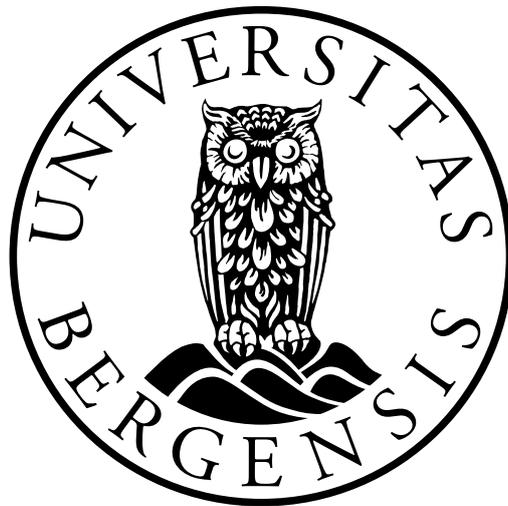# Weichselian vegetation and palaeoenvironment in western Norway and northern Russia

Evidence from pollen analytical investigations

Linn Cecilie Krüger

Dissertation for the degree philosophiae doctor (PhD)

at the University of Bergen

2012

Scientific environment

This thesis is part of the fulfilment for the degree philosophiae doctor (PhD) at the University of Bergen, and consists of a synthesis and three individual papers. The work has been funded by the Research Council of Norway through the project "The Ice Age Development and Human Settlement in northern Eurasia (ICEHUS)"; grant no. 167131/V30. The work has been carried out at the Department of Earth Science (GEO) and the Department of Biology (BIO). I have been a member of the Ecological & Environmental Change Research Group (EECRG) at BIO and the Research Group in Quaternary and Paleoclimate at GEO. Associate professor Aage Paus, BIO, has been the main supervisor, and the project manager of ICEHUS, Professor John Inge Svendsen, GEO, was co-supervisor.
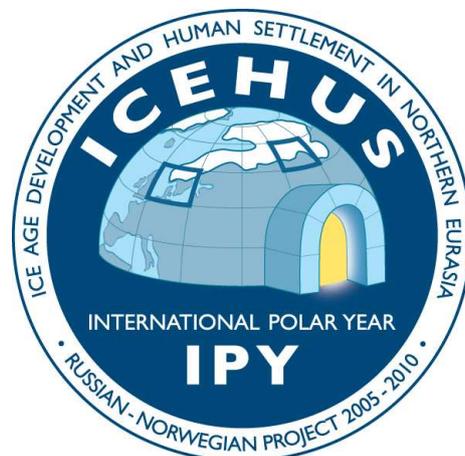
Acknowledgements

It has been a long journey to perform the work needed to complete this thesis, and I would never have managed to make it through without help from many people whom I will forever be grateful to.

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Many thanks go to the other members of the ICEHUS-group; Jan Mangerud, Øystein S. Lohne, Herbjørn Presthus Heggen, Richard Gyllenkreutz, and Mona Henriksen, for their support, enthusiasm and valuable comments during our group meetings. Inger Karlsen is thanked for making me feel welcome as an employee at the Department of Earth Science.

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Bergen, April 2012

Linn Cecilie Krüger

Abstract

This thesis focuses on the vegetation history and environmental changes in western Norway and northern Russia during the last glacial period (the Weichselian). Pollen grains deposited in lakes and bogs are used as the main palaeoecological tool to reconstruct the vegetation in this period characterised by a changing climate. The work is presented in three individual papers.

Paper I deals with the vegetation development on the islands Stord and Bømlo in southern Hordaland, western Norway, at the end of the Late-Weichselian/Marine Isotope Stage (MIS) 2. The two small basins studied, Vassnestjern and Dåfjordsmyr, were deglaciated around 14.6–14.5 ka BP, which is in accordance with other studied sites in the region. The pioneer vegetation was relatively sparse and characterised by snow-bed taxa like *Salix*, *Rumex* and *Oxyria* in addition to grasses. The vegetation became gradually denser during the Lateglacial interstadial (Bølling-Allerød). *Empetrum* was an important element of the vegetation from around 13.7 ka BP. At least two short-lasting (100–150 years) episodes of reduction in humus-soil vegetation are recorded within the interstadial. These cold periods have been correlated with the GI-1d (14.025–13.9 ka BP) and GI-1b (13.26–13.05 ka BP) events in the Greenland Isotope records. Responses to the Younger Dryas (YD) cooling (12.85–11.65 ka BP) are clearly reflected as an opening of vegetation and reduction in humus-soil communities. Re-establishment of heath communities followed by the development of birch forests were responses to the Holocene warming.

Paper II presents pollen records from Dimnamyra and Løkjingsmyra, two small bog basins in the Sunnmøre region, western Norway. The study revealed that the outer coast of Sunnmøre was deglaciated around 15.3 ka BP, slightly earlier than previously thought. The new records from Sunnmøre are compared with the data from southern Hordaland presented in paper I, as well as other published records from western Norway and the European continent. The pioneer vegetation, characterised by snow-bed communities, was quite similar along the coast of western Norway. However, the subsequent development of extensive heath vegetation during the Lateglacial interstadial recorded in south-western Norway is almost absent further north. The vegetation was dominated by grassland, and responses to the GI-1d and GI-1b events are not detected in the Sunnmøre records. A pronounced peak in Poaceae is recorded around 12.9 ka BP, probably reflecting warmer and/or drier conditions. The YD event is clearly reflected also in the Sunnmøre records as a change towards more open vegetation and increased occurrence of snow-bed communities. Pollen-climate transfer functions were used to reconstruct mean July temperatures (T_{jul}) for several sites in western Norway. Extremely little variability through the Lateglacial is reconstructed for the southern sites, and YD temperatures appear to have been overestimated. The estimated temperatures of the northern sites accord better with the biostratigraphical signals of the sites. However, all sites along the transect show similar vegetational responses, and the inconsistency in the reconstructed T_{jul} between the sites

suggests that the results from pollen-based temperature reconstructions from the Lateglacial must be interpreted with caution.

The focus of paper III is the vegetation development and the glacial history of the Polar Ural Mountains, northern Russia. Sediment and palynological records are presented from the shallow Lake Gerdizty at the eastern rim of the mountain chain. Two till beds were identified in the bottom sediments of the lake. The lowermost, fine-grained till was deposited by an ice-sheet from the Siberian lowland sometime towards the end of MIS 5 or during MIS 4. This implies that the lake is not positioned outside the limits of all Weichselian (MIS 5d–2) glaciations, as assumed when the lake was cored. The overlying, coarser sediments originate from a local ice cap that was flowing from the mountain area in the west sometime during MIS 4, i.e. after 78 ka BP, but before ~65 ka BP when lacustrine sediments started to accumulate in the basin. Throughout the Middle Weichselian/MIS 3 and the major part of the Late Weichselian/MIS 2, the landscape was characterised by open vegetation of steppe and tundra communities. Some dwarf shrubs were present in the earliest phase, but no trees were growing locally, thus indicating summer temperatures below 10 °C. When climate improved at the end of the Late Weichselian, the vegetation became denser with increasing importance of shrubs. Birch-spruce forests developed in the vicinity of Lake Gerdizty shortly after the transition to the Holocene, indicating higher summer temperatures than today.

List of papers

This thesis consists of three papers. In the following, they will be referred to by Roman numerals (I–III).

I.   Karlsen*, L. C. (2009).
Lateglacial vegetation and environment at the mouth of Hardangerfjorden, western Norway.
Boreas 38(2): 315–334.

*The author changed surname from Karlsen to Krüger after the publication of this paper.

II.   Krüger, L. C., Paus, A., Svendsen, J. I. & Bjune, A. E. (2011).
Lateglacial vegetation and palaeoenvironment in W Norway, with new pollen data from the Sunnmøre region.
Boreas 40(4): 616–635.

III.   Svendsen, J. I., Krüger, L. C., Mangerud, J., Paus, A. & Murray, A.
Glacial and vegetation history of the Polar Ural Mountains during the Last Ice Age.
To be submitted to *Quaternary Science Reviews.*

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Authorship declaration

Papers II and III in this thesis are co-authored. The contributions from each author are listed below.

Paper II

Krüger, L. C., Paus, A, Svendsen, J. I. & Bjune, A. E. (2011).
Lateglacial vegetation and palaeoenvironment in W Norway, with new pollen data from the Sunnmøre region.
Boreas 40(4): 616–635.

Linn Cecilie Krüger: Field work at Løkjingsmyra, pollen analysis, numerical analyses, preparation of all figures, writing and editing.
Aage Paus: Data contribution, reading and commenting.
John Inge Svendsen: Field work at Dimnamyra, reading and commenting.
Anne E. Bjune: Climate reconstructions, reading and commenting.

Paper III

Svendsen, J. I., Krüger, L. C., Mangerud, J., Paus, A. & Murray, A.
Glacial and vegetation history of the Polar Ural Mountains during the Last Ice Age.
To be submitted to *Quaternary Science Reviews*.

John Inge Svendsen: Project management, leading author, writing of sections concerning lithostratigraphy, chronology, glacial geological investigations, and discussion of the glacial and climate history, editing.
Linn Cecilie Krüger: Pollen analysis, numerical analyses. Responsible for writing most of the methods chapter, the results concerning the pollen stratigraphy and numerical analyses, and the discussion of the vegetation history. Preparation of several figures (MS and XRF results, age-depth model, pollen diagrams, PCA diagrams), and editing of the final draft.
Jan Mangerud: Data contribution (results from glacial geological research), reading and commenting.
Aage Paus: Data contribution (Lake Yamozero pollen data), reading and commenting.
Andrew S. Murray: Carried out all OSL dates and assessed the results.

