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Evidence for birch forests and a highly productive environment near the margin of the Fennoscandian ice sheet in the Värriötunturit area, northeastern Finland

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Preface

This Master's thesis is Fredrik Bogren's degree project in Physical Geography and Quaternary Geology at the Department of Physical Geography, Stockholm University. The Master's thesis comprises 60 credits (two terms of full-time studies).

Cooperation with University of Helsinki.

Supervisor has been Karin Helmens at the Department of Physical Geography, Stockholm University. Co-supervisors have been Minna Väliranta, Department of Environmental Sciences, University of Helsinki and Benedict Reinardy, Department of Physical Geography, Stockholm University. Examiner has been Stefan Wastegård at the Department of Physical Geography, Stockholm University.

The author is responsible for the contents of this thesis.

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Abstract

High-resolution records of early Holocene deposits are rare, and as a consequence reconstruction of terrestrial environments very soon after the deglaciation has often been difficult. In this study the palaeoenvironmental conditions of early Holocene (c. 10600-7500 cal. yr BP) are reconstructed in the Värriötunturit area of northeastern Finland, using evidence from plant macrofossils and pollen preserved in a lake sediment sequence retrieved from the small lake Kuutsjärvi. Special emphasis is put on the environment immediately following the deglaciation as the base of the sediment sequence is rich in minerogenic material interpreted to have been deposited by meltwater pulses from the retreating ice sheet. The abundance and variety of fossil remains in these early meltwater deposits provide evidence for a very productive ice-marginal environment in the area between the lake and the ice sheet, and the presence of tree-type *Betula* macro remains as well as high percentage values of tree-type *Betula* pollen suggests that a subarctic birch forest established just a few years after the deglaciation. In the following centuries the birch forest around the lake became rich in an under growth of ferns, and at c. 9400 cal. yr BP a transition into a mixed pine and birch forest took place. Due to absence of indicator plant taxa in the sediment it was not possible to reconstruct temperature conditions for any parts of the sequence in this study. However, the rapid colonisation of birch forests suggests that the climate was warm already during deglaciation, which is also in accordance with climatic conditions reconstructed for the early Holocene in the nearby Sokli area just 10 km away, as well as in other parts of Fennoscandia and Russia.

Keywords:

Early Holocene, productive ice-marginal environment, subarctic birch forests, plant macrofossils, pollen, palaeoenvironmental reconstructions, palaeoclimate reconstructions, Värriötunturit, Kuutsjärvi, northeastern Finland, northern Fennoscandia.

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1 Introduction

1.1 Background

The global climate is projected to change considerably due to human induced warming in the coming decades and centuries, and particularly in the arctic and subarctic regions temperatures are expected to increase multiple times the global average, which is attributed to the so called polar amplification mechanism (IPCC, 2013). This means the climate and environment in Fennoscandia will be significantly different in the near future, with changes in species richness in the boreal region (Saetersdal et al., 1998) as well as a latitudinal shift in the treeline further to the north (MacDonald, 2010). To understand the complexities of these imminent future shifts, and to be able to refine and evaluate climate models, data on climate and environmental changes of the past are crucial (Shuman, 2014). Furthermore, all anthropogenic influence on the climate will inevitably be interconnected with future natural variations, which is yet another reason why it is important to have knowledge about causes and effects of the past variations (Bradley, 2008).

In contrast to the currently ongoing anthropogenic warming, climate change during the majority of the Holocene was however caused predominantly by external forcing factors such as orbital variations and changes in insolation (Bradley, 2008; Borzenkova et al., 2015). Instrumental climate data tracking these changes does in general only exist for the last 150 years or so (or in some local regions at best for up to 300 years), and thus other sources, i.e. natural archives, are needed to track changes further back in time (Bradley, 2008). One such type of natural archive especially abundant in Fennoscandia are lake sediments, which can contain a number of different biological and chemical proxies that can be used to reconstruct past climate and environments, either through direct qualitative interpretation or through quantitative statistical measures (Shuman, 2014).

In this study palaeoenvironmental reconstructions are made based on macrofossil analysis on a lake sediment sequence. Macrofossils are preserved remains of organic material, such as seeds, leaves and bark, and the method is unique as it can confirm the presence of plant or animal taxa in a direct way. In other words, if a taxon is found in the sediment, it is very strong evidence for a local presence of that specific taxon in or near the natural archive at some point in time (Birks, 2013). By confirming the past distribution of species in this way (and with the assumption that the age of the fossil remain can be determined properly), the environment and climate can then be reconstructed by interpretation of the ecology as well as by using modern analogues in species distribution (Shuman, 2014).

1.2 Climatic variations during the Holocene

After an abrupt warming following the Younger Dryas, oxygen isotope ($\delta^{18}O$) data from the Greenland ice sheet suggests that the global temperatures throughout the Holocene remained relatively stable compared to the fluctuations seen during the last glaciation (Seierstad et al., 2014; Lowe and Walker, 2015). However, palaeoenvironmental reconstructions using a variety of proxies have shown that the climate variability in northern Europe during the Holocene has been rather complex, with proxies pointing in different directions regarding reconstructed temperatures. In sea surface temperature (SST) records based on marine foraminifera from the Barents sea, the summer temperatures were at its highest in the early Holocene after which they decreased and remained stable throughout the rest of the epoch (Hald et al., 2007). Terrestrial pollen records from Fennoscandia (even from the northern parts close to Barents sea) are on the other hand often showing lower than present summer temperatures during the early Holocene, and then a period during mid-Holocene (roughly 8000 to 5000 cal. yr BP) with warmer than present summer temperatures (e.g. Seppä and Birks, 2001; Seppä et al., 2009). This period is commonly called the Holocene Thermal Maximum (HTM) and is also represented in e.g. direct temperature measurements from boreholes in the Greenland ice sheet (Dahl-Jensen, 1998), as well as in a weaker pattern in the global temperature trends from the Greenland oxygen isotope data (Vinther et al., 2006; Seierstad et al., 2014).

However, in the last few decades studies on plant macrofossils and chironomids (*Chironomidae*, lake flies) have, similar to the aforementioned SST records, suggested that the climate in Fennoscandia during early Holocene could have been warmer than previously thought. Macrofossil inferred temperatures from indicator plant taxa in northern Fennoscandia indicate that the very beginning of Holocene (between 11000 and 10000 cal. yr BP) had several degrees warmer summer temperatures than present (e.g. Väliranta et al., 2015; Shala et al., 2017), which is also in agreement with what Luoto et al. (2014) found in chironomid-based records in northern Finland. This corresponds to the peak in summer insolation at northern latitudes, during a time when the winter insolation also was lower than present. The combination indicates that the seasonality was greater, with warmer summers and colder winters, and thus that the climate in Fennoscandia was more continental during the early Holocene (Engels et al., 2014). Furthermore, findings of macro- and megafossils (very large wood pieces) from boreal trees (Kullman, 1999; Paus, 2010; Paus et al., 2011; Paus and Haugland, 2017) as well as broad-leaved deciduous trees (Kullman, 1998a,b) in the southern Scandes and central Norway dated back to at most c. 9700-9500 cal. yr BP suggest these trees were growing in the area shortly following the deglaciation, which could also infer high temperatures during the early Holocene.

Most proxies indicate that a long-term cooling trend started in Fennoscandia during the late Holocene (from c. 5000 cal. yr BP to the present), likely related to the decreased insolation in northern Europe (Borzenkova et al., 2015). This triggered readvance and reformation of old glaciers in the Scandes (Karlén, 1988; Nesje and Kvamme, 1991), as well as an altitudinal shift in the tree line (Kullman, 1995). Looking at higher resolution climatic shifts during the entire epoch, some irregularities in the general long-term trends appear. One of the most severe cold period in Fennoscandia during the entire Holocene was probably the Little Ice Age (LIA) between c. 500 and 100 cal. yr BP (Lowe and Walker, 2015), and in the early Holocene, three distinct shorter cold events are recorded around 8200, 9300 and 11400 cal. yr BP in oxygen isotopes from the Greenland ice cores (Rasmussen et al., 2007; Thomas et al., 2007). The cold event at 8200 cal. yr BP is commonly referred to as the *8.2k event* and is also detected in some studies using pollen and geochemical data in northern Fennoscandia (e.g. Allen et al., 2007; Seppä et al., 2007). The event is widely believed to have been caused by huge fresh water input into the Atlantic from the collapsing glacial lake Agassiz in North America (Barber et al., 1999; Clarke et al., 2004), and the duration of the event is suggested to have been a mere 160 years (Thomas et al., 2007).

1.3 The method of macrofossil analysis

Macrofossils are, as already briefly mentioned above, remains of organic material found in anoxic environments favouring preservation, e.g. in peat or lake sediment. For remains to be considered macrofossils as opposed to a microfossils (e.g. pollen), they should typically be of at least 0.5 mm in size and should be studiable using a stereo microscope of fairly low magnification, often 10x-40x. Most remains are usually of plant origin in the form of seeds, leaves, roots, bark, etc, but animal macrofossils such as ephippium (resting stage) of water fleas (*Cladocera*) or statoblasts (resting spores) of moss animals (*Bryozoa*) are often found in lake sediment and can also be identified and utilised in palaeoenvironmental reconstructions to a certain extent. In lake sediment the remains can be deposited by wind, water streams, slope wash, animals or by falling from plants near the littoral zone, in combination reflecting the local environment inside and in close proximity to the lake. This is in contrast to mires, where the plants are deposited in situ, and thus in mire environments it is much more rare to find macro remains from the surrounding local area (Birks, 2013).

The biggest advantage of macrofossil analysis is that it can confirm that a taxon was locally present in the area. Pollen, on the other hand, generally gives a more regional picture of the vegetation due to longer dispersal distances of the pollen grains, and therefore cannot be used to definitely confirm occurrence of taxa locally (Birks, 2001, 2013). Especially certain conifer pollen can be dispersed over very long distances (e.g. *Picea* and *Pinus*) due to their air sacks attached to the pollen (Szczepanek et al., 2017), and in arctic or tundra environments this can skew the result (Birks, 2013). Moreover, with macrofossil analysis it is also often easier to identify a taxon into species level, whereas with pollen this is sometimes much harder (Bennett and Willis, 2001; Birks, 2001). Apart from giving an indication of the local vegetation and environment, macrofossils can also provide information on climate by the use of indicator species of certain taxa (often aquatic or wetland species) that is known to be controlled primarily by temperature. The contemporary distribution of these species combined with modern-day mean July temperature measurements is used to infer a minimum required July temperature for the taxa found in the macrofossil assemblage, and as a result the palaeoclimatic conditions of the studied area (Iversen, 1954; Isarin and Bohncke, 1999; Väliranta et al., 2015).

Despite these clear advantages of macrofossil analysis, it is however important to consider that even if a taxon is not found in the macrofossil assemblage, it does not automatically mean that the taxon was absent in the local vegetation. This is because macrofossils are inherently rare in comparison with e.g. pollen, and different rates in decomposition (Mauquoy and van Geel, 2007) as well as other taphonomic factors such as distance to shore (Shala et al., 2014b) can mask the true abundance of certain taxa. As such, different methods can provide different information of the palaeoenvironment and therefore many proxies are increasingly used in combination in so called multiproxy studies to get a more complete picture and to enhance the interpretation of the environment (Birks, 2013).

1.4 Aim of the study

Presented herein is a high-resolution macrofossil analysis of a sediment sequence from the small lake Kuutsjärvi in northeastern Finland. The sequence is covering the early Holocene, and initial investigations have provided evidence for well-preserved macrofossils in a bottom minerogenic rich section overlain by gyttja. This section is thought to have been deposited by glacial meltwater very soon after the deglaciation, thus providing an excellent glance on the vegetation and climate in the area just at the transition between the last glaciation and the current interglacial period. Furthermore, radiocarbon dating indicates that the time-resolution of the sediment sequence is on the decadal scale, with a resolution of 1 cm sediment equalling c. 15 years. Studies on records covering the early years after deglaciation are still rare in Fennoscandia, and especially studies on sediment sequences of this resolution. This study constitute one part of a larger multiproxy collaboration on the sediment sequence, with the aim to reconstruct the environment and climate in the area throughout the Holocene. The specific aim of this part is to contribute to the knowledge of early Holocene environments and climate in northern Fennoscandia, based on the macrofossil analysis method. The following four main objectives were specified:

a) To reconstruct the deglaciation phase of the study area, and establish the process that deposited the minerogenic rich sediment in the bottom of the sequence.

b) To reconstruct the ice-marginal environment during early Holocene, and the subsequent vegetation development in the area during the first few thousand years of the Holocene.

c) To evaluate on the climate in the area during the early Holocene, and determine the minimum July temperature based on presence of indicator plant taxa identified during the macrofossil analysis.

d) To evaluate on the migration pattern of tree species into the area following the deglaciation, as well as the possibility of plant refugia nearby.

2 Site description

2.1 Regional setting and study area

This study was conducted using sediment from the small lake Kuutsjärvi, located above the arctic circle within the Värriö Strict Nature reserve in northeastern Finland (67°44’50” N 29°36’37” E, approximately 341 m a.s.l.), just next to Värriö Subarctic Research Station (operated by the Institute for Atmospheric Research at University of Helsinki). Due to the very small size of the lake (6715 m^2), as well as the apparent influence the surrounding area have had on its formation (which is described in more detail in section 2.3 and 4.2), a study area incorporating the entire northern part of the Värriötunturit fell chain is outlined in Fig. 1. The regional setting and local characteristics of the area will first be be described below, while the immediate area surrounding Kuutsjärvi is described in detail in section 2.3.

