Vegetation change in the northwestern Putorana Plateau (North Siberia, Russia) during the Late Holocene inferred from pollen spectra

Diplomarbeit
zur Erlangung des akademischen Grades
Diplom Geoökologe

Universität Potsdam

Institut für Erd- und Umweltwissenschaften

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Bad Belzig, Januar 2015

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Abstract

Northern Siberia is well suited as a source for different climatic archives, due to its isolation and therefore minor, anthropogenic influences. It is common that even small global temperature changes could cause the highest impacts in sensitive arctic ecosystems. Changes like the shifting of treeline, the ratio of tree and shrub vegetation compared to grasses and herbs, as well as the presence of certain species in the area, provide important information regarding environmental changes of the past.

In this study a pollen data set was generated and statistically analyzed. The results from palynological and statistical analyses were used to generate five pollen assemblage zones (PAZ). Each PAZ has a different pollen composition, pointing out various changes of the local vegetation around the lake during a specific period. The results of the principal component analysis confirm these indications and allow taking conclusions on changes in temperature and the local ecosystem.

The oldest part (PAZ 1) covers a period from 420 BC until 812 AD and characterizes the Roman Warm Period and the following epoch of the Dark Ages. The composition of this zone is dominated by tree and shrub pollen with a decreasing trend at the end of the period, which is a result of colder conditions. The second PAZ reaches from 868 AD – 1484 AD, describes the Medieval Warm Period (MWP). Trees like *Larix* and *Alnus* are indicator plants for warmer conditions. They show an increase around 1200 AD, which is known as the warmest stage during the MWP. From 1500 AD to 1624 AD the vegetation signal showed a significant decrease in pollen arrangement, which is visible in a decrease of tree pollen grains, except from cold tolerant *Betula*, assigned to the Little Ice Age (LIA). The following fourth zone describes the transition period after the Little Ice Age until 1953 AD and the beginning of modern Global Warming. The PAZ 4 has the lowest proportion of total tree and shrub pollen grains in relation to herbaceous plants. After 1978 AD a significant increase of tree species and a decrease of herbaceous plants indicate higher temperatures and therefore the period of modern Global Warming.

Overall, the single proxy approach has generated good results. The data shows a continuing cooling trend with more or less stable stages of warm and cold events, over the last 2500 years. Since 1978 AD the mean cooling is interrupted and the composition of the vegetation reached a level that indicates conditions like in the period of the Roman Climatic Optimum.

Zusammenfassung

Nordsibirien eignet sich aufgrund seiner Abgeschiedenheit und den damit verbundenen geringen anthropogenen Einflüssen sehr gut als Bezugsquelle unterschiedlichster Klimaarchive. Es ist bekannt, dass schon geringe weltweite Temperaturveränderungen die stärksten Auswirkungen in den sensiblen Ökoregionen der Arktis hervorrufen. Diese Veränderungen, wie die Verschiebung der Baumgrenze, das Verhältnis von Baum- und Strauchvegetation zu Gräsern und Kräutern, sowie das Vorkommen bestimmter Arten im Gebiet, geben wertvolle Hinweise auf die ökologischen Veränderungen im Laufe der Zeit.

Als Untersuchungsbasis wurde ein Pollendatensatz generiert und statistisch ausgewertet. Mit Hilfe statistischer palynologischer Analysen konnte der Kern in fünf Pollenzonen aufgegliedert werden. Jede Zone zeigt eine differenzierte Pollenzusammensetzung, welche auf temporäre Vegetationsveränderungen in der Umgebung des Sees hindeutet. Die Ergebnisse der durchgeführten Hauptkomponentenanalyse untermauern diese Hinweise und lassen Rückschlüsse auf temperaturbezogene Veränderungen im lokalen Ökosystem zu.

Der älteste Kernabschnitt umfasst einen Zeitraum von 420 v.Chr. bis 812 n.Chr. und beschreibt das Klimaoptimum der Römerzeit und die nachfolgende Periode des dunklen Zeitalters. Baum und Strauchpollen dominieren die Pollenzusammensetzung mit einem schwindenden Anteil zum Ende der Periode, was auf sich abkühlende Bedingungen hinweist. Der zweite Kernabschnitt von 868 n.Chr. bis 1484 n.Chr. beschreibt das Mittelalterliche Klimaoptimum mit einem leichten Maximum der wärmezeigenden Pflanzen (*Larix* und *Alnus*) um das Jahr 1200 n.Chr. herum, was dem allgemeinen Wärmemaximum dieser Periode entspricht. Ab 1500 n.Chr. bis 1624 n.Chr. ist in der dritten Pollenzone ein deutlicher Rückgang wärmezeigender Arten und ein Anstieg der Pollenkonzentration der Kältezeiger (*Betula*) zu erkennen. Diese Zone kann der Kleinen Eiszeit zugeordnet werden. Die nachfolgende vierte Zone beschreibt den Zeitraum des Übergangs der Kleinen Eiszeit bis zur Hälfte des 20. Jahrhunderts. Dieser Zeitraum weist den insgesamt geringsten Anteil von Baum- und Strauchpollen in Bezug zu Gräser und Kräuterpollen auf. Ab 1978 n.Chr. ist ein signifikanter Anstieg der Wärmezeiger zu beobachten, begleitet von einem Absinken der Pollenanzahl der Kältezeiger, wie auch Gräsern und Kräutern. Diese Periode zeigt den deutlichen Temperaturanstieg in der Phase der Globalen Erwärmung an.

Insgesamt erwies sich der Ansatz über einen Single-Proxy als wenig nachteilig. Die Daten aus dem Kern belegen einen seit 2500 Jahren anhaltenden Abkühlungstrend mit mehr oder weniger stabilen Phasen der Erwärmung und Abkühlung dazwischen. Erst seit 1978 n.Chr. wird dieser allgemeine Abkühlungstrend unterbrochen und die Vegetationszusam-

mensetzung erreicht ein Niveau, das auf Bedingungen wie zur Zeit des Klimaoptimums der Römerzeit hinweist.

1. Introduction

1.1 Scientific Background

Since the last decades the examination of the climate change is getting more important for scientific research. In the discussion of natural and human influences to the climate system, the paleoclimatology get an important role. Continuous worldwide weather records exist since 150 years (Pearce, 2007). In contrast there are many continental and lacustrine sediment profiles analysed with a signal representing the Interglacial cycles (Birks and Birks, 2004; Seppä and Birks, 2002; Esper et al., 2012; Kokorowski et al., 2008; Max et al., 2014; Tarasov et al., 1999; Meyers et al., 1993). The paleoclimatology comes with a huge method range to capture the chronological climate variability for example via ice-coring projects ($\delta^{18}O$ changes, pollen records, or volcanic ash layers), dendroclimatology (tree-ring records, information's from sediment, biomarker, or isotopic ratios), palynology (pollen analysis), varve chronology (sediment deposition) and sclerochronology (coral rings, dripstones). It is possible to reconstruct spatial pattern e.g. temperature in specific time scales of the last Interglacial cycle. Paleo-climatic reconstructions are the base for interpretation and conclusions about the climatic variability over long time scales, as well to validate numeric models to simulate beyond long time and great spatial scales as shown in Esper et al. (2012), Mann et al. (2003) and Jones and Mann, (2004). The study of arctic environmental records gives us a qualitative and quantitative survey of past climate variations and offer a possible perception of future changes in this region. The arctic region is a highly sensitive, vulnerable ecosystem (Blarquez et al., 2009; Osawa, 2010). Due to global warming several fundamental changes took place in permafrost regions, which are all related to each other. According to the IPCC (2014) and McDonald (2010) the effects of climate change are the highest in the arctic regions. The freeze-thaw cycles in the upper centimetres (active layer) are changing in the last decades (Maximov et al., 2010; Osawa, 2010). Thawing permafrost reactivates greenhouse gases like carbon dioxide or methane out of the organic matter and increase thermal erosion (Blok et al., 2010; Zech et al., 2010). Warmer conditions also reduce the organic layer consequently changing the environmental soil behaviour. That results in vegetation changes and spacious biome variations.

To reconstruct periods of past climate change, there are various studies available (Andreev and Klimanov, 1989; Seppä and Birks, 2002; Bhiry and Robert, 2006; Tarasov et al., 2005; Kienel and Sieger, 1999; Leclercq and Oerlemans, 2012; Wang et al., 2014; Bezrukova et al., 2011; Marcott et al., 2013; Monserud et al., 1998). Some of them just concentrate on one proxy analysis, others use multi proxy considerations for their studies.

Meyers (2003) or Andreev and Klimanov (2000) concentrate on one proxy or one field to reconstruct past climatic based events.

Jackson and Lyford (1999) have been considered various aspects of pollen dispersal and how they affect the interpretation of past pollen assemblages. The relevance of pollen analysis to examine timberlines and treelines has been pointed out by Birks and Birks (1980) which is an important work understanding the treeline shift dynamics and therefore the effects for the interpretation of the pollen data set.

Paleo-vegetation reconstruction is essential for establishing how vegetation types or plant communities are recorded in the sediment. Therefore it include materials from soils, alluvium, duff layers and mud-water interface in lakes, where lacustrine provide the most reliable results for reconstruction of past environment (Lozhkin and Anderson, 2006; Lozhkin and Anderson, 2011; Anderson et al., 2002). All type of tree, Shrub and Herb species pollen grains can be found in lacustrine materials.

Fossil pollen grains are well suited as a primary source for information of past vegetation compositions. The work of Erdtman (1921) played a significant role in the development of pollen analysis and was the basis for the consideration of vegetation and climatic changes. Davis mentioned 1963 the correlation between percentage vegetation composition and the percentage pollen-grain composition in the pollen quantity in the sediment. That should be always considered while interpreting pollen-grain samples.

1.2 Aims and Objectives

The aim of this work is to reconstruct the changes in vegetation of the past 2500 years based on a rehashed sediment core from the Khatanga region.

The aims of this thesis are the characterization of changes in vegetation structure by identification of pollen spectra composition and by statistical analysis and interpretation of pollen spectra with regard to temperature changes.

At the end the results from the pollen spectra are compared with other studies and put in context to scientific research.

2. Observation Area

2.1 Geographical settings

The study area (70.40’2.8” N and 97°42’57.1 E) is located in central northern of the autonomy region Taymyrsky Dolgano-Nenetsky District in Krasnoyarsk in Russia (Figure 1). It spans from north east of the Putorana-Plateau to the river Kheta. The Putorana-Plateau is a lifted basalt plateau, reflecting a mountainous area at the north-western edge of the Central Siberian Plateau (Figure 2). It is restricted by the Taimyr-Lowland in the north, the Anabar-Plateau in the east, the Tunguska basin in the south and by the West-Siberian lowland in the west. The highest mountain is the Mount Kamen (1701m) in the north-western part of the Putorana plateau. Mountains can have an influence on air circulations e.g. windward and leeward effect, which could have significant effects on vegetation. The Kheta River is a left branch of the Khatanga River and does have a length of approximately 604 km. The area of its drainage basin is 100,000 km². (Great Soviet Encyclopedia, 1969–1978) The Kheta is formed by the confluence of the Ayan and Ayakli Rivers, both originate in the Putorana-Plateau.

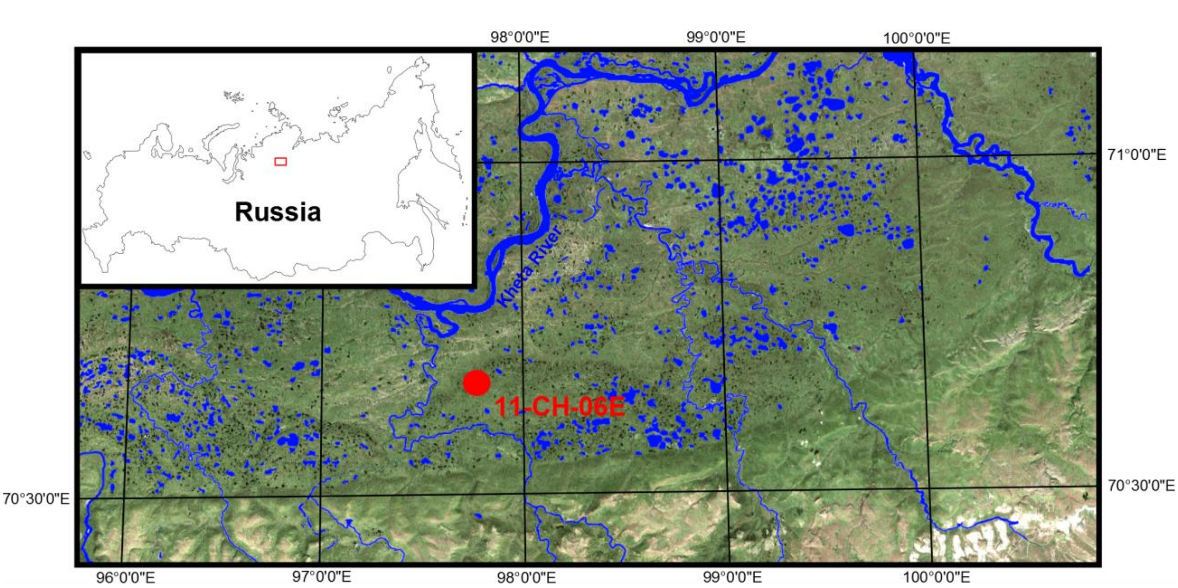

Figure 1: Overview of investigated area and position in northern Russia; in red: labelled position of sampled lake 11-CH-06E. (Figure processed with ArcGIS 10.1, included ArcGis WebMap as base map.)

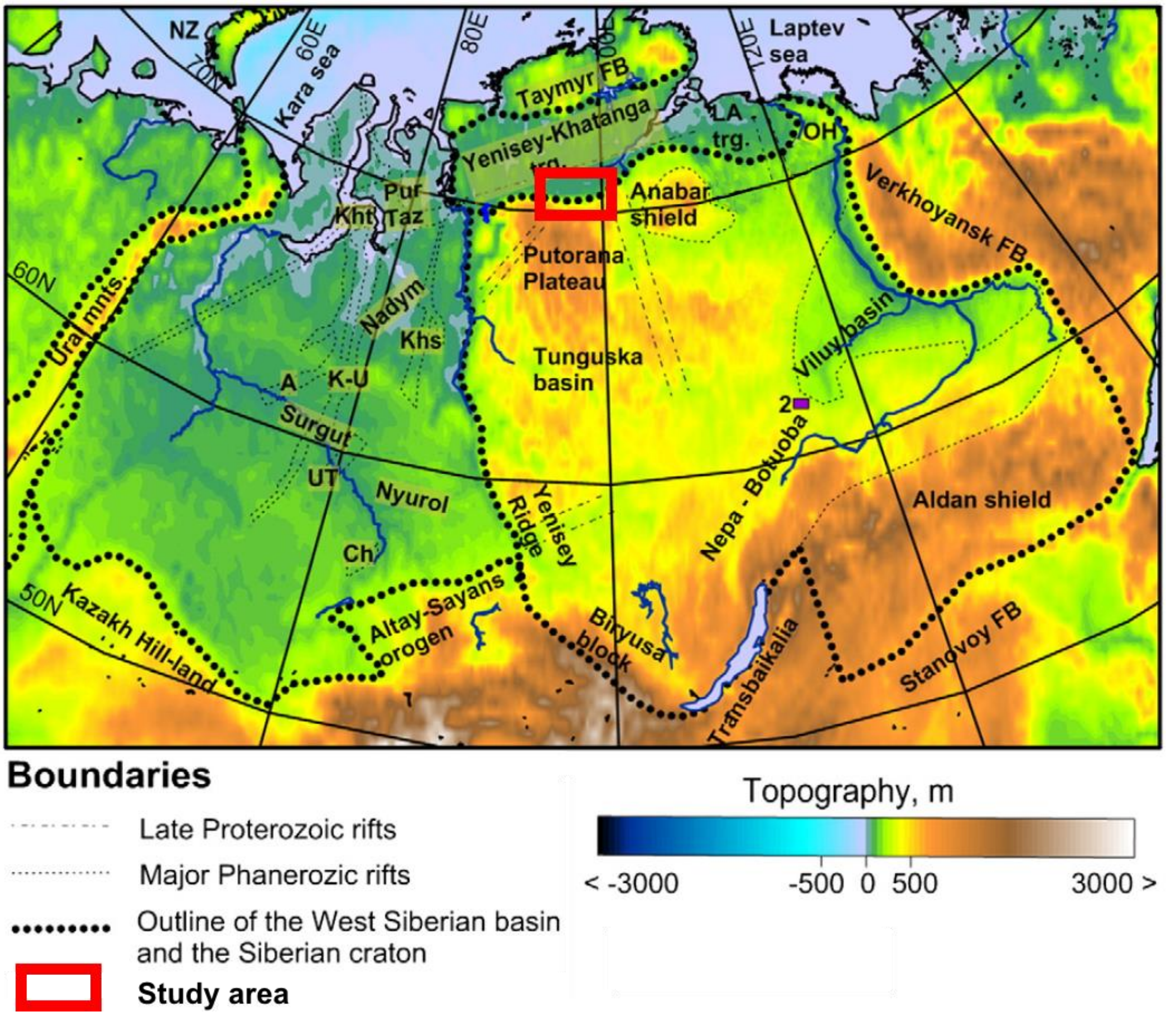

Figure 2: Topography of the West Siberian basin (WSB) and the Siberian craton (SC) based on ETOPO1 (Amante and Eakins, 2009) modified from Cherepanova et al., 2013.

The Taymyrsky Dolgano-Nenetsky District spans over an area of 879,900 square kilometres with approximately 35,000 inhabitants. The population density is about 0.04 inhabitant/km², most of them living in the former administrative centre of Dudinka (Russian Federal State Statistics Service, 2013). Therefore the human influx to the environment and the study side outside the town is very low compared to the enormous soiling in the greater Siberian cities (Tutubalina and Rees, 2001).

2.2 Climate

Northern Siberia has a distinct continental climate. Merely near the polar coast a maritime climate trend is visible. The Arctic Sea is frozen from October till June. During thawing in the end of June it is covered with pack-ice. Most time of the year the sea ice shows behaviour like a massive land mass and is influenced by changes in the wind system.

Therefore it can have an important impact on the hydrological balance at the Siberian landmass (Kriegsmann and Brümmer, 2013).

The study area is located in a humid continental climate with a mean temperature of -12°C and an annual mean precipitation of 450 mm/year, averaged from data of the Dudinka and Khatanga weather station 400 km and 300 km away from the study area Figure 3.

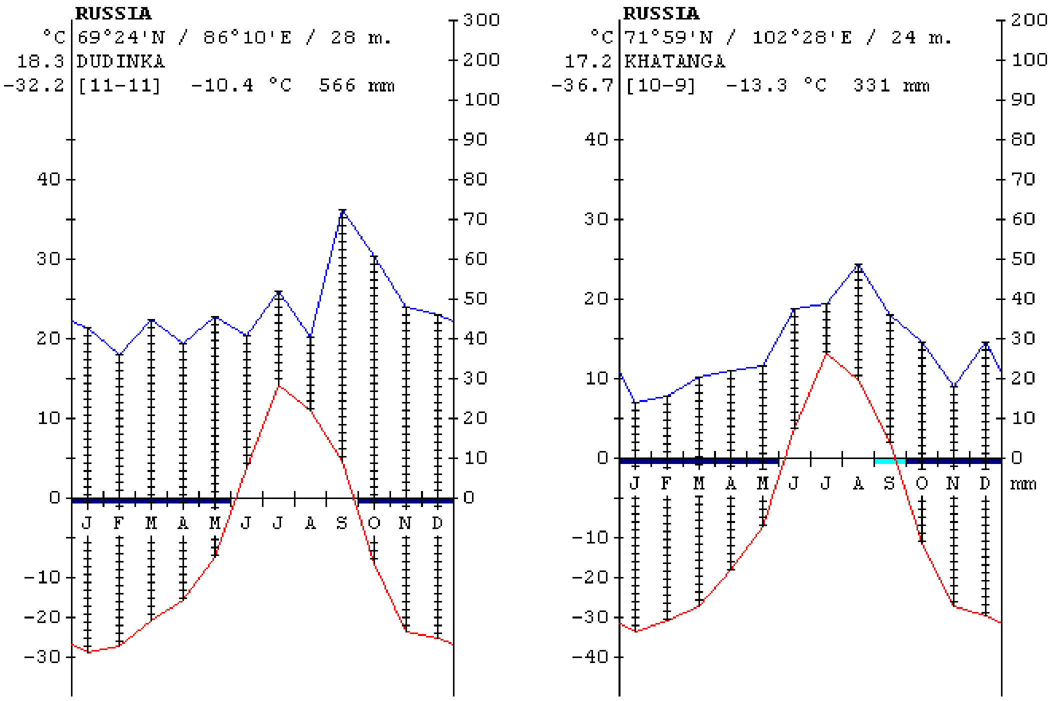

Figure 3: Data from Dudinka (left) and Khatanga (right) weather stations, graphics from www.globalbioclimatics.org (2014)

The wind is changing seasonal, especially visible between summer and winter circulation and the wind speed is perennial low (<20 km/h). The wind direction in the summer is dominated by the vast low pressure system in middle south Asia. It evolves in May and reaches its maximum in July and August. In September and October it starts to weaken and gets replaced by a high pressure system, which reaches its maximum between November and March. The wind direction predominantly goes from north to south. The high pressure area in central Asia caused a predominant wind direction from south to north. Between these main circulations, a west wind circulation dominated the study area (Kriegsmann and Brümmer, 2013; Vergasova et al., 1995; Kodama et al., 2007).

Data from the meteorological station in Khatanga and Dudinka indicates four months (June till September) with a monthly average temperature above 0°C. The warmest month is July with an average temperature of 12°C. The coldest month is January with an average temperature of -33°C. However, there is a great temperature gradient of 80°C between the maximal and minimal temperatures in course of the year. During summer the temperature can reach more than 30°C and in winter less than -50°C.