Contents

1. Introduction

The last (Weichselian) ice age lasted from the end of the Eemian around 117 ka (thousand years) BP (Mangerud 1991) until the onset of the Holocene ~11.7 ka BP (Walker *et al.* 2009) (cf. Fig. 1). During this period, huge ice sheets of variable sizes covered parts of northern Eurasia (e.g. Svendsen *et al.* 2004). The major part of Norway was covered by the extensive Scandinavian ice sheet during the Last Glacial Maximum (LGM, ~28–20 ka BP) (Mangerud 2004; Mangerud *et al.* 2011). The final eastward withdrawal started in the North Sea around 19–18 ka BP (Sejrup *et al.* 2009), and the earliest deglaciated coastal areas in southern Norway (Jæren) were ice-free around 17–16 ka BP (Knudsen 2006). The deglaciation continued in the following millennia, but due to unstable climate, the withdrawal was interrupted by halts and re-advances. Thus, only a narrow strip of land was exposed along the coast of western Norway before the final ice withdrawal started ~11.7 ka BP, at the transition to the Holocene. In comparison, northern Russia was less extensively glaciated during the last glacial cycle (Svendsen *et al.* 2004). Here, large areas have been ice free since the end of the penultimate glaciation, >130 000 years ago, whereas others experienced one or several periods of glaciation during the Weichselian (Svendsen *et al.* 2004).

The presence of these large fluctuating ice sheets had an enormous impact on the surrounding environment (i.e. sea levels, hydrology, vegetation, and animal and human populations). The project "Ice Age development and human settlement in northern Eurasia (ICEHUS)" aimed to study long-term development in the east (Russia) and more short-lived, rapid fluctuations in the west (Norway). The work presented in this thesis is mainly focusing on the vegetation and climate history in these two regions, from the time of the last deglaciation to the transition into the Holocene.

The main study area in this thesis is western Norway, which has been a key area for studying the Lateglacial vegetation development and environmental history for many decades. Earlier studies have reconstructed the vegetational changes from deglaciation, when pioneer vegetation colonised freshly exposed soils, to the development of denser vegetation as the ice sheet moved further away from the site, via reversal during ice re-advances and a final vegetation closure in the early Holocene (e.g. Fægri 1940; Chanda 1965; Larsen *et al.* 1984; Johansen *et al.* 1985; Kristiansen *et al.* 1988; Paus 1988, 1989a, b, 1990; Birks *et al.* 2000). This broad picture in the vegetation development is recorded at all sites along the coast, but as summarised by e.g. Birks (1994), there were differences in the vegetation types between south and north. Analyses of lake sediment cores from several new sites, presented in this thesis, aimed to increase our knowledge about the Lateglacial conditions along the west Norwegian coast. The objectives were to determine the timing of deglaciation and to infer the vegetation development at the studied sites so that differences between the areas could be further elucidated.

In Russia, the study area is the Polar Ural Mountains. Previous studies of the vegetational changes in the Polar Urals are mainly covering the Holocene (Koshkarova *et al.* 1999; Panova *et al.* 2003; Andreev *et al.* 2005; Jankovská *et al.* 2006). Our study aimed to localise sediments covering a longer time span and thus improve our understanding of the environmental and glacial history further back in time in this region.
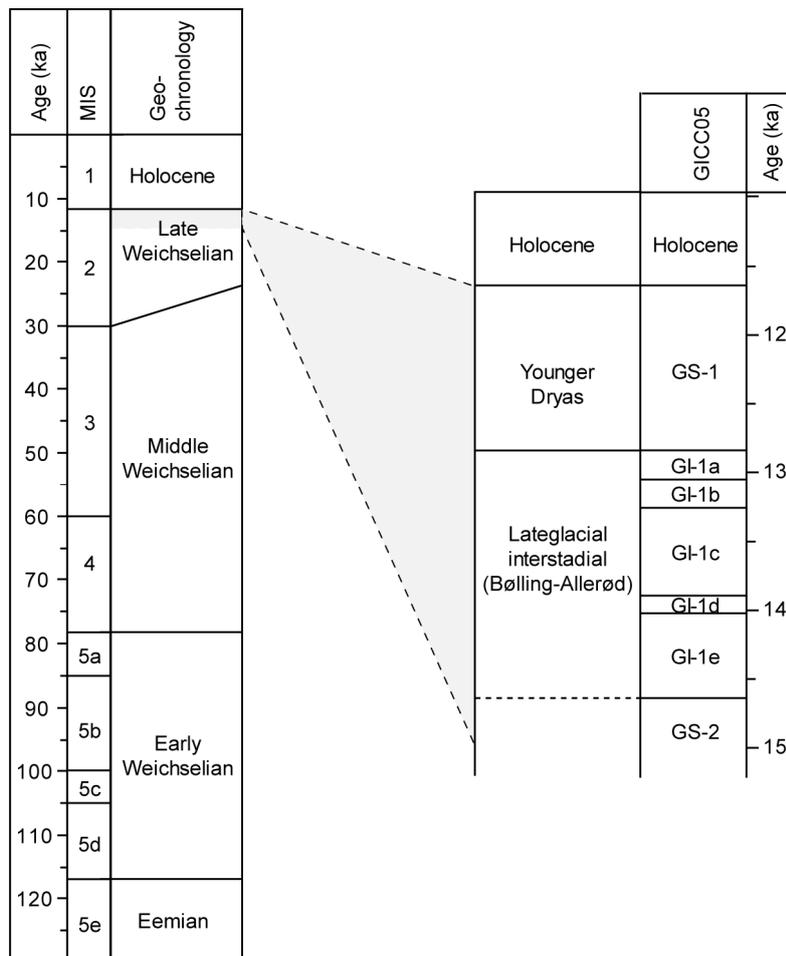
Fig. 1. Chronostratigraphical division of the last interglacial/glacial cycle. GICC05 = Greenland Ice Core Chronology 2005 (Lowe *et al.* 2008). GS = Greenland Stadial; GI = Greenland Interstadial. MIS = Marine Oxygen Isotope Stage.

2. Study areas

Sediment cores from four small lakes or filled-in bogs in western Norway (Figs 2–3), and one lake in northern Russia (Figs 2, 4), were investigated. All the Norwegian sites are located outside the limit of the Younger Dryas (YD) end moraine (Mangerud 2004), and were selected to ensure continuous sediment sequences covering the whole period from deglaciation and onwards. The present-day climate in western Norway is oceanic, with mean July and January temperatures at the sites of around 13 °C and 0–2 °C, respectively (DNMI 2012) (Table 1). The present vegetation at the sites is characterised by bog and heathland communities surrounded by *Juniperus communis* shrubs and trees of *Betula pubescens, Pinus sylvestris, Corylus avellana* and *Sorbus aucuparia*.

Fig. 2. Map of northern Europe and Russia showing the key sites in this study in red. For the sites in western Norway, see also Fig. 3. Other sites mentioned in the text are given in black; M. Kurja = Mamontovaya Kurja. Ice sheet limits for the Last Glacial Maximum (LGM) and the Weichselian maximum are marked (cf. Svendsen *et al.* 2004).

The northern Russian site, Lake Gerdizty, is found at the eastern rim of the Polar Ural Mountains, close to the extension limit of any Weichselian ice sheets (cf. Svendsen *et al.* 2004). The climate in the region is continental. The summer temperatures of 13 °C are similar to western Norway, but the winters are much colder with mean January temperatures of -23 °C (http://meteo.infospace.ru/climate/html/). The area is dominated by open tundra vegetation. However, the lake is located approximately at the northern modern range limits of birch, larch and spruce (cf. Kremenetski *et al.* 1998; MacDonald *et al.* 2000), and trees or

shrubs of birch, spruce and larch are growing close to the lake today (D. Nazarov, pers. comm.).