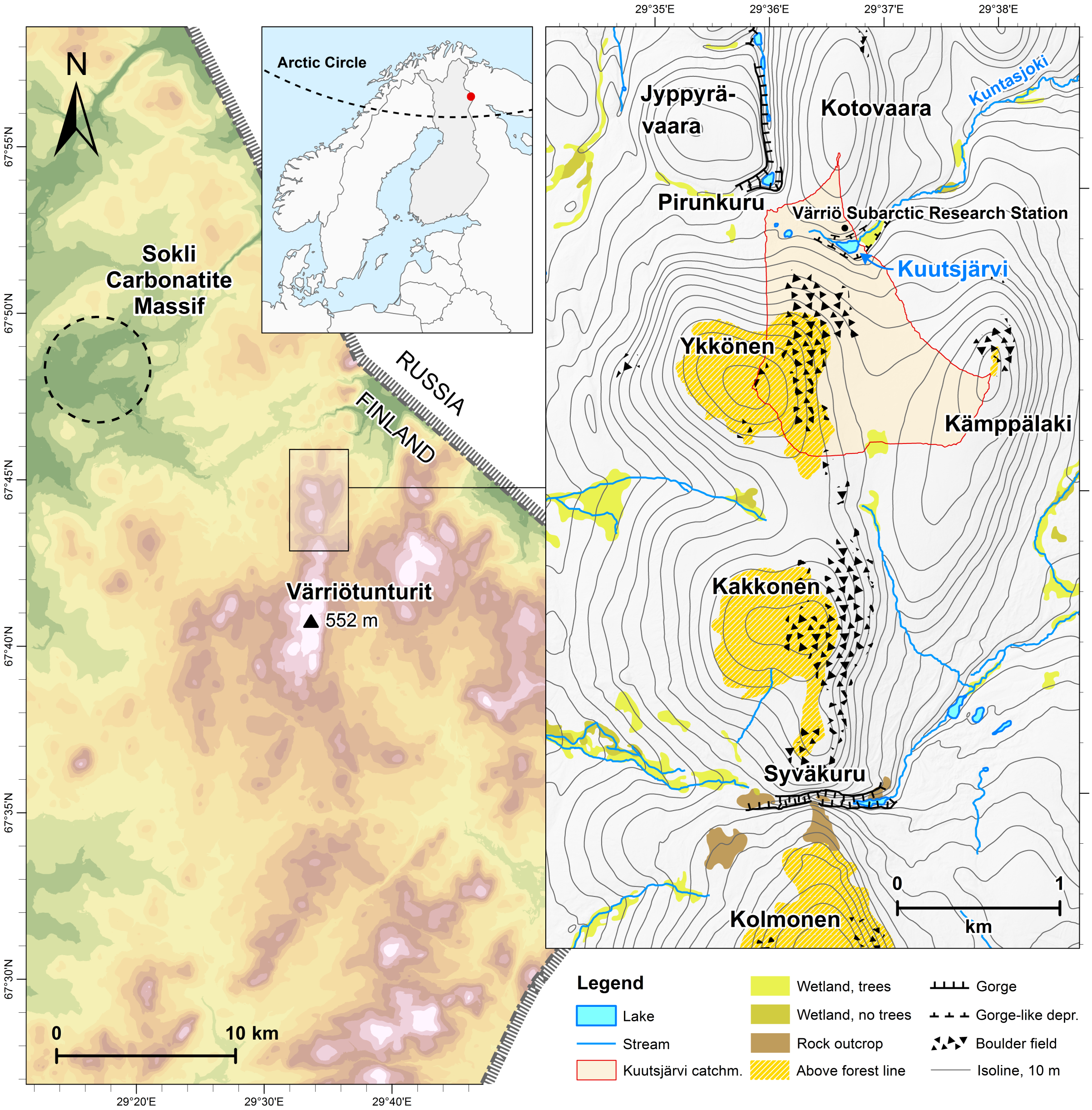

Figure 1. Detailed zoom-in map of the study area in the northern part of the Värriötunturit fell chain. The small orientation map at the top shows the location of the study area in a Fennoscandian setting, and the underlying topographical map shows the study area in a regional setting in northeastern Finland. As Kuutsjärvi is a very small lake situated just south of Kotovaara it is not depicted in much detail on this map, instead a selection of photos of the lake can be seen in Fig. 2 and a close up map view of the lake can be seen in Fig. 3. Note that the catchment of Kuutsjärvi was calculated in Esri ArcGIS using elevation data of 2 meter resolution, and may therefore not be a perfect reflection of the true catchment area. The black dot north of Kuutsjärvi marks the position of Värriö Subarctic Research Station. This map contains data from the *Elevation Model 2 m*, *Elevation Model 10 m* and *Topographic 1:100 000* database provided by the National Land Survey of Finland under CC BY 4.0 license (downloaded 2019/03).

With its highest summit at 552 m a.s.l., the Värriötunturit fell chain is a sequence of rounded peaks stretching approximately 10 km in a N-S direction in the northeastern parts of Finland, close to the Russian border. To its east and south the topography is substantially mountainous in the form of similar rounded peaks, while to the north and west the topography is much gentler. Geologically the whole region is quite homogeneous with a bedrock consisting mainly of granitoids and paragneiss, alongside scattered smaller patches of ultramafic and volcanic rock, all of which are of Precambrian age and belonging to the Fennoscandian shield (Geological Survey of Finland, 2019a). However, just some 10 km northwest of the study area there is an anomaly in the bedrock; the so called Sokli Carbonatite Massif consisting of an igneous intrusion of carbonatite dating back to the Devonian, around 365 Ma (O'Brien and Hyvönen, 2015). The Sokli area has been subject to several palaeoenviromental studies due to its unique conditions for sediment preservation in the deeply weathered bedrock (Shala, 2014), harbouring records for the entire Weichselian (MIS 2-5d) and stretching as far back as to the Eemian interglacial (MIS 5e) and into the Saalian glaciation (MIS 6; see e.g. Helmens et al., 2012; Helmens, 2014; Plikk et al., 2016; Helmens et al., 2018).

Superficial deposits in the region are dominated by till and peat, but block fields and exposed bedrock outcrops cover extensive areas on and near the mountain peaks (Geological Survey of Finland, 2019b). Additionally, systems of glaciofluvial deposits are stretching in the form of esker chains in a NW-SE direction throughout the region, reflecting the general retreat pattern of the ice sheet. One such esker chain is outlined in the southern parts of the study area, crossing the Värriötunturit fell chain. Vegetation-wise the region is within the mixed conifer forest zone (Väliranta et al., 2009) with tree vegetation mainly consisting of spruce (*Picea abies*), pine (*Pinus sylvestris*) as well as birch (*Betula pubescens* and *Betula pendula*). The overall majority of the region are also well below the altitudinal tree line, except for the highest elevated mountain peaks, e.g. the peaks of the Värriötunturit fell chain. The latitudinal limit of spruce is situated c. 100 km to the north, whereas the latitudinal limit of pine is situated an additional c. 50 km further north from the spruce limit. Beyond the pine limit there are pure birch forest almost all the way to the Barents sea coast, before the landscape is turning into a dwarf-shrub tundra (Helmens et al., 2012). Present-day climate conditions in the region are subarctic and classified as Dfc according to the Köppen system (Beck et al., 2018). Closest meteorological station to the study area is conveniently located at the Värriö Subarctic Research Station (station name: Salla Värriötunturit, 67°44'55" N 29°36'41" E), and climate data measured between 1975-2018 reveal a mean annual temperature at -0.4 °C, mean January temperature at -11.7 °C, mean July temperature at 13.3 °C and mean annual precipitation at 589 mm (Finnish Meteorological Institute, 2019).

The study area (Fig. 1) comprises of the three peaks Ykkönen, Kakkonen and parts of Kolmonen of the Värriötunturit fell chain, as well as the slightly smaller peak Kämppälaki east of Ykkönen, and the two smaller peaks north of Kuutsjärvi, Jyppyrävaara and Kotovaara. In between Kakkonen and Kolmonen the deep gorge Syväkuru is located, with a depth of as much as 60 m measuring in relation to the surrounding peaks (Johansson, 1995). Another similar deep gorge, Pirunkuru, is found northwest of Kuutsjärvi in between the peaks Jyppyrävaara and Kotovaara. These two gorges are very straight and are likely formed in weakness zones in the bedrock. The depression in which Kuutsjärvi is situated (Kuutsjärvenkuru) does also share similarities with these gorges, but is not as deep and steep. Overall the area is extensively forested, but Ykkönen, Kakkonen and Kolmonen reach above the forest line into tundra environment, only sustaining open fell heaths with lone scattered trees in the form of krummholz on top of their peaks. Patches of wetlands are spread out across the area, mainly within valleys and along streams. The dominating wetland type is with forest growth, but smaller treeless mires are also found, especially west of the Värriötunturit fell chain.

2.2 Glacial history of the region and study area

The region of northern Finland where the study area is situated has probably been regularly glaciated throughout the Quaternary, including during some of the smaller mountain type ice sheets associated with the 40 ka cyclicity in the beginning of the period (see Kleman et al., 2008). However, direct evidence for earlier glaciations than the Saalian (MIS 6) are uncommon and only one occurrence of till attributed to pre-Holstein cold stages (prior to MIS 9 or MIS 11) has been found in Finland (Johansson et al., 2011). From the Weichselian glaciation (MIS 5d - MIS 2) there is more evidence and unlike the southern parts of Fennoscandia that was not fully glaciated until MIS 4 c. 70 ka and the last glacial maximum (LGM, MIS 2) c. 20 ka, the northern parts underwent at least three phases of stadials and interstadials throughout the Weichselian glaciation (Johansson et al., 2011, and references therein). The ice sheet history in northern Finland has, however, proven to be quite dynamic as recent data from Sokli suggests that the area was unglaciated until MIS 5b (Alexanderson et al., 2008; Helmens et al., 2012) and that it even was ice free during parts of MIS 3 (Helmens, 2014).

In the subsequent extensive cold stage, the LGM (MIS 2), the ice stretched far beyond the Fennoscandian peninsula connecting with the ice over Barents sea (The Barents-Kara ice sheet) to the north and the study area was at this period underneath the interior parts of the Fennoscandian ice sheet (Hughes et al., 2016). During the Younger Dryas the ice front remained outside of the study area, in the Kola peninsula to the east of the study area, meaning that the study site was not deglaciated until relatively late, during early Holocene. Data from models made by Hughes et al. (2016), Stroeven et al. (2016) and Patton et al. (2017) are providing evidence for a very rapid deglaciation of the remaining ice sheet after the end of Younger Dryas. Radiocarbon datings from lake Loitsana in the nearby afformentioned Sokli Carbonatite Massif time the deglaciation to around 10700 cal. yr BP (Shala et al., 2014a). At this phase of the deglaciation the ice divide was cutting through just north of the study area, stretching in a W-E direction, and the ice sheet retreated in a northwestern direction as evident by the esker systems in the region (Johansson, 1995).

In the Värriötunturit area glaciofluvially eroded gorges are prevalent (Johansson, 1995), with the most prominent ones being Syväkuru and Pirunkuru. These gorges were most likely carved out over multiple deglaciations, which is evident by terraces of deposited boulders at the mouth of Syväkuru and Pirunkuru where cosmogenic nuclide dating has yielded ages older than the last deglaciation (Karin Helmens, personal communication). The gorges were probably partly eroded by subglacial meltwater prior to the ice retreat, as the hydrostatic pressure enables water flowing independently of topography (Johansson, 1995). However, an esker chain is stretching on top of Kolmonen instead of following the valley through Syväkuru, showing that at least during parts of deglaciation the subglacial channels diverted into other routes. Erosion also took place after the deglaciation by proglacial meltwater, which is noticeable by the lack of material left inside the gorges, as well as the very clear channels cut into the sediment in a fan shape east of Syväkuru.

2.3 Kuutsjärvi and its immediate surroundings

As mentioned in section 2.1, Kuutsjärvi itself is situated in a gorge-like valley between Ykkönen and Kotovaara (Fig. 1), with steep sides both to the north and south of the lake (see right-hand photo in Fig. 2). Although the depression is not as deep and distinct as the other gorges described above, it is clear that the lake must have been carved out by glacial meltwater in a similar fashion as Syväkuru and Pirunkuru. This is also strengthened by the bathymetry of Kuutsjärvi, presenting a very deep profile with a sediment depth of more than 6 meter and an overlying water depth reaching up to 8 meters in the majority of the lake, with only a thin strip on the eastern part, near the outlet, with shallow water. On the basis of these characteristics, the lake can be described as a *plunge lake* (see e.g. Meinsen et al., 2011) which must have been created by especially heavy flows of meltwater during the last deglaciation, or more likely, last several deglaciations. Today the lake has an inlet situated at the western side and an outlet (Kuntasjoki) at its eastern side (Fig. 3). The inlet and outlet are very small streams in comparison to the wide channel they are flowing through, thus making it unlikely these streams have been responsible for any significant preglacial or postglacial erosion of the valley.

The lake is oligotrophic (Tallberg et al., 2015) and is (except for the research station) surrounded by forests (Fig. 2). At its southern side, i.e. on the northexposed steep slope, the adjacent vegetation is lush and primarily covered in spruce (*Picea abies*), birch (*Betula pubescens/Betula pendula*) and aspen (*Populus tremula*) with undergrowth of blueberry (*Vaccinium myrtillus*), lingonberry (*Vaccinium vitis-idaea*) and ferns. At the northern side however, the soil is dryer and the vegetation is primarily composed of pine (*Pinus sylvestris*) with little undervegetation present. Both the inlet and outlet are densely vegetated with tall herbs and willow (*Salix spp.*), and the beginning of the outlet also forms a small wetland. Furthermore, the lake is fringed by a narrow strip of aquatic, shore and wetland vegetation consisting of shrubs (e.g. *Betula nana*, *Salix spp.*), dwarf shrubs (e.g. *Calluna vulgaris*, *Empetrum nigrum*, *Ledum palustre*, *Vaccinium spp.*), herbs (e.g. *Carex spp.*, *Menyanthes trifolata*, *Cornus suecica*, *Chamerion angustifolium*), ferns (e.g. *Equisetum spp.*) and mosses (e.g. *Sphagnum spp.*). The catchment area of the lake (drawn in Fig. 1 based on digital elevation model data) is relatively small and mainly comprises of areas south of the lake, up on the hills of Ykkönen and Kämppälaki.

Figure 2. Photos of Kuutsjärvi photographed during the summer of 2018 (left-hand side of figure, looking towards the southeastern part of the lake) and spring of 2019 (right-hand side of figure, looking towards the southwestern part of the lake; photographer: Karin Helmens). In both photos it can be seen that the forest reach near the shoreline of the lake, and that the shore vegetation zone is very narrow. In the winter environment of the right-hand photo the steep rising slope on the southern side of the lake is especially visible.

