Tree-limit ecotonal response to Holocene climate change in the Scandes Mountains of west-central Sweden

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Jonas Bergman

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Abstract

The aim of this thesis was to reconstruct the Holocene vegetational and climatic development in the Sylarna-Storulvån area, western Jämtland, in the central Scandes Mountains. Temporal trends and fluctuations in the elevation and vegetational character of the tree-limit ecotone were studied mainly by means of pollen and plant macrofossil analysis of two lake sediment sequences (Lakes Stentjärn and Spåime), located above the present-day tree-limit. The lake sediments were also subjected to high-resolution elemental and mineral magnetic measurements, which contributed useful complementary information on the local environmental development. Plant macrofossil data indicate the presence of a short-lived deglaciation flora, dominated by light-demanding herbs and dwarf-shrubs, followed by the establishment of birch-pine forest. The vegetational data obtained were compared with previously published records of radiocarbon-dated subfossil wood remains (megafossils), collected mainly in the study area. A general conformity was revealed between the stratigraphic plant macrofossil data and pollen accumulation rates, and the comparison between the non-stratigraphic megafossil data and the pollen influx/plant macrofossil records also revealed a high level of consistency of the inferred tree-limit variations for *Pinus sylvestris*, *Betula pubescens*, and *Alnus incana*. Records of climatic humidity inferred from peat humification data (DOH) were obtained from two separate profiles at a nearby peat deposit (Klocka Bog), situated below the forest-limit. Evaluation of the DOH records exhibits millennial-scale trends, which are significantly correlated between profiles during the periods 6500-4000 cal yr BP and 2100-0 cal yr BP. Within these periods, the time between 5800 and 4800 cal yr BP, and 1800 cal yr BP until the present, are recognised as episodes of increasing climatic humidity. In general, the vegetational, geochemical and sedimentary records were shown to correlate with several Holocene climatic events and transitions, identified elsewhere in north-western Europe. The climatic forcing of some of these sub-Milankovitch scale perturbations is unclear, but a coupling to internal circulation dynamics of the North Atlantic Ocean is hypothesized. Chronologies of the geological archives studied within the project were based on radiocarbon dating and tephrochronology. At Lake Stentjärn, three Holocene cryptotephra horizons were detected, one of which was geochemically correlated with the Icelandic Askja-1875 eruption. At Klocka Bog, at least seven cryptotephra horizons were recorded in the two peat profiles, and five of the horizons were geochemically correlated with the Askja-1875, Hekla-3, Kebister, Hekla-4, and Lairg A tephras, respectively.

Key words: Holocene climate, palaeoecology, tree-limit ecotone, alpine vegetation, deglaciation, tephrochronology, pollen influx, peat humification, plant macrofossils

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by

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This thesis is based on four papers listed below as App. I-IV. The papers are reprinted with permission from Elsevier B. V. (Paper I), John Wiley and Sons Ltd, (Paper II), and Hodder Arnold Publishers (Paper IV).

Appendix I: Bergman, J., Hammarlund, D., Hannon, G., Barnekow, L. and Wohlfarth, B. 2005: Deglacial vegetation succession and Holocene tree-limit dynamics in the Scandes Mountains, west-central Sweden: stratigraphic data compared to megafossil evidence. *Review of Palaeobotany and Palynology 134*, 129-151.

Appendix II: Bergman, J., Wastegård, S., Hammarlund, D., Wohlfarth, B., Roberts, S. J. 2004: Holocene Tephra horizons at Klocka Bog, west-central Sweden: aspects of reproducibility in subarctic peat deposits. *Journal of Quaternary Science 19*, 241-249.

Appendix III: Bergman, J. and Hammarlund, D.: Recurrent episodes of increased effective humidity during the late Holocene inferred from mid-Swedish peat deposits and lake sediments. *Manuscript submitted to Quaternary Science Reviews.*

Appendix IV: Hammarlund, D., Velle, G., Wolfe B.B., Edwards T.W.D., Barnekow, L., Bergman, J., Holmgren, S., Lamme, S., Snowball, I., Wohlfarth, B. and Possnert, G. 2004: Palaeolimnological and sedimentary responses to Holocene forest retreat in the Scandes Mountains, west-central Sweden. *The Holocene 14*, 862-876.

Collection of surface sediments from a small lake surrounded by mountain birch forest in the Storulvån valley, west-central Sweden.

Introduction

The Holocene climate development is still relatively poorly understood, and as demands for prediction of future climate intensifies, studies of past climate change are becoming increasingly important. The global warming and its possible human-induced amplification during the last century have resulted in a more direct need for knowledge about the natural climate development of the past, so that accurate predictions can be made about future climate change. The IPCC (Intergovernmental Panel on Climate Change) has stated (e.g. 2001) that modern human society has a discernible influence on global climate and is at least partly responsible for the increasing global average temperature. The reports also admit that there are still many uncertainties regarding climate prediction. Hence, the importance of understanding the "natural", non-linear nature of climate systems and their development over short and long time spans has never been greater than it is today. Just how difficult it is to accurately predict and understand future climate without proper understanding of past climate variability, was recently demonstrated in a study involving palaeotemperature reconstructions from the Northern Hemisphere, based on multi-proxy data (Moberg et al., 2005). Reconstruction of past climate change and variability from vegetational records is difficult and always leaves room for different interpretations. Plant life generally responds in a complex way to environmental changes, regardless if the change involves biotic or abiotic parameters, since most ecosystems and plant communities also have an inherent complexity, mainly due to the adaptation ability of biological life. As a result, the borders between different vegetation communities are often characterised as spatial transition zones, or *ecotones* (e.g. Kent et al., 1997). A vegetation ecotone encompasses elements of plant communities from both sides of the transition, and can be regarded as a tension zone where each element is highly sensitive to changes in biotic and abiotic parameters. Hence, spatial movement of ecotones and changes in vegetation composition within ecotones are very useful indicators of environmental change, and if at least one of the communities is primarily limited by abiotic parameters, such as climate, ecotonal change becomes a very useful indicator of climate change. Arctic and alpine tree-limit ecotones are transition zones, which are mainly controlled by climatic parameters, such as summer temperature, but also snow conditions, precipitation, and length of the growing season. Alpine tree-limit ecotones are unique in the way that different vegetation types occur within relatively narrow altitudinal zones, and because of this, ecotonal responses to environmental change do not involve any migratory movements over significant distances with subsequent time lags. Studies of the altitudinal distribution of trees and forest ecosystems have shown that tree-limit ecotones worldwide are mainly controlled by growth-season temperature (Körner, 1998).