The precipitation differs between 10 mm and 50 mm per month. Most rainy days occure within winter months, but the highest average monthly precipitation is measured between June and November.

2.3 Geological and geomorphological realities

The study site is located at the Siberian platform and is part of the Siberian craton. The Siberian platform is an ancient structure and has its roots in the Precambrian time. It is found in the north eastern part of the Eurasian plate (Simkin, et. al., 2006). The Siberian platform extends from the Arctic Ocean (Kara and Laptev Sea) in the north, to the Lena River in the east, the Baikal Lake in the south and the Yenisei River in the west, which separates it from the western East Siberian lowland. The Siberian Craton extends to an area of approximately 4 x 10^6 km². The basement is separated by Proterozoic suture zones and is composed off Archean and Proterozoic blocks of various origins (continental terranes, orogenic belts and magmatic arcs) (Y. Cherepanova et al., 2013). Most of the craton is covered by a thick layer of Riphean–Phanerozoic sediments and by Permo-Triassic flood basalts in the north-west (Rosen, 2002). The Siberian Craton is not as well studied and sampled as other cratons in the world (Chain and Koronovskij, 1995; Ionov et. al., 2005)

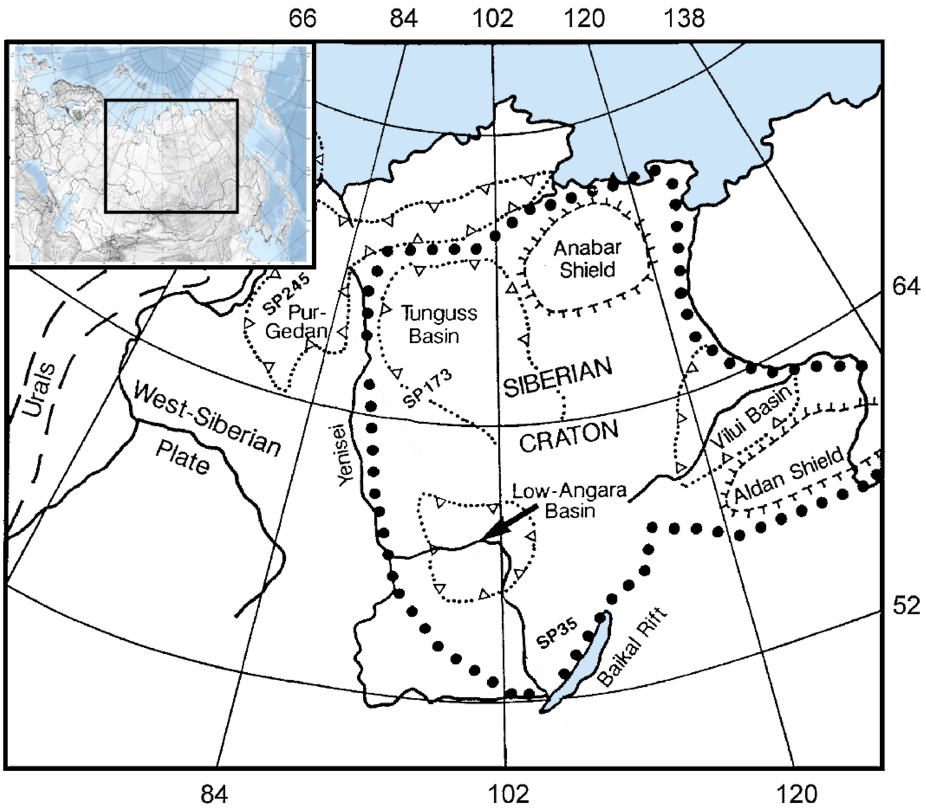

Figure 4: Simplified tectonic map of the Siberian Craton and the surrounding region (Pavlenkova et al., 2002)

The quaternary sediments of the Siberian platform vary in their genetic types and are widely spread over the Siberian Platform. The northwest is marked by glacial sediments whereas the southern areas are influenced by periglacial and lacustrine-alluvial sediments (Koronovskij, 2002).

Based on its position 20 km north from the layered basalt plateaus the studying site is located in the North-Siberian-Lowland. The geological bedrock is part of the basalt layer from the Siberian Traps and grounded on a layer of fine, sandy river flood sediment.

The sedimentological conditions are important for the reactions of the ground to permafrost conditions over long time scales. Fine, sandy underground created from temporary flooding of a river shows different reactions when creating permafrost polygons and lakes, compared to coarse, stony underground.

The last glacial period at the end of the Pleistocene, reached its maximum around 17,000 – 18,000 years ago (LGM). The study site was not covered by glacier in the Holocene (Mangerud et al., 2008; Astakhov, 2004). Glaciation in the Holocene in northern Siberia was limited to local ice shields and higher altitudes (Svendsen et al., 2004).

The lake (technical name: 11-CH-06E) is part of a series of ponds and lakes created by a tributary of the Kheta river inside an alluvial fan, which extends over 50 km in diameter.

Most of the ponds and lakes around the study site are connected by small, partly overgrown streams, which indicate a certain hydrological exchange.

2.4 Soil

The soil is formed by permafrost conditions. The resulting soil is named Cryosol which is declared by the diagnostic cryic- (underfloor) soil horizon. A Cryosol is characterized by permanent freezing (temperature <0°C in two or more years), a massive ice condition by low water content and clearly visible ice crystals in the soil matrix. The near-surface horizons are strongly mixed as a result of kryoturbation by seasonal freezing and thawing. Organic material is built in the upper soil. A frost heave contributes to a subsequent grain size sorting. This leads to the creation of stone rings or on inclined surfaces to stone strips and solifluction. (Fao, 2006; Soil Atlas of the northern Circumpolar Region, 2008)

The soil around the investigated lake is a turbic Cryosol (CRtu) (Soil Atlas of the northern Circumpolar Region, 2008), seen in Figure 5. Turbic Cryosols are mineral soils in permafrost conditions. They show marked evidence of cryoturbation laterally within the active layer, as indicated by disrupted, mixed, broken horizons or displaced material or a combination of both (Harris et al., 1988). Turbic Cryosol can be subdivided into several subtypes (Smith et al., 2009; Migala et al., 2014).

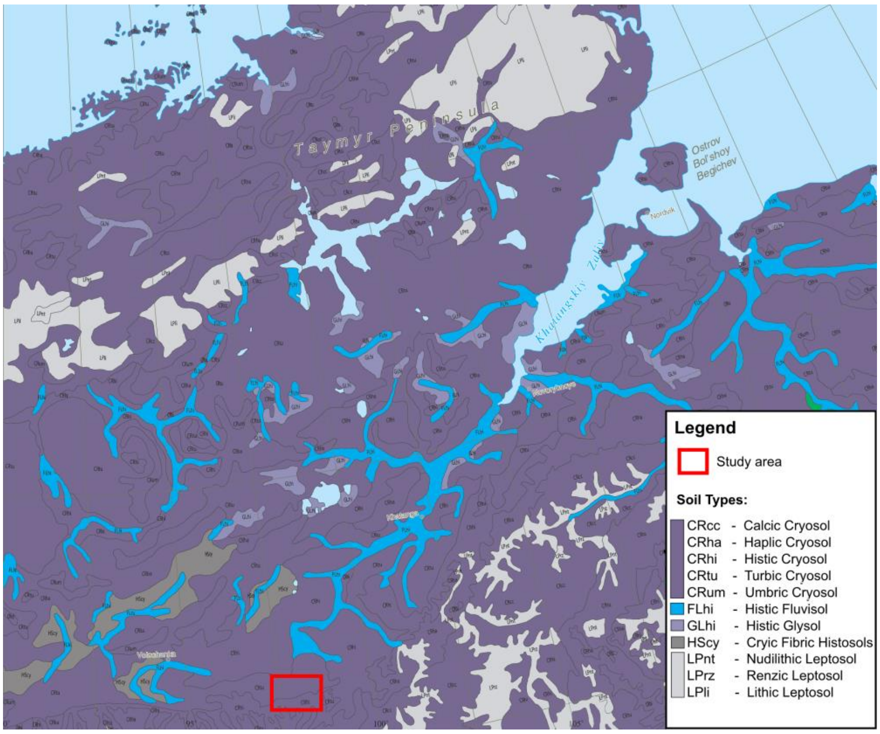

Figure 5: Soil types in the study area (Soil Atlas of the northern Circumpolar Region, 2008).

2.5 Permafrost

All over the planet where cryotic annual mean temperatures of under 0°C and an annual precipitation, which does not allow glaciation, can be found, the ground could start to form a permafrost soil (French, 1996). By the international permafrost association it is defined from Everdingen (1998) as ground (soil or rock and included ice or organic material) that remains at or below 0°C for at least two consecutive years.

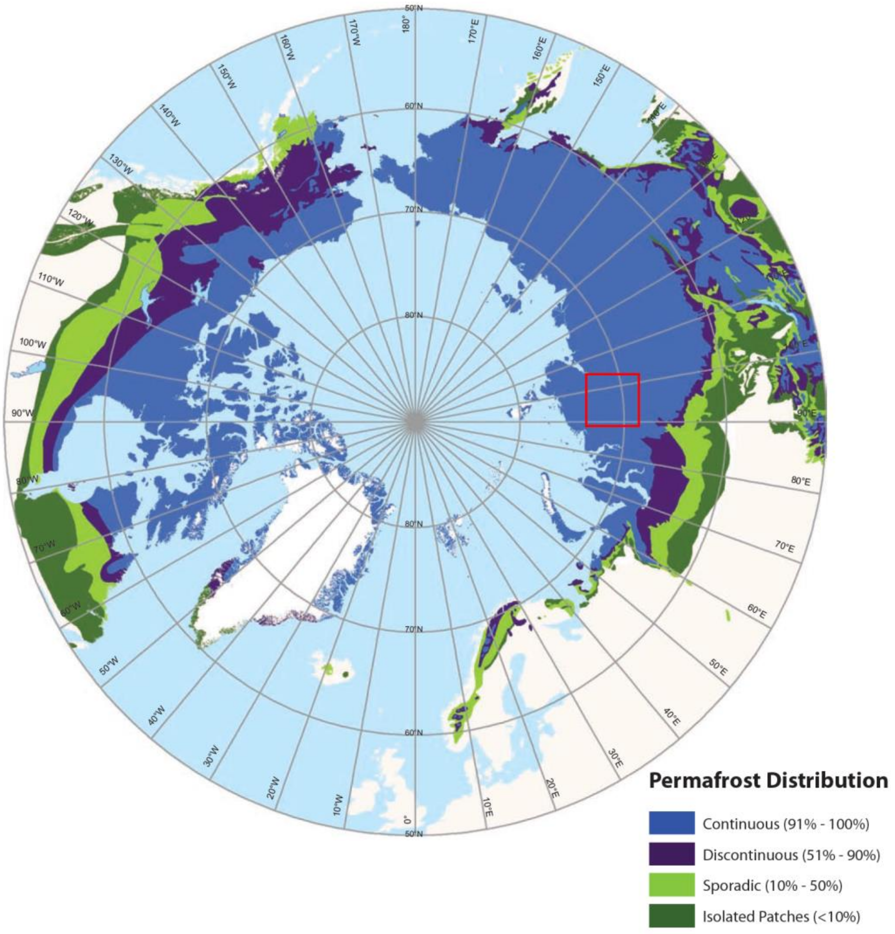

Figure 6: The distribution of the various permafrost zones in the northern circumpolar region. Red square indicates the location of the study area (Soil Atlas of the northern Circumpolar Region, 2008).

Table 1: Annual middle threshold of air temperature for extension classes of the permafrost (Soil Atlas of the Northern Circumpolar Region, 2008; French, 1996).

Permafrost- extension	Permafrost in northern latitudes	Permafrost in high mountains
continuous	-6°C until -8°C	-6°C until -8°C
discontinuous	-3°C until -4°C	-1°C until -2°C
infrequent	-1°C until -2°C	0°C

In summer the upper 50 centimetres till 2 meter thaw. The thickness of this active layer depends on the substrate, exposition and the vegetation on the ground (French, 1996). As a result of the frozen ground it is possible that a polygon structure is formed, which is not visible in the continuous overgrown study site. During the frost period the soil gets cracks and in the melting period these gaps are filled with water. The gaps do not close in the summer, therefore the process may be repeated year by year. Based on the first crack, the soil pressure is reduced in the exposure zone around the crack. Out of this exposure zone it could be another initial crack. Because of the pressure reduction the two initial cracks will be connected by secondary cracks. This behaviour caused in a rectangular ice-crack form polygon, especially in homogenized sediment soils (Hartge and Horn, 1991).

The lakes around the study site are predominantly affected by thermokarst erosion processes. Sediment Layers on the edge of the ice-wedges are bending upwards along the least resistant. The bending is a reason for the expansion of the permafrost soil during heating in summer. These bulges form the polygon walls/ shoulder. If there is not enough volume in the covering sediment layer, it also starts to crack and a process called thermo-erosion starts. The loss of ground ice results in the forming of depressions that are mostly filled with melting water and the phase of thermokarst starts to form thermokarst-lakes. The ice-wedge forming until wide forms is a very slow process. After a while the freezing and thawing processes lead to a substantial change in local and regional geomorphology. The ground surface starts to degrade, collapse, subsidence and erode (French, 1996, Washburn, 1980). These forming processes could be affected by disturbance of climate change, human activity, shifting of drainage or the vegetation cover (French, 1996). Typical development stages of Siberian thermokarst lakes are specified in Figure 7. These stages can take place on big time scales, affecting local vegetation and therefore influences the pollen signal in the lake sediment.

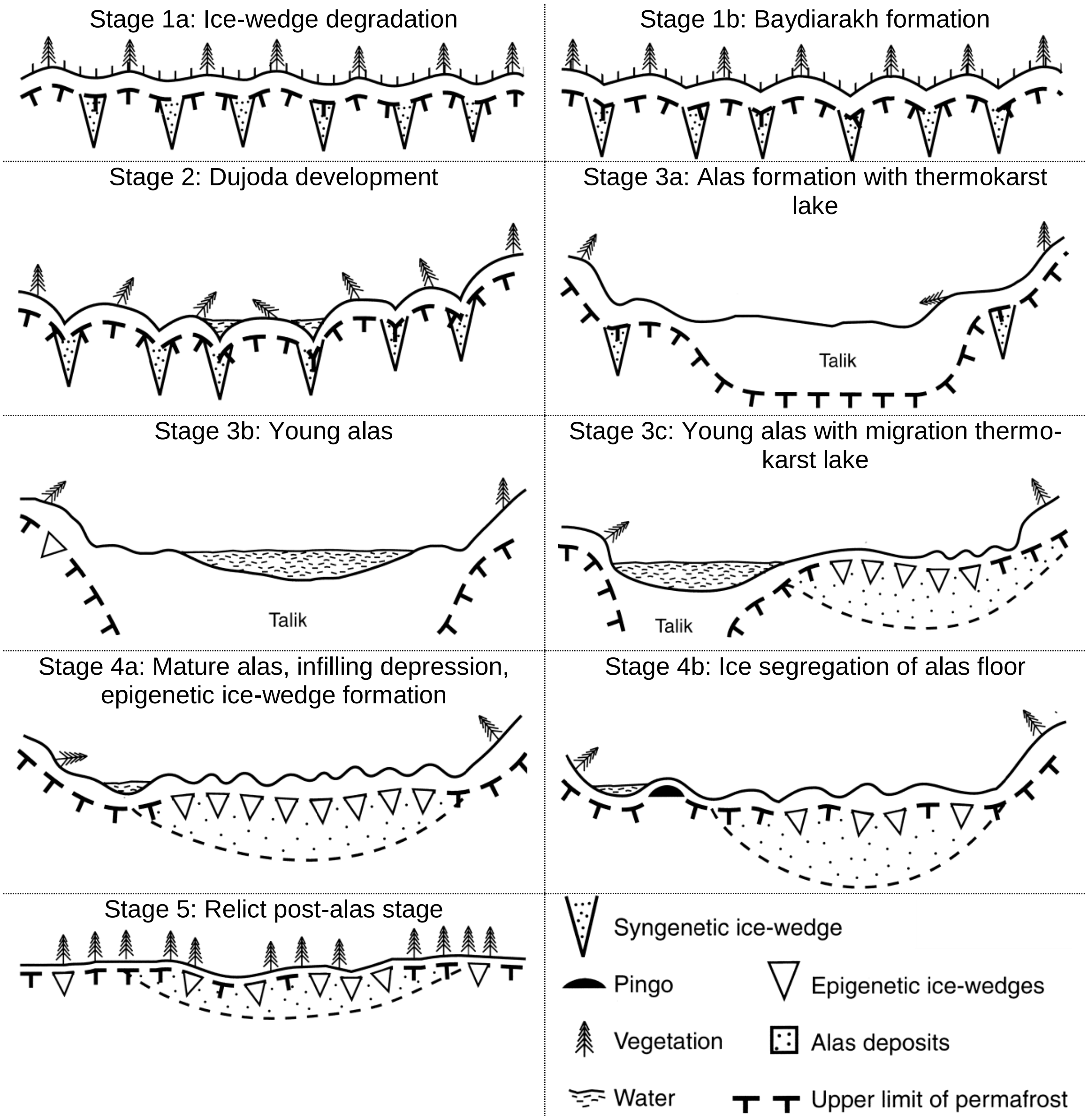

Figure 7: The sequence of development of alas thermokarst relief in central Yakutia, according to Soloview (French, 1996), modified.

Because of the low precipitation there is no glaciation in the study area. This allows freezing of the soil in the study area up to 400 m (Soil Atlas of the northern Circumpolar Regions, 2008).

The thickness of the frozen ground depends on the mean annual temperature and on environmental factors (relief, rock/soil type, snow coverage and vegetation) (French, 1996). The vegetation is due to regional cover thickness, variable pattern, isolation from wind and solar radiation the most difficult parameter for forecasting the permafrost thickness. The active layer is thicker on well-drained bare soil/ rock and thinnest under well overgrown landscapes (French, 1996).

2.6 Vegetation

Due to the extreme annual temperature differences, the Siberian vegetation is specialized on short growing periods, harsh winds, permafrost soil and a low precipitation.

Based on the classification of Chernov (1985) the study area is part of the “typical tundra”. The subdivisions of the arctic vegetation especially the setting of limits and crossovers are not always consist in literature. Aleksandrova (1980) and Yurtsev (1972) subdivided the area with background information of the mean annual temperature, the proportion of trees, the cover ratio and the flora spectrum. From north to south Aleksandrova (1980) suggest to classify the northern and southern polar desert, the northern and southern arctic tundra and the northern, middle and southern subarctical tundra (Figure 8). Chernov (1985) considered the topography and the latitude to separate vegetation boarders. But he mentioned a considerable overlap in species composition of plant communities and a decrease of their diversity, confirmed with the ideas of Nuttall (2000). Washburn (1956) pointed out that also strictly limited optimal soil conditions can create a wide range of extraordinary conditions for the vegetation in permafrost regions. That benefits species in sheltered areas to grow more northern under even suboptimal climatic conditions. The subzone of the arctic tundra occupies Taymyr peninsulas and develops locally along the shores of the Anabar and Kolyma rivers. At its southern border the mean July temperature does not exceed 5°C. French (1997) and Aleksandrova (1980) mentioned that the northern forest limit does not cross this boarder in the Holocene till present day.

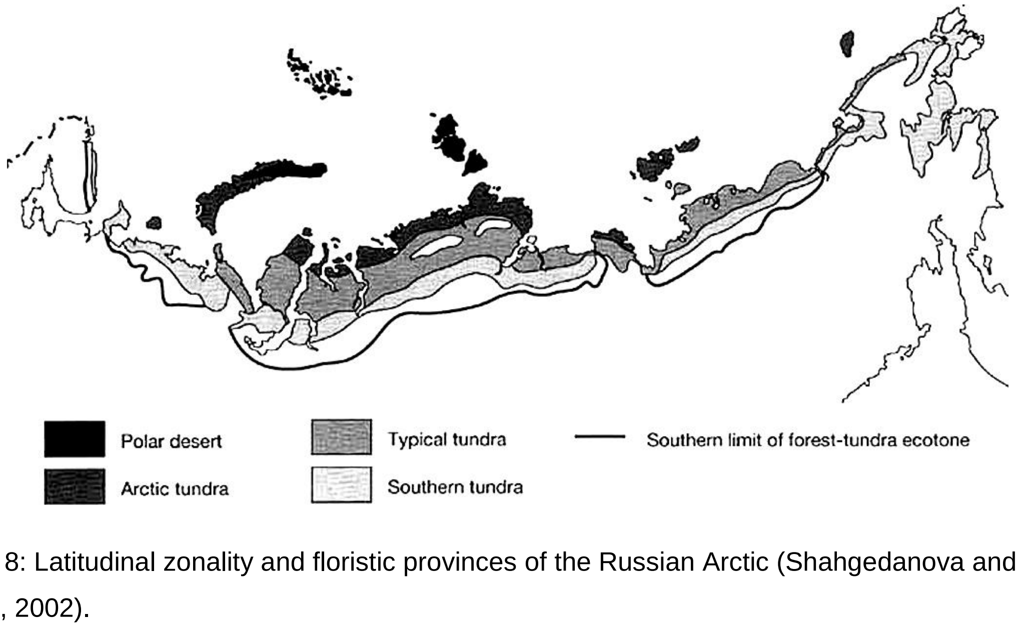

Figure 8: Latitudinal zonality and floristic provinces of the Russian Arctic (Shahgedanova and Kuznetsov, 2002).

Mosses play an important role in the environment of the tundra. Moss cover influences the soil temperature, the moisture, prevents the development of thermokarst and helps to stabilize vegetation. During spring mosses absorb water, creating bog-like conditions and prevent the soil in the summer from drying out. Dwarf willows and flowering plants root in the moss cover. Horizontal development of roots within the moss cover is a typical phenomenon of tundra plants (Aleksandrova, 1980).

