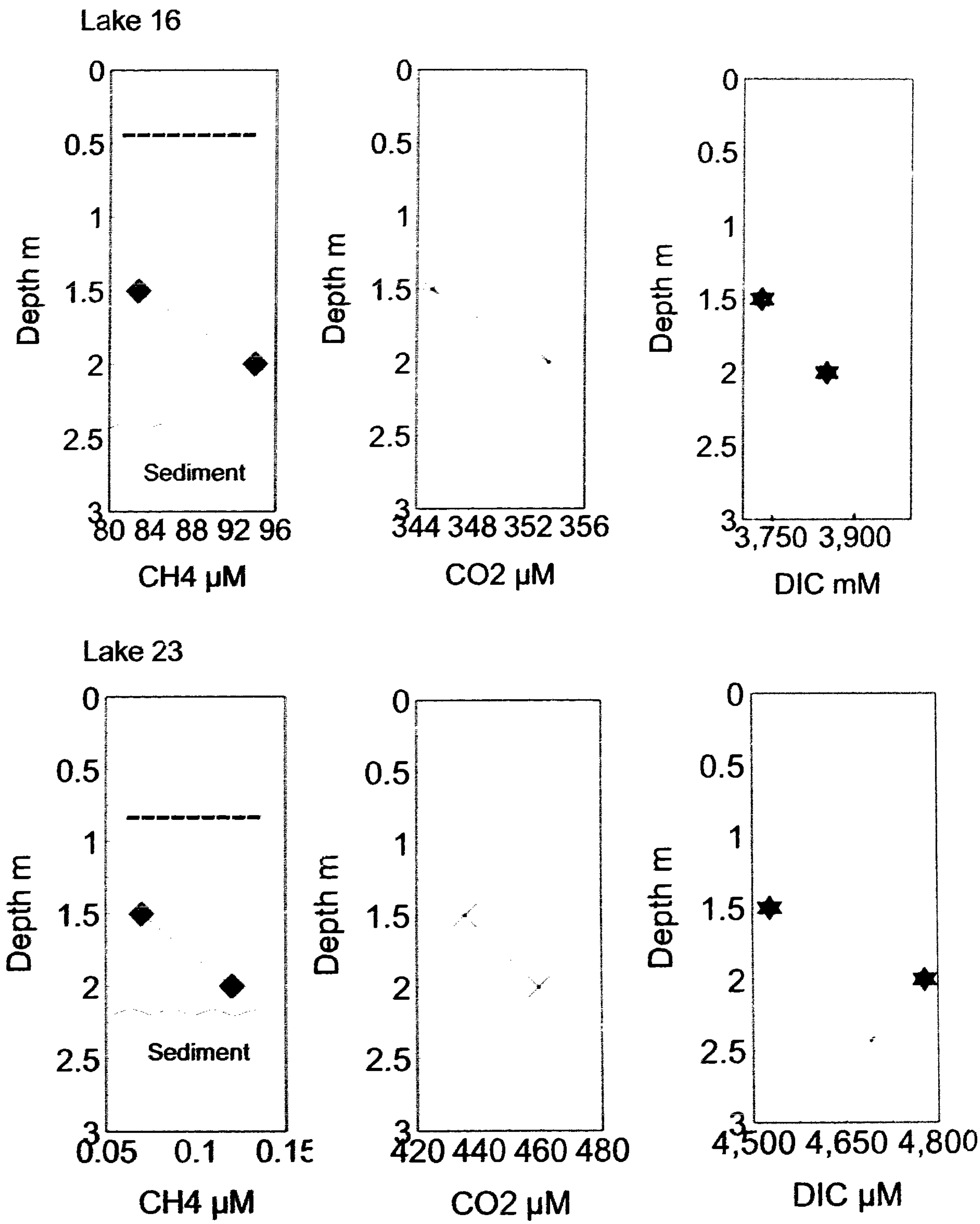



Lake 79
Conductivity Profile
Depth m
Conductivity µS/cm
0
0.5
1
1.5
2
200 220 240 260
Lake 79
Temperature Profile
Depth m
Temp °C
0.5 1 1.5 2
Lake 80
Conductivity Profile
Depth m
0
0.4
0.8
1.2
1.6
240 245 250 255 260
Conductivity µS/cm
Lake 80
Temperature Profile
Depth m
Temp °C
0.5 1 1.5 2
Lake 81
Conductivity Profile
Depth m
248 252 256
Conductivity µS/cm
Lake 75
Temperature Profile
Depth m
0.4 0.8 1.2 1.6
Temp °C

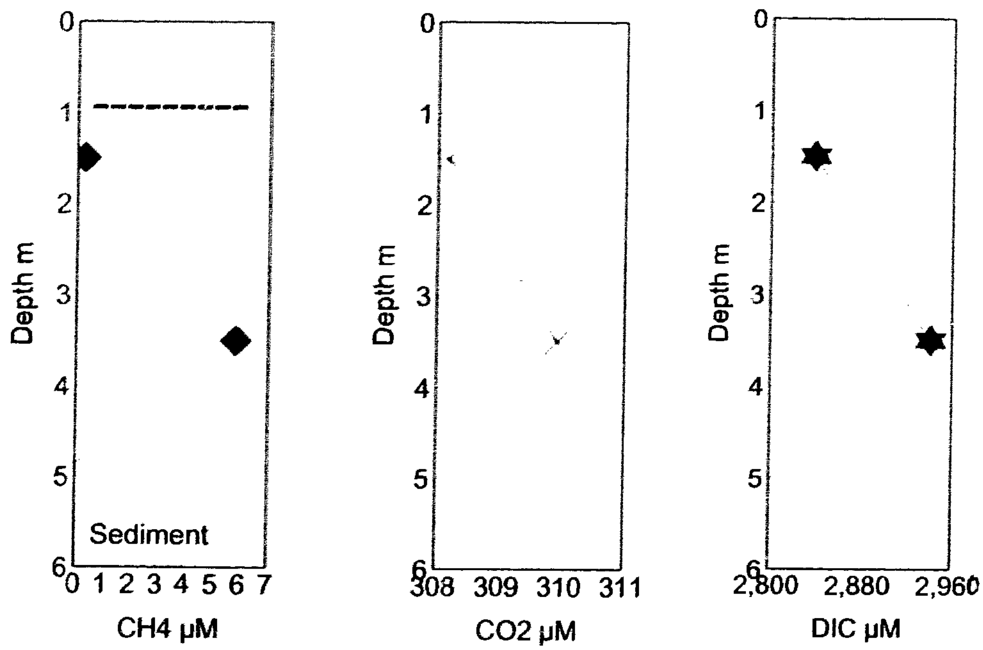
Appendix C - Methane, Carbon Dioxide and Dissolved Inorganic Carbon Profiles