Tree-limit variations in the Scandes Mountains have been the subject of numerous studies during the last century (Andersson, 1902; Gavelin, 1909; Smith, 1911; Lundqvist, 1959; Aas and Faarlund, 1988, 1996; Kullman 1993; Kvamme, 1993; Eronen and Huttunen, 1993; Vorren 1993; Barnekow, 1999a, 2000; Barnett et al., 2001). The Sylarna-Storulvån area in western Jämtland is particularly well investigated, and several studies focusing on the long-term Holocene vegetational development have been conducted over the last decades. The Holocene tree-limit dynamics in the area are partly known through radiocarbon dating of subfossil wood remains, or *megafossils*, found at and above the present-day tree- and forest-limits (Kullman, 1995, 1996; Kullman and Kjällgren, 2000). These tree remains have usually been retrieved in non-stratigraphical settings, such as small peat deposits, shallow lakes, or snow beds, and are rarely found *in situ*. All macroscopic subfossil wood remains (mainly trunks and roots) have been radiocarbon dated. The unprecedented megafossil data set collected in the southern Scandes Mountains has raised numerous questions concerning the early Holocene vegetational composition (Kullman, 1996, 1998a, 1998b, 1998c), the late Weichselian and early Holocene deglaciation history (Kullman, 2002a), and the migratory spread of trees (Kullman, 1998a, 2000a).

Plant communities from past times have as mentioned above, left various trace evidence of their spatial distribution and composition in different geological archives, such as lake sediments and peat deposits, in the form of subfossil organic material, e.g. plant macrofossils and pollen. Hence, past vegetational changes are recorded over time in sedimentary and sedentary stratigraphic sequences along with other palaeoenvironmental evidence. Alpine lake sediments can be excellent stratigraphic archives, which can be analysed for a wide range of geochemical, geophysical, and palaeobiological indicators, such as total carbon and nitrogen content, mineral magnetic properties, and insect data to name a few. Lakes located above the present-day tree-limit may contain sedimentary records, which have captured past tree-limit ecotonal fluctuations. Also, alpine lake ecosystems, and their catchments, respond quickly to climatic fluctuations, which often trigger significant ecological changes as they are well exposed to atmospheric influences in the alpine environment. Consequently, the incorporation of a wide range of methods in palaeoenvironmental studies will make it possible to more accurately explain how the different proxy data have been affected by local conditions, and hence gain a wider understanding of past environments and climate. The different parameters complement and support each other, and therefore, a stratigraphic *multi-proxy approach* is ideal for studies of this kind.

Accurate chronologies are fundamental in investigations of stratigraphic sequences. The need for accurate dating of short-term palaeoclimatic events is becoming ever greater as more detailed reconstructions of past climatic fluctuations and environmental changes are demanded. Holocene organic sediments and peat can be dated with reasonably good precision and resolution through measurements of the ^{14}C content of organic material. However, radiocarbon dating carries with it a number of problems, such as unknown limnic reservoir effects, which can be avoided by dating of terrestrial plant macrofossils. Also, the general precision of the age estimates may be unsatisfactory for reconstruction of sub-centennial-scale variations. One promising approach to improve chronologies is by searching for temporal marker horizons, or isochrones in the geological archives. The most suitable, widespread Holocene marker horizons that can be found in north-western Europe and elsewhere in the North Atlantic region are distal deposits of volcanic ash, or *tephra horizons*, predominantly of Icelandic origin. Horizons of tephra (microscopic volcanic glass shards) found in Scandinavia are derived from the largest and most explosive (Plinian) eruptions, which have the potential to spread tephra particles to land areas outside of Iceland. The term *tephrochronology* was proposed for this "absolute geological dating method based on measurements, correlations, and dating of volcanic ash layers", where layers of tephra are used as time-parallel marker horizons (Thorarinsson, 1944). Tephrochronology can be considered to be an absolute, high-precision dating method if the tephra particles are derived from historically documented volcanic eruptions. Prehistoric tephras are very useful as a relative, and a "secondary absolute" dating method, since they can be used for high-precision correlation of records from other geological archives containing equivalent tephra horizons. Also, by high-precision "wiggle matching" of radiocarbon dates, mainly from peat sequences, many prehistoric Holocene tephras have been assigned remarkably precise age estimates (e.g. van den Bogaard et al., 2002; Plunkett et al., 2004).

Project objectives

The main aim of my doctoral work has been to reconstruct the Holocene environmental and vegetational development of the Sylarna-Storulvån area since the deglaciation, and to investigate the potential of tephrochronology in west-central Sweden. More specifically, the distribution and altitudinal fluctuations of the tree-limit ecotone have been studied and compared to existing local megafossil data sets and to previous tree-limit studies from central Scandinavia. The following specific objectives were addressed by individual research efforts included in the thesis work:

1. To provide a high-resolution Holocene climatic and environmental reconstruction for the study area using a multi-proxy approach based on lake sediment and peat archives.

2. To investigate the degree of correspondence between the megafossil data and biostratigraphic lake sediment records, especially plant macrofossils, and if possible describe the primary mechanisms that control the different records (App. I and IV).

