LATE-QUATERNARY VEGETATION HISTORY, LENA RIVER, SIBERIA

THE LATE-QUATERNARY VEGETATION HISTORY OF THE LOWER LENA RIVER REGION, SIBERIA

by

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ABSTRACT

Scientists believe that the global climate is undergoing significant changes due to anthropogenic increases of carbon dioxide (CO_2) and other Greenhouse gases. The relationship between climate and vegetation is not fully understood. Knowledge of the response of vegetation to past climate change aids in the understanding of potential vegetation responses to climatic changes due to the Greenhouse effect. The objectives of this thesis were to determine if vegetation in the lower Lena River Region has changed in the past, what were the factors which caused the changes and over what time scales did the changes occur. To address the objectives, the pollen, stomate and sediment stratigraphy of a core from a medium size lake, located in north-central Siberia, were analysed. Radiocarbon dating indicates that the record spans the last 12310 yr BP, and possibly the last 15000 yr BP. The early part of the fossil record was characterised by short rapid changes in the vegetation. The initial shrub tundra was quickly replaced by herb tundra with sparse vegetation cover. This was followed by a reversion to shrub tundra conditions at ~12000 yr BP. A clear Younger Dryas signal is found in this record between 11000 and 10000 yr BP, characterised by a shift from shrub tundra to herb tundra dominated by taxa with arctic affinities. The warming at the close of the Younger Dryas signalled the first appreciable climatic amelioration at this site. Following 10000 yr BP, *Alnus* became abundant in the pollen record and likely on the landscape. The dominance of *Alnus* was short lived however. At ~8500 yr BP arboreal vegetation, dominated by *Larix dahurica*, became abundant in the pollen and stomate record. The expansion of forests was the result of changes in the orbital parameters of the earth as predicted by Milankovitch cycles. Arboreal vegetation persisted in this region until ~3500 yr BP when the modern shrub tundra vegetation was established.

The use of a new technique, stomate analysis, proved extremely useful. Stomates accurately recorded the expansion and retreat of treeline across this region. This study clearly indicates the usefulness of this technique, especially for investigating fluctuations of treeline.

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CHAPTER ONE

INTRODUCTION

Scientists are becoming more convinced that the global climate is undergoing significant changes due to increased levels of greenhouse gases as a result of anthropogenic activity. Temperatures are perhaps the best indicator of these changes in our climate. Given that the circumpolar treeline is sensitive to changes in climate, especially fluctuations in temperature, this geographical boundary could serve as an important indicator of climate change. The Intergovernmental Panel on Climate Change (IPCC, 1990) estimates that increases in temperatures in high latitudes will be 50-100% greater than the global mean. Such temperature variations could have significant impacts on northern vegetation and could result in profound feedbacks to the global climate system (Pastor and Post, 1988 and Foley et al., 1994). In northern Canada, for example, it is estimated that the Boreal forest may shift up to 400 km north of its present location as a result of global warming (Zoltai, 1988). Rizzo and Wiken (1992) predict that a doubling of carbon dioxide (CO_2) will result not only in shifts in vegetation boundaries, but also in a rearrangement of the species comprising Canadian ecosystems. In northern Eurasia, where the largest continuous belt of boreal forest is found, there is much uncertainty about how the Eurasian tundra and northern boreal forest will respond to possible warming.

Fluctuations in climate have been shown to have direct impacts on vegetation. The boundary between tundra vegetation and the forest tundra region, known as treeline, is especially useful for studying these changes. Evidence has shown that treeline has shifted both latitudinally and altitudinally in response to past changes in climate (Ritchie et al., 1983; Kullman, 1989, 1992 and 1993; MacDonald et al., 1993).

Although an abundance of studies have assessed how climate change will affect an area such as Canada, few studies have shown what the effect of increased levels of CO_2 will be on the ecosystems of the former Soviet Union. The former Soviet Union occupies approximately one-sixth of the earth's land surface (Peterson, 1993). Given that a large proportion of the circumpolar treeline, and hence the boreal forest, is found in northern Russia and Siberia the importance of this ecosystem cannot be underestimated. Unfortunately, prior to the collapse of communist governments in the former Soviet Union, information about ecosystems from this area was sparse for western scientists.

To begin to gather information on this problem the Palaeoecological Analysis of the Circumpolar Treeline or PACT project was initiated. PACT is a multidisciplinary collaborative effort between Canadian and Russian scientists dedicated to studying how circumpolar treeline has changed in the past. PACT is collecting and utilizing existing data from northern areas throughout Canada, Russia and Scandinavia. This data will be used to reconstruct how circumpolar treeline has changed throughout the Holocene. The research for this thesis will specifically consider how vegetation has changed in the lower Lena River region of north-central Siberia.

Climate change in the past has occurred at varying rates and intensities. During the early to mid Holocene, changes in the earth's orbit which occurred over thousands of years, resulted in warmer summers across northern latitudes (COHMAP Members, 1988; Kutzbach and Webb, 1993; Webb et al., 1993). At this time the northern hemisphere was nearest the sun during the summer solstice (Kutzbach and Webb, 1993). The increased solar insolation caused treeline to move north of its present location in north western Canada (Ritchie, 1984), and it is thought that this warming may have had similar effects in northern Siberia. If this hypothesis is correct, then perhaps the vegetation that was present in northern Siberia during the early and mid Holocene may be a good indication of what the present day tundra - forest zone will look like after climate warming. Changes in climate have also impacted on vegetation at more rapid time scales. These short and rapid climate fluctuations cannot be attributed to changes in the earth's orbit. The Younger Dryas is perhaps the best example of this phenomena. The Younger Dryas is characterized by a return to near glacial conditions between 11000 and 10000 yr BP, likely caused by changes in global ocean circulation patterns (Dansgaard et al., 1989; Fairbanks, 1990; Kennett, 1990 and Peteet, 1995). The rapid warming at the close of the Younger Dryas may be the closest analog for climatic changes expected from global warming due to the greenhouse effect. By studying this period it may be possible to better predict what the response of the global system will be to future warming or even cooling. Combined, the impact of long-term orbital variations on the circumpolar treeline and the processes and impacts of the Younger Dryas in northeastern Asia will form the basis for this thesis.

The remainder of this chapter will focus primarily on the palaeoecological aspects of circumpolar treeline. Palynological studies from several circumpolar regions will be reviewed and past fluctuations in treeline position will be deduced from them.

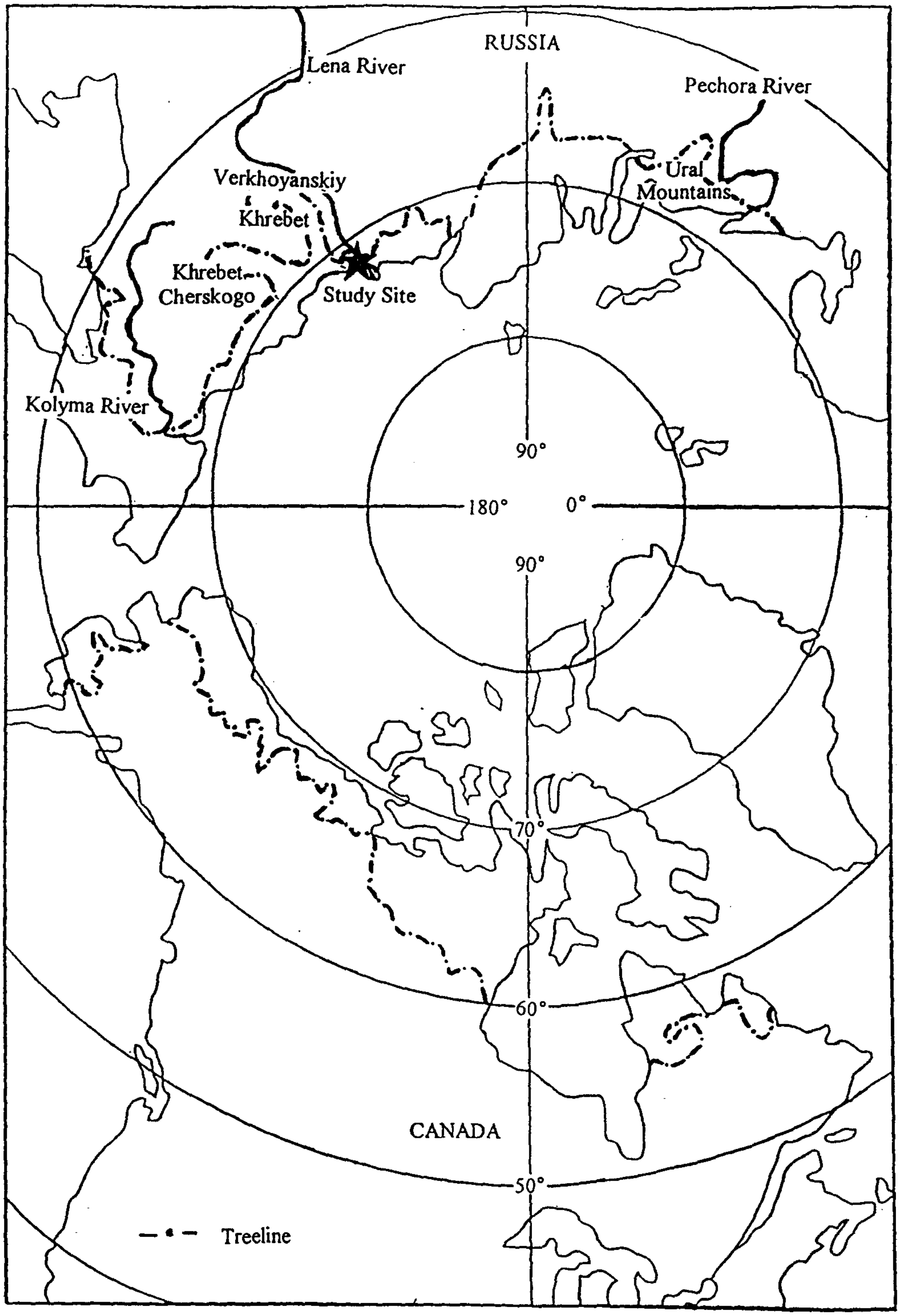
1.1 Treeline

The debate over how to define treeline plagued many early studies of this geographical boundary. A firm definition of what constitutes treeline was presented by Payette (1983). For the purpose of this study treeline is considered to be the boundary between the tundra and the forest tundra. North of this boundary, in the tundra region, flora is reduced to a cover of non-arboreal vegetation comprised of various species of shrubs and herbs. At treeline, the vegetation is dominated by arboreal species with tree growth forms and a height of at least 5 m (Payette, 1983).

In the former Soviet Union, the latitude of treeline appears relatively uniform (Figure 1). This contrasts markedly with the situation in Canada where Hudson Bay displaces treeline several hundred kilometres to the south. In the former Soviet Union only along the major north-south trending mountain ranges is treeline depressed an appreciable distance to the south (Along the Ural, Verkhoyanskiy Khrebet, and Khrebet Cherskogo mountain ranges for example). In contrast, along many of the major river systems which flow northward across the former Soviet Union, treeline extends much further north, reaching the Arctic coast in some cases (in the Kolyma River region).

Throughout the former Soviet Union, several species of trees are found at treeline. In the west, in the European sector, *Pinus sylvestris* (scots pine) and *Picea obovata* (siberian spruce) dominates. East of the Ural Mountains, treeline is formed primarily by species of *Larix*, *L. sibirica* (siberian larch) and *L. dahurica* (dahurian larch) (Gorchakovsky and Shiyatov, 1978).

Figure 1. Circumpolar Treeline. The position of treeline throughout the circumpolar region is illustrated. In addition, selected mountain ranges and major rivers are also shown.


RUSSIA
Lena River
Pechora River
Verkhoyanskiy
Khrebet
Ural
Mountains
Khrebet
Cherskogo
Study Site
Kolyma River
90°
180°
0°
90°
70°
60°
CANADA
50°
Treeline

1.2 The Relationship Between Climate and Treeline

The factors controlling the location of treeline are not fully understood. Several hypotheses have been developed which attempt to account for the geographic position of this ecotone. Climate is likely the dominant factor controlling the position of treeline; however, other factors such as the ability of trees to successfully reproduce and physiological characteristics must be critical.

There are several climatic variables that may restrict the growth of trees beyond treeline. The most obvious factor is temperature, while radiation receipt, wind speed and precipitation have also been proposed (Grace, 1989). Halliday and Brown (1943) were the first to infer a relationship between the northern most position of trees in Canada and the 10° C isotherm in July. Bryson (1966) noted that the position of treeline in Canada corresponded to both the 10°C isotherm and the mean position of the arctic front in July. The arctic front delineates the boundary between areas to the north which receive dry cold arctic air masses from those areas to the south which are dominated by warm, moist air masses (Bryson, 1966). A similar relationship was recognized in northern areas of the Former Soviet Union by Krebs and Barry (1970). In a study by Timoney et al. (1992), the authors cautioned that climate alone could not account for the variability in both the width of treeline and the dominant vegetation cover found at this ecotone. Instead local and regional factors such as soils, parent material, topography, feedbacks resulting from the vegetation cover itself and fire history must be considered in tandem with synoptic scale climate in order to fully understand this ecotone.

Sirois (1992) argues that factors at even smaller scales must also be considered to explain the position of treeline. Trees must first be able to survive at treeline. Accomplishing that, they must then be able to produce viable seeds which produce seedlings.

1.3 Palynological investigations of the forest tundra - tundra ecotone across northern circumpolar regions

Investigations of treeline, both high altitude and high latitudes, have been undertaken throughout the circumpolar region using various proxy indicators. The most widely utilized techniques for reconstructing treeline are palynology and dendroecology. Palynological reconstructions are based primarily on the analysis of fossil pollen from lake sediments or peat deposits. Pollen reconstructions are often augmented by the use of additional proxy indicators such as, plant macrofossils (needles and seeds) and more recently, plant microfossils (leaf stomata). Stomata, which aid in the transfer of gases into and out of plants, are the lignified remains of leaf and needle guard cells. Dendroecological reconstructions are based on the analysis of dead tree remains which are sometimes found north of the present day position of this ecotone. These remains can then be radiocarbon dated, providing both the extent of treeline fluctuations and the timing of these changes. A summary of vegetation changes that have occurred since the last glacial is given in Table 1.

Table 1. Postglacial vegetation changes in circumpolar regions. Table 1 provides a general summary of vegetation changes which have occurred in Canada, Scandinavia, and the former Soviet Union. The reconstructions are based primarily on palynological evidence in Canada and the former Soviet Union. Scandinavian reconstructions are primarily from macrofossil and fossil remains of trees from north of the present day position of treeline. The reconstruction from western Canada is based primarily on the following work; Ritchie, 1982 and 1984; Cwynar, 1982; Cwynar and Spear, 1995; and MacDonald, 1987a. The vegetation history of central Canada is from the work of Moser and MacDonald, 1990; MacDonald et al., 1993; and MacDonald, 1995 . Eastern Canadian vegetation history is from the work of Richard et al., 1982; Gajewski et al., 1993; and Payette, 1993. The reconstruction from Scandinavia, based primarily on macrofossil remains and dead trees, comes from the work of Karlén, 1976; and Kullman, 1989, 1992, 1993. The vegetation history of the western former Soviet Union is based primarily on the work of Gorchakovsky and Shiyatov, 1978; Khotinskiy, 1984a; and Peterson, 1983 and 1993. Studies by Khotinskiy, 1984a; Arkhipov et al., 1994; Volkov, 1994; and Votakh and Klimanov, 1994 are used in the reconstruction of vegetation for the area between Ural mountains and the Lena River region. Finally, the vegetation history of eastern Siberia is based on pollen diagrams from Khotinskiy, 1984a and Lozhkin et al., 1993.

Circumpolar Postglacial Vegetation History

Region	Age of Deglaciation	Early Holocene (10-7 ka)	Mid Holocene (7-3 ka)	Late Holocene (3 ka - present)
Western Canada	14 - 11 ka BP	northward extension of Picea forests	treeline retreat	establishment of modern vegetation by ~6 ka
Central Canada	10- 6 ka BP	*Betula* tundra	northward extension of *Picea* forests	treeline retreat ~3.5 ka, establishment of modern tundra
Eastern Canada	11 - 6 ka BP	short lived herbaceous or dwarf shrub tundra	establishment of *Picea* at present northern limits ~4 ka	~3-2 ka - deforestation of forest tundra sites -modern tundra established
Scandinavia	10 - 8 ka BP	maximum limits of treeline is reached	treeline retreat beginning ~5 ka	establishment of modern vegetation; some indication of treeline advance in the last 100 yrs.
Western Russia	12 - 10 ka BP	maximum limits of *Picea* and *Larix* forests reached	treeline retreat commencing ~5 ka BP	~3.5 ka - southward extension of tundra vegetation types
Central Siberia	17 - 14 ka BP in the west ? to the east	maximum limits of *Larix* forest reached	treeline retreat commencing ~5 ka BP	3.5 ka - establishment of modern tundra vegetation
Eastern Siberia	? Beringia possibly 25 ka BP	maximum limits of *Larix* forest reached	treeline retreat commencing ~5 ka BP	3.5 ka - establishment of modern tundra vegetation

1.31 Western Canada

Most areas of northwest Canada were ice free by ~14000 - 11000 yr BP (Ritchie and Hare, 1971). Shortly following the retreat of ice from the northwest of Canada, tundra vegetation became established. The early tundra phase was dominated by *Betula nana* (dwarf birch) on the Tuktoyaktuk Peninsula, while in the Campbell Hills area the tundra was predominantly an open herb tundra with very little dwarf birch (Ritchie, 1984). The discrepancy between the early vegetation of these two areas may have been the result of the limestone rocks which dominate the Campbell Hills (Ritchie, 1984). The limestone substrata tends to inhibit the establishment of dwarf birch (Ritchie, 1984). An early to mid Holocene expansion of *Picea* forests in the northwest of Canada, between 10000 and 6000 yr BP, has been attributed to increased summer insolation (Ritchie et al., 1983). Milankovitch theory predicts that at this time summer insolation in northern latitudes was as much as 9-10% greater than at the present time. At approximately 6000 yr BP, the *Picea* forests were replaced by the modern tundra vegetation. Recent studies, (Cwynar and Spear, 1995 and MacDonald, 1995) indicate that the *Picea* forests were intially of *Picea glauca* (white spruce) which were later replaced by *Picea mariana* (black spruce) at about 6400 yr BP. The forests were replaced initially by a shrub tundra assemblage dominated by *Alnus* (alder) (Ritchie, 1984; MacDonald, 1995; Cwynar and Spear, 1995;) before the modern day vegetation was established.