A summary of the location and climatic data of the sites is presented in Table 1, and more detailed information about the sites is given in the individual papers.
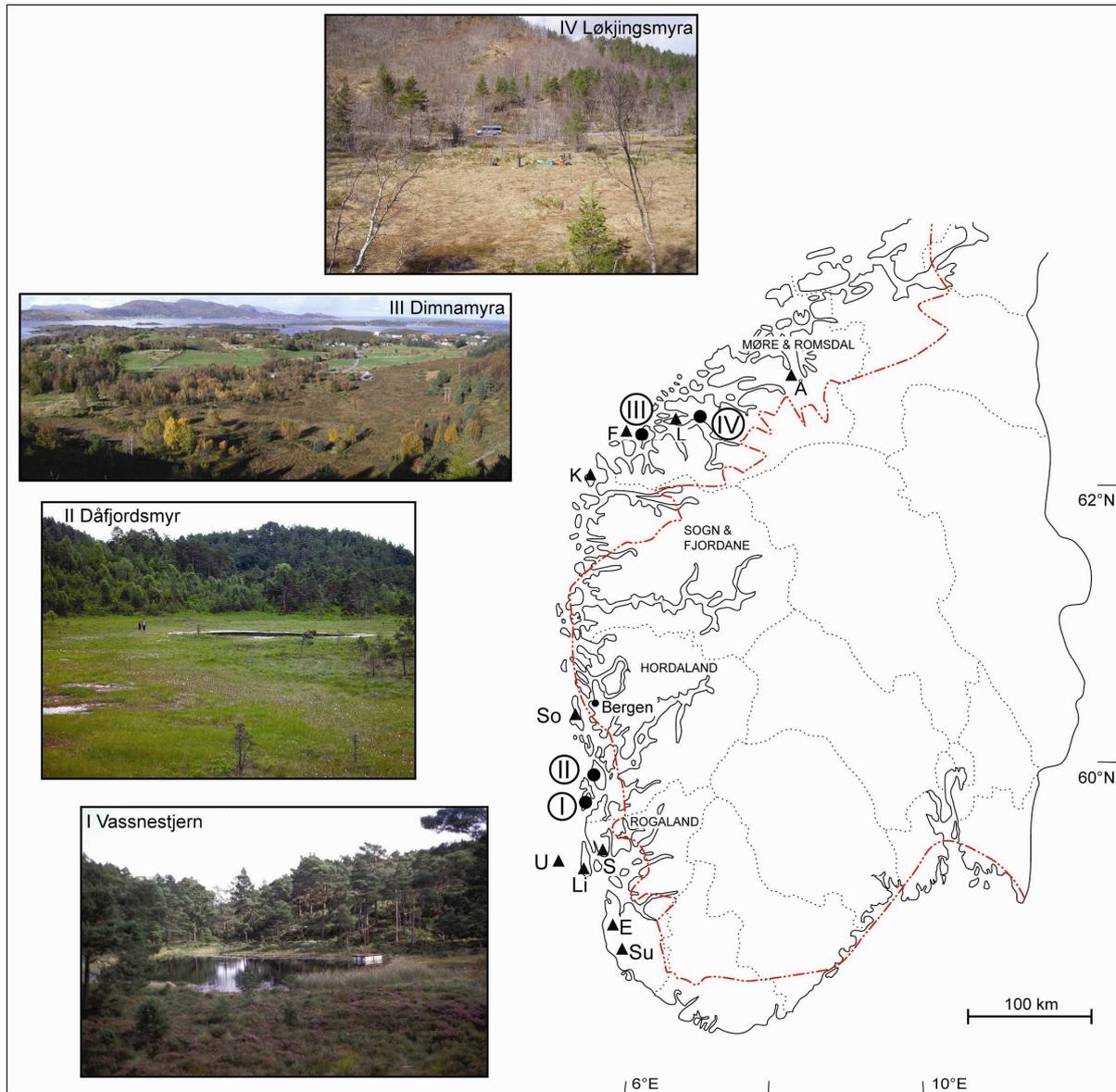
Fig. 3. Map of southern Norway showing the position of the four sites in western Norway presented in this work (I–IV, marked with a black dot) accompanied by a photography of each basin. Other studied sites in western Norway are indicated by a triangle and letters; Su = Sumpamyra, Jæren, Rogaland (Paus *et al.* 2003b); E = Eigebakken, Jæren, Rogaland (Paus 1989a); Li = Liastemmen, N Rogaland (Paus 1989b); S = Sandvikvatn, N Rogaland (Paus 1988); U = Utsira (Paus 1990); So = Sotra (several sites), Hordaland (Mangerud 1970, 1977; Krzywinski & Stabell 1984); K = Kråkenes, Sogn & Fjordane (Larsen *et al.* 1984; Birks *et al.* 2000); F = Frøystadmyra, Sunnmøre, Møre & Romsdal (Svendsen & Mangerud 1990); L = Lerstadvatn, Sunnmøre, Møre & Romsdal (Kristiansen *et al.* 1988); Å = Ålvatnet, Møre & Romsdal (Johansen *et al.* 1985). The red dashed line indicates the position of the YD end moraine (Mangerud 2004). Photos: I: Aage Paus, II: Øystein S. Lohne, III: Jan Henrik Koren, and IV: Linn C. Krüger.

Table 1. Characteristics of the sites studied in this work, including altitude (Alt), present size of the sediment basins (Size), present-day mean July (T_{jul}) and January temperature (T_{jan}), and present-day total mean annual precipitation (P). The numbers in the first column refer to the numbers in Fig. 3.

	Site	Location	Alt (m)	Size (km²)	Catchment (km²)	T_{jul} (°C)[*]	T_{jan} (°C)[*]	P (mm)[*]
I	Vassnestjern	59°38'N, 5°13'E	52	0.001	0.03	13.3	2.0	1550
II	Dåfjordsmyr	59°50'N, 5°21'E	41	0.033	0.14	13.5	1.5	1760
III	Dimnamyra	62°19'N, 5°48'E	32	0.040	0.3	12.8	1.2	2075
IV	Løkjingsmyra	62°29'N, 6°48'E	120	0.035	1.5	13.2	0.4	1590
V	Lake Gerdizty	66°50'N, 65°58'E	213	1.2	5	13.0	−23	533

[*]Sources of climate data: DNMI (2012), http://meteo.infospace.ru/climate/html/, Rivas-Martinez and Rivas-Saenz (1996–2009).

Fig. 4. Lake Gerdizty, northern Russia, during field work in March 2006. Photo: Dmitry Nazarov.

3. Scientific approach and methods

3.1. Pollen analysis and statistics

After von Post presented the first percentage pollen diagram almost hundred years ago (von Post 1916), pollen has been widely used as a proxy to reconstruct past flora, vegetation and environment. The major advantage of pollen grains is their resistance to degradation after incorporation into sediments. Secondly, pollen grains are produced in large quantities during the flowering period and are more easily scattered over the landscape than other plant remains. However, pollen as a proxy for vegetation reconstruction also has some limitations. The most severe is the taxonomic resolution; the pollen grains can often only be determined to genus or family level. This poses a problem for the interpretation of the pollen record since a family or genus often consists of species with different edaphic and/or climatic demands. Secondly, the pollen production is not equal for all taxa, and is often associated with the pollination method. Insect-pollinated taxa have a much lower pollen production than the wind-pollinated ones, and their pollen grains are sparsely distributed over the landscape. On the other hand, pollen from wind-pollinated taxa might be transported over large distances and can introduce pollen from species that were not present in the area during the time period investigated. This is particularly an interpretative source of error in open vegetation types as found shortly after deglaciation or in areas beyond the tree-line, e.g. tundra vegetation (e.g. Ritchie & Lichti-Federovich 1967; Gajewski 1995; Paus 2000). However, since pollen grains are generally frequent in the sediments, statistical analyses based on pollen can be carried out, and past flora, vegetation and environment can be reconstructed.

During field work in western Norway, an overview of the stratigraphy in each basin was made by coring of transects using a Russian corer (papers I and II). As the LGM ice sheet presumably removed most of the older sediments in Norway (Mangerud 2004), the sediments found in the basins are covering the period from the final deglaciation until present. One single core or a few overlapping cores were sufficient to sample all the sediments of interest for this study, i.e. from the deglaciation to the early Holocene. Material was taken where these sediments were thickest, generally in the central, deepest part of the basins. Coring in Lake Gerdizty, northern Russia, was carried out from ice during winter (Fig. 4). Several cores from multiple bore holes in the central part of the lake were sampled (paper III).

In the laboratory, the stratigraphy of the cores was described, either according to the system of Troels-Smith (1955) (papers I and II), or by division into lithostratigraphical units based on the major components (clay, silt, sand, gyttja) (paper III). Sediment samples of 1 cm^3 were prepared for pollen analysis using standard methods including acetolysis and hydrofluoric acid treatment (Fægri & Iversen 1989). Tablets containing *Lycopodium* spores were added prior to preparation in order to calculate absolute pollen concentration

(Stockmarr 1971). The aim was to count 500 terrestrial pollen grains in each sample; however, this was not always accomplished due to low pollen concentration. Pollen and spore identifications are based on keys in Moe (1974), Fægri & Iversen (1989), Moore *et al.* (1991), and the modern reference collection at the Department of Biology, University of Bergen. The percentage calculation basis in the pollen diagrams is the sum of terrestrial pollen taxa (ΣP), whereas the representation of all other microfossils (including spores) is calculated as ΣP + X where X represents the microfossil in question.

The pollen diagrams were divided into local pollen assemblage zones (paz) by optimal sum of squares partitioning (Birks & Gordon 1985), and the number of statistically significant zones was determined by comparison with a broken-stick model (Bennett 1996, program BSTICK, H. J. B. Birks & J. M. Line, unpublished). In order to extract more information from the palynological data and to detect potentially underlying patterns in the terrestrial vegetation development, the terrestrial pollen and spore data were treated numerically by ordination (program CANOCO for Windows 4.5, ter Braak & Smilauer 2002). Palynological richness, used as an indication of the vegetational density and the degree of interspecific competition (cf. Grime 1973), was estimated by rarefaction analyses (program RAREPOLL, Birks & Line 1992). The statistical base sum for the analyses was the smallest number of terrestrial pollen and spores identified in the samples, however, excluding samples with very low sums.

3.2. Climate reconstructions

Several different approaches can be used to reconstruct past climatic conditions from biostratigraphic data (see e.g. Birks 1995, 2003; Birks *et al.* 2010). One of these is the indicator species approach (Iversen 1944), which relies on the finding of fossil occurrences of species with known modern climatic demands (e.g. minimum July temperature, see e.g. Kolstrup 1979; Aalbersberg & Litt 1998).

Another approach is the multivariate approach involving mathematical transfer functions (Webb & Bryson 1972; Bryson & Kutzbach 1974; Huntley & Prentice 1988; Birks 1995; Birks 1998; Birks 2003; Birks *et al.* 2010). This approach requires a calibration data set consisting of modern pollen and spore assemblages from surface samples and the associated modern climatic variables. The relationship between the modern pollen and spore assemblages and the modern climate is numerically modelled, giving a transfer function which subsequently can be used to quantitatively reconstruct past climatic variables from a fossil pollen and spore assemblage (Fig. 5) (Birks 1995, 2003; Birks *et al.* 2010).

A modern pollen-climate data set from Norway and northern Sweden was recently published (Bjune *et al.* 2010). This data set was developed some time ago and was used to reconstruct the Lateglacial temperature and precipitation development at Kråkenes based on fossil pollen and spore data (Birks & Ammann 2000; Birks *et al.* 2000). The pollen-climate

transfer functions were developed using weighted-averaging partial least squares (WA-PLS) regression (ter Braak & Juggins 1993). Birks *et al.* (2000) warn that the results are only preliminary due to the lack of modern analogues for the Lateglacial assemblages, but they are also citing ter Braak (1995) that WA-PLS can perform well in non-analogue situations. It was therefore decided to use the WA-PLS transfer functions in an attempt to reconstruct mean July temperature (T_{jul}) and mean annual precipitation from the sites in this study (papers I and II). For comparison purposes, mean July temperature was also reconstructed from earlier presented sites in western Norway (Paus 1988, 1989a, b; Paus *et al.* 2003b). A few amalgamations of the taxonomic groups in the modern data set were necessary to ensure consistency between modern and fossil data sets (see paper II).