3. To establish a tephrochronology for the study area, temporally linking the different records by the use of tephra isochrones and radiocarbon dating, and enabling high-resolution chronologies to be created, adequate for evaluation of short-term (centennial-scale) climatic fluctuations (App. II).

4. To explore the role of temperature and precipitation variations and their connection with altitudinal and compositional fluctuations of the tree-limit ecotone, as well as other vegetation boundaries, and to study how the lake sediment records relate to records of peat humification (App. III).

Study area

Geology and landscape

South-western Jämtland (Fig. 1) belongs to the central part of the Caledonian mountain range. The bedrock is mainly composed of metamorphic Palaeozoic rocks such as gneisses, amphibolites and mica-schist. In the north, around Lake Ånnsjön, phyllites and peridotites dominate. Quaternary deposits are overlying the bedrock in most of the area, although the mountain peaks have large exposed and frost-shattered rock surfaces, often surrounded by boulder fields. Hummocky till with a varying boulder frequency blankets the pre-montane terrain, and in the valleys, glaciofluvial deposits are abundant. Glaciolacustrine sediments, mainly sand and silt, can be found in the Lake Ånnsjön area, where peat deposits are also abundant (Lundqvist, 1969). The highest area is the Sylarna massif, with peaks reaching above 1700 m a.s.l. (Fig. 2). During the late 19th century, four niche glaciers, supposedly formed during recent millennia (Lundqvist, 1969), occupied east-facing cirques at 1450-1600 m a.s.l., but all have disappeared or retreated significantly since approximately the 1930's (Kullman, 2004a, 2004b). The area was geologically surveyed during the 1960's and Quaternary deposits were mapped. Several peat deposits, such as the Klocka Bog, were stratigraphically investigated and studied by means of pollen analysis (Lundqvist, 1969).

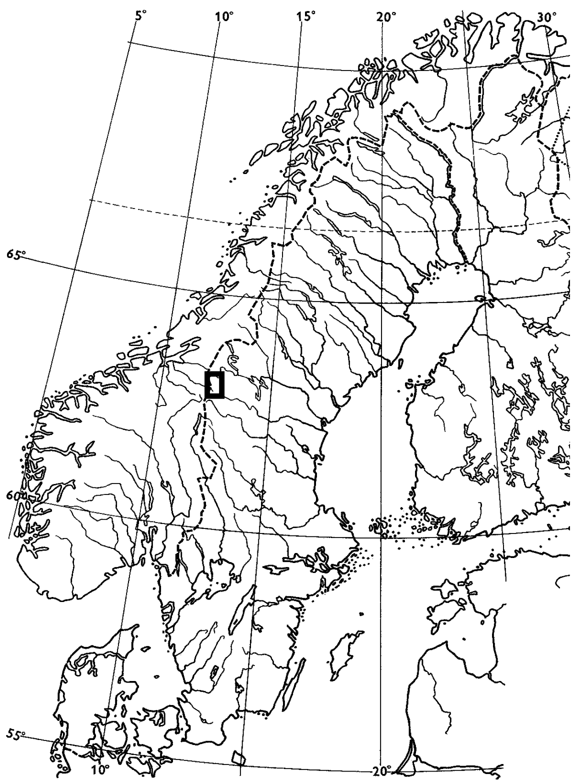

Fig. 1. Map of Scandinavia with the study area of Sylarna-Storulvån in western Jämtland marked with a black box.

Deglaciation and land uplift

The final deglaciation of the study area is estimated to have occurred at ca 11,000-10,500 cal yr BP (Lundqvist, 1998), with ice-marginal recession from west to east. Several generations of proglacial lakes were dammed and subsequently drained, along the Handölan valley and in the Ånnsjön area, as the eastward-receding ice front retreated to successively lower elevations. No ice-marginal features are found above 1300 m a.s.l. in the study area, so probably this marks the occurrence of nunataks protruding through the Late Weichselian Fennoscandian ice-sheet (Borgström, 1989). Estimates of land uplift (Fig. 3) have been based on shoreline displacement data from the inner Trondheimsfjord area at Frosta/Verdalsöra, approximately 75 km west of the study area (Kjemperud, 1981; Sveian and Olsen, 1984). These results have been interpolated (Dahl and Nesje, 1996), along a west-east profile with corresponding data from the Gulf of Bothnia, eastern Sweden (Mörner, 1980; Dahl and Nesje, 1996). Quantifications of land uplift based on shoreline displacement calculated from the east coast are associated with great uncertainties and should be considered as approximations (Lundqvist, 1969). Hence, in App. I, III and IV, the presented palaeoecological data have generally not been corrected for land uplift.

Climate and vegetation

The climate of the study area is moderately oceanic but characterised by a pronounced oceanic-continental gradient from north-west to south-east. The precipitation gradient is especially steep in the western part of the study area, where precipitation rates increase with altitude (Fig. 4). Mean air temperatures for January and July range from -8 °C to -11 °C and from 10.5 °C to 12 °C, respectively, along the north-west/south-east gradient. Mean annual air temperatures in the range of -1 °C to 1 °C and mean annual precipitation varies between 900 and 700 mm (Fig. 4). These values are based on meteorological data collected during the period