This section includes the profiles for the sixteen lakes with water columns sufficiently deep to necessitate two sampling locations - one just above the sediment/water interface and the second between one third to one half the way down the water column. The lakes are presented sequentially with each lake being represented by three graphs with the first of the three graphs indicating the location of the sediment/water interface as well as the ice/water interface.

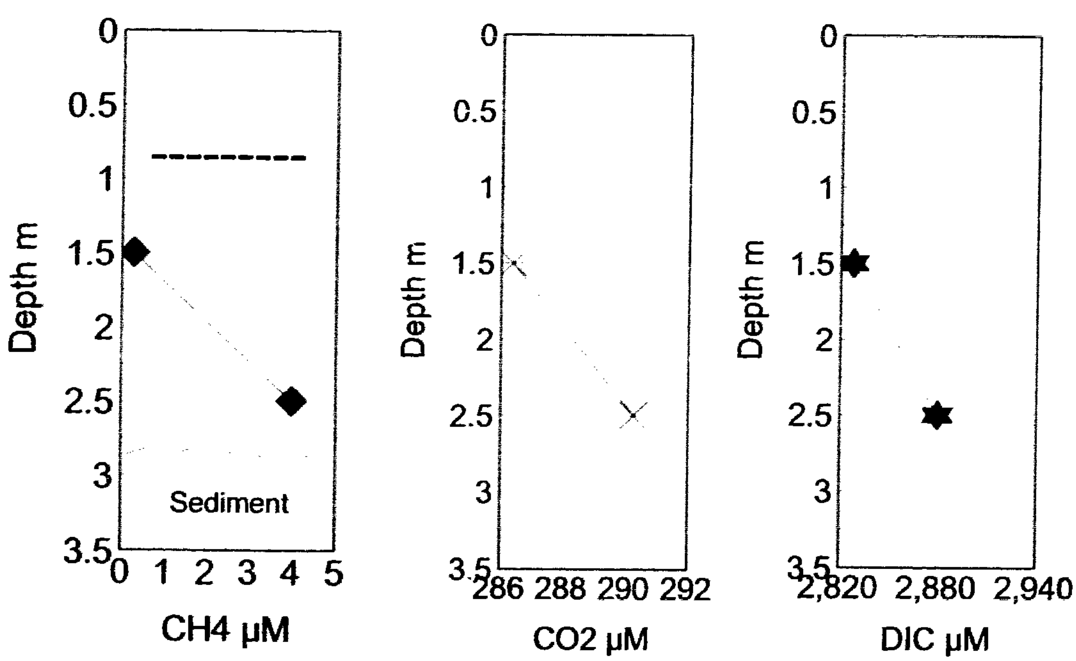
CO2, CH4, and DIC Profiles



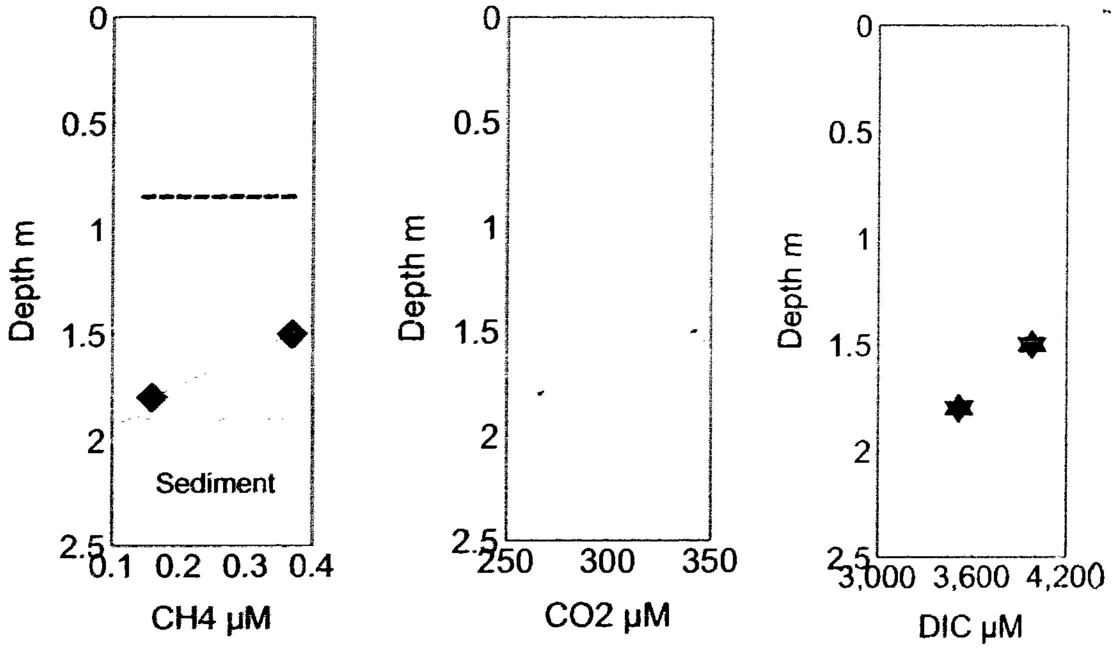
Lake 25



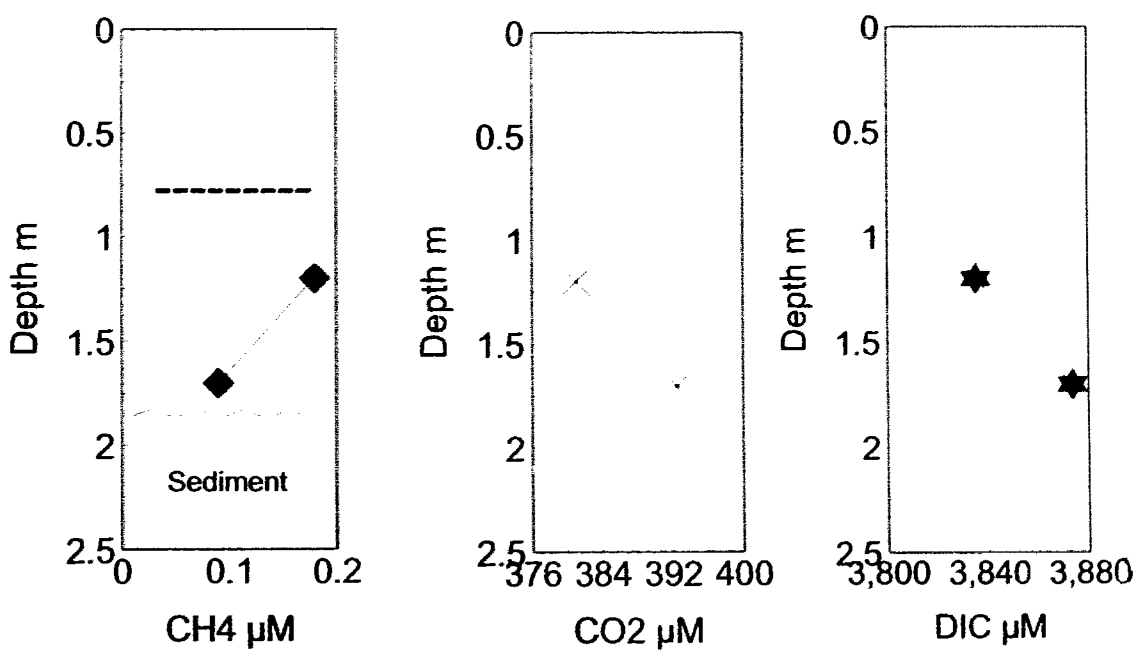