Fig. 5. Schematic representation of the stages involved in the quantitative reconstructions of past climate from pollen-stratigraphical data using a modern calibration data set and transfer functions. Modified from Fig. 9.2 in Birks (2003).

3.3. Chronology

To be able to determine the timing of deglaciation, to correlate the pollen records, and to estimate pollen accumulation rates (PAR, pollen grains deposited per cm^2 per year), it is crucial to construct an accurate chronology. The chronologies for the sites in western Norway are based on radiocarbon (^{14}C) dates. Sediment samples were sieved and any plant remains were hand-picked for identification. Identified, terrestrial plant remains were immediately dried after determination to avoid fungal growth that could lead to too young ages (e.g. Wohlfarth *et al.* 1998). The use of solely terrestrial plant remains reduces the risk of obtaining too old ages due the presence of old carbon preserved in the sediments (e.g. Donner *et al.* 1971; Andree *et al.* 1986; Olsson 1986; Moore *et al.* 1998). In some cases, plant remains were absent, and bulk samples had to be dated. All the ^{14}C-dates were calibrated to calendar years using the newest available on-line version of the programme OxCal (Bronk Ramsey 2001, 2005, 2009), including the data sets IntCal04 (Reimer *et al.* 2004) (paper I) or IntCal09 (Reimer *et al.* 2009) (papers II and III). As a test, the dates in paper I were also calibrated including IntCal09, but the differences from the IntCal04 results were small, so the published chronologies were used in the comparisons between the sites. The calibrated dates are presented as ka BP (thousand calendar years before AD 1950).

The concluded chronology for Lake Gerdizty is mainly based on Optically Simulated Luminescence (OSL) dates. The OSL method is independent of the carbon content in the samples and can date material that is far beyond the reach of the ^{14}C technique. The highly minerogenic sediments of the shallow Lake Gerdizty are suitable for dating by this method. Quartz sand grains were prepared and analysed following the single aliquot protocols (Murray & Wintle 2000) at The Nordic Centre for Luminescence Research, Risø, Denmark.

4. Main results and discussion

4.1. Lateglacial and early Holocene vegetation in western Norway

The two southernmost sites, Vassnestjern and Dåfjordsmyr in southern Hordaland (Fig. 3), were deglaciated around 14.6 ka BP, which is in accordance with the results from the Bergen region (Mangerud 1977; Lohne *et al.* 2004). However, this is significantly later than the Jæren area in Rogaland, which was deglaciated sometime around 17–16 ka BP (Paus 1989a; Knudsen 2006). Thus, ice free areas open for plant immigration existed for several thousand years in southern Norway before the studied areas in southern Hordaland were deglaciated. Further north, Dimnamyra, on the outer coast of Sunnmøre, was deglaciated around 15.3 ka BP, approximately at the same time as previously studied sites in the area (Kristiansen *et al.* 1988; Svendsen & Mangerud 1990). However, due to low pollen concentration in the lowermost sediments, the pollen records do not allow interpretation of the vegetation development around this site before approximately 14.8 ka BP. Løkjingsmyra, the other Sunnmøre site, is located further inland, and was deglaciated somewhat later (around 14 ka BP).

The basins show an overall similar stratigraphy, typical for the Lateglacial; a basal unit of highly minerogenic sediments overlain by brownish silty gyttja followed by less organic gyttja silt of Younger Dryas (YD) age and brown Holocene gyttja. The Lateglacial vegetation developments along the coast show several similarities, however, there are also some relatively large differences. The following section will give a short overview of the vegetation development in western Norway mainly based on the pollen records in papers I and II, and the major differences will be discussed. Summary diagrams showing percentage and PAR values for *Salix, Rumex/Oxyria*, Poaceae, *Artemisia, Betula, Empetrum*, and *Huperzia selago* are given in Figs 6–12. For more detailed pollen diagrams, see papers I and II.

At all sites, the earliest pioneer vegetation was sparse and open, dominated by snow-bed species like *Salix, Rumex, Oxyria* and various grasses (Figs 6–8). *Artemisia* (Fig. 9) and Chenopodiaceae were growing on well-drained minerogenic soils. During the Lateglacial interstadial (Bølling-Allerød or GI, cf. Fig. 1), the vegetation became gradually denser as the ice sheet withdrew inland. The increasing representation of *Betula* (Fig. 10) indicates immigration and humus soil development. *Betula* statistics and PAR values suggest that tree birch was growing in the vicinity of Vassnestjern in the late part of the interstadial, around 13 ka BP (paper I). However, this remains to be confirmed by macrofossils (cf. van Dinter & Birks 1996; Birks & Bjune 2010). From Dimnamyra and Løkjingsmyra, total *Betula* PAR is too low to reflect presence of local tree birch (Fig. 10). No *Betula* species differentiation was attempted during analysis, but it is assumed that the sources were local *B. nana* and long-distance transported tree-birch pollen. It has been suggested that scattered birch trees were growing in the region at sheltered localities (Johansen *et al.* 1985; Kristiansen *et al.* 1988,