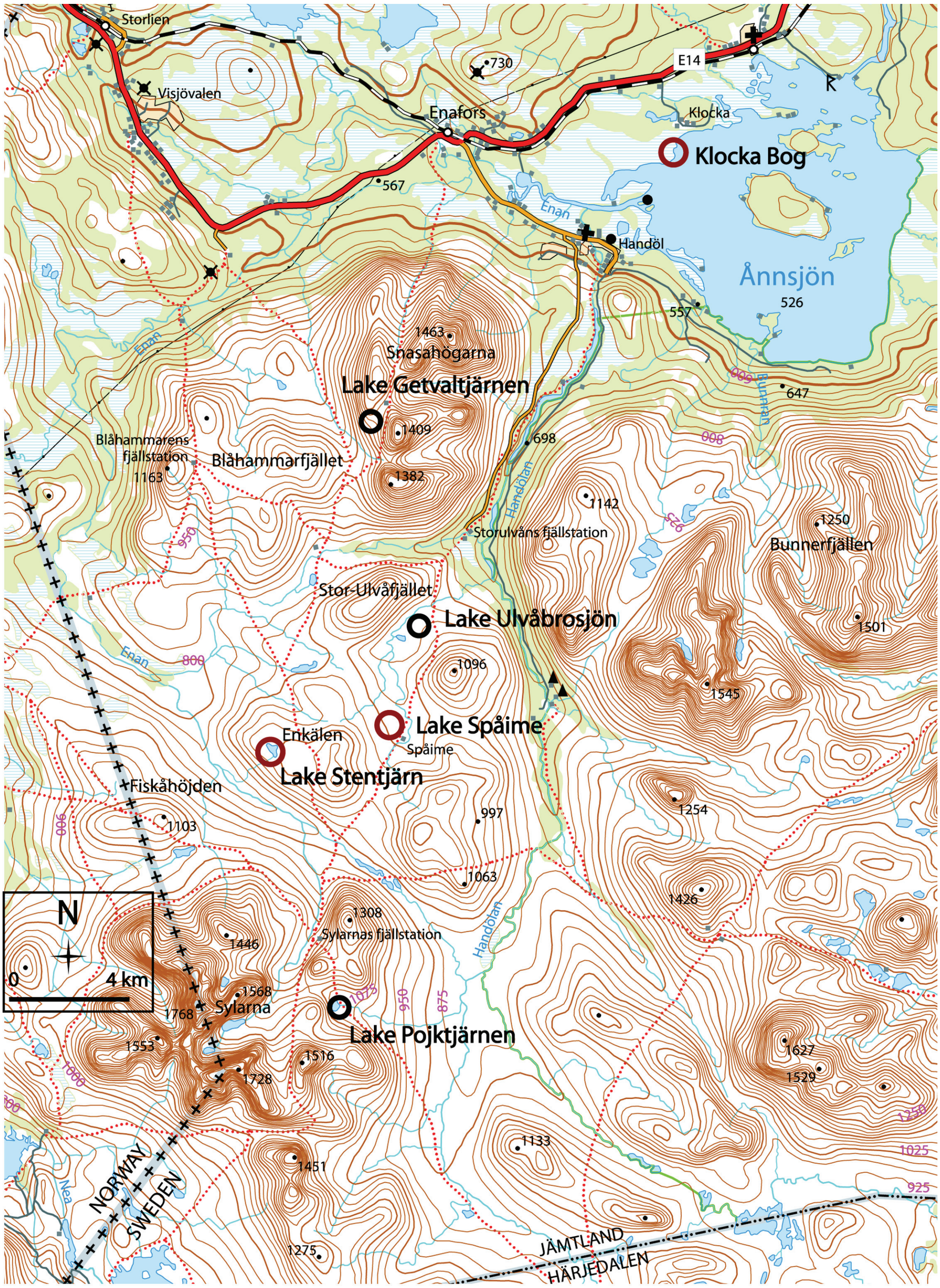

Fig. 2. Map over the Sylarna-Storulvån area in western Jämtland. The distribution of boreal and subalpine forest is shown in green. Studied sites are marked by red circles, and surveyed sites by black circles.

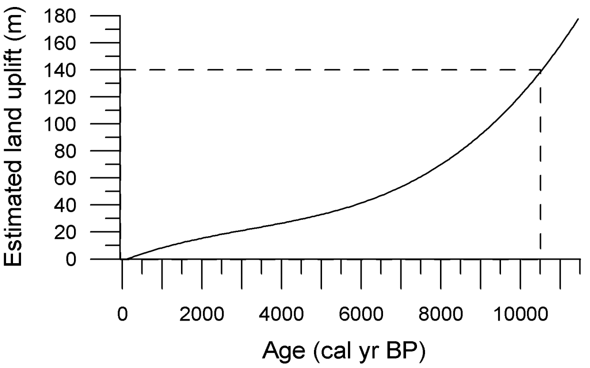

Fig. 3. Estimate of land uplift in the Sylarna-Storulvån area since deglaciation. Dashed lines indicate the approximate deglaciation of Lakes Spåime and Stentjärn. The land uplift estimate is based on data summarized by Dahl and Nesje (1996).

1961-1990 at several stations situated in valleys at 400-800 m a.s.l. (Alexandersson et al., 1991). As a mean, 45 % of the precipitation falls as snow, but this proportion increases with altitude (Rafstedt, 1984) to about 2/3 in the alpine zone. The closest meteorological station with "long-term" data (Storlien/Visjövalen) is located at 642 m a.s.l. to the north-west (Fig. 2). Temperature measurements from this station indicate a mean summer (June-August) warming from ca 9.6 °C to 10.7 °C since the early 20th century, although the annual variability is significant, from 8 °C to 12 °C (Alexandersson, 2002). Annual precipitation at Lake Spåime and Lake Stentjärn can be estimated to 900-1000 mm and 1000-1100 mm (Fig. 4), respectively (Raab and Vedin, 1995). Mean annual and mean July air temperatures at Lake Spåime can be estimated to -2 to -1 °C, and 8.6-9.1 °C, respectively, and at Lake Stentjärn to -3 to -2 °C, and 8.0-8.5 °C, respectively. Small lakes in the alpine zone are generally ice-covered from mid-October to late May. In the Klocka area (Fig. 2), measured mean annual precipitation amounts to ca 630 mm (data from 1961-1990; Alexandersson et al., 1991). The snow cover in the region generally lasts for 200 days, and the length of the growing season ranges from about 140 days in the lower valleys to less than 120 days in the alpine zone (Raab and Vedin, 1995).

