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Vegetation reconstruction during the last millennium – derived by a lacustrine pollen record from Northern Siberia (Chatanga, Russia)

Masterarbeit

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"The large area of Taymyr (about the size of Great Britain or northern Alaska), is still mostly undisturbed and its great variation in landscape and climate makes me believe that classification of its vegetation will be representative of the Siberian Arctic as a whole."

(Matveyeva, Nadezhda V. 1994)

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List of abbreviations

i. a.	inter alia
AD	anno domini
AP	Arboreal pollen
AWI	Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research
BP	before present
cf	confer (probably belongs to the identified species)
CAVM	Circumpolar Arctic Vegetation Map
CONISS	Constrained Incremental Sum of Squares
CRAN	Comprehensive R Archive Network
e.g.	for example
etc.	et cetera
n	number
NAP	Non-arboreal pollen
NE	North-East
NPP	Non-pollen palynomorphs
p.p.	Taxonomy: pro parte
PAZ	Pollen assemblage zones
PCA	Principal Component Analysis
PC1	First Principal Component
PC2	Second Principal Component
RDA	Redundancy Analysis
SW	South-West

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Abstract

Northern Central Siberia is sparsely investigated even the area is provides many suitable archives for palaeoenvironmental studies. Studies are needed to understand the reaction of the highly sensible ecosystem to environmental dynamics and build the basic for ongoing research. The objective of this thesis is to reconstruct the vegetation development at 72°N in Arctic Siberia and to deduce environmental reasons for the changes in the vegetation cover. Sediment samples from a small lake in the vicinity of Chatanga on the Taimyr Peninsula were prepared for light microscopy and pollen analyses were conducted at the Alfred-Wegener-Institute for Polar and Marine Research in Potsdam. The ages of the upper samples were determined by the Environmental Radioactivity Research Centre at the University of Liverpool and deductively ascertained for the rest of the core. The dataset of the pollen count was used to generate highly resolved pollen diagrams of the last millennium: one entire pollen diagram for all taxa, which have been counted throughout the short core, and the other pollen diagram, pollen influx diagram and Iversendiagram for the primary taxa. Statistical analyses were performed to verify significant pollen assemblage zones and to construct synthetic environmental gradients. The pollen assemblages are reflecting three phases of vegetation development during the last millennium, which correspond to the termination of the Medieval Warm Period to the subsequent Little Ice Age and to the Recent Warming period. The Medieval Warm Period reaches till 1308 AD and is predominantly characterized by the regression of *Alnus* pollen, whereby the percentages of Cyperaceae pollen are increasing. *Betula* and the herb species do not show comparably trends. The mild climate of the Medieval Warm Period became cooler and drier, which is reflected by the decrease of *Alnus* pollen so that the dense canopy of the shrub tundra became more lightly and sedges established the light places during the termination of the Medieval Warm Period to the Little Ice Age. The percentages of *Salix*, *Artemisia* and *Potentilla* mainly increased, next to other herbs in general, between 1308 AD and the beginning of the Recent Warming in the middle of the 20th century. *Alnus* and *Betula* present lower pollen content during the period of the Little Ice Age, so that *Salix* could have established on the favorable places, where *Alnus* and *Betula* grew once before. *Larix* displays the northernmost tree species and is known for its heavy and large pollen. Due to the increase of *Larix* pollen content over that time period, it is likely that the vegetation cover was more lightly than during the Medieval Warm Period so that *Larix* had less competition or stress to produce pollen and the pollen could have been accumulated easier due to the scare vegetation cover around the lake. The vegetation consisted mainly of herbs and grasses, shrubs were growing on well exposed places, because the climate during the Little Ice Age was cooler and drier than today. Since the second half of the 20th century, the percentage content of *Alnus* and *Betula* pollen increased markedly, whereby *Salix* and *Larix* regressed next to Cyperaceae, Poaceae and also *Artemisia*. The flowering herb species produce less pollen than wind pollinated plants like *Betula*, *Alnus*, *Salix* or all grasses. However the percentages of the herb taxa became less abundant, their pollen has been increasingly accumulated since the second half of the 20th century, which reflects that the climate became warmer and moister in the recent decades. Larch is underrepresented in the lake accumulations too, because single trees and groups of *Larix*

gmelinii were documented at the study site. Either *Larix gmelinii* is under competition or stress to produce pollen in the study area or the pollen doesn´t get representatively accumulated within the lake.

Zusammenfassung

Der Norden Zentralsibiriens ist wenig erforscht, obwohl das Gebiet zahlreiche Archive für die Erforschung der Landschafts- und Klimageschichte bereitstellt. Jede einzelne Untersuchung trägt dazu bei, die Reaktion des hochsensiblen Ökosystems durch sich ändernde Umweltbedingungen zu verstehen und die Grundlagenforschung voranzutreiben. Das Ziel dieser Masterarbeit ist, die Vegetationsentwicklung in der Umgebung eines kleinen arktischen Sees, 72°N in Sibirien, zu rekonstruieren und dafür verantwortliche Umwelteinflüsse abzuleiten. Um das Ziel zu erreichen, wurden Seesedimentproben aus einem See in der Nähe von Chatanga auf der Taimyr Halbinsel, für palynologische Untersuchungen im Labor des Alfred-Wegener-Instituts für Polar- und Meeresforschung aufbereitet. Das Alter der oberen Proben wurde am Forschungscenter für Umweltradioaktivität an der Universität Liverpool bestimmt und anhand deren Alters für die tieferen Proben deduktiv ermittelt. Die Deduktion ergab, dass der Seesedimentkerns die Vegetationsgeschichte der letzten eintausend Jahre umfasst. Es wurden fünf Pollendiagramme aus den Ergebnissen der Pollenzählung generiert. Ein Gesamtdiagramm bildet die Schwankungen aller Taxa ab, die in den Zählungen erfasst wurden. Die Untersuchung basiert hingegen auf den übrigen Diagrammen, die die hauptsächlichen Taxa über den Kern hinweg beinhalten. Das sind das generierte Pollendiagramm, das Pollenakkumulationsdiagramm und ein Iversendiagramm für die dominanten Pollentaxa. Durch die statistischen Analysen konnte die Anzahl der Pollenzonen festgestellt und wahrscheinliche Umweltgradienten ermittelt werden. Die Pollenzonen gliedern die Vegetationsentwicklung der letzten eintausend Jahre in drei Abschnitte, welche den Übergang der Mittelalterlichen Warmzeit hin zur Kleinen Eiszeit, die kleine Eiszeit selbst, sowie die globale Klimaerwärmung des letzten Jahrhunderts wiederspiegeln. Der Ausläufer der Mittelalterlichen Warmzeit reicht im Untersuchungsgebiet bis zum Jahr 1308 und ist vorrangig durch den Rückgang von *Alnus* Pollen gekennzeichnet, wohingegen die Prozentwerte von Cyperaceae Pollen steigen. *Betula* zeigt, wie krautigen Pflanzen auch, keine vergleichbaren Trends. Das milde Klima der Mittelalterlichen Warmzeit wurde kühler und trockner, was den Rückgang von *Alnus* Pollen erklärt. Der Deckungsgrad der Sträucher in der Tundra reduzierte sich, was die Verbreitung der Sauergräser auf den lichteren Stellen begünstigte. Während der Kleinen Eiszeit, von 1308 bis Mitte des 20. Jahrhunderts, stiegen die Prozentwerte von *Salix*, *Artemisia* und *Potentilla* merklich an. Auch die Werte der anderen Kräuter verzeichnen einen generellen Anstieg. Die Vorkommen von *Alnus* und *Betula* sind während der Kleinen Eiszeit geringer geworden, sodass *Salix* möglicherweise auf den günstigen Standorten vorgeherrscht hat. Die Lärche ist die am nördlichsten vorkommend Baumart im Gebiet und bekannt für ihre großen, schweren Pollen. Die Zunahme an *Larix* Pollen in den Proben der Kleinen Eiszeit kann daher rühren, dass die Vegetation zu dieser Zeit sehr licht und spärlich war, sodass die Lärchen zum einen keiner Konkurrenz oder Stress unterlagen, Pollen zu produzieren und dieser zum anderen durch die lichtere Vegetation

leichter im See abgelagert werden konnte. Die Vegetation bestand hauptsächlich aus Gräsern und Kräutern. Die Sträucher wuchsen vorrangig auf günstig exponierten Standorten, da das Klima während der Kleinen Eiszeit kälter und trockener als heute war. Ab Mitte des 20. Jahrhunderts, stiegen die Prozentwerte von *Alnus* und *Betula* Pollen in den Proben merklich an, wohingegen diese von *Salix*, *Larix*, Cyperaceae, Poaceae sowie *Artemisia* merklich zurückgingen. Die blühenden Arten der Krautflora produzieren weniger Pollen als windbestäubte Pflanzen. Obwohl die krautigen Taxa in der Phase der globalen Erwärmung prozentual zurückgingen, wurden ihre Pollen im See vermehrt abgelagert, was zeigt, dass das Klima in den letzten Jahrzehnten für alle Taxa begünstigend wärmer und feuchter wurde. Die Lärchenpollen sind auch unterrepräsentiert. Einzelne Bäume und Gruppen von *Larix gmelinii* wurden im Untersuchungsgebiet dokumentiert. Die Klimaveränderung kann die Konkurrenz erhöhen oder Stress verursachen, sodass *Larix* entweder weniger Pollen produziert oder diese, durch die dichtere Vegetation nicht repräsentativ im See abgelagert werden können.

1 Introduction

Ecosystems are on temporal and spatial change all over the world due to dynamics in abiotic and biotic environmental factors. The Arctic is regarded as a key region because the certain ecosystems are particularly sensitive to climate change and respond very quickly to environmental dynamics because of the variously temperature-related processes, so that warming climate results in earlier and higher rates of ice and snow melts as well as to the thawing of permafrost, so that the sea level rises and the active layer becomes deeper, which lead to more intense erosion processes and thermokarst development due to the unstable land surfaces. Rising temperatures favor taller and denser vegetation (ACIA 2004) so that the vegetation composition changes respectively biomes and the timberline expand northward. The denser canopies and the longer growing seasons lead to a decreasing albedo and increasing solar heating of the land surface, which gives a positive feedback to the thawing of ice, snow and permafrost again.

But northern central Siberia is sparsely investigated although the human influence is limited and should stimulate the research interest in the unspoilt landscape with its highly sensible ecosystems and the numerous suitable archives for palaeoenvironmental studies.

Since the term climate change has become more and more attention, studies like this are needed to understand how ecosystems respond to changed environmental factors in the past, to build a basis for ongoing research which might be able to estimate future environmental development. But long term monitoring data is absent and it is not directly possible to determine the vegetation and climate history or to track the paths of past environmental changes. So, indirect methods like pollen, diatom or tree ring analyses became powerful tools to infer past environmental conditions. Some of these proxy methods were already realized in the vicinity of the study area. Jacoby et al. (2000), Naurzbaev et al. (2002) and Sidorova et al. (2013) refer the climate history on the Taimyr Peninsula from tree ring chronology, while Kienel et al. (1999) and Laing and Smol (2003) inferred the Holocene environmental dynamic from diatoms. Andreev et al. (2002), Andreev et al. (2004), Andreev and Klimanov (2000), Hahne and Melles (1997), Kienel et al. (1999), Klemm et al. (2013), Kraus et al. (2003) and Naidina and Bauch (2001) investigated the Holocene vegetation and climate history in northern Central Siberia from pollen records. But the climatic variability for the Holocene period has increased throughout the last 2000 years and leads to a need for widespread regional and temporal coverage (Laing and Smol). Fedotov et al. (2012) reconstructed the thawing permafrost periods of the last 170 years on western Taimyr Peninsula and gives one of the few highly resolved pollen records available from northern central Siberia. The Diploma theses of Heinecke (2011) and Klemm (2010) are one of the few highly resolved pollen records currently available in the vicinity of the study area, which highlights the need for further calibration data sets from this region.

The main objective for the palynological work presented in this thesis is to recognize the stages of vegetation development in the vicinity of Chatanga during the last millennium. Records of this period bear critical information about significant climate changes including the transition from the Medieval Warm Period to the Little Ice Age, the Recent Waming and the beginning of anthropogenic global warming. The second aim of this study is to examine, whether the ascertained vegetation changes can be related to recorded climatic variations from other palaeoenvironmental studies in the vicinity of the study area.

2 Study Area

2.1 Geographic setting and general features of the study area

The investigated lake is situated in Russia, northern the arctic circle at 72° 23′ 55.9″ N, 102° 17′ 19.5″ E within the east of the Yenisei-Chatanga trough and in the south of the Taimyr Peninsula (Figure 1). This lowland is also known as Taimyr Lowland and represents a part of the North Siberian Lowland, which reaches from the Yenisei estuary in the west further east until the Olenek estuary.

Since 2007, the territory of Taimyr is no longer autonomous and belongs to the territory of Krasnojarsk Krai. Dudinka is the former capital of Taimyr and handed over all administration responsibilities to the city Krasnojarsk. Both settlements are connected by the Yenisei River, which flows almost directly from south to north into the Kara Lake and frames the Yenisei-Chatanga trough in the west. From there, the lowland is orientated over ca. 1000km to the northeast, where the Chatanga River flows into the Laptev Sea. Most of the settlements are in the vicinity of the mentioned rivers (Yenisei and Chatanga), because they embody important traffic routs for the population living in the far north, which is already of low density, and so the direct human influence into the study area is limited at the present and negligible for the outlying regions.

Figure 1: Location of the study area in northern Central Siberia. [Map created by Moritz Scharnhop, 2014, based on NASA-satellite picture of the earth, visible online <http://visibleearth.nasa.gov>, last call October 2014]

2.2 Climate

The northern part of Central Siberia represents a sensitive transition zone between west and east Siberia. (Hahne and Melles 1997) While the wetsern parts of Taimyr Peninsula are increasingly influenced by marine climate, the eastern area is characterized by high to extremely high degree of continentality (Atlas Arktiki; Aleksandrova 2009, Jones et al. 2010) due to the Siberian Anticyclone, the huge land masses and the Putorana Plateau. The Siberian Anticyclone is a dominant and persistent high pressure system with the “coldest” and “densest air masses” in the Northern Hemisphere with “greater intensity than the persistant pressure systems of the North Atlantic (Icelandic Low) and the North Pacific (Aleutian Low) regions”, status of 1991 (D´Arrigo et al. 2005). It generally forms in October, when the air masses of the lower troposphere begin to cool in response to strong and continuous radiative cooling (Panagiotopoulos et al. 2005). Due to the huge landmasses, ones of the continent and twice of the pack-ice-covered Arctic Sea, and less clouds, which enable the loss of long wave radiation and reveal extremely cold and dry conditions over Northern Siberia (Lydolf 1977), the Siberian High exists during the whole winter season. In January and February, when the temperatures are lowest, the winter circulation reaches its high and the Siberian Anticyclone moves westward over Siberia and then northward over the frozen Artic, from where it can brings unusually cold air to Eurasia and also America. (D´Arrigo et al. 2005; Panagiotopoulos et al. 2005) During the warmer summer months from June to September the snow melts and the water surfaces and vegetation communities influence the absorption of radiation as well as the evapotranspiration rate. About these summer months a low pressure system replaces the Siberian High and brings damper air, a denser cloud cover and also higher precipitation into the Arctic regions. In October, when the temperatures are decreasing rapidly, the Siberian High starts to form again.

The climate diagram of Chatanga (Figure 2) is based on local weather observations and describes the climate conditions at the study site the best, because the climate station of Chatanga is the nearest to the study lake. The following results are based on the interpretation of the mentioned diagram: The Dfc-climate is defined after the Köppen-Geiger Climate Classification as fully humid and snow climate with cool summer temperatures (5-12°C). Large differences in the mean January -34°C and mean July 12°C temperatures also reflect the continental regime of Chatanga. During the very short summer, which begins in early June and ends in September, the temperatures are ranging from 5°C to 12°C and the precipitation is around 30mm per month. The highest monthly precipitation falls in September, when the temperatures starting to decrease, but is still less than 40mm. So the annual precipitation of 272mm is relatively low (in comparison: Dresden has 696mm/year). In general, most of the precipitation of Chatanga falls as snow during winter, between October and May, where it gets largely accumulated, and begins to melt in early June.

Chernov and Matveyeva (1997) pronounce that the maximum temperatures in the tundra can be very high, but not for a prolonged time. According to them, the maximum air temperature in the southern tundra and forest-tundra can stay at 25°C for more than a week. During our field trip, we also observed that the temperatures of July can rise over 30°C throughout the day and will not strongly decrease during night on polar day.

The area into the south of the Taimyr Peninsula, including the whole area of the Chatanga River, is characterized by 1600 hours of sunshine. (Atlas Arktiki) In view of the events of polar day and polar night it means 164 days in darkness and 66 days full of light, while the remaining days of the year are in between. In the region of Chatanga, the prevailing wind direction is NE-SW and vice versa but all other directions are also common and the wind blows perennial as a calm to fresh breeze with a speed of about 4.6 at the Beaufort-Scale in July and 4.8 in January. (Atlas Arktiki)

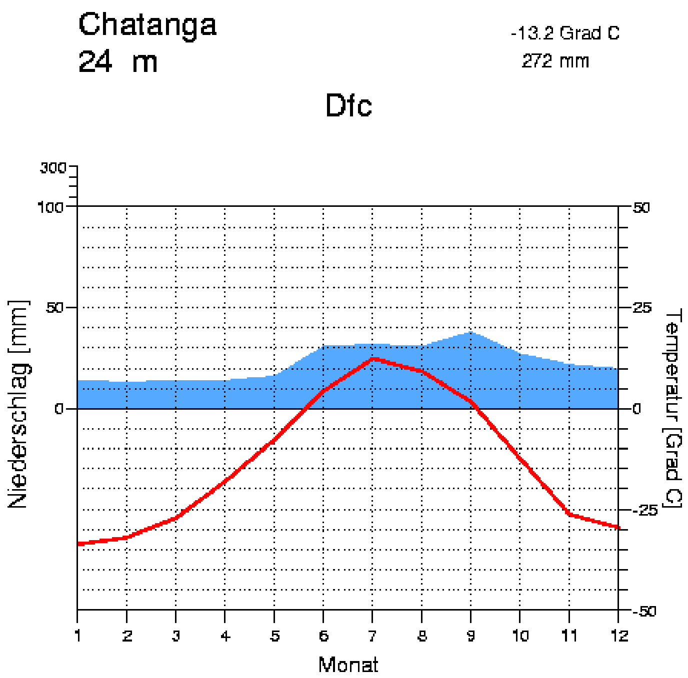

Figure 2: Climate diagram of Chatanga.
[Muehr, B. (15.06.2007) online: http://www.klimadiagramme.de/Asien/Plots/chatanga.gif, last call 18.05.2014]

2.3 Permafrost and the permafrost-effected soil

Permafrost is the general framework for the northern latitudes but also a sensible key factor in certain ecosystems. Because on the one hand it affects e.g. the stability of landforms, the characteristic of the soil, water runoff, vegetation cover and on the other hand it gets affected by interaction with other environmental factors like soil, water and air temperatures, precipitation, irradiation, vegetation cover. All those factors influence the intensity and extent of permafrost.

Jones et al. 2010 define permafrost as “perennially frozen ground which remains at, or below, 0°C for at least two consecutive years”. These criteria are fulfilled by 60% of the Russian land surface (Jones et al. 2010), where all four types of permafrost (continuous, discontinuous, sporadic and isolated patches) are present and form the biggest frozen block of lithosphere in the Northern Hemisphere (see Figure 3). The study area around the investigated lake 11-CH-12 lies within the continuous permafrost zone around 500km far away from the southern boundary to discontinuous permafrost and isolated permafrost fragments. In this region, continuous permafrost reaches a thickness of about 400-600m (Andreev et al. 2002; Fedotov et al. 2012; Gundelwein et al. 2007).