see also Paus 1995). However, the pollen-based interpretation of Kristiansen *et al.* (1988) is not supported by macrofossil data (Birks & van Dinter 2010).
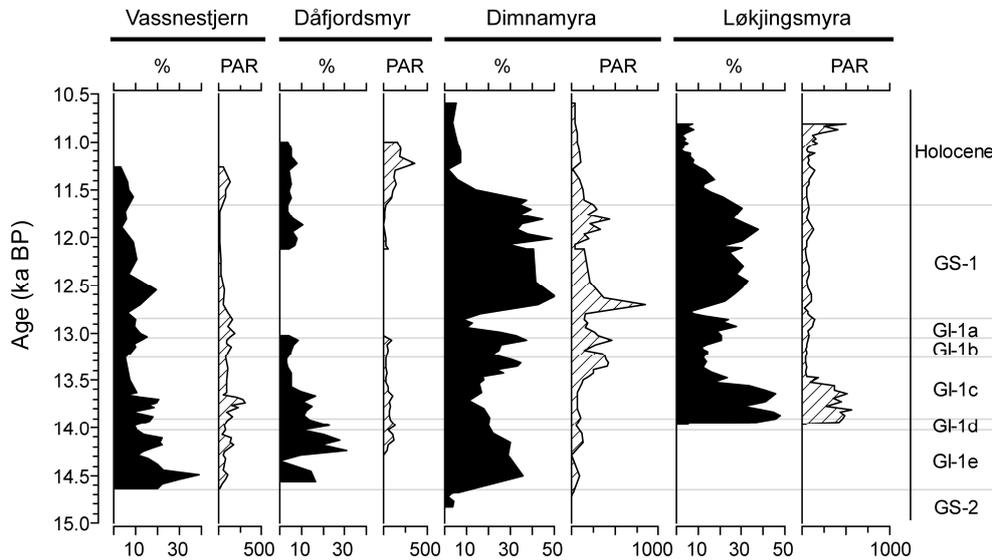
Fig. 6. Summary diagram of *Salix* % and PAR (grains cm^{-2} a^{-1}). The column to the right shows the events in Greenland isotope records following the Greenland Ice Core Chronology (GICC05) from Lowe *et al.* (2008), converted to calendar years BP by subtracting 50 years.
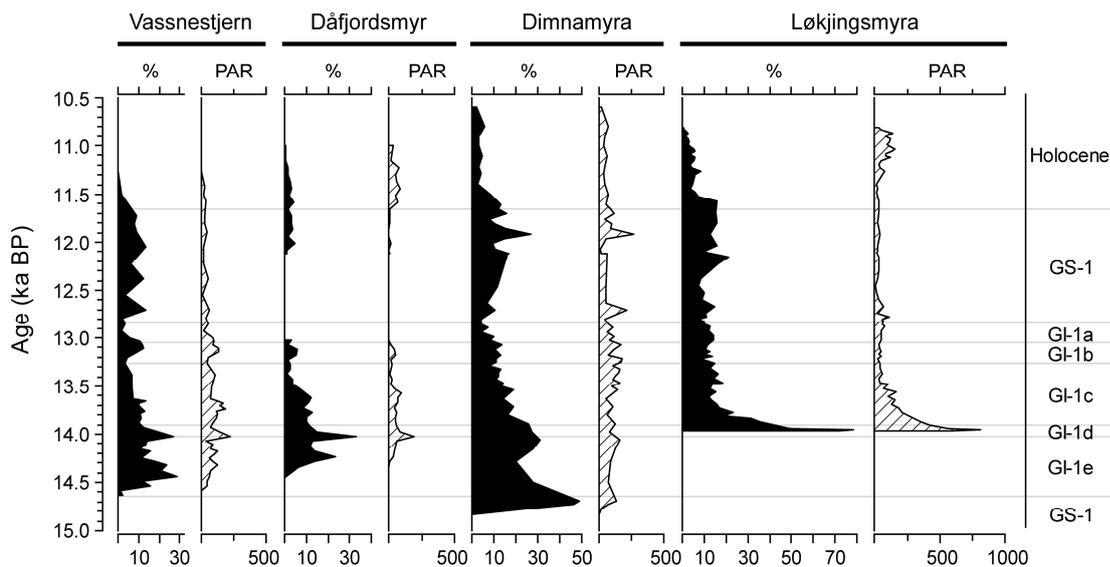
Fig. 7. Summary diagram of *Rumex* and *Oxyria* (combined curve) % and PAR (grains cm^{-2} a^{-1}). Events to the right as described in Fig. 6.
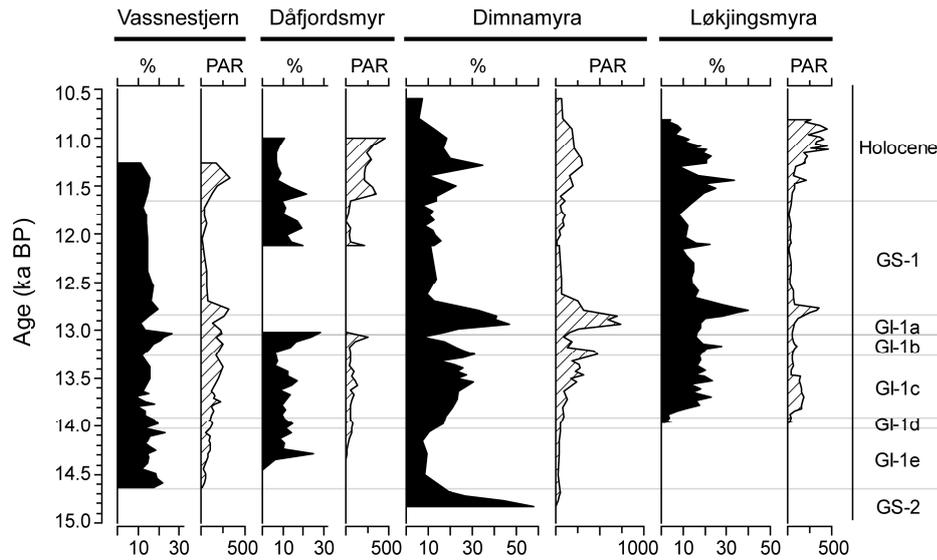
Fig. 8. Summary diagram of Poaceae % and PAR (grains cm^{-2} a^{-1}). Events to the right as described in Fig. 6.
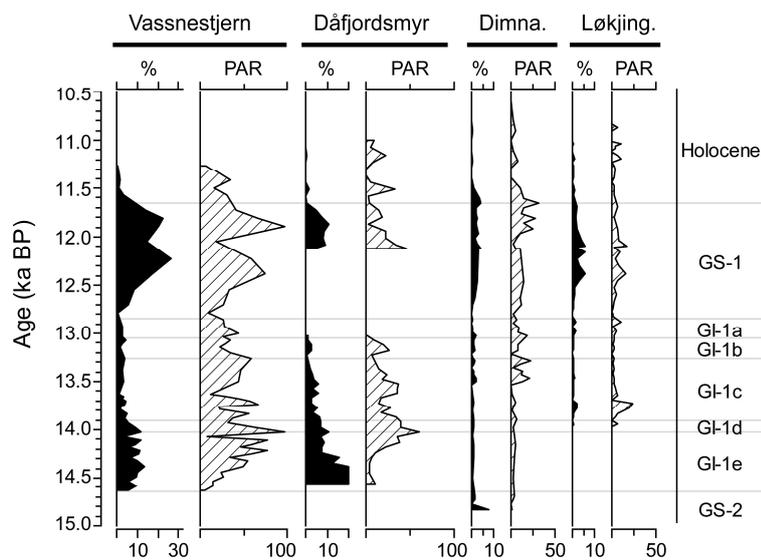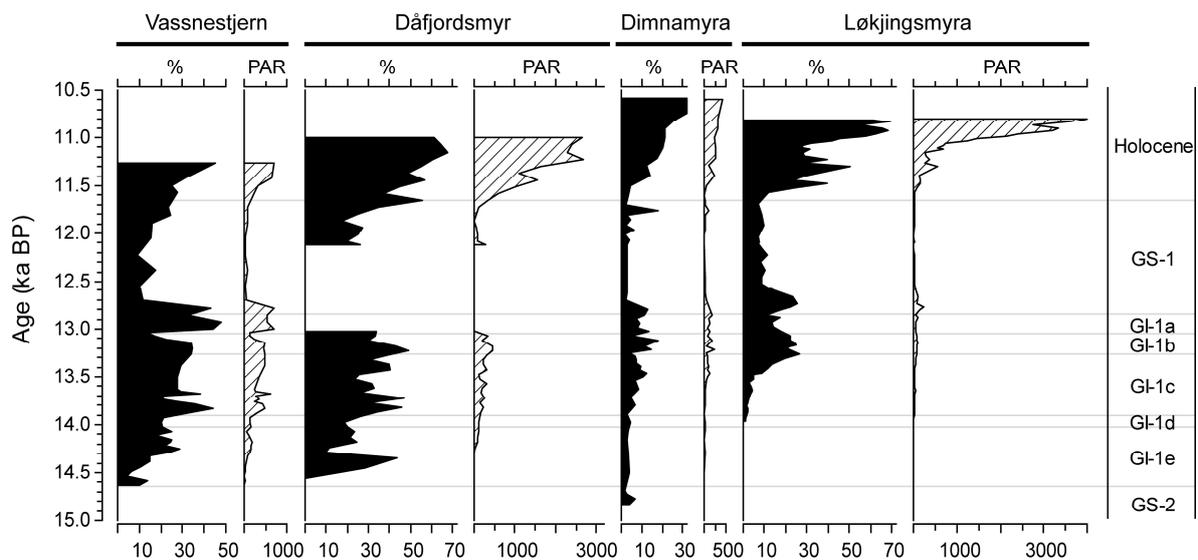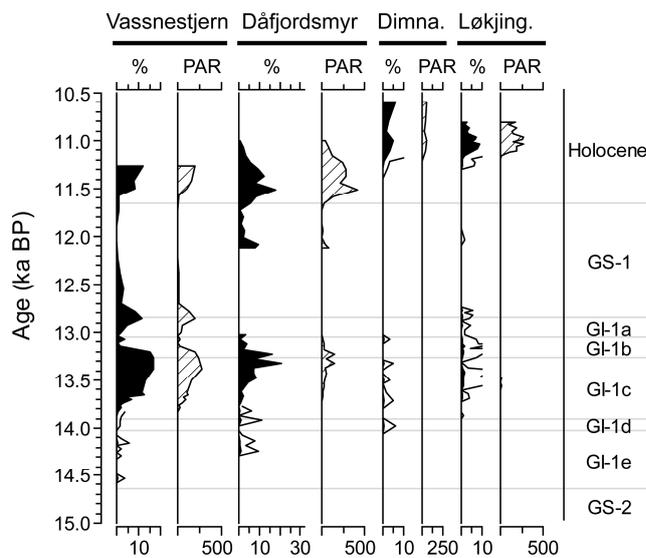

Fig. 9. Summary diagram of *Artemisia* % and PAR (grains cm^{-2} a^{-1}). Dimna. = Dimnamyra, Løkjing. = Løkjingsmyra. Events to the right as described in Fig. 6.

In addition to birch (dwarf shrubs and/or trees), *Empetrum* was an important constituent of the interstadial vegetation in southern W Norway (paper I, see also Paus 1988, 1989a, b). In southern Hordaland, heath vegetation expanded from around 13.7 ka BP (paper I). As discussed in paper II, the interstadial *Empetrum* occurrences in the Sunnmøre region and mainland Europe were limited (see also Fig. 11). Several factors might have influenced the expansion of *Empetrum*; e.g. climate, edaphic conditions, vegetational density, migrational delay (e.g. Paus 1989a). In Sunnmøre, the interstadial vegetation was mostly dominated by grasslands and *Salix* snow-beds. Melt-water from the snow-beds that percolated the

vegetation would have created conditions unfavourable to heath vegetation. In northern Norway, there was a similar situation during the Lateglacial interstadial showing a mosaic vegetation of pioneer communities on dry, open, gravelly soil mixed with snow-bed communities in depressions. Pollen of *Empetrum* is only sparsely recorded in this period (Alm 1993; Fimreite *et al.* 2001; Aarnes *et al.* 2012). In contrast, on mainland Europe, closed interstadial forests including pine and birch prevented the development of extensive *Empetrum* heaths (e.g. Bohncke *et al.* 1988; Litt & Stebich 1999; Merkt & Müller 1999; Leroy *et al.* 2000).

Fig. 10. Summary diagram of *Betula* % and PAR (grains cm^{-2} a^{-1}). Events to the right as described in Fig. 6.

**Fig. 11.** Summary diagram of *Empetrum* % and PAR (grains cm^{-2} a^{-1}). The white curves in the percentage diagrams indicate 10 × exaggerations. Dimna. = Dimnamyra, Løkjing. = Løkjingsmyra. Events to the right as described in Fig. 6.

A maximum in Poaceae pollen recorded at the end of the Lateglacial interstadial at several sites in the Sunnmøre region (Dimnamyra, Løkjingsmyra (Fig. 8); Johansen *et al.* 1985; Kristiansen *et al.* 1988; Svendsen & Mangerud 1990) is interpreted to reflect a warm phase (cf. paper II).

Vegetation responses to the YD cooling are clearly reflected in all the pollen records in western Norway. The vegetation became sparser and more open, reflected by the reduction in total PAR, *Betula* and *Empetrum*. Tree birch disappeared from most sites in western Norway during the YD, but could have survived at sheltered sites in south Rogaland (Paus 1995). The increasing percentage values of snow-bed taxa like *Salix, Rumex* and *Oxyria* are seldom mirrored in the PAR diagrams (see e.g. Figs 6–7). However, the YD percentage and PAR increases in for example *Cerastium*-type, *Silene vulgaris*-type, and *Ranunculus flammula*-type (e.g. Figs 5–8 in paper II) suggest the expansion of snow-bed and moist open-ground communities in this period. An increase of vegetation on open, dry mineral-soils is suggested by the rise in percentage and PAR values of Chenopodiaceae and *Artemisia* (Fig. 9). It is suggested that since the *Artemisia* PAR values decrease during YD on the European mainland (see Fig. 13 in paper II), the PAR increase in western Norway was due to expansion of locally growing *Artemisia*. This increase could reflect the presence of *A. norvegica*, which at present is found in both continental and oceanic areas in western Norway (e.g. Gjærevoll 1990; Lid & Lid 2005).