1.32 Central Canada

The vegetation history of central Canada differs significantly from areas in the far northwest of the country. The initial vegetation became established after 7500 yr BP following deglaciation. A tundra environment dominated by *Betula* and a significant peatland component existed until *Picea* forests expanded between 5000 and 3500 yr BP (Moser and MacDonald, 1990; MacDonald et al., 1993). The expansion of *Picea mariana* in central Canada between 5000 and 3500 yr BP was not attributed to Milankovitch forcing since the expansion of the forests occurred significantly after the thermal maximum which occurred between 10000 and 6000 yr BP. MacDonald et al. (1993), attribute the asynchronous advance of treeline in central Canada to a shift in the summer position of the Arctic front caused by changes in frontal wave characteristics. Under this scenario, a northward displacement of the Arctic front in western Canada can result in a southward shift of the front in areas in central and eastern Canada (MacDonald et al., 1993). After 3500 BP the modern vegetation was established in central Canada. The tundra vegetation, established following 3500 yr BP, has changed little since the establishment of the modern vegetation (Moser and MacDonald, 1990). The deterioration of the *Picea* forest was likely caused by climatic cooling (Moser and MacDonald, 1990).

1.33 Eastern Canada

Deglaciation of northeastern Canada occurred considerably later than in western and central Canada. Gajewski et al. (1993), estimate that northwestern Quebec became ice free by 6000 yr BP. Coastal areas of Labrador were ice free as early as 10500 yr BP (Elliott-Fisk, 1983). Deglaciation is thought to have occurred from the east to west in eastern Canada. Coastal areas were the first to become free of ice followed by central areas of Labrador and then finally northwestern Quebec (Dyke and Prest, 1987).

Following deglaciation in eastern Canada, most sites were occupied by tundra for a brief period (Gajewski et al., 1993; Elliott-Fisk, 1983). Shortly after 6000 yr BP, *Alnus* became important throughout northwestern Quebec (Gajewski et al., 1993). The decline of *Alnus* at about 3800 yr BP was suggested to represent a forest tundra environment becoming more dense over time (Gajewski et al., 1993). Gajewski et al. (1993), found that *Picea* densities increased at the same time as the *Alnus* declined. Maximum forest density occurred between 3800 and 2000 yr BP in northeastern Canada (Gajewski et al., 1993; Elliott-Fisk, 1983). There is no evidence, however, that the northern limits of trees exceeded the modern position of treeline in northeastern Canada (Gajewski et al., 1993; Payette and Filion, 1985). Trees reached their northern limits in Quebec and Labrador along two major pathways, the Labradorian pathway, which was deglaciated early in the Holocene, and the Hudsonian pathway which became open later in the Holocene (Payette, 1993). The Labradorian pathway was associated with the more humid climate of the coast and thus had a more diversified group of trees associated with it. The Hudsonian pathway formed only after the glaciers had retreated to Hudson Bay and included a less diversified group of trees, of which only black spruce has reached the northern treeline in western Quebec (Payette, 1993).

Following 2000 yr BP forests in northeastern Canada appear to become less dense as a result of climatic deterioration and a failure to regenerate following fires (Gajewski et al., 1993). It is believed that in the late Holocene the frequency and intensity of fires increased in northeastern Canada due to increased fuel loads associated with the dense forests. The increased fires, combined with the cooler climate during the last 2000 yr BP, has resulted in some failure to regenerate following fires (Gajewski et al., 1993). As a result, treeline in northeastern Canada appears to becoming more fragmented along its northern edge, but it does not appear to be regressing southwards.

1.34 Scandinavia

Research indicates that northern areas of Scandinavia were ice free by about 9300 yr BP (Lundqvist, 1986; Kullman, 1989, 1992). Deglaciation in Scandinavia was complicated both by the mountainous terrain and the maritime climate. Deglaciation in western Scandinavia was interrupted by several readvances between 10000 and 9000 yr BP, likely due to a more abundant supply of precipitation (Lundqvist, 1986).

Vegetation reconstructions in Scandinavia have been based primarily on reconstructions utilizing macrofossil and fossil tree remains. The fossil tree remains, recovered from lakes and on the tundra above treeline, indicate that the early Holocene was much warmer than today. Both the altitudinal and latitudinal tree limits of *Pinus sylvestris* were located at higher elevations and latitudes reaching their maximums at ~8000 yr BP (Kullman, 1992). At this time, pine forests were found 165 m above the present day altitudinal tree limits (Kullman, 1993). Palynological and dendroecological studies indicate that after 4000 yr BP treeline regressed to the present day position (Hyvärinen, 1993; Kullman, 1993).

1.35 Western Russia and Central Siberia

Much of northern Russia and portions of central Siberia were covered by ice during the last glacial maximum. At that time, ice extended eastward from Scandinavia, across northern Russia as far east as to the Severnaya Dvina drainage basin (Velichko, 1995). Dating of end moraines across the glaciated portions of the European sector of the former Soviet Union indicates that the maximum glacial extents were reached at 24000 yr BP in the areas furthest east (western Siberia), 21000 yr BP in the central Russian plain and 18000 yr BP in the west of the Russian Plain (Velichko, 1995).

The early Holocene marked a significant change in the vegetation across European Russia and central Siberia. At about 10300 yr BP zonal vegetation (i.e. tundra, forest and steppe assemblages) was established (Khotinskiy, 1984a). At the same time as the vegetation shifted to zonal assemblages, there was also a change in atmospheric circulation to a zonal pattern (Khotinskiy, 1984a). The shifts seen in the vegetation patterns and postulated for the circulation patterns is considered by many Russian investigators to be the beginning of the Holocene.

The climate of the early Holocene, as inferred from pollen data, appears to have been considerably warmer than at the present time. Shrub and herb tundras were replaced by arboreal vegetation between ~9000 and 3500 yr BP. Treeline expanded as much as 300 km north of its present day position in some areas (Khotinskiy, 1984a). The expansion of treeline in the former Soviet Union appears to have occurred synchronously across all of northern Eurasia. Fossil wood samples, collected by PACT members, from the modern tundra, have been radiocarbon dated and all indicate that a forest existed across northern Russia from ~9000 to 3500 yr BP. After 3500 yr BP, arboreal vegetation was replaced by modern assemblages of herb and shrub tundra across northern Russia.

In the last few hundred years there has been some indication that treeline has expanded in northern regions of central Siberia and the European Soviet Union. According to Gorchakovsky and Shiyatov (1978), there has been a slow rise in the upper forest limit of the Boreal Zone of northern Russia during the first half of the 20th century. On the More-ju River west of Vorkuta, a similar expansion of a forest island during the last century has also been recorded by Tolmatchev (1972).

1.36 Eastern Siberia

The extent of glaciation in eastern regions of Siberia has been extensively debated by Soviet scientists. Many investigators believe that glaciation in eastern Siberia was restricted to mountain regions, such as the Verkhoyansk Range (Isayeva, 1984; Velichko, 1995; and Sher, 1995). Others (Grosswald et al., 1992) believe that a large panarctic ice sheet, similar to the Antarctic ice sheet, covered the present shelves of the Laptev, East Siberian and Chukchi Seas as well as the coastal areas of east Siberia (including the present study area). Numerous radiocarbon dates of sediments and animal remains refute the existence of glaciers throughout northeastern Siberia (Sher, 1995). A radiocarbon date of 21600 yr BP, on mammoth remains found insitu from the Bykov Peninsula near Tiksi, does not support the hypothesis of a panarctic ice sheet. Numerous other dates of mammoth remains have been obtained from throughout northeastern Siberia (Sher, 1995). Additional evidence against the glacial hypothesis includes the existence of Yedoma across the coastal lowlands and to areas to the south (Sher, 1995). Yedoma are fine-grained sediments which have high amounts of segregated ice, large vertical ice wedges and are known to be prone to plastic deformation (Sher, 1995). Analysis of these sediments has provided no evidence that they have experienced any deformation which would be expected had this area been glaciated (Sher, 1995). Finally, it would be expected that if glaciers of the extent proposed by Grosswald et al. had existed, evidence of isostatic rebound such as raised beaches would exist. According to Sher (1995) this type of evidence has not been found.

The vegetation history of eastern Siberia is very similar to the remainder of the former Soviet Union. A reorganization of vegetation assemblages in the early Holocene resulted in the development of the zonal vegetation that is seen across northern Russia today. Similar to the remainder of the former Soviet Union, a period of warmer temperatures and increased precipitation, resulted in an expansion of trees between 9000 and 3500 yr BP across northeastern Siberia. After 3500 yr BP the climate appears to have deteriorated resulting in the contraction of the taiga and the expansion of tundra to their present positions.

1.4 Research Objectives

The primary objective of this study is to determine the rate and extent of Holocene treeline fluctuations in the Lower Lena River Region, Siberia. A secondary objective of the research is to determine if the Younger Dryas cooling event was recorded in north-central Siberia. It is believed that the return to near glacial conditions between 11000 and 10000 yr BP was a hemispherical phenomena, and many believe it may have been a global occurrence. Given that this area appears to have been ice free during the last glacial, there is a strong possibility that evidence of the Younger Dryas may be found in the Lower Lena River Region of Siberia. Additional questions will also be addressed by the current study, including:

1. Are stomates useful proxy indicators to determine the presence of conifers north of treeline?

2. Has climate change in the Lower Lena River region occurred gradually, over thousands of years, or have the changes been short and rapid, occurring over periods of 100 years or less?

3. Alternatively, does the record indicate that climate fluctuations in the past occurred at both time scales?

To begin to address the objectives and questions of this study, a 365 cm lake core was recovered using from a tundra lake in the Lower Lena River region of north-central Siberia. Fossil pollen, stomates, the organic content of the sediments and the sediment stratigraphy were all analysed. Chronological control was obtained from radiocarbon dating aquatic moss and wood fragments recovered from the lake core.

CHAPTER TWO

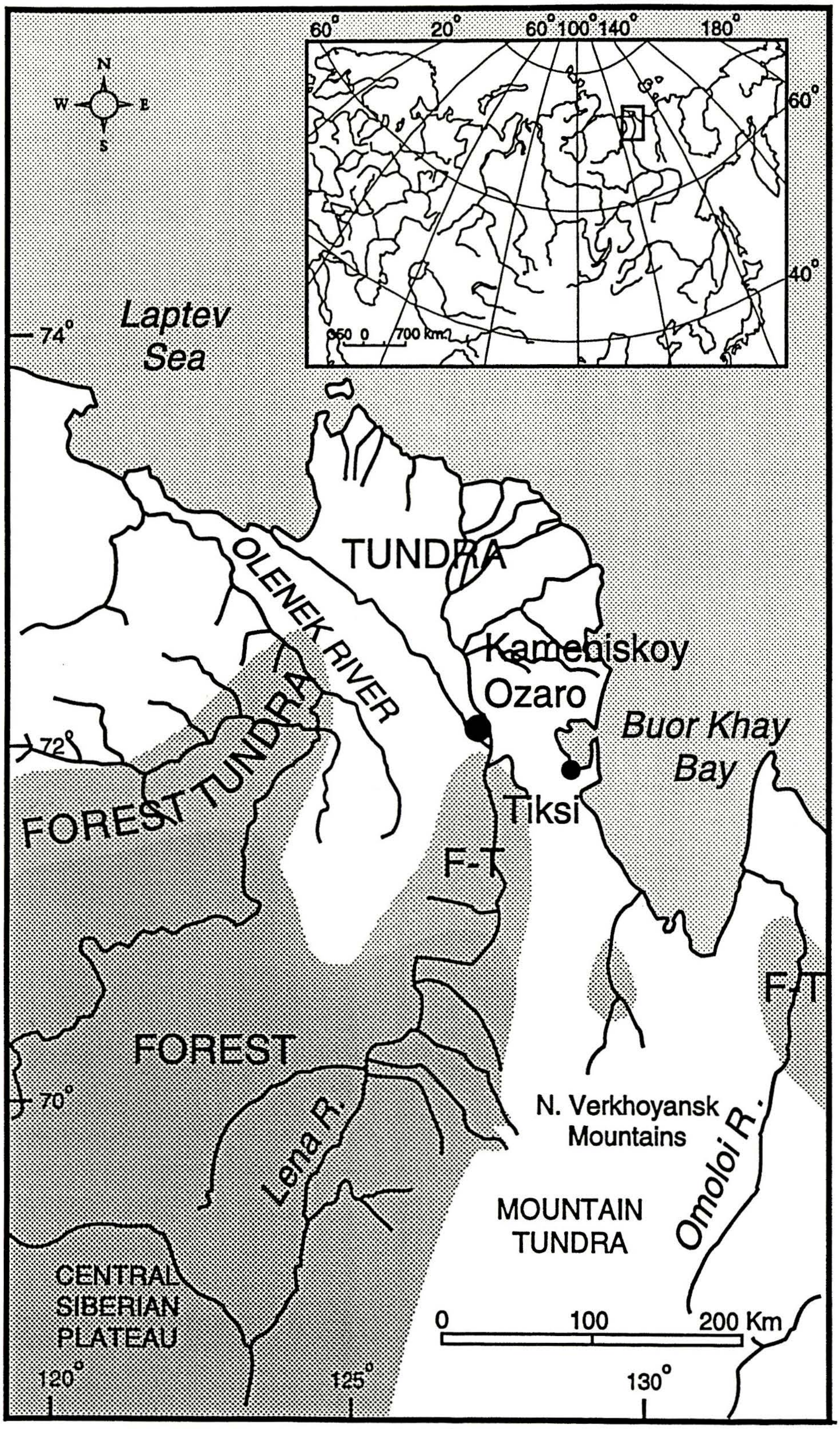
STUDY AREA

The area selected for this study is in the Sakah Republic (formerly Yakutia) of north central Siberia, approximately 100 kilometres northwest of Tiksi. The study area is within the present day tundra zone, with the forest tundra and forest zones found at successively greater distances to the south. A lake core was raised from Kameniskoy Ozaro (unofficial name), in the summer of 1994. Kameniskoy Ozaro is a medium sized lake (~84 ha) at an elevation of approximately 40 m above sea level (a.s.l.), and a depth of 4 m. It is some 35 m above the Lena River and does not seem to be affected by flooding from the river. Figure 2 provides an aerial view of Kameniskoy Ozaro. The coordinates of the sampling site as determined by a Geographical Positioning System (GPS) are 71° 52.41 N, 127° 04.39 E. The site is approximately 100 kilometres south of the Lena River delta and ~150 kilometres from the coast of the Laptev Sea (Figure 3). It is less than 1 kilometre from the main channel of the Lena River.

The study area is bounded to the east by the north-south trending Verkhoyanskiy Khrebet (North Verkhoyansk Mountains). To the west of the site the relief gradually rises up to the central Siberian Plateau. North of the site is the Lena River delta, formed as the river drains into the Laptev Sea. The relief around the lake is slight with sinuous, nearly parallel, north-south oriented ridges of exposed bedrock separating intervening troughs. There are numerous lakes, of various sizes, in the study area, which form a complex drainage pattern through the many lakes before reaching the Lena River. Drainage in the area is directed northwards through the Lena River. The lake chosen for this study drains through a below ground channel on its eastern side into an adjacent lake. Drainage is then directed through this lake into the Lena River.

Figure 2. Aerial view of Kameniskoy Ozaro. Located in north-central Siberia, the lake has an area of approximately 84 ha and a depth of 4 m. The lake has no channels entering or exiting its basin. Drainage occurs through an underground channel on the east side of the lake (right side of picture).

Figure 3. Map of the Study Site. The lake core was obtained from Kameniskoy Ozaro, indicated by the circle . The boundaries separating the forest, the forest-tundra and the tundra zones are also shown on the map.


60°
20°
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40°
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Laptev
Sea
74°
TUNDRA
OLENEK RIVER
Kamenniskoy
Ozaro
Buor Khay
Bay
Tiksi
72°
FOREST TUNDRA
FOREST
F-T
F-T
FOREST
70°
Lena R.
N. Verkhoyansk
Mountains
Omoloi R.
MOUNTAIN
TUNDRA
CENTRAL
SIBERIAN
PLATEAU
0
100
200 Km
120°
125°
130°

2.1 Bedrock Geology

The study area is part of the Verkhoyano-Kolyman orogenic system which formed as a result of folding and faulting during Mesozoic times (Grosswald et al., 1992). The study site itself is located in a large geosyncline through which the Lena River flows (Brown et al., 1994). This syncline marks an ancient fold in the strata and is a characteristic feature in this part of Russia (Brown et al., 1994). Bedrock in the area are from the Cretaceous and are predominantly sandstones (Markov, 1970 in Grosswald et al., 1992). The strike of the bedrocks are nearly north-south based on visual inspection of exposed bedrock ridges from photos and air photos. Deposits in the area are predominantly colluvium, of Quaternary age (Zarkhidze et al., 1991). There is also the possibility of alluvial deposits of Holocene age occurring in the study area as well (Zarkhidze et al., 1991).