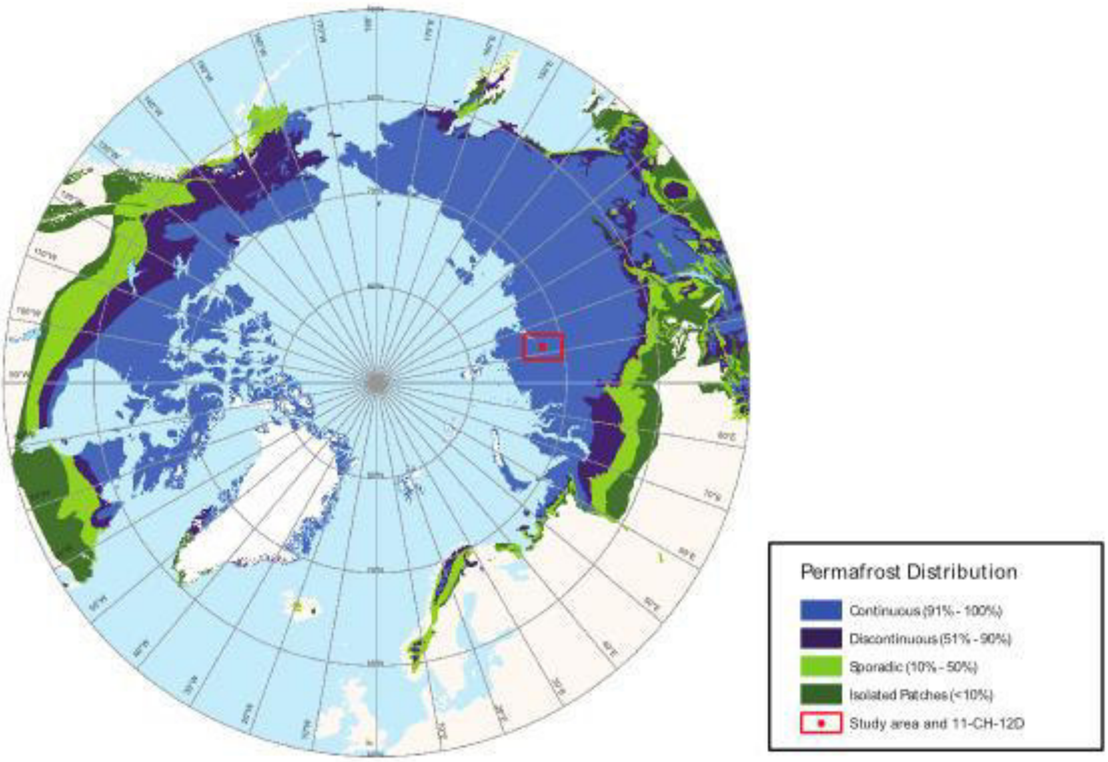

Figure 3: Distribution of the various permafrost zones in the northern circumpolar region. [According to Jones et al. 2010, Soil Atlas of the Northern Circumpolar Region, © European communities]

The characteristic low and harsh temperatures of the Artic become the key factor of the pedogenesis because they reduce the biological and chemical weathering, while on the other side the physical weathering gets supported and intense erosion processes. Permafrost-affected soils are Gelisols (soil taxonomy) but they are also known as Cryosols (Canada) or Cryozems (Russia) (Jones et al. 2010). They typically consist of an active layer and a perennially frozen basis layer or ice. The active layer is the upper part of the otherwise completely frozen ground, which thaws during spring and summer and refreezes in autumn and winter, so that soil processes can function only during a short period each year. The depth of the active layer mainly depends on the seasonal climate conditions but also on the exposure and irradiation, the characteristic of the soil and the overlying vegetation composition. (Jones et al. 2010) The vegetation cover acts as a thermal blanket during summer that isolates the permafrost from thawing. We observed significant lower active layer under dense moss polygons than immediate proximity under shrubs and trees. Conversely, a closed snow cover isolates the soil and either prevents deep freezing or rapidly thawing.

Cryosols are the characteristic soils of the Siberian Province and especially on the Taimyr Lowland. (Andreev et al. 2002, Jones et al. 2010) The example, shown in Figure 4, presents such a profile, which was made during fieldwork on expedition into the Chatanga region, in July 2013. The depth of the profile was limited by the underlying permafrost and so conforms to the depth of the active layer (here 36cm), which mostly varied between 30cm and 60cm. Also Fedotov et al. 2012 observed 0-45cm active layer during the summer months in the area of the Labaz Lake, 24km away from 11-CH-12, with underlying soil, which remains frozen throughout the year.

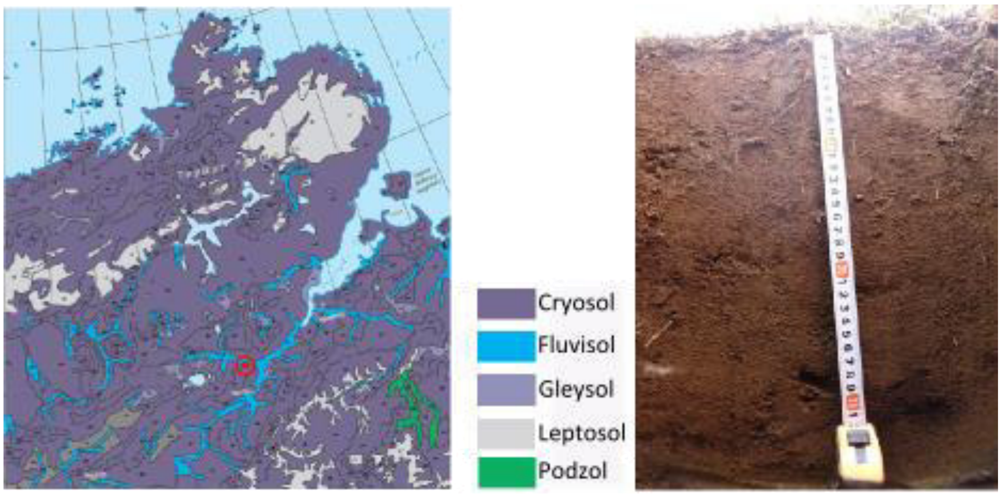

Figure 4: left: Soil map of the Taimyr Peninsula and the study area (red circle symbol). [According to Jones et al. 2010, Soil Atlas of the Northern Circumpolar Region, © European communities] Cryosols are the dominant soil types within this region and Fluvisol.

2.4 Thermokarst and thermokarst lakes

Thermokarst is the process of the thaw of ice-rich permafrost accompanied by collapse of the ground surface and the formation of depressions, lakes and other negative relief. (Brouchkov et al. 2004; Czudek and Demek 1970) So thermokarst development depends on the presence of sufficient ground ice and a trigger (e.g. forest fires, ecological changes, climate change; see Brouchkov et al. 2004) that disturbs the equilibrium of the permafrost system. The stages of the thermokarst development are shown in Figure 5. Due to the initiation of thermokarst development, depressions are formed which are going to fill up with water. The so called "Alas" (Yakutia) are thermokarst lakes, which can catalyze further thermokarst development to form flat depressions with an undulating bottom where slopes and numerous of water filled dimples can be found.

The Siberian Province is widely interspersed by lakes (Figure 6, A and D). Thermokarst lakes are prominent in the lowlands of the Arctic tundra but some of them may also originate from other geomorphological processes, e.g. from fluvial floodplain genesis (Figure 6, B). The study lake lies within a characteristic depression with landslides and the overflow as well as the planted runoff in the east of the lake indicate, that the water surface is higher elevated than the next bigger stream (Figure 6, C). Due to these facts, 11-CH-12 is assumed to represent a typical thermokarst lake, which is located in the region of Chatanga in northern Central Siberia.

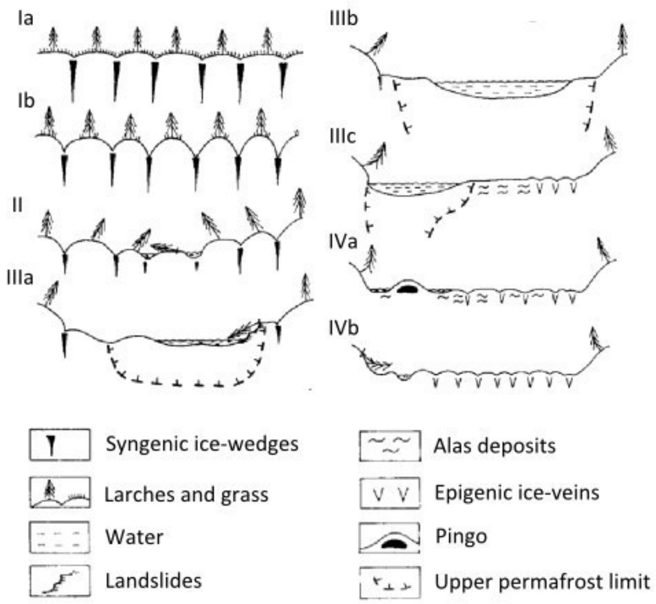

Figure 5: Main development stages of thermokarst relief. [According to: Czudek and Demek 1970] Ia: Original lowland surface with syngeneic ice-wedges; Ib: Initial thermokarst stage; II: Small thermokarst depressions; IIIa: Young alas; IIIb: Mature alas; IIIc: Ol.

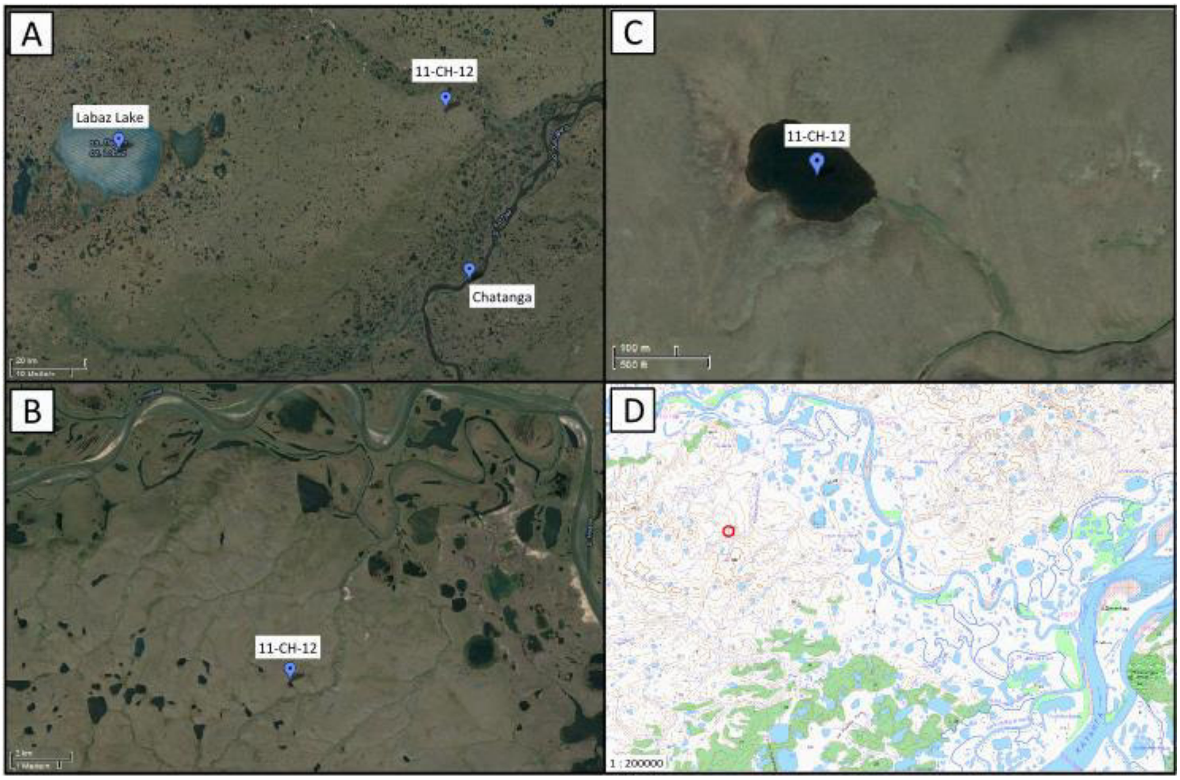

Figure 6: A: Situation of the study lake (11-CH-12) in the vicinity of Labaz Lake and Chatanga. The landscape is widely dissected by lakes of different sizes. B: Thermokarst lakes are lying here on a higher level than lakes in the north-west to north-east of the study lake, which are of fluvial origin. C: Typical thermokarst depression with landslides and alas (11-CH-12). [According to © 2014 TerraMetrics, Kartendaten © Google maps, screenshot online: <www.google.de/maps>, last call 22.10.2014] D: Topograhic map showing the position of the study lake (framed by the red circle) in the catchment of Nowaja and Chatanga rivers. [According to Maps for the world, "Topographic map ggc S-48-31,32" online: <http://loadmap.net/en>, last call 24.10.2014]

2.5 Geotectonic

The North Siberian Lowland is a large-scale depression between the variscan consolidated Byrranga Mountains on the Taimyr Peninsula in the north (Franz 1973) and the Putorana Plateau on the Siberian Platform in the south. However, Kontorovich (2011) vents that the Yenisei-Chatanga trough is traditionally considered as a part of the Siberian Platform, the genesis is different and graphically descriptions of the Siberian Craton do not include the investigated area (Franz 1973, Koronovsky 2002, Reichow 2009). The basement of the Siberian Platform originated from the Precambrian (Koronovsky 2002) and is therefore much older than the basement of the adjacent and investigated Chatanga trough. The Yenisei-Chatanga depression consists of 4000-5000m huge marine and terrestrial sedimentations originating from the Mesozoic and Cenozoic eras, which are covered by younger accumulations (up to 150m) of the Pleistocene and Holocene (Franz 1973). The Late Quaternary history of the study area is still debated. Grosswald (1998) assumes that the Late Weichselian ice sheet covered the whole Taimyr Peninsula, while Velichko et al. (1984) find that the glaciation was restricted to the mountain areas of Taimyr and the Putorana Plateau, so that the Yenisei-Chatanga trough was free of ice in this variant. In spite of those theories, the entire investigated area was lifted and lowered during the Quaternary and thereby formed by transgression and glacial processes. (Franz 1973)

It is also encouraging, that the Yenisei-Chatanga trough lies within the Siberian Trops Province (Reichow et al. 2009), but the erupted basalts have been found primary in the West Siberian Basin and on the Siberian Craton. The depression itself does not consist of Siberian Trops and furthermore divides the outcrops at the Putorana Plateau from relicts on the Taimyr Peninsula (compare to the illustration in Reichow et al. 2009).

2.6 Relief and water regime

In spite of the modern climate conditions with typically short summers and annual low precipitation rates in the study area, the Chatanga River system primarily formed the Taimyr Lowland and riverine landforms can be found these days. The lake cover in the investigated area is about 25% (Walker et al.2005). The development of thermokarst formed numerous lakes, so that the undulating landscape is interspersed with more and less dynamic water bodies (see Figure 6, A, B and D). Also the investigated lake is a water filled thermokarst depression of about 220 x 130m size on a hummock, 70m above sea level, which lies in the area of the mouth between the two rivers Nowaja and Chatanga (Figure 6, D). Even though the Nowaja is the tributary of the Chatanga, its length (411km) is around 200km longer than the Chatanga, because the Chatanga is the confluence of the two rivers Cheta and Kotuy, whose tributaries also take a longer way from the Putorana Plateau. That means the Chatanga is a relatively short river but also represents a whole river system, which formed a basin between 0m and 100m elevation above sea level and drains an area of 364,000km² into the Laptev Sea.

The local water regime around the study lake presents small-scale variations and depends on the micro relief, the exposure as well as on the depth of the active layer. The smaller elevations are better drained than the dimples. The ground ice and snow smelt rapidly on sun exposed slopes.

Their runoff proceeds along the table of the frozen ground within the active layer and can induce solifluction processes, which result in landslides, before the water gathers systematically in the depressions.

The investigated lake show landslides exactly on the south exposed slopes (Figure 7), which are actually overgrown and therefore more stabilized. Furthermore, the lake is characterized by an overflow, which is vegetated by species of *Salix* (Figure 8). Due to the relatively dense occurrence of *Salix* within the area of outlet, it is assumed, that the lake spends water to the next tributary of the Nowaja River (Figure 6, B and C) during water rich periods of the year, but do not operate as a permanent overflow.

Figure 7: Landslide on the sun-exposed slope of 11-CH-12 overgrown with grasses concerning to the families of Cyperaceae and Juncaceae. [Photo: Ruslan Gorodnichev, 2011]

Figure 8: Overflow in the east of 11-CH-12, which is planted by Willows (*Salix*). [Photo: Ruslan Gorodnichev, 2011]

2.7 Vegetation of the present

The vegetation of the Artic has to tolerate one of the most unfavorable living conditions on earth. Continuous permafrost and low active layer depths prevent that plants can produce deep growing roots. The annual low precipitation rates, icy frost, extremely cold and long winters as well as the missing of thermal and ultraviolet radiation during the polar night reduce the vegetation period within the arctic region of the short duration of the summer. Only species, which are tolerant in temperature and moisture, can reproduce under the given conditions. Due to the missing competition, those species are able to build long lasting populations.

The arctic flora is primarily influenced by the predominating climate conditions. That´s why the general division of the vegetation in Central Siberia takes place from north to south and forms vegetation zones (see Figure 9). The zones are usually interlocked so that their transition is gradual (see Figure 11). Naturally, subzones can establish in between due to regional changes of environmental factors, e.g. differences in elevation.

	Russia		
CAVM subzone	**Alexandrova (1980)**	**Yurtsev (1994)**	**Matveyeva (1998)**
A	Northern polar desert	High Arctic tundra	Polar desert
	Southern polar desert		
B	Northern Arctic tundra	Arctic tundra: northern variant	Arctic tundra
C	Middle Arctic tundra	Arctic tundra: southern variant	Typical tundra
	Southern Arctic tundra		
D	Northern sub-Arctic tundra	Northern hypo-Arctic tundra	
	Middle sub-Arctic tundra		
E	Southern sub-Arctic tundra	Southern hypo-Arctic tundra	Southern tundra

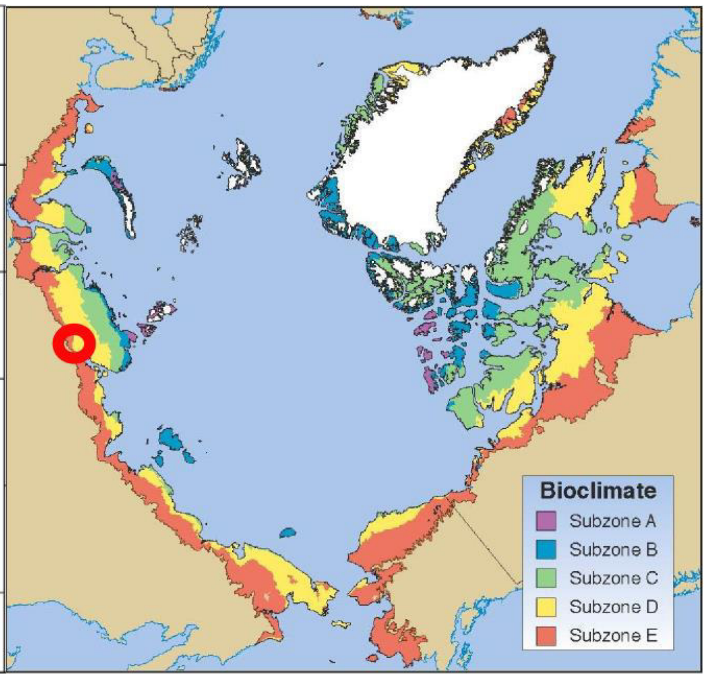

Figure 9: Table of the arctic bioclimatic zonation approaches for Russia and the map of the CAVM subzones pointing the investigated area by the red circle. Modified from CAVM Team 2003. The study area lies within the subzone E, also known as "southern tundra", "southern hypo-arctic tundra" or "southern sub-arctic tundra". [According to Walker et al. 2005] There are also bioclimatic zonation approaches for Northern America and Fennoscandia, but they were consciously excluded here.