3 Material and methods

3.1 Field work and subsampling

The coring of Kuutsjärvi was conducted prior to this study during the winter in the beginning of 2016. Two sediment cores of approximately 5.6 m each (subsequently named *KJ1* and *KJ2*, and hereafter referred to as such) were retrieved in 2 m-sections from the middle part of the lake using a heavy PP-piston corer (Putkinen and Saarelainen, 1998) with a diameter of 6 cm. The approximate distance between the boreholes were circa 1 m (Karin Helmens, personal communication) and while GPS coordinates were never documented, the approximate position of the coring was noted on a map. This approximate position is marked out in Fig. 3.

Immediately after the coring of these two main cores, one of them, KJ1, was subsampled at the Värriö Subarctic Research Station next to the lake (see proximity of the station in Fig. 3). Two distinct sediment sections were noted in the core; organic bearing sediment (predominantly gyttja or diatom rich gyttja) and minerogenic rich sediment interlayered with gyttja. Subsampling of the gyttja (1-541 cm) was done in 1 cm samples without considering different lithological units, while the bottom more minerogenic part of the core (541-562,5 cm) was subsampled after lithology (see further detailed description of the lithostratigraphy in section 4.1). The other core, KJ2, was kept intact for ITRAX-scanning (to obtain geochemical data) and ancient DNA analysis (neither included in this study). Both the sample bags from KJ1 and the intact KJ2 core were after fieldwork brought to the University of Helsinki where they were stored in a cold room at the Department of Environmental Sciences. All of the above was done before this study started. However, due to the lack of available sediment left for macrofossil analysis in some of the KJ1 sample bags from the bottom minerogenic section of the core, the same bottom section of KJ2 also had to be subsampled. To make it easier to match the two cores with each other, this subsampling was done in exactly the same lithological units as for KJ1, and during this subsampling a more detailed sediment log was also drawn (see section 4.1 and Fig. 4).

In addition to the field work in 2016 prior to this study, another field work was conducted in the study area in June 2018, as a part of this study. During this fieldwork the present environmental setting and geomorphology of the area was investigated, which included aerial photography using a drone. To get a picture of the present-day macrofossils preserved in the sediment, surface sediment samples were also retrieved from Kuutsjärvi. These samples were collected from a small boat using a Limnos sediment corer (a description of it is available in Kansanen et al., 1991) and only the top few cm of the sediment was transferred into a small plastic bag on site. Several samples were taken, but only three of them were

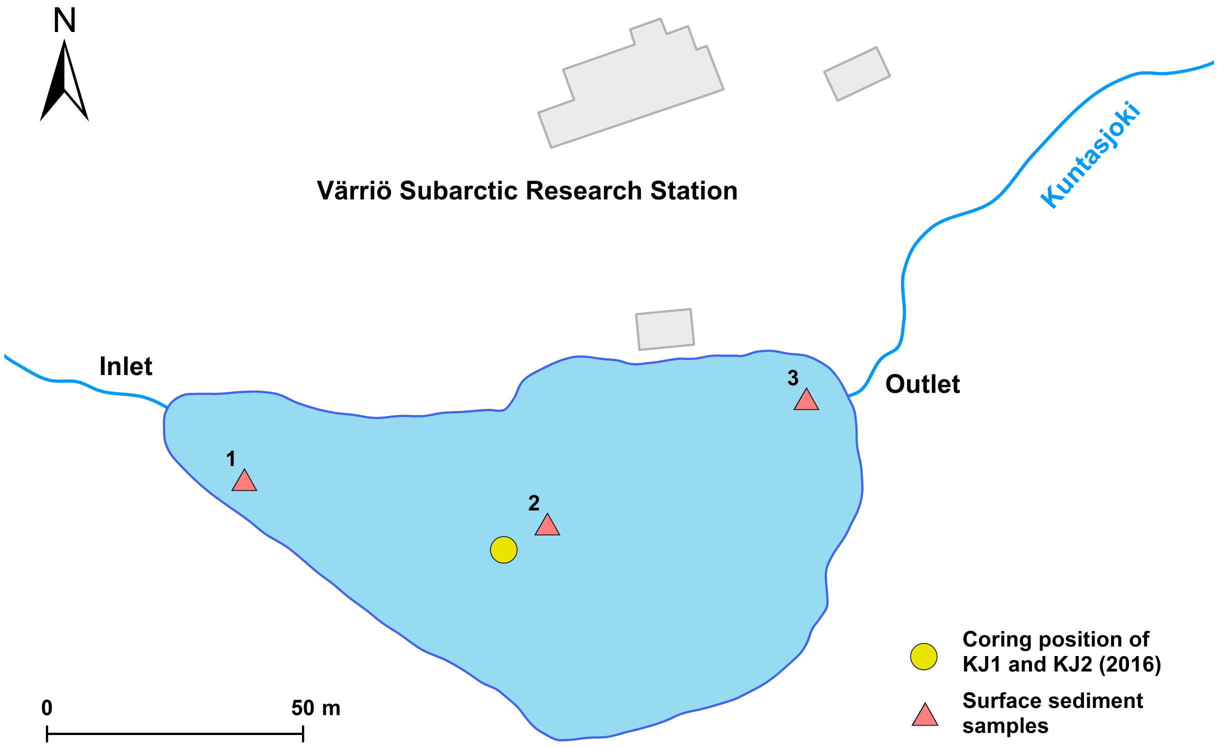

Figure 3. Close up map of Kuutsjärvi showing its inlet and outlet (Kuntasjoki), as well as its proximity to the Värriö Subarctic Research Station. The green circle mark out where the coring of KJ1 and KJ2 was undertaken in beginning of 2016, and the red triangles mark out where the surface sediment samples were taken during the summer of 2018.

later analysed, one near the inlet, one in the deep part of the lake, and one close to the outlet. These three sample spots are noted in Fig. 3. After arriving back in Stockholm the sample bags were stored in a fridge for seven months until analysis in January 2019.

3.2 Macrofossil preparation and analysis

When radiocarbon dateable macrofossils were collected from the KJ1 sample bags by Minna Väliranta (prior to the start of this study), preliminary analyses showed that the upper part of the sediment core contained only scarce macrofossil remains. Accordingly, in this study it was decided early on not to analyse the whole core, but rather focus on the minerogenic part and the lower part of the gyttja, as the early Holocene is of most interest to the multi-proxy project on Kuutsjärvi. Subsequently, only sample bags from the depths 340-541 cm were included, as well as the sample bags from the minerogenic part (hereafter referred to as 'A-samples', see further description in section 4.1). All of the A-samples were analysed, while the gyttja samples were analysed in a 4 cm interval. On a few occasions when a sample bag was missing from the gyttja sequence, or when there was very little material left in a particular bag, a deviation from the 4 cm interval was allowed. Specifically this was the case between the depths 369 and 375, resulting in an unanalysed gap of six cm; between 413 and 418 cm, a gap of five cm; and between 461 and 466 cm, also a gap of five cm. Consequently nearby samples close to these deviating depths are also instead analysed in a denser interval.

The material left for macrofossil analysis following other analysed proxies varied slightly in the sample bags, but were for the most part around 20 ml within the gyttja samples (with two sample bags containing only around 15 ml and a few ones slightly more than 20 ml), and between 15-50 ml within the A-samples. The greater variance in sample volume within the minerogenic section is due to the varying thickness of each unit (see description of the lithostratigraphy in 4.1), but regardless all available sediment left in the each bag were analysed. For the contemporary surface samples, approximately 50 ml were analysed from each sample bag. Note that the macrofossil count in the resulting diagram was not adjusted for the different volumes, because of differences in sedimentation rate between the gyttja and minerogenic rich sediment.

Before analysis the sediment was sieved using a 125 μm mesh sieve to get rid of fine minerogenic material but still ensure the retainment of even the smallest seeds. The analysis of the remaining sediment was then carried out by putting small amounts of material at a time in a gridded petri dish, whereafter it was scanned through using a stereo microscope at 10x-40x magnification. In those cases when it was necessary to distinguish a specific pattern in e.g. a bark piece or a seed wing, a high-power light microscope with up to 100x magnification was used as well. All identifiable macrofossils were identified into lowest taxonomic level possible and counted in absolute numbers, while unidentifiable macrofossils in some cases were estimated in relative abundance (subjective scale). This was for example the case with 'unidentifiable moss remains' (see Fig. 8), where it was possible to determine that the remains were of moss origin, but due to decomposition and missing diagnostic parts of the remains, not any further details than that.

As reference literature for the most common macrofossils found in northern Europe, Birks (2013) and Mauquoy and van Geel (2007) was used. Identification of more specific macrofossil details are based on the following literature: Eurola et al. (1992), Hallingbäck and Holmåsen (1995) and Laine et al. (2016) for mosses; Berggren and Anderberg (1981), Anderberg (1994) and Cappers et al. (2006) for seeds; Sweeney (2004) for needles; Tomlinson (1985) for buds and budscales; and Kats et al. (1977) for bark. For information on ecology of the identified species, Mossberg et al. (1992) and Anderberg and Anderberg (2019) was primarily used. The stratigraphic taxa diagram (Fig. 8) was compiled and plotted using the program C2 version 1.7.7 (Juggins, 2016). Zones in the diagram was determined by visual inspection of the data.

3.3 Loss on ignition, radiocarbon dating and other proxies

While the focus in this study is solely on macrofossil analysis, other proxies such as pollen, diatoms, chironomides, as well as loss on ignition (LOI, to determine organic carbon amount), have also been analysed using the same sediment by researchers affiliated with University of Helsinki and Stockholm University. As these proxies are not within the scope of this thesis, and have not been analysed as a part of it, they will not be included as separate entities. However, when it comes to loss on ignition values, radiocarbon ages and some selected pollen taxa, these will be presented along with the macrofossil analysis data presented in Fig. 8 (see section 4.4) to enhance interpretation. Therefore a brief description of their methods will follow here:

Loss on ignition: The loss on ignition analysis was carried out by Sanna Piilo at the Department of Environmental Sciences at University of Helsinki during the autumn of 2016, using material from the KJ1 samples bags. General LOI methodology was used, with sediment first drying at 105° C and then combusting at 550° C, thus avoiding combustion of inorganic carbonates. See e.g. Heiri et al. (2001) for a more detailed methodology description.

Radiocarbon dating: Material for radiocarbon dating was collected by Minna Väliranta from KJ1, using two sample bags of the minerogenic section (A6 and A13, see section 4.1 for further description of the sediment) and 17 sample bags of the gyttja section. Of these six radiocarbon ages from the gyttja is included herein, as only lake sediment between 340-541 cm was used in this study (a radiocarbon sample from 332 cm is included as it is very close to 340 cm). The material collected for dating were terrestrial plant remains, such as seeds, leafs or needles, this to avoid dating uncertainties associated with non-terrestrial material, such as incorporation of old carbon (Hua, 2009). The radiocarbon samples were taken at different occasions, one in mid 2017 that was sent to Poznan Radiocarbon Laboratory and another one in late 2018 that was sent to the Helsinki Accelerator Laboratory. The resulting radiocarbon ages (Table 1) were calibrated (in this study) with Clam 2.2 (Blaauw, 2010) in R 3.6 (R Foundation for Statistical Computing, 2018) using the IntCal 13.14 calibration curve (Reimer et al., 2013). An age-depth model using smooth spline (0.5 smooth setting) was created for the six samples in the gyttja section, whereof one

Table 1: AMS radiocarbon ages, calibrated ages and weighted average ages (from the age-depth model) of macrofossils collected from the KJ1 sample bags. The first letters in the sample code indicate which laboratory that analysed the material; Poz = Poznan Radiocarbon Laboratory and Hela = Helsinki Accelerator Laboratory. When calibrated results occurred as two or more probability intervals, all intervals with a probability of 5% or more are included as separate rows. The number in brackets are the probability for each interval. All ages are in yr BP.

Sample code	Depth (cm)	^{14}C age	Calibrated age (2σ)	Weighted avg.
Hela-4215	332	6408 ± 53	7259 - 7426	7338
Hela-4216	371	7044 ± 62	7731 - 7976	7979
Poz-91405	417	8000 ± 40	8722 - 9007	8731
Hela-4217*	462	7534 ± 72	8186 - 8446	*
Hela-4218	506	8962 ± 37	9926 - 9998 (22.9)	
			10001 - 10064 (16.3)	10087
			10119 - 10225 (55.7)	
Poz-91406	540	9310 ± 50	10372 - 10609 (84.3)	10580
			10612 - 10660 (6.9)	
Hela-4220*	550.5 (A6)	8801 ± 76	9602 - 10157	*
Hela-4219*	561.9 (A13)	9259 ± 73	10248 - 10589 (93.7)	*

* Sample excluded from the age-depth model, see text for more information

(Hela-4217) was rejected as an outlier. The two samples from the minerogenic section (Hela-4220 and Hela-4219) were also excluded from the age-depth model as the sedimentation is expected to have been instantaneous deposition events (see section 4.1). These samples were instead calibrated individually, also with Clam 2.2 in R 3.6. See Table 1 for details about the samples, radiocarbon ages, calibrated ages and weighted average ages (based on the age-depth model).

Pollen analysis: The pollen samples were prepared and counted by Sakari Salonen at the Department of Geosciences and Geography at University of Helsinki. The same methodology described in Salonen et al. (2018) was used. Note that as this study focuses on macrofossils, only a small selected taxa consisting of tree-type *Betula* and *Pinus* pollen is included in the plant taxa diagram (Fig. 8).

3.4 DEM analysis of geomorphology and topography

A part of this study has been to try to reconstruct the deglaciation pattern of the area, in order to explain the sequences of minerogenic sediment in the bottom of the Kuutsjärvi sediment core (as described briefly in section 3.1, and in more detail in 4.1). This reconstruction has been done visually by inspection of geomorphology and topography, using a high-resolution (2 m) digital elevation model (DEM) based on airborne LIDAR scanning. The data was downloaded as a DEM image (georeferenced .tiff file) available from the National Land Survey of Finland, and then processed further using Esri ArcGIS 10.6 (Esri, 2018). In the program the *Hillshade* tool was used to get a 3D shading of the surface, and thus bring out the geomorphology from the DEM. Different settings were elaborated with to make sure that all details in the geomorphology was considered. In addition to this, in order to enhance topographical understanding of the area, a colour ramp was added to the underlying DEM and the *Contour* tool was also used create isolines over the area.