2.2 Glacial History

It has been proposed by Isayeva (1984) and many others (Sher, 1995; Andreev, *per. com.*) that the Tiksi area was not glaciated during the last glaciation. This however, is highly debated. For example, Grosswald et al. (1992) claim there is abundant evidence of the presence of glaciers in this area. According to Grosswald et al. (1992), evidence that this is a glaciated landscape includes "fresh looking U-shaped valleys, giant flutes, rock drumlins, and other ice-erosional features." In an earlier study by Grosswald and Spektor (1990, in Grosswald et al., 1992) field observations also revealed sandstone boulders with well preserved glacial striae and crescentric gouges. Finally, Grosswald et al. (1992) suggest that Accelerator Mass Spectometry (AMS) ^{14}C dates of 6450+/-110, 6870+/-80, and 8500+/-160 from basal lake sediments suggest a late Pleistocene deglaciation of this area.

Observations made by PACT members during field work in the summer of 1994 do not support the findings of Grosswald et al. (1992). Glacial landforms such as striae and drumlins were not encountered within the field area (Edwards, *per. com.*).

2.3 Soils

In the tundra zone around the study site soils are thin and weakly developed, particularly on the top of the ridges running parallel to the lake. In the hollows between ridges soils are deeper. Soils become deeper and more developed in areas further to the south, with the deepest and most developed being found beneath the closed canopy forests of the Taiga region.

Soil conditions in this area are strongly influenced by permafrost conditions in the particular area. In the immediate study area, continuous permafrost is very close to the surface, being found only 20-30 cm below the surface in the summer months (Andreev, *per.com*). Drainage is impeded by the permafrost forming characteristic Tundrovo-gleyevye or Cryic gleysols. Continuous permafrost conditions are found throughout the study area. The southern limits of the continuous permafrost is located approximately 1000 km to the south of the study site (Davdova and Rakovskaya, 1990).

2.4 Climate of the Region

The climate in this region is dominated by a cold continental regime. Total annual precipitation varies between 300 - 400 mm with the majority of the precipitation occurring during the summer months (Brown et al., 1994). Winters are cold and dry. The mean annual temperature in January is approximately -36°C, while precipitation is very low averaging about 10-25 mm for the month. Summers tend to be cool and somewhat wetter. The mean July temperature is about 8°C and precipitation varies between 50 - 75 mm. Precipitation is higher in the summer months mainly because the arctic front is displaced northwards. This allows a higher proportion of storms to pass over the area resulting in greater amounts of precipitation during those months.

The dominance of trees in the forest tundra and forest zones has dramatic impacts on the albedo of the surface. The albedo will be significantly reduced by the presence of trees, especially evergreens, as opposed to a snow covered surface such as in tundra regions. The changes in the albedo from 0.36 over tundra surfaces to 0.26 over forested regions result in significant feedbacks on the climate (Foley et al., 1994). It is suggested that the presence of forest above the snow cover results in an additional 8 Wm^{-2} absorbed solar radiation or a temperature difference of approximately 1.6°C (Foley et al., 1994).

2.5 Present Day Vegetation

The study area encompasses three vegetation zones, the tundra in the north, the forest to the south, and between the peripheral zones is the transitional zone known as the forest tundra.

The tundra region in this area is characterized by low lying shrub species such as *Betula nana*, *Alnus crispa and A. fruticosa* (green alder and speckled alder) and Ericaceae (heaths). Along river banks shrub *Salix* (willow) occurs as a result of the more mesic conditions. In low lying areas with poor drainage, *Eriophorum* (cottongrass) and Cyperaceae (sedges) are abundant as are mosses and lichens. On drier sites a diverse assemblage of tundra herbs and grasses can be found. Approximately one kilometre to the south of the study site there is a stand of krummholz *Larix dahurica*.

Moving southward the low lying vegetation of the tundra ecotone is gradually replaced by the transitional zone known as the forest tundra. The forest tundra zone is comprised of vegetation elements common to both the forest and the tundra regions. Scattered individuals of *Larix dahurica* occur in the more sheltered locations, especially where conditions are more moist such as along the banks of rivers and lakes or in areas where greater amounts of snow accumulate in the winter. These scattered individuals form the northern limits of trees in this area. Shrub *Betula, Alnus* and *Salix* occur in poorly drained boggy or damp areas. On rocky well drained sites, the vegetation is more characteristic of tundra vegetation with herbs dominating, including Ericaceae.

Further south the vegetation becomes dominated by the closed canopy of the Boreal forest or Taiga. In the lower Lena River region the forest is dominated almost exclusively by *Larix dahurica*. Tree species of *Betula* are relatively uncommon in the forests of this area. In areas east of the Lena River, *Pinus pumilla* (dwarf siberian pine) forms a thick subcanopy beneath the *Larix*. Further to the west the forest is a mixture of *Larix dahurica* and *Picea obovata*.

2.6 Physiology of the Dominant Treeline Species - *Larix dahurica*

The environmental setting at treeline across Siberia creates conditions which are unique compared to other circumpolar treeline sites in the world. Siberia, owing to its geographical position, is dominated by a severe continental climate. Winters are extremely cold, January temperatures average -36°C (Brown et al., 1994), with temperatures as low as -67.7°C having been recorded . In continental areas of the Northwest Territories in Canada, winter temperatures are not as severe, with mean January temperatures ranging from -25 to -30°C (Matthews and Morrow, 1985). As a result of the more continental climate in Siberia, temperature and precipitation regimes are very different and may account for the dominance of *Larix dahurica*. *Larix spp.* are one of several types of conifer species which are deciduous. Every fall *Larix* sheds its needles and goes into a dormant state similar to deciduous species of hardwoods. In a study by Sakia (1978) it was found that the buds and twigs of *Larix spp.* could resist freezing down to temperatures below -70° C, comparable to species of *Pinus*. *Picea*, however, showed damage to leaf buds at temperatures of -40°C (Sakia, 1978). This likely explains why *Larix* and *Pinus* form the northern forests across much of Siberia. By being deciduous, *Larix* needles effectively avoid the harshest period of the year, when temperatures can commonly be as low as -40°C and precipitation as little as 10-25 mm per month (Brown et al., 1994). The deciduous nature of *Larix* may therefore account for its dominance along treeline in central Siberia.

CHAPTER THREE

METHODS

3.1 Field Methods

Three lake cores were obtained from Kameniskoy Ozaro, one 330 cm long, one 308 cm long and the third 321 cm long. The top 35 cm of the record were retrieved using a plastic tube sampler. For this study the 330 cm core and the 35 cm plastic tube core were used for all analyses. The 321 cm core was kept in Russia for analysis by the Soviet scientists and the third core was retained as an archive core. The long cores were obtained using a modified Livingstone Piston corer (Wright et al., 1984). Field work was undertaken when the lake was ice free; therefore, two rubber rafts and a wooden deck served as the coring platform. Coring stopped when the impenetrable base of the lake basin was encountered.

Kameniskoy Ozaro was selected to study since it is north of the present day treeline. Given that one of the aims of this study is to determine past fluctuations in the position of this ecotone this was an important selection criteria. Changes in the position of this ecotone should be apparent in the fossil pollen and stomate record. A second important criteria used in determining the selection of this lake for coring purposes was the absence of streams running into and out of the lake. This would reduce the possibility of pollen and stomates being deposited in the lake from outside of the region.

Given that Kameniskoy Ozaro is considered to be a medium sized lake, it should provide a regional pollen signal as opposed to a highly local signal from a small lake or an extra-regional signal that would be obtained from a very large lake (Prentice, 1985). Satisfactory coring sites in this area were very limited for several reasons. First, most of the lakes were very shallow. Therefore, many of these lakes would freeze to the bottom during the winter and would cause severe mixing of the sediments. Secondly, in many of the lakes there simply was not enough accumulated sediment to obtain a reasonable length record (PACT Members, 1996).

3.2 Laboratory Procedures

3.21 - Radiocarbon Dating

Accelerator Mass Spectrometry (AMS) radiocarbon dates were obtained from aquatic moss and wood fragments from the core. An initial set of six dates, spaced evenly throughout the core, were selected based on the presence of macrofossils, while a second set of 4 dates were chosen based on significant changes that were seen in the pollen and stomate record. Samples were taken from 61cm, 71.5cm, 117cm, 145cm, 192-194cm, 229cm, 249cm, 252.5cm, 287.5cm, and 298cm. No material suitable for dating could be found below 298 cm. All samples were sent to Ramon Aravena at the University of Waterloo for pretreatment and then to Isotrace Radiocarbon Laboratory's Accelerator Mass Spectrometry facility at the University of Toronto.

3.22 - Loss on Ignition

A 1 ml sub-sample was processed following the procedures developed by Dean (1974) to determine the organic content in each sample. Samples were weighed and then oven dried for 24 hours to remove any moisture from the samples. Samples were then burned in a muffle furnace at 500°C for one hour to remove the organics. Samples were then cooled in a desiccator and reweighed. The difference between the oven dried weight and the burned weight is the percentage loss on ignition and is directly related to organic carbon content (Dean, 1974).

3.23 - Pollen Analysis

To obtain a high resolution record the 330 cm lake core was subsampled at every 3.5 cm. The plastic tube section of the core (0-35 cm) was sampled at closer intervals (1 cm), but analysis was performed on every 7th sample since there were no major changes in either the pollen or stomate records in this portion of the core. Where major shifts in the pollen and stomate record occurred samples were counted at 3.5 cm intervals. One ml of sediment was processed at each interval following the guidelines of Faegri and Iverson (1989). Samples near the bottom of the core contained large amounts of fine grain sediments so these samples were sieved following the methods developed by Cwynar et al. (1979). One calibrated and pretreated Lycopodium tablet was added to each sample so that pollen and stomate concentrations could be calculated (Stockmaar, 1971. and Maher, 1981). Samples were treated with Hydrochloric Acid (HCl), Potassium hydroxide (KOH), and Hydrofluoric Acid (HF) to remove calcium carbonate ($CaCO_3$), organics and silica, respectively (Faegri and Iverson, 1989). A treatment using Acetolysis (a mixture of 9 parts Acetic Acid to 1 part Sulfuric Acid) in a hot water bath for 5 minutes was used to remove cellulose from the samples. The pollen and stomates remaining after the acid treatments were dyed using a Safarin colouring agent and were then mounted in silicon oil (2000 cs) for analysis using a standard microscope at 400 x power.

Pollen and Stomate Accumulation Rates (PAR and SAR, respectively) were calculated by determining the sedimentation rate and the pollen and stomate concentrations at each interval. By combining these results the total accumulated pollen/stomates can be calculated per year. The sedimentation rate was determined by plotting eight Accelerator Mass Spectrometry (AMS) dates on an age vs. depth graph. A straight line plotted through the points using linear regression provided the average sedimentation rate for the core.

Pollen identification followed guidelines developed by McAndrews et al. (1973), Moore et al. (1991), Bassett et al. (1978), Kapp (1969), Faegri and Iverson (1989) and a modern reference collection. Attempts were made to distinguish between *Alnus fruticosa* (speckled alder) and *Alnus crispa* and *Betula alba* (white birch) and *Betula nana*. Determinations were based on visual inspection of the thickness and shape of the pore openings, with *Betula alba* and *Alnus fruticosa* (See, Mayle et al., 1993b) having thicker and more pronounced pore openings (Andreev, *per.com*). At each interval at least 300 pollen grains and 100 Lycopodium tablets were counted. The pollen sum was based on terrestrial pollen types only. Pollen and stomate concentration and PAR and SAR diagrams were developed based on the fossil pollen and stomate counts. The diagrams were visually divided into pollen assemblages based on changes that occurred in the pollen concentration diagram.

3.24 - Stomate Analysis

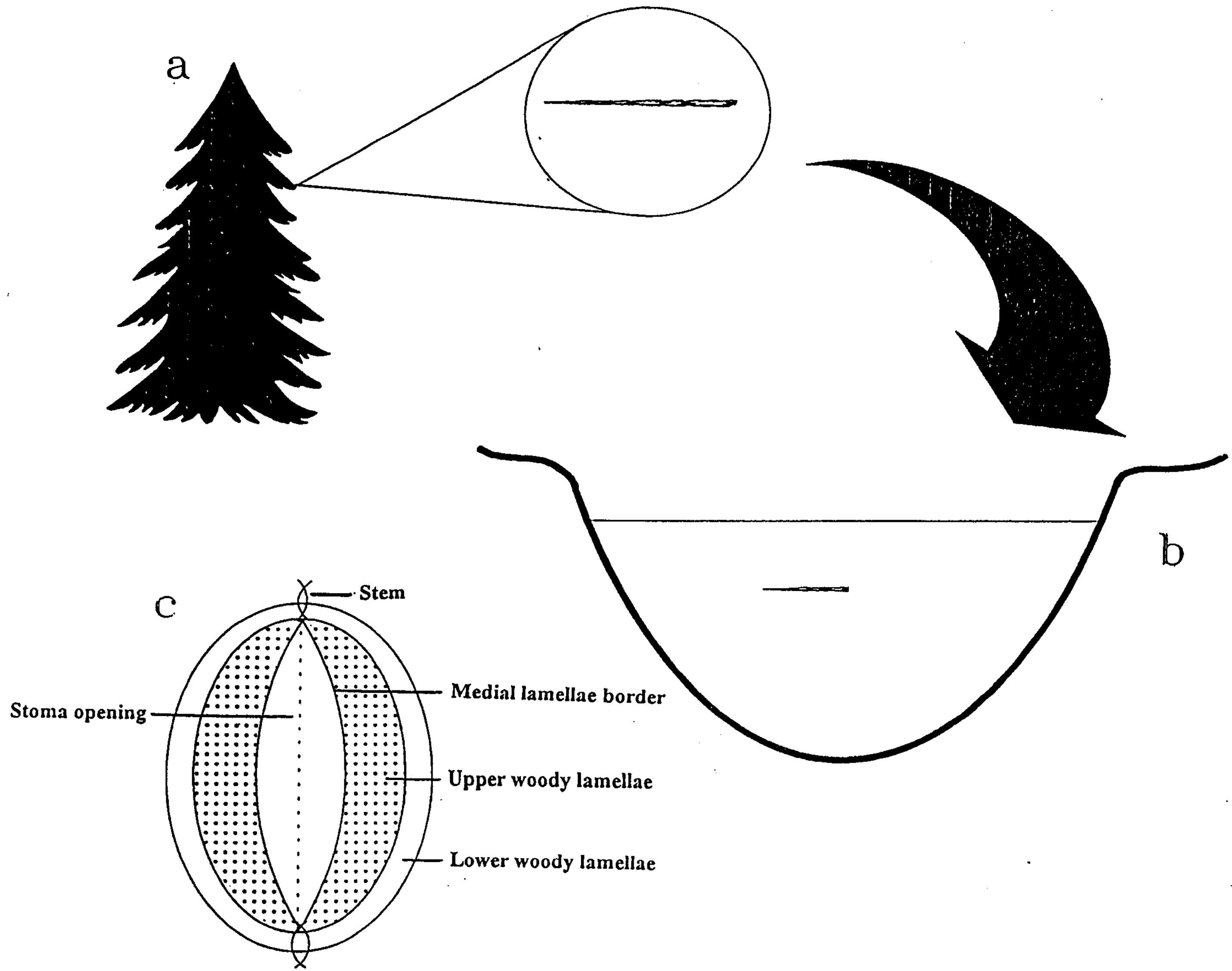
In most instances, the fossil pollen record provides a useful method to reconstruct past changes in vegetation assemblages. Studies of treeline dynamics, utilizing pollen analysis alone, have been hampered due to the differential preservation of some pollen types and, more importantly, the long distance transport of several types of pollen (Ritchie 1984). Conifer species such as *Pinus* and *Picea* both produce copious amounts of pollen which are easily transported by wind (Ritchie, 1984). This problem is further exacerbated at sites north of treeline where the open nature of the environment enhances the transport of exotic pollen. As a result the deposition of arboreal pollen in tundra lakes is not uncommon and must be kept in mind when trying to ascertain the extent and timing of previous shifts of treeline. In addition, some pollen types (i.e. *Larix* and *Populus*) are not preserved well in sediments for various reasons, and therefore are often underrepresented in the pollen record (Ritchie, 1984). To overcome the problems associated with the analysis of pollen, a new technique, stomate analysis, has been developed elsewhere (See; Hansen, 1995 and Trautmann, 1953) and will be utilized in this study. This will be a useful technique for the study of vegetation changes in the Lena River region since treeline is formed by *Larix dahurica*, a species whose pollen is often poorly preserved and underrepresented in the fossil pollen record.

Stomates are specialized cells that allow the diffusion of gases into and out of leaves and needles of plants. They become preserved in sediments when a needle falls from a tree and becomes deposited into a lake (Figure 4a). Once in the lake, the needle begins to decay leaving the lignified stomate in the sediments (Figure 4b). It has been suggested that the preservation of stomates, after the remainder of the leaf or needle has decayed, is the result of lignification of their guard cells (Hansen, 1995; Hansen et al., 1996 and Clayden et al., 1996). The morphology of a stomate consists of the upper and lower woody lamellae, the medial lamellae borders, the stem and the stoma opening (Figure 4c.). Stomates are distinguished based on variations in the above morphological characteristics.

Stomates were identified using a modern reference collection and the key developed initially by Trautmann (1953) and modified by Hansen (1995). The modern stomate reference collection included samples collected by Dr. Les Cwynar and Susan Clayden from the University of New Brunswick. Samples collected from needles from the study area were processed at Dr. Cwynar's lab following the same procedures developed for processing pollen. Preparation of the fossil stomates followed the same procedures. Stomates were mounted in silicon oil (2000 cs) and counted in the same manner as pollen, using a standard microscope at 400x power.

The analysis of stomates in sediments is a very useful technique, since it indicates the local presence of the species in an area. Stomates are similar to macrofossils, given the fact that their source must have been very close to the depositional environment. It is unlikely that the leaves and needles from which the stomates are derived were carried a great distance given that lakes selected for studies such as this often have no streams flowing in and out of them.