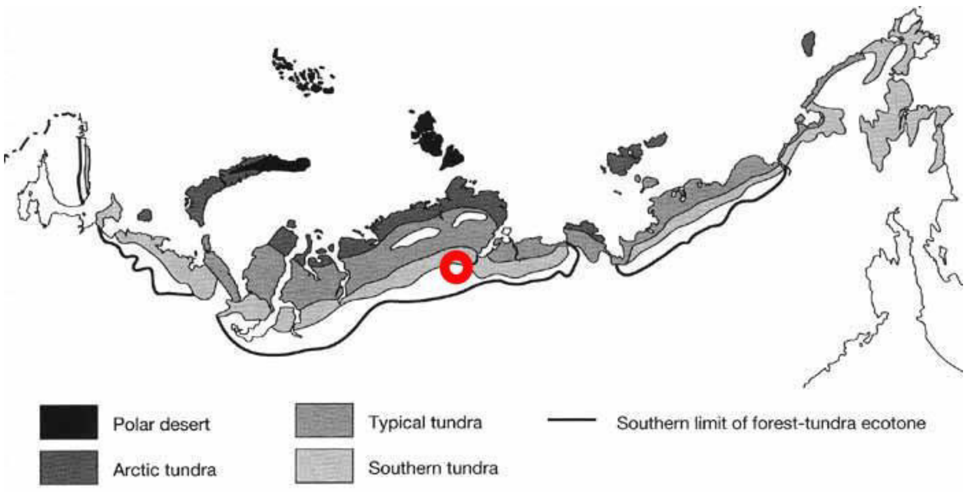

Figure 10: Latitudinal zonality and floristic provinces of the Russian Arctic. The position of the investigated area is marked by the red circle in the "southern tundra" close to the northern limit of the "forest-tundra ecotone". [According to Chernov and Matveyeva 1979, Yurtsev 1994, online <http://www.rusnature.info/reg/f9-6.jpg>, last call 28.10.2014] Taimyr is the only place on Earth where the tundra zone is represented over a vast area with three subzones, bounded to the north by the polar desert and to the south by the forest-tundra zone (Chernov and Matveyeva 1979).

The investigated area lies within the tundra zone. The term "tundra" refer to the treeless expanses beyond the climatic timberline (Bliss 1962, Matveyeva 1994) and one of the characteristic features is the "relatively small flora that has been selected out by the severe environments" (Bliss 1962). But the expansion is gradual and subzones are needed to describe the vegetation that appears best. Due to different national and international approaches in the literature, which were made to divide and define the sub-categories of the tundra, the Circumpolar Arctic Vegetation Map (CAVM) Team 2003 (Walker et al. 2005) collected the different approaches of the circumpolar arctic tundra region, north of the tree line, and generated a new system of bioclimatic subzones with their major vegetation units and composition. The plus of this classification is that the characteristic of the subzones describe the vegetation properties of the zone unique and make the literature more comparable. According to Walker et al. (2005) the bioclimatic characteristic of the study area belongs to the subzone E, which is well known in the literature as "southern tundra" (Andreev et al. 2002, Gundelwein et al. 2007, Hahne and Melles 1997, Kienel et al. 1999, Matveyeva 1998, Sommerkorn 2008, and others). It is the most densely vegetated subzone of the circumpolar tundra region and covered by 53% of erect shrub vegetation, 13% of tussock-sedges, dwarf-shrub and moss tundra, 11% of wetlands and 11% of mountain complexes (Walker et al. 2005). The southern tundra is the warmest part of the Arctic Tundra Zone with mean July temperatures of 9-12 °C (Walker et al. 2005 based on Matveyeva 1998) and an summer warmth index (sum of the mean monthly temperatures greater than 0°C) about 20-35°C (Walker et al. 2005 modified from Young 1971), what is applicable for the climate diagram of Chatanga (Figure 2). The vegetation of the study area (see pictures in Figure 12) is characteristic for the 13% of tussock-sedges, dwarf-shrub and moss tundra. The dominant vegetation units are "erect dwarf-shrub tundra" and "low-shrub tundra" (Walker et al. 2005). The horizontal structure of the plant cover is typically closed with 80-100% of vascular plants, whereby the vertical structure consists typically about 2-3 layers (Walker et al. 2005). The moss layer is 5-10cm thick with a high variety of mosses and lichens and covers the entire ground. The herbaceous dwarf-shrub layer is about 20-50cm (Walker et al. 2005). *Vaccinium uligonosum*, *Vaccinium vitis ideae*, *Cassiope tetragona*, *Empetrum nigrum, Arctostaphylos uva-ursi* and *Ledum palustre* are typicall herb species next to *Pedicularis capitata*, *Pedicularis rostratocapitata*, *Dryas punctata*, *Dryas octopetala*, *Pyrola rotundifolia*, *Artemisia*, *Potentilla palustris*, *Rubus chamaemorus*, *Saxifraga nelsoniana* and *Saxifraga hieracifolia*. Cyperaceae is one of the leading families of the tundra flora (Alexandrova 1980) and the entire complex of sedges (*Carex*) and Cotton grasses (*Eriophorum angustifolium*, *Eriophorum scheuchzeri*) are found in the most important tundra associations. *Equisetum arvense* is common for damp locations whereas Poaceae and *Lycopodium clavatum* are common on drier and sun exposure places. Wolly Willows (*Salix lanata*) and a smaller form of willow, Glaucous willows (*Salix glauca*), Dwarf birches (*Betula nana*) and Green alder (*Alnus viridis* spp. *fruticosa*) are typically species of the shrub layer in the study area. Alexandrova (1980) divides the “southern tundra” (table in Figure 9 and Figure 10) by the occurrence of taller shrubs and more cover of shrub than in the “typical tundra” (table in Figure 9 and Figure 10), so that sometimes a local specific low-shrub layer (third layer) to 80cm can develop on watersheds. Although there is a lack of real tree vegetation, toward the southern part of the subzone E, patches of open forest can possibly penetrate into this subzone along riparian corridors (Walker et al. 2005), see Figure 11. They consist in the investigated area of Dahurian larch (*Larix gmelinii*), into the west in the vicinity of the Yenisei River and also into the east in the vicinity of the Olenek River of Siberian spruce (*Picea obovata*), Siberian pine (*Pinus sibirica*) and tree birches (*Betula pubescens, B. exilis*).

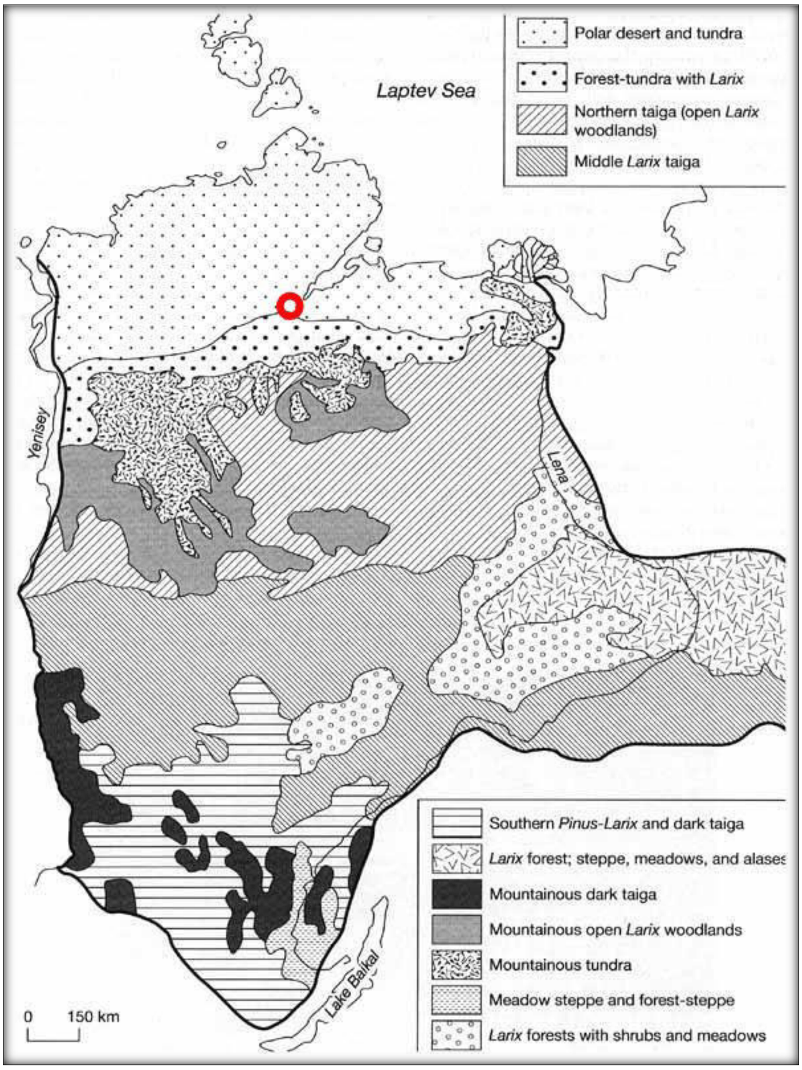

Figure 11: Vegetation of Central Siberia. The investigated lake (red circle) is located at the ecotone of tundra and forest-tundra with *Larix*. The boundary of the northern taiga, where *Larix* build open woodlands, is situated approximately 200km south of the lake. But groups of *Larix* as well as single individuals characterize the study area, see pictures in Figure 12. Like Walker et al. (2005), groups or single individuals of *Larix* penetrate into the study area. [Compiled by Tishkov, A. using data from Sochava 1979, online <http://www.rusnature.info/reg/f9-6.jpg>, last call 28.10.2014]

Small-scale vegetation pattern can occur due to differences in microclimates, exposure, active layer depth, and soil or water regime. These patterns are from high importance, because they built the source of potential pollen input into the lake. The single pictures of Figure 12 show the vegetation formation in the surroundings of the lake. Single individuals and small groups of *Larix* are growing approximately 2-4m in height on barrows and especially on the barrows alongside the rivers (see also Figure 8). Hahne and Melles (1997) observed dense alder brushes on rock placers in the vicinity of the Lama Lake especially there, where single larch trees occur. Around the investigated lake, these observations could not be confirmed. But *Salix glauca*, *Vaccinium vitis ideae*, *Empetrum nigrum*, *Pedicularis* and *Dryas* were found on the top or above short slopes, where drier conditions predominate. Mainly *Salix*, but also *Betula* were found in the vicinity of the lake and built dense canopies especially in the area of the overflow of the lake. *Carex* and

Eriophorum, *Lycopodium*, *Equisetum* and *Sphagnum* ssp. were mainly found on the lakeshore. *Hippuris vulgaris* and *Potamogeton* were found in the lake, underwater.

Figure 12: Vegetation in the close surroundings of the lake 11-CH12. [Photo: Ruslan Gorodnichev, 2011]

2.8 Vegetation and climate history of the late Pleistocene and Holocene

It is still debated, if the higher precipitation during the late Weichselian led to the formation of the Eurasian ice sheet and covered the whole Taimyr Peninsula (maximum variant of Grosswald 1998) or if it was restricted only to the mountain areas, so that east Siberia remained unglaciated (minimum variant of Velichko et al. 1984). During that time from 11,000-10,300 years BP, the climate in the vicinity of Chatanga was clearly more severe, cooler ($\Delta T°_{year}$ -3°C) and moister (ΔP_{mm} -150mm) than today (Figure 14)(Hahne and Melles 1997; Andreev and Klimanov 2000) and tundra existed around 300km more south in the area of the recent open *Larix* woodlands (Figure 13). Scarce steppe-like communities with *Artemisia*, Poaceae and Cyperaceae dominated the unglaciated areas of the Taimyr Peninsula (Andreev et al. 2004). The Weichselian-Holocene boundary in Europe and Russia has been dated by Khotinskiy (1984) to 10,300 years BP.

The subsequent warming of around 4°C and the increasing annual precipitation rates of around 175mm (Figure 14) introduced the Preboreal (10,300-9,200 years BP) in the Chatanga region. Characteristic increases of the values of arboreal pollen, mainly of *Betula exilis* type and *Salix*, increasing values of the pollen concentration as well as the increased Sphagnum spores content were observed in palaeoenvironmental studies of the Taimyr Peninsula, whereby all herb pollen taxa but especially Cyperaceae decreased dramatically. (Hahne and Melles 1997; Andreev et al. 2004) According to Andreev et al. (2004), Andreev et al. (2002), Andreev and Klimanov (2000), Velichko et al. (1997) and Nikol`skaya (1980), the vegetation of the Taimyr Peninsula changed in the beginning of the Holocene to shrub and forest tundra. The position of the forest-tundra approximately corresponded to the modern one and single larch trees and smaller groups of larches expanded from the south into the study area.

After a short cooling period at the transition from the Preboreal to Boreal, the warming ($\Delta T°_{year}$ +2°C) and the moisture increasing (ΔP_{mm} +100mm) continued into the Boreal (9,200-8000 years BP) (Figure 14). The so called Holocene climate optimum led to the maximal treeline movement, approximately 200km farther north than today, so that the study area was situated within the forest-tundra at that time (Figure 13). Dense larch forests developed on the Taimyr Peninsula which is also reflected in the relatively high *Larix* pollen content (30%) in the area of the Lama Lake (Hahne and Melles 1997; Andreev et al. 2004). *Picea*, *Populus*, *Juniperus* and *Alnus* became of high importance around the Lama Lake, so that the Boreal is characterized by the highest pollen concentration values coming from the tree and shrub pollen taxa because the non-arboreal pollen reached their lowest values of the Holocene. (Hahne and Melles 1997)

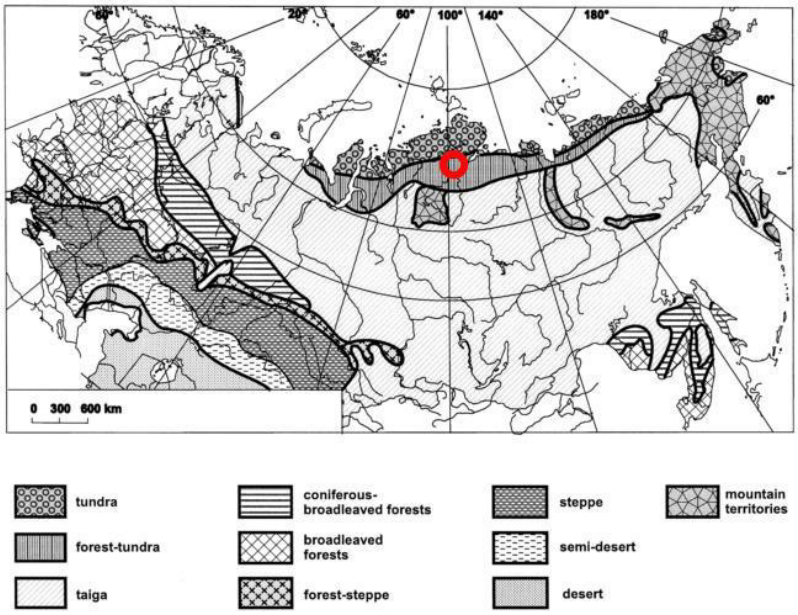

Figure 13: Vegetation in the Holocene climatic optimum and pointing the position of the study lake 11-CH-12 (red circle). [According to Velichko et al. 1998 after Khotinskiy 1984]

At the transition to the Atlantic period, *Larix* pollen contents decrease to 10% due to the assumption that the moister conditions resulted in a limiting factor and so larches could not grow and reproduce longer in some areas at the Taimyr Peninsula (Hahne and Melles 1997). However, the climate conditions were generally comfortable ($\Delta T°_{year}$ +2°C, ΔP_{mm} +100mm, Figure 14) during the Atlanticum (8,000-5,000 BP), but cooler intervals have been recorded by Hahne and Melles (1997) and Andreev and Klimanov (2000). Spruce became an important species around the Lama Lake, so that the vegetation changed to larch-spruce forests ones in the vicinity of the study area, but never occupied the landscape of the Labaz Lake. The northern limit of *Picea* has always been near the Lama Lake (Hahne and Melles 1997). Up from the late Atlantic period, larch obviously had reached its northernmost range in Central Siberia. Fossil larch stamps have been dated between the Taimyr Lake and the Chatanga Bay to 5,700-5,500 years BP, showing that larch have been present up to 300km further north than today (Hahne and Melles 1997). Andreev et al. (2004), Andreev et al. (2002), Andreev and Klimanov (2000), Clayden et al. (1997), Belorusova et al. (1987), Kul`tina et al. (1974) and Nikol`skaya (1980) observed the beginning of dramatically decreases in arboreal pollen in records from the Taimyr Peninsula due to gradual deforestation on northern Taymyr and the disappearance of spruce from the forest communities at the transition to the Subboreal. Palaeoecological records from the Arctic region of East and West Siberia indicate that the climate generally cooled during the late Holocene, leading to a southward retreat of the treeline between 5300 and 3800 years BP. (Andreev and Klimanov 2000; Fedotov et al. 2012; Hahne and Melles 1997; Kienel et al. 1999; Laing and Smol 2003)

The Russian Subboreal (5,000-2,5000 years BP) includes two cool and one mild event and the annual precipitation is reconstructed to decrease continuously (Khotinskiy 1984; Andreev and Klimanov 2000). The forest degenerated completely and the tundra expanded southward, approximately to the same like on modern conditions, which is reflected in the decrease of arboreal pollen contents on the Taimyr Peninsula (Andreev et al. 2002; Andreev and Klimanov 2000; Clayden et al. 1997; Velichko et al. 1997; Kul`tina et al. 1974 and Nikol`skaya 1980).

The Subatlantic period includes the past 2,500 years. The climate of the Chatanga region recovered from the cool and relatively dry conditions (3,000 years BP) to milder conditions than today ($\Delta T°_{year}$ +1°C, ΔP_{mm} +40mm, Figure 14) around 1,000 years BP. But then, the climate cooled and dried once again around 500 years BP ($\Delta T°_{year}$ -0.75°C, ΔP_{mm} -50mm, Figure 14). The modern vegetation cover of tundra and forest-tundra established the Taimyr Peninsula. The treeline is actually regressing southward in some parts of Russia (ACIA 2004) due to the effects of industrial pollution (e.g. in the surroundings of Norilsk). In outlying regions, the northernmost larches are growing in dwarf-form and can be found in depressions or on favorably exposed slopes in the vicinity of the Labaz Lake. They produce pollen only in warm summers (Hahne and Melles 1997). Herbs and grasses (species of the families of Ericaceae, Rosaceae, Asteraceae, Ranunculaceae, Saxifragaceae, Caryophyllaceae, Cyperaceae and Poaceae) dominate the landscapes on the Taimyr Peninsular for the first time since the Last Glacial and led to increased non-arboreal pollen contents in the pollen records (Andreev et al. 2002; Andreev et al. 2004; Hahne and Melles 1997). They build vegetation communities together with shrubs like *Salix*, *Betula* and *Alnus*. The more detailed description of the vegetation changes in the vicinity of Chatanga during the last 1,000 years is part of this study and will be presented by analyses of a lacustrine pollen record.

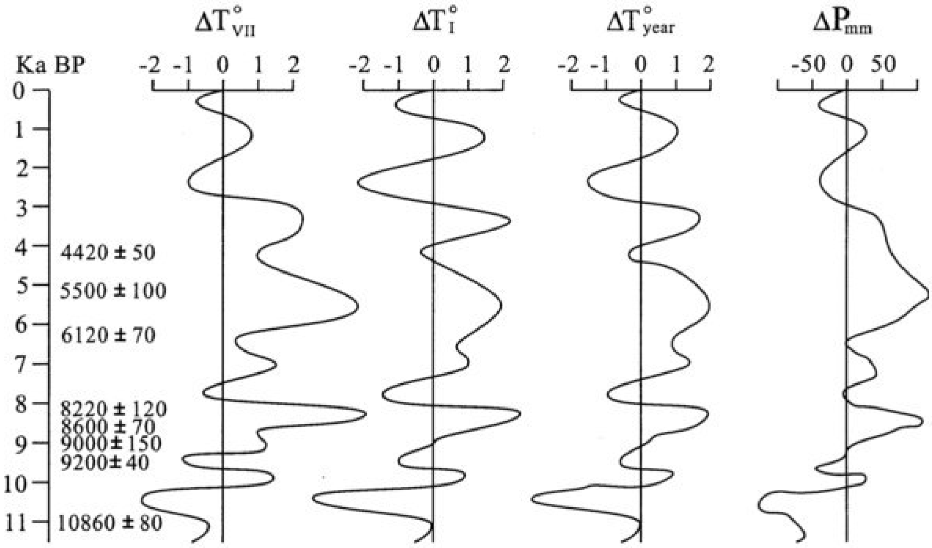

Figure 14: Average palaeoclimate curves in the vicinity of Chatanga. [Andreev and Klimanov 2000]

3 Methods

3.1 Lacustrine samples and available data

3.1.1 Lake sampling

The field work was done by a group of Russian and German scientists in 2011 during a summer expedition into the Chatanga region conducted by Prof. Dr. Ulrike Herzschuh, Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research Unit Potsdam, Germany, in cooperation with Prof. Dr. Ljudmila Pestryakova, North Eastern Federal University of Yakutsk, Russia. During this joint project different lakes within one transect from northern tundra to southern tree-tundra sites, alongside the Chatanga River, were accessed by helicopter. The study core was taken from a location within the tundra taiga transition zone.