Lake 26



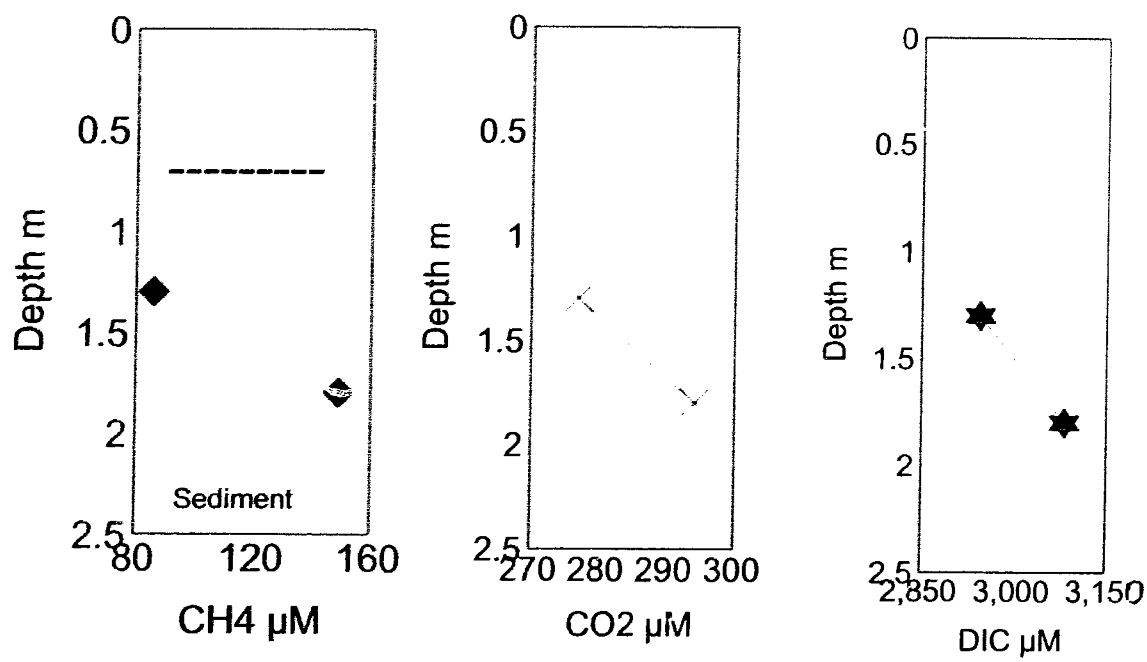
Lake 29



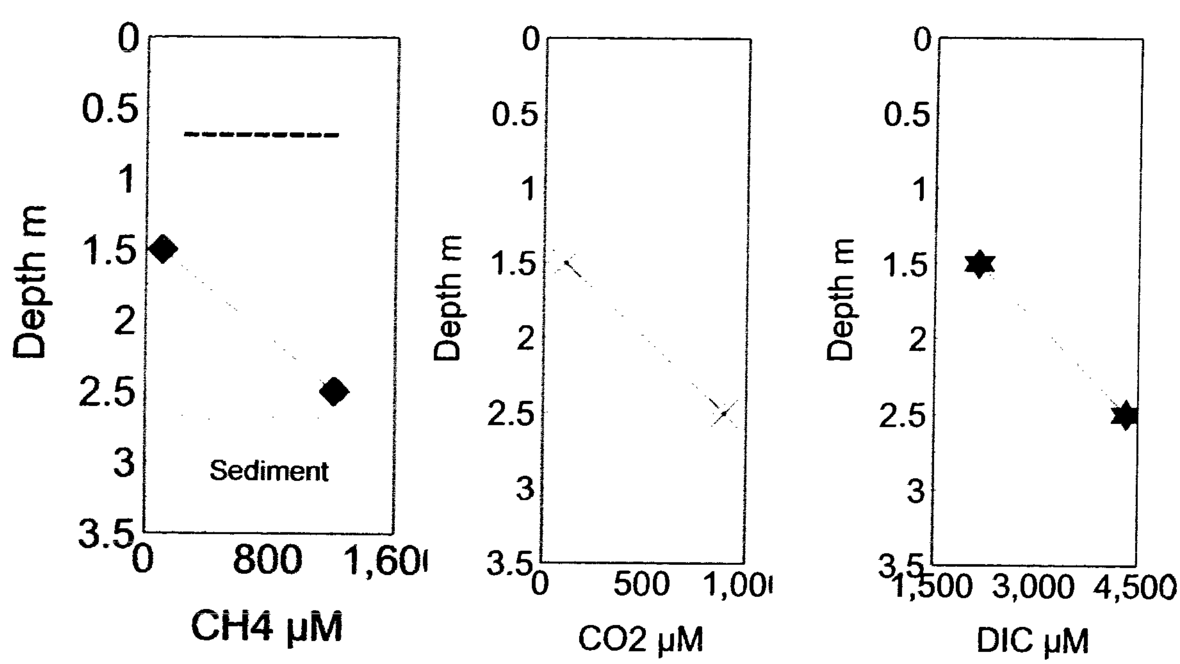
Lake 31



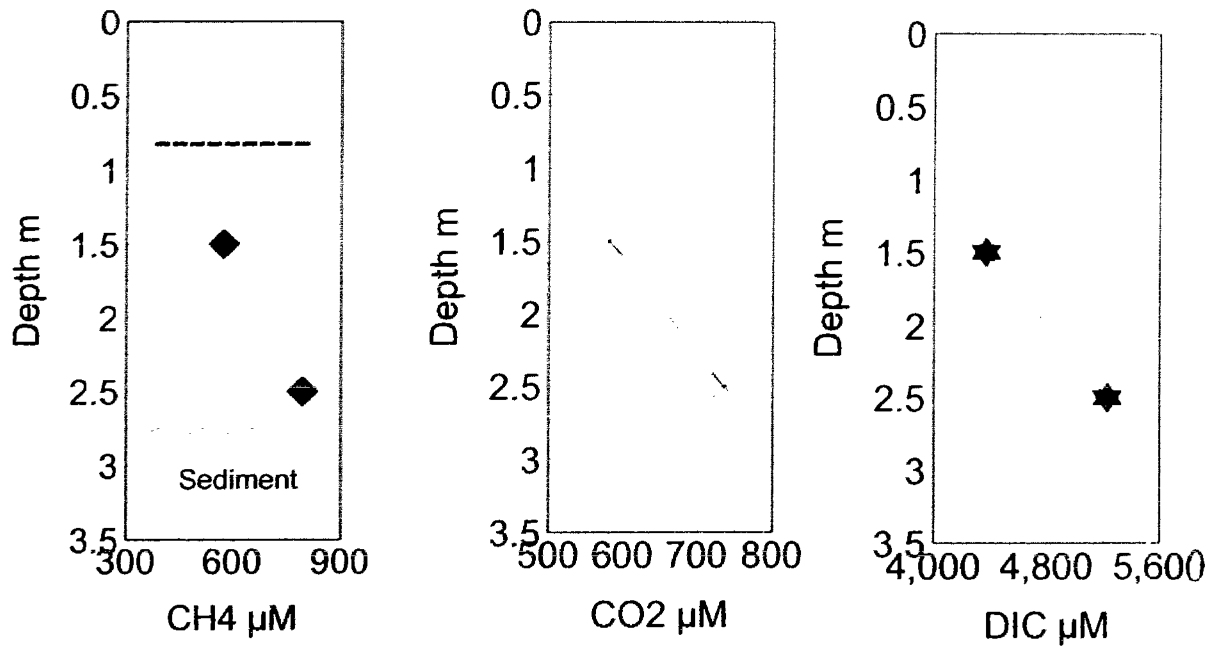
Lake 32



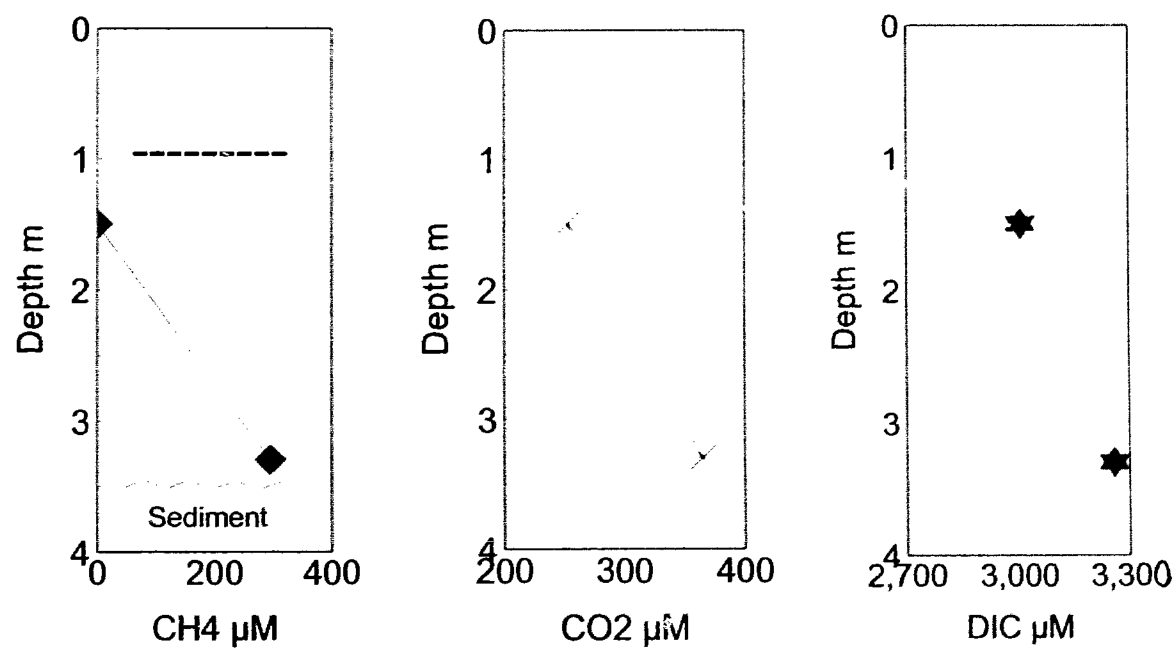
Lake 57



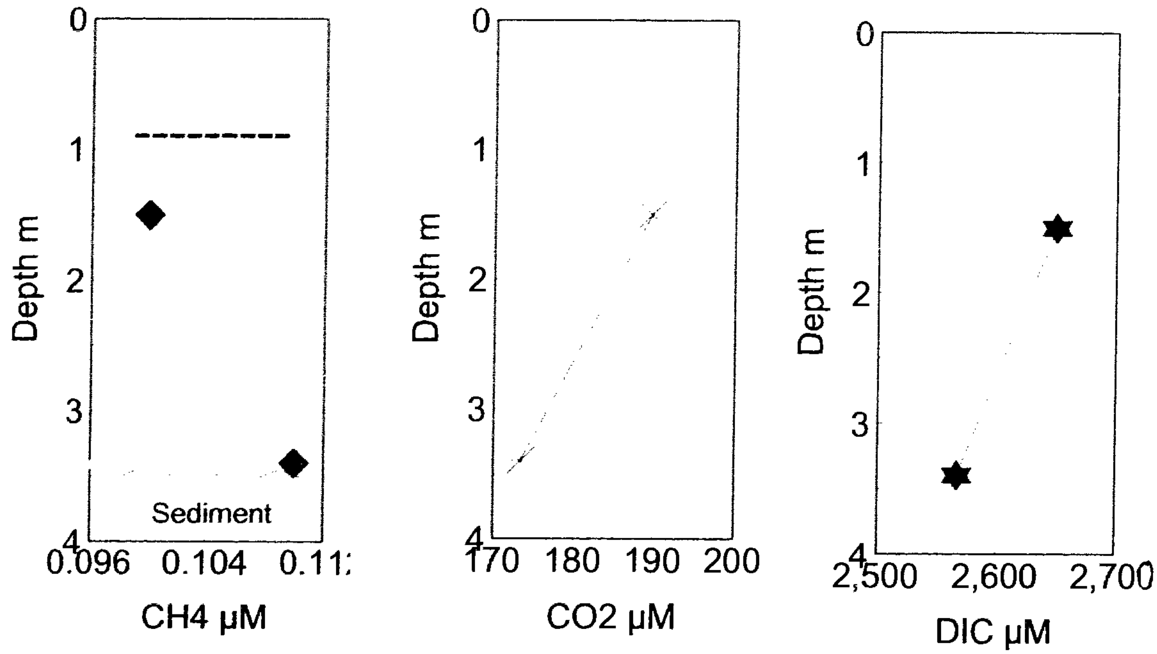
Lake 63



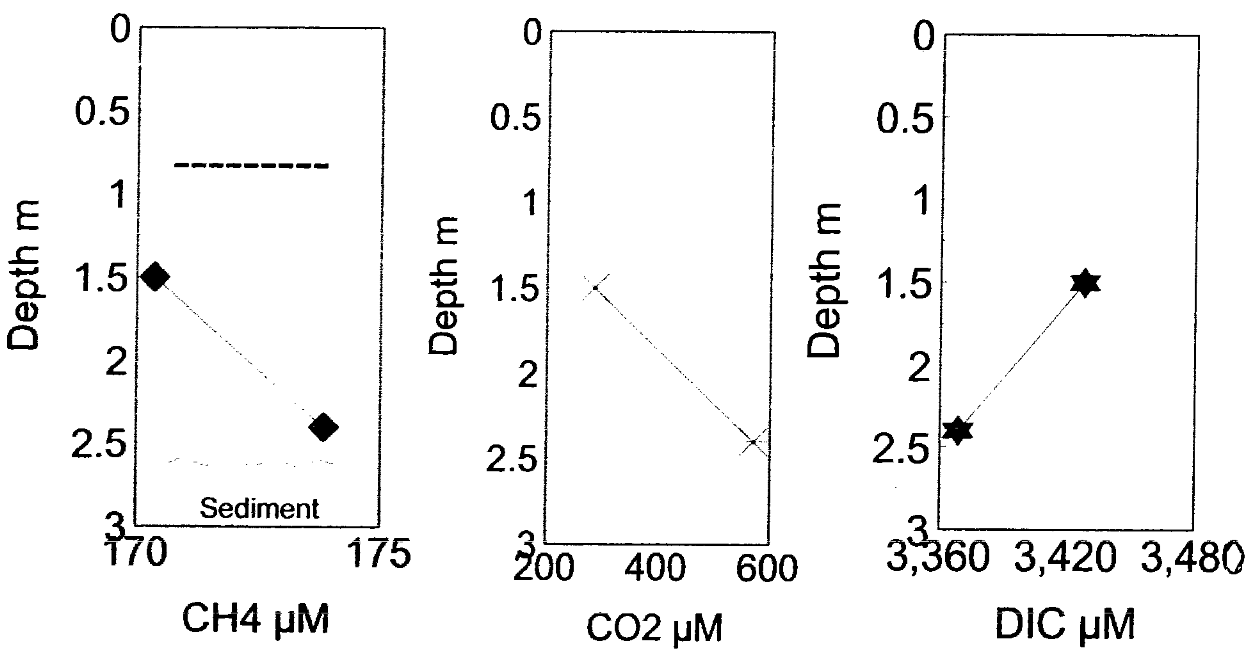