Sedges are another common plant in the typical tundra. Their basic zone association is often referred to as sedge-moss tundra.

Young (1971) pointed out that there is a major difference in species composition between east and west and a strong increase in the number of Siberian species resulting from the increasing in more continentally direction and approach to the asiatic centre of species origin. The vegetation coverage increases from the northern arctic tundra from 40-70%, to the southern tundra with a closed vegetation cover up to 98% (Aleksandrova, 1980).

In the border region from arctic to subarctic, the vegetation on the Taymyr peninsular is characterized by the occurrence of *Betula nana* in prostrate on watersheds as well as *Salix lanata*, which indicates that the tundra of this region belongs to the subarctic type. The tundra between the rivers Khatanga and Olenek is represented by creeping shrubs (*Betula exilis, Salix pulchra, S. repens*) with a maximal high of 20 cm (Andreev, 1975). At 72°30’00” N the first *Larix gmelinii* forests are documented. Those trees had short stems, thick branches flattened to the ground and submerged in the moss sward (Andreev, 1975).

The southern tundra has a lack of real tree vegetation. Individual trees, mostly *Larix* occur in large quantities in zonal habitats in the southern tundra along rivers. The treeline in the southern tundra is formed by *Alnus fruticosa* as an admixture to dwarf birch and willow associations (Shahgedanova and Kuznetsov, 2002). Another characteristic are rows of bushes (max. 0.5 m high) developing on watersheds. It consists mostly of *Alnus*, *Betula* and *Salix*. In the shelter of the bushes rich grass, shrub and dwarf vegetation develops. Patches of bare ground are less widespread than in the typical tundra. The forest line is formed by *Larix sibirica* with an increasing amount further south (Aleksandrova, 1980). Central Siberia can be divided in relation to the vegetation cover into three parts. (1) The northern subzone with sparse swampy forests. (2) The central subzone of drier Larix forests and (3) the southern subzone dominated by *Pinus sylvestris* stands (Shahgedanova and Kuznetsov, 2002).

Further south, in the northern regions of Central Siberia *Larix gmelinii* dominate almost entirely the open forest. 150 years old *Larix* trees are about 12 m high. The canopy of the forest is low, in comparison with western regions the productivity and phytomass decreases enormously (Bazilevich, 1993). The vegetation composition of the middle Taiga varies from west to east because of the increasing continentally eastwards. A composition of *Larix sibirica* prevails in the moister western regions which extend to the Yenisey- Lena divide. *L. cajanderi* become the dominant *Larix* species westwards of the Yenisey- Lena divide. Dark taiga species like *Picea obovata* and *Pinus sibirica* are also important in this region (Shahgedanova and Kuznetsov, 2002).

The vegetation in the southern taiga shows a higher variance due to the higher diversity of climatic and soil conditions. In the west of the southern taiga forests are composed of *Pinus sylvestris- Vaccinium vitis- ideae* and in the east by *Larix gmelinii* and dark taiga species like *Picea obovata* and *Pinus sibirica.* Eastwards of the Yenisey River, *Larix gmelinii* becomes dominant due to its shallow root system which allows growing on thin soil layers above the permafrost (Bazilevich, 1993).

The taiga forest has less endemic species. Among forest ecosystems, *Larix* forests are characterized by very low species- richness. Their flora comprises not more than 450 species (Lavrenko and Sochava, 1956; Milkov and Gvozdetsky, 1976).

The mean vegetation composition is shown in Figure 9 and the taxonomic diversity of flora in Northern Eurasia is illustrated in Figure 10.

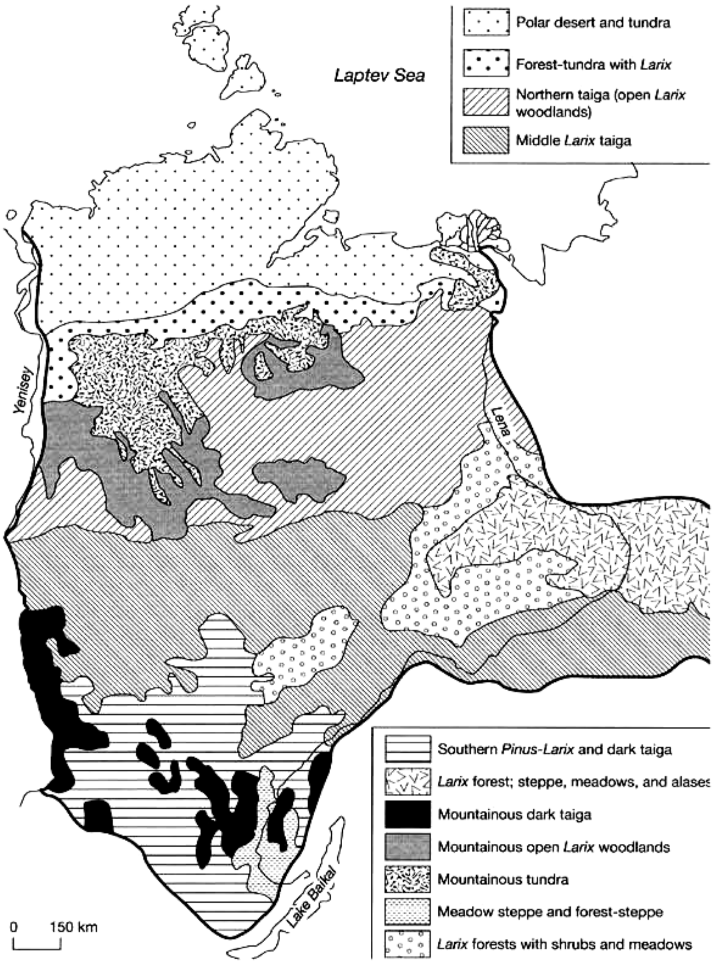

Figure 9: Vegetation of Central Siberia. Compiled by Tishkov (2002), using data from Sochava (1979).

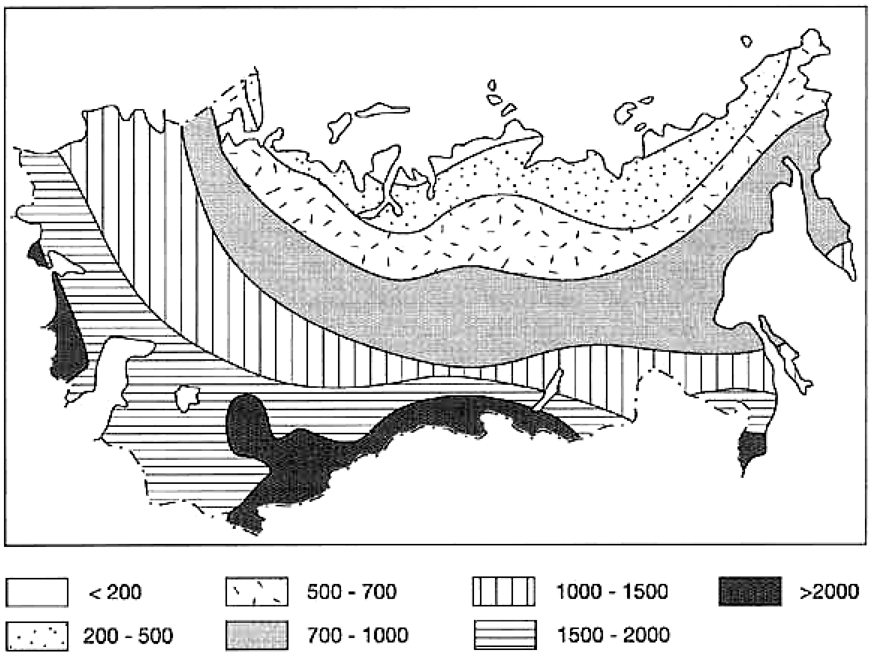

Figure 10: Number of species of vascular plants on a standard area of 100 km^2 (Malyshev, 1992).

According to Aleksandrova (1980) the investigated lake is located between the southern subarctic tundra and the southern limit of forest-tundra ecotone. Due to the mean vegetation of *Larix* forest around the study area, it is important to understand the habitat issues and growing factors of the local trees and shrubs, especially *Larix*.

Larix gmelinii as well as *L. cajanderi* habitat serves the northern borderline in distribution of timber vegetation, limited by climatic conditions (Bobrov, 1972). It is influenced by a warmth deficit and a short vegetation period (Abaimov and Koropachinsky, 1984). Sokolov et al. (1977); Bobrov (1978) and LePage and Basinger (1991) studied the genus *Larix Mill.*. They mentioned the eastern limit of *L. sibirica* habitat and the western limit of *L. gmelinii* habitat are either directly close or overlapping one another. It was shown that these species in the contact zone are involved in natural hybridization. They form a stripe of hybrid populations described by Szafer (1913) as *Larix czekanowskii*. The extension of these stripes of hybrid populations varies from 50 – 70 km in the north, to 250 – 300 km in the central part. In the southern region of Siberia. *L. gmelinii* and *L. cajanderi* have definite habitats, but in their contact zone (which appeared at the end of Pleistocene), hybrid populations with combining features of their mother species were formed. Pollen grains from hybrid *Larix* trees are difficult to differentiate from original forms (Larsson-Stern, 2003). Due to different habitat requirements between *Larix gmelinii* and possible hybrid forms, it is important to understand the expansion and overlapping of their pattern and therefore possible effect on the study area.

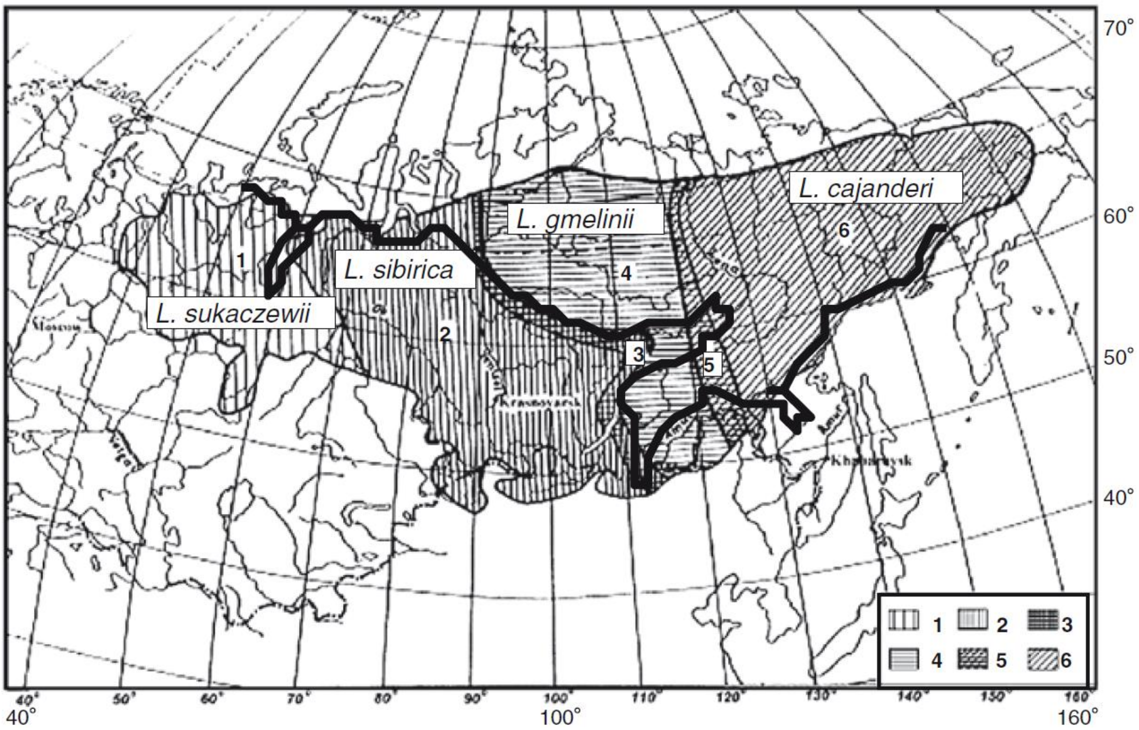

Figure 11: Distribution of larch species in Siberia and adjacent territories: (1) *Larix sukaczewiiDyl*., (2) *L. sibirica Ledeb*., (3) *L. x czekanowskii Szaf*., (4) *L. gmelinii (Rupr.) Rupr.,* (5) *L. gmeliniix L. cajanderi,* (6) *L. cajanderi Mayr*. Southern boundary of continuous permafrost zone (indicated as thick black line) approximately follows southern limit of *L. cajanderi* distribution and southern and western boundaries of *L. gmelinii* (Modified from Abaimov et al., 1997).

All larch species resemble one another. They are monoecious timber plants with needles on short shoots which buck off in autumn. Siberian larch species occupy vast habitats. Their territory is characterized by a wide range of ecological conditions. Siberian larch species have adapted during their evolution process to the changing environment. They have acquired definite morphological features and adaptations to ecological properties with respect to warmth, moisture, soils rich in elements of mineral nutrition, and permafrost (Osawa, 2010). Good quality seeds can keep in the cones for 3–4 years. In the northern part of Central Siberia, 9–20% of the produced seeds are still viable in the autumn of the following year (Abaimov 1997; Abaimov et al., 2000).

L. gmelinii trees can reach 40 m height and a diameter of 80–100 cm in optimal ecological conditions (Shcherbakov, 1975; Dylis, 1981; Falaleev, 1985). *L. gmelinii* forms dwarfs, shrub-like and semi-dwarf forms at the northern limit of distribution and in the mountainous areas. It reaches its age-limit of 609 years old in Taimyr (Vaganov et al., 1999). The mean age of uneven-aged stands can amount to 250–260 years, and limits of its variation in a separate stand are 383–435 years old (Bondarev, 1995).

L. gmelinii bloom at 9–13°C (Kruklis and Milyutin, 1977). The seed dormancy of *L. gmelinii* is an important different to *L. sibirica* and *L. cjanderi*. The tree seed is able to bloom in optimal conditions, which makes it more resistant to short disadvantageous climatic phases. Their total maturity completes only by spring of the following year (Karpel and Madvedeva, 1977). *L. gmelinii* is a light-loving tree and especially resistant to low temperatures of air and soil compared to other *Larix* species. Its seedlings and saplings can survive under a canopy of taller trees for 100 years and more (Abaimov, 1997). Otherwise their resistance to climate continentality is inferior only to *L. cajanderi* (Nazimova and Polikarpov, 1996). *L. gmelinii* grows well on acid podzolic, cold permafrost, dry sandy, swamped, stony and rich alluvial soils (Dylis, 1981). It grows best on fertile drained soils with deep thawing permafrost. It forms a superficial root system in the permafrost. When the depth of thawing decreases, it is able to form adventitious roots (Pozdnyakov, 1975). The seed germination energy of 76% and the rate of filled seeds changes in different years from 23% to 84% and is also the highest of all *Larix* species. *L. gmelinii* is characterized by a very high reproductive potential in comparison with other *Larix* species. On open sites, it has the first fruits at 9–12 years, in tree stands at 20–25 years. Heavy crops occur every 4–5 years (Karpel and Medvedeva, 1977). One tree can have up to 18,000 and even 38,000 cones (Kruklis and Milyutin, 1977).

Betula nana L. is widespread in the arctic regions of Eurasia, Greenland, Iceland, North America and Siberia (De Groot et al., 1997). It is a highly branched cold-tolerant shrub that often grows up to 1 m in height and is a characteristic species of open raised bog and tundra environments. It characteristically spreads out mainly via vegetal rhizomes. That generates the possibility to react very fast to environmental changes, which makes it very important for the evaluation of pollen spectra with regard to climatic changes. Remains of *B. nana* include pollen grains, fruits, catkin scales, bud scales, leaves and periderm. The pollen grains are very difficult to identify because the *B. nana* pollen grains are similar to those of birch trees, such as *Betula pendula* and *Betula pubescens*. Pollen grain size for these species partially overlaps, despite the mean values being higher for *B. nana* (Koperowa and Srodon, 1965, 1968; Clegg et al., 2005; Blackmoore et al., 2003). To distinguish among them, the general pollen morphology, pollen grain size and grain diameter/pore depth ratio should be taken into consideration (Birks, 1968). For this reason *B. nana* pollen grains are often identified as cf*. Betula nana, Betula nana*-type or they are included into a general category of *Betula* pollen (van Dinter and Birks, 1996). *B. nana* tends to form reproducible hybrids of dwarf-birch with *B. pubescens* or *B. pendula*. These hybrids can grow up till 3-4m high (Reichinger, 1981).

Betula pendula and *B. pubescens* are widespread at temperate latitudes and occur up to arctic permafrost regions to the east of the Yenisey and the upper Lena valley (Makhnev, 1969, 1986; Maliouchenko et al., 2008; Andersson, 2005). *Betula pendula* occupies relatively dry areas with well drained soils, whereas *B. pubescens* shows preference for habitats with better moistened and more acid soils. The northern boundary of *B. pendula* range lies in the northern taiga subzone, on the contrary *B. pubescens* is more cold-resistant and expands up to the forest–tundra. In the south *B. pendula* prevails in the steppe zone, while *B. pubescens* is represented by isolated micropopulations in topographic depressions. These species are physiologically close to each other. They form hybrids and can be hardly differentiated in parameters such as relative growth rate, net assimilation rate, specific density of leaves, the total area of leaves per unit biomass, and the proportion of leaves and roots in the biomass of the whole plant (Mortensen, 1995; Myking and Heide, 1995; Niinemets et al., 2002; Portsmuth and Niinemets, 2007).

Green alder (*A. viridis subsp. fruticosa, formerly A. crispa, hereafter A. viridis*) dominates the shrub canopy in upland forests. It is the most widely distributed alder species within interior, western, and northern Alaska and big areas in Siberia (Figure 12). *Alnus viridis* is a dominate tree and occupies broad expanses of arctic scrublands where its range has expanded significantly over the past century (Sturm et al., 2001; Tape et al., 2006). *A. viridis* resprouts vigorously following fire, serving as a key-stone species in early successional dynamics (Chapin et al., 2006).

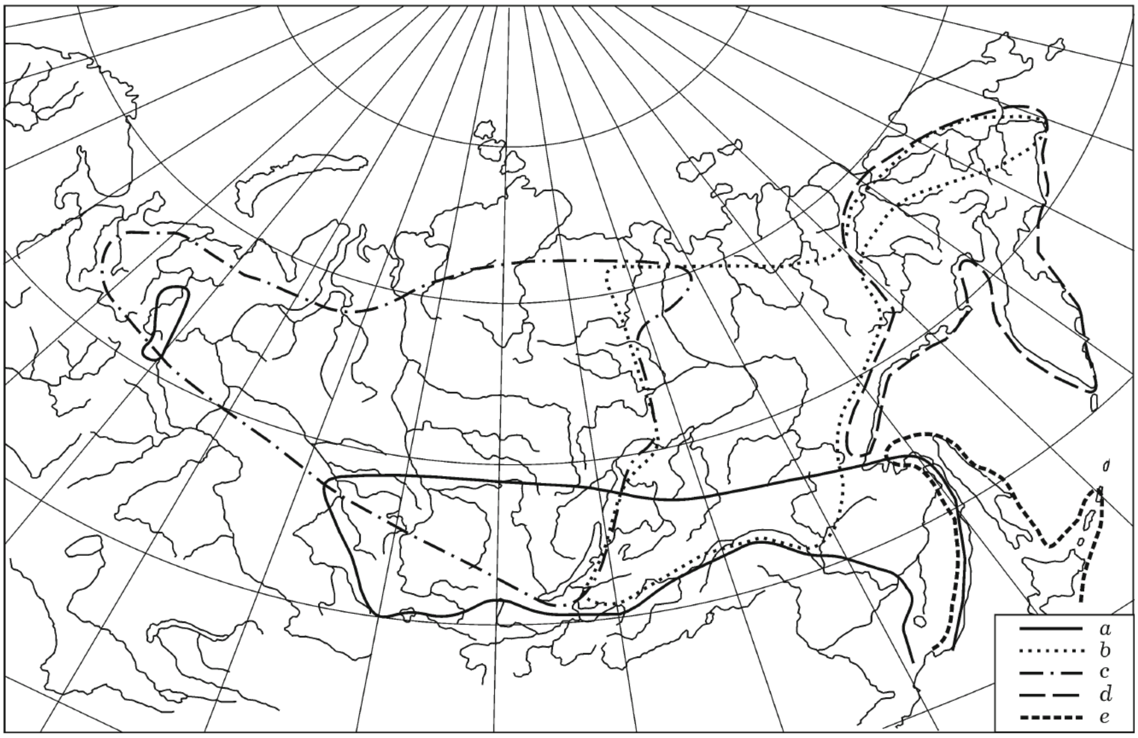

Figure 12: Distribution of *Alnaster mandshuricus* (a), *A. glutipes* (b), *A. fruticosus* (c), *A. kamtschaticus* (d), *A. maximowiczii* (e), according to Cherepanov et al. (2013).

The main local vegetation at the study site can be separated into three basic habitats.

1. *Larix* forest on dryer ground with shrubs like *Salix*, *Alnus*, some *Betula nana* and herbaceous plants like *Vaccinium vitis-idaea, Ledum palustre, Vaccinium uliginosum, Dryas punctate*, *Poaceae, Brassicaceae and Rosaceae* sharing the underground with mosses.
2. Dried up ponds and brooks with higher moisture in the underground and a thicker moos cover sharing the place with predominant *Cyperaceae*.
3. Lakes and Ponds with aquatic plants.

Between these habitats exists a mixture of transition vegetation assemblages. The transient regions between waters and *Larix* forest are mainly affected by different *Cyperaceae* species, large amounts of *Betula nana*, *Alnus fruticosa* and *Ledum palustre*.