It was ensured that the cores were drilled at the measured maximum depth of the body of water to reduce the disturbance of the sediments by lake level fluctuations. The maximum depth was localized via depth measurements throughout the lake surface out from a boot by using a hand depth sounder.

The core ID "11-CH-12D" originates from the year of the expedition (2011), the locality (Chatanga) and the lake number (No.12), which was drilled two times (A and D) with a UWITEC gravity corer. 12A embodies a long core, while 12D, the short core with a length about 32cm, was drilled to enable high resulted time scale pollen analyses. Therefore the short core was sliced horizontal every half centimeter into 64 samples in total. This work was done directly in the field. The samples got preserved in Whirl-Pak´s to maintain the layer sequence and to prevent any contamination of the material during their transport. Furthermore to facilitate the transport to the AWI, meanwhile the samples were stored cool and dark.

Besides the core, limnological parameters such as pH, conductivity, total hardness, mineral contents and water transparency were gathered to describe the water quality. The latter is also known as Secchi depth because the water transparency gets measured by use of the Secchi disk. Documentations of the surrounding lake flora were done to promote a better understanding about the lake characteristic and furthermore the potential input of local plant material.

Figure 15: Fieldwork at and around the lake 11-CH-12 to enable analyses of the interdependent, limnological and terrestrial, units as a local system. [Photo: Ruslan Gorodnichev, 2011]

3.1.2 Age determination

Radiometric dating is a widely used tool to determine the age of lake sediments precisely and to deduce information about the accumulation rate over time.

Therefore 13 subsamples from the upper 7.25cm of the core 11-CH-12D were sent to the Environmental Radioactivity Research Centre at the University of Liverpool in Great Britain, where P.G. Appleby and G.T. Piliposian did the radiometric analyses. The report was sent to the Alfred-Wegener-Institute for Polar and Marine Research in Potsdam. Appleby and Piliposian did the radiometric analyses of ^{210}Pb, ^{226}Ra and ^{137}Cs by using Ortec HPGe GWL series well-type coaxial low background intrinsic germanium detectors (Appleby et al. 1986). The atmospheric natural fallout of ^{210}Pb (“unsupported” ^{210}Pb) was ascertained via its gamma emissions while ^{226}Ra got determined via its daughter radionuclide ^{214}Pb emitted following three weeks storage in sealed containers to allow radioactive equilibration. ^{137}Cs was measured by its emissions to get chronostratigraphic dates. Calibrated sources and sediment samples with a known activity were used to gain the absolute efficiencies of the well-type detectors. Corrections were made using the ^{137}Cs record as reference chronology, because there were significant discrepancies between well-defined ^{137}Cs dates and the untreated ^{210}Pb dates. (Appleby and Piliposian 2011)

3.2 Pollen analysis

3.2.1. Sample treatment

Fossil pollen analyses are only feasible due to the resistance of the pollen membrane against different concentrated acids and bases. The pollen preparation of all 64 samples from the 11-CH-12D core was conducted in the pollen laboratory of the Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research in Potsdam following the standard procedures from Faegri and Iversen (1989). At first, subsamples were taken out from the Whirl-Pak´s, containing the sliced 11-CH-12D core samples, with syringes to get 1ml volume of each sample for pollen analyses. The lab work was done on six appointments because every single one encompasses a two days preparation where ideally a maximum number of 12 subsamples could have been treated.

On the first day in the lab and before the pollen extraction could have been started, the subsamples were profitably contaminated with a calibrated quantity of *Lycopodium* spores, which do not occur naturally in the deposit (Stockmarr, 1971), for further calculations of the pollen concentrations within the subsamples. Approximately 20848 *Lycopodium* spores per tablet, Batch Nr. 1031, were added. Then the sodium bicarbonates from the spores tablets and carbonates included in the sample materials got removed by adding 10% hydrogen chloride (HCl). The thereby formed froth was subdued by use of a few drops of Ethanol. These and the coming steps were usually followed by washing the suspensions with purified water until the pH-value retrieve neutral. Also to centrifuge the suspensions in a Heraeus Multifuge 1S Centrifuge by a speed of approx. 3000 radiations per minute for 3 minutes to concentrate the sample material on the ground of the tubes to allow decanting of the fluids. Afterwards the humic acids were dissolved by 10% potassium hydroxide (KOH) treatment and heating the suspension in hot water bath for 10 minutes to keep the reaction potential. This step is closely followed by sieving the coarse particles through a nylon strainer with a mesh size of 200µm. The samples were washed again so that 40-45% hydrogen fluoride (HF) could be added to dissolve siliceous particles during night.

On the second day, the samples in HF got washed and the water residues had been reduced by glacial acetic acid (CH_3COOH) before the acetolysis was conducted. Acetolysis names the treating with a fresh mixture of nine parts acetic anhydride ($C_4H_6O_3$) to one part 95-98% sulfuric acid (H_2SO_4) and heating in boiling water bath for 2.5 minutes to remove cellulose components as well as to stain the pollen grains and spores amber-coloured. After the last washing process the samples were fine sieved through a 7µm mesh size strainer in an ultrasonic bath (VWR Ultrasonic Cleaner) for max. 30 seconds so that the pollen grains would not rupture. Strong exines, e.g. these from *Larix* pollen, rupture faster than thin exines, e.g. these from Cyperaceae, which can stand much longer treatment. (Faegri and Iversen, 1989) Until further analyses the samples were stored in water-free glycerol.

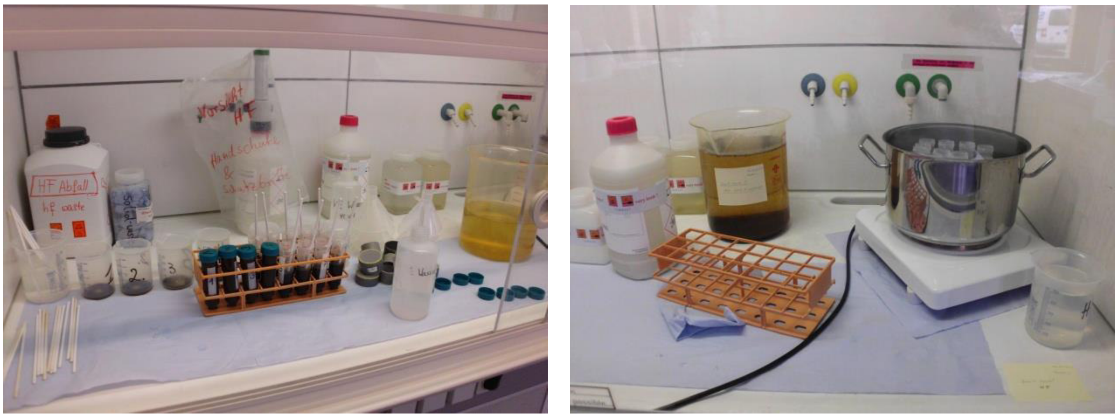

Figure 16: Sample treatment under the exhaust hood in the pollen laboratory of the Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research in Potsdam. [Photos: Xenia Schreiber]

3.2.2 Light microscopy

The extracted pollen and spores material is stored in smaller tubes and got stirred to homogeneous suspensions before analysing. A single drop of the regarding sample was transferred to a slide, covered by a cover slip, then sealed with nail varnish and labeled with the appropriate sample ID to produce a permanent mount for pollen counting. Due to the fact that smaller grains seemed to float toward the edges of the cover slip, the counting process took always the whole slide, even if every second row, into account. The number of pollen grains, spores and non-pollen palynomorphs (NPP´s) were counted for each sample by use of a Carl Zeiss Axiolab Microscope. The magnification of 100 obtained an overview about the sample slide. The more detailed solution of 400 by using a 40x objective and 10x ocular was required for the identification and counting of the individual objects.
One sample counting applies only to be completed, if a minimum of 300 terrestrial pollen grains and 200 *Lycopodium* spores has been gathered. The pollen grain determination followed the keys of Beug (2004), Moore et al. (1991) and Savelieva et al. (2013). Some grains were compared to images given in the "Online Publication on fossil and recent Pollen and Spores" (PalDat - Palynological Database) or the pollen collection of the Alfred Wegener Institute. Even if the determination was not clear, the analysis was supported by special advice from Bastian Niemeyer (AWI Potsdam). Non-pollen palynomorphs were determined on their species level by use of Moore et al. (1991) and Van Geel et al. (1989).

The aim was to ascribe the pollen grains as taxa on their family or genus levels, however most pollen grains were ascertained as taxa-types, e.g. Ericaceae could be distinguished into two morpho-types, *Vaccinium* type and *Cassiope* type. Pollen grains, which belong to the plant family of Ericaceae, but were not identifiable upon the level of their morpho-types, due to their broken or collapsed appearance, were counted on their next lower taxonomic level. The same applies for Rosaceae and Ranunculaceae. Pollen grains which were considered to be indeterminable were counted as "pollen indet". Taxa, which were ascertainable but where features for further identification were missing or visually not obviously, were counted as "cf *Saxifraga*" or "cf *Scrophulariaceae*".

The mounts of NPP´s are not decisive factors for the results of pollen analyses but their variations can be helpful to interpret the lake ecology or to compare those to the pollen grain fluctuations. That´s why all NPP taxa which could be found in most of the samples were also counted, e.g. *Botryococcus, Pediastrum* and *HdV-187D* (Kramer et al. 2010).

The sequence of the sample ID was randomized during the counting process to prevent subjective expectations on the counting results. And after a minimum of 300 terrestrial pollen grains and 200 *Lycopodium* spores were counted in each sample, the first 10 analyzed samples were counted again to review the counting results.

Exemplary pictures from microscopy work can be found in the Appendix 8.1.

3.3 Data treatment

3.3.1 Palynological data treatment

In this study, 41 different pollen taxa and five types of non-pollen palynomorphs have been counted for all 64 samples, also *Lycopodium* marker spores and the group of indeterminable pollen grains. The single pollen grains from *Tilia*, *Populus* and *Juglans* were excluded from any further analyses, because their sparsely occurrences are assumed to be contaminations and do not represent the local vegetation. However, Table 1 presents those 38 pollen species and five types of NPP, which are at the basis of the pollen analysis.

The results of the pollen counting were summarized in one Excel chart for palynological data treatment. Thereby the identified taxa, except the marker spores, were arranged in groups of arboreal pollen (AP), non-arboreal pollen (NAP), pollen of water species and non-pollen palynomorphs (NPP). AP and NAP represent pollen grains of terrestrial species. Their total amounts had been ascertained for each sample to calculate the percentage values from the number of individuals per identified taxa in relation to the respective total number of terrestrial pollen grains. Thereby, the pollen of the water species had been excluded because they are assumed to be overrepresented in lake sediments. Furthermore this study focuses on terrestrial pollen.

Two different pollen diagrams were generated by the free version of C2 1.7.5 (Juggins 2014). Number one (Appendix 8.2) presents all taxa of pollen and non-pollen, which were counted throughout the core. The second diagram (Figure 20) shows the main terrestrial pollen taxa, which were used for statistical analyses, and additional representative herb species, which are not included in statistical analyses but who were found during field observations on expedition and so present the local vegetation community. The fluctuations of the NPP´s and the relation of AP to NAP are also displayed in Figure 20. This pollen silhouette diagram generates an impression of subsequently pollen assemblage and will be used to reconstruct the vegetation history.

Table 1: List of abundant taxa within the core 11-CH-12D.

Marker spores	*Lycopodium* Batch. 1031	
Arboreal pollen	*Betula* *Alnus* Pinaceae *Salix* *Larix*	
Non-arboreal pollen	Cyperaceae Poaceae *Vaccinium* type *Cassiope* type Ericaceae *Artemisia* *Senecio* type *Matricaria* type *Potentilla* type Rosaceae *Rumex* *Rumex aquaticus* Brassicaceae Caryophyllaceae Ranunculaceae *Thalictrum* Lamiaceae	*Valeriana* *Linnea borealis* Chenopodiaceae *Primula* type Gentianaceae Apiaceae Fabaceae *Parnassia* Fenestratae *Urtica* *Plantago* Rubiaceae cf *Saxifraga* cf Scrophulariaceae *Potamogeton* *Myriophyllum*
Indeterminable pollen	Pollen indet	
Non-pollen palynomorphs	*Pteridium* type *Lycopodium* (local type) *Pediastrum* *Botryococcus* *HdV-187D*	

3.3.2 Statistical analyses

To support the interpretation of the pollen diagram, those taxa were considered for further statistical analyses, which showed percentages of abundance higher than a specific threshold. In this thesis, the threshold value for these taxa was set at 0.5% (Brewer et al. 2002; Lisitsyna et al. 2011) and furthermore had to occur in at least six of the investigated 64 samples. All terrestrial pollen taxa (n=36) were investigated into threshold analyses. The group of indeterminable pollen ("Pollen indet.") was excluded as it includes pollen grains of different species and morpho-types and do not reflect representative fluctuations. It was assumed that their uncertainty might interfere with the deduction of ecological parameters.

Due to ensure a statistical relevance of the taxa, the following 19 were used to perform the statistical analyses: *Betula*, *Alnus*, Pinaceae, *Salix*, *Larix*, Cyperaceae, Poaceae, *Vaccinium* type, *Cassiope* type, Ericaceae, *Artemisia*, *Senecio* type, *Potentilla* type, Rosaceae, *Rumex*, Brassicaceae, Caryophyllaceae, Ranunculaceae and cf Saxifragaceae.

The remaining 17 terrestrial taxa had been excluded, because they did not occur on a regular basis throughout the short core: *Matricaria* type, *Rumex aquaticus, Thalictrum,* Lamiaceae, *Valeriana, Linnea borealis,* Chenopodiaceae, *Primula* type, Gentianaceae, Apiaceae, Fabaceae, *Parnassia,* Fenestratae*, Urtica, Plantago,* Rubiaceae and cf. Scrophulariaceae.

For cluster and ordination analysis the reduced dataset was processed in the free version of R 3.0.3 (Murdoch 2014). The CRAN packages 'rioja' (Juggins 2013) and 'vegan' (Oksanen et al. 2013) were used to provide functions for the analysis of Quaternary science data. These packages are constructed to fulfill constrained clustering and stratigraphic diagrams ('rioja', Juggins 2013) as well as ordination methods and functions for community and vegetation ecologists ('vegan', Oksanen et al. 2013).

The percentages had been square-root transformed to reduce the influence of outliers and to stabilize the variance of percentage data before calculations.

The cluster analysis and the broken-stick model were applied to structure the investigated data into statistically significant pollen assemblage zones. The constrained incremental sum of squares cluster analyses (CONISS) is a multivariate method to detect differences and similarities between adjacent samples, thus pollen assemblage zones (PAZ) can be identified (Grimm 1987). This analysis was conducted by the method of Bray-Curtis (Beals 1984) to produce a distance matrix based on the differences between samples. Samples corresponding to the same clustering zone are assumed to reflect similar pollen composition, while samples of neighboring groups are more different. The analysis reveals patterns of uniform pollen content and displays the quantitative defined clusters in the CONISS dendrogram. A broken-stick model was applied to verify the results of the cluster analyses in terms that it verifies the number of PAZ that can be significantly described over the length of the core. (Bennett 1996)

The following Principal Component Analysis (PCA) was conducted to investigate the variation of the pollen spectra composition and environmental gradients which are related to the species assemblages within the zones. The instruction for the PCA without any ecological parameters in R is implemented by use of the Redundancy Analysis (RDA). This method is designed to display two principal components as synthetic environmental gradients in the RDA biplot (ter Braak and Verdonschot 1995). The first principle component (PC1) embodies the variable explaining the highest possible variance of the data, while the second axis (PC2) describes another theoretical gradient which is uncorrelated to PC1 and represents the most of the remaining variance. The fit of these explanatory axes are revealed as eigenvalues. PC1 and PC2 together should explain the least residual sum of squares. The taxa scores are represented as arrows and point in the direction of increasing change in abundance for that variables.

3.3.3 Pollen concentration and pollen accumulation rate

The pollen concentration is the measurement for the amount of pollen grains within one sample. In this study, the total amounts of terrestrial pollen grains were used to generate the sample specific pollen concentrations as follows:

$$pollen\ concentration\ \left[in\left(\frac{grains}{cm^3}\right)\right] = \frac{\left(\frac{\sum terrestrial\ pollen\ grains\ *\ \sum added\ marker\ spores}{\sum counted\ marker\ spores}\right)}{sample\ volume\ [in\ cm^3]}$$

The number of the added *Lycopodium* markers (Batch Nr. 1031) has a concentration of approximately 20848 spores per tablet.

As opposed to the pollen concentration, the pollen accumulation rate (PAR) depends on the sedimentation rate of the sample material and describes the annual quantity of grains, which were deposited per square centimeter each year. Calculations of the sample specific PARs were performed to reflect real relative past plant population densities around the study site independently for the investigated taxa (Seppä and Hicks 2006):

$$PAR\ \left[in\left(\frac{grains}{cm^2 yr}\right)\right] = \frac{\left(\frac{\sum pollen\ *\ \sum added\ marker\ spores}{\sum counted\ marker\ spores}\right)}{sample\ volume\ (in\ cm^3)} * sedimentation\ rate\ \left[in\ \frac{cm}{yr}\right]$$

The sedimentation rates of the upper samples shown in were ascertained by Appleby and Piliposian as part of the age determination at the Environmental Radioactivity Research Centre at the University of Liverpool in Great Britain. On the understanding that the sedimentation rates of the lower subsamples are uniform at 0.029 cm y^{-1} (Table 3), linear sedimentation rates were extrapolated for the rest of the core to estimate the PAR over time.

The pollen concentration and influx diagram is shown in (Figure 22). It was generated similar like the pollen diagram by using the free version of C2 1.7.5 (Juggins 2014) Also the cluster analysis was carried out by use of the free version of R 3.0.3 (Murdoch 2014) and the CRAN packages 'rioja' (Juggins 2013) and 'vegan' (Oksanen et al. 2013) to show statistic relevant assemblage zones within the pollen influx data.

4 Results

4.1. Lacustrine samples and available data

4.1.1 Lake measurement results

The first measurements were made to describe the position of the study lake. They revealed that the lake is situated northern the arctic circle at 72° 23′ 55.9″ N and 102° 17′ 19.5″ E. The shortest distance from the lake in the south to the Kara Sea in the north is about 554km among the southern Tundra. 11-CH-12 itself lies 70m above sea level and enfolds a size of approximately 220 x 130m.

Several depth measurements were done at the 0.0286 km^2 lake surface to localize a deep point of the body of water. At this point and the measured maximum depth of about 14.3m, the 32cm short core was drilled and immediately sampled on-site. In contrast to these samples, which were sent to the Alfred Wegener Institute in Potsdam for further CNS-, age- and palynological analyses, additional hydrochemistry parameters had been conducted in the field. The pH-value of about 7.5 is neutral. The conductivity refers to 25°C of water temperature, averages 34.9µS/m inside the lake. And the total hardness is about 0.2479mmol/l. The results of the water ion analysis, e.g. Fe^{2+}, NH_4^+, PO_4^{3-} and Cl^- are shown in Table 2 and enable further description about the water quality. The Secchi depth is about 5m and so the water transparence amounts one third of the measured maximum water depth.