4 Results and interpretation

4.1 Lithostratigraphy

Both KJ1 and KJ2 retrieved from Kuutsjärvi demonstrate the same general pattern in the lithostratigraphy. The sediment consist predominantly of organic rich sediment, in the form of gyttja or more or less

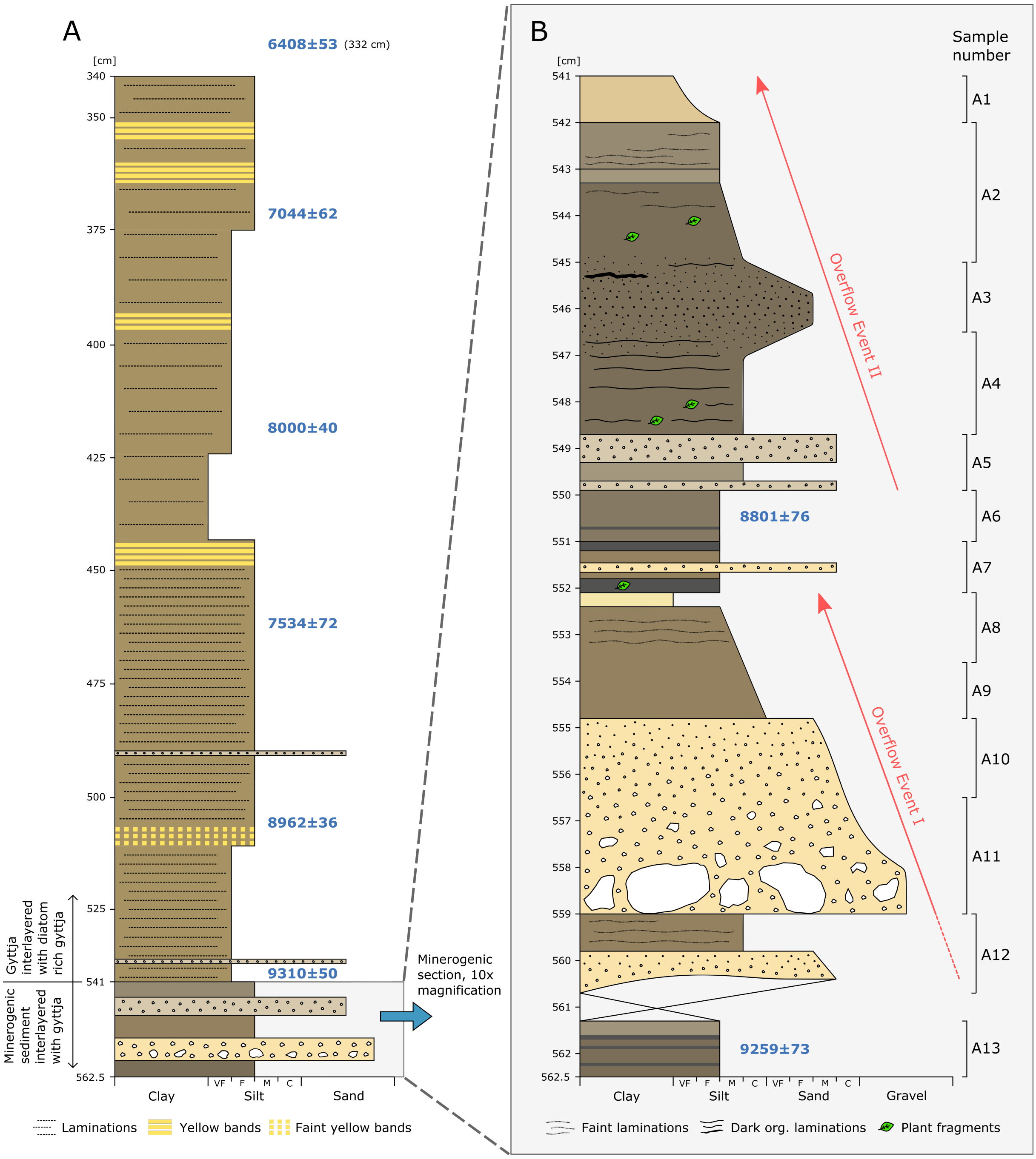

Figure 4. Sediment log drawn from KJ1 (gyttja part) and KJ2 (minerogenic rich part), showing: A. full depiction of the sediment used in this study, between 340-562.5 cm; and B. magnification of the bottom minerogenic rich part (541-562.5 cm) displaying the two distinct overflow events. The colours of the sediment in this depiction represent near original sediment colour, and does not indicate any other significant aspect of the sediment. Blue numbers are radiocarbon ages (non-calibrated, yr BP). Note the hiatus in B between approx. 560.5-561.5 cm.

mineral rich gyttja, overlaying a lower section containing minerogenic material interlayered with gyttja. A depiction of the sediment can be seen in Fig. 4, wherein KJ1 was used to draw the gyttja part and KJ2 to draw the minerogenic rich part.

4.1.1 The minerogenic section

The base of the core, between 541 and 562.5 cm, is dominated by minerogenic material and will hereafter be referred to as the *minerogenic section*. As this section only comprises of approximately 20 cm in total while at the same time displaying a great deal of variance, it is magnified into a separate log in Fig. 4B. In the figure the A-sample codes for each subsample unit are noted, and these will for the most part be used instead of the depth when referring to different lithological parts in the text below.

Two main types of sediment are present in the section: silty gyttja in the very bottom between c. 561.5-562.5 cm (A13) and between c. 550-552 cm (A7 and A6); and organic bearing minerogenic sediment in the rest of the section (between A12-A8 and between A5-A1), in which dark organic laminations and occasionally clearly visible plant fragments are incorporated. The sequences of silty gyttja show some shifts in colour but are generally lacking other characteristics, such as visible organic material. The sequences of minerogenic sediment on the other hand are normal graded from gravel and sand into fine silt and clay, and the interpretation is that these represent glaciofluvial sediment from so called 'overflow events', or pulses of glacial meltwater periodically transporting minerogenic material into the lake. Key characteristics for this interpretation is the clear pattern of very coarse to very fine material (i.e. normal grading sequences), with the inclusion of fine silt and clay (glacial flour) at the top of the sequences. Furthermore are the fact that the coarsest material, especially the gravel seen in Overflow Event I, would require such high energy it is unlikely it was transported into the lake by any other means. The only reasonable alternative deposition process would in that case be through mass movements in the sediment on the lake side (due to the steep sides of Kuutsjärvi). However, this does not explain the very high abundance and variety of macrofossils in the record (see section 4.4), as well as the inclusion of water animal remains such as *Daphnia* ephippium and *Plumatella* statoblasts throughout the events (also described in section 4.4), showing they were clearly more gradual in contrast to abrupt mass movements.

During these overflow events, the initial influx of coarse material probably took place in late spring and early summer, while the subsequent finer sand and silt is thought to have been deposited throughout the rest of the summer and autumn, in conjunction with more organic material (hence the darker colour of this sediment). Lastly, the overlying clay most likely stayed in suspension until the freezing of the lake during winter, explaining the lack of plant remains in the clay units. Consequently this suggests the overflow events occurred during a single year each, although not necessarily annually. The sediment in sample unit A12 is notable as it is either a precursor to Overflow Event I deposited during the same year, or a separate overflow event entirely. However due to its lack of fine silt and clay at the top, which are clear characteristics of the the other two events, a separate overflow event can most likely be ruled out. Moreover, the sand layer in A12 was observed to be much thinner in KJ1 (noted before subsampling), in contrast to the rather thick layer seen in KJ2 (depicted in Fig. 4), suggesting it may have been a more localised influx linked to Overflow Event I. The hiatus seen just below the A12 sand layer in KJ2 was caused by sampling for ancient DNA from the gyttja below, prior to this study (Karin Helmens, personal communication).

It should also be noted that these two particular cores (KJ1 and KJ2) did not reach the bottom of the sediment in Kuutsjärvi. Below the two overflow events seen in the minerogenic section of this sediment sequence, a series of additional thinner overflow sediment sequences were found in previous cores retrieved in 2014. These earlier overflow events does not contain as much coarse material, but still have the distinct grading from sand into fine silt and clay, similar to the events in Fig. 4B. In the lowermost part just above the bedrock, a thick silty-clayey unit is found, and this is interpreted to have settled in the Kuutsjärvi depression right after the first catastrophic meltwater discharge (see further description of this in section 4.2).

4.1.2 The gyttja section

In the upper section (340-541 cm), which is dominated by gyttja and hereafter referred to as the *gyttja section*, layers of yellow bands are spread unevenly throughout the core. In Fig. 4A the clearest and most densely packed bands are marked out, even though it should be noted that the entire gyttja section was rather yellowish in colour. Investigation into the yellow bands prior to this study revealed that they were made up of mostly silica, with the interpretation that they represent biogenic silica from diatom blooms (Karin Helmens, personal communication). This gyttja can therefore be described as diatomaceous gyttja. Generally the gyttja section does not seem to present any large shifts, but the grain size varies slightly

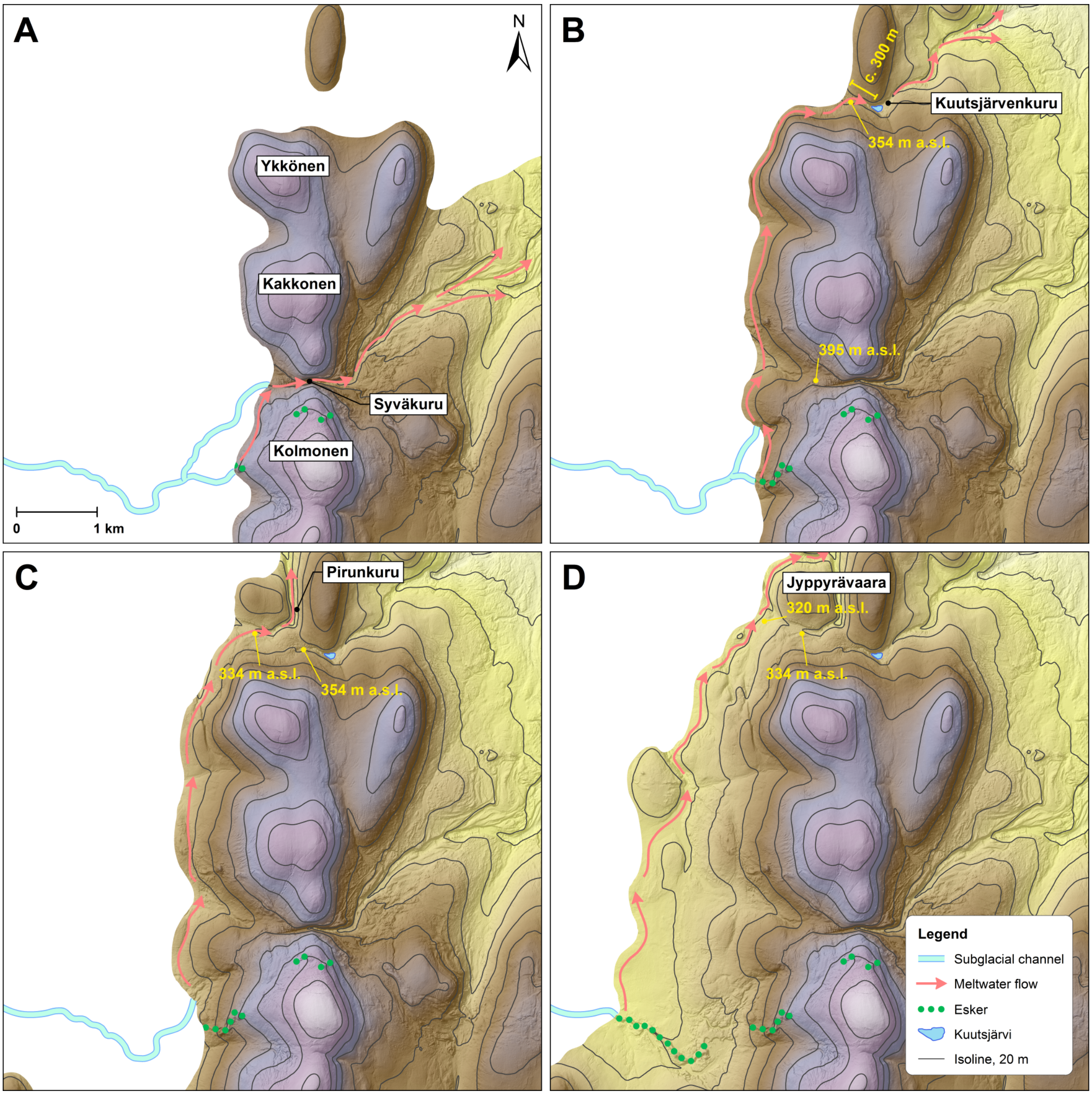

Figure 5. Schematic illustration of the deglaciation pattern in the study area, showing how glacial meltwater from the retreating ice sheet was flowing over different cols into several gorges during separate episodes of the retreat. See section 4.2 for further explanation. During Episode B when meltwater was running through Kuutsjärvenkuru the distance between the coring site and the ice sheet was c. 300 m. Note that the yellow labels indicate elevation at the thresholds in present day m a.s.l. This map contains data from the *Elevation Model 2 m* database provided by the National Land Survey of Finland under CC BY 4.0 license (downloaded 2018/10).

within the silt spectrum ranging from silty clay to clayey silt or silt. The laminations in the sediment also tend to be denser in the bottom part (between approximately 445 and 541 cm) than at the top (between approximately 340 and 445 cm). Two thin but distinct sand layers are found at c. 535 cm and c. 490 cm, each of them interpreted as to have been deposited during a single year, probably during spring snowmelt or heavy summer/autumn precipitation.