Lake 65



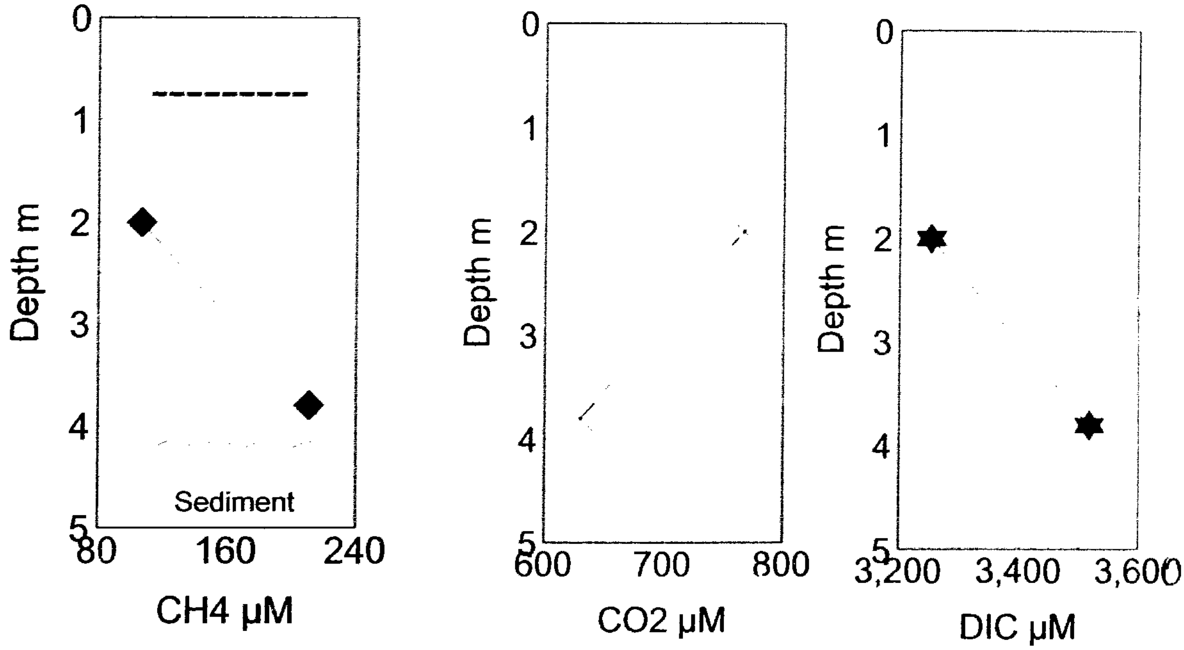
Lake 66



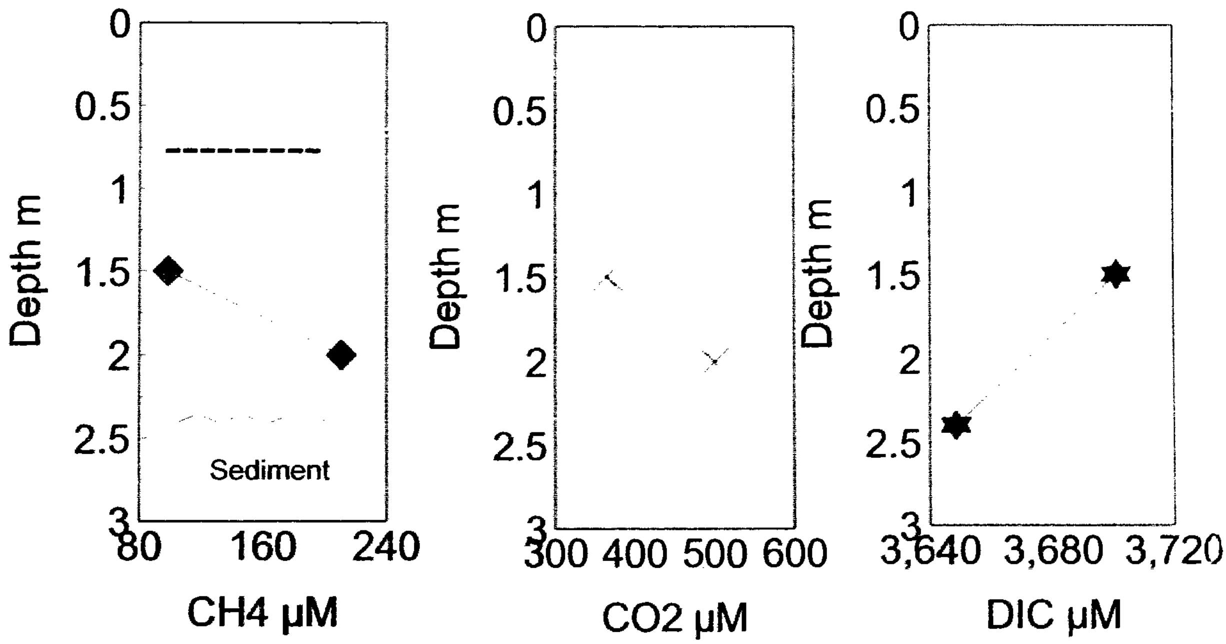
Lake 71



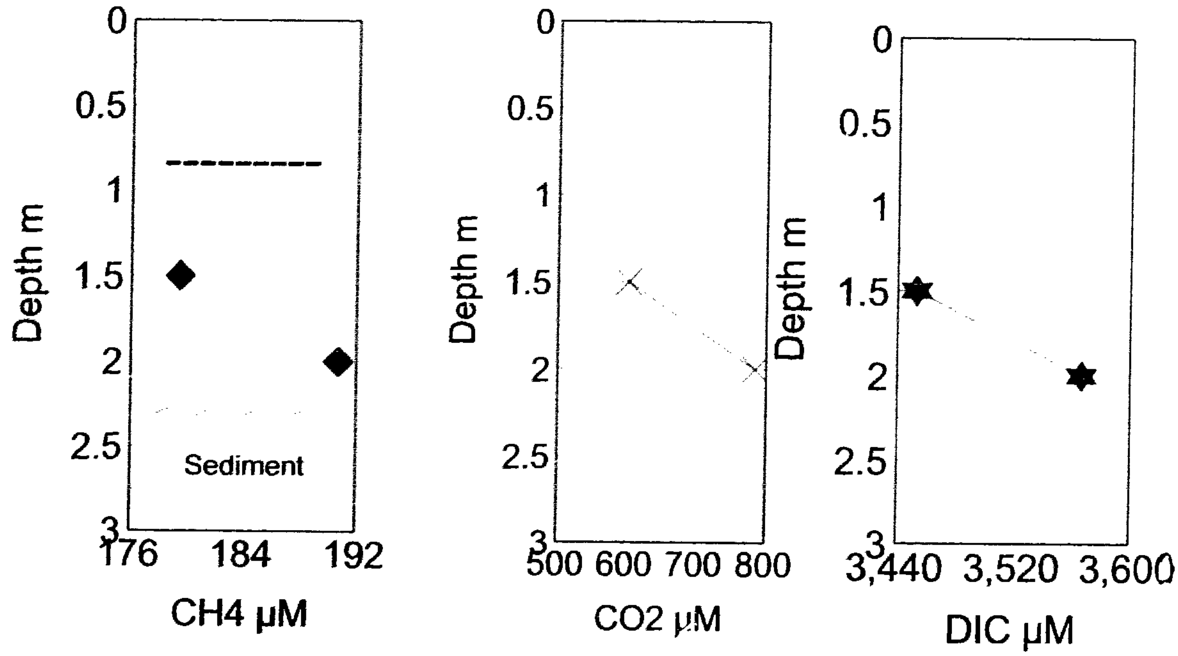
Lake 74



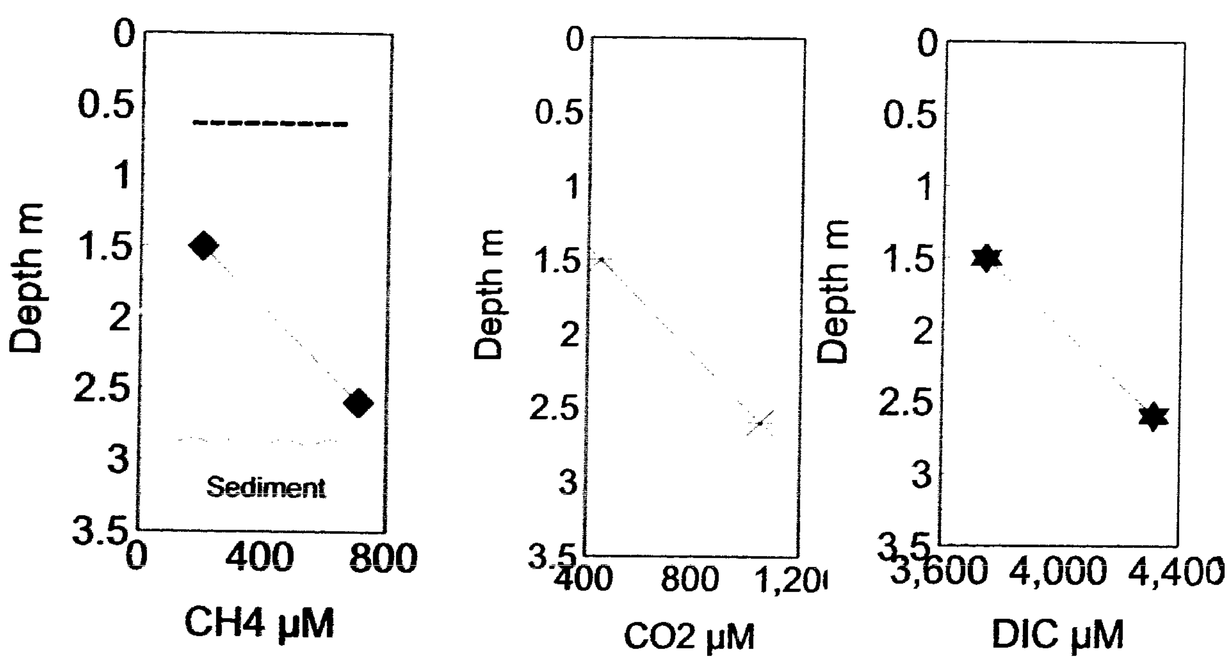
Lake 75



Lake 76



Lake 77



Appendix D - Total Lake Volumes and Under-Ice Volumes for Mackenzie Delta Transect Lakes

This section includes Table D1 which gives estimated total lake and under-ice volumes for each of the lakes on the Mackenzie Delta transect which were sampled in the spring of 1994. Results from Models 1 and 2 are given as estimated total volumes and results from methods A and B applied to each of these models are given as estimated under-ice volumes on a per lake basis.

Table D1. Lake volumes for the Mackenzie Delta transect lakes are calculated by Models 1 and 2. Under-ice volumes for each lake are calculated by using Method A (ice thickness depth) and Method B (ion concentration factor).