The regional vegetation, from the valleys to the mountain peaks, includes boreal forest at low elevations, which grades into the subalpine birch-dominated forest zone at higher elevation. At the upper margin of the mountain birch zone the tree-limit ecotone is situated, which *sensu stricto* is the zone between the climatic forest-limit and the tree-limit (the upper altitudinal limit of tree-sized individuals). More generally, the tree-limit ecotone can be referred to as the zone between the subalpine forest and the tree species limit (Fig. 5). As the subalpine forest gradually disappears with increasing elevation, the low-, middle-, and high-alpine vegetation zones (Rafstedt, 1984), follow in consecutive order. Definitions of forest- and tree-limits generally follow Matthews et al. (2001), as shown in Fig. 5.

Mountain birch (*Betula pubescens* ssp. *czerepanovii* (N.I. Orlova)) forms the local tree-limit and forest-limit at approximately 900 and 800 m a.s.l., respectively, although the regional tree-limit for mountain birch is at ca 925 m a.s.l. Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst) dominate the regional coniferous forest, with single tree-sized specimens extending to ca 825 and 875 m a.s.l., respectively. However, krummholz of *Picea* and *Pinus* can be found far beyond their respective tree-limits (Kullman and Kjällgren, 2000). Grey alder (*Alnus incana*) grows in small stands or as isolated individuals within the subalpine mountain birch zone, to a maximum elevation of about 870 m a.s.l. (Kullman, 1992). The vegetational zones in the study area and their relations to present and past climate have been studied in detail by Kullman (e.g. 1992, 1994, 1995, 1998d, 2001). Other tree species that occur below the forest-limit are aspen (*Populus tremula*), rowan (*Sorbus aucuparia*), bird cherry (*Prunus padus*), and goat willow (*Salix caprea*). The field layer in the tree-limit ecotone is generally dominated by dwarf shrubs, such as *Vaccinium myrtillus*, *Empetrum nigrum*, *Betula nana*, *Calluna vulgaris*, and *Juniperus communis* (Rafstedt, 1984; Kullman, 1995). Human impact on the tree-limit ecotone has been negligible during most of the Holocene (Kjällgren and Kullman, 1998), although limited summer farming may have had a slight influence during the last ca 1500 years in some parts of the province (Wallin, 1999).

Site descriptions

Klocka Bog (63°17.5'N, 12°29'E; Fig. 6a) is a bog-fen complex situated at 526 m a.s.l. on the north-western shore of Lake Ånnsjön, about 1 km south of the village Klocka (Lundqvist, 1969). Pioneer studies aimed at detecting Holocene tephra horizons were performed by Persson (1966, 1971). The peat deposit is surrounded by coniferous forest, dominated by *Picea abies*, and is in its western part dissected by several small streams. The eastern part

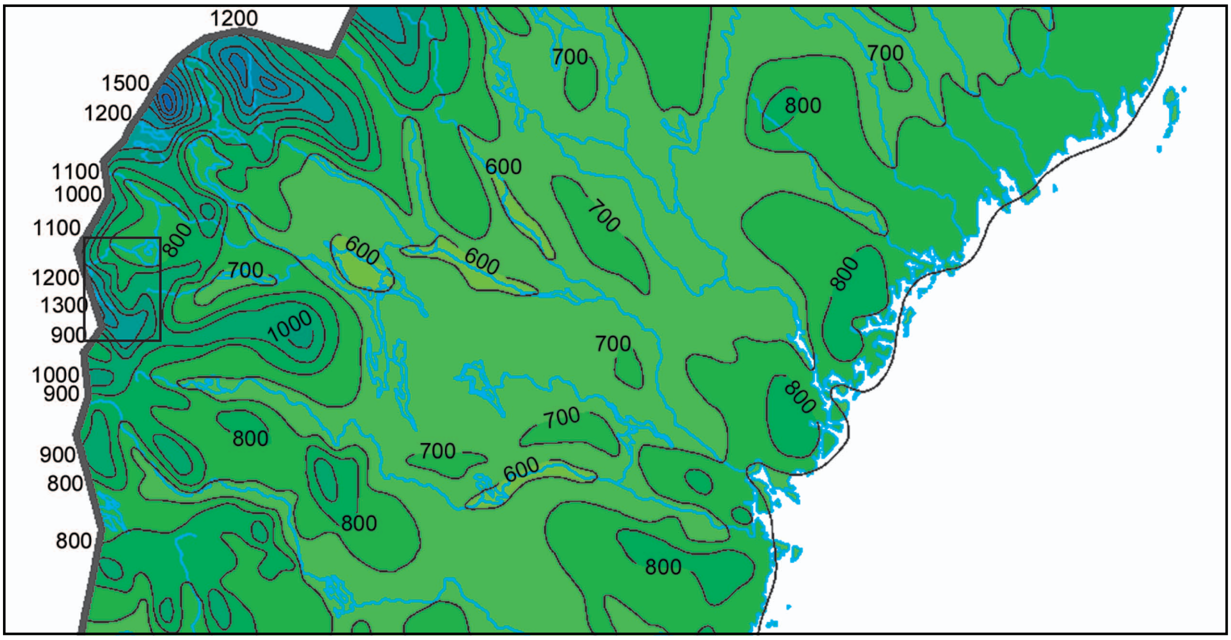

Fig. 4. Present-day actual annual precipitation (Raab and Vedin, 1995; data from SMHI 1961-1990) in central Sweden and the study area.

is dominated by ombrotrophic bog areas, with a vegetation of mainly *Betula nana*, *Vaccinium uliginosum*, *Empetrum nigrum*, *Rubus chamaemorus*, *Sphagnum* spp., and lichens. The fen areas, or pools, are dominated by *Sphagnum* spp., *Eriophorum* spp., *Andromeda polifolia*, and *Drosera* spp. The eastern edge of the bog is influenced by ongoing wave erosion, possibly as a result of a transgression induced by a higher rate of land uplift in the eastern part of the Lake Ånnsjön depression. This erosion has created a more or less vertical erosion scarp and exposed a 2-2.5 m thick peat sequence along the shore of Lake Ånnsjön. The bog is underlain by glaciolacustrine silt.