A characteristic feature of the YD is dominant percentages of *Huperzia selago* (Fig. 12). This signal appears in several diagrams from western Norway, e.g. N Rogaland (Paus 1988), S Hordaland (paper I), Sotra (Mangerud 1970, 1977; Krzywinski & Stabell 1984), and Sunnmøre (Svendsen & Mangerud 1990, and paper II). A similar pattern, although less pronounced, is reflected in the PAR records. Hence, *H. selago* was growing locally, most probably reflecting the change to more open areas with moist soils. Reduced competition with the decreasing *Empetrum* could also explain the *H. selago* increase at some sites in southern W Norway, e.g. Vassnestjern, Dåfjordsmyr (paper I) and N Rogaland (Paus 1988). In southern Rogaland, no *H. selago* increase is recorded (Paus 1989a). Most probably, the Rogaland YD vegetation was too closed and shady for dominant *H. selago* (Paus 1989a). In northern Norway, *H. selago* shows restricted occurrences during the Lateglacial. A slight increase is recorded in the late YD or at the onset of the Holocene, almost simultaneously with the increase in *Empetrum* (Vorren *et al.* 2009). Here, other factors than the competition between *Huperzia* and *Empetrum*, e.g. soil-humus content, must have been decisive for the development of *H. selago*.

Responses to the Holocene warming are distinctly reflected in all the diagrams in this study. Increasing total PAR and a reduction in arctic-alpine pioneers and snow-bed taxa indicate closing of the vegetation. Vassnestjern and Dåfjordsmyr show a phase with *Empetrum* and dwarf-birch vegetation before the establishment of tree-birch, but the length of this phase is uncertain due to the lack of dates from the Holocene part. *Betula* pollen statistics (paper I) and extrapolation of the age-depth curve for Vassnestjern suggest that tree
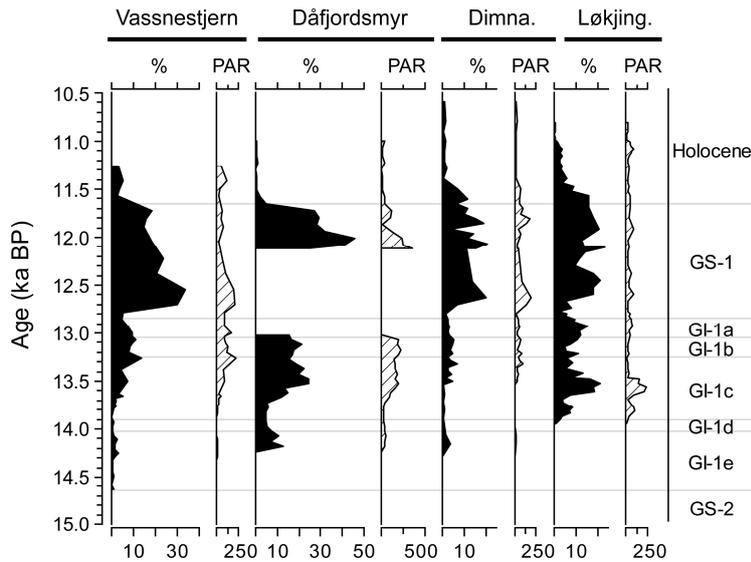
Fig. 12. Summary diagram of *Huperzia selago* % and PAR (grains cm^{-2} a^{-1}). Percentage calculation basis is ΣP + the number of *H. selago* spores. Dimna. = Dimnamyra, Løkjing. = Løkjingsmyra. Events to the right as described in Fig. 6.

birch was established at around 11.1 ka BP. However, the sedimentation rate is assumed to have been higher in the Holocene compared to the YD (cf. Fig. 4 in paper II), so this must be regarded as a minimum age for the timing of the tree birch establishment.

The records from Dimnamyra and Løkjingsmyra show a three-step succession in the early Holocene, starting with the development of herb-rich grassland. Hence, a relatively open vegetation persisted for some time into the Holocene. Subsequently, dwarf-shrub vegetation with *Empetrum*, *Vaccinium* and dwarf-birch expanded. At Løkjingsmyra, local birch forests had established around 11 ka BP, and local arrival of tree-birch individuals must therefore have occurred somewhat earlier. The time elapsed from tree birch arrival to expansion of woodland is probably comparable to the 50–100 years needed for the early Holocene birch woodland development at Kråkenes (Birks & Birks 2008).

4.2. Lateglacial climatic oscillations in western Norway

The overall trend in the vegetation development reflected in the records from western Norway is increasingly denser vegetation during the Lateglacial interstadial and the development of humus-soil communities. However, the records from Vassnestjern and Dåfjordsmyr reflect at least two short-lived episodes that signal opening of the vegetation. This includes decreasing *Betula*, *Empetrum*, and total PAR, and increasing Poaceae and *Oxyria*-type (paper I). The inferred cold episodes lasted a few hundred years and correlate chronologically to the minor climatic events GI-1d (14.025–13.9 ka BP) and GI-1b (13.26–13.05 ka BP) identified in the Greenland isotope records (e.g. Björck *et al.* 1998; Johnsen *et al.* 2001; Lowe *et al.* 2008) (Fig. 13). Based on the similarities in the biostratigraphy, these

episodes are probably the same as the interstadial coolings recorded in N Rogaland (Paus 1988, 1989b), but the poorer chronological control in those studies complicates a precise correlation.

The situation was quite different in northern W Norway. Neither Dimnamyra nor Løkjingsmyra (Fig. 13) or most other sites studied (Larsen *et al.* 1984; Johansen *et al.* 1985; Svendsen & Mangerud 1990; Birks *et al.* 2000) give indications of interstadial coolings similar to the GI-1d and GI-1b events. Only the Lerstadvatn record shows a phase of biostratigraphical changes interpreted to reflect a climatic deterioration in the Late-Allerød (Kristiansen *et al.* 1988). This could correlate to the GI-1b event.

The difference between N-Rogaland/Hordaland and Sunnmøre is attributed to the variations in the interstadial vegetation at the sites (paper II). The open heath vegetation with scattered birch trees around Vassnestjern and in N Rogaland was probably more sensitive to climatic changes (cf. Smith 1965) in contrast to the grass and herb communities further north. However, the possible responses to the G-1b event recorded at Lerstadvatn cannot be explained by this, but local factors (e.g. site exposition, wind, drought), could probably have played a role.
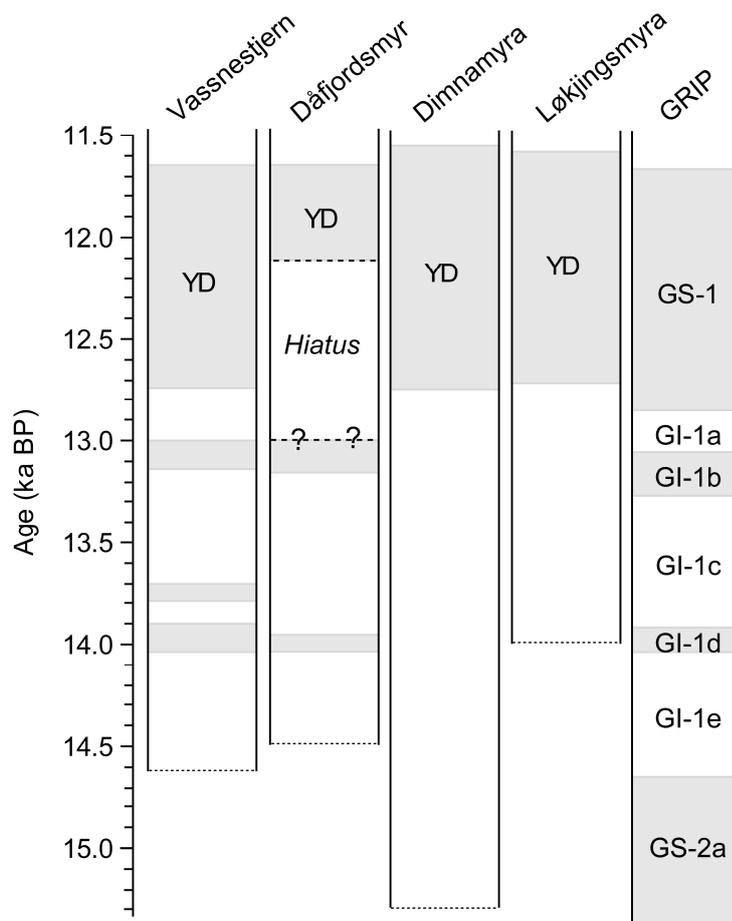
Fig. 13. Diagram showing the periods of vegetational changes assumed to reflect cooling episodes (grey shading) from deglaciation until the onset of the Holocene reflected in the pollen diagrams from the four studied sites in western Norway. The events in the Greenland isotope records (GRIP) (e.g. Björck *et al.* 1998; Lowe *et al.* 2008) are shown to the right.

In S Rogaland, further south, no evidences of any interstadial cooling are registered in the pollen records (Paus 1989a). This has been attributed to the denser and more mature interstadial vegetation with a higher inertia to change (cf. Smith 1965; see Paus 1989a).

The GI-1b event can be correlated to the Gerzensee fluctuation in Switzerland (Lotter *et al.* 1992), although in Lake Gerzensee, the signals of a climatic event are only evident in the δ^{18}O record and not in the biostratigraphical records. Responses to the GI-1b event are found in Lateglacial biostratigraphical records from Denmark (Andresen *et al.* 2000) and Estonia (Amon *et al.* 2012), and possible also from north-eastern Germany (de Klerk 2008). The late interstadial vegetation at these sites was characterised by pioneer birch forests that probably were more easily influenced by the climatic cooling than the pine forests that were growing on the Swiss Plateau in the second half of the Lateglacial interstadial (Lotter *et al.* 1992).

It must be noted that these minor climatic events lasted only around 100–200 years (cf. Fig. 13), and therefore the vegetational responses might not be noticed in the palynological records if the sampling resolution is too coarse. In addition, good chronological control is a prerequisite for unambiguous correlation between records.

4.3. Weichselian vegetation history in the Polar Ural Mountains

In paper III, the focus is the Polar Ural Mountains, northern Russia. The Weichselian vegetation development and the glacial history at the boundary between the European plain and the West-Siberian lowland have been investigated.