4.2 Deglaciation of the Värriötunturit area

Based on what was found in the composition of the bottom minerogenic section of KJ1 and KJ2, together with geomorphological evidence found in the high-resolution (2 m) digital elevation model over the area, a probable deglaciation pattern is here proposed (Fig. 5). Johansson (1995) did a similar reconstruction over the Värriötunturit area, but in much coarser time slices and involving a slightly larger area compared to this study. That particular reconstruction does however not fully explain the coarse minerogenic material seen in the bottom sediment of Kuutsjärvi, and some aspects of it does not seem to match with evidence now seen in the high-resolution DEM (which was not available in the 1990's). Therefore, the deglaciation pattern presented herein is primarily meant to use available geomorphological and topographical evidence in order to explain how it is possible to have overflow sediments interlayered with gyttja in the early phases of Kuutsjärvi's lake evolution. The four episode time series on the deglaciation presented in Fig. 5 is described in detail as follows:

Episode A: Initially only the peaks of the Värriötunturit fell chain and the low-lying areas to the east were ice free, while the ice remained thick enough to be able to discharge its meltwater through the Syväkuru gorge situated between Kakkonen and Kolmonen (395 m a.s.l). Exactly how much of the northeastern part of the area that was ice-covered at this stage is difficult to estimate based on this data alone. However, it remains clear that the area directly east of Syväkuru must have been ice free, as the water flow evidently carved out distinct channels in the sediment (as seen on the DEM of Fig. 6). These channels also suggest the water torrent must have been very heavy, as the meltwater flow spread out in a fan shape and deposited boulders outside of the main channel. The water deviating northwards appears to eventually came to a halt, as the traces in the sediment suddenly disappears (Fig. 6). This can be interpreted as the remaining ice sheet blocking the meltwater from flowing further, and thus the ice sheet extent to the northeast presented in this reconstruction (Fig. 5A) would seem reasonable. The southern stretch of the subglacial channels were based on the clear esker chain left behind. In the deglaciation reconstruction made by Johansson (1995) an additional subglacial channel was inserted north of Ykkönen, but there does not not seem to be any direct evidence for that in the DEM, neither depositional nor erosional, and therefore it was left out in this reconstruction for simplicity.

Episode B: As soon as the ice retreated below the col west of Syväkuru (395 m a.s.l.), the gorge dried up and meltwater started to accumulate between the ice sheet and the Värriötunturit fell chain. Due to the topography of the region (see Fig. 1 for a wider perspective), in combination with the northwestern ice sheet retreat, the only drainage path possible was alongside Kakkonen and Ykkönen towards the north. The accumulated meltwater was therefore released first after the ice sheet had retreated enough for the opening of the Kuutsjärvenkuru depression (354 m a.s.l.). Clear ice-marginal channels to the west of the Värriötunturit fell chain, as well as the deeply eroded Kuutsjärvenkuru depression in itself (Fig. 5 and Fig. 6), indicate that this first phase of meltwater discharge was very heavy. However, following this initial phase of erosion it is likely that the meltwater only spilled over periodically, depositing the aforementioned overflow sediments (section 4.1) into Kuutsjärvi. This becomes evident when taking into account that the initial flood-like erosion likely lowered the elevation of the col, and thus allowed the ice to discharge meltwater through Kuutsjärvenkuru during a longer period of time. The same mechanism is mentioned by Mannerfelt (1945) in relation to the drainage of the Drommen ice lake in Jämtland, northwestern Sweden. Each overflow event is interpreted to have taken place just during a single year, which suggests the time period in which the ice was capable of discharging overflow sediments into Kuutsjärvi was likely fairly short, presumably merely during approximately 10 years time (see section 4.3 for more details about this time estimation). During this time period the ice sheet was standing only c. 300 m northwest of Kuutsjärvi (Fig. 5B).

Episode C and D: As soon as the ice retreated further to the northwest, the water could drain through Pirunkuru (334 m a.s.l.) instead of the higher elevated Kuutsjärvenkuru (354 m a.s.l., Fig. 5C). This marks the end of the overflow events stage of Kuutsjärvi, and the start of the continuous lake phase corresponding with the depth 541 cm in the sediment record (see section 4.1 and the sediment log in Fig. 4). When the ice retreated into even lower topography (approximately 320 m a.s.l.), the water could no longer drain through Pirunkuru, but instead took the path nortwards west of Jyppyrävaara (Fig. 5D). This further separated the ice sheet and its meltwater from influencing the environment in the immediate area around Kuutsjärvi.

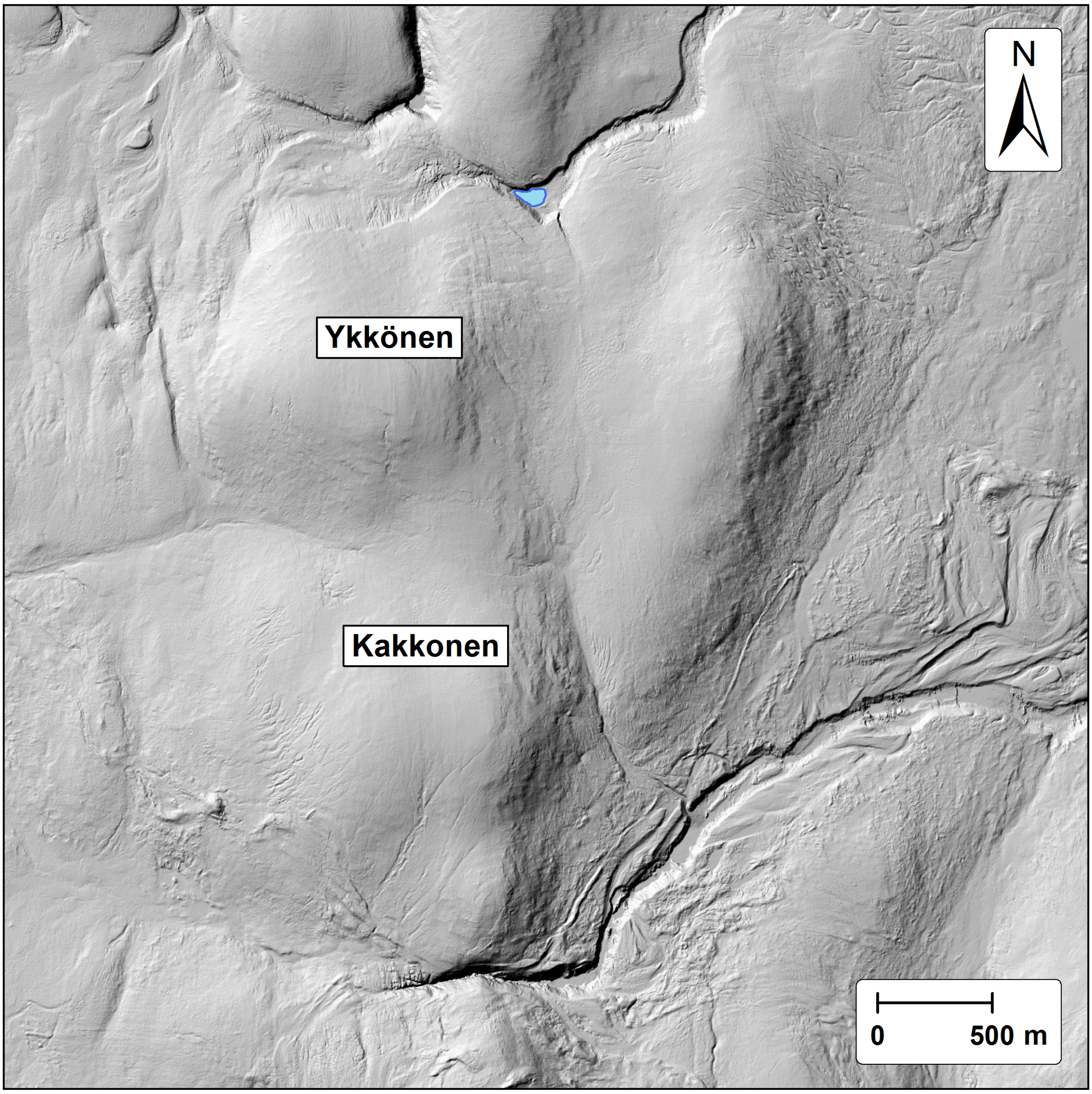

Figure 6. Raw hillshade map created from the DEM showing the meltwater channels to the west of Ykkönen and Kakkonen flowing into Kuutsjärvenkuru, as well as the deep channels to the east of Syväkuru. The blue polygon is Kuutsjärvi. This map contains data from the *Elevation Model 2 m* database provided by the National Land Survey of Finland under CC BY 4.0 license (downloaded 2018/10).

4.3 Chronology

Eight radiocarbon samples were dated in the sediment sequence interval used in this study (including one sample from 332 cm, see section 3.3 and Table 1). For the gyttja section, an age-depth model was created (Fig. 7) which positioned the uppermost depth (340 cm) at c. 7500 cal. yr BP and the lowermost (541 cm) at c. 10600 cal. yr BP. One sample (Hela-4217, see Table 1) was excluded from the model and considered an outlier, since it was not in line with the other samples. The age-depth model shows that the sedimentation rate is relatively linear throughout the gyttja section, with each cm corresponding to c. 14.5-16 years, suggesting a high temporal resolution of the sediment sequence. The sedimentation rate is slightly higher in the lowermost part and is decreasing towards the top. Two radiocarbon samples from the minerogenic section were calibrated individually, and the lowermost sample (A13) was in line with the basal gyttja age, while the mid sample (A6) appears to be too young at c. 9600-10150 cal. yr BP. As mentioned previously, the interpretation is that each overflow event took place during a single year each,

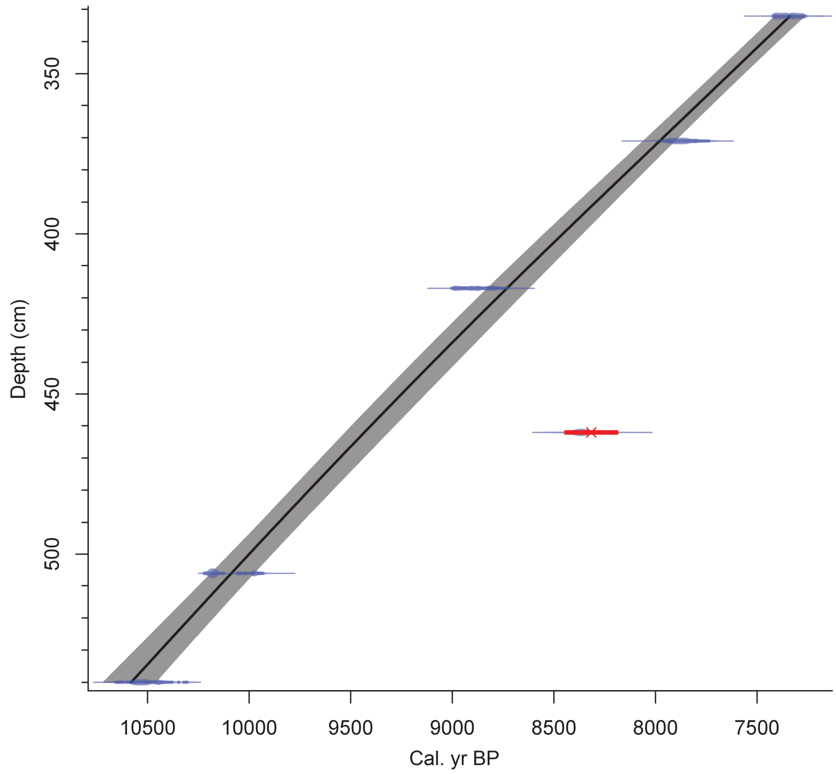

Figure 7. Age-depth model created using the six radiocarbon ages from the gyttja section, whereof one was rejected (marked in red). Note that the uppermost sample is from 332 cm, i.e. slightly outside the sediment interval used in this study.

because of the clear grading profile from coarse to fine material in the sediment record. The gyttja in between could however potentially have been deposited during several years, as the overflow events were not necessarily annual events, but the time period for the whole overflow event sequence, including the five smaller events not present in the KJ1/KJ2 sediment record (see section 4.1), is not likely to be longer than 10 years. Based on this interpretation, the suggested radiocarbon age in A6 is unrealistically young, and it is therefore considered an outlier.

The deglaciation age of c. 10600 cal. yr BP correspond quite well with the nearby lake Loitsana in Sokli, where the bottom of the sequence (the deglaciation) was dated to c. 10700 cal. yr BP (weighted average age from age-depth model, see Shala et al., 2014a,b). While this is slightly older than the weighted average age in this study, the 2σ probability interval of the calibrated ages are within the same scope (Table 1), even though the interval in Shala et al. (2014b,a) is larger, which is likely related to a larger radiocarbon age error interval. According to Johansson (1995, 2007) the Sokli area deglaciated less than 100 years after the Värriötunturit area, thus it is expected these two areas would yield roughly the same deglaciation age, or with a slightly older age for Kuutsjärvi. This rapid ice retreat rate also further strengthen the interpretation that the overflow events were deposited over a single year, and that the whole overflow event sequence was deposited during a very short time period.

4.4 Proxy interpretation and environmental reconstruction

The macrofossil taxa is summarised in Fig. 8 together with loss on ignition (LOI) values and the selected pollen taxa of tree-type *Betula* and *Pinus* provided by Sakari Salonen. From the results, four main zones could be distinguised, whereof Zone I was further subdivided into four subzones. Zonation was based on visual inspection of the plant composition in combination with sedimentological changes (see Fig. 4). The remains found were in general very well-presevеd, especially those in the overflow event units of the lowermost zone, which would rule out the possibility of redeposition of old interglacial material following the deglaciation. This is nevertheless also shown by the radiocarbon dating of the remains (Table 1). An assortment of the macrofossils found during the analysis are shown in Fig. 9.

4.4.1 Zone I, 562.5 - 541 cm (c. 10600 cal. yr BP)

Zone I represents the 'overflow event stage' of Kuutsjärvi, where the gyttja sedimentation was interrupted by large amounts of minerogenic influx, transported by glacial meltwater from the retreating ice sheet (see section 4.1 and 4.2). In order to better describe the different parts of this stage, the zone was further divided into four subzones, in which Zone I-b and Zone I-d represent the two separate overflow events, while Zone I-a and Zone I-c represent the in-between gyttja sedimentation (Fig. 8). In the pollen record *Pinus* pollen percentages stay below 1% throughout the zone, while tree-type *Betula* pollen is rising throughout, starting from approximately 30% in the lowermost part of the zone and reaching above 80% in the upper part, which in combination with the tree-type *Betula* macrofossil remains indicate the establishment of an open sub-arctic birch forest in the area. Characteristic for the whole zone is the generally high amount of well-preserved remains in contrast to successive zones (even though some seeds among the herbs were only possible to identify into genus level), both in terms of absolute number and variety of taxa found. More specifically the highest variety and abundance of macrofossil remains are found in the overflow sediments, and there is a distinct difference in amount and variety between the gyttja and overflow events. The details of the subzones are described under each corresponding section below.