Table 2: Ion values of the lake water sampled from 11-CH-12. [Data: Ruslan Gorodnichev, 2011]

Fe^{2+} [mg/l]	Ca^{2+} [mg/l]	Mg^{2+} [mg/l]	Si [mg/l]	NH_4^+ [mg/l]	$\sum Na^+ + K+$ [mg/l]	PO_4^{3-} [mg/l]	HCO_3^- [mg/l]	SO_4^{2-} [mg/l]	Cl^- [mg/l]
0.0233	5.83	2.49	1.13	0.17	0.93	0.1	31.27019	0.28	0.17

4.1.2 Age-depth-model

The ^{210}Pb and ^{137}Cs dating of 13 subsamples from the top 7.25cm of the Chatanga lake sediment core was done by P.G. Appelby and G.T. Piliposian at the Environmental Radioactivity Research Centre, University of Liverpool, Great Britain.

The results carried out for the age-depth-model are shown graphically in Figure 17.

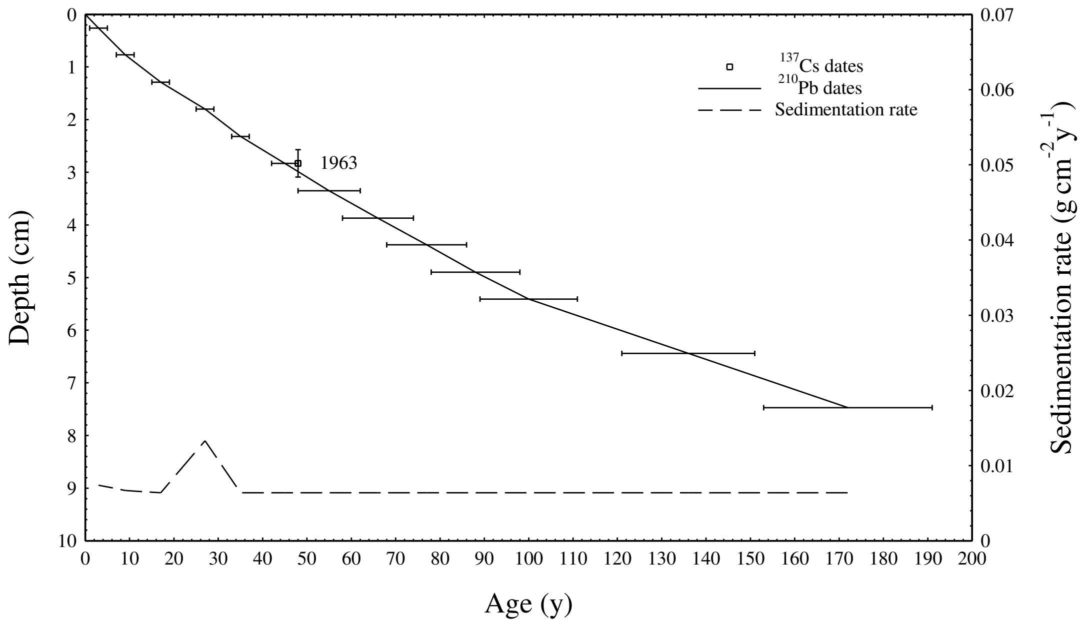

Figure 17: Age-depth-model of the upper 7.25cm of Chatanga lake sediment core (11-CH-12D). Radiometric chronology displaying the ^{210}Pb dates, sedimentation rates and the 1963 depth suggested by the ^{137}Cs record, ^{137}Cs date is shown as reference point. [Appleby and Piliposian, 2011]

The signal of unsupported ^{210}Pb varies in subject to the sedimentation rate. If the sedimentation rate is small, ^{210}Pb will be considerably high. The analyses indicate a relatively constant sedimentation rate until the last third of the 20th century, with a mean value of 0.0064±0.0007 gcm^{-2}y^{-1}, which equals a low accumulation rate of 0.037 cm y^{-1}. P.G. Appelby and G.T. Piliposian indicate the 1963 ^{137}Cs fallout maximum from the atmospheric nuclear weapons tests. (Appleby and Piliposian, 2011) 1986 shows a low fluctuation of the ^{210}Pb dates simultaneously to the significant high peak of the sedimentation rate (0.056 cm y^{-1}), which could be explained with the higher amounts of contaminated material accumulated into the lake after the reactor accident of Chernobyl.

Discrepancies between the calculated ^{210}Pb dates and ^{137}Cs record could be due to a lowering of recent ^{210}Pb supply rate to the core site or a consequence to the loss of material from the top of the core shortly before or during coring. These were rectified by P.G. Appelby and G.T. Piliposian for the post 1963 dates by using the ^{137}Cs date as reference point. (Appleby, 2001, Appleby and Piliposian, 2011)

The uniform sedimentation rates (Table 3) of the lower subsamples (6.25cm and 7.25cm) enable to estimate the time period covered by the whole short core. The linear extrapolation of the last two accumulation rates (0.029 cm y^{-1}) yields that the study core covers an interval about the last 1072 years, so that the core approximately dates back to the year 939 AD (Figure 18).

Table 3: ^{210}Pb chronology and sedimentation rate of the upper samples of 11-CH-12D. [Appleby and Piliposian 2011]

Depth		Chronology			Sedimentation Rate		
		Date	Age				
cm	g cm^{-2}	AD	y	±	g cm^{-2} y^{-1}	cm y^{-1}	± (%)
0.0000	0.00	2011	0	0			
0.2500	0.02	2008	3	2	0.0074	0.086	4.1
0.7500	0.06	2002	9	2	0.0067	0.074	5.0
1.2500	0.12	1994	17	2	0.0064	0.057	4.7
1.7500	0.20	1984	27	2	0.0133	0.056	8.8
2.2500	0.28	1976	35	2	0.0064	0.057	10.3
2.7500	0.35	1966	45	3	0.0064	0.052	10.3
3.2500	0.41	1956	55	7	0.0064	0.049	10.3
3.7500	0.48	1945	66	8	0.0064	0.048	10.3
4.2500	0.55	1934	77	9	0.0064	0.046	10.3
4.7500	0.62	1923	88	10	0.0064	0.045	10.3
5.2500	0.70	1911	100	11	0.0064	0.032	10.3
6.2500	0.93	1875	136	15	0.0064	0.029	10.3
7.2500	1.16	1839	172	19	0.0064	0.029	10.3

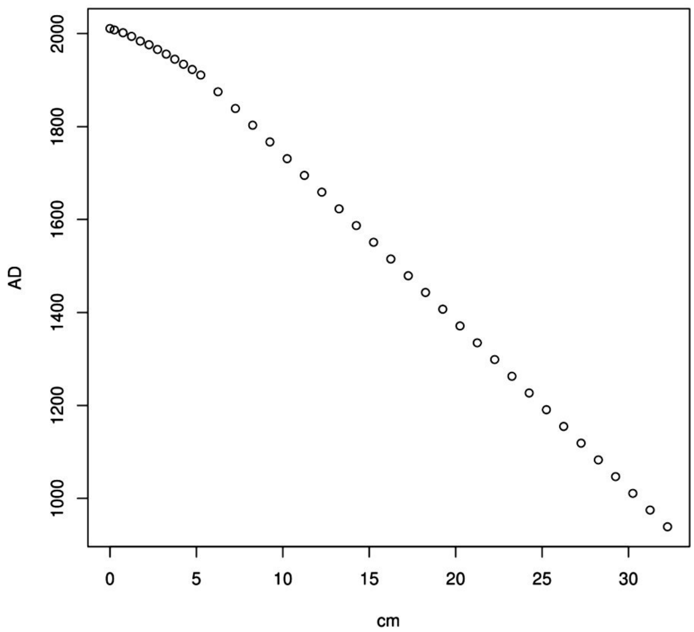

Figure 18: Linear extrapolated time scale for the whole short core 11-CH-12D.

4.2 Cluster and ordination analyses

The nineteen statistical relevant taxa were used to perform cluster and ordination analyses.

The obtained dendrogram of CONISS is shown on the right side of the pollen diagram in Figure 20 and displays the hierarchical ranking of pollen assemblage zones, which can be identified. The classification on the first hierarchical level presents two significant pollen assemblage zones, whereby the classification on the second level lead to cluster the upper zones into two subzones. Also the broken-stick model (Appendix 8.3) verifies that more than two but less than three significant PAZ can be described over the length of the core. And so the following classification has been revealed:

- PAZ I (975-1308 AD) reaches from 32-22.5cm and includes the lower 20 samples of the core. This zone is among others characterized by a precise decrease of *Alnus*.
- PAZ II spans the rest of the core 11-CH-12D and is divided into two subzones (PAZ IIa and PAZ IIb). PAZ IIa (1308-1961) contains 38 samples between 22cm and 3.5cm depth. This zone is characterized i.a. by increasing percentages of herb and grass pollen. PAZ IIb (1961-2011 AD) includes the six upmost samples, from 3.5cm upwards, which are characterized i.a. by increasing percentages of tree and shrub pollen, such as *Betula* and *Alnus*, and decreasing percentages of herb and grass pollen, above all those of Cyperaceae.

Two principle components (PC1 and PC2) were ascertained by ordination analysis. They are displayed as axes of synthetic environmental gradients in the RDA biplot (Appendix 8.4). PC1 explains the highest possible variance of the data (42.97%). PC2 is uncorrelated to PC1 and represents the most of the remaining variance (21.76%). In summary, both principal components are explaining 64.73% of the total variance of the data set (Table 4).

Table 4: Unconstrained eigenvalues [λ] of the principal components PC1 and PC2.

Axis	Eigenvalue λ	Cumulative variance %
PC 1	0.4297	42.97
PC 2	0.2176	64.73

Figure 19 shows the results of the cluster analyses combined with those of ordination analysis. The samples are displayed as symbols of their corresponding zone. The samples of the zones are clearly correlated to the axis of the first principle component (PC1) and are broad scaled to the second gradient (PC2). PAZ I and PAZ IIb are almost located in the negative quadrants of PC1, whereas PAZ IIa is first of all related to the positive quadrants of PC1. Thereby it is noteworthy, that the vegetation composition of the youngest section (PAZ IIb) is similar to the composition of PAZ I. Environmental gradients determine PAZ I and PAZ IIb similar to each other but completely opposed to the intermediate zone (PAZ II).

Alnus and *Betula* are negative correlated with axis 1. Together with Ericaceae, *Cassiope* type and Caryophyllaceae, they are the characterizing species in the PAZ I and PAZ IIb. Different to that, PAZ IIa is more dominated by herb taxa. *Rumex*, *Potentilla* type, Cyperaceae and also *Salix* are plotted in the positive quadrant of both axes and explain a half of the samples within this zone. The other samples are also located positively to the first axis, but negatively to the second axis. These samples are more characterized by Poaceae, *Artemisia*, Rosaceae, cf. *Saxifraga* and Brassicaceae. Also *Larix* is more dominant in PAZ IIa than in PAZ I and IIb.

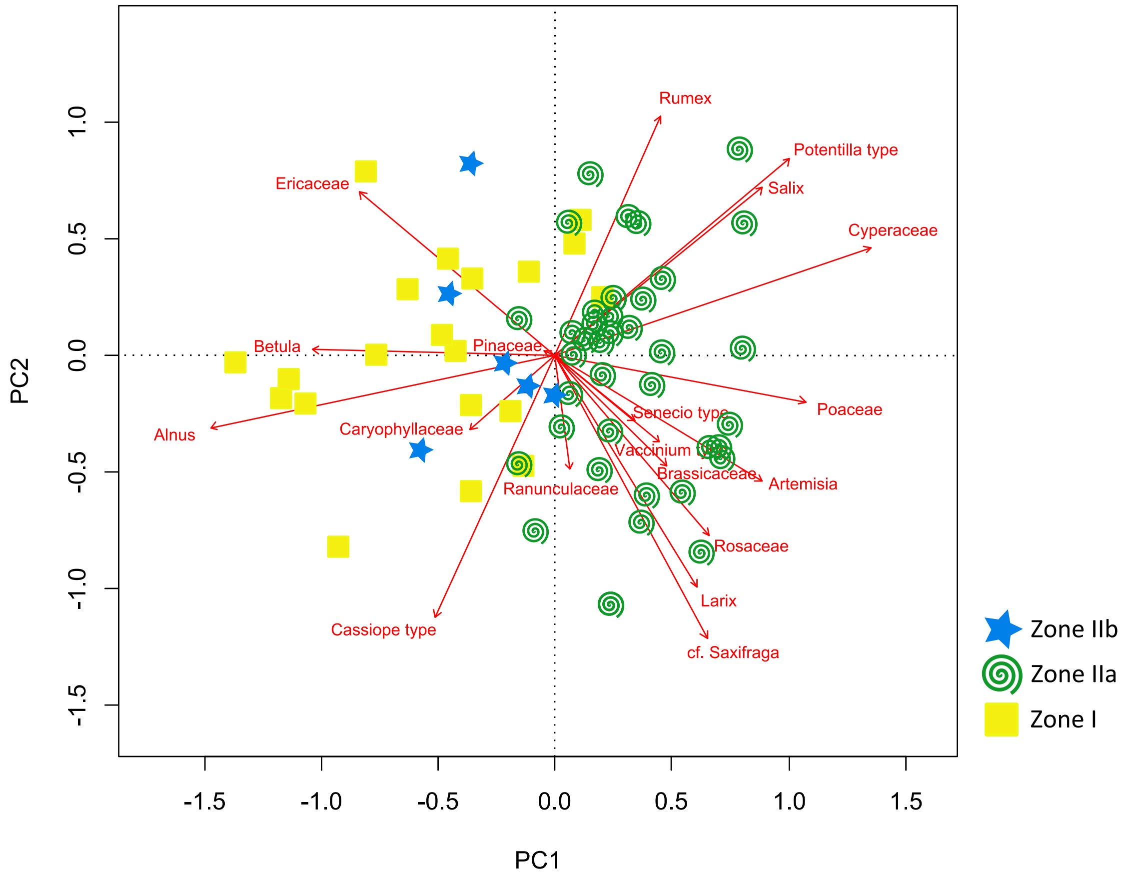

Figure 19: RDA biplot of the first two axes, which together explain 64.73% of the total variance of the data set. The 64 investigated samples are printed as symbols according to their zones. The depth from 32cm to 22.5cm is displayed by the yellow squares of Zone I. The samples between 22cm and 3.5cm of the core are presented by the green helix of Zone IIa and the upper samples from 3cm to the top of the core are displayed by the blue stars. The taxa scores are printed as red arrows.

4.3 Pollen diagram

4.3.1 General Characteristics of the pollen diagram and the pollen spectra

General characteristics of the pollen diagram

The pollen diagram in Figure 20 displays highly resolved abundance fluctuations for terrestrial pollen taxa (AP, NAP), types of NPP as well as the sample specific relation of the sum of tree and shrub pollen to sum of herb and grass pollen (AP:NAP). The percentages are plotted as silhouettes against depth and ascertained ages of the samples. An exaggeration line (exaggeration multiplier factor 10) visualizes small abundant taxa more clearly. The dendrogram as the result of the cluster analysis structures the pollen assemblages into three significant zones – PAZ I, PAZ IIa and PAZ IIb.

The pollen spectrum of the pollen diagram includes the following 29 terrestrial taxa: *Betula*, *Alnus*, Pinaceae, *Salix*, *Larix*, Cyperaceae, Poaceae, *Vaccinium* type, *Cassiope* type, Ericaceae, *Artemisia*, *Senecio* type, *Potentilla* type, Rosaceae, *Rumex*, Brassicaceae, Caryophyllaceae, Ranunculaceae, cf Saxifragaceae, *Thalictrum,* Lamiaceae, *Valeriana,* Chenopodiaceae, *Primula* type, Gentianaceae, Apiaceae, Fabaceae, *Parnassia and* cf Scrophulariaceae. These conform to all taxa which were used for statistical analyses (n=19) and supplemented species, which were found during field surveys (n=10) to reflect the local flora, because the pollen percentages of herbs and grasses are dominating in the pollen assemblage.

Characteristic of the pollen spectra throughout the core

The following characteristic of the pollen spectrum is also given as an overview in Table 5. On average, the non-arboreal pollen predominate slightly the pollen assemblages throughout the short core with 53.49% and vary between 28.06% and 68.42% in relation to the sum of arboreal pollen (Figure 21). Cyperaceae shows the highest percentages among all taxa with a minimum of 12.71% and a maximum of 49.04%. The sedges provide in average one third (33.33%) of the pollen assemblage. Although Poaceae have been found to show the second highest percentages of NAP with a mean value of 7.52%, they also show a high variability in their abundance from 1.00% to 11.64% in consecutively samples, in 27-26cm depth of the core. Herb taxa, which are pollinated by insects, present obviously lower percentages. Most of them present higher percentages up from the central part to the top of the core (22-3cm) and more scattered deposits in the lower and upper samples. However, the Ericaceae together with their morpho-types *Vaccinium* type and *Cassiope* type, allocate the most common herb taxa (on average 4.05%), whereas their combined minimum of 1.73% is found in the upper most samples (4cm depth) and their maximum reach up to 10.98% in the depth of 27cm. Also Rosaceae together with *Potentilla* type (0.21-4.18%, mean of 1.73%) and the types of Asteraceae (0.00-4.99%, mean of 1.67%) – *Artemisia* and *Senecio* type – show comparatively low values. All other herb taxa occur in average less than 1.00%, e.g. *Rumex*, Brassicaceae, Caryophyllaceae and Ranunculaceae (including *Thalictrum*).

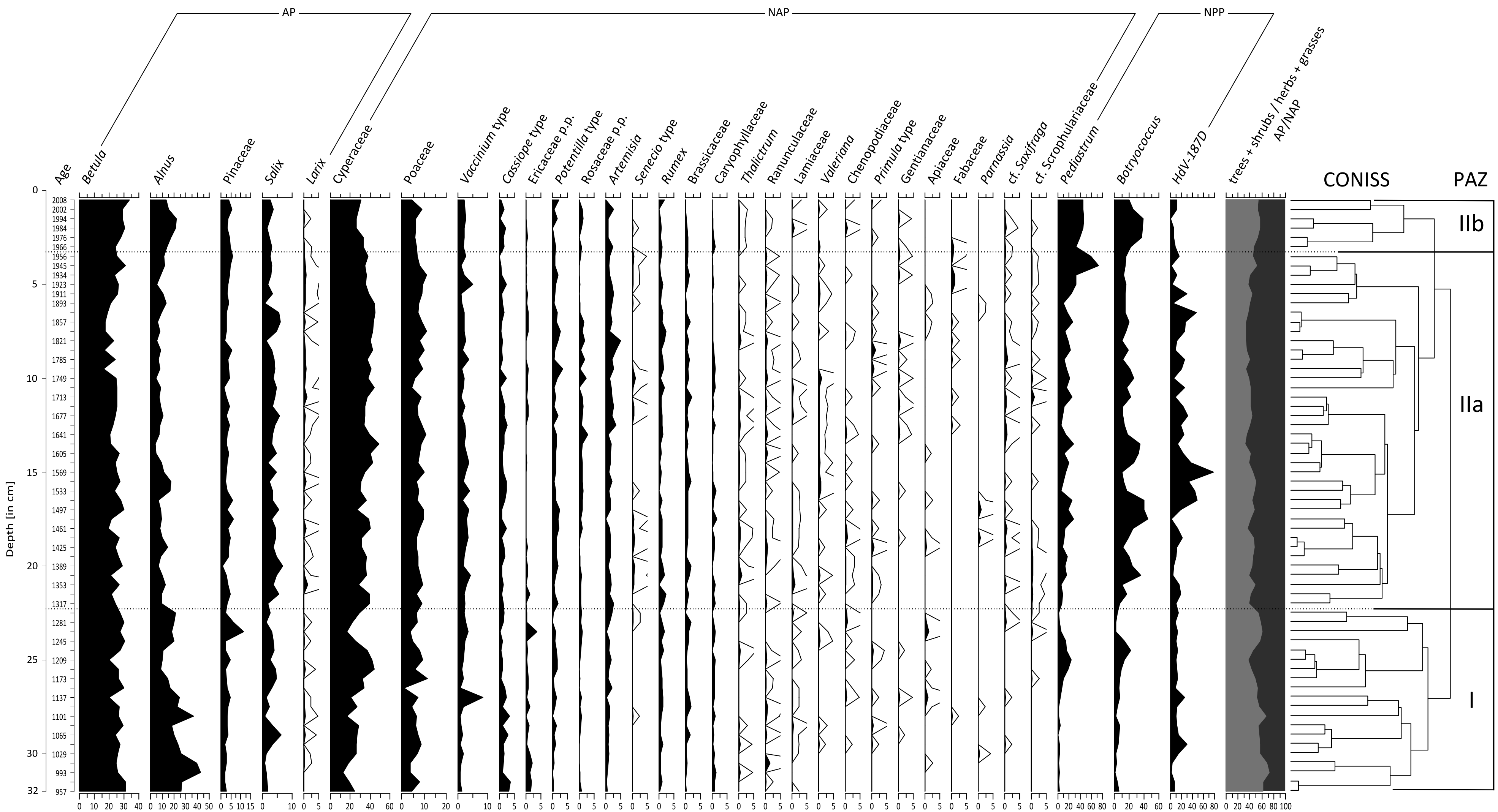

Figure 20: Pollen diagram of the representative 29 pollen taxa within the 64 samples of 11-CH-12D. The Age-depth model is illustrated on the left side of the diagram. The result of the cluster analysis is shown on the right hand side. The ascertained pollen assemblage zones are divided graphically via the dotted lines.