Figure 4 (a-c). How stomates become incorporated into lake sediments. a) A needle falls from a tree into the lake. b) While in the lake, the needle decays leaving the stomates behind as a record in the sediments. c) The fossil stomates can then be identified based on the specific morphological characteristics which are shown.


a
b
c
Stem
Medial lamellae border
Stoma opening
Upper woody lamellae
Lower woody lamellae

CHAPTER FOUR

RESULTS

4.1 Sediment Stratigraphy

Sediments from the base of the core (365 cm) up to 338 cm are a mixture of sand and clays (Figure 5). These sediments are predominantly sand with concretions of clay within the sand. At this point organic sedimentation began. From 338 cm to 326 cm grey brown lake mud or gyttja was deposited. The lake muds grade sharply into a layer of sand and clays which were deposited from 325 cm to 308 cm. After 308 cm, deposition of gyttja resumed. The sediments became more organic and a layer of aquatic moss was found between 301 cm and 286 cm. At 265 cm the sediments became sandier and there was a visible change in the colour of the sediments from the brown to a light brown-grey. This sand phase extended to about 250 cm where the sediments again became organic rich lake muds. The next 140 cm of the sediment record (from 250 to 110 cm) is composed of fine grained lake muds with layers of aquatic moss interspersed throughout. A layer of aquatic moss was deposited between 246.5 cm and 239 cm, with two additional layers being found at 193.5 cm and 177 cm. A substantial moss layer was recorded between 148 and 110 cm, with the moss being significantly thicker between 114 and 110 cm. The final 50 cm of the long core (110 to 60 cm) was predominantly lake muds but the texture of the sediments did become slightly sandier. Another layer of aquatic moss was recorded between 75 and 60 cm.

The top 35 cm of the sediment record was recovered using the plastic tube sampler. These sediments had a significantly higher water content than samples recovered from the long core. These sediments were similar in texture to sediments between 110 and 60 cm. Fragments of aquatic moss were found throughout the samples taken from the plastic tube with thicker layers being found between 3 and 7 cm and 20 and 23 cm.

4.2 Loss on Ignition

LOI records a sharp decrease in the percentage of organics, decreasing from ~16% at 329.5 to as low as ~3% between 326-308.5 cm (Figure 5). After 308.5 cm the percentage of organics in the sediments increases again to as much as 28 % before decreasing below 20 % around 284 cm. Values as low as 10% occur around 270 cm. After 270 cm, the percentage of organics in the sediment increases to 20-25% near 205 cm. From 205 cm to ~107 cm values are moderate, about 15%, but the overall pattern is of decreasing values. Values decrease slightly to about 10% between 107 cm and 20 cm. The final 20 cm of the record are marked by a sharp increase in the percentage of organics, with values approaching 25%.

4.3 Radiocarbon Dating

Dating control for the fossil pollen and stomate records was obtained from radiocarbon dating of aquatic moss and wood fragments. One bulk date was obtained on moss and wood fragments from 192-194 cm. Ten radiocarbon dates are provided in Table 2 and plotted on an age vs. depth profile in Figure 5. Two of the radiocarbon dates were considered to be too young, one at 61 cm and the other at 249 cm, and were not plotted on the age vs. depth profile. These dates were both several thousand years too young and were therefore not used to calculate the sedimentation rate of the record. The rejected date at 249 cm produced a magnitude less carbon after processing than other samples. This small amount of datable gas could have easily been contaminated causing the date to be younger than expected. There are several possible sources for this contamination. The most likely are, a contaminated sediment may have been processed prior to this sample, contaminating samples which were dated after it. Secondly, give the small amount of dateable gas, it is possible that a dust particle would have been enough to cause the date to be younger than expected. The source of contamination for the date at 61 cm is more uncertain. Nuclear testing has occurred in the area and could have contaminated the upper sample. It appears from the age vs. depth profile that there has not been major changes in the sedimentation rate at this site. Therefore a single regression line plotted through the 8 acceptable dates provides the overall sedimentation rate for this record. The regression yielded a sedimentation rate of 0.02 cm/yr for the last 12310 yr BP.

Figure 5. Sediment characteristics and radiocarbon chronology. Provides the results of analysis of sediment stratigraphy, percent organics, and radiocarbon dating. Radiocarbon dating was performed by Isotrace Laboratories in Toronto.

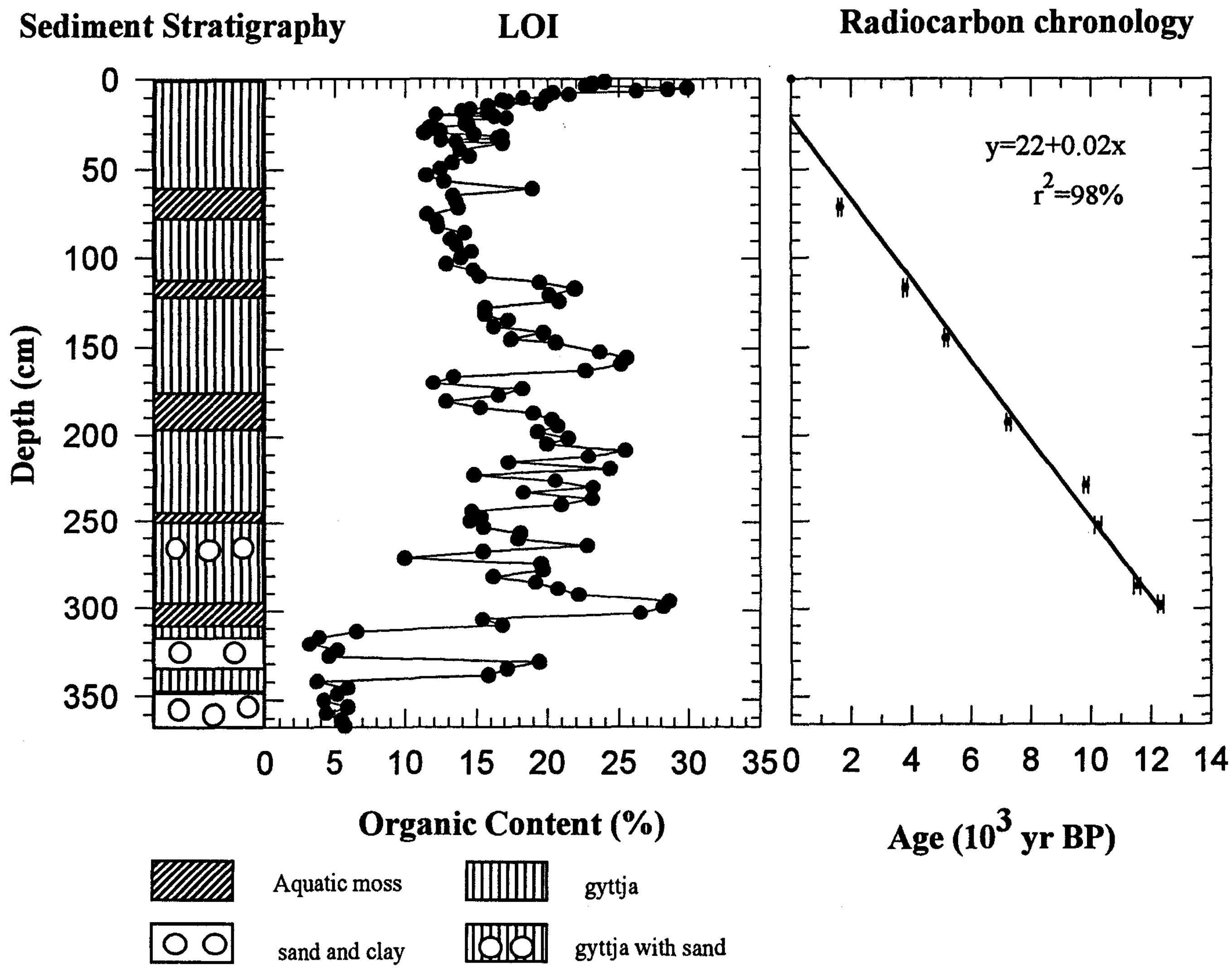

Sediment Stratigraphy
LOI
Radiocarbon chronology
Depth (cm)
0
50
100
150
200
250
300
350
0
5
10
15
20
25
30
35
Organic Content (%)
0
2
4
6
8
10
12
14
Age (10^3 yr BP)
y=22+0.02x
r^2=98%
Aquatic moss
gyttja
sand and clay
gyttja with sand

Table 2. Radiocarbon Dates for Kameniskoy Ozaro. Table 2 outlines important aspects of the radiocarbon dates used in this study. Included in the table is the lab which performed the work, the material used in the dating process and the amount of datable carbon (CO_2 STP) that was obtained from each sample. Dates are presented as uncalibrated conventional radiocarbon dates in years BP.

Results of ^{14}C Accelerator Mass Spectrometry Analysis

Depth (cm)	Description	Lab	Lab Number	CO_2 (ccSTP)	Age (^{14}C yr BP)
61	aquatic moss	Isotrace	TO-5254	3.7	-2000 ± 50*
71.5	aquatic moss	Isotrace	TO-5719	2.8	1630 ± 60
117	aquatic moss	Isotrace	TO-5245	2.3	3780 ± 70
145	aquatic moss	Isotrace	TO-5255	0.7	5150 ± 70
192-194	moss and wood	Isotrace	TO-5720	2.8	7250 ± 80
229	aquatic moss	Isotrace	TO-5246	3.1	9830 ± 80
249	aquatic moss	Isotrace	TO-5256	0.3	7300 ± 280*
252.5	aquatic moss	Isotrace	TO-5721	1.1	10240 ± 120
287.5	aquatic moss	Isotrace	TO-5722	1.8	11520 ± 110
298	aquatic moss	Isotrace	TO-5247	4.3	12310 ± 100

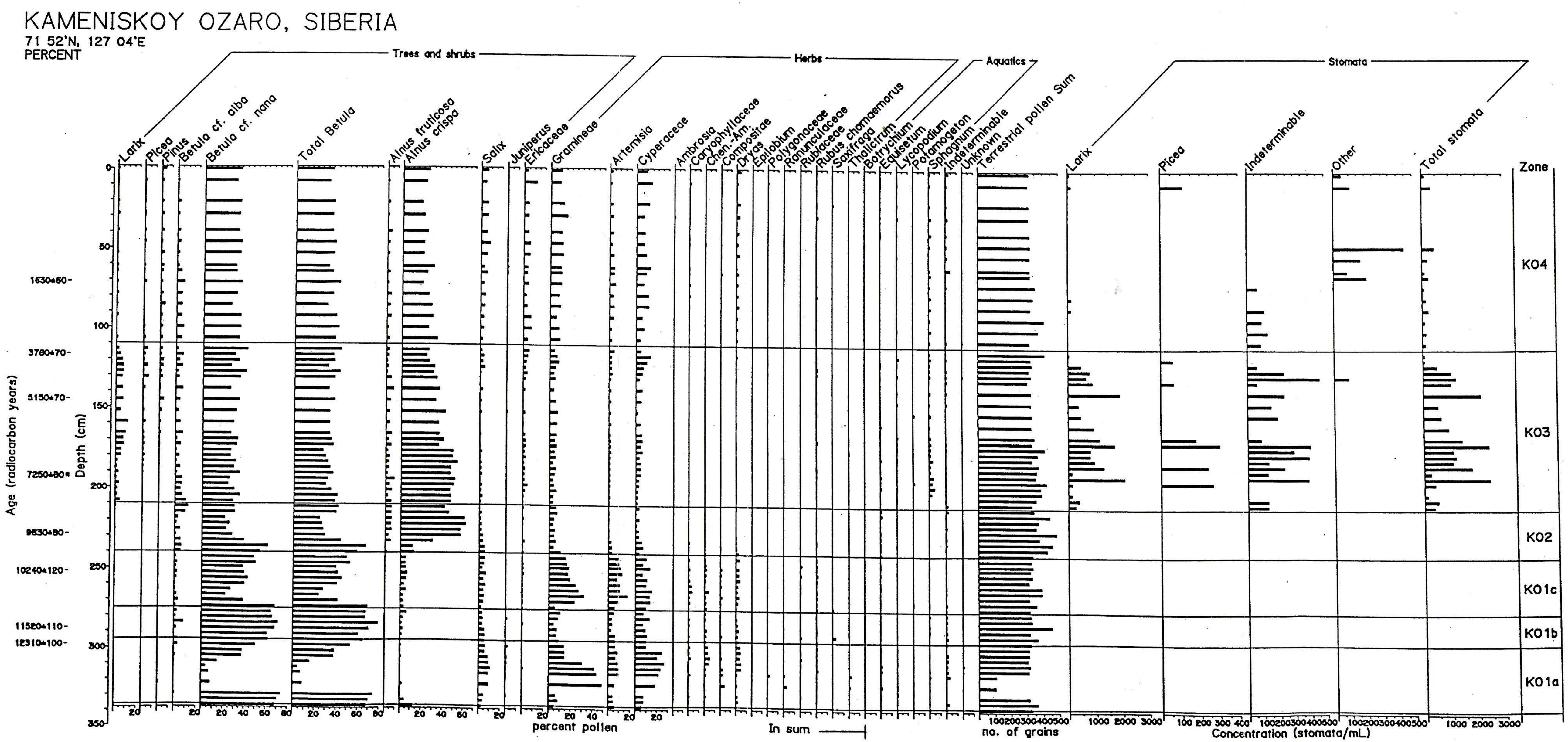
***rejected as contaminated**

4.4 Pollen and Stomate Stratigraphy

Six zones, based on pollen assemblages, were determined for Kameniskoy Ozaro. The position of the zones were determined by visual inspection of the pollen percentage diagram. Each zone boundary delineates a period where there were significant changes in the frequency of pollen of several taxa. The six zones are illustrated in the pollen percentage diagram (Figure 6) and the pollen accumulation rate diagram (PAR) (Figure 7).

The bottom 30 cm of the core contained no pollen. Analysis of other proxy indicators from this zone, such as diatoms and chironimids, have also been unsuccessful (Cwynar, *per. com.*).

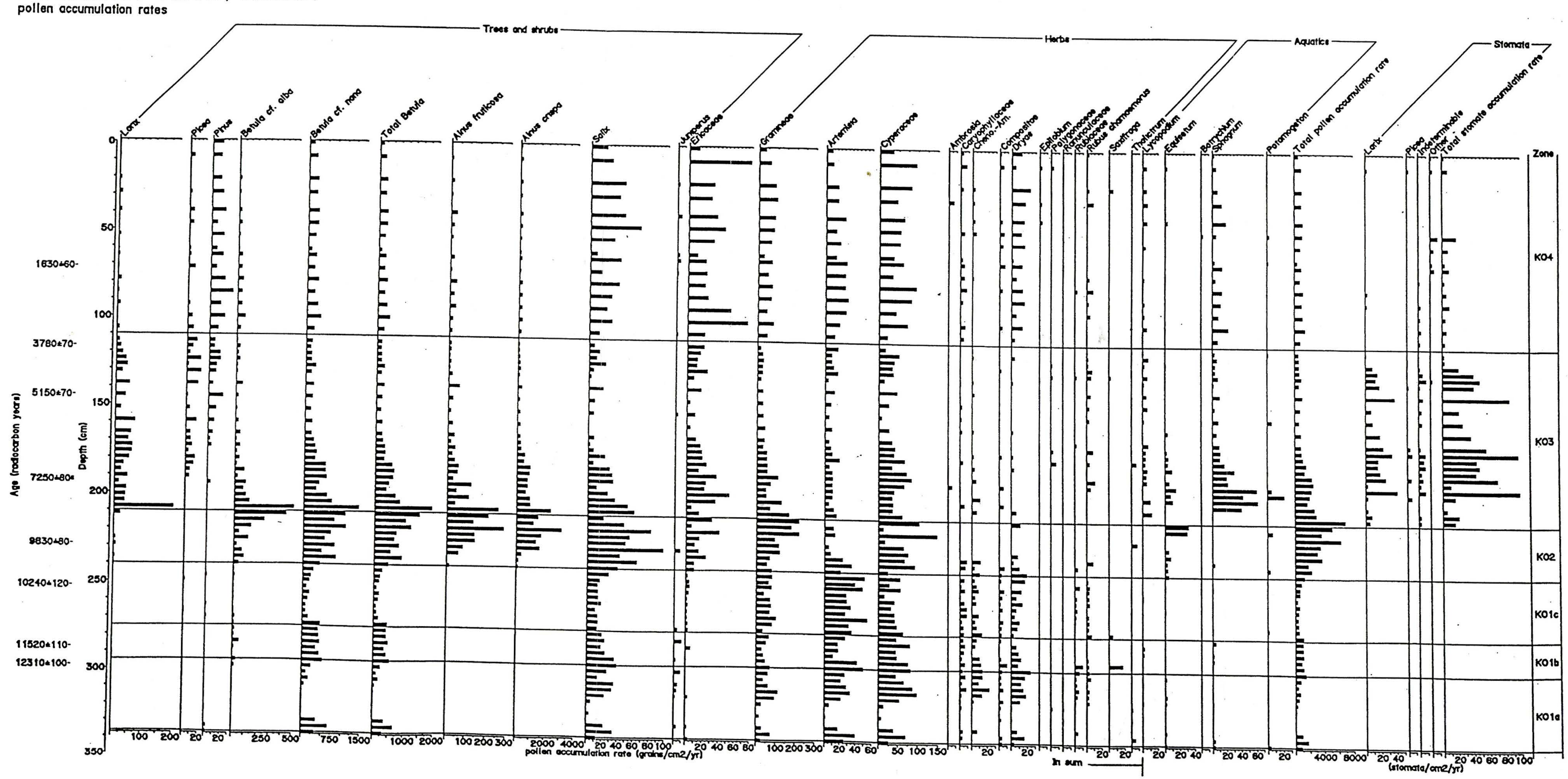
Figure 6. Pollen and Stomate Percentage Diagram, Kameniskoy Ozaro. Figure 6 is the pollen percentage diagram from Kameniskoy Ozaro, illustrating changes in the relative percentages of pollen during the late Pleistocene and the Holocene. Six zones were distinguished based on changes in the fossil pollen assemblages. Zone KO1a, a herb dominated zone, is characterised by a sharp decrease in *Betula* pollen with a concomitant increase in the pollen of several herbs. Zone KO1b, the *Betula cf. nana* zone, a shrub tundra environment dominated by *Betula cf. nana*. Zone KO1c, another herb dominated zone, distinguished by a decrease in shrub *Betula* and a rise in the pollen of herbs. Zone KO2, the *Alnus - Betula* zone, marks the appearance of *Alnus* in the fossil pollen record. Zone KO3, *Larix* zone, distinguished by the appearance of *Larix* in both the fossil pollen and stomate records. Zone KO4, *Betula - Alnus* zone, delineates the onset of the modern shrub tundra vegetation around this site.