Lake Spåime (63°07'N, 12°19'E; Fig. 6b) is located at 887 m a.s.l., ca 10 km north-east of the Sylarna Mountains. Its catchment covers an area of ca 3.5 km^2 and ranges ca 200 m in altitude along the east- to north-east-facing mountain side of Mount Enkälen (Fig. 2). The lake measures ca 400×100 m (ca 3 ha) and has a maximum depth of approximately 3.5 m. The catchment vegetation is of low alpine character, dominated by heath communities with dwarf-shrubs, willows, grasses and sedges. No tree specimens of *Betula pubescens* occur in the lake catchment at present. Lake Spåime has an open hydrology with its main inflow and outflow located at the southern and northern ends, respectively, and is part of a well-developed stream

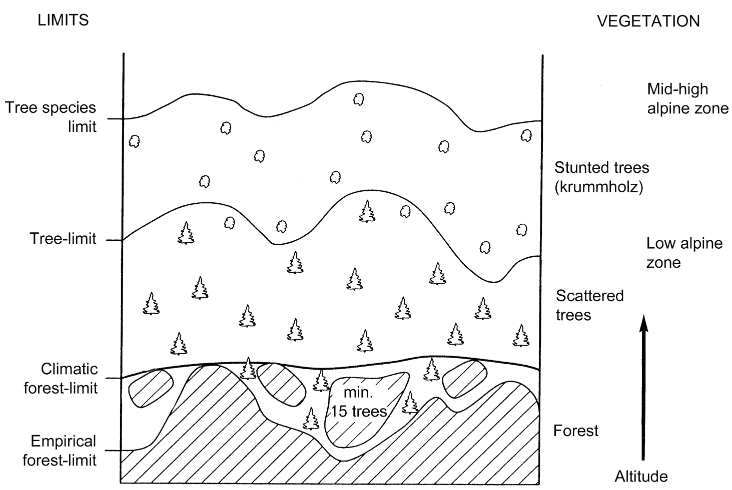

Fig. 5. Generalised model of the alpine tree-limit ecotone, modified after Matthews et al. (2001). The climatic forest-limit is defined as the upper altitudinal limit of continuous forest (maximum 30 m between stems), or forest stands of minimum 15 trees. The empirical forest-limit is the observed limit, which is often reduced from the climatic forest-limit because of local environmental factors (e.g. slope gradient, substrate conditions etc) and human influence. The tree-limit is the uppermost altitudinal limit of trees exceeding 2 m in height, and is unique for each species. Locally relevant alpine vegetation zones are indicated to the right.