The shallow Lake Gerdizty at the eastern border of the Polar Urals (Fig. 2) shows a sediment thickness of up to 7.6 m (see Fig. 2 in paper III). The lowermost fine-grained sediments of silt and clay (unit A) have low organic content, but a relatively high pollen concentration (see Fig. 6 in paper III). The record includes pollen from taxa not native to the northern taiga zone (*Engelhardia*, *Ilex*, *Liquidambar*, *Nyssa*, *Platycarya*, *Pterocarya*, *Carpinus*, *Carya*, *Castanea*, and *Juglans*). The pollen grains of these "exotic" tree taxa are most likely of pre-Quaternary age. The sediments are considered as a till bed deposited by the Barents-Kara Ice Sheet, either sometime towards the end of MIS 5 or during MIS 4. Pre-Quaternary strata on the Siberian lowland could have been the source for the "exotic" pollen grains.

A thick, compact diamicton (unit B) with very low pollen concentration is found above the fine-grained till (unit A). This is interpreted as till deposited by a local glacier flowing from the Ural Mountains and reached maximum size sometime during MIS 4, i.e. after 78 ka BP, but before ~65 ka BP, when lacustrine sediments started to accumulate (cf. Fig. 5 in paper III). The identified till beds imply that Lake Gerdizty is not positioned outside the limits of all Weichselian glaciations as originally thought when this basin was chosen for coring.

Lacustrine, fine-grained sediments (units C and D) are found above the till beds and have been the main focus for the pollen analytical investigations. The constructed age-depth model (Fig. 5 in paper III) indicates that these sediments accumulated between 65 ka and 5 ka BP, i.e. during MIS 3–1 (cf. Fig. 1). This long time interval is accumulated in only 2 m of sediments, and therefore, the temporal resolution of the pollen record is low. However, it is assumed that the main trends in the vegetation development are captured by the pollen record (Fig. 14).

The landscape around the lake after the glacier had melted away around 65 ka BP was dominated by open and light-demanding vegetation. Grasses and sedges were important elements. Together with *Thalictrum*, *Oxyria*, *Artemisia*, and Chenopodiaceae, they made up a mixture of tundra and steppe vegetation. Some dwarf-shrubs of *Salix* and *Betula* were probably present, but no trees were growing in close vicinity. Around 50 ka BP, there was a shift from dominant Cyperaceae towards more Poaceae, and decreasing occurrence of dwarf-shrubs. This increase in steppe vegetation is interpreted to reflect drier and probably also cooler conditions.

The interpretation that the vegetation around Lake Gerdizty was denser and the climate was warmer shortly after the deglaciation (~65 ka BP) than later in MIS 3 accords with the results from Lake Yamozero (Fig. 2) (Henriksen *et al.* 2008). Here, a phase of forest tundra/open birch forest culminated around 58 ka BP, and after a transition phase of dwarf-shrub tundra the vegetation developed into steppe and desert vegetation (Henriksen *et al.* 2008). The records of deglaciation and interstadial conditions early in MIS 3 at Sokli, NE Finland (Fig. 2) (Helmens *et al.* 2000), also supports the interpretation that early MIS 3 was more favourable than later MIS 3 phases. At Sokli, the inferred local vegetation in early MIS 3 was low-arctic tundra, but distributional limits of birch and spruce tree were assumed a few hundred kilometres to the S or SE of this site (Bos *et al.* 2009).

The landscape around Lake Gerdizty remained open and treeless throughout MIS 3 and most of MIS 2. At Lake Yamozero, the steppe and desert vegetation persisted until ~15 ka BP. Open grass steppe or steppe tundra during late MIS 3 (from ~40 ka BP) and early MIS 2, is also recorded at Mamontovaya Kurja within the Pechora Basin (Fig. 2) (Halvorsen 2000), as well as in areas east and northeast of the Ural Mountains (e.g. Andreev *et al.* 2003; Andreev *et al.* 2006; Müller *et al.* 2010).

Dwarf-shrub communities with *Betula*, *Salix* and *Juniperus* re-established around Lake Gerdizty from ~15–14 ka BP, probably as responses to a climatic warming at the onset of the Lateglacial Interstadial (Bølling-Allerød). Signals of the Younger Dryas cooling are hardly recognizable in the record, probably because of the low temporal resolution. This event is clearly recorded at both sides of the Ural Mountains (e.g. Andreev *et al.* 2003; Paus *et al.* 2003a; Väliranta *et al.* 2006; Henriksen *et al.* 2008) as well as in the central part of the mountain chain (Lake Bolshoi Schuchye; Bjune & Svendsen, unpublished).

Fig. 14. Pollen percentage diagram from the lacustrine sediments from Lake Gerdizty including total pollen concentration of terrestrial taxa. Grey shading indicates 10 × exaggeration.

The transition to the Holocene is marked by increases in *Betula* and total pollen concentration. Birch and spruce trees became regionally established sometime in the early Holocene. Due to the poor chronological control precluding calculation of PAR values, and the lack of species determination of the *Betula* grains, the exact timing of the tree establishment is not possible to deduce from the Lake Gerdizty records. The majority of studies from sites close to or within the Polar Urals indicate an early Holocene establishment of trees (Koshkarova *et al.* 1999; Kultti *et al.* 2003; Panova *et al.* 2003; Kultti *et al.* 2004; Jankovská *et al.* 2006; Jones *et al.* 2011). However, some other studies have suggested that birch and spruce trees established already in the late YD (Surova *et al.* 1975; Väliranta *et al.* 2006). A similar early establishment of single trees in the vicinity of Lake Gerdizty is therefore a possibility, but more studies are required to solve this question.

### 4.4. Palaeoclimatic reconstructions in western Norway

Using the indicator species approach, the assumed presence of birch trees around Vassnestjern in the last half of the Lateglacial interstadial indicates local summer temperatures above 10 °C. The disappearance of birch trees and the break-up of humus-soil communities during YD signal decreasing temperatures. The absence of trees throughout the Lateglacial in the Sunnmøre region indicates summers colder than 10 °C during the whole period. More information about the temperature conditions at the studied sites is not possible to acquire as very few pollen grains from taxa with known climatic demands are identified in the analysed samples. One limitation of the indicator species approach is that it relies on presence/absence data, and is therefore sensitive to count size, i.e. the chance of finding grains of indicator taxa increases with increasing number of pollen grains counted (Birks *et al.* 2010). In a study, Paus (1992) found that counting sums (ΣP) of 500 and 1000 resulted in approximately 66 and 80 %, respectively, of the number of taxa recorded at $\Sigma P = 2000$. Thus, a doubling of the pollen sum used in the present work (from 500 to 1000) potentially could have increased the number of sparsely pollen-producing indicator taxa. However, increasing the count size is time consuming, and there is always a chance that the added taxa are long-distance transported pollen types with low value in respect to reconstruction of local conditions in the past.

The temperature reconstructions based on transfer functions are shown in Fig. 15. At the five southernmost sites, there is very low variability through the Lateglacial (Fig. 15). Hardly any temperature depression is found for the YD, a result that is clearly different from interpretation of the biostratigraphy. Further north, Dimnamyra shows a drop in temperatures of about 3 °C at the onset of the YD, showing a curve resembling the chironomid-based temperature reconstructions from NW Europe which indicates 4–5 °C temperature drop at the onset of this period (e.g. Brooks & Birks 2001; Lang *et al.* 2010). The temperature

reconstructions from Løkjingsmyra also show a decreasing trend during the YD, but the reduction is more gradual.

The differences between the temperature reconstructions at the sites in western Norway were surprising since all pollen records clearly signal variations throughout the Lateglacial. It could well be that other factors than mean July temperature, for example growing-degree days or winter temperature, controlled the Lateglacial vegetation development. However, it is difficult to see how this can explain the differences in reconstructed T_{jul} between the southern and northern sites.

The limited YD temperature decrease at the southern sites could perhaps be explained by the higher YD tree pollen percentages compared with the sites further north. The influence of long-distance transported pollen can be significant in open, treeless landscapes (e.g. Ritchie & Lichti-Federovich 1967; Hicks 1994; Gajewski 1995; Paus 2000; von Stedingk *et al.* 2008), and the southern sites are located closer to the forests on the continent. However, the modern surface samples from open areas (arctic/alpine/coast) will unavoidable also contain some long-distance transported tree pollen. The use of PAR estimates in the reconstructions has recently been suggested as an aid to overcome the problem with long-distance pollen (see Paus 2012).
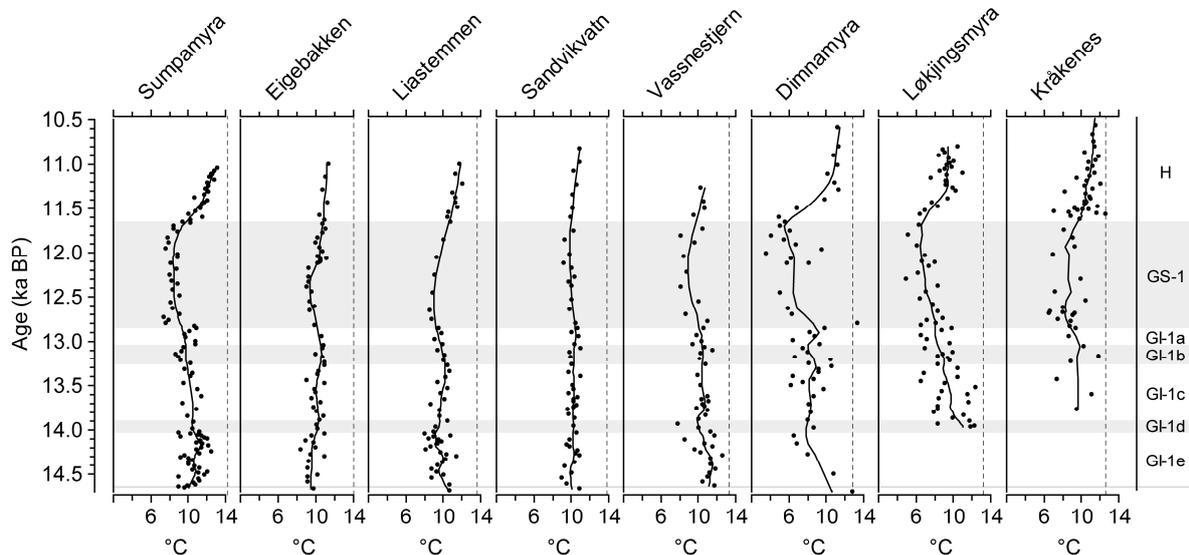

Fig. 15. Reconstructed mean July temperature for eight sites in western Norway. The fitted line is a LOWESS (locally weighted scatter-plot smoother; span = 0.2), used to highlight the long-term trends. For easier comparison of the temperature variability through the Lateglacial between the sites, the x-axes have equal lengths and scaling for all sites. The dashed, vertical line is the present-day mean July temperature for each site (DNMI 2012). This is a modified version of Fig. 11 in paper II. Note that samples older than ~14.7 ka BP from Sumpamyra, Eigebakken, Liastemmen, and Sandvikvatn were omitted from the temperature reconstructions because they contain high amounts of long-distance transported and reworked pollen grains (Paus 1988, 1989a, b; Paus *et al.* 2003b).