KAMENISKOY OZARO, SIBERIA
71 52'N, 127 04'E
PERCENT
Trees and shrubs
Herbs
Aquatics
Stomata
Larix
Picea
Pinus
Betula cf. alba
Betula cf. nana
Total Betula
Alnus fruticosa
Alnus crispa
Salix
Juniperus
Ericaceae
Gramineae
Artemisia
Cyperaceae
Ambrosia
Caryophyllaceae
Chen.-Am.
Compositae
Dryas
Epilobium
Polygonaceae
Ranunculaceae
Rubiaceae
Rubus chamaemorus
Saxifraga
Thalictrum
Botrychium
Equisetum
Lycopodium
Potamogeton
Sphagnum
Indeterminable
Unknown
Terrestrial pollen Sum
Larix
Picea
Indeterminable
Other
Total stomata
Zone
K04
K03
K02
K01c
K01b
K01a
Age (radiocarbon years)
Depth (cm)
1630±60-
3780±70-
5150±70-
7250±80-
9830±80-
10240±120-
11520±110-
12310±100-
percent pollen
In sum
no. of grains
Concentration (stomata/mL)

Figure 7. Kameniskoy Ozaro Pollen Accumulation Rates diagram. Changes in the pollen and stomate accumulation rates are shown in Figure 7. Six zones depicting the changes seen in the pollen and stomate percentage diagram are illustrated. The sharp increase in the PAR of several taxons at the boundary of zones KO1c and KO2 may be the result of a decrease in the sedimentation rate.

KAMENISKOY OZARO, SIBERIA
pollen accumulation rates



4.41 - Zone KO1a (*Salix-Dryas-Artemisia*-Cyperaceae-Gramineae zone) - ? yr BP to ~12050 yr BP (336.5 - 294.5 cm)

This is the basal zone of the core. The zone is delineated by the rapid decrease of *Betula cf. nana* at approximately 326.5 cm. At the same time there is a concomitant rise in the pollen of several herbs, including: *Dryas*, Gramineae, *Artemisia* and Cyperaceae. At the onset of zone 1a, *Betula cf. nana* pollen accounted for approximately 74 % of the total pollen; however, it decreased abruptly at ~326 cm to minimum values as low as ~4 %. Maximum percentages are attained by several herb species; *Dryas* (~5%), and Chenopodiaceae-Amaranthaceae (~5%), as well as Gramineae (41 %) and Cyperaceae (up to 26 %). Pollen accumulation rates in zone 1a could only be estimated, since no basal date was obtained. Assuming a constant sedimentation rate of 0.02 cm/yr, the pollen accumulation rate is quite low, 200 - 500 grains/cm^2/yr, with values as low as 36-62 grains/cm^2 /yr being recorded between 315.5 and 322.5 cm. The change in sediments from sands and clays in zone 1a, to organics in 1b, indicates that sedimentation rates were likely not constant as assumed. Therefore; pollen accumulation rates in this zone, have to be considered as tentative estimates only.

4.42 - Zone KO1b (*Betula cf. nana* zone) - ~12 050 yr BP to ~11 000 yr BP (294.5 cm - 275 cm)

This zone is delineated by the increase of *Betula cf. nana* pollen. *B. cf. nana* rapidly increased from ~53% at the onset of the zone to 78% before stabilizing between 66 - 69%. *Betula* pollen reaches maximum percentages (~78%) in zone 1b. Zone 1b is also characterised by the gradual decrease in the pollen of herbs such as *Artemisia,* Chenopodiaceae-Amaranthaceae, and Gramineae. Cyperaceae pollen decreases abruptly from ~24% at the top of Zone 1a to ~6-12% throughout Zone 1b. *Saxifraga* is recorded in the fossil pollen record for the first time in zone 1b, accounting for only ~2.5%.

Pollen accumulation rates in Zone 1b reflect the changes that were seen in the pollen percentage diagram. Total pollen accumulation rates range from ~700 grains/cm^2/yr at the onset of zone 1b, to a maximum of ~1300 grains/cm^2/yr. Total pollen accumulation rates at the close of zone 1b decrease slightly to approximately 1100 grains/cm^2/yr.

4.43 - Zone KO1c (Gramineae - Cyperaceae - *Artemisia* - *Dryas* zone) - ~11 000 yr BP to 10 000 yr BP (275 cm to 240 cm)

Zone 1c is distinguished in the fossil pollen record by the rapid decrease in the pollen of *B. cf. nana* and the concomitant rise of herbaceous taxa such as: *Dryas, Artemisia,* Gramineae and Chenopodiaceae-Amaranthaceae. Percentages of *Betula* pollen decrease from ~69 % at the onset of the zone to lowest values of ~23 % before recovering to near initial values (~67 %) at the top of zone 1c. *Artemisia* reaches maximum percentages (~17%) in zone 1c, as does Caryophyllaceae (~3%), and Rubiaceae (~1%). Percentages of the shrub *Alnus crispa* remain low in this zone (~2-6%).

PAR's record the dramatic decrease in *Betula* pollen, decreasing from ~450 grains/cm^2/yr at the onset of zone 1c to as little as 69 grains/cm^2/yr before recovering to ~300 -400 grains/cm^2/yr at the beginning of zone 2. PAR's indicate that the deposition of *Salix* pollen was decreasing in this zone, pollen percentages, however, indicate that the percentages of this taxon were remaining stable or increasing slightly. A similar trend is seen in the pollen percentages and PAR's of Cyperaceae. The large increase in Gramineae pollen percentages is recorded in the PAR diagram although the increase is not as dramatic. The PAR diagram does illustrate the dramatic increase in the pollen of *Artemisia* which was recorded in the pollen percentage diagram. Total PAR in zone 1c shows a significant and rapid decrease at the onset of the zone (decreases from 1100 grains/cm^2/yr to ~300 grains/cm^2/yr) before rapidly increasing at the close of the zone to ~1200 grains/cm^2/yr.

4.44 - Zone KO2 (*Alnus - Betula* zone) - ~10 000 yr BP to 8500 yr BP (240 cm to 210 cm)

Zone 2 is delineated by the increase of *Alnus* pollen percentages (from ~5% at the close of zone 1c to as much as 60% in zone 2), and the rapid decrease in *Betula* pollen (~62% near the beginning of zone 2 and as low as 21% before slightly recovering to ~ 40% at the close of zone 2). The remainder of the fossil pollen record is dominated by *Alnus crispa* and *Betula cf. nana*, with *Betula* increasing slightly from zone 2 onwards while *A. crispa* shows decreasing pollen percentages for the remainder of the pollen record. Zone 2 is also characterised by the overall decrease in the pollen percentages of herbs and grasses. *Artemisia* decreases from ~10% at the close of zone 1c to values less than 1% in zone 2. Similar decreases are also seen in Gramineae (10% to 3-6%), *Dryas* (~2% to <1% to 0%), and Chenopodiaceae-Amaranthaceae (~1% to <1% to 0%). Cyperaceae percentages also decrease dramatically in zone 2, decreasing from 10% in zone 1c to 2-6%. Zone 2 is also distinguished by the appearance of *Alnus fruticosa* in the pollen record (2-5%).

PAR's in zone 2 do not closely follow the patterns that are seen in the pollen percentage diagram. The decrease in *Artemisia* pollen percentages is reflected in the PAR diagram as is the changes seen in percentages and PAR's of total *Betula* and *Betula cf. nana*. All other taxa show increases in PAR's at the close of zone 2, even when their respective percentages may have been indicating a decrease in the taxa. Total PAR increases steadily throughout zone 2 and the beginning of zone 3. Total PAR increases from ~1200 grains/cm^2/yr at the onset of zone 2 to almost 7000 grains/cm^2/yr at the close of zone 2.

4.45 - Zone KO3 (*Larix - Picea* zone) - ~8500 yr BP to 3450 yr BP (210 - 110 cm)

Zone 3 is delineated by the emergence of *Larix dahurica* and *Picea obovata* in the pollen record. *Larix* pollen reaches maximum percentages of 11% in zone 3. Zone 3 also marks the first appearance of two other arboreal types in the fossil pollen record, *Picea* (maximum percentages of ~4%) and *Pinus* (~1%). Percentages of *Betula cf. nana* pollen show an increasing trend throughout zone 3 -increasing from 28% at the onset to 34% at the top of zone 3. This increasing trend continues for the remainder of the record, reaching ~35% at the top of zone 4. At the same time as *Betula* is increasing, percentages of *Alnus* increase initially and then decrease steadily throughout the remainder of zone 3 and 4. At the beginning of zone 3 *Alnus crispa* percentages increase from 41% up to ~51% and then steadily decline to ~31%. *Sphagnum* reaches maximum percentages in zone 3, reaching values of 1-5%. Other aquatic species, such as *Lycopodium spp.* (~1%) also reach maximum percentages in zone 3. The majority of herbs occur at percentages of less then 1% in zone 3, the exceptions being only *Artemisia* and Gramineae. Percentages of Ericaceae increase from the bottom of zone 3 to the top (from <1% at the onset to ~4% at the top of the zone). Ericaceae percentages continue to increase in zone 4 also.

At the beginning of zone 3 pollen accumulation rates for most species continue the pattern of increase that began at the end of zone 2. Only a few taxa show decreasing PAR's at the bottom of zone 4, including, Ericaceae, Cyperaceae, Gramineae and *Equisetum*. Total pollen influx also continues to increase at the start of zone 3, up to 7000 grains/cm^2/yr before decreasing to ~1000 - 2000 grains/cm^2/yr. Following the sharp rise in pollen accumulation rates at the beginning of this zone, PAR's for most taxa decrease rapidly. *Betula cf. nana* pollen decreases from ~1400 grains/cm^2/yr to approximately 700 grains/cm^2/yr. *Alnus crispa* has a similar pattern, decreasing from 2300 grains/cm^2/yr to ~1000 grains/cm^2/yr. *Larix* pollen also shows a similar pattern, decreasing from approximately 200 grains/cm^2/yr to about 35 grains/cm^2/yr. *Sphagnum* reaches maximum PAR's in zone 3 with values as high as 61 grains/cm^2/yr before decreasing to <10 grains/cm^2/yr during the remainder of the zone.

4.46 Zone KO4 (*Betula - Alnus* zone) - 3450 yr BP to present (110 cm - 0 cm)

The delineating characteristic of the final zone in the fossil pollen record is the decrease in *Larix* and *Picea* pollen. *Larix* pollen percentages are low throughout the entire zone, accounting for less then 1 %. Zone 4 is dominated by *Betula cf. nana* and *Alnus crispa* once again. *Betula* pollen percentages account for ~30 - 40%, while *Alnus crispa* percentages vary between 19 - 30%. *Pinus* pollen is found throughout zone 4 but in only very small percentages, <5%. Arboreal pollen from *Betula cf. alba* is also present, but again only in very small percentages - <7%. Shrubs and herbs become abundant once again. *Salix* reaches percentages as high as 9%, Ericaceae - 7%, *Artemisia* - 5%, *Dryas* - 3% and Gramineae - 12%. Cyperaceae percentages increase from lower values in zones 2 and 3 to maximums for zone 4 of ~11%. *Sphagnum* continues to be found in the pollen record although in very small percentages, 2% and less.

PAR's reflect the patterns seen in the pollen percentage diagram. Increases in herbaceous taxa are apparent in the PAR diagram as is the increase in *Pinus* pollen. The continued presence of *Sphagnum* in the pollen record is reflected in the PAR diagram. Total pollen influx is relatively constant in zone 4 varying between 1400 grains/cm^2/yr and 400 grains/cm^2/yr.

4.5 Stomate Stratigraphy

For much of the fossil record from Kameniskoy Ozaro stomates are lacking. The first appearance of stomates in the record occurs in zone 3. This correlates well with the first appearance of the treeline species, *Larix dahurica*, in the pollen record. The majority of stomates in samples from zone 3 were identified as *Larix*, accounting for 90 % of the stomates in most instances. Stomate accumulation rates reach maximum values in zone 3. Total stomate accumulation rates in zone 3 range from lowest values of 0 stomates/cm^2/yr to values as high as 43 stomates/cm^2/yr. *Larix* stomates account for the majority of the stomates that were deposited, reaching maximum accumulation rates of ~38 stomates/cm^2/yr.

The number of stomates found in the sediments decreases in zone 4. *Larix* stomates are found only as scattered individuals. An unknown type of stomate (labelled "Other" on the percentage diagram) becomes the most abundant. This unknown type looked very similar to stomates from birch leaves; however, a positive identification could not be made. The stomate accumulation rate changes dramatically in zone 4, decreasing from a high of 43 stomates/cm^2/yr in zone 3, to a maximum of only ~9 stomates/cm^2/yr. The majority of the stomates found in zone 4 were of an unknown type (referred to as "Other" on the pollen diagrams), with maximum accumulation rates of ~9 "other" stomates/cm^2/yr.

CHAPTER FIVE

VEGETATION DEVELOPMENT IN THE LOWER LENA RIVER REGION OF SIBERIA

5.1 Vegetation Reconstruction

The analysis of a 335 cm lake core and 30 cm plastic tube core resulted in the reconstruction of the late Pleistocene and Holocene vegetation in the vicinity of Kameniskoy Ozaro. Analysis of the fossil pollen from this lake identified six pollen zones:

i. Gramineae - Cyperaceae-*Dryas-Artemisia-Salix* zone

ii. *Betula cf. nana* zone

iii. Gramineae - Cyperaceae - *Artemisia* - *Dryas* zone

iv. *Alnus* - *Betula* zone

v. *Larix* - *Picea* zone

vi. *Betula* - *Alnus* zone

The changes delineated by these six zones reflect changes in the vegetation around this lake over a minimum of the last 12300 years BP. The past vegetation of this site will be reconstructed based upon the analysis of pollen percentages and accumulation rates, sediment characteristics and fossil stomates. Chronological control is based on the results of 8 AMS radiocarbon dates.

5.11 - Zone KO1a (*Salix-Dryas-Artemisia*-Cyperaceae-Gramineae zone) - ? yr BP to ~12050 yr BP (336.5 - 294.5 cm)

The origin of Kameniskoy Ozaro is unknown; therefore, speculation is all that can be offered. The shape and location of Kameniskoy Ozaro suggests that it may be the result of fluvial scouring by the Lena River. The lake is situated in sandstone bedrock, parallel to the Lena River. It is possible that during periods of increased flow, especially following melting of mountain glaciers in the late Pleistocene, that the lake bed was carved by fluvial processes in the sandstone bedrock. More resistant layers of sandstone were not worn away resulting in a depression surrounded by the more resistant bedrock. As flows in the Lena River decreased the lowered topography was stranded. Eventually the lake filled in the depression and sediments began to accumulate. Sediments at the bottom of the lake core, sands and some pebbles, would appear to support this interpretation. It is uncertain as to when sedimentation began since no basal date could be obtained. Assuming a constant sedimentation rate of 0.02 cm/yr throughout the record, a basal date of 14000 - 15000 yr BP is possible.

The basal zone is delineated by the abrupt decrease in the pollen of *Betula*, and the concomitant rise in the pollen of several herbs, including: Cyperaceae, Gramineae and *Salix*. Assuming a late Pleistocene date for the basal zone, it is likely that the dominant vegetation at the onset of this zone, *Betula*, was probably *Betula cf. nana* (Ritchie, 1984). Low percentages of *Betula cf. alba* in this zone are probably of exotic origin and do not reflect the local presence of that taxon at this time. *Betula* species are known to produce copious amounts of pollen and is often overrepresented in the pollen record (Ritchie, 1984), but the high percentages of *Betula cf. nana* (up to 80%) at the onset of zone 1a probably indicates local presence of the species. In a study of the modern representation of vegetation in the pollen record, Ritchie (1977 and 1982) found that 2-3 % dwarf birch ground cover could result in 13-28 % pollen in nearby lake sediments. It would appear that the abundance of dwarf birch was approximately 6 times greater in zone 1a than it is in the modern tundra. Zone 1a from Kameniskoy Ozaro is similar to zone HL-2 from Hanging Lake in the northern Yukon of Canada (Cwynar, 1982). Both zones are initially characterised by high percentages of *Betula*, followed by abrupt decreases in this pollen type to very low percentages. At the same time as *Betula* is decreasing in both records the pollen of grasses, sedges and herbs increase dramatically. The last 14000 yr BP of the Hanging Lake record shows some similarity to the present record and lends support to the belief that the present record began about 14000 - 15000 yr BP.

The shrub tundra which characterises the onset of zone 1a was quickly replaced by a vegetation assemblage dominated by Gramineae, Cyperaceae and several herbs. The dominance of taxa such as Gramineae, Cyperaceae, *Dryas* and *Artemisia* during the middle of zone 1a probably indicates a shift from shrub tundra conditions to a vegetation assemblage dominated by low lying vegetation types. Conditions were likely colder and drier given the presence of cryophytic and xerophytic taxa in the pollen record, such as *Dryas*, a herbaceous taxon whose presence is often used by palynologists to indicate such conditions. Additional evidence of cold and dry conditions includes the presence of Caryophyllaceae and

Chenopodiaceae-Amaranthaceae, both herbaceous taxa which are commonly represented in dryland arctic situations (Polunin, 1959). Maximum values of *Salix* in this basal zone are not unquestionable. Arctic willows are low plants found in a variety of habitats including well drained sites. The maximum of *Salix* pollen in this zone is likely a relict of pollen percentage diagrams. Given that pollen percentage diagrams depict only relative changes in pollen, a decrease in other species, such as *Betula cf. nana*, could possibly account for the maximum percentages of *Salix*. In this case, *Betula cf. nana* may have decreased on the landscape due to the colder and drier conditions that likely existed at that time, while *Salix*, may not have been affected by the change. Pollen accumulation rates would give a better indication if in fact this scenario occurred; however, without reliable dating control it is not possible to accurately determine the rate of pollen influx. A large decrease in the percentage of organics at this time supports the hypothesis of a shift to a more open, less productive type of vegetation cover, such as a tundra environment.