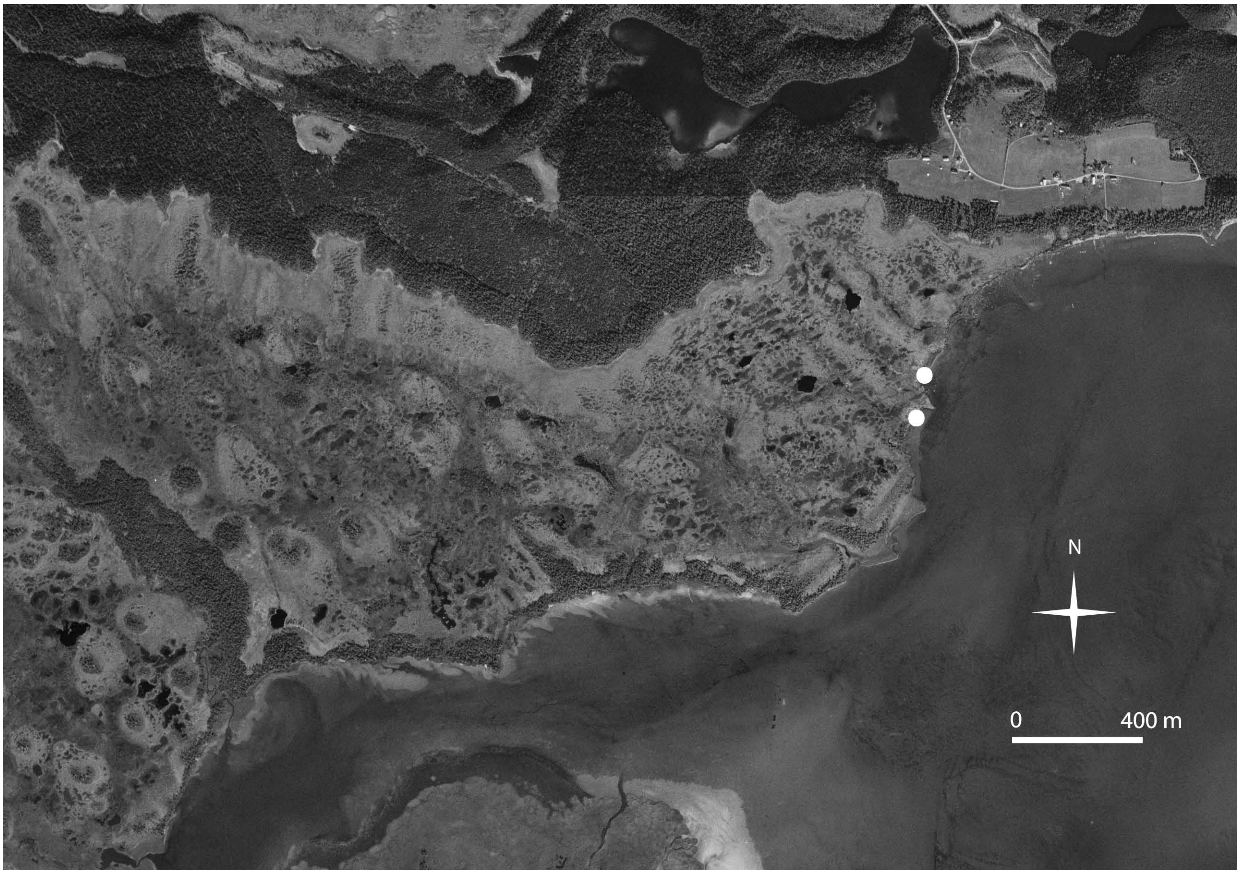

Fig. 6a. Aerial photo of Klocka Bog. Sampling sites are indicated by white dots.

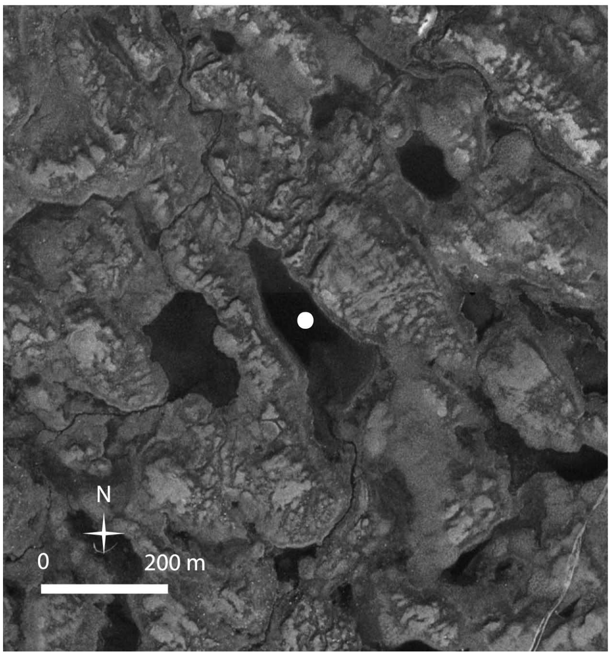

Fig. 6b. Aerial photo of Lake Spåime.

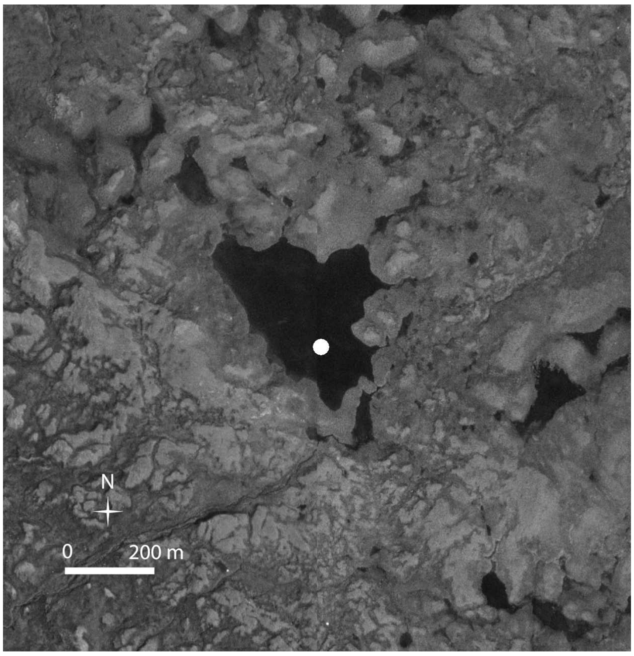

Fig. 6c. Aerial photo of Lake Stentjärn.

system. A rough estimate of lake volume and discharge through the outlet stream indicates a residence time of the lake water of 5-10 days.

Lake Stentjärn (63°06'N, 12°14.5'E; Fig. 6c) is situated at 987 m a.s.l., near the summit of Mount Enkälen (Fig. 2). It measures ca 375×300 m (ca 7 ha) and has a maximum water depth of about 6 m. The catchment area extends across ca 30 ha and is covered mainly by heath vegetation dominated by dwarf-shrubs, such as *Empetrum nigrum, Betula nana*, and *Vaccinium uliginosum*. Other common vascular plants are willows, grasses, sedges, and a variety of alpine herbs. The lake is drained by a small outlet stream (ca 20 ls^{-1}) to the south.

Other lake sites in the area were initially included in the project, but these were considered unsuitable for further studies for various reasons. Lake Pojktjärnen, located at 1048 m a.s.l., on the eastern flank of the Sylarna massif was cored and the sediments retrieved were subjected to magnetic susceptibility measurements (N. Hansen, unpublished data). The sediments are extremely poor in terrestrial macrofossils, and no material suitable for radiocarbon dating was found. Lake Ulvåbrosjön, is situated at 835 m a.s.l., above the forest-limit in the central part of the Handölan valley (Fig. 1). The lowermost part of its sediment sequence is dominated by silty laminations, obviously of glacial origin. However, the upper part of the sequence seemed disturbed. Lake Getvaltjärnen at 1155 m a.s.l., located near the summit of Mount Getryggen was successfully cored, but the sediment sequence proved to be less than a meter thick, and radiocarbon dating showed that it only spans the last 3700 years.

Methods

All methods performed solely or partly by the author during the course of the project are described briefly in this section. For more detailed descriptions of methodologies, see App. I-IV. Project participants responsible for individual methods or analyses are listed in Table 1.