Tree and shrub pollen vary between 31.58% in the middle section and 71.94% in the lowest samples around 31cm depth (46.51% in mean). *Betula* embodies the most common species inside the group of AP with a minimum of 16.31% and a maximum of 33.94%. Consequently, *Betula* shows the second highest mean value (25.23%) of all terrestrial taxa. The highest values of *Alnus* are present in the lower part of the pollen diagram (till 27cm), whereas the percentages reach their maximum of 42.93% in the depth of 31cm. Due to lower values towards younger samples and especially in the middle section, *Alnus* accounts 14.02% for an all sample mean and is reaching a minimum of 4.31%. Most pollen percentages of Pinaceae (including the species of *Picea* and *Pinus*) are fluctuating around the mean of 3.64%, but some samples show a high variability in terms of the minimum value at 0.92% and the maximum at 11.64%. *Salix* presents a similar mean of 3.37% and minimum at 0.71% like Pinaceae. Higher values of *Salix* were found in the middle and upper section (21-6cm) of the core and increases up to 6.73%. *Larix* embodies the lowest common species inside the group of AP (on average 0.25%), which were ascertained in 37 of 64 samples with abundances not higher than 1.31%.

Table 5: Overview of the minimum, maximum and mean for AP, NAP and their corresponding taxa, which occur on average higher than 1% throughout the core 11-CH-12D.

	Taxa	Minimum	Maximum	Mean value		
AP	*Betula*	16.31%	33.94%	25.23%	**Minimum**	31.58%
	Alnus	4.31%	42.93%	14.02%	**Maximum**	71.94%
	Pinaceae	0.92%	11.64%	3.64%	**Mean value**	46.51%
	Salix	0.71%	6.73%	3.37%		
NAP	Cyperaceae	12.71%	49.04%	33.33%	**Minimum**	28.06%
	Poaceae	1.00%	11.64%	7.52%	**Maximum**	68.42%
	Ericaceae	1.73%	10.98%	4.05%	**Mean value**	53.49%
	Rosaceae	0.21%	4.18%	1.73%		
	Asteraceae	0.00%	4.99%	1.67%		

4.3.2 Characteristic of the pollen assemblage zones (PAZ)

The following results refer to the pollen diagram (Figure 20), the Iversendiagram (Figure 21) and the statistical processing of the percentages directed towards their zones (Appendix 8.5).

PAZ I (975-1308 AD) is the oldest zone of the core and includes 20 samples in the depth between 32cm and 22.5cm. This zone is characterized by higher percentages of tree and shrub pollen to those of herbs and grasses. However, the sum of AP is decreasing around 10% (from 60-70% to 50-60%). The variations between the amount of AP and NAP are accompanied by the contrary abundance fluctuations of *Alnus* and Cyperaceae. *Alnus* is decreasing around 5% (from 25% to 20%) on side of AP, while Cyperaceae is increasing around 5% (from 25% to 30%) over the first section. The percentages of Poaceae are a quarter less to Cyperaceae, but present comparable fluctuations. Generally, *Betula* is the most common taxa within PAZ I, fluctuating between 20% and 30% but neither present high fluctuations nor show in- respectively decreasing trends like *Alnus* and Cyperaceae. But a distinct pattern emerges in view of *Vaccinium* type and Pinaceae

(Pinus and Picea) in comparison to *Betula*. While *Vaccinium* type and Pinaceae increase simultaneously (smaller increases at 32cm, 30cm, 29cm and 25cm; greater at 27cm, 23.5cm depth), *Betula* is always decreasing at the mentioned depths. The peaks of *Vaccinium* type (8.35% at 27cm depth) and Pinaceae (11.64% at 23.5cm depth) are also reflected by *Potentilla* type, Rosaceae, *Rumex*, Brassicaceae, Caryophyllaceae and Apiaceae whereas *Betula*, *Alnus*, Cyperaceae, Poaceae and *Artemisia* show counter developments at those points. In general, all other taxa do not present significant pattern. *Cassiope* type belongs to Ericaceae but do not show similar development, while *Vaccinium* type is increasing from 1% to 2%, *Cassiope* type is decreasing by half from 3% to 1.5% over the first section. Although *Larix* belongs to the family of Pinaceae, that species represents a separate group inside this study but do not present significant fluctuations and is less abundant (<0.5%). Notwithstanding the single peak of *Salix* at the depth of 29 cm (6.22%), *Salix* pollen occurs between 1-4% within PAZ I.

The pollen assemblage zones are also characterized by their quantities of non-pollen palynomorphs. They were not involved for calculations of the cluster analysis, but they show abundance fluctuations within the three ascertained zones. *HdV-187D* for example show contrary fluctuations as *Pediastrum* or *Botryococcus* and has higher abundances with two maxima in the depth between 27cm and 30cm (30% and 26%), while the other two of NPP (*Pediastrum* and *Botryococcus*)are less abundant. *Pediastrum* and *Botryococcus* develop similar. Both are relatively less abundant in the lower most samples (1-5%) but increase to values more than 20% around 24-25cm before they decrease to their levels before.

PAZ II includes 44 samples from 22cm onwards to the top of the core, which encompass the years from 1308 to 2011. This zone was statistically clustered into the following two subzones:

PAZ IIa represents more than half of the core. These thirty-eight samples at the depth between 22cm and 3.5cm of 11-CH-12D encompass the years between 1308 and 1961. On average, this zone is characterized by higher percentages of herb and grass pollen (59.36%) compared to those of trees and shrubs (40.64%). The relation of AP to NAP does not show a significant trend over the period of time. However, NAP present higher proportions between 13.5cm and 7cm depth (1623-1857 AD) where they count the maximum reflecting two-third (60-68%) of the sum of terrestrial pollen. The percentages of Cyperaceae vary between 27% and 49% within PAZ IIa. Their fluctuations are mainly determining the variations of NAP and run counter to the fluctuations of *Betula* (16-31%) and *Alnus* (4-17%), which change similar and determine most of the fluctuations of AP. Poaceae show the second highest percentages (4-11%) of NAP in that zone. The fluctuations of Poaceae are comparable to Cyperaceae but delayed. At the depth of 13.5 cm Cyperaceae and Poaceae are representing more than a half (approximately 58%) of the terrestrial pollen. At the same point, *Alnus* is reaching the minimum of 4.31% within the whole core and the percentages of *Betula* and Pinaceae are also decreasing. Pinaceae and *Salix* show counter fluctuations. At the depth of 20cm and also between 6.5 and 7.5cm *Salix* has been found to present the highest percentages of the whole core (6.73%) whereas Pinaceae decreases to its minimum of 0.92% for the whole core. Next to *Salix*, also *Larix* and in general most of the herb taxa, these are *Vaccinium* type, *Artemisia*, *Senecio* type, *Potentilla* type, Rosaceae, *Rumex*, Brassicaceae, Ranunculaceae, *Thalictrum*, *Valeriana*, *Primula* type, Gentianaceae, *Parnassia*, cf *Saxifraga* and cf Scrophulariaceae are more abundant in PAZ IIa as in the section before. It is obviously that Rosaceae show a characteristic establishment within PAZ IIa, at the depth between 17cm and 7cm whereby the higher percentages are concentrated between 13cm and 7cm reaching a maximum of 2.86%. Also Lamiaceae, *Valeriana*, Gentianaceae, cf Scophulariaceae and *Primula* type occur more often within this depth. And as mentioned before, also Cyperaceae and Poaceae present their highest composition of the whole core within this part. The same trend applies for *Artemisia*, *Senecio* type, Brassicaceae, cf *Saxifraga* and *Larix* on the one hand and for *Rumex* and *Potentilla* type on the other hand. Although the latter groups of taxa present higher abundances between 13cm and 7cm, their single fluctuations run counter to one another.

According the NPP, all three of the investigated types have their maximum occurrences within PAZ IIa. *Pediastrum* and *Botryococcus* show similar fluctuations which run counter to those of *HdV-187D*, whereby *Botryococcus* is more abundant in the lower part of PAZ IIa reaching the maximum of 45%, while *Pediastrum* is more abundant in the younger part of PAZ IIa and presents the maximum of approximately 73%. *HdV-187D* has been found to have its maximum of the whole core (approximately 78%) at the depth of 15cm within PAZ IIa, whereas *Pediastrum* and *Botryococcus* decrease to lower values around 13% and 10%.

PAZ IIb includes the six upmost samples of the core from 3.5cm up to the top of the core. These samples are dated to the years between 1961 and 2011. The percentages of tree and shrub pollen are slightly higher (53.25%) in the uppermost zone compared those of herbs and grasses (46.75%). The most common taxa of AP are increasing – *Alnus* is increasing to a high of 22% at the depth of 1.5cm and the percentages of *Betula* are increasing to a maximum around 34% at the top of the whole core (mean of 29%). These increases are accompanied by simultaneously occurrences of Lamiaceae and Chenopodiaceae, each around 0.7%, and decreases of Pinaceae (>1%), *Salix* (>1%), Cyperaceae (>7%) and especially *Artemisia* (around 0.9%).

Pediastrum (42%) and *Botryococcus* (30%) are most abundant within PAZ IIb. Different to their establishments, *HdV-187D* is decreasing to a minimum of 0.45% within the whole core at the depth of 1.5cm (mean at 7%).

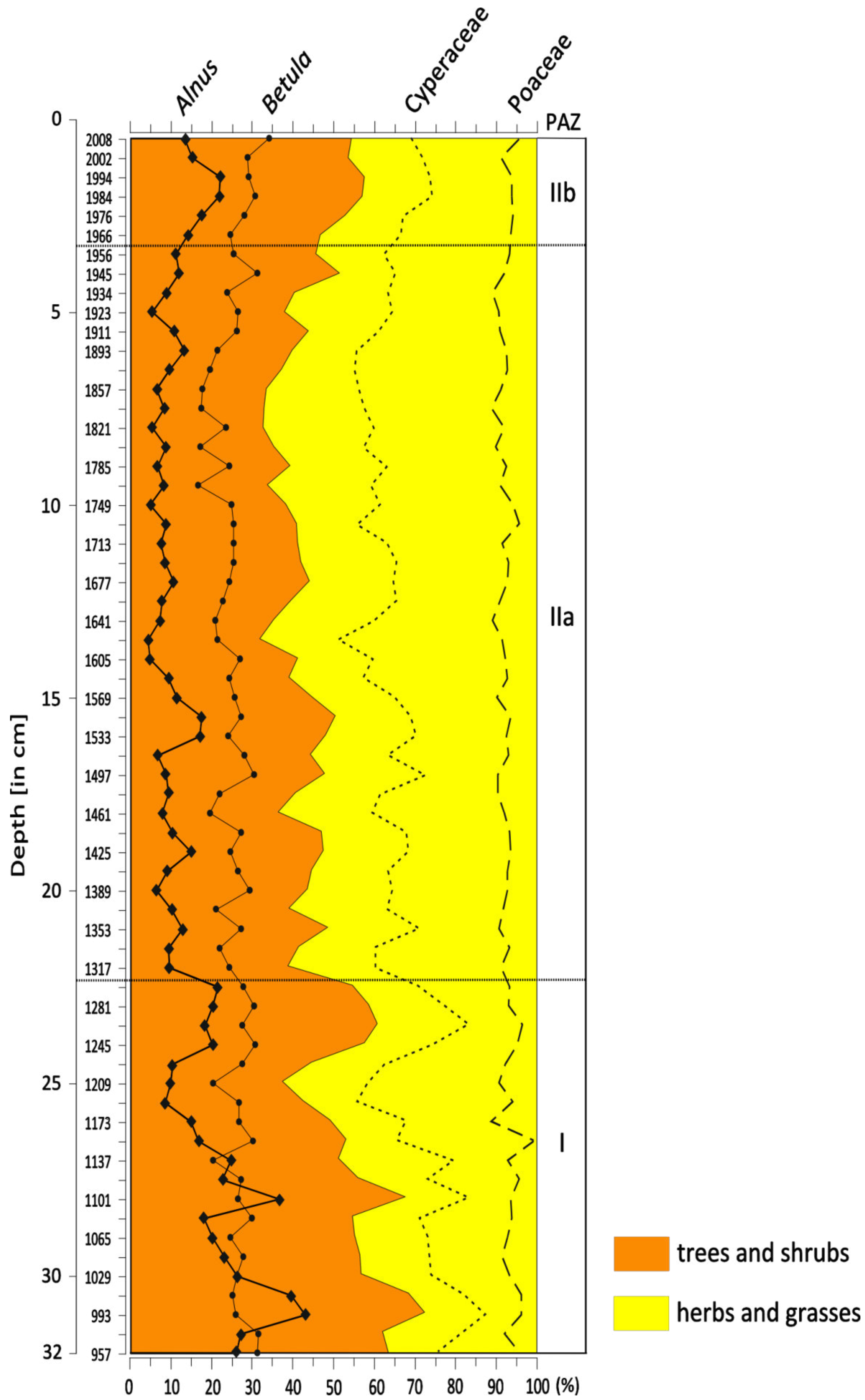

Figure 21: Iversendiagramm. Relation between trees and shrubs (AP) to herbs and grasses (NAP) with their commonest taxa *Alnus* and *Betula* (AP), Cyperaceae and Poaceae (NAP).

4.3.3 Pollen concentration and pollen influx

The following results refer to the pollen concentration and pollen influx diagram in Figure 22. The sample specific pollen concentration of all terrestrial pollen varies around 8,600 to 37,500 grains per cubic centimeter throughout the core. The mean pollen concentration is approximately 22,600 grains/cm^3. However, the total amounts of pollen grains, which were accumulated on one square centimeter per year, depend on the sedimentation rates over time. The so called influx of the entire pollen composition of terrestrial plants varies between around 250 and 2050 grains cm^{-2} y^{-1} (mean around 750 grains cm^{-2} y^{-1}).

The cluster analyses verify three phases of statistic significant pollen accumulation rates. Their subdivisions are similar but not equivalent to those of the pollen assemblage zones. The first phase of the pollen influx encompasses the lower fourth of the core from 32 to 24cm. Within this period *Betula, Alnus,* Ericaceae, and *Cassiope* type show decreasing pollen accumulation rates (PARs) of approximately two-third of their first ascertained values (baseline values of the short core). Whereas the accumulation rates of *Salix,* Cyperaceae, Poaceae, *Potentilla* type and *Artemisia* are increasing about 50 to 300% of their baseline values. A local peak of *Salix* at the depth of 29,5cm can be also found for Cyperaceae, Poaceae, *Cassiope* type and *Potentilla* type. The transition to the second phase at the depth of 24cm is strikingly, because almost all of the regarded taxa (except Pinaceae) are characterized by an abrupt decrease of their pollen accumulation. Also the pollen concentration and the pollen influx of the entire pollen of terrestrial plants are pointing that change. This change is also visible in the Ericaceae, but in 23cm depth. Compared to the first section, the total amounts of pollen per samples are reflecting the lower pollen accumulation rates in the second phase (24-5cm) of the core. Both are increasing after the depression within this phase until the second event, where most of the regarded taxa drop again at 5cm. Several fluctuations with smaller peaks and lows of the single taxa are represented in the development of the entire pollen influx and pollen concentration. However, one peak and one low are characterizing the major range of the PARs in the middle of this section around 14 to 12cm depth. The peak at 14cm is represented in increasing *Betula,* Pinaceae, *Salix,* Cyperaceae, Poaceae, *Vaccinium* type, *Cassiope* type, *Potentilla* type and *Artemisia* accumulation rates at the same time. All of these taxa drop down to a low at 12cm depth, so that the pollen influx and the pollen concentration point the second depression throughout the core, while the first one was more significant. Like the transition from the first to the second phase, that from the second to the third phase is associated with a decrease in the PARs too. This signal at 5cm depth embodies the third depression of lower pollen concentration within the samples.

In contrast to the development after the first depression into the second phase, the upper 5cm are displaying a positive trend of PAR development to higher pollen influx and pollen concentration. This pattern applies for all taxa with a local maximum around 2cm depth. At this point, the investigated taxa reach up to a maximum, on average two times higher than the baseline values in the first phase.

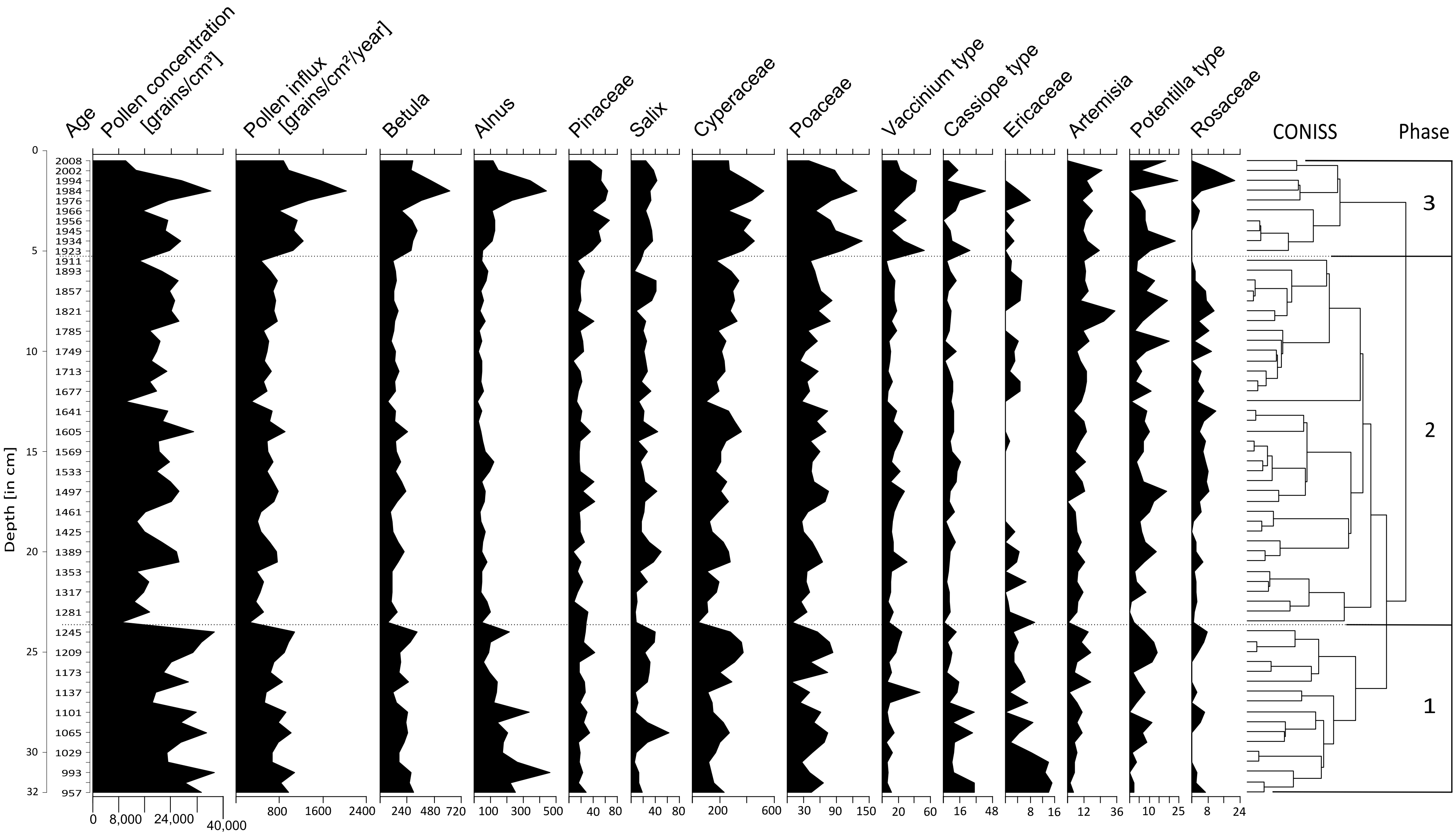

Figure 22: Pollen concentration and pollen influx diagram for the most common taxa: *Betula, Alnus,* Pinaceae, *Salix,* Cyperaceae, Poaceae, Ericaceae, *Vaccinium* type, *Cassiope* type, Rosaceae, *Potentilla* type and *Artemisia*.