At the close of zone 1a, at approximately 12050 yr BP, the herb tundra vegetation which had dominated the middle part of zone 1a was once again replaced by shrub tundra. *Betula cf. nana* was again the dominant species on the landscape. It appears that the vegetation assemblages in zone 1a were quite different from the present day tundra. A lack of substantial *Alnus crispa* pollen indicates that this species was likely absent from this area, unlike today where its presence on the landscape gives pollen percentages as high as 25%. The complete dominance of *Betula cf. nana* pollen also distinguishes the vegetation assemblages at the onset and the close of zone 1a from modern tundra conditions.

5.12 - Zone KO1b (*Betula cf. nana* zone) - ~12050 yr BP to ~11000 yr BP (294.5cm - 275 cm)

Zone 1b is marked by the continued dominance of *Betula cf. nana* in the pollen record which was briefly halted in the mid stages of zone KO1a. Zone 1b is also delineated by the coeval decrease in the percentages of Gramineae Cyperaceae and *Salix* as well as the percentages of the xerophytic and cryophytic taxons described in zone KO1a. *Alnus crispa* pollen is found throughout zone 1b but at very low values. Given that *Alnus* is a prolific pollen producer and is often overrepresented in pollen records (Ritchie, 1984) it is unlikely that such low values indicate that the species was locally present on the landscape. Zone 1b appears to be a continuation of the *Betula* shrub tundra that was found at the beginning and close of zone 1a.

Pollen accumulation rates in zone 1b indicate that the vegetation cover was likely quite sparse around Kameniskoy Ozaro in the late Pleistocene and early Holocene. PAR's in zone 1b are some of the lowest values in the record.

The organic content in zone 1b increased substantially from the very low values seen in zone 1a. Zone 1b has the highest LOI values of the entire record. The increased organics in the sediments supports the idea of a shift back to a shrub tundra environment. The increased vegetation coverage of the dwarf birch shrub tundra likely resulted in more organics being deposited into the lake basin. Alternatively, the vegetation coverage of the shrub tundra environment may have reduced the amount of inorganic material being washed into the lake.

The shift in the pollen record from herb dominated taxa in zone 1a to the high dwarf birch percentages in zone 1b reflects a change from tundra conditions to dwarf birch shrub tundra. The dwarf birch shrub tundra community existing at this site between 12050 yr BP and 11000 BP is similar to the "Allerod bush tundra" proposed by Velichko (1995) which replaced earlier arctic tundra communities in eastern Siberia.

5.13 - Zone KO1c (Gramineae - Cyperaceae - *Artemisia* - *Dryas* zone) - ~11000 yr BP to 10000 yr BP (275 cm to 240 cm)

A sharp decrease in dwarf birch pollen marks the onset of zone 1c. At the same time the values of: Gramineae, Cyperaceae, *Artemisia* and *Dryas* rose significantly. The percentage increase in Gramineae, Cyperaceae, *Artemisia*, and *Dryas* are all reflected in the PAR diagram. The influx of Cyperaceae in zone 1c is not; however, as dramatic an increase as the other taxa mentioned above. Therefore the large percentage increase in Cyperaceae was likely only a relative change and not the result of an increase of this taxa on the landscape. The occurrence of *Salix* pollen increases slightly at the onset of zone 1c. This increase; however, is not reflected in the pollen accumulation rate diagram. PAR's indicate that the importance of *Salix* was in fact decreasing and that percentage increases were likely the result of relative changes in pollen deposition and not reflecting what was actually occurring around the site. The taxa present in zone 1c is very similar to those which occurred earlier in the record in zone 1a. The presence of xerophytic and cryophytic taxa such as Chenopodiaceae-Amaranthaceae and Caryophyllaceae again suggest that the climate became colder and likely drier between 11000 and 10000 yr BP. The substantial increases in both the pollen accumulation rates and the percentages of *Artemisia* supports the belief that this area was drier between 11000 and 10000 yr BP. *Artemisia* is a herbaceous low shrub species found throughout the Soviet steppe and low arctic (Khotinskiy, 1984a; Lozhkin et al., 1993; and Velichko, 1995.). Presence of this taxon is typically used to indicate arid conditions. The high proportion of herbaceous species, grasses and sedges indicates that this must have been an open environment with very little shrub coverage, especially between 11000 yr BP and ~10550 yr BP. The presence of Ericaceae and *Rubus chamaemorus*, both taxa of wet heath conditions (Cwynar, 1982) do not; however, support the idea that this period was arid. PAR rates for both of these species are very low, but as Ritchie (1984) points out, the pollen of Ericaceae is usually underrepresented in the pollen record. The increase in these mesic heath plants, typical of the tundra, may be the result of the cold climate that existed at that time. According to Khotinskiy (1984a) winters were very cold, but summers even though they were short, were fairly warm. This resulted in increased seasonality at this time. A higher permafrost table, due to colder winter temperatures, could have increased soil moisture in the short summer by impeding drainage or increasing melting of the permafrost. This may have resulted in the mesic conditions necessary for very localized development of heath species. Cwynar (1982) used a similar explanation to account for the development of Ericaceae taxa in the northern Yukon at 11000 yr BP.

Total pollen influx decreased to the lowest levels of the entire record during zone 1c, while the percentage of organics in the sediments dropped significantly at the beginning of zone 1c until ~10550 yr BP, again indicating that vegetation coverage was likely meagre. Between 10550 and 10000 yr BP it appears that some climatic amelioration occurred. The percentage and influx of shrub species such as *Betula cf. nana* and *Salix* both increased.

5.14 - Zone KO2 (*Alnus - Betula* zone) - ~10000 yr BP to 8500 yr BP (240 cm to 210 cm)

A major change in the dominant vegetation marks the onset of zone 2. *Betula cf. nana* is replaced as the dominant taxon by *Alnus crispa*. *Alnus fruticosa*, a hybrid species of *A. crispa* and *A. hirsuta* (Andreev, per. com.), is consistently recorded in the pollen record after ~9850 yr BP. Tree birch continues to occur in the pollen record in zone 2. Zone 2 is also delineated from the previous zone by the disappearance of those taxa with arctic affinities. Low values of Ericaceae continue; however, the PAR diagram indicates that the influx of this pollen type increased substantially at 9860 yr BP. This probably indicates a higher proportion of Ericaceae on the landscape, possibly due to a wetter environment. *Artemisia* becomes less important in the pollen record at this time. This supports a shift to a wetter environment given the affinity of *Artemisia* for dry habitats.

High percentages and PAR's of *Alnus crispa* may be giving a false impression as to how important this species actually was on the landscape. As noted in zone 1c, *Alnus* is a prolific pollen producer and is usually overrepresented in the pollen record (Ritchie, 1984). Ritchie (1984) estimates that *Alnus* pollen percentage:cover percentage ratios may be as high as 20:1 in northwest Canada. If this is also true in northern Siberia, than the increase in *Alnus* percentages from ~1-5% in zone 1c to values as high as ~60%, at ~9300 yr BP, may be implying a vegetation shift of only minor magnitude. On the landscape, the increase in pollen from *Alnus* may have translated into a shift from a landscape with only a few *Alnus* shrubs, or perhaps none if long distance transport was responsible for the earlier *Alnus* pollen, to one that included possibly 3 % *Alnus* shrubs.

Knowing that *Betula* and *Alnus* are prolific pollen producers, it is uncertain whether the low pollen percentages of *B. cf. alba* and *A. fruticosa* are recording the local presence of the species or transport of pollen from distant populations. Currently, *B. cf. alba* is found 350 km south of the study site, while *Alnus fruticosa* is found along coastal uplands as far west as only the Verkhoyansk Mountains.

The increase in the PAR of Ericaceae in zone 2 suggests that the site may have continued to become more mesic. The decrease in abundance of xeric taxon such as: *Artemisia*, Chenopodiaceae-Amaranthaceae, *Dryas*, and Caryophyllaceae support the belief that this period signalled the onset of more mesic conditions.

The percentage decreases in Gramineae and Cyperaceae were not reflected in the PAR diagram. For both species the PAR diagram suggests that they were in fact becoming more abundant on the landscape. The decreases in the percentages of both species were likely due to the percentage increase in *A. crispa* and *A. fruticosa*.

Zone 2 is marked by the almost complete disappearance of *Artemisia* from the pollen record. The decrease in *Artemisia* appears in many records across Russia at the boundary of Preboreal stage 2 and the Boreal period (between ~10 000 yr BP and 9000 yr BP). In central Yakutia the *Artemisia* decline commences at ~9800 yr BP (Andreev, unpublished). In the European portion of Russia, Khotinskiy (1984a) determined that *Artemisia* began to decline at ~9900 or 9800 yr BP. In central Siberia east of the Ural mountains, Khotinskiy (1984a) has shown that in the area near Sverdlovsk, the *Artemisia* decline began slightly later at approximately 9100 yr BP. Finally in the far east, Lohzkin et al., (1993) date the decline of *Artemisia* much earlier than in the other regions, at 12500 yr BP. The decline in *Artemisia* across many regions of the former Soviet Union was likely due to a shift to a wetter climate. This agrees with other palynological evidence that suggests that the climate was becoming wetter and probably warmer.

Pollen accumulation increases throughout zone 2 and reaches maximum values for the entire record at ~ 9000 yr BP. PAR's for most taxa show increasing values at the boundary between zones 2 and 1c. These increases are evident for: *Larix, B. cf. alba, B. cf. nana, Salix, A. fruticosa, A. crispa,* Ericaceae, Cyperaceae, and Gramineae and are not reflected as percentage increases for all species. It is likely due to a change in the sedimentation rate. There is a change in the sedimentation rate of 0.02 cm/yr that was averaged for the entire record to 0.01 cm/yr between 193 cm and 229cm. This may have resulted in the increased deposition rate of pollen of most taxa at that time. The organic content is moderately high throughout zone 2.

Pollen and sedimentological evidence suggests that zone 2 represents the first appreciable climatic amelioration at Kameniskoy Ozaro. The presence of *B. cf. alba* and *A. fruticosa* both suggest range extensions of several hundred kilometres at the least, and possibly more, if in fact the pollen was locally derived as opposed to being transported from populations further away. The high PAR's and moderate LOI values suggest decreased erosion into the lake, likely due to the increased vegetation cover.

5.15 - Zone KO3 (*Larix* - *Picea* zone) - ~8500 yr BP to 3450 yr BP (210 - 110 cm)

The increased pollen representation of *Larix* and *Picea*, coupled with the presence of these taxa in the stomate record, suggest forests extended north of this site between 8500 and 3450 yr BP. Taxa common to open environments, such as grasses, *Artemisia*, and Cyperaceae are low throughout zone 3. Zone 3 marks the first appearance of fossil stomates in the sediment record, most of which are *Larix* with only scattered occurrences of *Picea*.

The presence of *Larix* pollen and stomates, likely *Larix dahurica* (Polunin, 1959., Ritchie, 1984), indicates the presence of a forest vegetation assemblage in this area between 8500 yr BP and 3450 yr BP. Macrofossils of *Larix* trees from this area, which predominantly date from the same time period (MacDonald, *per. com.*), provide additional evidence of the presence of trees in this region. A study examining the modern pollen from surface samples on the Taimyr Peninsula (Clayden et al., 1996), indicates that *Larix* pollen in forest sites reach maximum percentages of approximately 10%. These low values in a forest dominated by *Larix* trees are not unexpected since it is well known that the pollen of *Larix* is often underrepresented in the pollen record (Ritchie, 1984). Fossil stomates are therefore very useful indicators of the local presence of this species. Stomates are similar to macrofossils in that the source of the stomates was likely close to the depositional environment. Derived from the leaves and needles of plants, it is unlikely they were transported far from their source. The presence of *Larix* pollen, stomates and macrofossils all indicate an advancement of *Larix* trees into this area between 8900 yr BP and ~ 3450 yr BP.

At approximately 6850 yr BP *Picea* appears in the pollen record. This was likely *Picea* *obovata*, one of the species which contributes to the boreal treeline in west - central Siberia (Polunin, 1959). Today *Picea obovata* is found 350 kilometres to the south along the Lena River. Maximum values of Picea occur in zone 3; however, these values must be considered low for this species. Ritchie (1984) estimated that 10% *Picea* pollen was an adequate threshold to indicate the local presence of spruce in the Inuvik-Tuktoyaktuk area of northwest Canada, particularly in areas where *Betula* and *Alnus* are also present. The presence of those species will surely mask the presence of a less prolific pollen producer such as spruce. In northern Europe, Huntley and Birks (1983) proposed that 5% spruce in pollen records from that area indicated that spruce was locally abundant on the landscape. Thus, the low percentages of spruce in zone 3 may be recording the presence of that species at the study site; however, the low values do not provide definitive evidence for the presence of this species. The occurrence of *Picea* stomates in the sediment record provide stronger evidence of spruce existing at this site. *Picea* stomates occur sporadically in zone 3 and in low concentrations. Scattered individuals of *Picea obovata* were likely found at this site between 6850 yr BP and 3800 yr BP. Low percentages and influxes of haploxy type *Pinus* pollen, in zone 3 are likely the result of long distance transport of *Pinus pumilla* pollen. Pine pollen is often carried great distances in the wind due to the bissacate shape of the grain. As a result, pine is often overrepresented in the pollen record of forest tundra and tundra sites in particular (Huntley and Birks, 1983). Values of *Betula cf. nana* and *Alnus fruticosa* decrease slightly throughout zone 3. Pollen influxes of both of these species indicate that the decrease in these species was more dramatic than indicated by the pollen percentages. Birch and alder, both pioneering species, are commonly the first large shrub-genera to migrate into an area. These species are shade intolerant and quickly become out competed by longer lived more shade tolerant taxa. The decreasing values of birch and alder throughout zone 3 may be reflecting the early appearance of birch and alder and the subsequent decline as these taxa were out-competed by *Larix* and *Picea.*

Heath vegetation continued to expand in importance until ~ 8500 yr BP. At this time, the percentages of Ericaceae decreased slightly. This decrease is also reflected in the PAR of Ericaceae and possibly reflects a decline in shrubs and herbs due to the development of forest cover. Following 5800 yr BP the percentage and pollen influx of Ericaceae begins to increase again, this trend continues for the remainder of zone 3. The presence of *Sphagnum, Lycopodium* and *Equisetum* in zone 3 suggests environmental conditions which were perhaps the wettest during this record. Combined these species suggest that the climate was more mesic in the early to mid Holocene than it is today.

Pollen, stomatal, and sedimentary evidence suggest that temperatures were much higher in the early to mid Holocene than they are today in the Lower Lena River Region. *Larix dahurica* likely dominated on the drier upland sites, with *Picea obovata* along river banks and mesic upland sites (Polunin, 1959). Scattered individuals of tree birch and alder likely formed a pioneer vegetation which was quickly out competed by the longer lived and more shade tolerant species of *Larix* and *Picea. Pinus pumilla* likely did not reach this site judging by the low pollen percentages and lack of stomates of this species in the fossil record. The low influxes of those taxa common to open environments, such as Gramineae and Compositae, indicate that forests may have been quite extensive, shading out the understorey vegetation. The continued increase in the influx of Ericaceae pollen types suggests the further development of heath vegetation. Poorly drained sites around the lake which may have been too wet for trees were likely dominated by Ericaceae and sphagnum bogs.

5.16 - Zone KO4 (*Betula - Alnus* zone) - 3450 yr BP to present (110 cm - 0 cm)

Zone 4 marks the establishment of the modern vegetation dominated by low lying shrub species of *Betula cf. nana* (dwarf birch) and *Alnus crispa*. Percentages of *Betula cf. nana* increase throughout zone 4; however, this is not reflected in the PAR diagram. In fact, it appears that *Betula cf. nana* has been decreasing in importance throughout the last 3450 yr BP. Conversely, percentages of *Alnus crispa* appear to decrease when pollen accumulation rates, although quite low, do not decrease. Arboreal species of *Picea* and *Larix* are found sporadically throughout zone 4 in only small percentages. *Pinus* pollen percentages reach maximums in zone 4. These values are quite low for this prolific pollen producer and probably is the result of long distance transport rather than the local presence of the species. Zone 4 is also delineated from the previous zone by the increase in pollen percentages and PAR of: *Salix*, Ericaceae, *Artemisia*, Cyperaceae, Gramineae and *Dryas*. *Sphagnum* continues to occur in small percentages throughout zone 4; however, there is a decrease in the occurrence of this species in the last few centuries.

Larix stomates are uncommon in zone 4, with only scattered individual stomates being found. Zone 4 marks the appearance of an unknown type of stomate referred to in the record as "other". This unknown type appeared to be very similar to the stomates from *Betula;*

however, reference material of this taxon was not available at McMaster so a positive identification could not be made. Given that this technique has not been used extensively in the past, few reference collections of stomates exist; therefore, it was not possible to obtain reference material for this taxon. In addition, it is uncommon for stomates of non-conifers to be preserved since they contain less lignin, the substance which is likely responsible for conifer stomate preservation (MacDonald, *per. com.*).

Vegetation changes which occurred at the boundary of zone 3 and 4 indicate that a dramatic change in the climate must have occurred. The shift from vegetation assemblages dominated by arboreal species to shrub tundra conditions likely reflects colder temperatures and possibly a decrease in precipitation. Low percentages of pollen from *Larix* and *Picea*, and the low influx of stomates of these taxa indicate that these species were absent or occurred as scattered individuals on the landscape. *Larix* stomates in the top few samples of zone 4 could have been transported to the lake from the stand of krummholz *Larix* that is found about 1 km south of the lake. It is possible that *Larix* needles could have been blown across the snow cover during the winter months and deposited on the frozen lake until the summer thaw. Alternatively, *Larix* needles are quite small, so they may have been transported to the lake by the wind.