3. Methods

3.1 Field Work

The expedition into the Khatanga region, Northern Siberia, in 2011 was conducted by Prof. Dr. Ulrike Herzschuh, Alfred-Wegener-Institut Helmholtz-Centre for Polar and Marine Research in Potsdam (Germany) in cooperation with Prof. Lyudmila Pestryakova, Yakutsk Federal University Yakutsk in Russia. The transport of researchers and technical equipment between the different locations was managed via helicopter. The study site of this thesis (Lake 11-CH-06) was sampled as one of many other lakes. Sampling took place using an inflatable dinghy on the 150 x 300 m lake. The maximal water depth of the lake is 4.8 m, which was measured using a hand echo lot. In addition, several other limnological parameters were measured on-site. This includes conductivity, alkalinity, pH, temperature of the surface water and the transparency determined by means of a Secci disc. To recover well preserved cores, a UWITEC gravity corer with a diameter of 6 cm was used. The retrieved short core 11-CH-06E featured about 46 cm with well-preserved sediment. Already in the field it was sliced into 90 samples of approximately 0.5 cm thickness, to prevent disturbance, maintain the layer arrangements during transport and to save space. The samples were stored in plastic bags (Whirl-Packs), shut tight and stored cool until transport to the Alfred-Wegener-Institut Helmholtz-Centre for Polar and Marine Research in Potsdam. The participants of the expedition took a vegetation survey record of the environment around the study site.

3.2 Pollen analysis

3.2.1 Pollen sample treatment

From the 90 samples of the short core a total set of 60 samples was prepared and analyzed. Due to the complex and expensive preparation method and the following time consuming analysis, 30 samples were not prepared. The pollen preparation was conducted in the laboratory at the Alfred-Wegener-Institut Helmholtz-Centre for Polar and Marine Research in Potsdam. The pollen treatment is based on standard methods for pollen preparation (Faegri and Iversen, 1989). Firstly, 1.5 ml material was used from the samples taken in the field. From the first 30 samples (0.25 cm – 15.25 cm), each sample was chosen, between sample 30 and 90 (16.25 cm – 44.25 cm) every second sample was selected for the preparation. Two *Lycopodium* spore tablets (Batch No.: 938934; approx. 10679 ± 953 spores/ tablet) were added as a marker. In a next step, a 10% hydrochlorid acid (HCL) solution was added to dissolve any carbonate and to dissolve the substrate of the added calcium carbonate *Lycopodium* spore pills. After that step, 25 ml potassium hydroxide (KOH) was added and heated for 10 minutes in a 90°C water bath to accelerate the process to remove humic acids. After that, the samples were sieved through a net (mesh size 200 µm). After neutralization with unionized water in a Heraeus IS multifuge, 40-45% hydrofluoric acid (HF) was added to the samples to remove silicium silicates and remained in the samples for 16 hours. Then, the samples were drained and refilled with HF. The samples were heated in a hot water bath to support the reaction. After a heating period for 1.5 hours, a cooling for 0.5 hours and another 1.5 hours heating period, the samples were neutralized and stored in unionized water. Following this, the samples were filled with 100% acetic acid (CH_3COOH) to remove as much water as possible from the sampled material. This is important for the next step, when a 1:9 mixture of 96% sulphuric acid and acetic anhydride ($C_4H_6O_3$) was added for acetolysis in order to color the pollen grains and spores yellow-brown. After a short heating in a hot water bath, the samples were centrifuged and neutralized. Then, the samples were sieved through a net (mesh size 7 µm) in an ultrasonic bath (VWR USC 100T) to reduce very fine materials which are left in the samples. During the last stage the samples were stored in glycerol.

3.2.2 Pollen data treatment

The pollen grains and spores in the samples were counted using a Zeiss Axioskop 40 Microscope with a 40 x dry objective and a 10 x ocular, which investigates a magnification of 400. Every sample was counted until a minimum of 300 terrestrial pollen grains were reached. In addition selected spores and non-pollen palynomorphs (NPP's) were also counted. The pollen grain analysis based on the pollen grain key of Beug (2004), Moore et al. (1991) and Savelieva et al. (2013).

Most of the counted pollen grains are ascertainable on the family or genus level. A classification into different morphological (e.g. Pinus haploid/ diploid) types did not take place. All statistical analysis were performed with percentage data of the counted taxa.

To include a counted taxon into further analysis a minimum abundance of 0.5% in at least five samples out of 60 was required in this thesis. The percentages of pollen grain producing species were compared, excluding the aquatic species. Non-pollen palynomorphs percentages were compared separately. The percentage of Lycopodium marker spores were compared with the total amount of pollen grains. The species in the pollen diagram were arranged according to their growth form (tree, shrub or herb) and their appearance or taxonomy.

Pollen taxon and influx diagrams were generated with “C2” Software, “R” Project Software and the vector/graphic Software “Inkscape”.

The pollen-influx (Pi) (see Figure 16) is a product of the pollen-concentration (PC) and the sedimentation-rate (SR) (Hicks and Hyvarinen, 1999):

$Pi = PC * SR$

The Cluster analysis is a multivariate method for quantitative definition of stratigraphic zones and was conducted with “R.programm” (The R Project for Statistical Computing) and the CONISS algorithm. Compared to ordinary analysis, only stratigraphically adjacent clusters are considered for merging in unconstrained cluster analysis. The method of incremental sum of squares is popular for unconstrained analysis and has proved particularly satisfactory for pollen frequency data. CONISS is a FORTRAN 77 program for stratigraphically constrained cluster analysis by this method. Several data transformations lead to different implicit dissimilarity coefficients (Grimm, 1987).

The principal component analysis (PCA) biplot summarized the extent to which the objects represented by the rows differ in relation of the objects represented by the columns. Generally, when the rows are brands and the columns are attributes, the principal components analysis biplot shows the highest patterns obvious in the data in terms of how the brands differ in constraint of the attributes.

The RDA (Redundancy Analysis) constrained linear ordination method, which combines multiple regressions with principal component analysis (PCA). The number of recognized axes corresponds to the number of explanatory variables. Each canonical axis is a linear combination of all explanatory variables (Borcard et al., 2011). The generated report includes environmental variables, which are constrained ordination axes (RDA-axes). Unconstrained axes are named as PC axes. The table with the partitioning of the variance between the one explained by constrained axes (environmental variables) and the one explained by unconstrained axes (variance not explained by environmental factors) shows the proportion of the total variance, which is explained by all environmental factors.

3.2.3 Isotope geochemistry

The short core was examined for two methods to date sampled material. The upper 3.25 cm (14 samples) were radiometric dated. It was done by P.G.Appleby and G.T.Piliposian (2011) at the Environmental Radioactivity Research Centre at the University of Liverpool. Dried material was send in for an analysis of ^{210}Pb and ^{137}CS using Ortec HPGe GWL series well-type coaxial low background intrinsic germanium detectors (Appleby et al., 1986). ^{210}Pb was determined via its gamma emissions at 46.5 keV, and ^{226}Ra by the 295 keV and

352 keV γ-rays emitted by its daughter radionuclide. The samples were stored in sealed containers for 3 weeks to allow radioactive equilibration. ^{137}Cs was measured by its emissions at 662 keV. The absolute efficiencies of the detectors were determined using calibrated sources and sediment samples of known activity. Corrections were made for the effect of self-absorption of low energy γ-rays within the sample (Appleby et al., 1992).

The second method was the ^{14}C dating, to complete the age determination of the core. Four subsamples from the 11-CH-06E core and 5 subsamples from the parallel core 11-CH-06D were sent to the Foundation of the Adam Mickiewicz University to Poland.

To create the age-depth model, the dataset from the 14 samples from the ^{210}Pb and ^{137}CS dating was used. The dataset produced an almost linear trend, therefore the sedimentation rate of the last samples from the bottom were used to create a linear age-depth model (Figure 18).

Derived from the constant sedimentation in the upper part of the core beneath 1.25 cm, a sedimentation rate of 0.018 cm/a was suggested for the entire core.

4. Results

4.1 Field and core data

The investigated lake is located in the geological region of the Khatanga-Kheta depression with influences from the Putorana-Plateau. The lake is situated at the northern outer border to the Plateau on the edge of an alluvial fan. The alluvial fan is characterized by a higher number of lakes per km² as it is ordinary in the northern environment outside the alluvial fan.

The 46 cm short core was already sampled in the field. There was no cryoturbation typical structure visible during sampling. This is a sign that the lake is not completely frozen in the winter.

During the stay at the lake some important water parameters were measured in 30cm depth. The maximum of 4.8 m water depth was determined by hand echo lot. The maximal visibility of 2.5 m was measured by secci disc. All other parameters were collected with a WTW Multi 350i sonde. It showed an alkalinity of 0.4 mol/l, a conductivity of 35.3 µS/cm (Tref 25°C) and a pH-value of 6.42.

The investigated short core is well composed with pollen grains over the entire length and did not show any important effects of disturbance.

4.1.1 Characteristics of pollen spectra

In the short core 11-CH-06E, 37 different taxa were identified. (A list of all counted species can be found in the appendix). Aquatic pollen producing species like *Potamogeton* were not included in the evaluation, because this study investigates with pollen grain data from terrestrial taxa.

To be taken into consideration in this study, the minimal amount of pollen grains must be 0.5% in at least 5 from 60 samples referred to all counted pollen producing species, excluded aquatic species. The following pollen producing taxa were not considered in the pollen diagram.

Asteraceae, Epilobium, Fabaceae, Hippuridaceae, Picea, Polygonaceae, Ranunculaceae, Rubicaceae, Valerina, Rumex aquaticus

Pinus windsleeve fragments are also shown in the diagram. They were counted all over the core as more or less destroyed pollen grains. Based on the various destruction forms it was not usful to count two destroyed pollen grains as on single *Pinus* grain. Due to a constant counting of fragments the results are also helpful to interpret the results.

The following findings (Figure 13) represent the 13 remaining species, which are consistent represented in the samples along the core. Tree and shrub pollen dominate all taxa with a variation between 76% and 92% and an average of 84%. *Betula* occurred most frequently with an overall share of 44%, a minimum of 31% and a maximum of 57%. *Alnus* pollen taxa are the second most common species in the counted core with a minimum of 26%, a maximum of 48% and an average of 37%. *Larix* has an average of 2%, a minimum of 0.26% and a maximum of 7.67%.

The total amount of herb taxa varies between 8% and 24%. *Cyperaceae* occurred with a mean of 9.7% and *Poaceae* with an average of 2%.

Alnus and *Larix* show a similar trend with a higher amount of pollen grains below the middle to the under part of the core. The amount leads to a decrease for *Alnus* from the middle to the upper part until sample 2 (2.25 cm) and for *Larix* in sample 3 (1.25 cm). *Salix* indicates a more irregular trend due to its low concentration in the samples with a predominantly stable stage between 43.25 cm and 24.25 cm and a high rise in the last 2 upper samples. Compared to *Alnus* and *Larix* there are some similarities in the trend visible. *Betula* reveals an opposing trend compared to *Alnus* and *Larix*. The low concentration of *Betula* starts to increases from the under part to the upper part with a local maximum between 8.25 cm and 9.25 cm. In contrast to *Alnus* and *Larix*, the concentration of *Betula* pollen grains has been decreasing since the late 19th century. *Pinus* and *Picea* show a variable trend through the whole core. The percentage of *Pinus* pollen grains decrease slightly from the bottom to the top. *Picea* pollen grains are only present in the lower half of the core (44.25 cm - 21.25 cm) and remains under the 0.5% limit to be included in the statistical interpretation.

Herbs, such as *Cyperaceae*, *Poaceae* and *Brassicaceae*, offer a slightly inconsistent fluctuation over the whole time, with some comparable stages (Figure 13). *Cyperaceae* slightly increases to the top of the core with a minimum of 3.7%, a maximum of 15% and an average of 9.6%. There is a significant minimum between 10.25 cm and 8.25 cm, which can also be found in the trend of *Brassicaceae*, *Artemisia* and *Poaceae*. *Artemisia* increases from the bottom to the middle of the core, then decreases and reach its local minimum (0%) at around 9.25 and 4.25 cm depth, with a local maximum (2.6%) at 5.75 cm. *Poaceae* has the highest stable amount of pollen grains (5.8%) in the upper part of the core between 6.75 and 1.75 cm with a decrease in the upper two samples. It reaches its minimum of 0.3% at 1.25 cm. *Asteraceae* can be found up to one sample only in the upper part of the core. It reveals a negative trend to *Picea* pollen but did not reach the 0.5 % boarder and was not included in the statistical analysis. *Artemisia* varies over the core, with bigger spreads between minima and maxima in the upper part. *Caryophyllaceae*, *Rosaceae* and *Ledum* slightly increase from the bottom to the top.

The Non-pollen palynomorphs (NPPs) show a comparable trend in the core. Ascospores (single and multi-part), *Botryococcus*, *Larix* stomata and *Pediastrum* are well represented in the lower part of the core (44.25 cm – 21.25 cm) and show a decline from the middle to the top of the core (21.25 cm – 4.25 cm). The trend of indetermined Alga 2 is completely contradicted to this, with a sudden increase in the middle of the core.

The pollen concentration is relatively high throughout the whole core. It shows a minimum of 16,800 grains/cm^3, a maximum of 80,000 grains/cm^3 and an average of 44,500 grains/cm^3 (± 7500 grains/cm^3). Together trees and shrubs pollen grains reveal a minimum of 76%, a maximum of 92% and an average of 84% of all counted pollen grains. Herbaceous plants are part of the remaining percentages and vary between 8% and 24%.

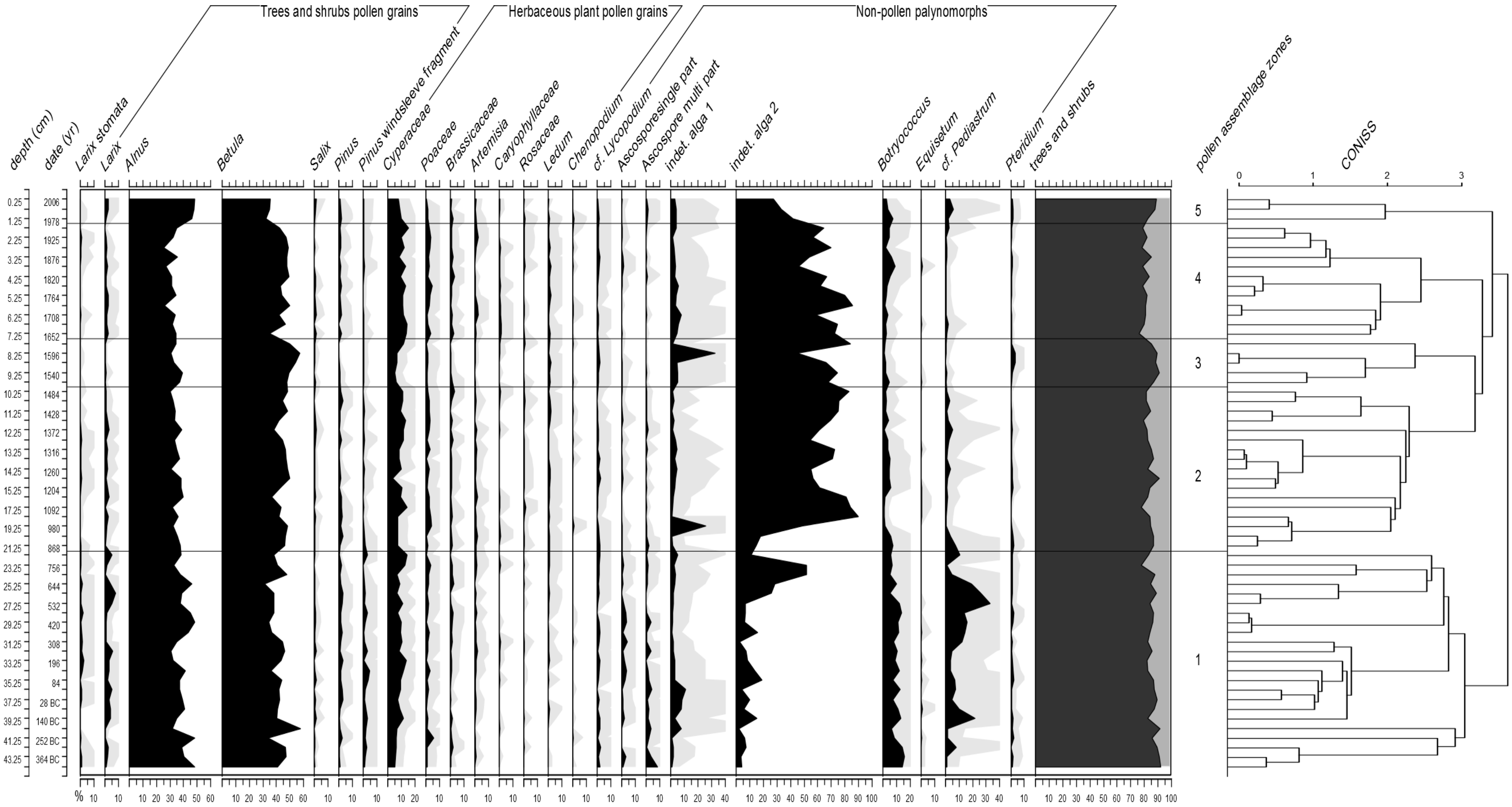

Figure 13: Pollen diagram over time for lake 11-CH-06E, gray silhouettes are exaggerated values, five pollen assemblage zones (PAZ) are shown, derived from the CONISS analysis (right).

4.1.2 Cluster analysis

All 13 taxa were included in the cluster analysis. The result is shown in Figure 13. Based on this analysis it is possible to classify 5 statistically relevant sections. The pollen assemblage zone (PAZ) 1 includes the lower 23 samples (89 - 44) and reaches from 44.25 cm – 22.25 cm depth. This zone is characterized by a larger number of *Larix*, *Alnus* and *Pinus* pollen grains compared to the rest of the short core. *Alnus* and *Betula* pollen grains slightly decrease on average. *Salix* indicates the highest variations in contrast to the other PAZ. Herbaceous plants increase slightly e.g. *Cyperaceae*, *Brassicaceae*, *Artemisia* and *Ledum*. *Rosaceae* has its minimum in the PAZ 1. The PAZ 1 can be subdivided into 3 visible occurrence parts. The first part reaches from 44.25 cm to 40.25 cm. It is affected by a low amount of *Larix*, *Salix*, *Pinus*, *Cyperaceae*, *Artemisia* and *Ledum*. *Alnus* and *Betula* show a higher amount of pollen grains in this part. Part 2 reaches from 40.25 cm to 31.25 cm. *Larix*, *Alnus*, *Pinus*, *Artemisia*, and *Caryophyllaceae* have a higher amount of pollen grains in this part. The third part stretches from 31.25 cm to 22.25 cm and mark the transition from PAZ 1 to PAZ 2. *Larix* has low amounts of pollen grains in part 3 with two maxima first around 26.25 cm and second, like *Cyperaceae* and *Artemisia,* at 22.25 cm. *Alnus*, *Pinus* and *Ledum* have their highest amount of pollen grains in this part of the PAZ 1.

PAZ 2 reaches from sample 43 – 21 and represents a depth from 21.25 cm to 10.25 cm. The main characteristics are a stable and constant pollen grain relationship compared to the other PAZ. *Alnus*, *Larix* and *Artemisia* show a slight decrease in the upper part, the transition zone between PAZ 2 and PAZ 3. *Betula* starts to increase at the top of this zone at 10.75 cm and has two minima at 16.25 cm and 12.25 cm. *Pinus* shows variable amounts in this zone with two maxima, the first between 20.25 cm and 16.25 cm and the second at 10.75 cm. At the transition to PAZ 3, *Pinus*, *Cyperaceae*, *Brassicaceae*, *Artemisia* and *Rosaceae* reveal a high decrease.

PAZ 3 spans the samples 20 – 16 at a depth from 9.75 cm to 7.75 cm. This zone displayed a rapid decrease of *Larix*, *Pinus*, *Cyperaceae*, *Brassicaceae*, *Caryophyllaceae* and *Artemisia*. In contrast, *Betula* increases to the middle of the PAZ 3 and reaches an upper part maximum of the short core at 8.25 cm. The PAZ 3 marked the beginning of a slight decrease of *Alnus* starting at 9.25 cm. At the transition to PAZ 4, *Larix*, *Salix*, *Pinus*, *Brassicaceae*, *Poaceae*, *Artemisia* and *Caryophyllaceae* reveal a high increase in their amount of pollen grains.

PAZ 4 identifies the samples 15 – 4 at a depth from 7.25 cm to 1.75 cm. The main characteristics of this zone are the fast increase of *Larix*, *Salix*, *Pinus*, *Cyperaceae*, *Brassicaceae*, *Poaceae* and *Caryophyllaceae* after PAZ 3, followed by relatively stable conditions.

Alnus reaches 2 minima of total amount of pollen grains at 5.75 cm and 2.75 cm. *Brassicaceae* shows a total maximum of its amount of pollen grains at 4.25 cm, *Artemisia* at 6.25 cm and 2.25 cm. *Larix*, *Alnus*, *Salix*, *Caryophyllaceae* and *Ledum* show a minimal decrease in the transition from PAZ 4 to PAZ 5.

PAZ 5 contains sample 3 – 1 and reaches from 1.25 cm to 0 cm. This zone shows a high increase of *Salix* and *Alnus* Pollen grains and a visible increase of *Larix*. *Betula* pollen grains reach a local minimum, while herbaceous pollen grains predominantly decrease, except *Rosaceae*.

4.1.3 Ordination analysis of pollen RDA

The first axis of the pollen RDA illustrated 20.5% of the total variance of the data set. Axis 1 and 2 combined explained 36.2% of the variance of the data set.