4.4.1.1 Overflow sediments (Subzone I-b and Subzone I-d)

In the overflow event subzones the organic content drops below 5% (Fig. 8) and the sediment changes to a sequence of gravel or coarse sand grading into silt and clay (Overflow Event I and Overflow Event II, see Fig. 4B). Well-preserved plant remains of tree-type *Betula* and dwarf shrubs (*Betula nana*, *Salix sp.* and *Empetrum nigrum*) dominate the macrofossil assemblage in the overflow sediments, together with different kind of seeds from herbs, where *Chamerion angustifolium*, *Cerastium sp.* and *Juncus spp.* are especially prevalent. Leaves of mosses (*Bryum sp.*, *Polytrichum strictum* and *Polytrichum jensenii*) are also present, as well as possibly a single remain of a *Pinus* budscale in Subzone I-b (Fig. 8). This myriad of remains, which is a strong contrast to the lack of remains in the over- and underlying gyttja units, was transported with the meltwater and must have originated from plants growing in-between the ice-margin and the lake, i.e. in an ice-marginal environment since the ice sheet supposedly was standing only a few hundred meters away from the lake (see Fig. 5B, section 4.2). This in turn suggests the area became vegetated very quickly after the deglaciation.

While seeds or leaves from light demanding tundra herbs such as *Dryas octopetala*, *Saxifraga cernua (cf.)* and *Cerastium sp.* all indicate a rather open landscape (Mossberg et al., 1992; Anderberg and Anderberg, 2019), the high abundances of tree-type *Betula* macrofossils also suggests trees were already growing in the area at this stage. Although no pollen samples were analysed in the overflow sediments, the gyttja underlying Subzone I-b contains tree-type *Betula* pollen percentage values of c. 30%, whereas the overlying gyttja contains c. 70% (Fig. 8). Modern pollen spectras suggest that a *Betula* pollen percentage of 50-60% would indicate the presence of birch forest (Prentice, 1978), and it is thus likely that the area already very soon after deglaciation was covered in pioneer birch forests. Since the hills of Ykkönen and the other Värriötunturit peaks were deglaciated even earlier (see Fig. 5), it is also possible that some local forests were thriving in pockets of favourable conditions already before the deglaciation of the low-lying areas. Most likely, the birch forest was still rather open and incorporated a mix of trees and herbs, as e.g. the highly abundant *Chamerion angustifolium* are common not only in entirely open environment, but also in those kind of scattered birch forests (Mossberg et al., 1992; Anderberg and Anderberg, 2019). Many of the other herbs prefer dry or sandy soil, such as *Vaccinium vitis-idaea*, *Campanula rotundifolia* and *Dryas octopetala*, and these were likely also growing in the forest. The remaining herbs and shrubs, *Epilobium palustre*, *Epilobium dawuricum*, *Carex spp.*, *Juncus spp.*, *Rorippa islandica*, *Betula nana*, *Empetrum nigrum* and *Salix sp.*, often prefer wetter habitats (Mossberg et al., 1992; Anderberg and Anderberg, 2019) and were likely growing near the stream channel, or close to the shore around Kuutsjärvi.

In general the macrofossil assemblages are very similar between the two overflow events, but the lithostratigraphy shows that Overflow Event II lacks coarser sediment in the form of the gravel present in Overflow Event I (Fig. 4B), suggesting it was probably less energetic. Although this could possibly

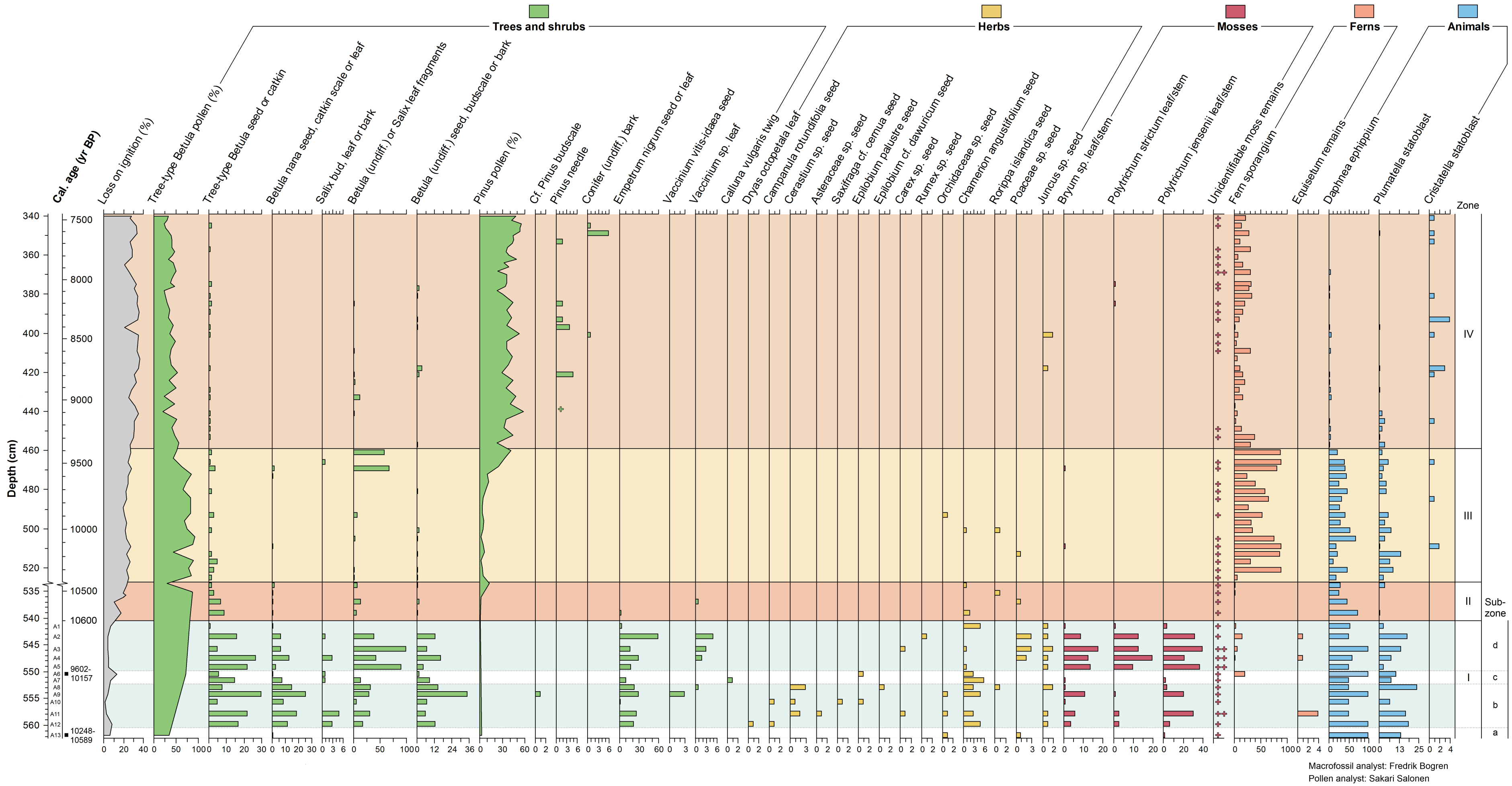

Figure 8. Macrofossil and pollen taxa diagram for trees, shrubs, herbs, mosses, ferns and animals from the KJ1/KJ2 sediment sequence retrieved from Kuutsjärvi (KJ2 was only used for sample A6 and A13). Macrofossil taxa remains are expressed in absolute numbers and drawn as histograms, or expressed as + (present) or ++ (highly abundent). Pollen taxa are expressed as percentages of total sum of terrestrial pollen and spores (not shown in this diagram). The diagram is divided into four main zones, in which Zone I is further divided into four subzones. The calibrated age axis are based on the age-depth model in the gyttja section (Zone II-IV) and single calibration intervals (2σ) in the minerogenic section (Zone I, square icons indicate the depth where the radiocarbon sample was collected), see Table 1 for details. Note the change in scale at approximately 530 cm.

explain the decrease in variety of herb species seen in Subzone I-d, the assemblage is nevertheless very similar to Subzone I-b in terms of amount of plant remains. The only significant difference is that ferns start to appear in Subzone I-d, and that it contains a lot more remains of mosses (*Polytrichum jensenii*, *Polytrichum strictum* and *Bryum sp.*) and *Salix sp.* or undifferentiated *Betula* leaf fragments than Subzone I-b (Fig. 8). All three moss taxa are related to wet habitats, whereof *Polytrichum strictum* commonly grows on fens and bogs, while *Polytrichum jensenii* and *Bryum sp.* are often growing near stream channels or lake shores (Hallingbäck and Holmåsen, 1995) where seasonal flooding might occur (Ulvinen et al., 2002). This shows that the second weaker overflow event probably was confined to the stream channel, while the first overflow event washed a larger area and thus also incorporated more plant remains from the surrounding environment outside the channel.

4.4.1.2 Gyttja sediments (Subzone I-a and Subzone I-c)

Both the gyttja subzones consist of low organic (around 10%) silty gyttja containing few terrestrial plant remains compared to the minerogenic overflow sediments (Fig. 8). In the lowermost gyttja sequence (Subzone I-a) the only identifiable remains found were single seeds of *Betula nana*, undifferentiated *Orchidaceae sp.* and *Poaceae sp.*, as well as two leaves of *Polytrichum jensenii*, thus providing no good basis for interpretation of the environment. The combination of few remains and tree-type *Betula* pollen percentage at c. 30%, could however possibly suggest that the area around the lake was more scarcely vegetated at this time, although it is not expected that any major changes would occur in the environment between the two gyttja units since the time period is very short (see section 4.3). In Subzone I-c plant remains are recorded in greater numbers compared to Subzone I-a, and the general assemblage seems to follow the overflow sediments (but with fewer herb and moss remains). This confirms that the taxa previously found in Subzone I-b (Overflow Event I) are also present in the environment close to the lake, since the regular inlet stream likely was not transporting remains from as far away as the glacial meltwater.

In contrast to the small number of plant remains, both subzones do contain a high abundance of aquatic animal remains in the form of *Daphnia* ephippium (water flea eggs; Ebert, 2005) and *Plumatella* statoblasts (asexual dormant stage; Wood et al., 2005). However, both these animals are very common and can tolerate many different lake environments, and therefore this might not indicate anything in particular. The species of *Plumatella* was not determined, but the most common species in Norway (*Plumatella fruticosa*) prefer colourless and slightly acidic water conditions (Økland and Økland, 2002).

4.4.2 Zone II, 541 - 530 cm (10600 - 10400 cal. yr BP)

Following the last overflow event a shift into gyttja once again occurs, also around 10600 cal. yr BP (roughly the same as the deglaciation age, see section 4.3). Zone II represents sediment with more minerogenic material and less organic matter than following zones of the gyttja section, as evident by the lower loss on ignition values. Throughout the zone the LOI is increasing, which can be an indication of soil formation and further catchment stabilisation in the area surrounding the lake. Compared to the previous gyttja unit (Subzone I-c), even less terrestrial remains are found, and although in general the same kind of tree, shrub and herb species are recorded as before, virtually all of them decrease in numbers (Fig. 8). At the same time pollen percentages shows tree-type *Betula* almost reaching 90%, while *Pinus* pollen is starting to increase only in the uppermost parts of the zone. This is probably reflecting pine becoming more common in scattered occurrences in the area, even if birch are still the prevailing tree type of the forests.

The shrubs and herbs found in this zone (*Betula nana*, *Salix sp.*, *Chamerion angustifolium*, *Rorippa islandica*, *Poaceae sp.*) are likely part of the shore vegetation or the immediate forested area around Kuutsjärvi, but many of the plant remains that were present in the overflow sediments and absent in this zone were likely growing further away and thus required stronger water energy for transport into the lake. This was probably the case with the identifiable moss remains and possibly also fern sporangia which disappeared entirely in this zone (Fig. 8). Interestingly, *Plumatella* statoblasts are also completely absent, which is harder to explain as this taxa is, as mentioned previously, tolerable to many different