Percentages of Ericaceae increased in zone 4 reaching maximum percentages for the entire record. This increase is mirrored in the PAR diagram and likely indicates the further development of heath vegetation. The further development of tussock tundra is reflected by an increase in the percentages and accumulation rates of Cyperaceae. A return to a more open environment is reflected by the increase in the percentages and accumulation rates of several taxa, including: *Artemisia,* Gramineae and *Dryas.*

Zone 4 is marked by the return to tundra conditions. A shrub tundra, dominated by *B. cf. nana* and *A. crispa* is interspersed on the landscape by heath communities in the lower more poorly drained areas. Cyperaceae and Gramineae also occurred in these wetter areas. Drier, more open sites, are dominated by *Artemisia* and *Dryas*, although the importance of *Dryas* been decreasing in the last ~1000 yr BP. Decreasing total pollen influx in zone 4 also indicates a shift to less productive shrub tundra conditions.

CHAPTER SIX

DISCUSSION

6.1 Factors controlling vegetation development in the Lower Lena River Region

The previous chapter described important changes in the vegetation which have occurred in the lower Lena River region of Siberia during the late Pleistocene and the Holocene. The following discussion will relate the vegetation changes which have occurred in the Lena River region to similar changes that have taken place at circumpolar treeline sites throughout the northern hemisphere. The vegetation history of parts of the former Soviet Union has been investigated, with over 900 papers being published between 1962 and 1977 (Grichuk, 1984). Much of this data is published in Russian and is not radiocarbon dated. A few papers published in English journals provide very broad reconstructions of palaeoenvironments (Grichuk, 1984; Velichko, 1995; Khotinskiy, 1984a; and Peterson, 1983 and 1993) but these lack detailed information. Given the interpretive problems with much of the earlier work on Russian palaeoenvironments, studies from northwestern Canada and Beringia will have to be relied upon to help interpret the factors which caused the vegetation changes. These factors include: soil development, competition, climate (most notably temperature and precipitation), fire, pathogens and dispersal ability. Isolating a single factor responsible for vegetation changes is made difficult by the fact that several factors may cause a similar change in the vegetation. Records from northwestern Canada and Beringia are likely the most similar to the study area. Although studies from areas in the European part of the former Soviet Union are abundant, these sites are significantly different than the current site. The European areas of the former Soviet Union have a maritime climate; whereas, the current study site is a severe continental climate. The different climate regimes are thus responsible for significantly different vegetation assemblages making comparisons between these areas more tenuous than areas in Beringia and northwestern Canada.

6.11 Zone KO1a (*Salix-Dryas-Artemisia*-Cyperaceae-Gramineae zone) - ? yr BP to ~12050 yr BP (336.5 - 294.5 cm)

It appears from the record from Kameniskoy Ozaro that by the time the lake had formed and began to accumulate sediments, *B. cf. nana* was already present in the area. It does not appear that vegetation lags, such as those caused by soil development on newly glaciated landscapes (Pennington, 1986), were acting in this area. Zone 1a represents a tundra environment dominated by shrub *Betula*, which was quickly replaced by a herb tundra. The herb tundra which dominates much of zone 1a is similar to the high arctic vegetation zone in Canada, described by Ritchie (1993). A similar shift to herb tundra is not seen in records from near the current study site (Grosswald et al., 1992) or in southwestern Beringia (Lozhkin et al., 1993), where the records extend beyond the last 20000 yr BP. However, the record from Grosswald et al. (1992) only covers the last ~8000 yr BP. In northwestern Canada, Cwynar (1982) found a similar zone at Hanging Lake in the northern Yukon. This zone was characterized by a large percentage decrease in *Betula* pollen and increases in grasses, sedges and *Salix*. This change in the vegetation assemblage at Hanging Lake was interpreted to represent climatic amelioration. The same cannot be true in north central Siberia. Keigwin and Lehman (1994) found evidence of cooling centered around 14300 - 15000 yr BP from an ocean core in the north Atlantic ocean. The authors interpreted this cooling period to be the equivalent of the HEINRICH event 1, the marine equivalent of the Oldest Dryas. According to Keigwin and Lehman (1994), the cooling of North Atlantic surface waters resulted in the reduced production of North Atlantic Deep Water (NADW). NADW drives ocean currents throughout the world and is responsible for the transport of warm water from equatorial areas northwards. Without the production of NADW the system is shut down and the exchange does not occur. Cooler ocean surface temperatures could have caused a southward displacement of the polar jet causing the cold and dry conditions over north central Siberia.

The rapid change in the vegetation in zone 1a represents the shift to the more arid conditions of the Sartan Glaciation (Late Würm in western Europe (Grichuk, 1984) and Late Wisconsin in North America). Kutzbach and Guetter (1984 and 1986) estimated that in high northern latitudes, precipitation and temperatures were considerably depressed between 18000 and 12000 yr BP. This may have been due to a more continental regime at this time. The oceans were considerably lower and coastlines extended further offshore. The coastline of the Lena Delta was likely over 200 km further offshore during the Sartan glacial than it is today (Velichko, 1984).

The shift to herb tundra early in zone 1a is in good agreement with the model projections of Kutzbach and Guetter (1986), and the HEINRICH event 1 proposed by Keigwin and Lehman (1994). It is difficult to draw concrete conclusions about what zone 1a truly represents without adequate dating control at the bottom of the zone. Based on the literature, and similarity to the Hanging Lake record (Cwynar, 1982), it would appear that zone 1a is of late Sartan glacial times.

6.12 Zone KO1b (*Betula nana* zone) - ~12050 yr BP to ~11000 yr BP (294.5cm - 275 cm)

Kutzbach and Guetter (1986) suggest that the climate between 12000 and 10000 yr BP, was still much colder than today; however, climatic amelioration was occurring. The shift to the shrub tundra vegetation from herb tundra at Kameniskoy Ozaro appears to agree with their findings. The increase in *Betula* pollen percentages at approximately 12000 yr BP is also seen at several sites in southwestern Beringia (Lozhkin et al., 1993). In western Canada, there is also evidence from several sites for increased deposition of *Betula* pollen at about 12000 yr BP (Cwynar, 1982; Ritchie, 1982). The increase of shrub birch at 12000 yr BP in northern Russian is unlikely the result of decreased competition, lags due to soil development or reproductive ability of birch. Prior to 12000 BP, the vegetation at the site was herb tundra, dominated by low lying vegetation types, species which could not out-compete shrub birch. The probable cause for the increase in *Betula* was likely the result of changing climatic conditions. Climate was becoming more favourable at this time (Kutzbach and Guetter, 1986) allowing for the expansion of birch in the Lower Lena River Region, southwestern Beringia and the northwest of Canada. The widespread increase in *Betula* in northern Siberia, Beringia and northwest Canada also indicates that this was due to a change in climate rather than local changes such as competition or soil development. It would seem unlikely that local factors would be working to produce the same vegetational changes over such a large geographic extent.

6.13 Zone KO1c (Gramineae - Cyperaceae - *Artemisia* - *Dryas* zone) - ~11000 yr BP to 10000 yr BP (275 cm to 240 cm)

The vegetation assemblage in zone 1c is quite similar to the middle stages of zone 1a and likely represents one of the most perplexing climatic changes of the last 20000 years. The herb dominated tundra, which characterizes zone 1c, is likely the equivalent of the Younger Dryas chronozone, a cooling period between 11000 and 10000 years BP that is clearly seen in sediment and sea core records in eastern North America (Mott et al., 1986; Levesque et al., 1993; Mayle et al., 1993a, 1993b; Levesque et al., 1994) and Europe (Bard et al., 1987; Dansgaard et al., 1989; Lehman and Keigwin, 1992; Bard et al, 1994; Goslar et al., 1995). Evidence is also accumulating from other parts of the world (Fairbanks, 1989; Engstrom et al., 1990; Gasse et al., 1991; Kudrass et al., 1991; An et al., 1993; Markgraf, 1993; Blanchon and Shaw, 1995; Maloney, 1995 and Linsley, 1996) suggesting that this was in fact a global phenomena.

In all of these studies it has been concluded that the Younger Dryas was not the result of long term climate forcing due to changes in the earth's orbital parameters. Climatic changes such as the Younger Dryas occurred very rapidly (usually within 1000 years), at rates which were much more rapid than Milankovitch cycling could account for. Numerous explanations have been put forward to account for the cause of the Younger Dryas, including: decreased production of North Atlantic Deep Water (NADW), decreased CO_2 in the atmosphere, and external forcings (volcanism and solar output) (Berger, 1990; Stuiver and Braziunas, 1993). The actual cause of the Younger Dryas has still not been determined satisfactorily.

The synchroniety of the occurrence of the Younger Dryas globally raises the question as to why this event was recorded in only select areas. The global distribution of Younger Dryas sites appears to be related somewhat to proximity to the oceans, lending support to the belief that the Younger Dryas was due to decreased production of NADW and changing oceanic circulation. The strongest Younger Dryas signals occur in the circum North Atlantic and within other oceanic areas throughout the world. With the exception of sites on the loess plateau of central China, most Younger Dryas signals reflect a shift back to glacial conditions. Sites in Siberia and throughout Russia (Velichko, 1995) also indicate that this climatic event resulted in a reversion to near glacial conditions.

One hypothesis developed to account for the cause of the Younger Dryas is a decrease in the production of NADW. NADW production may have been shut off by a cap of cold freshwater, discharged into the North Atlantic ocean as the continental ice sheets were retreating. Blanchon and Shaw (1995) provide evidence of at least 3 catastrophic discharges of meltwater into the Atlantic resulting in metre-scale sea-level-rise. The large influx of freshwater would cap the waters of the North Atlantic Ocean and decrease evaporation, the driving mechanism which causes ocean surface waters to become more dense and sink and return equatorward. The freshwater, being less dense than the seawater would not sink but instead would form a pool of cold surface water in the North Atlantic. The colder ocean temperatures would cause adjacent landmasses to become cooler in the same way that today the ocean circulation of the North Atlantic keeps northern Europe much warmer than areas of eastern Canada at similar latitudes (Broecker, 1987).

The cooling of the North Atlantic ocean and the decreased production of NADW, would also have an impact on the Pacific Ocean. Today, the Atlantic and Pacific Oceans are connected by a giant conveyor belt which transports warm equatorial waters northward. If the NADW was cut off, as some believe, then the entire oceanic conveyor belt would shut down. This could have resulted in colder surface temperatures in the northern Pacific. Evidence of increased sea ice coverage around 11000 yr BP was recorded in the interior seas adjacent to the northern Pacific (Kallel et al., 1988), indicating colder surface water conditions. The colder surface waters could have caused a southward displacement of the polar front across eastern Asia and the study site. Haung et al. (1992) found that increased sea ice in the winter months strengthened the development of high pressure over eastern Siberia and China, which would cause extremely cold conditions. Evidence from throughout eastern Asia seems to support the above scenario and could account for the occurrence of the Younger Dryas climatic event in north central Siberia.

A second hypothesis to account for the occurrence of the Younger Dryas is the reduction of the concentration of atmospheric CO_2 (Kudrass et al., 1991). Under this scenario, the decreased atmospheric concentration of CO_2 would result in an anti-greenhouse effect. Kudrass et al., (1991) suggests that the Younger Dryas in eastern Asia was the result of low atmospheric CO_2 concentrations. Similar to the NADW hypothesis, the low CO_2 concentrations were due to a cold injection of fresh water in northern oceans, thus inhibiting the exchange between the atmosphere and the oceans. CO_2 became trapped in the oceans due to the reduced exchange between the oceans and the atmosphere. Atmospheric CO_2 levels may have been further depleted in the warming prior to the Younger Dryas by increased consumption of CO_2 by plants. The warm Allerod (12000 - 11000 yr BP) was a period of re-colonization of ice-free areas, CO_2 use by vegetation would have been greatly increased but it is uncertain if this requirement would have had such dramatic consequences.

There are uncertainties with the CO_2 hypothesis, including a discrepancy between atmospheric CO_2 concentrations from the glacial maximum to the Younger Dryas. Atmospheric CO_2 concentrations inferred from the Sulu Sea cores (Kudrass et al., 1991) suggest that CO_2 concentrations remained low from the glacial maximum into the Younger Dryas. Atmospheric CO_2 concentrations inferred from ice cores indicate that atmospheric CO_2 concentrations in fact increased at the end of the last glacial maximum (Kudrass et al., 1991). Determining the validity of the CO_2 hypothesis is beyond the scope of this study. Data from the current study do provide evidence that vegetation increased prior to the Younger Dryas, providing some support to the hypothesis that increased plants may have contributed to lower atmospheric concentrations of CO_2.

In addition to the atmospheric CO_2 and the NADW hypotheses, it has also been proposed that the Younger Dryas may have been the result of external forcings such as volcanic eruptions or possibly changes in solar output. Evidence for the existence of an extensive volcanic eruption at the time of the Younger Dryas exists in the form of the Vedde Ash (Mangerud, et al., 1984).

Although the ultimate cause of the Younger Dryas remains uncertain, the Kameniskoy Ozaro record clearly shows that this cooling event was evident in northeastern Siberia. This, in itself, is a crucial extension of the geographic scope of the Younger Dryas.

6.14 Zone KO2 (*Alnus - Betula* zone) - ~10000 yr BP to 8500 yr BP (240 cm to 210 cm)

The onset of the Holocene in north central Siberia is characterised by the expansion of *Alnus crispa* and *Alnus fruticosa* populations. The vegetation around Kameniskoy Ozaro changed very little from the late Pleistocene except for the expansion of *Alnus* and the small increase in tree birch (*Betula alba*). The low percentages of *Betula alba* pollen are likely due to long distance transport of this prolific pollen producer or possibly the occurrence of only scattered individuals on the landscape.

The *Alnus* rise is typically seen in pollen records from northern regions of the world, although not exclusively (See, Mayle et al., 1993b). In southwestern Beringia, the *Alnus* rise occurred much earlier, ~12500 yr BP, than in sites across Canada (Lozhkin et al., 1993). At the site for this study, the *Alnus* rise occurs ~10000 - 9900 yr BP, somewhat later than in southwestern Beringia but earlier than in Canada. In the Northwest Territories the *Alnus* rise typically occurs between 5700 and 7800 yr BP (Ritchie, 1982, 1984; Spear, 1983; MacDonald, 1995 and 1987a). In the northern Yukon, it occurs slightly earlier at about 8900 yr BP (Cwynar, 1982). Across southern and central parts of the Yukon the *Alnus* rise occurs much later, between 7000 and 5000 yr BP (Cwynar and Spear, 1995), more similar to areas in the Northwest Territories. Across areas of central Canada the onset of the *Alnus* rise occurs at ~6800 yr BP (Moser, 1988; MacDonald et al., 1993). In eastern Canada, where glacial ice persisted until the mid Holocene, maximum percentages of *Alnus* pollen do not occur until ~6000 - 5000 yr BP (Gajewski et al., 1993).

Numerous hypothesis have been developed to explain the increase of *Alnus* in the mid Holocene. In most cases the *Alnus* rise followed the advance of *Picea* into an area. Many investigators interpreted the rise in *Alnus* to possibly be a response to increased fires, thus opening the landscape and allowing the establishment of *Alnus* (Ritchie, 1985 and 1984). This would be necessary to allow this shade intolerant taxon to become established (Mayle et al., 1993). Given the wide geographical area over which the increase in *Alnus* was recorded, it is doubtful that fire or stand openings were so widespread as to facilitate the alder rise across northern areas of Canada and Russia.

It has also been suggested that the increase in alder pollen, especially in eastern North America, was the result of the ability of the members of this genus to fix nitrogen (Richard et al., 1982). *Alnus* is able to fix nitrogen through a symbiotic relationship with actinomycete fungi (Mayle et al., 1993). It is this ability that gives *Alnus* a competitive edge over other species colonizing freshly deglaciated landscapes or recently disturbed soils (Mayle et al., 1993). Given that eastern Canada was only deglaciated shortly before the rise in *Alnus*, the ability to fix nitrogen may explain the increase in alder in that area. This hypothesis does not hold true in western areas of Canada; however, where deglaciation occurred several thousand or more years prior to the alder rise. At the current study site, the alder rise, like in western Canada, did not occur immediately following deglaciation. Given that this site has probably not been glaciated in the past 20000 yr BP (Isayeva, 1984 and Sher, 1995), it does not appear that alder's ability to fix nitrogen can be invoked as the reason for the rise in alder pollen in Siberia.

Climate has also been proposed to have been responsible for the sudden increase of alder throughout northern areas (Moser, 1988). Alder occurs typically on mesic sites, often along streams, lakeshores, coasts and the margins of bogs (Mayle et al., 1993), thus the increase in the percentages of this genus in pollen records has been interpreted as a shift to a more mesic and cooler climate (Ritchie, 1984). In southwestern Beringia, Lozhkin et al. (1993), interpreted the increase of alder at ~12500 yr BP to be the result of climatic amelioration, resulting in summer temperatures which may have been warmer than today. Modelling experiments (Kutzbach and Guetter, 1986 and COHMAP members, 1988) suggest that northern hemisphere summer insolation was peaking at about the time of the alder rise in north central Siberia. If climate was in fact controlling the sudden expansion of alder in north central Siberia then the low percentages of alder pollen prior to ~10000 yr BP may be the result of a climate which was simply too harsh for alder to grow successfully. As climate amelioration progressed at the boundary of the Pleistocene and Holocene, conditions became more favourable for alder to expand. Alder was then able to easily increase on the landscape due to a lack of competition from arboreal vegetation.