5 Discussion

5.1 Pollen source area, pollen productivity and pollen deposition

Pollen is an important item of food for small animals living in and around the water, which will then displace the exines before excreting them again. (Faegri and Iversen 1989) And in case that the pollen swims on the water surface and is not yet accumulated on the ground of the lake, the temporary active overflow of the lake can also bear a special problem for the pollen deposit. Ritchie (1974) investigated pollen deposits from moss polygons and lake surface sediments. He found out that recent samples from lake mud reflect accurately the surrounding vegetation, whereas samples from moss cushions are subject to large fluctuations because the regional pollen rain is variably masked by the local elements of the plant communities. Beside the random effects of the nature, lake sediments are reliable archives for palynological studies.

Pollen analysis is one of the most important tools for reconstructing past vegetation changes over timescales from hundreds to thousands of years but the understanding is not as simple, because plants have different pollen production and dispersal characteristics so that the relationship between the pollen assemblage and the surrounding vegetation is not transferable one to one. (Davis 1963; Davis 2000)

The Pollen source area depends on the lake size. "The larger the basin size, the greater the proportion of pollen loading coming from the regional sources." (Poska et al. 2011) The investigated lake (0.0286 km^2) is much smaller than the neighboring Labaz Lake (470km^2) and therefore expected to reflect mainly the local vegetation. However, a regional influx of pine and spruce pollen has been found in the samples of the core. *Pinus* and *Picea* pollen are prepared to fly over long distances due to their special air sacs (see in Appendix 8.1). Pine pollen is smaller and lighter than spruce pollen and known to traverse greater distances, so that *Pinus* is often found in stratigraphic pollen assemblages far beyond the tree line and *Picea* forms a significant proportion of the tundra pollen assemblage (Campbell et al. 1999). The pollen of *Pinus* and *Picea* are displayed by their family Pinaceae in the pollen diagram (Figure 20) and are likely to represent the long-distance transport of pollen, because the species limit of distribution does not reach into the study area, e.g. *Picea obovata* has its northern limits in the Yenisei and Poppigai estuary and between these northern ranges south of the Putorana Plateau (Roloff et al. 2008). The relatively high influence of long-distance transported pollen has been accepted in lacustrine pollen records from the northern latitudes due to the scant vegetation like the short growing seasons and the harsh growing conditions. The low pollen productivity (mean of 20,000 grains per cm^3) of the vegetation in the study area is reflected in the low pollen concentration of the samples (Figure 22). Another reason for less pollen in lacustrine deposits can be the rapid growth of the deposits, so that the pollen influx is highly distorted by the sedimentation rate (Faegri and Iversen 1989). But the ascertained sedimentation rate of the core (0.029 cm per year) is typically low (Douglas et al. 1994) for the northern latitudes so that the lower bioproductivity suggests the lower pollen concentration (Kraus et al. 2003). Beside the Pinaceae pollen, *Alnus* seems to reflect the local-regional flora, because alder shrubs were not documented in the immediate lake surroundings but in the region and the pollen represent a key species in the pollen diagram. *Alnus* depends, like *Betula*, *Salix*, Cyperaceae and Poaceae to the wind pollinated plants. These taxa produce higher amounts of pollen than insect pollinated species, e.g. *Cassiope*, *Vaccinium*, *Senecio*, *Potentilla*, *Rubus*, *Saxifraga* as well as other herb species, which have been found in the study area and are expected to display the local flora.

Modern studies estimate the relatively pollen productivity as a step further towards the quantitative reconstruction of the vegetation history, e.g. Räsänen et al. (2007) and Poska et al. (2011). They found out, that *Picea* and *Pinus* depend to a group of plants, which produce higher amounts of pollen than Poaceae, Cyperaceae and *Betula* and these in turn more than *Salix*, *Artemisia*, *Vaccinium* and *Empetrum*. So, Pinaceae is overrepresented in the lake deposits due to their high amounts of pollen production and the long-distance transport, while *Salix*, *Artemisia* and Ericaceae might be underrepresented in relation to Poaceae, Cyperaceae and *Betula. Larix* is known to produce large and heavy pollen (Fedotov 2002), which is poorly dispersed (Hahne and Melles 1997). Due to the local habitats of larch around the lake site but the low pollen percentages within the samples, *Larix* is also assumed to be underrepresented in the lake deposits. A reason can be the grain morphology that the pollen is too large and too heavy, without any air sacs, to get representatively accumulated within the lake. Furthermore, *Larix gmelinii* represents the only tree species at the study site and in the lake samples so that their pollen productivity differs from shrubs and herbs. In artificially greened forests, *Larix gmelinii* enters the reproductive stage in the age of 20 years but achieve the highest amounts of fruits only after 35 years (Roloff et al. 2008). The growing conditions are much worse northern the treeline and mostly temperature limited, so that these single individuals or small groups of larch trees are under competition or stress and produce less pollen than further south and in artificially greened forests.

5.2. Stages of the vegetation development inferred from the palynological record and the reference to climate signals

The length of the short core reaches back to the year 957 AD and covers therefore a bit more than the last one thousand years. Previous developments in the study area can be not deduced from the core, but the record from the Lama Lake (Hahne and Melles 1997) reveals the boundary of the first Holocene non-arboreal pollen (NAP) maximum around 40% at 1000 years BP, due to the generally cooling trend, which also resulted in the lowering of precipitation in the Northern Hemisphere and the southward retreat of the treeline since 5300 BP. However the vegetation community around the Lama Lake is different to that of the study site, because of the natural occurrence of spruce and tree birch (*Betula exilis*), the pollen record of this study set in this trend with exactly the same values. The relation of NAP to AP increases from 40% to 50% within PAZ I, especially due to the decrease of the percentages of *Alnus* pollen.

The pollen spectrum was subdivided into three pollen assemblage zones (PAZ I, PAZ IIa and PAZ IIb) by cluster analysis. The principle environmental gradients, which explain most of the variance in the pollen composition, were ascertained via the principle component analysis (see RDA-biplot, Figure 19). In view of the natural indicator values of plants (Ellenberg et al. 1992), it is likely that the first axis is reflecting the temperature gradient from warmer to cooler conditions. The distribution of the taxa ranges from southern tundra vegetation, reflected by *Betula* and *Alnus*, to typical tundra vegetation, which is mostly reflected by the concentration of the herb species as well as Cyperaceae and Poaceae. (Alexandrova 2009) The oldest and the youngest zones, PAZ I and IIb, are likely to reflect the southern tundra vegetation community, while the temperature gradient between these both changed to cooler conditions, so that PAZ II is likely to reflect the typical tundra association. Due to the fact, that all tundra communities are tolerating well-lit till full light places and need the sun irradiation due to the short growing season, it is more likely that the second axis reflects the moisture gradient. Cyperaceae, *Salix* and *Rumex* indicate damp and wet sites, while *Potentilla* was observed during expedition to grow on temporary flooded areas of the lakeshore. On the other hand, Saxifraga, *Cassiope* and *Larix*, were observed to grow on well exposed heights around the lake, which are well drained. The second axis is not reflecting the vegetation development throughout the sequence. PC2 is more likely to indicate the different habitat requirements of the tundra vegetation in view of the availability of water.

The following description of the vegetation change during the last millennium is based on the just discussed temporal placement of the pollen spectrum in the vegetation history of northern Central Siberia, the results of the cluster and ordination analyses as well as the palynological data.

PAZ I (975-1308 AD): southern tundra

The oldest part of the core lasts until the beginning of the 14th century and is characterized by a significant decrease of one of the main taxa, *Alnus*. Despite the grouping of *Alnus* pollen into a single taxonomic unit and the possible loss of palaeoecological information, it is likely that alder played an important role in plant succession and ecosystem dynamics throughout the late Quaternary period and that alder species facilitate the establishment of conifers (May and Lacourse 2012). This would indicate the warmer conditions of the Medieval Warm Period and matches with the temperature gradient (PC1), which associates the vegetation community of the southern tundra. Hahne and Melles (1997) reported that *Larix* grew in form of dwarf shrubs on favourable places in the area of the Labaz Lake, where they produced pollen only in warm summers, which might explain the negligible quantities of *Larix* within 11-CH-12D. The interaction between *Alnus* and *Larix* couldn´t be documented in this pollen record, however the pollen of green alder (*Alnus viridis*) have been found in the samples, which indicates that the shrubby growth form of *Alnus* must have been present during that time too. The percentages of *Betula* are rather homogenous (30% pollen) than those of *Alnus. Betula* shrubs, e.g. *Betula nana*, and variously *Salix* shrubs have been always a major part of the southern tundra and also in the study area. *Betula* is an important species in plant community succession and the most common shrub species throughout the core. The dwarf birch shrubs are known to establish damp and protected sites, but they have been found also on favourable exposed slopes, whereas *Salix* is more typical to grow on fresh and well protected sites of the lakeshore. It is likely that *Salix* formed an admixture to *Betula* so that they formed a *dwarf* birch and willow association in fresh and protected sites around the lake, while single individuals of dwarf birch are likely to grew also on the slopes. On this better drained places, *Betula* formed lighter associations with herbs like *Cassiope* (Ericaceae), *Vaccinium* (Ericaceae), *Saxifraga* (Saxifargaceae), *Pedicularis* (Scrophulariaceae), *Dryas* (Rosaceae), *Parrya* (Brassicaceae) and others.

Salix was found to produce less pollen than *Betula* and can therefore be relatively lower represented than birches (Räsänen et al. 2007; Poska et al. 2011). But in view of the pollen influx diagram (in Figure 22), it is obviously that *Salix* was less abundant than *Betula* in the vegetation community due to around one tenth of the pollen influx of *Betula*. Interestingly, there can be deduced an interaction between *Salix*, Cyperaceae, Poaceae and *Potentilla* type, each in comparison to *Alnus*. While *Alnus* is decreasing drastically, the other mentioned taxa present higher pollen influx rates. The reason for that interaction can be found in the results of the ordination analysis. The RDA-biplot presents *Alnus* well correlated to the temperature gradient and so as one of the major taxa of the southern tundra association. The decrease of *Alnus* in relation to the increase of *Salix*, Cyperaceae, Poaceae and *Potentilla* type visualizes temperature decreases. So that the continuously decrease of *Alnus* within the first pollen assemblages zone reflects the reaction of the cooling climate. Similar developments have been found in Andreev et al. (2002) and are known to represent the transition between the Medieval Warm Period and the Little Ice Age. The mild conditions cooled between 1000 and 1308 AD in the study area and initiate the end of the Medieval Warm Period (Figure 23). Overpeck et al. (1997) found that the Arctic was not anomalously warm during the Medieval Warm Period but that milder conditions prevailed during the 9th and 14th century in the circumpolar Arctic. Andreev and Klimanov (2002) investigated different pollen spectra of the Russian Arctic and indicated the Medieval Warm Period also between the 9th and 14th century. Sidorova et al. (2013) analysed larch tree samples from the permafrost zone in the east of the Taimyr Peninsula and datelined the Medieval Warm Period only between 917-1150 AD, because these were the northern ranges of *Larix* in northern Central Siberia and highly sensitive to climate fluctuations. Hahne and Melles (1997) documented significant decreases of spruce and larch pollen since in the record of the Lama Lake, while pine pollen increased significant due to the opened up spruce-larch forests and the tundra communities, which occupied the former forest areas since 2500 BP so that the long-distance transport of pine pollen could be more effective. MacDonald et al. (2008) revealed from dendroecological studies that the Medieval Warm Period reached from 800-1300 AD within the Russian Arctic, which agrees with the pollen spectrum of this study the best.

PAZ IIa (1308-1961 AD): typical tundra

The middle part of the core reaches from 1308 to 1961 AD. The pollen spectrum of this period is first of all characterized by high amounts of *Betula* and Cyperaceae. *Betula* decreased a bit in comparison to PAZ I, but is further on homogeneous (around 25%), while Cyperaceae increased and fluctuates around 35% within the pollen assemblages of PAZ IIa. *Alnus* finally reached down to a level of around 9% within the pollen assemblages.

Due to the decreasing trend of the major taxa of the Medieval Warm Period, *Betula* and *Alnus*, on the one hand and increasing percentages of Cyperaceae, Poaceae, Salix and most of the herb species, e.g. *Artemisia*, *Potentilla* type, *Senecio* type, *Vaccinium* type, *Valeriana*, cf. *Saxifraga*, cf. Scrophulariaceae as well as others on the other hand, it is very likely that the climatic deterioration in the end of the Medieval Warm Period lead to the beginning of the Little Ice Age. The sum of arboreal pollen reached down to its minimum of the whole core (approximately 30%) in the beginning of the

16th century, whereas the non-arboreal pollen record their maximum of about 70%. The southern tundra vegetation communities changed to typical tundra associations within in the study area.

Cyperaceae, *Salix*, *Potentilla* type and *Rumex* have been found to present their highest percentages (49%, 7%, 3% and 1%) of the whole core. Due to the results of the PCA (Figure 19) it is likely, that these species mostly occurred on the damp and wet sites around the lake. Different kinds of *Eriophorum* (Cyperaceae), like *E. angustifolium* and *E. scheuchzeri*, are known to grow on wet places around the lakeshore. Other kinds, like *Carex* (Cyperaceae), are known to grow on damp sites and temporarily flooded areas, while some smaller individuals have been also found on better drained sites or on the top of the slopes. Even the other herb species, which are mostly insect-pollinated and produce therefore a lower sum of pollen, are displaying their maximum percentages and reflecting their commonest occurrences during that cold period. E.g. *Artemisia* and *Thalictrum* are indicating cold and dry climate (Kraus et al. 2003). *Saxifraga*, Brassicaceae, such as *Parrya* or *Cardamine*, *Parnassia*, *Valeriana*, Rosaceae, like *Rubus*, or Scorphulariaceae, like *Pedicularis*, are likely to have formed lighter communities on sun exposed and well drained areas. The percentages of *Larix* pollen are still very low, but increased remarkably during the Little Ice Age. The reason for that development is not clear, because the northern ranges of *Larix* are temperature limited (Andreev and Klimanov 2000; Frost and Epstein 2014; Hahne and Melles 1997; Laing and Smol 2003; Naidina and Bauch 2001; MacDonald et al. 200 and others). A cooler and drier climate over hundreds of years would infer the lowering of *Larix* pollen through to the retreat of the individuals. A reason for the low increases could be the lower pollen concentration during the Little Ice Age and the generally lower pollen influx of the wind pollinated plants (Figure 22), so that in relation to those, the sum of *Larix* pollen might increase.

Fedotov et al. (2012) reconstructed the thawing of the permafrost during the last 170 years from lake sediment samples and pollen analyses on the Taimyr Peninsula. He found out, that the Little Ice Age most likely ended 1840 on Taimyr. That corresponds exactly to the pollen record of this study, because the sum of AP started to increase at that time (see the development of AP to NAP in Figure 21 around 1840). Also Laing and Smol (2003) inferred from rare diatom assemblages in a lake on the western Taimyr Peninsula a warming for the last 100-150 years. They assumed a stronger summer insolation and the heating of the water surface since the last 120 years. The pollen concentration and pollen influx of the investigated core increased significant (Figure 22) in the beginning of the 20th century as a response to the improvement in growth conditions.

PAZ IIb (1961-2011 AD): southern tundra

The youngest part of the core reaches from the middle of the 20th century to the time, when the core was drilled and presents the last 50 years of the vegetation development. The present vegetation communities of the southern tundra established the study area. The pollen influx diagram records distinctive increases of the pollen concentration and pollen influx rates of the investigated taxa (Figure 22). A distinct increase of the percentages of *Alnus* and *Betula* are characterizing the response to the improvement in growth conditions and form the major taxa of the southern tundra again. The sample composition develops to comparable pollen assemblages like during the Medieval

Warm Period, what can be deduced from the dispersion of the samples in the RDA-biplot (Figure 19). The warming would generally lead to the northward expansion of the treeline, but the thawing of the ice can induce also a decrease of the tree cover (Frost and Epstein 2014). Fedotov et al. (2012) found three phases of increased permafrost melting on the Taimyr Peninsular since the last 170 years and clustered the pollen record into three phases. The youngest pollen assemblage zone of Fedotov et al. (2012) reaches from 1961 to the present and includes the youngest phase of significant permafrost thawing (1960-1965). The temporal placement of the pollen assemblage zone of the recent warming, inferred from the Lake Makarov and the Lake Dalgan (Fedotov et al. 2013), matches exactly with the PAZ IIb of this study. Fedotov et al. (2012) observed increasing active layer depths and surface temperatures since the past 50 years and inferred that the global Arctic Oscillation changed towards a positive phase. Osborn and Briffa (2006) as well as Sidorova et al. (2013) came to the result, that the 20th century warming is the warmest period during the past millennium or longer in the Northern Hemisphere (Osborn and Briffa 2006). However, the warming is not unprecedented in the Siberian north. Frost and Epstein (2014) compared satellite photos from 1965-1969 with modern imagery and quantified changes in tall shrub and tree canopy in widely distributed Siberian ecotonal landscapes. They conclude that the shrub (mostly of *Alnus*) and tree cover (*Larix*) is increasing in most of the tundra ecotones in Northern Siberia, but the rates increase vary regionally and at the landscape scale (Frost and Epstein 2014).

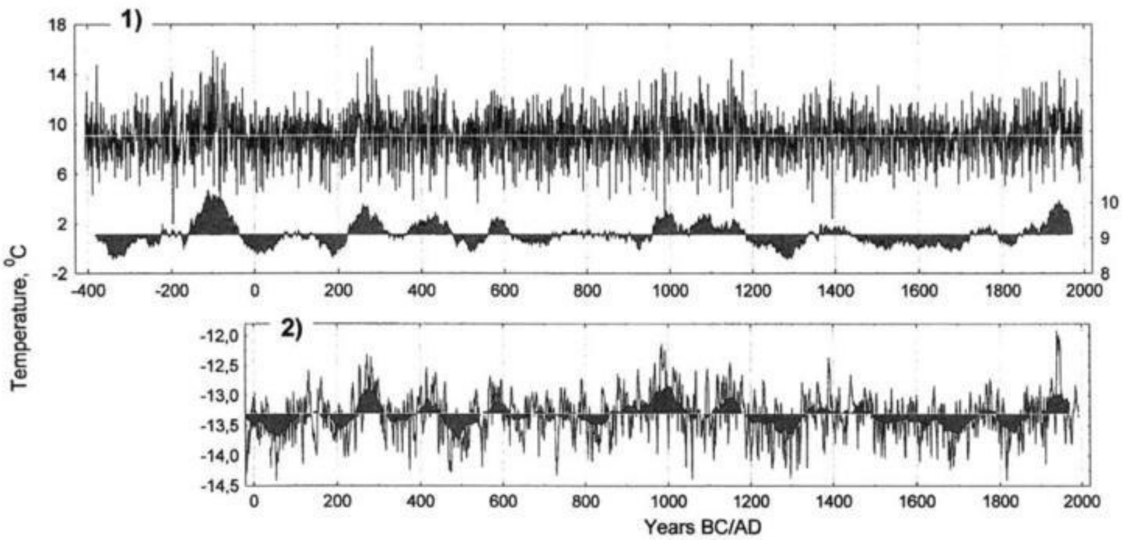

Figure 23: Reconstructions of Taimyr early-summer temperatures. (1) shown as yearly values and roughly 50-year smoothed values and reconstructions of mean annual temperatures (2) shown as five-year and superimposed 50-year smoothed values. [Naurzbaev et al. 2002]

5.3 Limitation of the data set and possible enhancements

The exines of the pollen grains are so inert, that analyses of fossil pollen are generally possible to reconstruct past vegetation and environmental changes. But it is necessary to be aware of the uncertainties, which can limit the interpretation of the pollen assemblages. For example, different plants produce different amounts of pollen and some pollen grains disperse more effectively than others, so that some species are underrepresented and other overrepresented in the samples. Furthermore, wetland plants are more likely to be growing nearby the lake and so will be better represented than distant dry-land plants. And some pollen are more delicate, so that they are damaged or decomposed more easily. Such pollen will produce a lack in the pollen assemblages, which cannot be comprehensible afterwards. The process of pollen analyses follows the principle of random. The lake is one of numerous thermokarst lakes in the vicinity of Chatanga. The core represents a sample of the lake. The slices of the core get sampled for laboratory work and in turn one drop of the extracted pollen-glycerol suspension gets counted for vegetation analyses. It is difficult to distinguish the pollen taxa on the species level, so that the pollen are mainly determined on a family level, which may lead to wrong conclusions due to different habitat requirements of species of a single family. Of course, it is necessary to be aware of the uncertainties of the scientific methodology, but they are natural and need to be accepted.