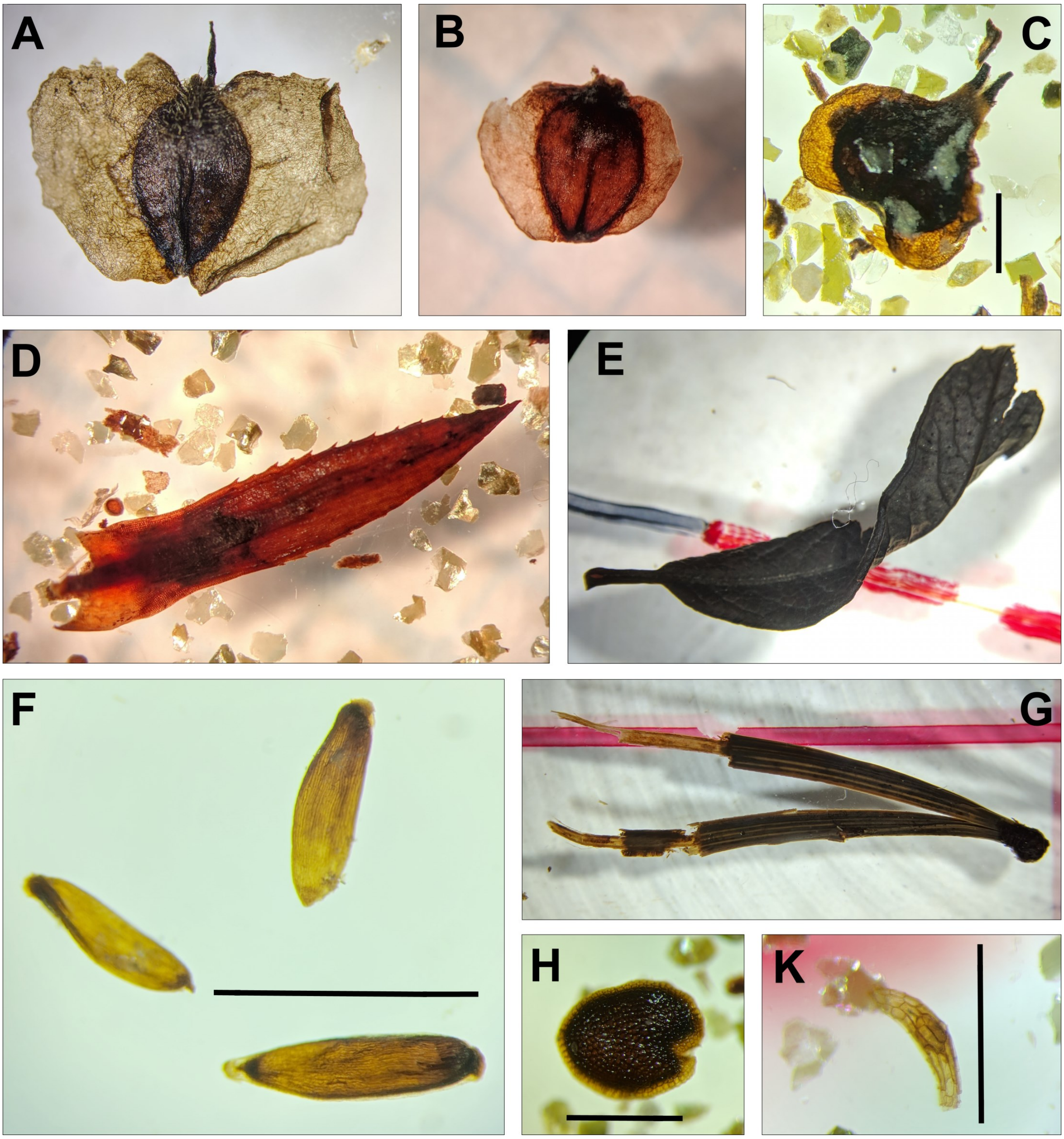

Figure 9. Photo examples of plant macrofossils found during the analysis (the depth or A-sample code where the depicted remain was found is noted in square brackets next to the name): (A) Tree-type *Betula* seed [533 cm]; (B) Undiff. *Betula* seed (possibly hybrid) [A12]; (C) *Betula nana* seed [A8]; (D) *Polytrichum jensenii* leaf [A3]; (E) *Salix sp.* leaf [A2]; (F) *Chamerion angustifolium* seeds [A7]; (G) *Pinus sylvestris* needle [421 cm]; (H) *Rorippa islandica* seed [A8]; (K) *Orchidaceae sp.* seed [A9]. Black scale lines next to some macrofossils are 1 mm (size was not measured for all remains).

lake conditions. Possibly the lake water changed into some of the conditions Økland and Økland (2002) lists as avoided by *Plumatella fruticosa*. However, it also cannot be ruled out that the reason why some macrofossils suddenly disappears are due to factors related to decomposition, as the sediment in this zone (as well as certain other parts of the gyttja section) was noted as particularly decomposed during analysis.

4.4.3 Zone III, 530 - 460 cm (10400 - 9400 cal. yr BP)

A slight increase in grain size can be seen in the beginning of Zone III simultaneous with a LOI stabilisation at c. 30%. In the macrofossil assemblage, the zone mark a shift with a sharp increase in fern sporangia at the same time as *Plumatella* reappear in the record, at around 10400 cal. yr BP. Tree-type

Betula start to appear less frequent in the samples as well, but remain at a high percentages (around 80%) in the pollen record (Fig. 8), suggesting *Betula* forests were still covering the surrounding area. The ferns are probably a distinct element of the shore vegetation at this point, but it is possible that the birch forests adjacent to the lake were also marshy and covered with an undergrowth of ferns, similar to what is seen in the present-day forest on the southern lush side of the lake. This has also been reported in early Holocene birch forests in western Norway (Karlsen, 2009). Strangely not a lot of other shore taxa were found in the sediment, except for occasional single seeds of e.g. *Rorippa islandica*, *Betula nana* and *Poaceae sp.* found scarcely throughout the zone. However, in the pollen record spores of *Dryopteris* (a fern genus) were also found at high percentages around this time (Sakari Salonen, in preparation; not included in Fig. 8), further strengthening the interpretation that ferns were very abundant in the local environment.

In the upper part of the zone, high abundences of *Betula* or *Salix* leaf remains are found in two samples. This sudden increase in single samples is hard to definitely explain, but could maybe be related to events of very high water input into the lake, such as heavy rain during summer or autumn, or a severe snowmelt season. All these deviations may also show that the taphonomic factors varied quite a lot within the zone, which further stresses that the absence of macrofossils is no proof for the disappearance of the taxa from the surrounding environment.

4.4.4 Zone IV, 460 - 340 cm (9400 - 7500 cal. yr BP)

The last zone represents a transition in the environment from a forest dominated by birch into a mixed birch and pine forest at around 9400 cal. yr BP. This is evident in the pollen record (Fig. 8), where a simultaneous decrease in tree-type *Betula* pollen is coupled with a sharp increase in *Pinus* pollen, in levels commonly associated with pine-birch forests (c. 60% *Pinus* pollen, see diagram in Prentice, 1978). In the macrofossil taxa the same pattern is observed, where the remains of tree-type *Betula* are slightly reduced while *Pinus* remains appear in the form of needles and bark. Despite the fact these *Pinus* remains were not detected until c. 440 cm., seemingly lagging behind the shift seen in the pollen record, it can always just be a coincidence that the remains were not deposited at the coring spot. In fact, not a lot of macrofossils are found in this zone, thus making it hard to draw any definite conclusions from the assemblage. For example, the total absence of *Betula nana* and the decline in fern sporangia may not indicate anything in particular as both these taxa are present by the shore of the lake today, but were not found in the surface samples (see section 4.6). It is however clear that the fern decline follows the increase in pine, and possibly this is a reflection of the forest in the area surrounding the lake becoming less dense and wet at this stage.

A sharp decline in *Daphnia* ephippium and *Plumatella* statoblasts is recorded as well, at the same time as *Cristatella* statoblasts are becoming more abundant (Fig. 8). *Cristatella* is usually associated with more coloured lake water, but also with warmer water temperature since it ideally avoid lakes with summer water temperatures below 16 °C (Økland and Økland, 2000). Apart from the change in taxa, a shift in the sediment can be seen (see sediment log, Fig. 4A) with the introduction of more frequent yellow bands, indicating diatom blooms in the lake. Moreoever, the laminations in the sediment are becoming less dense and the gyttja is more clayey in the beginning of the zone. This in combination with the increase of the LOI to levels of 30-35% (Fig. 8) suggests that the catchment stabilised further due to soil formation at this stage.

4.5 Temperature reconstruction

One objective of this study was to try to determine the minimum July temperature (T_{jul}) in the early Holocene based on presence of indicator plant taxa. However, it is evident from the macrofossil analysis that none of the taxa commonly used as indicator species (see e.g. Isarin and Bohncke, 1999; Helmens et al., 2012; Väliranta et al., 2015; Shala et al., 2017), for example many *Potamogeton* species, *Najas spp.*, and *Typha spp.* that are known to be controlled especially by temperature (cf. Väliranta et al., 2015), were found in this study. Tree taxa such as *Betula* and *Pinus* are however sometimes used as indicator species and are often attributed minimum July temperatures of 10 °C and 12 °C respectively (see e.g.

Table 2: Macrofossil analysis results of three surface sediment samples from Kuutsjärvi (see sampling position for each sample in Fig. 3). Numbers represent pieces found in absolute numbers in the sample, while + and ++ indicate the abundance as presence in the sample (+ = present, ++ = highly abundant). The volume of the samples were approximately 50 ml each and all of the material in each sample was analysed.

Macrofossil	Sample 1	Sample 2	Sample 3
Sarmentypnum s.l. (on lake bottom)	++	++	++
Unidentifiable moss remains	+	++	+
Undifferentiated bark/wood	++	+	+
Betula undiff./*Salix* leaf remains			10
Tree-type *Betula* seed or catkin	7	4	4
Empetrum nigrum seed/leaf			4
Pinus needle	1		
Picea needle	9	1	
Juniperus needle	1	1	2
Carex sp. seed		1	
Daphnia ephippium	4	12	
Cristatella statoblast		1	

Helmens et al., 2012), but this probably more accurately depicts the tree line of these species and not single occurrences of trees growing in favourable spots. Temperatures from trees should also ideally only be inferred if evidence for sexual reproduction is detected (e.g. seeds), not based solely on e.g. needle or bark findings (Minna Väliranta, personal communication). As such, it is hard to conclusively say anything about the temperature conditions of the area in this study, but this will be discussed further in section 5.

4.6 Contemporary surface sediment analysis

In order to have a modern reference, the present-day macrofossil assemblage were determined from contemporary surface sediment samples sampled from Kuutsjärvi in June 2018. The results of the analysis of this sediment are presented in Table 2. The sampling position for each sample referred to in the text below are plotted in Fig. 3.

The plant remain assemblage found in this uppermost modern sediment record proved to be quite similar to the fossil taxa in the gyttja section from Kuutsjärvi. Tree-type *Betula* seeds, leaves and catkin scales, as well as *Empetrum nigrum* seeds and leaves were found, in similar amounts as in the fossil record, while the high abundances of conifer needles found here on the other hand was not detected in the early fossil samples. Another species not found at all in the fossil samples were the *Sarmentypnum (s.l.)* moss, which at present seems to grow on the bottom of the lake as it was entangled in the coring equipment in all samples. Moreover, fern sporangia is not found at all in these modern samples (despite the fact that ferns were observed in field on the lush southern side of the lake), in contrast to their very high abundance in the gyttja section of early Holocene. Otherwise interestingly is that the macrofossils found depended a lot on where the sample was taken, indicating transportation by the inlet stream must play a big role for which kind of remains that end up being preserved in the lake sediment. Sample 2, retrieved from the middle pelagic part of the lake (see Fig. 3), contains more *Daphnia* ephippium than the other two samples, and presented a lot less plants remains. Sample 1, cored near the inlet, on the other hand, provided a lot of needles, seeds and catkin scales, but fewer animal remains. Sample 3, retrieved near the outlet, contained a lot of leaf and seed remains of *Betula*, together with a few *Empetrum nigrum* seeds and *Juniperus* needles, but was lot less variable in terms of species diversity compared to the other samples. Overall the material was fairly degraded, very similar to what was found in parts of the fossil gyttja section of KJ1, with lots of remains rendered indistinguishable.

5 Discussion

5.1 The ice-marginal environment during the early Holocene

The unique circumstances surrounding the deglaciation of the Värriötunturit area enabled a rare opportunity to reconstruct the climatic and environmental conditions not only in the early Holocene, but also in an environment just at the margin of the retreating ice sheet immediately following the deglaciation. The macrofossils found in the minerogenic section were in general very well-preserved (see Fig. 9) and radiocarbon dating of the remains yielded a calibrated age interval between c. 10300-10600 cal. yr BP, both in the bottommost sample (A13) and the sample just above the minerogenic section (540 cm; see Table 1 for details). This, which is in accordance with ice retreat reconstructions for Fennoscandia (e.g. Stroeven et al., 2016; Hughes et al., 2016), is confirming a Holocene age for the sequence, and it can thus be concluded with no uncertainty that the macrofossils deposited were contemporary and not redeposited from previous interstadial or interglacial sediments. While no taxa that could be used as clear temperature indicators were identified (more on this in section 5.4), the plant taxa assemblage in itself suggests that the area surrounding Kuutsjärvi must have been productive and full of vegetation already during the overflow events, i.e. very shortly after deglaciation when the ice-margin was situated within 300 m from the lake. Pollen percentages and macrofossil assemblage together point towards the presence of an open subarctic birch forest in the area at this stage, which is in stark contrast to the common view of ice-marginal environments of the retreating ice sheet. Perhaps the sheltered depression of the meltwater stream channel were a favourable environment for these pioneer birch forests.

One particularly interesting site to compare this study with is lake Loitsana in the Sokli Carbonatite Massif area (67°48'17" N 29°16'46" E, 214 m a.s.l.), situated only c. 10 km to the northwest of Kuutsjärvi (see Fig. 1). The lake is unique as it harbours an unusually long sediment record incorporating not only sediment deposited during the Holocene, but also sediment from the Weichselian interstadials (MIS 5d, MIS 5c and MIS 3; Helmens et al., 2012, 2018) as well as sediment from the Eemian interglacial (MIS 5e; Helmens, 2000; Plikk et al., 2016). Immediately following the deglaciation of the Loitsana area the large Sokli ice lake was dammed between the retreating ice sheet and the higher elevated areas to the southeast. The lake persisted for less than 100 years and partial drainage in three stages eventually created an extensive shallow water environment. In the sediment from this shallow lake stage remains of tree-type *Betula* as well as many high-temperature indicator plant taxa such as narrow-leaved *Potamogeton spp.*, *Typha spp.* and *Nymphaea spp.* was found, suggesting warmer than present summer temperatures and a productive early Holocene environment (Shala et al., 2017; Helmens et al., 2018), similar to the reconstructed environment around Kuutsjärvi in this study.

However, during this productive shallow water stage the ice margin was situated more than 3 km from the coring spot, and during the larger lake stages when the ice-margin were closer, only low percentages of *Betula* pollen and occasional macrofossil remains of tree-type *Betula* were preserved in the sediment (Helmens et al., 2018). This implies there might have been a difference between these two sites in terms of ice-marginal environment immediately following the deglaciation. However, the initial size of the ice lake and distance from the shore in the first stages may likely have contributed to fewer macrofossil remains preserved, as also suggested by Helmens et al. (2018). Furthermore the authors argue that a large percentage of grasses in the pollen sum may have skewed the pollen-based reconstructions, hampering interpretation of the terrestrial vegetation. Large amount of *Poaceae* pollen (c. 26%) is only present in the very beginning of the Kuutsjärvi sediment record (Subzone I-a), but then rapidly decreases to c. 7% in Subzone I-c (Sakari Salonen, in preparation; *Poaceae* pollen is not shown in Fig. 8). There is a possibility that grasses occurred in high percentages during the earlier overflow events not included in this study (see section 4.1). Additionally, as briefly touched upon in section 4.4, even within Zone I there might have been a succession from a slightly more open into a denser birch forest near the lake, as evident by fewer plant remains and lower pollen percentages of tree-type *Betula* in Subzone I-a compared to Subzone I-c (Fig. 8). In any case this succession must have been extremely rapid, as the overflow event stage likely only comprise of 10-15 years at most (see section 4.1 and 4.3).