Another problem with the pollen-based climate reconstructions is the relatively low taxonomic resolution, meaning that pollen from plants with different climatic demands belongs to the same pollen type. The low taxonomic resolution leads to wider climatic tolerances and less accurate reconstructions (e.g. Seppä *et al.* 2004). However, this is a general weakness for pollen as a proxy. Even if some amalgamation of pollen types was necessary in the modern data set, this cannot explain the N–S discrepancy in the reconstructions from western Norway.

This study shows that quantitative temperature reconstructions based on pollen data from the Lateglacial can give very unreliable results and must be interpreted with caution. It might be better to use other proxies, e.g. chironomids, in the palaeoclimatic reconstructions. Mean July air temperature has been shown to be the dominant factor for chironomid distribution, and several chironomid-based mean July air temperature-inference models have been developed during the last decade or so (e.g. Olander *et al.* 1999; Brooks & Birks 2001; Larocque *et al.* 2001; Heiri *et al.* 2011; Self *et al.* 2011). As opposed to terrestrial plants, chironomids are not delayed by soil maturation, and are therefore expected to react more rapidly to temperature changes. However, the chironomid assemblages might also respond to other factors than climate, e.g. nutrient levels, oxygen availability, which can cause a bias in the inferred temperatures (e.g. Hammarlund *et al.* 2004; Velle *et al.* 2010b). In addition, also the fossil chironomid assemblages sometimes lack modern analogues leading to unreliable temperature reconstructions (e.g. Velle *et al.* 2005; Velle *et al.* 2010a).

4.5. Climate history in northern Russia

Summer temperatures in northern Russia during the last 100 ka have been inferred from the pollen data from Lake Yamozero (Henriksen *et al.* 2008) and Lake Gerdizty (Fig. 16), and by interpreting the glacial history (paper III). The presence of boreal forest during MIS 5a at Lake Yamozero (Henriksen *et al.* 2008) and even further north (Houmark-Nielsen *et al.* 2001) suggest summer temperatures higher than today. Summer must have been very cold in the following MIS 4, when mountain ice caps formed in the Ural Mountains. The deglaciation of Lake Gerdizty around 65 ka BP imply warmer conditions, however, the absence of trees throughout MIS 3 and 2 indicates that summer temperatures were below 10 °C. Warmer summers at the onset of the Lateglacial interstadial (Bølling-Allerød) are reflected by the development of dwarf-shrub vegetation, but temperatures remained below 10 °C. The Lake Gerdizty record does not give information about the Younger Dryas conditions, but a change to drier and colder conditions is clearly reflected at Lake Yamozero (Henriksen *et al.* 2008). The development of birch and spruce forests around Lake Gerdizty in the early Holocene indicates that the summer temperatures must have been higher than today.
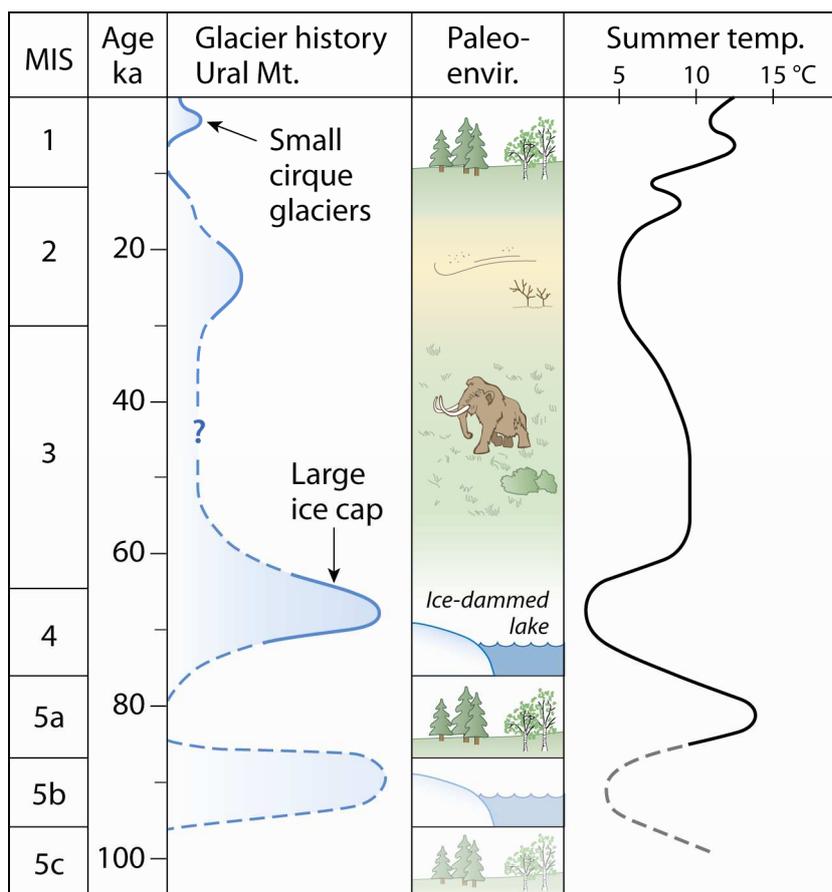
Fig. 16. Inferred glacial, environmental and climate history over the last 100 ka in northern Russia. The ice-dammed lakes are from Mangerud (2004) and Krinner *et al.* (2004). The reconstructed environment during MIS 5a is based on the pollen stratigraphic record from Lake Yamozero (Fig. 2) (Henriksen *et al.* 2008).

5. Conclusions

This work has presented new pollen records from western Norway and the Polar Ural Mountains, and several conclusions can be drawn:

Western Norway:
- The coastal areas in southern Hordaland were deglaciated around 14.6 ka BP. The coastal Sunnmøre further north was deglaciated around 15.3 ka BP, and the inland region around 14 ka BP.
- The pioneer vegetation was similar at the sites in southern Hordaland and in the Sunnmøre region, with a mosaic of snow-beds and vegetation on open, minerogenic soils.
- *Empetrum* became an important element in the vegetation at the southern sites from around 13.7 ka BP. In the north, the heath vegetation was sparse, and the vegetation consisted of snow-beds communities and grasslands.
- Responses to the short-lived climatic events like G1-1d and GI-1b are only recorded at the southern sites, whereas the Younger Dryas cooling is reflected in all diagrams.
- The pollen-based temperature reconstructions overestimate Younger Dryas July temperatures for the southern area.

Polar Ural Mountains:
- Lake Gerdizty in the eastern Polar Urals contains two till beds of early Weichselian age, and lacustrine sediments accumulated during the last 65 ka BP.
- The landscape was characterised by open, treeless vegetation of steppe and tundra throughout MIS 3 and 2.
- Summer temperatures were lower than present until the onset of the Holocene when birch and spruce trees established in the area.

6. Further perspectives

Whether tree birch was present in western Norway in the Lateglacial or not is still a subject of debate. The answer has implications for the reconstruction of Lateglacial temperature conditions. To solve this question, future studies integrating pollen data (including PAR estimates) and macrofossil/megafossil analyses are necessary. The focus area must be south-western Norway, which has the shortest migration distance from the European mainland, and probably also was among the warmest areas in Norway during the Lateglacial.

In order to further increase the knowledge of the Lateglacial vegetation and climate development along the coast in western Norway, more sites with well-developed Lateglacial sediments in southernmost Rogaland and in the area between southern Hordaland and the Sunnmøre region should be investigated. In the latter area, this can be quite challenging because of the extreme western position of the YD ice margin (e.g. Mangerud 2004 and references therein) and the smaller Lateglacial land areas due to higher relative sea-level (e.g. Anundsen 1985; Svendsen & Mangerud 1990; Lohne *et al.* 2007). The studies should include both pollen and macrofossil analyses, and also analyses of other proxies like chironomids and geochemical sediment features. Good chronological control is essential for comparison between the sites and for estimation of PAR. Ideally, for the purpose of accurate comparison, the sites should be of similar size and shape, so that the pollen source areas and pollen depositional features are as similar as possible.

The search for lakes containing long sediment records should be continued in the Polar Urals and northern Siberia to reveal more about the vegetation development during the last interglacial/glacial cycle and also to get a better understanding of the glacial history in the area. This will also facilitate more precise palaeoecological comparisons between Norway, influenced by the Atlantic Sea, and the continental Siberia. In this respect, the preliminary results from ongoing analyses of sediment records from Lake Bolshoi Schuchye in the central part of the Polar Ural Mountains are promising. The cores, which are up to 25 m long, provide a much better temporal resolution than the Lake Gerdizty cores, and thus there are possibilities that short-lived vegetational changes can be detected in the pollen records.

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