Table 2: Results of the pollen RDA

Axis	Eigenvalue	Cumulative Proportion	Proportion Explained of species data %
1	2.659	0.204	20.5
2	2.047	0.362	15.7
3	1.505	0.478	11.6
4	1.171	0.568	9

Table 3: Results of the non-pollen RDA

Axis	Eigenvalue	Cumulative Proportion	Proportion Explained of species data %
1	3.601	0.360	36
2	1.433	0.503	14.3
3	1.143	0.618	11.4
4	0.917	0.709	9.2

The result of the pollen PCA is shown in the biplot in Figure 14. The results of the pollen RDA are shown in Table 2. It reflects the five zones defined by the cluster analysis. All PAZ zones are spread in the diagram. The PAZ 1 is highly represented in the negative quadrants of both axis and except of 196 BC, 196 AD, 308 AD and 756 AD in the negative quadrant of the first axis. The PAZ 2, PAZ 3 and PAZ 4 are predominant in the positive quadrants of axis 1, whereas PAZ 3 is only represented in the positive quadrant of the second axis, except from 1680 AD and 1820 AD – 1876 AD. PAZ 5 is mostly represented in the positive quadrant of axis 2, except 2006 AD and completely in the negative quadrant of axis 1. *Alnus* is the only species in the negative quadrant of both axes. It explains a part of PAZ 1 and half of PAZ 5 and shows a high negative correlation to *Ledum*. *Cyperaceae*, *Poaceae* and *Chenopodium* show similar trends. Together with *Brassicaceae*, *Rosaceae* and *Ledum* they are all part of the positive quadrant of both axes and explain groups of samples from PAZ 1, PAZ 2 and PAZ 4. *Artemisia* and *Pinus* are close together in the positive quadrant of axis 2 and specify parts of the PAZ 1, PAZ 2 and PAZ 5. *Larix* and *Salix* are also very close together, explaining parts of the PAZ 1. *Betula* shows a negative correlation to them and explains parts of the PAZ 2 and large segments of PAZ 3.

The PAZ 4 is mostly explained by herbaceous plants. Trees, especially *Alnus* are the dominant species in PAZ 1 and PAZ 5. The PAZ 3 is dominated and explained by *Betula*. PAZ 2 has the most spread values and offers no clear trend or influence.

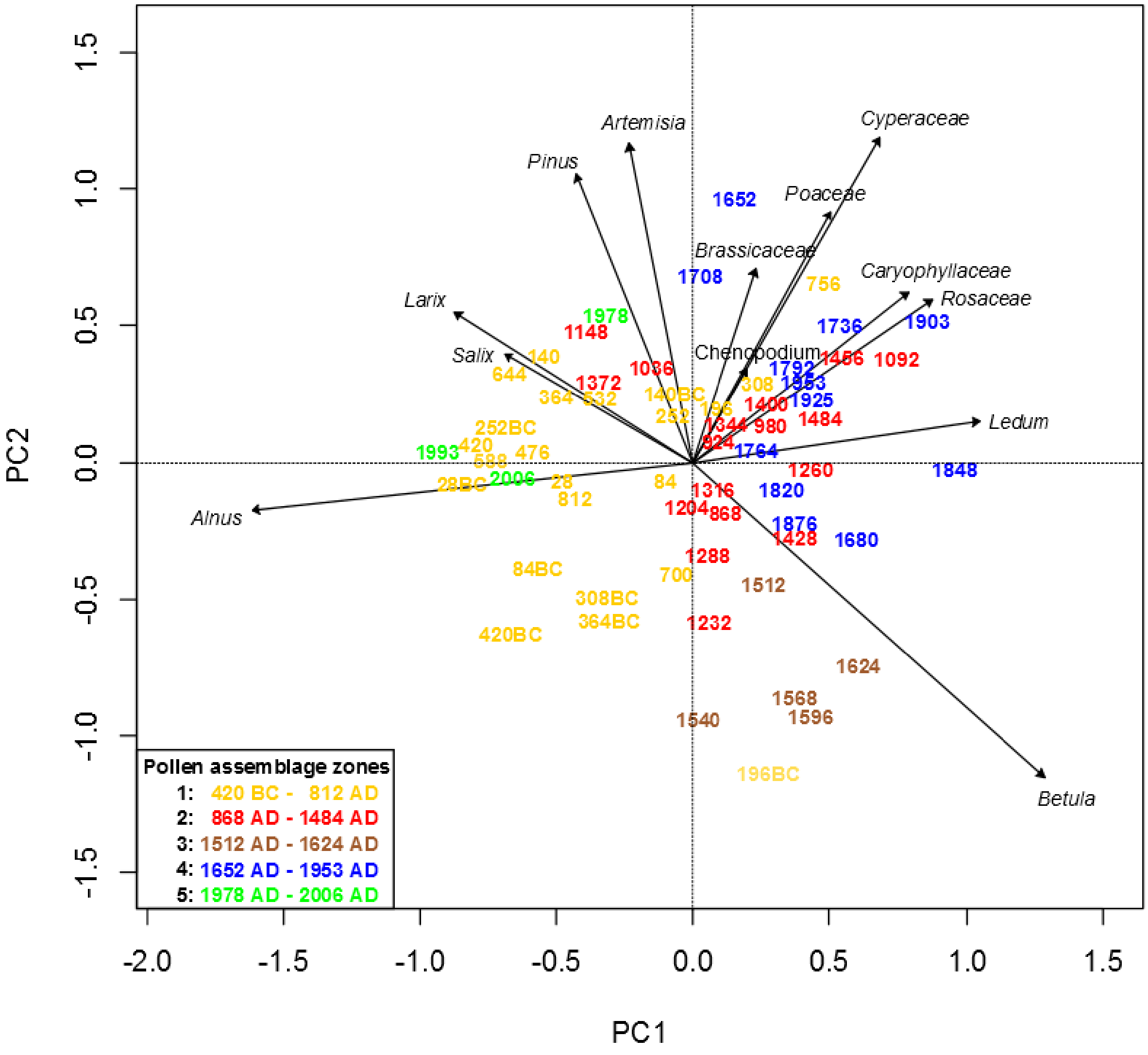

Figure 14: Results of the principal component analysis (PCA) for pollen. Samples are coloured according to the periods and pollen assembled zones (PAZ) they represent.

4.1.4 Ordination analysis of non-pollen RDA

The first axis of the non-pollen RDA represented 36% of the total variance of the data set and the first 2 axes together explained 50.3% of the variance of the non-pollen data set. The results of the non-pollen RDA are shown in Table 3.

All PAZ zones are arranged in the diagram. PAZ 1 and PAZ 5 are completely represented in the positive quadrant of axis 1, except 2006 AD. Large parts of the PAZ 1 are also situated in the positive quadrant of the second axis. The PAZ 2, PAZ 3 and PAZ 4 are predominant in the negative quadrant of axis 1, except from 924 AD, 868 AD and 1848 AD. The PAZ 2, PAZ 3 and PAZ 4 are spread over the positive and negative quadrants of axis 2. PAZ 5 is mostly represented in the positive quadrant of axis 1, except 2006 AD and completely in the negative quadrant of axis 2. The indeterminate Alga 1 is the only species in the negative quadrant of both axes. It explains some parts of PAZ 2, mainly the PAZ 5 and 1886 AD (PAZ 3) and 1596 AD (PAZ 3) and shows a high negative correlation to *Equisetum*. Ascospore multi part, Ascospore single part as well as *Pediastrum, Botryococcus and Larix* stomata show similar trends and can explain most of the PAZ 1. *Lycopodium* and *Pteridium* are close together and explain Parts of PAZ 5 and few parts of PAZ 1. *Equisetum* just represents 1848 AD, 308 AD and 364 AD. The indeterminate Alga 2 specifies parts of the PAZ 3 and PAZ 4. The indeterminate Alga 1 and 2 explain a preponderant part of all PAZ, except for PAZ 1.

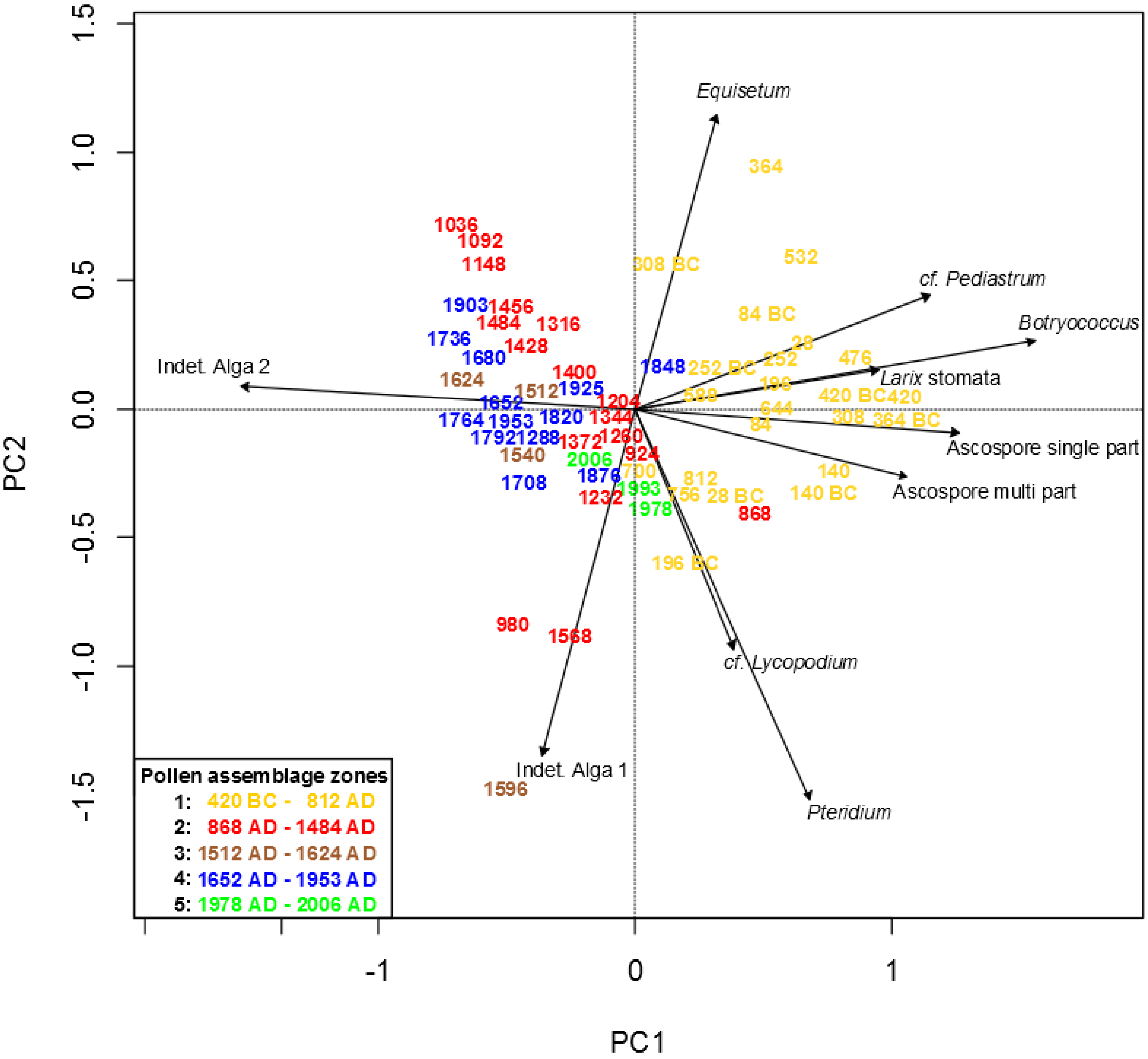

Figure 15: Results of the principal component analysis (PCA) for non-pollen. Samples are coloured according to the periods and pollen assembled zones (PAZ) they represent.

4.1.5 Concentration and influx

The average Pollen concentration over all samples is 44,500 pollen grains per cubic centimetre (pg/cm³ ± 7500 pg/cm³). The highest amount of pollen grains is 79,800 pg/cm³, the lowest 16,800 pg/cm³.

The pollen concentration and influx rate vary strongly over the entire studied period. There are small trends visible. The pollen concentration decreases from the bottom to the depth of 20 cm. After this time it slightly increases and remains relatively stable to the top. It reaches a maximum between 8.25 cm and 9.25 cm. This maximum is also visible in the *Betula* and *Alnus* influx diagram. *Larix*, *Alnus* and *Betula* were chosen because of their high influence of 84% to the entire pollen concentration in the short core.

The influx rate of *Larix* decreases from the bottom to the middle of the core then remains stable. *Larix* influx rate shows an average value of 11 grains/a, a minimum of 1 grain/a, a maximum of 65 grains/a and did not increase between 8 and 9 cm like *Betula* and *Alnus*. *Betula* and *Alnus* influx is mainly stable along the core with varying values for Alnus from 49 to 542 grains/a and an median of 188 grains/a. Influx rates of *Betula* reaches from 69 to 680 grains/a and an average of 222 grains/a. There are some greater variations for *Betula* and *Alnus* in the under part of the core and a maximum between 8 and 9 cm. At the top is a low increase trend of *Alnus* visible.

The influx rates, pollen concentration and the influx of mixed species are shown in Figure 16.

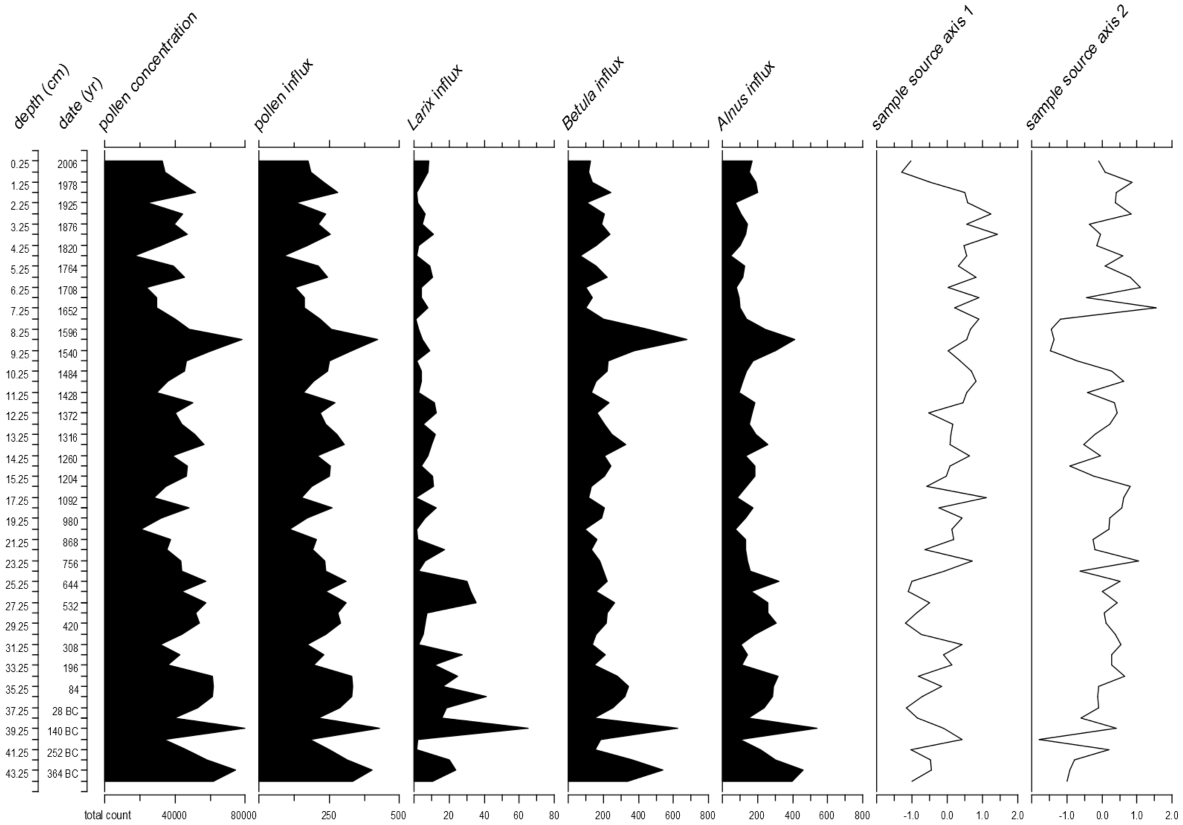

Figure 16: Pollen concentration (grains/cm^2) and pollen influx (grains/a) diagram for the entire pollen composition, *Larix*, *Betula* and *Alnus* and sample source of axis 1 and 2 (results from the PCA).

4.2 Age depth model

The age-depth-model was established on the basis of the upper 10 cm. It based on Pb/Cs measurements as reported by Appleby and Piliposyan (2011). The age-depth-model for the core 11-CH-06E is shown in Figure 17.

The ^{210}Pb dates are distinctive over the first centimetres. The maximum value of the ^{137}Cs activity occurs in the uppermost section of the core. Below this it declines monotonically with depth. There was no evidence of a sub-surface peak that might record the 1963 fall-out maximum from the atmospheric testing of nuclear weapons (Appleby and Piliposyan, 2011). The sedimentation rate decreases at the first centimetre and starts to be quite constant at least lasting since 1965, identified by the general dating model (Appleby, 1992). The mean sedimentation rate during the whole period lays at 0.0054 g/cm²*a, which is a mean of 0.026 cm/a. The error amounts to ±19.2%. To verify the sedimentation level and check if it is at a constant level, four ^{14}C samples were commissioned by Tomasz Goslar, Poznań Radiocarbon Laboratory in Poland. Sample 19, 33, 59 and 72 of the 11-CH-06E core were determined. The results were displayed in Figure 18. The age of the short core was ascertained by the sedimentation rate, based on the Pb/Cs values. It show a relatively constant value (0.018 cm*y^{-1}) from a depth of 2.00 cm. This rate was extrapolated for the whole short core and displayed in Figure 17.

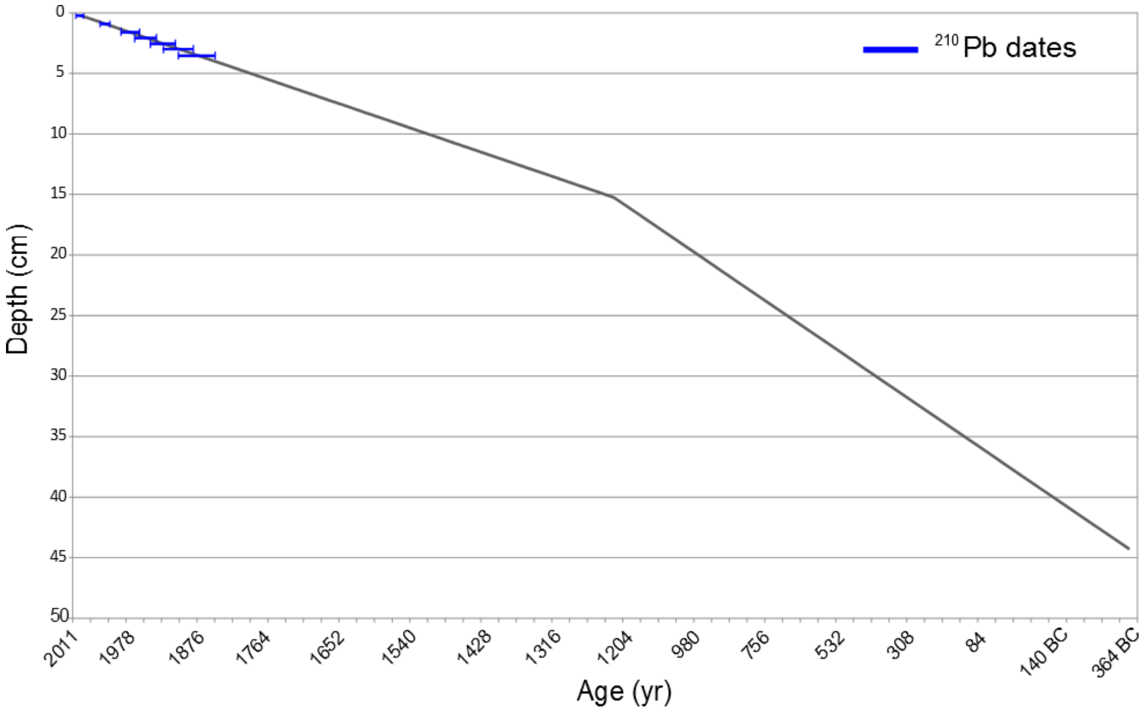

Figure 17: Radiometric chronology of the Chatanga lake sediment core 11-CH-06 showing the ^{210}Pb dates and the age-depth extrapolation for the short core 11-CH-06E based on Pb/Cs.

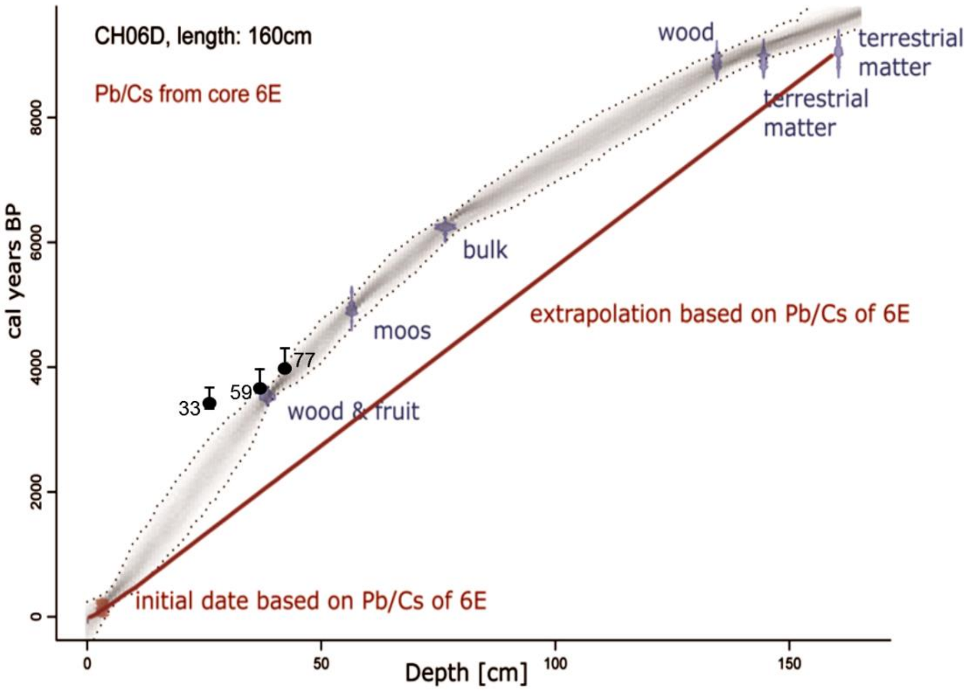

Figure 18: 14C dating model Core 11-CH-06D and 11-CH-06E together with the extrapolation based on Pb/Cs of short core 11-CH-06E.