Lake No.	Lake Area (m^2)	Lake Depth (m)	Ice Thickness (m)	Ion Concentration Factor	Model 1 Total Lake Vol. m^3	Under-Ice Vol. (m^3) Model 1 Method A	Under-Ice Vol. (m^3) Model 1 Method B	Model 2 Total Lake Vol. m^3	Under-Ice Vol. (m^3) Model 2 Method A	Under-Ice Vol. (m^3) Model 2 Method B
1	8130000	1.8	0.92		4005367	713571		14634000	7154400	
2	550000	2.1	0.73		316129	104361		1155000	753500	
4	40000	1.2	0.7		13137	1822		48000	20000	
5	175000	0.9	0.73		43107	3455		157500	29750	
6	70000	1.05	0.7		20117	1745		73500	24500	
8	460000	1.4	0.84		176262	21589		644000	257600	
9	170000	1	0.82		46528	1129		170000	30600	
10	640000	1.45	0.83	2.26	253947	47326	112510	928000	396800	411145
11	20000	1.8	0.64	1.96	9850	3265	5014	36000	23200	18323
13	540000	1.6	0.84	2.16	236392	47484	109385	864000	410400	399797
14	770000	1.35	0.8	1.74	284509	37605	163378	1039500	423500	596927
15	110000	1.4	0.74	4.40	42142	7270	9585	154000	72600	35026
16	25000	2.3	0.7	1.77	14506	5577	8188	57500	40000	32457
17	70000	1.35	0	0.52	25864	4087	49777	94500	94500	181868
18	360000	1.3	0.79	2.16	128064	15021	59152	468000	183600	216166
19	130000	1.55	0.75	3.76	55141	11693	14659	201500	104000	53569
20	1100000	1.45	0.91	3.34	436471	49648	130675	1595000	594000	477526
21	1000000	1.3	0.86		355807	33337		1300000	440000	
22	54000	1.2	0.71	1.41	17736	2459	12590	64800	26460	45999
23	520000	2.1	0.8	2.65	298885	87509	112672	1092000	676000	411656
24	1310000	1.35	0.93	3.22	484036	41748	150476	1768500	550200	549789
25	40000	4.6	0.72	1.64	76041	39575	46330	184000	155200	112107
26	420000	2.8	0.78	0.98	321879	124072	327874	1176000	848400	1197902
27	360000	1.45	0.82	3.80	142871	22957	37572	522000	226800	137275
28	1300000	1.6	0.91	2.85	569298	87000	200020	2080000	897000	730797
29	360000	1.9	0.82	1.46	187213	48931	128425	684000	388800	469211
31	150000	1.8	0.68	2.56	73900	22789	28837	270000	168000	105357
32	160000	1.9	0.72	1.68	83206	25181	49450	304000	188800	180672
33	670000	1.3	0.73	3.02	238391	40658	78872	871000	381900	288172
34	130000	1.5	0.72	2.39	28971	12038	12117	195000	101400	81559
35	230000	2	0.8	2.53	125904	34988	49733	460000	276000	181703
36	170000	1.2	0.8	2.62	55834	4827	21333	204000	68000	77944
37	340000	0.85	0.74	2.90	15332	1346	5286	289000	37400	99632
38	30000	1.7	0.69	1.38	13959	4073	10152	51000	30300	37091
39	210000	1.1	0.76	1.49	63224	4944	42365	231000	71400	154789
41	180000	1.4	0.79	3.82	68972	10116	18074	252000	109800	66034
42	360000	0.9	0.7	1.17	88676	2929	75608	324000	72000	276253
43	20000	1.35	0.75	3.76	2218	1168	590	27000	12000	7180
44	100000	1.9	0.63	3.25	52004	17903	15977	190000	127000	58373
45	60000	0.9	0.76	2.31	24343	2583	10521	54000	8400	23340
46	480000	1.15	0.8		151080	10679		552000	168000	
47	340000	1.5	0.77		139587	27849		510000	248200	
48	10000	0.8	0.69		2190	45		8000	1100	
49	350000	0.8	0.65		76634	1592		280000	52500	
50	40000	0.85	0.63		9306	616		34000	8800	
51	1400000	1.64	0.93		632251	104391		2296000	994000	
52	40000	0.9	0.74		9853	325		36000	6400	
53	110000	1.5	0.72		45161	10186		165000	85800	
54	70000	2	0.71		38319	12147		140000	90300	
55	30000	1.05	0.59		8621	1568		31500	13800	
56	60000	1.01	0.72		17243	1495		60600	17400	
57	50000	2.7	0.65		36950	15246		135000	102500	
58	70000	2.2	0.68		42151	15218		154000	106400	
59	70000	1.6	0.65		30655	10432		112000	66500	
60	25000	0.75	0.62		5132	130		18750	3250	
61	56000	1.35	0.75		20692	3269		75600	33600	
62	20000	1.25	0.71		6842	1060		25000	10800	
63	50000	2.6	0.7		35582	13669		130000	95000	
64	140000	1.9	0.74	1.94	72805	22033	37539	266000	162400	137151
65	210000	3.4	0.84		195428	81768		714000	537600	
66	100000	3.5	0.77		95798	42457		350000	273000	
67	230000	1.8	0.73	1.88	113313	32483	60404	414000	246100	220693
68	13000	0.65	0.63	4.66	2525	216	542	8450	260	1813
69	160000	1.1	0.76	2.57	48170	3767	18721	176000	54400	68401
70	440000	1.05	0.63	2.61	126447	18612	48439	462000	184800	176983
71	25000	2.55	0.89		17449	5759		63750	41500	
72	90000	0.95	0.85	1.51	23401	266	15446	85500	9000	56436
73	20000	1.4	0.8	1.97	7664	1124	3889	28000	12000	14207
74	20000	4.1	0.81	1.55	22444	10525	14485	82000	65800	52922
75	25000	2.4	0.67	1.58	16422	6286	10370	60000	43250	37887
76	1200000	2.25	0.79	2.08	739004	231010	355211	2700000	1752000	1297788
77	25000	2.8	0.63	1.53	19159	8494	12560	70000	54250	45890
78	60000	1.1	0.78	2.29	18064	1412	7877	66000	19200	28780
79	20000	1.6	0.82	3.00	8758	1747	2923	32000	15600	10679
80	150000	1.55	0.82	2.74	63635	11906	23208	232500	109500	84795
81	60000	1.2	0.86	2.99	19706	1262	6595	72000	20400	24095

Appendix E - Standard Deviations of Low Concentration Standards Obtained During Operational Analytical Runs

This section includes Table E1 which gives standard deviations of low concentration standards obtained during operational analytical runs. Detection limits were assumed to be 2 times the standard deviation for each variable.

Table E1 Standard deviations of low concentration standards obtained during operational analytical runs. Detection limits were assumed to be 2 times the standard deviation for each variable.

Gases	Standard Deviation	
	ppm	μM
Methane	0.15	
Carbon Dioxide	0.30	
Major Solutes		
Sodium		1.47
Calcium		1.06
Potassium		0.69
Magnesium		0.20
Cloride		0.18
Sulfate		0.06
Silica		0.06
Phosphate		0.01
Ammonium		0.12