5.2 Migration of trees into the study area following the deglaciation

In many other studies in Fennoscandia birch forests are reconstructed during the earliest parts of Holocene using pollen and macrofossil evidence retrieved from lake sediment records. In different locations on the Norwegian west coast birch forest were found to have established c. 11000-10800 cal. yr BP (e.g. Birks and Birks, 2008; Karlsen, 2009; Krüger et al., 2011), whereas in the central Norwegian mountains (above 1000 m a.s.l) the birch forest initiation is dated to c. 10300 cal. yr BP (Paus, 2010; Paus et al., 2011). In northwestern Norway, Bjune et al. (2004) reconstructed the establishment of birch forest in the Dalmutladdo area (close to the Finnish border) soon after the deglaciation around 10200 cal. yr BP, which is similar in time to the colonisation of birch forests in nearby Andøya at c. 10400 cal. yr BP (Vorren et al., 2009) as well as on Kvaløya in northernmost Norway (Birks et al., 2012), both of which are located outside the Younger Dryas ice extent (Stroeven et al., 2016). However, further to the east near the Varanger peninsula, tree birch forests are suggested to have established as early as 11000 cal. yr BP (Seppä, 1996). In Aareavaara in northeastern Sweden birch were recorded close to the retreating ice sheet (Möller et al., 2013), and in Kipojärvi in northernmost Finland birch forests were recorded in early Holocene at c. 9200 cal. yr BP, although this date is suggested by the authors to be a little too young (Väliranta et al., 2011b).

All in all this is consistent with the results in this study and suggests a very rapid migration of tree-type *Betula* closely along the ice margin during the final retreat of the ice sheet, following the Younger Dryas. A probable migration path into northern Finland and the northernmost parts of Norway are from refugia in Russia to the east, rather than from the southern parts of Fennoscandia. In northeastern European Russia evidence for scattered occurrences of tree-type *Betula* has been found during the early Holocene (Väliranta et al., 2006; Salonen et al., 2011; Väliranta et al., 2011a), together with evidence of lateglacial refugia in the area (Väliranta et al., 2011a). Furthermore, lateglacial establishments of birch forests dated to 14000-13000 cal. yr BP were found in the Rostov-Jaroslavl region of Russia southeast of Finland, and tree-type *Betula* were found to be pioneers in the recently deglaciated area of Russian Karelia (close to the southeastern Finnish border) c. 11500 cal. yr BP (Wohlfarth et al., 2007). Other studies in Fennoscandia also suggests lateglacial refugia for trees, most notable in the central Norwegian Scandes where stomata of *Pinus* and *Picea* was found on lateglacial nunataks (Paus et al., 2011), as well as in the central Swedish Scandes where *Betula pubescens*, *Pinus sylvestris* and *Picea abies* megafossils where found on a similar lateglacial nunatak (Kullman, 2002).

A minor plant fragment suspected to be a *Pinus* budscale was found in Subzone I-b in this study, and although uncertain this could indicate that scattered occurrences of pine existed in the area already before the transition into a mixed pine and birch forest at c. 9400 cal. yr BP. Due to the gentle low peaks of the study area any lateglacial survival of tree taxa is however unlikely, but the peaks of the Värriötunturit fell chain were nevertheless deglaciated some time before the low-lying areas (see Fig. 5). The occurrence of *Betula* trees and possibly *Pinus* on the Värriötunturit prior to the final deglaciation is therefore possible, and with the case of tree-type *Betula* it might explain the apparent small discrepancy seen in the extremely rapid migration of birch forests around Kuutsjärvi in comparison to the possible slower colonisation near the Sokli ice lake. Although the peaks of Ykkönen and Kakkonen at present are above the forest line with only scattered occurrences of trees (see Fig. 1), the peaks were due to glacial isostasy lower elevated in early Holocene. The current absolute uplift per year is 6 mm in the region (Kakkuri, 2012), which means the area was at least 64 meter lower elevated at the deglaciation. However, the uplift rate was likely much higher in early Holocene, so a greater difference can be expected, and considering that the area are just above the contemporary forest line at present-time, it is not unreasonable to assume the peaks were forested during the early Holocene. In Abisko in the northern Swedish Scandes the tree-type *Betula* tree line is suggested to have been at an altitude of 300-400 m higher than present in the early Holocene (Barnekow, 1999; Barnekow and Sandgren, 2001).

5.3 Climatic conditions during the early Holocene

Some studies recording birch forests during the early Holocene are also suggesting higher than present temperatures during the same time, reconstructed from pollen, indicator plant taxa or chironomids. This is consistent in e.g. central Norway (e.g. Paus, 2010; Paus et al., 2011), in northernmost Finland (Väliranta et al., 2011b) and as previously mentioned in Loitsana, 10 km from the Värriötunturit area (Shala et al., 2014b; Helmens et al., 2018). Furthermore, Väliranta et al. (2015) recorded higher than present temperatures in Russia, and this same pattern has also been observed in other proxies such as the SST record in the Barents sea (Hald et al., 2007). Altogether this also correspond with the increased summer insolation and reduced winter insolation at high latitudes during the early Holocene (Shala et al., 2014b, and references therein), indicating greater seasonality and a more continental climate in northern Fennoscandia.

It is not possible to define any temperature interval for the Värriötunturit area due to absence of plant indicator taxa, and possible reasons for this will be further discussed in the next section (5.4). However, based on evidence in the other studies in the nearby region it is likely the deglaciation took place in an already warm climate in disequilibrium with the ice sheet, that created favourable conditions for rapid birch migration and thus made it possible for trees to grow in very close proximity to the margin of the retreating ice sheet. In other words, it can be argued that the ice-marginal birch forests alone indicates warm summer temperatures during the early Holocene.

5.4 The absense of high-temperature indicator taxa in the sediment

Despite this study providing strong evidence for birch forests covering the area around Kuutsjärvi already at deglaciation age, no high-temperature indicator plant taxa were identified in the sediment record. This is somewhat unexpected considering the fact that the nearby aforementioned lake Loitsana site presented warmer than present temperatures reconstructed from many different aquatic and semi-aquatic plants (Shala et al., 2014b; Helmens et al., 2018). However, there can be several explanations for this and some of those will be discussed below.

First, there is a possibility that these indicator taxa in fact were present in the environment adjacent to the lake but for some reason were not preserved in the sediment, or at least not in the middle part of the lake. While the overflow sediments (Subzone I-b and Subzone I-d) contained a variety of plants, it seems like the shore vegetation was poorly represented in the gyttja section. It can be assumed that ferns made up a major part of the shore vegetation in Zone III, but the question is why an abundance of ferns are represented while other shore taxa are not. The middle and deepest part of the lake is usually not the best coring place for macrofossils (Birks, 2001; Väliranta, 2006), although this usually more accurately applies to larger lakes, and the surface area of Kuutsjärvi is a very small. At the same time the steep sides near the lake, as well as the steep bathymetry of the lake itself, is expected to increase deposition and preservation potential in terms of easier transportation of remains to the middle part. Shala (2014) found that there were no significant differences in amount of macrofossils depending on distance to the shore of lake Loitsana, and correlated this to steep slopes next to the lake. As shown by the contemporary surface samples retrieved in this study, this does not appear to be the case in Kuutsjärvi despite its much smaller size. The type and quantity of plant remains varied a lot depending on which part of the lake that was sampled, and the deep middle part seem to contain fewer plant remains in general (Table 2). It is therefore evident that the transportation by water must play a big role for taphonomy in Kuustjärvi, and it is possible that the slow moving flow of water input in the inlet simply did not provide enough energy to transport remains into the deepest part of the lake. It cannot be ruled out that slightly different macrofossil assemblage will be found if the coring is instead conducted closer to the inlet.

A second possibility for the differences noted between Kuutsjärvi and Loitsana could be the slight mean July temperature difference between the sites. The present-day mean July temperature near Kuustjärvi reported in this study seems to match well with mean July temperatures reported by e.g. Shala (2014) for lake Loitsana (only a 0.1 °C difference). However, the weather data used in this study include the years 1975-2018, and if the mean July temperature for Savukoski (the station used in the Loitsana study, located at 67°17' N 28°10' E, 193 m a.s.l.) is calculated based on this interval, the present-day value there would instead be 14.4 °C (Finnish Meteorological Institute, 2019). While the Savukoski weather station is much further from Loitsana than the Värriötunturit weather station, the elevation is more similar to lake Loitsana at 214 m a.s.l than the Värriötunturit station is at 341 m a.s.l, and it is therefore more representative to use this station for Loitsana. Nevertheless it can be concluded that there is likely a present-day mean July temperature difference between these two sites, which would be expected based on the elevation difference (c. 0.6 °C per 100 m, see e.g. Vedin, 2004). An explanation could be that this relative difference in altitude between the sites in early Holocene was enough to hamper high-temperature indicator taxa like *Typha spp.*, *Glyceria lithuanica* or *Potamogeton spp.* to thrive near Kuutsjärvi, but not enough to slow down the rapid colonisation rate of birch forests in the area. However, another possibility could be that the absence of the high-temperature indicator taxa is not related to temperature at all, but rather to the local environmental factors of the lake catchment. Kuutsjärvi is a very small and deep lake with forested steep slopes close to the shore. This means that the littoral zone is narrow, and might not have provided a good habitat for aquatic and shoreline taxa such as *Typha spp.* or *Potamogeton spp.* to thrive. It is on the other hand not surprising that these taxa were found in Loitsana, as the lake has a water depth of only 1-2 m and is surrounded by wetlands (Shala, 2014), thus providing a very suitable habitat for these kind of plants in contrast to Kuutsjärvi (Anderberg and Anderberg, 2019).

5.5 Conclusions

The deglaciation phase of the Värriötunturit area is unique as it provided the right conditions for preservation of plants remains from plants growing in the ice-marginal area immediately following the deglaciation, a time period that is rarely covered in lake sediment sequences. The findings of this study therefore constitute an important contribution to the growing knowledge on early Holocene climate and environment in northern Fennoscandia, and a few main conclusions can be drawn based of the results:

i) Subarctic birch forests were present in the ice-marginal environment immediately after deglaciation, and might also have been present on the ice-free Värriötunturit peaks before the final deglaciation of the low-lying areas. When the tree-type *Betula* pollen and macrofossil remains were deposited in the sediment during the overflow event stage (Zone I, Fig. 8) it is estimated that the ice sheet was situated only 300 m from Kuutsjärvi.

ii) The very rapid establishment of birch forest in the area in itself probably indicate a warm climate during early Holocene, which would also be in accordance with previous evidence from lake Loitsana in the nearby Sokli Carbonatite Massif area (Shala et al., 2017; Helmens et al., 2018), as well as other studies. However, no definite temperature conclusions can be made based on the result in this study as no applicable indicator plant taxa were found in the sediment sequence.

iii) Scattered occurrences of pine trees were possibly growing in the area already at deglaciation, but this remains uncertain based on the minor evidences in this study. A transition into a mixed birch and pine forest occurred around 9400 cal. yr BP, which is noted to be similar or slightly earlier than lake Loitsana only 10 km to the northwest (Shala, 2014) and a couple of hundred years earlier than Kipojärvi in northernmost Finland (Väliranta et al., 2011b). Just like birch, pine probably migrated into northern Finland from refugia in the east following the deglaciation.

5.6 Future research in the area

This thesis was focusing solely on macrofossil analysis but was part of a larger multi-proxy project on the lake sediment sequence from Kuutsjärvi, where also pollen, diatoms, chironomids and geochemical proxies have been, or will soon be, analysed. While this study provides a great deal of details about the local environment during the early Holocene, it is evident from the environmental interpretations that it would have been more challenging to make conclusions about the environment exclusively with regard to the macrofossil remains, especially in the gyttja zones. This is because remains were very scarce in the gyttja section, and thus it was difficult to infer with certainty if the taxa assemblage found were entirely representative for the vegetation in the area.

As it turns out, the supplemented pollen taxa provided excellent confirmation of the more regional distribution of birch and pine throughout the sequence, and in combination with the macrofossil remains it was possible to more accurately reconstruct the terrestrial environment. Without the pollen it would have been harder to e.g. pinpoint the shift from birch forest into mixed birch and pine forest, and also to definitely be able to conclude that complete birch forests were growing in the area following the deglaciation. On the other hand, while tree-type *Betula* pollen in itself suggest the near presence of birch in the area, based on modern pollen spectras (Prentice, 1978), the exact location of the birch forests in the ice-marginal environment would have been uncertain if not for the abundant tree-type *Betula* macrofossil remains present. In that sense macrofossils were essential to definitely confirm the trees, while the pollen provided the general picture. This proves that a multi-proxy approach is very beneficial and are important to consider in palaeoenvironmental studies, especially when using natural archives such as lake sediment, where the material is not preserved in situ as in mires.

The future multi-proxy study of Kuutsjärvi will likely be able to give an even more detailed reconstruction of the environment in the area, and also hopefully a temperature indication via the use of chironomids. A new core from Kuutsjärvi closer to the inlet might also be of interest for future studies, as it was noted in this study that more macrofossil remains appeared near the inlet. Additionally, other lakes in the area might be of interest, because just as Kuutsjärvi received overflow sediments from the retreating ice sheet, it is possible that there are similar overflow sediment deposits containing plant remains in the lakes in the two gorges Syväkuru and Pirunkuru. Although these lakes are less accessible for coring during winter, they might be interesting alternatives for future research as there is a possibility that they, unlike Kuutsjärvi, may contain indicator plant taxa that can be used to create an even more detailed reconstruction of the climatic conditions of the area in early Holocene.

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