The samples 11-CH-06E-59 and 11-CH-06E-77 are well suited to the ^{14}C samples from the parallel core 11-CH-06D. The sample 11-CH-06E-33 indicates an older age as expected and sample 19 was not included in the diagram due to an implausible value and an error while calibrating. Even after calibrating the three remaining samples with “CALIB RADIOCARBON CALIBRATION PROGRAM” (Stuiver and Reimer, 1993) there was no visible change in a younger direction. This can be the case, if older material was transported into the sample, or if there are strong variations in the ages of the samples in different depths. The results of the ^{14}C determination are presented in the age-depth-model, but are considered therefore as less valuable and were not used for the reconstruction of the age-model for the lower part of the core.

The merged information of the Pb/Cs dating, the derived sedimentation rate and the ^{14}C dating are shown in Figure 17. The kink at the depth of 15 cm is a visual effect result from sample taking (see chapter 3.2.1).

5. Discussion

5.1.1 Reconstruction of vegetation change

The pollen signal in the sediment of a lake depends on several different environmental parameters. The size of the lake is one important factor in view of the pollen signal. Small lakes or ponds are dominated by local taxa. Greater lakes are dominated by a more regional pollen signal (Sugita, 1993). The difference in the pollen signal between small and big lakes varies (Davis, 2000). There are several pollen studies from north Siberia available, many of them attend to smaller thermokarst or polygon mire lakes/ponds. These lakes reflect only predominant local pollen spectra. Nevertheless there are studies from large lakes near the study area available e.g. Labaz Lake (Andreev et al., 2001; Kienel and Siegert, 1999), Lake Kokora (Andreev et al., 2001), or the western Lama Lake (Hahne and Mellers, 1997). The lake 11-CH-06 extends to 150 x 300 m and is assumed to display local and some regional pollen signals.

Furthermore it is important that different pollen taxa were found in the lake sediment. These taxa have quite different morphological characteristics and habitat origin. Species like *Larix* produce big and heavy pollen grains, which refer to a habitat in the vicinity of the lake. Sugita (1993) showed that 50% of *Larix* pollen in a lake with 250 m radius derives from trees in 1000 m diameter around the lake. Small and light pollen e.g. *Alnus* and *Salix* pollen grains represent under the same conditions 50% from a source area of 10,000 m radius around the lake. Other taxa like *Pinus* and *Picea* have windsleeves and therefore they are able to compensate their size. These pollen grains can be transported over very long distances (Birks and Birks, 1980). Trees like *Pinus* and *Picea* do not belong to the local environment, but were found in the pollen signal in this study. Their pollen grains could be transported for more than 400 km from the southwest or southeast where the most northern *Pinus* and *Picea* populations occur (Moser and McDonald, 1989; Brubaker et al., 2005; Janssen, 1973). These pollen grains are overrepresented in the samples. Even so, it is possible to take conclusions about their appearance in relation to tree shifts due to climatic changes (Figure 19).

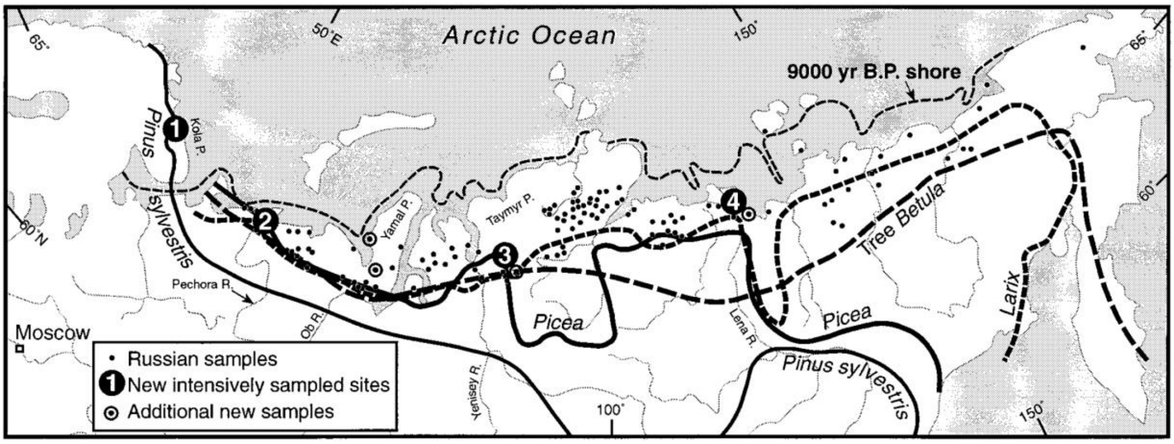

Figure 19: Arctic area in Russia and the modern range limits of arboreal species, *Betula*, *Larix*, *Picea*, and *Pinus* are illustrated as lines (Tree and Shrub Distribution in the USSR, 1991).

There is a higher chance for long distance transported pollen grains to deposit in a lake within an open landscape than in a well tree covered area. In such a case, the size of the lake is very important for a better understanding of under- and overrepresented species.

The mixture from regional and local taxa depends on these factors:

- height and strength of the pollen source
- wind speed and wind direction
- falling speed of the pollen grain (depends on shape, size and morphological characteristics e.g. windsleeves)

Therefore the amount of long distance transported pollen grains is an important factor in this study, especially from *Pinus* and *Picea*, which could help to estimate the influence of other long distance transported pollen grains e.g. *Betula* (Hjelmroos, 1991). Due to the difficult distinguishable forms of *Betula* pollen grains it is complex to decide if it is local or long transported taxa.

Due to more annual extreme conditions in northern Siberia, plants reduce their pollen productivity (Andreev et al., 2006; De Klerk et al., 2014). Therefore lakes in the higher attitudes of Siberia are generally more influenced by regional long distance transported pollen grains, especially in areas where trees just appear as shrubby plants (Andreev et al., 2001). Plenty of the local plants in the study area are pollinated by insects. As a result, these plants produce less pollen grain as self-pollinating plants, especially in unfavourable climatic periods (Birks and Birks, 1980).

Local changes in air mass movement and rain events are also an important field of view. Beitsch (2012) shows that polar cyclone causes more thick ice on the arctic oceans. The processes of freezing and melting have different longer-term or even climatologic consequences in arctic winter and summer. The heat flux between ocean and atmosphere over the cyclone-induced open water areas is increased in winter for a few days. This caused a heating and moistening of the shallow arctic boundary layer. At the same time the open water areas are freezing again. This increase of the ice mass in the winter months is a further important impact to the cyclonic season of the Arctic ice mass. In summer months, the cyclone systems reduce the sea ice concentration and the open water areas remain open. Strong summer storms can lead to increased exceptional reduction of the sea ice concentration causes in changing metrological conditions on land mass (Beitsch, 2012).

Kodama et al. (2007) pointed out that the wind direction depends on surface energy balance components. Surface heat fluxes over the tundra region of northern Alaska (Harazono et al., 1998) and of northern Canada (Rouse et al., 1987) depend on wind direction. These characteristics are transferable to the Siberian landmass (Rouse et al., 1987). Under offshore wind conditions, the air mass was warm and dry, which increased the ratio of evapotranspiration to net radiation by almost 10%. Under onshore wind conditions, the air mass was cold and humid, which increased the ratio of sensible heat flux to net radiation by 50%, causing a large sensible upward and latent heat fluxes to the atmosphere from the tundra surface (Harazono et al., 1998).

Rouse et al. (1987) also revealed that the surface energy partition has substantially changed by wind direction. He pointed out that the northern Siberian coastal tundra region shares the same characteristics of surface energy fluxes with northern Alaska and Hudson Bay by describing the surface energy partition, the heat fluxes dependence on wind direction and other meteorological parameters e.g. wind direction dependency of water as well as energy fluxes and synoptic conditions over a tundra near Tiksi, Siberia (Kodama et al., 2007). Therefore the mean wind direction is an important factor in consideration of changes in the vegetation over long periods.

Wildfires play an important role in the functioning of boreal forests. Forest fires are phenomenons which occur in 5 - 10 years or in 25 - 50 years in wetter places (Utkin, 1965). The influence of the burned forest to the local climate, the effects of seasonal permafrost thawing depth, the solarisation and the local wind circulation system cannot be underestimated in arctic regions (Forkel et al., 2012; Kharuk et al., 2013). Light competition that is typical for forest biomes is less important and replaced by root competition in arctic forests on permafrost conditions. In the zone of northern open forests, wildfire creates a traditional ecological function causes post fire succession and maintains biological biodiversity. It is supposed that without fire, the soil in this region would cool as a result of constant increase of the organic layer. The cooled soil feeds back to a higher increase in the organic layer thickness. This process could finally lead to the development of a treeless tundra biome, illustrate in Figure 20 (Osawa, 2010).

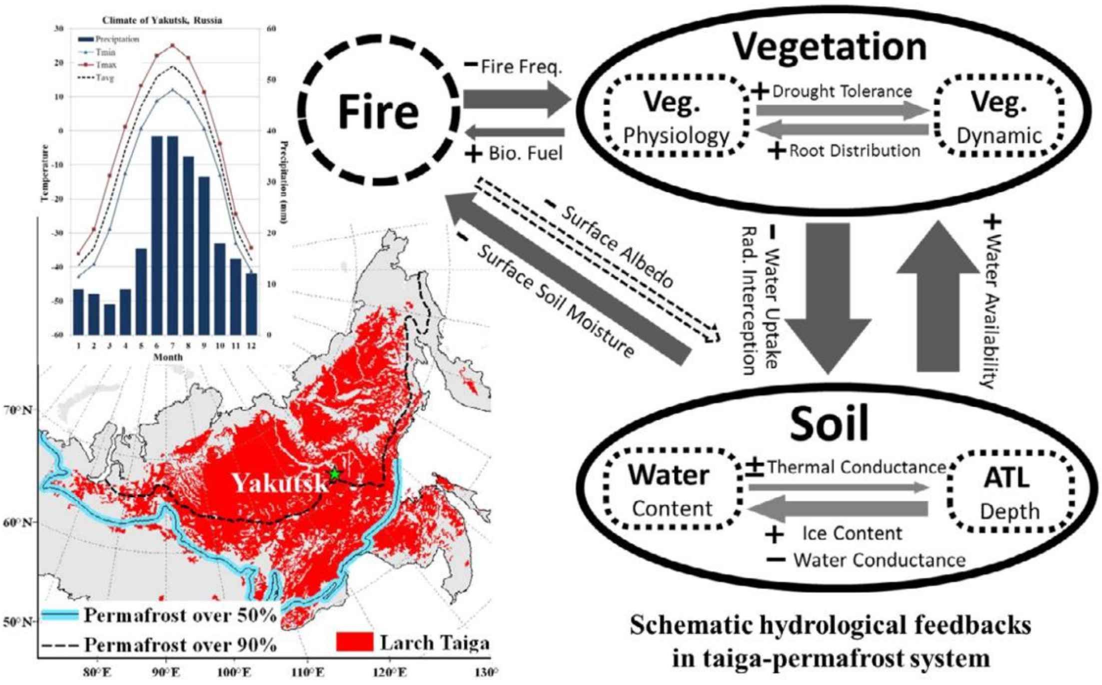

Figure 20: Schematic diagram of feedbacks of soil, vegetation and fire in the Siberian taiga–permafrost system (right-side diagram); spatial distribution of larch taiga (left-bottom figure, red area) and boundary of permafrost (left-bottom figure, dashed line and blue line) and climate of Yakutsk (left-top figure). In the schematic diagram: arrows show force directions between each factor. '+' ('−') means the following the forces direction, there is a positive (negative) correlation between two factors, and '±' means the correlation is still not clear (Zhang et al., 2011).

The annual variation in pollen deposition is sometimes higher than the variation between sites (Andersen, 1974, 1980; Hicks, 1994, 1996). There are years with a high average pollen deposition rate and years with an overall low accumulation rate (Hicks et al., 1994). Hicks, (2001) reveals that the annual variations of pollen are associated to climatic conditions and that the climate signal overrides the vegetation signal of the surrounding tree abundance at a temporal scale. The pollen signal gets dominant, if the annual deposition is averaged over a longer period then over a few years.

The main reasons for a visible change in pollen spectra are temperature and moisture. Within low temperature trees like *Larix* or *Alnus* reduce their production of fertile grains. A lower amount of fertile grains also reduces the chance and possibility to germinate successfully and is visible in reduced pollen spectra in the following years or decades (Summons and Walter, 1990).

5.1.2 Vegetation change inferred from pollen data

The pollen record from Lake 11-CH-06E presented in this study demonstrates visible changes in regional vegetation during the last 2500 years. The five pollen assemblage zones, defined by the cluster analysis and the pollen diagram, documented from results of the PCA analysis, indicate periods of changing environmental conditions.

The PAZ 1 and therefore the oldest part in the short core (420 BC until 812 AD) show a higher percentage of tree pollen grains in contrast to herbs. *Alnus*, *Larix*, *Pinus* and *Salix* also dominate the PAZ 1 values in the PCA. The highest value from *Larix* pollen grains and *Larix* stomata indicates a denser forest than in the other PAZ (Grace et al., 2002). The higher amount of tree pollen and the higher influx rates of *Betula*, *Alnus* and *Larix* pollen (Figure 16) support this assumption. The increasing trend of herbs such as Poaceae, Cyperaceae and Brassicaceae to the end of PAZ 1 are also illustrated by the PCA values (e.g. 756 AD) in the first quadrant. *Betula* does not dominate the PAZ 1, but displays a negative correlation to *Larix*, *Salix*, *Pinus* and also *Alnus*. *Betula* was found predominantly as *Betula nana* around the study area. *Betula nana* is an indicator plant for subarctic, open tundra vegetation. *Larix* and *Alnus* are indicators for a warmer condition and a denser forest (Zech et al., 2010). The high correlation of *Larix* and *Salix* indicate a plant association or even similar environmental requirements and reactions to environmental changes (Osawa, 2010). *Ericaceae*, especially *Ledum palustre* also form plant associations together with *Betula nana* (Ejankowski, 2010). *Ledum* is located near *Betula* in the PCA and illustrates uncorrelated values to the dominating PAZ 1 species. Furthermore *Ledum* shows a similar increasing trend like *Betula*, which indicates related habitat requirements (Ejankowski, 2010). It can be concluded that the second quadrant of the PCA (positive PC1 and negative PC2 values) represents forest like, warmer conditions and the fourth quadrant stands for colder, tundra like conditions (Figure 14). The data in PAZ 1 with a high amount of *Larix* and *Alnus* pollen grains between 200 BC and 200 AD is correlated to the PCA values (28 BC, 28 AD, 84 AD, and 140 AD). Bao et al. (2003) presented via multi-proxy analysis that there was a warmer and wetter period between 200 BC and 200 AD. There are also two other short temporary changing events in the PAZ 1. The first is a temporary cooling event at 196 AD until 308 AD and at 756 AD indicate a positive correlation and an increase to herb taxon especially *Cyperaceae*, but also *Poaceae* and *Brassicaceae.* At the same time span a short and high decrease of *Alnus. Betula* increase, but points to a low pollen influx, same like *Alnus*. In contrast, herb taxon increases percental. 756 AD is also correlated to herb species in the PCA. The pollen diagrams shows an increase of herb taxon and cold tolerate *Betula* and a decrease of forest species like *Larix*, *Alnus* and *Salix*, indicating a more open forest and colder climatic conditions. The second event is a warmer period between 364 AD and 812 AD, specified by high amounts of *Larix* pollen grains (532 AD and 700 AD) and also a high *Larix* influx rate. The PCA show a high correlation for *Alnus* (612 AD), *Larix* and *Salix* (532 AD and 644 AD) and a higher percentage of tree pollen grains compared to herbs showing a warmer and more forest like environment, intermitted only by the short cooling period around 756 AD. The period until 812 AD was the last stadium in a warmer and more forest promoting time period (PAZ 1). Similar findings were already presented in Ma et al. (2003). They did a reconstruction from stalagmites for the last 3000 years based on ^{18}O data in eastern Beijing region. They mentioned significant changing climatic conditions since 700 AD. Yang et al. (2002) and Bhattacharyya et al. (2007) figured out similar trends, based on multi-proxy analysis. They pointed out a warming period till 240 AD (Roman Warm Period), followed by a short cooling phase, which match with the findings from this study.

The environment and therefore the climatic conditions indicate different characteristics after 812 AD with the beginning of PAZ 2 (868 AD – 1484 AD). These changes are also clearly visible in the results of the non-pollen-palynomorphs. *Larix* stomata show a high correlation to values from PAZ 1 (420 BC, 364 BC, 252 BC, 28 AD, 84 AD, 196 AD, 308 AD, 588 AD and 644 AD) and to taxa like *Botryococcus*, *Ascospores* or cf. *Pediastrum*. That corresponds with the findings in the pollen record. More Larix stomata point to a higher sheet formation around the investigated lake due to warmer conditions and a denser forest. Species like *Pediastrum* are assumed to be influenced by higher summer temperatures resulting in more intensive blooming (Niemeyer et al., 2015). All NPP species, excluding indeterminate Alga 1 (negative correlated to Equisetum) and Alga 2 (negative correlated to nearly all other species) decreased from PAZ 1 to PAZ 2. The PAZ 2 is not clearly dominated by special taxon, as it is illustrated by the results of the PCA. Rather there is a trend visible. Herbs increase from 980 AD – 1148 AD, especially *Caryophyllaceae* and *Rosaceae* (924 AD and 980 AD) but also *Artemisia* (1036 AD). *Larix*, *Alnus*, *Salix*, *Betula* pollen grains and *Larix* stomata do not show a significant decrease and reveal no extraordinary pollen-influx. *Artemisia* and *Caryophyllaceae* are growing better on dryer habitats. Trees do not decrease in this time (980 AD – 1148 AD) indicating a temperate warmth, but therefore dryer period. Andreev et al. (2007) analysed pollen and charcoal stratigraphy to develop the last millennium in Siberia. They found out that 1020 AD climate conditions were similar too modern and that between 1100 AD and 1200 AD a short dry period with increased fire activity occurred. Depending on temperature and dryness these findings correlate with the results in this study. Between 1204 AD and 1260 AD the proportion of tree pollen grains increase and then slightly decrease until the end of PAZ 2 in 1484 AD, which match with findings from Alexandre (1987), who reveals a warming trend in the Medieval Warm Period from 1200 AD (Seppä and Birks, 2002). Years like 1372 AD are correlated with *Larix* and *Salix*, indicating warmer conditions, whereas after 1200 AD correlations with cold-preferring *Betula* distinctly rise. 1316 AD and 1428 AD are well suited with *Betula* pollen grains in the PCA, portend to the PAZ 2 and a decreasing pollen influx rate of *Larix*, which indicates a change to colder conditions. The relative stable period of PAZ 2 reflecting the Medieval Warm Epoch, lasted until 1410 AD, after that slightly drier and colder climate conditions occurred between 1410 AD and 1560 AD. These findings fit to the results of the PCA with high correlations of herb taxon since 1400 AD, especially *Caryophyllaceae* and *Rosaceae* (1400 AD, 1456 AD and 1484 AD) and no further PCA correlation between 1372 AD and 1978 AD with trees, which announces a period of cold and dry climate. When considering the NPP values for the PAZ 2, there is the big change from the transition of PAZ 1 to PAZ 2 visible, especially the high increase of indeterminate Alga 2 and the decrease of *Larix* stomata, *Pediastrum* and *Botryococcus,* indicate the change to a colder and maybe drier condition.

The PAZ 3 (1512 AD until 1624 AD) is characterized by a significant decrease of Larix, *Pinus*, *Cyperaceae*, *Brassicaceae*, *Poaceae* and *Artemisia* pollen grains and an intense increase of *Betula* pollen grains and influx rates. The PCA values of PAZ 3 show correlations with significant colder temperature and just rather merge with cold-preferring *Betula*. The only two species who do not decrease in this time and benefit from the conditions of PAZ 3 are *Ledum* and *Betula*, which are known to form plant associations and therefore have related habitat requirements (Osawa, 2010). At the beginning of the PAZ 3 in 1512 AD until 1540 AD *Alnus* shortly profits from the decrease of Larix. Exactly in this period *Betula* is suppressed from the overgrowth of *Alnus*. With the decrease of *Alnus* after 1540 AD, *Betula* shortly reacts with a high increase. The dominance of trees and bigger shrubs are low in this period, depending on the harsh and cold temperatures. The *Larix* forest was already represented in that time, documented by the finding of *Larix* pollen grains and *Larix* stomata, but the pollen productivity was reduced. Also herbs did not produce much pollen, because of fewer pollinators, due to the more extreme conditions. In the PAZ 3 *Pediastrum*, *Botryococcus*, *Ascospores* and also the indeterminate Alga 2 decrease, indicate to harsher and colder conditions in the environment. This cold term is well known as the Little Ice Age, the coldest section of a continuous cooling trend in the studied period (Andreev et al., 2007).