6.15 Zone KO3 (Larix - Picea zone) - ~8500 yr BP to 3450 yr BP (210 - 110 cm)

The most dramatic changes in vegetation at this site occurs in zone 3. Pollen and stomate data indicates that arboreal vegetation, predominantly *Larix dahurica* and *Picea obovata*, becomes established in the lower Lena River region at this time. The establishment of arboreal vegetation is in accordance with data from Savina and Khotinskiy (1984), which suggests that both January and July temperatures, as well annual precipitation were greater than present. The pollen and stomate evidence is in remarkable agreement with the dates of over 100 macrofossils, collected from across northern regions of Russia by the PACT project members. Radiocarbon dating of these wood samples yielded dates which fell predominantly between 8500 and 3500 yr BP (MacDonald, *per. com.*). The data collected by the PACT project is also consistent with numerous dates (Khotinskiy, 1984a) obtained from fossil wood found in the modern tundra by Russian scientists. The pollen, stomate and macrofossil evidence suggests that in northern Russia treeline moved north synchronously across the entire Russian federation between 8500 and 3500 yr BP.

The treeline history of Russia contrasts sharply with the situation in northern areas of Canada. Advances of treeline in northern Canada occurred asynchronously in western, central and eastern regions of the country. In the west, treeline advanced north of its present position between ~9500 and 5000 yr BP (Ritchie and Hare, 1971; Ritchie, 1984; Spear, 1993). In central Canada, treeline advance came somewhat later, at approximately 5000 yr BP (Moser and MacDonald, 1990; MacDonald et al., 1993). Across eastern Canada palynological data does not indicate that treeline has existed north of the present day position (Payette and

Fillion, 1985). Gajewski et al., (1993) have found that treeline in eastern Canada arrived at the current and maximum boundary between the forest-tundra and tundra ecotones at approximately 4000 yr BP. They affirmed the earlier finding that treeline had not existed north of the present position during the Holocene.

In almost all of the studies from the forest-tundra - tundra boundary a northward extension of treeline has been attributed to climate. Studies by Bryson (1966) and Krebs and Barry (1970) first developed the link between climate circulation and the northern limits of trees. In particular these studies found that the northern limits of trees in Canada and across Russia corresponded closely to the mean position of the arctic front in the summer (Figure 8). It can therefore be concluded that the position of the northern limits of trees in Canada and Russia is likely controlled by the same climatic factors that determine the position of the arctic front in the summer months. Unfortunately, those climatic factors are uncertain.

Pollen, stomate and macrofossil records from across Russia (this study; Khotinskiy, 1984a; Votakh and Klimanov, 1994) are in accordance with data from climate models which suggest that the early and mid Holocene was a period of warmer temperatures. Savina and Khotinskiy (1984) estimate that mean July temperatures in the study area 8000 years BP were approximately 10-12° C, some 2-4° C warmer than today. Estimates of mean July temperatures by Savina and Khotinskiy (1984) are strengthened by the results of a study by Klimanov (1984). In that study the author correlated modern pollen spectra to various environmental variables, including mean July temperatures. The statistical method used by Klimanov (1984) found that pollen percentages of 5.1-10 % *Larix*, were most typical where mean July temperatures averaged 10-14° C. *Larix* pollen percentages for this study commonly accounted for 5-10% of the terrestrial pollen sum, further strengthening the belief that summer temperatures were warmer in this area. Precipitation also increased across Siberia (Khotinskiy, 1984b). The increase in precipitation was likely the result of significant changes to the atmospheric circulation over northern Eurasia (Khotinskiy, 1984b). According to Khotinskiy (1984b) the increase in precipitation across Siberia could have resulted from reduced ice cover on the Arctic Seas, penetration of the Gulf stream into the Barents Sea, or the northwestward movement of air masses around Scandinavia and into Siberia. Between 8000 and ~5000 yr BP a decrease in the Siberian High likely resulted in moist air masses penetrating further east into Siberia, possibly as Khotinskiy (1984b) depicts, to the Lena River region. Mean July temperatures of 10-12° C are well within the optimum characteristics for Larch forest and forest-tundra (Savina and Khotinskiy, 1984). The expansion of forest across Russia, occur at the same time that models predict northern hemisphere solar radiation was peaking (between 12000 and 6000 yr BP) (Kutzbach and Guetter, 1986 and COHMAP members, 1988). Changes in the orbital parameters of the earth which resulted in increased solar radiation are summarised in Table 3. All of these factors combined to create summer conditions between 12000 and 6000 yr BP, which were warmer than today in the northern hemisphere.

These changes in the earths orbit provides the strongest evidence to account for the synchronous advance of treeline into northern tundra regions across Russia between 8500 and 3500 yr BP. Although the above hypothesis has to be considered speculative, due to the poor

Figure 8. Position of the northern limits of trees in Canada and Russia in relation to the position of the Arctic Front at the present time and at 8000 yr BP. Position of the Arctic front in Eurasia for July 1952-56, after Krebs and Barry, 1970. Present day position of the arctic front in July and August follows Bryson, 1966. The position of the arctic front at 8000 BP, after Ritchie and Hare, 1971. Present day position of treeline, after Ritchie and Hare, 1971.

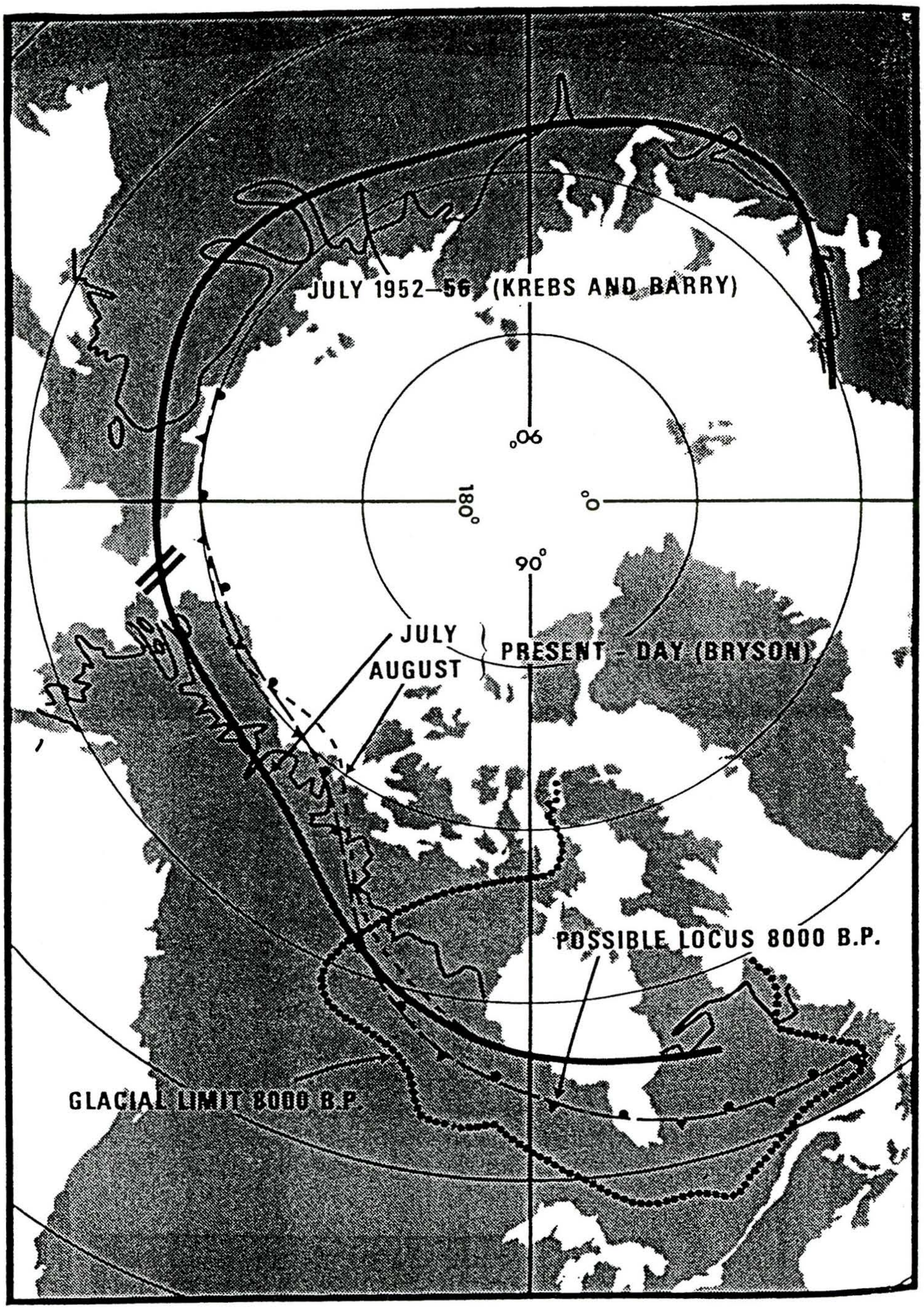

JULY 1952–56 (KREBS AND BARRY)
90°
180°
0°
90°
JULY
AUGUST
PRESENT - DAY (BRYSON)
POSSIBLE LOCUS 8000 B.P.
GLACIAL LIMIT 8000 B.P.

Table 3. Orbital parameters of the earth at 12000, 9000, 6000 yr BP and the present. Data and chart after, Kutzbach and Guetter (1986). Changes in these orbital parameters, as suggested by Kutzbach and Guetter (1986), may have resulted in the northern limits of trees in Russia moving synchronously northwards, to in some cases, the Arctic coast.

Orbital parameters of the earth for present day and between 12000 and 6000 yr BP

Years BP	Eccentricity of orbit	Axial tilt (degrees)	Perihelion*(degrees)
0	0.0167	23.44	78 (January 3)
6000	0.0187	24.11	179.1
9000	0.0193	24.24	228.8 (July 30)
12000	0.0196	24.15	277.9 (June)

*Perihelion is measured clockwise from the vernal equinox.
Data and chart is after, Kutzbach and Guetter, 1986

understanding of the link between climate and the boundary between the forest-tundra and the tundra, it appears that the synchronous advance of treeline across all of Russia was the result of a major climatic reorganization brought about by changes to the orbital parameters of the earth. This is in contrast to the situation in Canada, where regional warming caused asynchronous advances of treeline in western and central Canada.

6.16 Zone KO4 (*Betula - Alnus* zone) - 3450 yr BP to present (110 cm - 0 cm)

The modern vegetation around Kameniskoy Ozaro was established by 3400 yr BP. Since that time there has been very little change in the vegetation around this site. The modern vegetation zone is marked by the decline of *Larix dahurica* and *Picea obovata* from the pollen and stomate records. The decline of arboreal vegetation in the lower Lena River region occurred concurrently across northern areas of Siberia. In European Russia, spruce forests spread during this period in response to increased moisture (Khotinskiy, 1984a). Eastern Russia also became more mesic at this time, as evidenced by the spread of *Pinus pumilla* in southwestern Beringia (Lozhkin et al., 1993). In central Siberia, including the far north, Khotinskiy (1984a) concludes, based on pollen data from across the area, that temperatures and precipitation both decreased at this time. The data from this site appears to agree with this interpretation. The decline of the arboreal species and the increase in herbs, especially the xeric taxa *Artemisia*, seems to indicate that conditions were becoming more arid and cooler after ~3400 yr BP.

It appears, based on studies from across northern Russia, that the decline in arboreal vegetation that occurred near 3400 yr BP was the result of a shift to cooler and more arid conditions. Modelling experiments suggested that summer warmth was steadily decreasing by 6000 yr BP (Kutzbach and Guetter, 1986). Results from that modelling experiment estimate that northern hemisphere solar radiation in the summer months was only ~2% (at 3000 yr BP) higher than present day values (Kutzbach and Guetter, 1986). As a result of decreasing inputs of solar radiation, temperatures must have fallen below levels which were adequate for tree growth and establishment in northern Russia.

The decline of trees was likely not instantaneous, as Moser (1988) points out in central Canada. There is clear evidence of this approximately 1 km from the study site. At that point a stand of krummholz larch trees still exist. This stand is beyond the modern limit of trees for this area and is likely a remnant of the warmer period which proceeded the re-establishment of tundra vegetation in this area. Thus, this scattered stand of larch trees is likely not in equilibrium with climate. To be considered to be in equilibrium with the prevailing climate a tree must be able to successfully produce viable seeds and then these seeds must be able to germinate. This stand was investigated by the PACT team to determine the current status of the stand, including whether seeds are being produced or not. Field work at the site in 1994 found that seeds were being produced in this stand. In addition young trees were also sampled at the site. It is possible that this stand has survived and successfully reproduced since forests retreated from this area. A similar "forest island" was investigated by Tolmatchev (1972) on the Bol'shezemelskaya Tundra (Great Tundra), between the lower Pechora River and the Polar Ural Mountains. Tolmatchev found these stands of spruce trees were producing abundant seeds and there was abundant evidence of young trees (< 100 years old), indicating that in fact these forest were healthy and viable. Tolmatchev (1972) concluded that these spruce forests, which are growing 100 km from the present day treeline, are remnants of forests which formerly extended much further north than today. Tolmatchev also points out however, that these forests are not simply relicts, they are sexually reproducing and experiencing a "progressive transformation." Perhaps the same is occurring in the Lower Lena River region.

CHAPTER SEVEN

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

A 365 cm lake core from Kameniskoy Ozaro, northwest of Tiksi, Siberia, was analysed for pollen, stomates, and sediment characteristics. Analysis of these proxy indicators yielded a vegetation record that extends to the final stages of the Sartan glaciation (Late Wisconsin in North America). Results indicate that vegetation changes in north-central Siberia have occurred at varying rates and intensities as hypothesized in Chapter One. The pollen and stomate record from Kameniskoy Ozaro, records an advance of treeline into this area over a period of several thousand years. The treeline advance was the result of changes in the orbital parameters of the earth. The record also contains evidence of short, very rapid changes in vegetation which occurred over time scales of 1000 years and less. These changes, such as the Younger Dryas signal in zone KO1c, can not be attributed to long term orbital forcing and likely were caused by changes in global ocean circulation patterns. Comparison was made with other vegetation records from throughout the circumpolar region yielding the following conclusions:

1. The early part of the record, which likely represents the final stages of the Sartan glaciation (late Pleistocene), is noteworthy for the very unstable nature of the climate at that time. Two reversions to glacial or near glacial climates, captured in this record, interrupted

the climatic amelioration that was beginning throughout the northern hemisphere during the late Pleistocene.

2. The basal zone or *Salix-Dryas-Artemisia*-Cyperaceae-Gramineae zone represents a low lying herb dominated tundra. Adequate dating control is lacking in this part of the core so concrete conclusions about what this zone represents could not be made. The zone does indicate that there was a rapid shift in the vegetation, possibly reverting back to full glacial conditions. Assuming a constant sedimentation rate, similar to the rest of the record, the basal section of this zone likely dates to ~15000 yr BP. If this is true then this zone may represent the Oldest Dryas cooling period.

3. Zone 1c of the record provides unequivocal evidence of the occurrence of the Younger Dryas in north central Siberia. The zone is represented by a large decrease in the percentages and influxes of *Betula cf. nana* pollen and a concomitant increase in herbs, grasses and sedges. The pollen data indicates that the environment became more open at this time and the climate became inhospitable for shrubs. The occurrence of a Younger Dryas signal at this site provides additional evidence that this was not only a circum North Atlantic or northern hemisphere coastal phenomena, but in fact a global return to near glacial conditions.

4. Zone 2, the *Alnus-Betula* zone, from 10000 to 8500 BP, marks the expansion of *Alnus crispa* at this site. The *Alnus* increase at this site occurs later than in southwestern Beringia, but 2000 to 3000 years earlier than across Canada. The synchronous expansion across much of Canada has been attributed to an increase in moisture and a cooling climate.

5. Zone 3 of this record marks the establishment of arboreal vegetation in the Lower Lena

River region. Arboreal vegetation existed in this region from ~8500 to 3500 BP. A synchronous expansion of treeline occurred across the Russian tundra during this period. Pollen, stomate and macrofossil evidence all record this expansion. Given the vast geographical area and the synchroneity of the treeline advance, it would appear that this migration of trees into tundra areas was the result of changes in the orbital parameters of the earth as suggested by Milankovitch cycling.

6. The modern vegetation was established by 3400 BP, and is delineated by shrub tundra dominated by *Betula nana*. Trees were likely excluded from this area following a shift to a cooler and drier climate.

7. The use of a new technique, stomate analysis, proved to be an extremely useful tool for determining the extent and rates of fluctuations in the forest-tundra - tundra boundary. The results of the stomate analysis were in complete agreement with both the pollen and macrofossil evidence, not just from this site, but across northern Russia. The results from this study, coupled with the ease of this technique, should make analysis of this proxy indicator a requirement for all investigations of treeline.

8. This study has demonstrated the importance of recognizing that climate change in the past, and possibly in the future, has not always occurred at similar rates. The pollen record from Kameniskoy Ozaro, recorded evidence of both long term climate changes which occurred over thousands of years, and short term, extremely rapid fluctuations, requiring in some cases less than 100 years to take place. Future warming due to the Greenhouse effect appears to be occurring at a pace more similar to the short term climate changes, thus it is these changes

that we should be looking at to predict future climate change.

7.2 Future Recommendations

The Lower Lena River region appears to be a very climatic sensitive area, as evidenced by the record presented in this study. The sensitivity of the region makes this area a very important region for future research. Warming that is being predicted to occur in the next hundred years will surely be manifested early on in this region. In addition, the larch stand which was sampled for dendrochronological analysis, could be a very important site, providing an early warning of future warming. This site should be established as a long term research station where the larch trees can be monitored on a regular basis.

As for this study, I would recommend that the sediments from this record be analysed for changes in the charcoal content, especially at the upper boundary of the Larix zone. There is a strong possibility that, like in Canada, the retreat of the Russian treeline during the mid to late Holocene was the result of a combination of deteriorating climate and increased frequency of fires. The Russian literature did not appear to assess this possibility. There was no mention in any of the Russian studies used in this thesis, of the analysis of microscopic charcoal to assess this possibility.

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