The focus of this study was to reconstruct the vegetation changes of the last millennium inferred from a pollen record and to examine, whether the ascertained vegetation changes can be related to recorded climatic variations. The more detailed analysis and interpretation of the NPP´s would be desirable to deduce funded information about the local environment and the lake characteristic. Other analyses like grain size analyses, biochemistry analyses (total nitrogen, total carbon and total organic carbon) or stable isotope analyses can be done to apply a multi-proxy approach. Such analyses enable to reconstruct the environmental development and to find signals as possible impacts of these changes. This would support the determination of the parameters, which lead to the changes, and to understand the investigated area, the lake as well as the surroundings, as an entire system.

6 Conclusion

Palynological analyses were conducted to recognize the stages of vegetation development in the vicinity of Chatanga during the last millennium. Records of this period bear critical information about significant climate changes including the transition from the Medieval Warm Period to the Little Ice Age, the Recent Waming and the beginning of anthropogenic global warming. The phases of the vegetation changes were related to recorded climatic variations from other palaeoenvironmental studies in the vicinity of the study area. Three pollen assemblage zones were identified within the short core, which represent the three stages of vegetation development in the study area. The first pollen assemblage zone is the oldest one and reaches from 975 to 1308 AD. The pollen composition is characterized by southern tundra associations at the time of the Medieval Warm Period. The second pollen assemblage zone reaches from 1308 to 1961 AD and illustrates the change of the southern tundra vegetation to typical tundra communities. This period is reflecting the Little Ice Age which is assumed to end around 1840 on the Taimyr Peninsula. The youngest part of the core spans the last 50 years of the vegetation development within the study area. The pollen concentration and pollen influx rate of the investigated taxa increased remarkable since the beginning of the 20th century. The recent warming improves the local growing conditions but can also lead to the thawing of permafrost and limit the distribution of woody plants.

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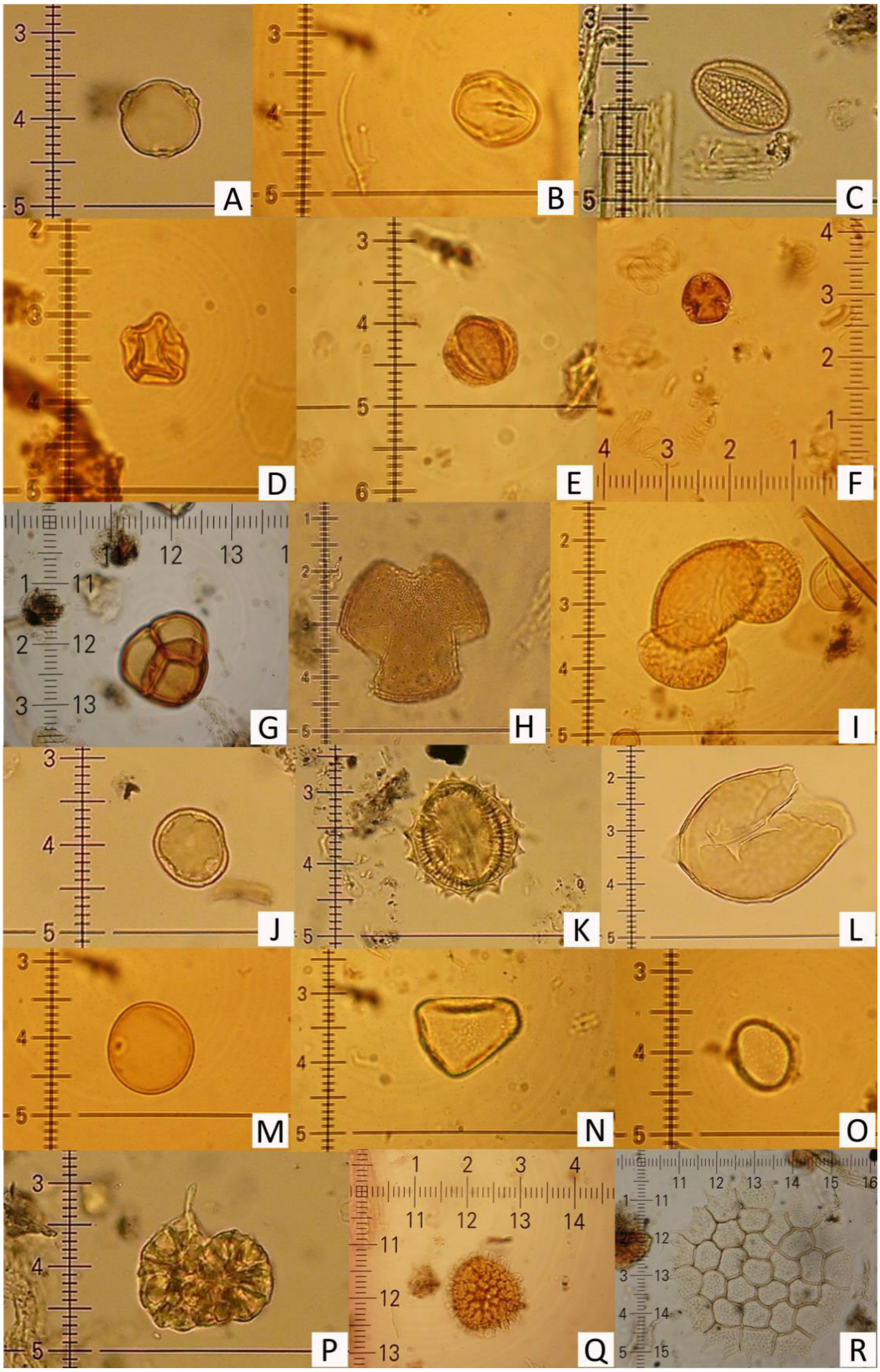
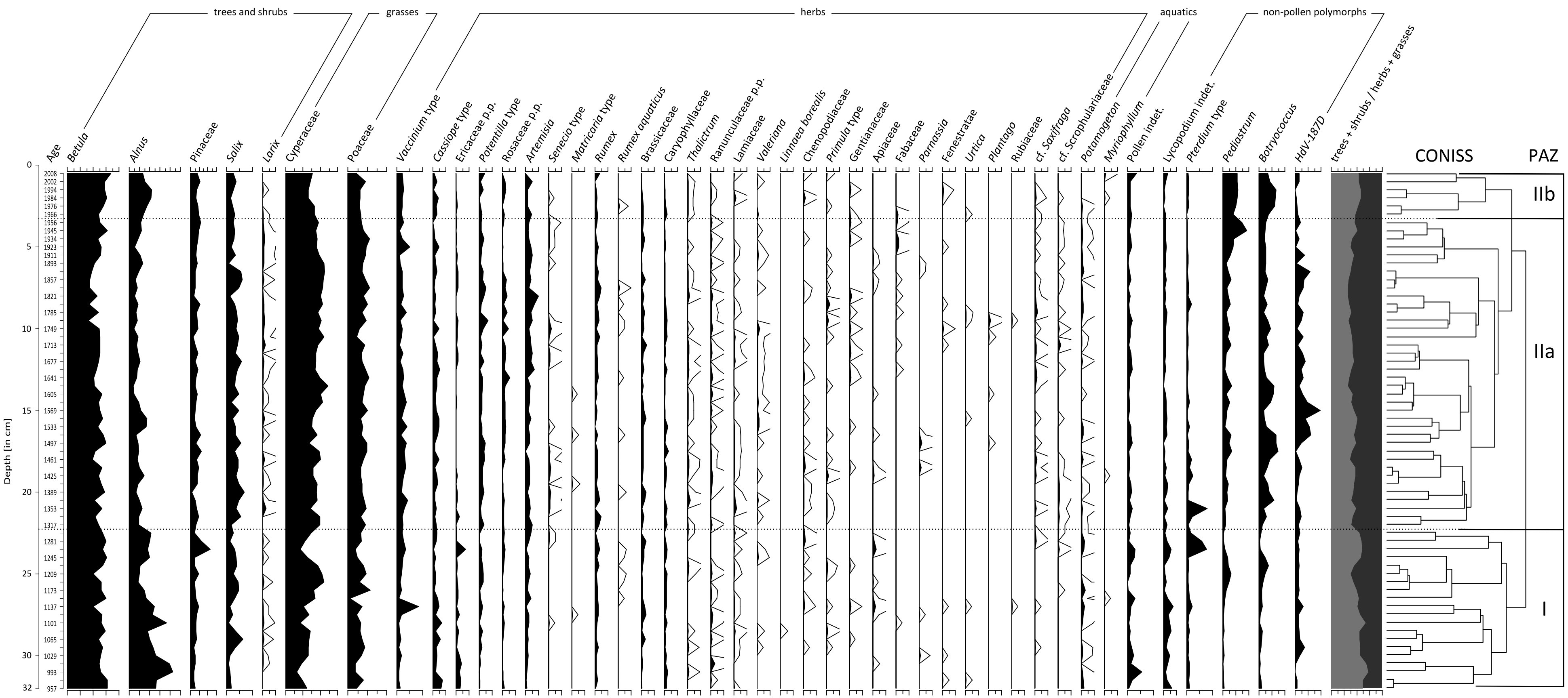
8 Appendix

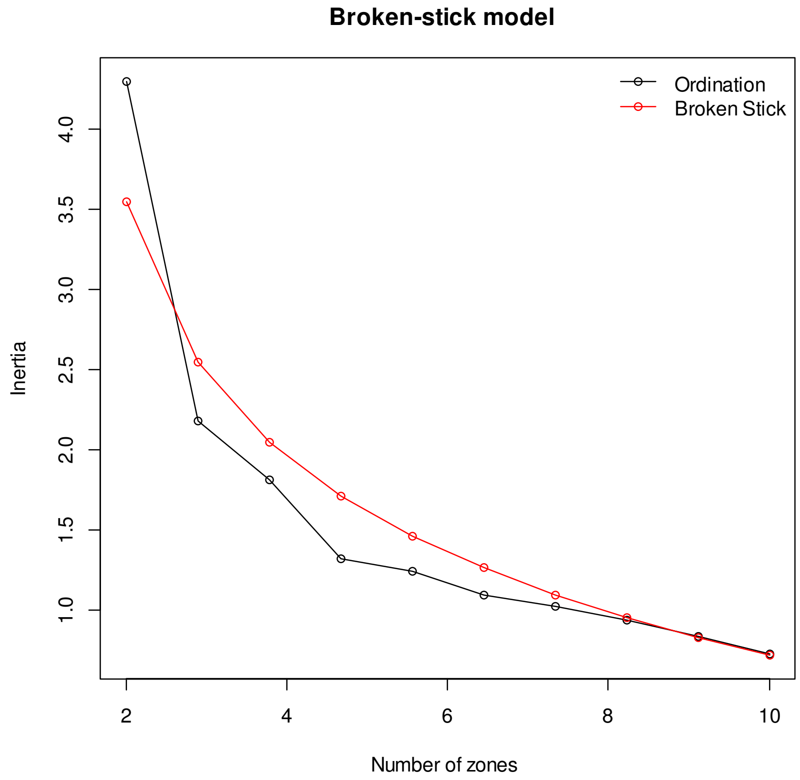
Appendix 8.1**:** Exemplary pictures from microscopy work. A: *Betula*. B: *Rumex*. C: *Salix*. D: *Alnus*. E: *Artemisia*. F: *Potentilla* type. G: *Cassiope* type. H: *Valeriana*. I: *Pinus*. J: *Thalictrum*. K: *Matricaria* type. L: *Larix*. M: Poaceae. N: Cyperaceae. O: *HdV-187D*. P: *Botryococcus*. Q: *Lycopodium*. R: *Pediastrum*. [Photos: Xenia Schreiber]



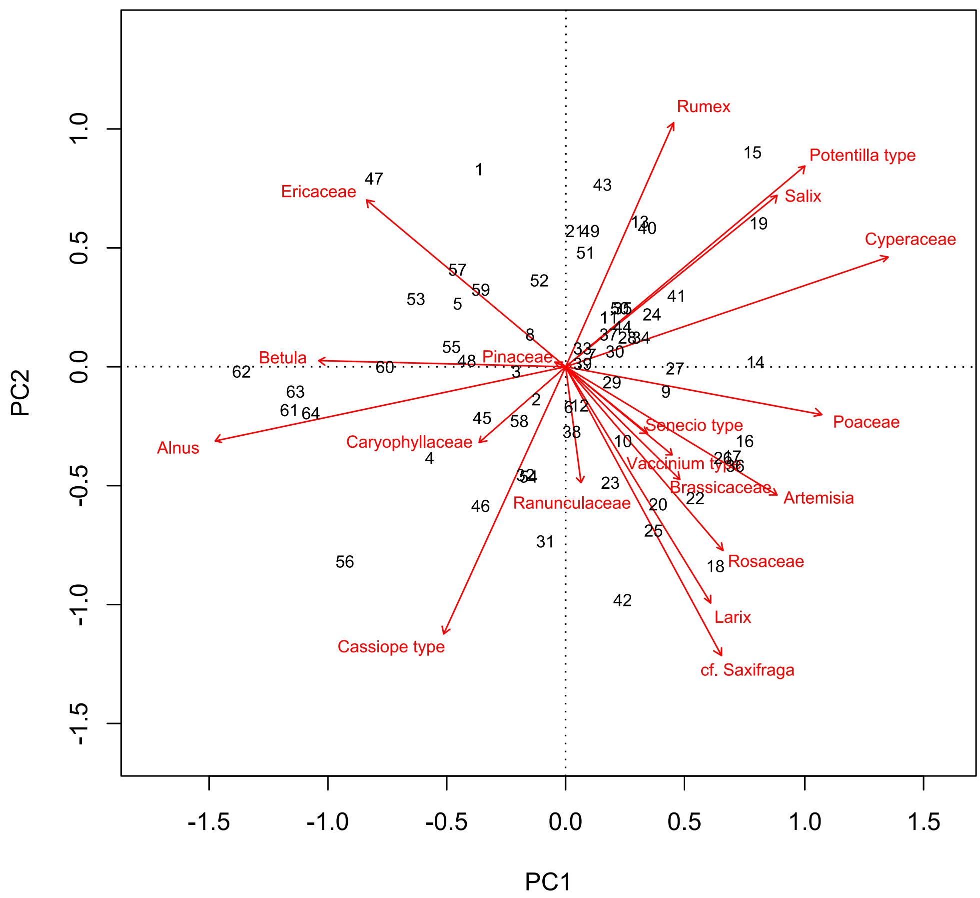
Appendix 8.2: Pollen diagram of all investigated taxa of 11-CH-12D. The Age-depth model is illustrated on the left hand side. The result of the cluater analysis is shown on the right hand side. The division of the sequence into the ascertained three pollen assemblage zones is graphically printed via the dotted lines.



Appendix 8.3: Broken-stick model verifying more than two but less than three numbers of zones, which can be significantly described over the length of the core 11-CH-12.



Appendix 8.4: RDA-biplot.



Appendix 8.5: Statistical processing of the percentages directed towards their zones.

	PAZ / Taxa	IIb			IIa			I		
		Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
AP	*Betula*	24.30	33.94	29.00	30.95	16.31	23.73	31.15	20.05	26.95
	Alnus	13.33	22.00	17.25	17.41	4.31	9.14	42.93	8.45	22.32
	Pinaceae	3.13	5.51	4.21	6.12	0.92	3.60	11.64	1.83	3.54
	Salix	1.56	3.77	2.71	6.73	0.78	3.83	6.22	0.71	2.70
	Larix	0.00	0.25	0.08	1.31	0.00	0.34	0.47	0.00	0.14
NAP	Cyperaceae	25.67	33.16	29.40	49.04	27.12	37.60	44.06	12.71	26.38
	Poaceae	4.55	8.99	6.47	11.31	4.40	8.29	11.64	1.00	6.36
	Vaccinium type	1.77	2.72	2.16	4.93	1.08	2.42	8.35	0.69	1.91
	Cassiope type	0.23	2.01	1.17	2.59	0.00	1.26	3.66	0.31	1.58
	Ericaceae p.p.	0.00	0.61	0.14	1.36	0.00	0.27	3.77	0.00	0.92
	Artemisia	0.00	2.61	1.25	4.99	0.00	1.83	2.00	0.24	1.01
	Senecio type	0.00	0.22	0.04	1.00	0.00	0.23	0.27	0.00	0.04
	Potentilla type	0.00	2.12	0.95	3.36	0.29	1.28	1.61	0.00	0.68
	Rosaceae p.p.	0.00	1.36	0.66	2.86	0.00	0.82	0.94	0.00	0.39
	Rumex	0.00	1.82	0.80	2.33	0.00	0.99	1.89	0.24	0.90
	Brassicaceae	0.00	0.81	0.37	2.11	0.00	0.82	1.90	0.00	0.67
	Caryophyllaceae	0.00	1.01	0.31	1.46	0.00	0.48	1.20	0.00	0.62
	Ranunculaceae p.p.	0.00	0.23	0.07	0.88	0.00	0.28	1.55	0.00	0.25
	Thalictrum	0.00	0.29	0.20	0.96	0.00	0.21	0.64	0.00	0.12
	Lamiaceae	0.00	0.67	0.16	0.98	0.00	0.17	0.57	0.00	0.18
	Valeriana	0.00	0.51	0.13	1.00	0.00	0.21	0.46	0.00	0.06
	Chenopodiaceae	0.00	0.67	0.16	0.68	0.00	0.13	0.82	0.00	0.14
	Primula type	0.00	0.30	0.08	1.29	0.00	0.14	0.57	0.00	0.09
	Gentianaceae	0.00	0.45	0.12	0.79	0.00	0.12	0.48	0.00	0.05
	Apiaceae	0.00	0.00	0.00	0.64	0.00	0.06	1.26	0.00	0.18
	Fabaceae	0.00	0.76	0.13	0.99	0.00	0.10	0.24	0.00	0.01
	Parnassia	0.00	0.00	0.00	1.10	0.00	0.07	0.42	0.00	0.03
	cf. *Saxifraga*	0.00	0.45	0.15	1.12	0.00	0.23	0.54	0.00	0.06
	cf. Scrophulariaceae	0.00	0.22	0.04	1.17	0.00	0.20	0.63	0.00	0.06
NPP	*Pediastrum*	31.90	45.80	42.03	73.16	5.76	18.70	24.21	0.64	6.28
	Botryococcus	20.00	39.46	30.19	44.90	7.47	19.71	21.82	1.44	6.53
	HdV-187D	0.45	11.88	7.11	78.40	1.75	20.43	30.21	0.96	11.87
trees + shrubs/herbs + grasses		46.33	57.14	53.25	51.08	31.58	40.64	71.94	37.11	55.64

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Dresden, am 20.11.2014

Selbständigkeitserklärung

Ich versichere, dass ich die vorliegende Arbeit selbständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe. Ich reiche sie erstmals als Prüfungsleistung ein. Mir ist bekannt, dass ein Betrugsversuch mit der Note "nicht ausreichend" (5,0) geahndet wird und im Wiederholungsfall zum Ausschluss von der Erbringung weiterer Prüfungsleistungen führen kann.

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