The PAZ 4 (1652 AD – 1953 AD) is characterized in the PCA predominantly by herbs and slightly by *Betula*. *Betula* and *Ledum* show an increasing trend, indicating a cool but stable climate. The decrease of *Larix*, *Alnus* and *Salix* reinforce this conclusion of a more herb promoting, but also cold condition. Artemisia has two maxima at 1708 AD and 1925 AD, which could indicate to dryer conditions. The NPP values indicate a condition like in PAZ 2, dominated by high amounts of indeterminate Alga 2. The PAZ 4 assigns the last period of the continuous cooling trend, changes complete since 1953 AD from the passage to the PAZ 5 (1978 AD - 2006 AD). The last 3 samples illustrate the enormous climatic warming phase since the middle 20th century. It is well indicated by an increase of warm climate and forest indicators like *Larix*, *Alnus* and *Salix* and a decrease of cold-preferring species like *Betula* and herbaceous plants. The PCA values (1978 AD, 1993 AD and 2006 AD) are mostly represented by *Alnus* and partly by *Larix*, *Salix* and *Pinus*. The forest became denser and a growth of the upper and higher vegetation like *Larix* and *Alnus* increases. The climate became more humid, which can also be seen in a decrease of *Poaceae* or *Ledum* with a negative correlation to the PAZ 5 values in the PCA. The indeterminate Alga 2 lost its high influence in the values of the PAZ 5. *Pediastrum* increases, which also could indicates warm conditions like in large parts of PAZ 1 (Mensing, 1999; Jankovska and Komarek, 2000).

5.1.3 Vegetation response to environmental and climate change

The results from the pollen spectra in this study match well with the results from other studies of climate and vegetation reconstruction. It is well known that *Betula*, *Alnus* and some herbs like *Cyperaceae* and *Poaceae* solely dominate the pollen spectrum in *Larix* forest tundra (Müller et al., 2008; Kaakinen and Eronen, 2000). *Larix* itself is well-known to be an underrepresented pollen type. Even a single *Larix* pollen grain is sufficient to prove the growth of *Larix* trees in this environment (Osawa, 2010). It must be mentioned that the over- and underrepresentation of some taxa must be interpreted as implication of the local environment, site preferences and climatological and geological characteristics (Müller et al., 2008; Anderson and Lozhkin and Anderson, 2002). Another important criterion for the interpretation is the reaction time and responds from local species to climatic changes. A *Larix* tree can reach several hundred years in the Siberian forest (Vaganov et al., 1999). Thereby it cannot react as fast as *Betula*, *Alnus*, *Salix* or especially herbaceous plants to a fast changing environment e.g. a short cooling or warming period. In colder and harsher periods *Larix* trees do not die immediately. They can reduce their amount of leafs, pollen grains and therefore seeds (Asshoff and Hättenschwiler, 2006; Abaimov et al., 2000; Nadezhda et al., 2008). Due to that behaviour, short and colder periods like the Little Ice Age (PAZ 3) are visible in the total amount of pollen grains, but do not effect the whole environment permanently. The fast increase of the amount of *Larix* pollen and also *Larix* stomata on the same level as it is occupied in PAZ 2 shows that the forest overcomes the cold period without significant changes. However, if the climatic conditions are changing over long time scales, even bigger trees like *Larix* have to adapt. That is obvious, considering the constant reduction of *Larix* and *Alnus* pollen grains after PAZ 1. Reactions to warmer conditions are similar. Herbs and small shrubs could react faster than trees. *Betula nana* for example reproduces primarily through vegetative reproduction especially in colder conditions (Alsos et al., 2003) and takes profit from a reduction of overgrown vegetation like *Salix*, *Alnus* and *Larix*, but also of herbs, which are competitors for resources (de Groot et al., 1997; Jonsell, 2000; Ejankowski, 2010). That behaviour is visible in PAZ 3, where nearly every plant decreases, but *Betula* increases.

To consider the vegetation response in this study it is reasonable to regard studies in this region, or at least in comparable arctic areas. There are studies available considering longer time scales in the Northern Arctic. Zech et al. (2011) investigated the last 200,000 years showing a cyclical trend between warm and cold intervals in earth history, embossed by trees and shrubs dominating warmer, and herbs dominating colder interceptions. That is a good starting base to consider the climatic variations in the Holocene, remembering much bigger changes in concentration of atmospheric gases, insolation values and therefore temperature changes over longer time scales (Figure 21).

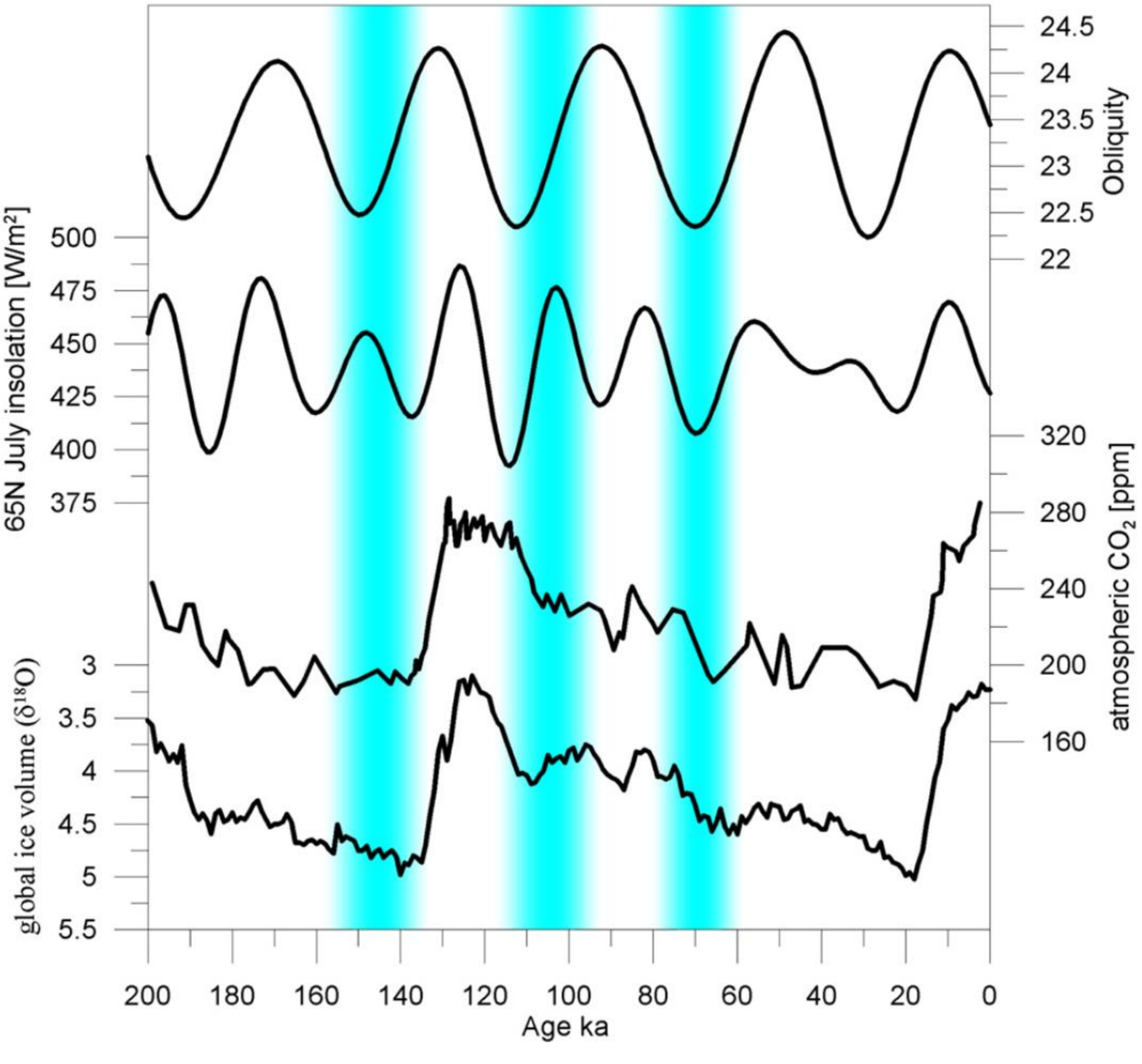

Figure 21: Comparison of glacial advances in the Dyanushka Valley (blue bars) with global ice volume, atmospheric CO2 concentration, and insolation parameters (Zech et al., 2011).

The mean development of vegetation change since the last 2500 years in this study can be determined on several scientific works. Monserud et al. (1998) reconstructed the mid-Holocene palaeoclimate of Siberia via vegetation modelling. The results reveal a warmer period (Holocene Climate Optimum) with a bigger influence of trees and shrubs on the vegetation. Kienel and Siegert (1999) did a multidisciplinary case study in the North Siberian Lowland (Lake Labaz) over the last 25000 years. The results have not such a fine resolution, but a trend with increasing *Betula* pollen grains over the last 2500 years and a decrease of *Larix*, *Alnus*, *Pinus* and *Picea* is still very clear visible. They found the last *Picea* pollen grains at around 4000 BP. The lake is located 180 km northwards from the investigated lake of this study. The last *Picea* pollen grains were found in the warmer PAZ 1 period around 1200 BP. That could indicate a continuous southwards tree shift of *Picea* and even *Pinus* since the Holocene Climate Optimum between 8000 – 6500 BP (Kumke et al., 2004).

The last 15000 years inferred from pollen records in northeast Siberia where studied by Müller et al. (2008). They illustrate a very detailed vegetation change (190 years per sample) with largest variations in the spectra between 15000 BP and 8000 years BP, followed by a slight cooling interrupted by warming and cooling sections. They reveal a percentage decrease of tree and shrub pollen grains since the last 2500 years, until 500 BP (Little Ice Age), followed by an increase of trees and shrubs after 500 BP until today (Figure 22). Their results are nearly identical to the findings from this study (Lake 11-CH-06E; resolution: 28 years per sample), but have not such a high resolution and could therefore just present longer climatically changes.

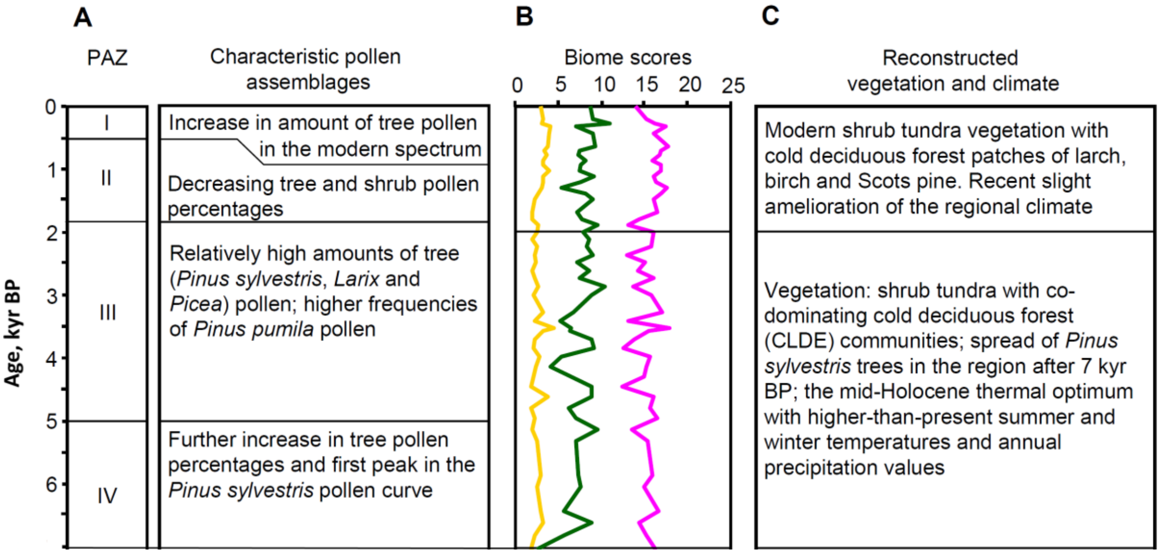

Figure 22: Local pollen zones and pollen assemblage characteristics of the PG1756 core around Lake Billyakh (A); time series of individual vegetation types (biomes) dominating in the study area since 15 kyr BP (B); summary of the reconstructed changes in vegetation and climate around Lake Billyakh (C), (Müller et al., 2008).

Andreev et al. (2012) and Oswald et al. (2003) reflect the Holocene vegetation change from records of the El'gygytgyn Impact Crater (500 km away from the investigated lake 11-CH-06E) and mentioned the Holocene Climate Optimum and a relatively stable behaviour in plant communities since 3500 BP. Similar findings are presented by Marcott et al. (2013) and MacDonald et al. (2008). They also did a reconstruction with proxy data for the past 11300 years. The most important findings are the warmer period between 10000 to 5000 BP and a treeline further northerly than today (Holocene Climate Optimum), followed by a general cooling trend until middle 20th century intermitted by a stable, but not extraordinary warm period (Medieval Climate Optimum). The following warming, since 1960, does not reach the dimension of the Holocene Climate Optimum, based on treeline shift data (Figure 23). These findings accord to the results presented in my study indicating a decreasing temperature gradient during the last 2500 years. Hahne and Melles (1997) pointed out similar results of a boreal forest development in this region commenced by 10000 year BP over most of Russia. Forest advanced to, or near the current arctic coastline between 9000 and 7000 year BP, retreated to its present position by between 4000 and 3000 year BP due to a decline of summer insolation and cooling of the arctic sea (MacDonald et al., 2007) Figure 19. Even with a significant warming trend since middle 20th century, the treeline has not reached former limits (Figure 19).

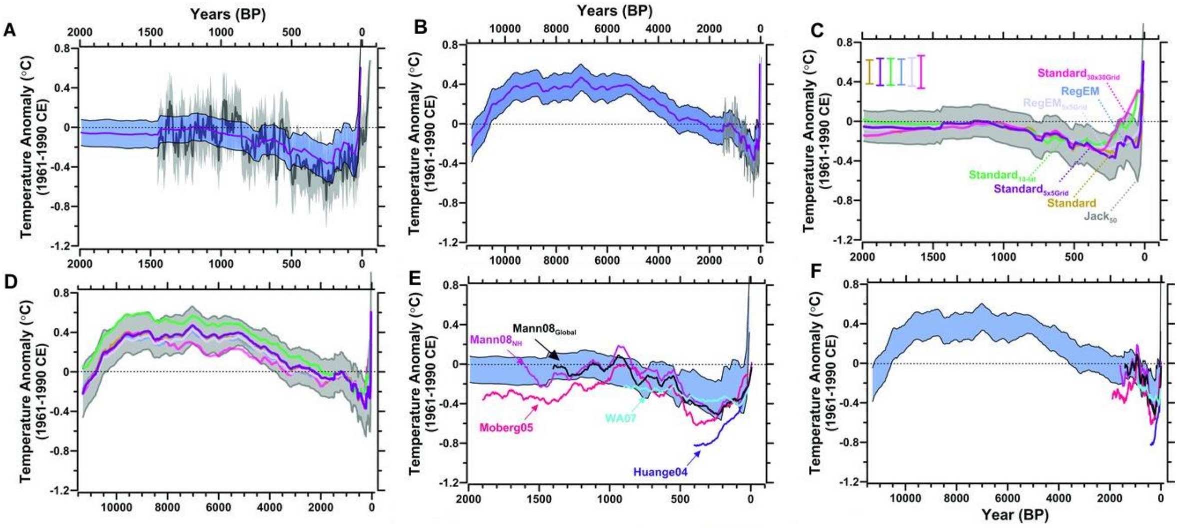

Figure 23: Comparison of different methods and reconstructions of global and hemispheric temperature anomalies. (A and B) Global stacked temperature calculation. (C and D) Global temperature anomalies stacked using several methods. (E and F) Published temperature anomaly reconstructions that have been smoothed with a 100-year centred running mean (Marcott et al., 2013).

Oswald et al. (2003) have tested the role of substrate in response of tundra to climatic change based on pollen records. They discover that substrate variations have an effect on how tundra responds to climate change especially in view to soil moisture. That is an important statement for considering the vegetation in an alluvial fan.

Furthermore the vegetation development from the beginning of the Holocene was comprehensible to other studies of arctic forest tundra. Herbs lose their dominance in the Holocene Climatic Optimum. Over time trees like *Betula*, *Salix*, *Alnus* and *Larix* become more and more dominant and indicate changes during warmer and colder Holocene periods, as specified in my study with a tree and shrub percentage of over 80% and a high influence from *Betula* and *Alnus*, which shows a negative correlated trend over the time, visible in the PCA angle of 130°. *Betula* increases up to 1925 AD and decrease after that time, whereas *Alnus* decreases in the same period and shows an increase in the last upper samples. This behaviour is also mentioned by Grau et al. (2012). They reveal the complicated interaction between trees, shrubs and soil-nutrient related to treeline seedlings. They found out that shrub-tree interactions are important drivers of subarctic treeline dynamics and that these interactions change over the ontogeny of a tree and are affected by climatic variations (Soliveres et al., 2010).

Climatic changes do not affect all regions in the world in the same way (IPCC, 2014). It is important to consider studies, which are representative for the contemplated region. Mann et al. (2002) pointed out that there can be significant differences in the gradient of summer-surface temperature, dependent on the locality (Figure 25). That is very important for understanding that e.g. the pollen spectrum in my study does not indicate a longer warm period during the Medieval Climatic Optimum in northern Siberia, even though it was a warmer stage in central England (Figure 25). Bezrukova et al. (2011) pointed out a similar view that the well-known average secular optimum reached its maximum around 1,000 years ago and did not have a significant impact on the harsh environmental conditions of the arctic forest near the Lena–Angara plateau. This accentuates the complexity of the climate variability in the Holocene and the response of regional ecosystems to global change (Bezrukova et al., 2011).

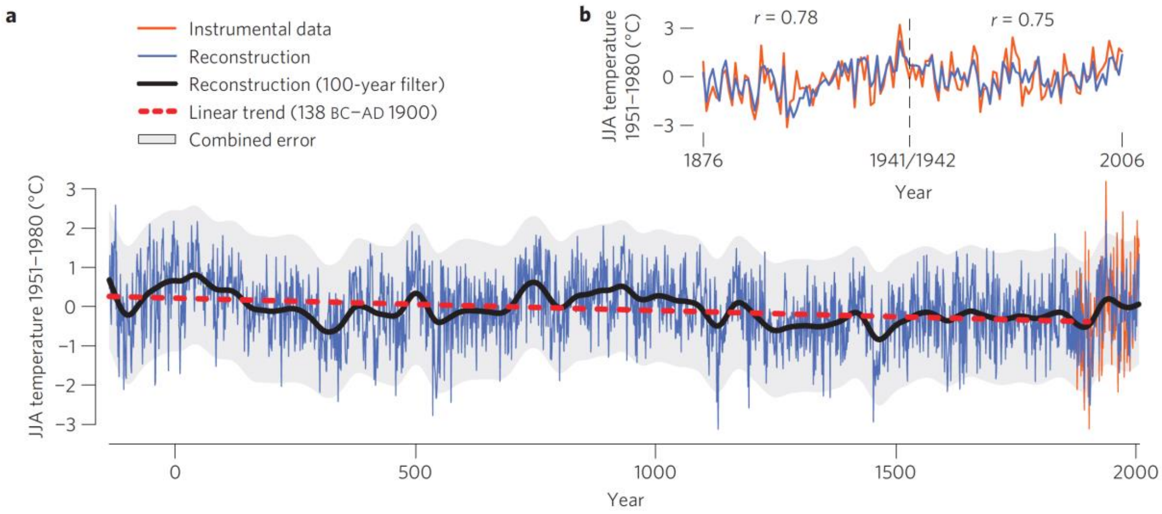

Figure 24: Multi-proxy reconstruction from 138 BC highlighting extreme cool and warm summers (blue curve), cool and warm periods on decadal to centennial scales (black curve, 100-year spline filter) and a long-term cooling trend (dashed red curve; linear regression fit to the reconstruction over the 138 BC–AD 1900 period), Esper et al., 2012.

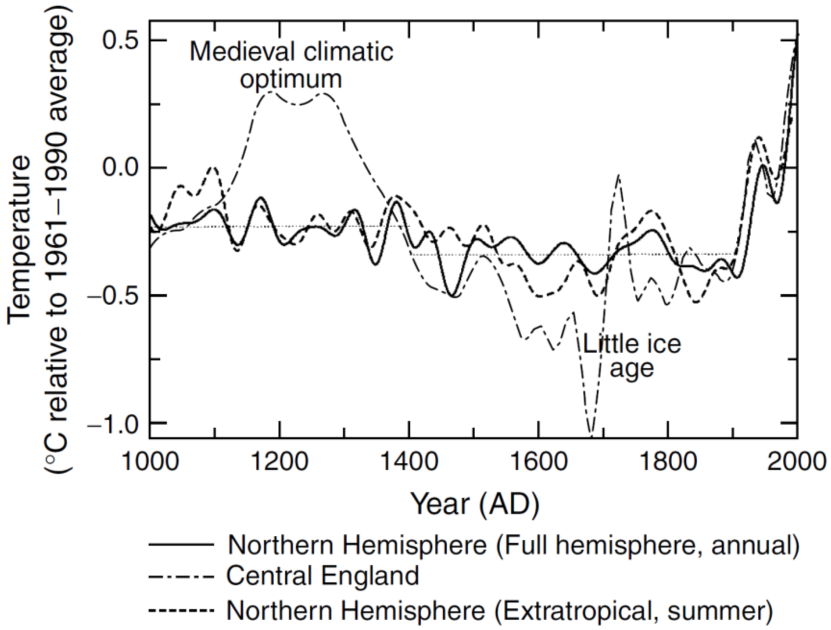

Figure 25: Summer surface-temperature trends over the past 1000 years (Mann et al., 2002).

McDonald et al. (2008) reconstructed the temperature departures for the northern hemisphere. The positive increase took place since 1880 AD and intensifies since 1970 AD (Figure 26), which affirmed the results of my presented study and proves the temperature increase in the study area since 1978 AD displaying the modern Global Warming.

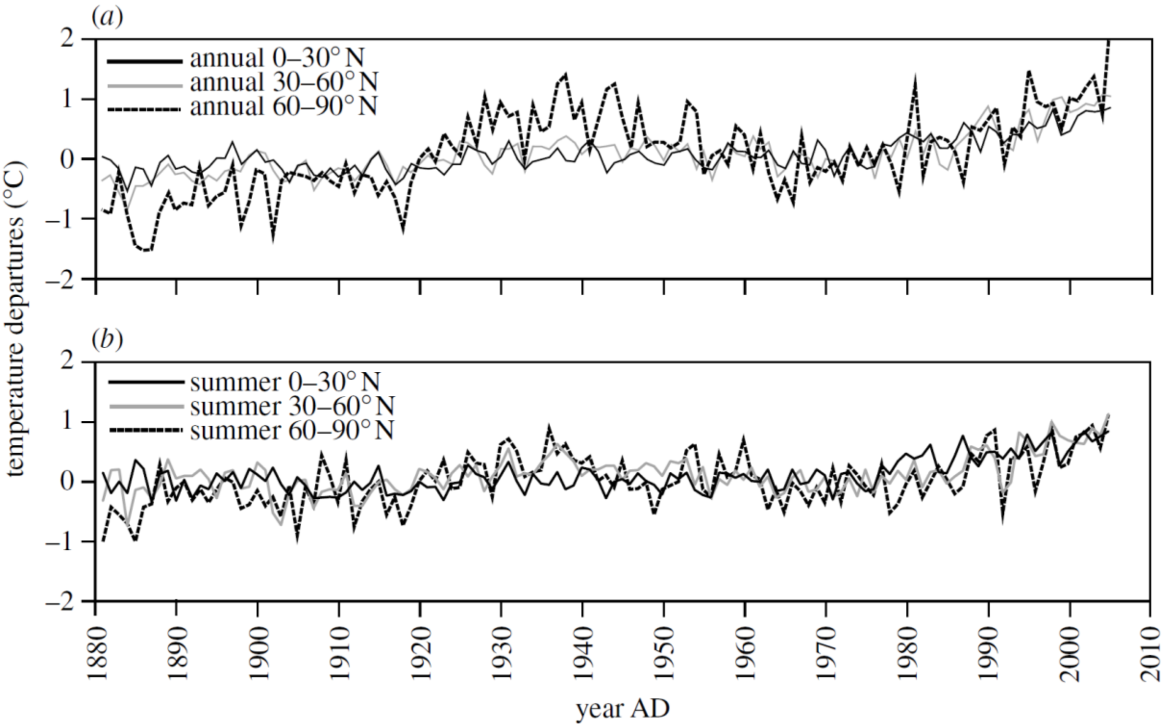

Figure 26: Northern Hemisphere (a) annual and (b) summer (June–August) surface temperature trends from 1880 to 2005 by latitudinal band (McDonald et al., 2008).

The mean evidence of the presented studies assume a slightly cooling trend across the last 2500 years intermitted by longer stable, short unstable and even colder periods as described in Esper et al. (2012) displayed in Figure 24. A tree-line shift of the local species around the investigated lake (11-CH-06E) cannot be proved during the examined period. But the findings of *Picea* and *Pinus* pollen grains in the under part of the core and their absence or reduction in the upper part, points to a southwards tree shift of these species, well known for long distance-transported pollen grains (Brubaker et al., 2005). Therefore the modern Global Warming since 1970 AD could cause a tree shift of e.g. *Larix* trees northwards and up to higher elevations (Figure 27), just affected by the minimal mean summer temperature.

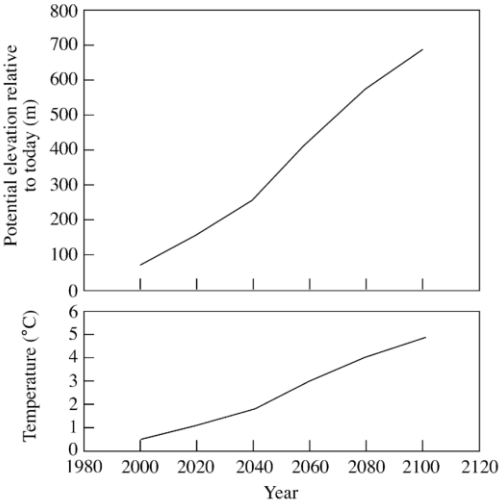

Figure 27: Potential increase in the elevation of the treeline, assuming a 4-5°C rise in temperature over 100 years presented in Grace et al. (2002).

On the one hand, dense forests could be considered as sinks for atmospheric CO^2 because of the enormous carbon storage in the permafrost (Oechel et al., 1993). Indeed needle biomass in *Larix* forests is generally low (< 1.0 Mg ha^{-1}). The period of active carbon uptaken by larch needles is restricted to less than 2 months, from mid-June to mid-August (Nakai et al., 2008). On the other hand, the southern areas could be influenced by thawing permafrost and causes a massive change in the carbon and methane emission rate (Kane et al., 1991; Billings et al., 1982). This net CO^2 source is attributed to soil surface drying, associated with high latitude warming (Oechel and Billings, 1992). Soil surface drying could be associated with deeper active layer thickness due to the change in energy and water fluxes caused by arctic warming (Wigley and Barnett, 1990).

5.1.4 Limitation of pollen data and possible improvements

Fossil pollen grain reconstruction of vegetation changes is a primary source of information about climate fluctuations in the past (Andreev and Klimanov, 1989). Nevertheless it is important to know the qualities and limits of these data for a further interpretation.

Pollen grains were produced from various plant species in different quantities and cycles depending on pollination type, local variations, climatic fluctuations and their morphology. The pollen grains in this study were mainly determined by family name or type, which could lead to a false interpretation for species, which are specified to various different ecological situations and habitat niches. The source area of the pollen grains is another important factor. For various species the origin habitat, transportation time and distance is not clearly assessable.

Furthermore the counting of all samples from the short core would give more detailed and precise information. Non-pollen palynomorphs are present in a high amount in the samples. Counting all these species and determine their taxa could help to get more information for the lake ecosystem and the changes in the depending environment. Especially aquatic organism like *Scenedesmus*, *Pediastrum* and *Botryococcus* are important. These species are indicators for special water parameters and could be useful to interpret climatic impacts on the lake ecosystem (Prager, 2006; Niemeyer et al., 2015).

So far, just the short core from the lake 11-CH-06E is prepared and analysed. The second core, the longer parallel core (11-CH-06D) with a length of 160 cm would give even more information about a longer timescale in the sediment of the lake. Analysing this core probably offer greater variations from trees, shrubs and herbs during the Holocene and could maybe indicate a tree shift in this area over the time.

To arrange the area as good as possible in the context of a global warming, it is necessary to take analysis of other cores from this region. A good solution might be the creation of a transect from the modern larch forest across the treeline northwards. Such an approach could allow recording the tree shift and also the rate of spread. At the same time a multi-proxy analysis would be helpful. Measured data from tree rings, diatoms, sedimentological, or geochemical investigations could support the evaluation and generate a much more detailed picture of processes in the past.

With regard to the study site inside an alluvial fan, sedimentological parameters could give conclusions about the mass transfer of sediments or even pollen grains from the drainage area in the Putorana Plateau. Therefore it would be possible to estimate how the water and material streams attain through the alluvial fan and if there are shifts or rearrangement in the sediment.

6. Conclusion

The investigated sediment core 11-CH-06E has recorded changes in the vegetation cover surrounding the lake for the past 2500 years, inferred from a pollen proxy approach. The aim was to identify these changes and draw conclusions related to the climatic variations, especially because of the high sensitivity of the areas in higher latitudes to temperature and moisture changes.

Five pollen assemblage zones were identified within the short core, each affected by a different composition of pollen species. All five PAZ are significant and well comparable with common historical periods.

- The PAZ 1 characterises the oldest part of the core and represent the Roman Warm Period and the transition to the Medieval Warm Period in 868 AD. The Dark Ages Cold Period is not visible in the dataset.
- The Medieval Warm Period (868 AD – 1484 AD) appears in The PAZ 2.
- Between 1512 AD and 1624 AD the results indicate the Little Ice Age in PAZ 3
- The PAZ 4 reflects the transition zone between the Little Ice Age and the modern temperature rise in the upper zone.
- The modern effects of Global Warming are visible in the PAZ 5.

The reconstructed and discussed results of the pollen record, allows taking the following conclusions:

1. The warmest period was the time between 420 BC and 812 AD, with the highest amount of *Larix* pollen grains and *Larix* stomata, as well as the lowest percentage of herbs in the pollen data set. This time span has similar climatic conditions and therefore similar vegetation compositions as today in a period of Global Warming.
2. The results show a mean decrease in temperature in the Medieval Warm Period, infer from lower amounts of tree and higher amounts of herb pollen.
3. The Little Ice Age is recorded in the pollen data with a clear temperature decrease and its climax around 1600 AD.
4. After 1624 AD, the temperature reached the lower limits from the Medieval Warm Period and remains relatively stable until 1953, documented by small changes in the pollen composition.
5. A high increase of tree percentage accords to the modern day climatic change and illustrates a rapid rise in temperature.
6. In general the analysed pollen data show a slight decrease of dense forest vegetation and mean temperature over the whole period until 1953 AD followed by a significant temperature increase and a denser forest indicating the modern Global Warming.

This study is suitable with the current scientific research to understand the reaction and feedbacks of vegetation in higher latitudes in relation to the climate system. It contributes to a higher resolution of scientific studies from this region and helps to understand the climate evolution in the Siberian Arctic.

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Appendix

Table 4: Results (1) counted pollen grains

sample No.:	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
Alnus	180	156	155	133	103	84	123	98	107	101	111	87	115	107	116	118	172	181	169	130	103	110	108	128	143
Asteraceae	0	0	0	0	0	1	0	0	1	0	0	0	0	1	1	0	0	0	0	0	1	0	0	0	0
Artemisia	3	2	4	5	8	4	2	0	2	1	2	7	9	2	3	1	2	2	0	1	2	4	2	1	6
Betula	134	114	109	161	150	161	165	172	168	140	141	167	143	158	117	172	323	297	211	167	166	151	154	160	142
Brassicaceae	4	1	7	3	3	3	8	3	11	3	3	2	5	3	8	0	2	2	3	6	10	4	0	5	1
Caryophyllaceae	1	1	0	0	0	3	1	1	1	3	1	3	4	5	5	1	2	0	1	0	4	1	0	0	2
Chenopodium	0	0	3	2	0	1	0	1	0	0	0	2	2	0	0	1	0	0	0	1	0	0	1	1	0
Cyperaceae	30	30	34	57	32	40	29	47	32	42	35	37	40	47	45	39	38	39	23	23	38	37	31	51	43
Ericaceae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	1
Fabaceae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hippuridaceae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	1	0	0	0	0
Larix	9	8	4	1	3	5	4	8	3	3	8	8	6	5	9	1	2	2	5	1	3	4	3	8	11
Ledum	1	0	3	2	2	5	2	8	4	4	6	3	1	2	5	3	3	11	5	6	1	5	6	5	1
Epilobium	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0
Picea	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pinus	3	6	7	3	5	6	2	5	4	7	3	6	7	0	7	0	1	2	4	3	6	10	4	3	2
Poaceae	1	6	5	9	11	11	8	10	6	15	10	8	3	6	12	2	9	9	5	4	5	9	8	12	10
Polygonaceae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	2
Primulaceae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ranunculaceae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rosaceae	2	0	3	2	2	2	1	3	0	0	0	1	1	0	1	3	0	0	0	2	1	3	1	2	0
Rubicaceae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rumex aquaticus	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	1	0
Salix	6	3	1	1	0	2	0	0	3	4	1	4	5	0	5	1	4	3	1	3	2	0	1	3	5
Valeriana	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 5: Results (2) counted pollen grains

sample No.:	**26**	**27**	**28**	**29**	**30**	**31**	**33**	**35**	**37**	**39**	**41**	**43**	**45**	**47**	**49**	**51**	**53**	**55**	**57**	**59**	**61**	**63**	**65**	**67**	**69**
Alnus	121	126	158	115	135	135	138	104	126	139	120	121	127	112	125	193	127	155	171	195	145	116	113	106	177
Asteraceae	2	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Artemisia	2	5	4	3	2	3	8	2	4	4	7	3	4	6	3	1	4	2	5	3	4	4	7	3	5
Betula	161	168	200	180	177	152	128	143	147	206	156	148	127	140	159	131	125	158	145	139	122	147	168	142	156
Brassicaceae	7	2	5	4	3	4	1	4	6	2	3	5	0	6	5	12	0	3	8	6	4	5	2	3	4
Caryophyllaceae	0	0	0	0	0	0	2	2	0	2	4	0	0	3	0	0	0	0	0	1	0	3	1	1	0
Chenopodium	2	0	2	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0
Cyperaceae	42	30	36	38	13	37	33	46	25	32	24	24	47	44	22	38	23	45	28	40	32	34	31	45	49
Ericaceae	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fabaceae	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hippuridaceae	0	2	0	0	0	2	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0
Larix	4	8	6	7	3	8	11	1	9	7	3	2	17	5	2	18	25	21	5	4	4	3	22	11	14
Ledum	2	2	3	6	6	3	4	2	4	2	3	4	3	4	2	2	3	3	2	0	2	1	2	3	0
Epilobium	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0
Picea	0	0	0	0	0	0	0	0	0	0	0	1	3	2	1	0	0	0	0	0	0	0	2	0	0
Pinus	8	2	2	3	6	1	7	7	10	6	10	4	1	7	4	7	11	11	6	6	8	6	3	10	7
Poaceae	4	11	2	10	5	4	9	9	13	17	2	5	2	12	7	8	4	8	5	3	9	6	6	2	14
Polygonaceae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	1	0	0
Primulaceae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ranunculaceae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Rosaceae	1	1	2	2	2	2	0	5	1	1	1	2	0	1	0	2	0	1	0	0	0	2	1	0	1
Rubicaceae	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0
Rumex aquaticus	2	0	2	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Salix	3	1	2	2	2	2	4	0	4	3	2	2	2	0	1	3	1	2	3	4	2	1	5	0	2
Valeriana	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 6: Results (3) counted pollen grains

sample No.:	**71**	**73**	**75**	**77**	**79**	**81**	**83**	**85**	**87**	**89**
Alnus	162	161	154	131	233	104	159	178	211	220
Asteraceae	0	0	0	0	0	0	0	0	0	0
Artemisia	2	2	4	3	5	0	2	2	5	1
Betula	192	182	165	131	269	189	112	216	249	187
Brassicaceae	2	1	3	0	10	1	3	9	2	3
Caryophyllaceae	2	0	0	0	1	1	0	0	1	0
Chenopodium	0	1	0	0	1	0	2	0	0	1
Cyperaceae	40	41	29	28	78	23	20	29	31	25
Ericaceae	0	0	0	0	0	0	0	0	0	0
Fabaceae	0	0	0	0	0	0	0	0	0	0
Hippuridaceae	0	0	1	0	0	0	0	0	0	0
Larix	9	23	12	14	28	2	1	12	11	6
Ledum	3	0	0	3	3	0	0	0	1	1
Epilobium	0	0	0	0	0	0	0	0	0	0
Picea	0	0	0	0	6	0	0	0	0	0
Pinus	8	12	12	3	2	4	8	2	4	5
Poaceae	5	9	4	2	12	3	19	5	6	5
Polygonaceae	0	0	0	0	2	0	0	0	0	0
Primulaceae	0	0	0	0	0	0	0	0	0	0
Ranunculaceae	0	0	0	0	0	0	0	0	0	0
Rosaceae	1	0	0	0	3	0	0	2	0	0
Rubicaceae	0	0	0	0	1	0	0	1	1	0
Rumex aquaticus	0	0	0	0	0	0	0	0	0	0
Salix	6	0	5	2	10	0	1	3	1	2
Valeriana	0	0	1	0	0	0	0	0	0	0

Table 7: Results (1) counted non-pollen palynomorphs

sample No.:	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
Ascospore multi part	2	1	1	3	5	1	6	7	4	8	1	4	0	0	4	4	2	6	5	4	4	3	6	10	1
Ascospore single part	3	7	5	2	1	0	2	1	11	1	1	2	5	1	3	1	2	1	3	1	7	5	5	4	11
Botryococcus	10	17	32	37	39	14	41	41	54	50	38	34	41	38	38	32	20	17	25	38	32	40	24	37	9
cf. Lycopodium	3	5	7	6	10	8	13	8	9	8	10	4	14	23	7	16	25	17	13	8	6	3	9	4	8
cf. Pediastrum	12	25	8	21	3	8	6	2	4	7	7	12	9	35	15	12	6	2	9	4	12	41	14	18	39
Equisetum	0	0	0	0	0	0	0	3	0	0	0	0	0	1	0	0	0	0	1	1	0	0	0	0	0
indet. alga 1	12	19	17	33	15	20	21	16	34	92	60	70	90	107	72	31	520	37	60	43	23	36	11	22	12
indet. alga 2	113	143	177	487	484	496	339	213	706	967	1208	1741	684	1331	1062	1546	722	516	829	573	1224	1048	954	608	460
***Larix* stomata**	0	1	1	0	7	2	3	1	1	1	1	1	5	3	2	0	2	1	0	1	3	0	3	1	2
***Lycopodium* marker spores**	244	204	168	156	281	159	187	163	229	413	176	158	307	241	239	182	250	150	150	160	161	201	230	162	196
***Pinus* windsleeve fragment**	3	3	3	3	6	4	3	6	3	3	3	3	6	5	11	6	5	3	3	4	2	5	12	3	2
Pteridium	5	6	6	5	5	0	7	5	7	9	10	4	8	5	7	8	52	28	14	7	3	3	5	5	9

Table 8: Results (2) counted non-pollen palynomorphs

sample No.:	**26**	**27**	**28**	**29**	**30**	**31**	**33**	**35**	**37**	**39**	**41**	**43**	**45**	**47**	**49**	**51**	**53**	**55**	**57**	**59**	**61**	**63**	**65**	**67**	**69**
Ascospore multi part	3	2	6	2	5	2	0	3	5	10	2	2	2	9	4	4	1	5	10	12	4	14	3	6	10
Ascospore single part	1	9	0	3	1	4	2	8	3	6	3	6	2	7	5	4	1	0	1	11	1	2	10	0	5
Botryococcus	21	40	51	35	30	39	27	26	27	25	29	22	20	35	28	47	23	44	40	34	36	27	29	26	34
cf. Lycopodium	7	7	22	8	17	8	9	12	6	16	7	7	7	9	8	6	8	2	0	5	6	6	2	6	4
cf. Pediastrum	15	17	9	27	10	7	23	19	18	9	18	23	37	5	28	92	116	122	41	50	45	42	13	10	11
Equisetum	0	1	0	0	0	1	2	2	1	0	0	0	0	0	0	0	0	1	0	1	2	0	0	1	0
indet. alga 1	20	50	31	33	22	21	32	40	30	374	6	4	18	13	20	15	9	7	5	5	3	7	6	9	9
indet. alga 2	314	758	709	405	344	417	1387	1961	2362	701	92	45	37	275	288	134	115	25	21	20	49	9	20	24	40
***Larix* stomata**	7	5	3	3	7	4	4	2	3	1	0	1	1	3	1	8	3	2	6	2	3	6	3	7	5
***Lycopodium* marker spores**	175	150	160	204	161	163	214	249	156	284	349	182	202	168	162	154	158	153	156	159	162	222	181	195	150
***Pinus* windsleeve fragment**	7	4	2	7	4	5	3	9	6	6	5	4	10	1	3	4	6	4	9	5	2	4	8	2	14
Pteridium	4	3	5	7	6	10	8	5	4	11	8	7	3	7	6	5	4	3	7	5	0	3	1	3	4

Table 9: Results (3) counted non-pollen palynomorphs

sample No.:	**71**	**73**	**75**	**77**	**79**	**81**	**83**	**85**	**87**	**89**
Ascospore multi part	8	2	2	3	11	0	0	0	7	3
Ascospore single part	6	12	2	7	8	11	4	1	9	20
Botryococcus	21	34	19	33	65	18	17	38	36	35
cf. Lycopodium	3	0	4	2	10	6	1	7	2	5
cf. Pediastrum	20	21	12	30	109	5	3	21	3	3
Equisetum	2	1	0	4	0	0	1	1	1	1
indet. alga 1	9	30	21	24	16	22	2	6	5	2
indet. alga 2	54	12	25	18	77	6	13	20	9	10
***Larix* stomata**	0	3	3	0	0	0	1	0	2	2
***Lycopodium* marker spores**	150	151	157	174	178	206	150	169	150	158
***Pinus* windsleeve fragment**	10	5	3	6	15	6	3	7	4	3
Pteridium	6	2	2	2	9	3	4	0	4	3

Danksagung

Mein besonderer Dank gilt Prof. Dr. Ulrike Herzschuh, die mir das Schreiben dieser Arbeit ermöglicht und mir mit Ihrer Vorlesung zur Paläoökologie dieses überaus interessante Wissenschaftsfeld erst einmal näher gebracht hat.

Des Weiteren danke ich Prof. Dr. Bernhard Diekmann für die Begutachtung meiner Arbeit.

Außerdem danke ich Juliane Klemm für die Hilfe bei der Einarbeitung in die Pollenkunde, Liv Heinecke für die stets bereitwillige Unterstützung bei Fragen und Problemen.

Besonderer Dank gebührt auch Bastian Niemeyer, der mich nicht nur bei der Pollenanalyse unterstützte, sondern sich auch in der finalen Phase meiner Diplomarbeit immer die Zeit nahm und mir mit Rat und Tat zur Seite stand.

Ich danke auch allen anderen Doktoranden und Doktorandinnen, den Masterstudenten, Ute Kuschel und natürlich unserer AG-meeting Gruppe für die tolle Arbeitsatmosphäre am Institut.

Gleichfalls bedanke ich mich bei allen Freunden und Bekannten, die zum Gelingen dieser Arbeit beigetragen und mich während des Studiums unterstützt haben.

Doch besonderen Dank gilt meinen Eltern, die mich mein gesamtes Studium über bestmöglich unterstützt haben und natürlich meiner Freundin, die mit ihrer unvergleichlichen Art mein Leben Tag für Tag aufs Neue bereichert.