	Lake Stentjärn	Lake Spåime	Klocka Bog	L. Pojktjärnen, L. Getvaltjärnen
Fieldwork	J. Bergman, D. Hammarlund, B. Wohlfarth	N. Hansen, D. Hammarlund, B. Wohlfarth	J. Bergman, D. Hammarlund	N. Hansen, J. Bergman, B. Wohlfarth
Pollen analysis	J. Bergman, L. Barnekow	S. Holmgren, L. Barnekow		
Plant macrofossils (^{14}C dating and analysis)	J. Bergman, G. Hannon	S. Lamme, L. Barnekow	J. Bergman	J. Bergman (L.Getvaltjärnen)
Cuticle analysis	J. Bergman	S. Lamme, J. Bergman		
Mineral magnetic susceptibility	J. Bergman	D. Hammarlund, B. Wohlfarth, I. Snowball	J. Bergman	N. Hansen (L. Pojktjärnen)
Elemental analyses/LOI	J. Bergman	S. Lamme, D. Hammarlund	J. Bergman	
Stable isotope analyses	D. Hammarlund, J. Bergman (in progress)	D. Hammarlund, T.W.D. Edwards, B.B. Wolfe		
Chironomid analysis		G. Velle		
Humification analysis (DOH)			J. Bergman	
Tephrochronology	J. Bergman	J. Bergman	J. Bergman	
EPMA geochemistry	S. Wastegård		S. Wastegård, S.J. Roberts	

Table 1. Compilation of methods used at the study sites and project participants responsible for execution and interpretation of the respective analyses.

Fieldwork and core correlation

Multiple, over-lapping sediment cores were collected from the ice of Lake Spåime and Lake Stentjärn in April 1999 and February 2002, respectively. The corings were performed where the thickest sediment successions were located and the bottom topography was flat, which was ca 50 m from the southern shore at Lake Stentjärn, and in the central, deepest part of Lake Spåime. Russian corers, 7.5 and 10 cm in diameter, and 1 m in length (Jowsey, 1966), were operated with steel rods.

Klocka Bog was sampled in July 1998 (profile 1), and again in July 2001 (profile 2). For profile 1, the peat sequence was sampled with a 7.5 cm Russian corer, whereas profile 2, situated ca 150 m south of profile 1, was cut out with a knife from a freshly cleared section at the erosion scarp. In both cases, samples were collected about 0.5 m inside the erosion scarp. The segments of the sampled sediment and peat sequences were lithologically described in the field, put in supportive liners and carefully wrapped in plastic for transportation. All cores were kept in cold storage (4 °C) before subsequent sub-sampling.

Overlapping sediment/peat core segments were correlated based on measurements of mineral magnetic susceptibility at 4 mm increments using a Bartington Instruments MS2E1 surface scanning sensor coupled to a Tamiscan-TS1 automatic logging conveyor. All cores used for analyses were adjusted and correlated based on visual lithological boundaries and significant changes in magnetic susceptibility.

Mineral magnetic susceptibility

Contiguous fresh sediment samples, approximately 4 cm^3 in volume, from the Lake Stentjärn sediment sequence were put in 7 cm^3 plastic boxes, which then were used for all magnetic measurements. Mineral magnetic susceptibility (χ) was measured with a Geofyzica Brno KLY-2 air-cored magnetic susceptibility bridge. After completion of the analyses, the samples were oven-dried at 40 °C overnight and weighed to enable calculation of mass-specific SI units.

Elemental and loss-on-ignition analyses

The dried contiguous sediment samples from Lake Stentjärn used for mineral magnetic measurements were ground to powder for determination of total elemental carbon (TC) and nitrogen (TN) content. Small amounts of homogenized sediment from each sample were put in tin capsules, weighed, and analysed using a Carlo Erba Instruments NC2500 elemental analyser. The reproducibility is within ± 0.5 % based on repeated analyses. TC data (App. I and IV) are expressed as percentages of elemental carbon in relation to total dry weight. A similar technique for determination of TC and TN content was applied to sediment samples from Lake Spåime, complemented by stable carbon and nitrogen isotope analyses (see App. IV). In addition, total organic carbon (TOC) content was determined on dried and fine-ground samples from the Lake Spåime sediment succession, based on temperature-controlled combustion in pure oxygen with subsequent detection of CO_2 by infrared absorption photometry in a Leco RC 412 Multiphase Carbon Determinator.

Contiguous peat samples from Klocka Bog, spanning 2-5 cm stratigraphically, with a volume of 2.5-5 cm^3 were cut out from the two profiles at Klocka Bog and oven-dried overnight at 105 °C. Samples were then weighed and ashed in a muffled furnace for 4 hours at 550 °C. Ash residues were left to cool to room temperature and weighed again in order to allow for calculation of loss-on-ignition. LOI results are expressed as percentages of organic matter content in relation to total dry weight.

Humification analysis

The degree of peat humification (DOH) was determined on 1-2.5 cm contiguous sub-samples from the Klocka Bog peat sequences. Samples were prepared according to Blackford and Chambers (1993), with a few laboratory modifications (Borgmark, 2005). Samples were treated with sodium hydroxide according to the original method, but centrifuged in order to shorten the filtering time. The light absorbance of the alkali peat extracts was measured in a spectrophotometer at 540 nm wavelength. Light absorbance data were initially given as index values (0-4), where dark samples are represented by high values, generally reflecting high concentrations of humic acids as a result of high DOH (Blackford and Chambers, 1993). These results were ultimately converted to standardized values (App. III).

Tephrochronology and EPMA

The Klocka Bog peat sequences and the lake sediment sequences from Lakes Spåime and Stentjärn were subjected to tephrochronological studies according to Pilcher et al. (1995). Samples spanning vertically over 2-5 cm were used for the initial screenings, where samples were ashed as previously described for LOI determination. The ash residues were then soaked in 10 % hydrochloric acid for approximately 12 hours, and mounted in Canada Balsam for inspection under a polarizing microscope at ×100-400 magnification. Screened samples that contained tephra particles were re-sampled at 1 cm contiguous intervals (2.0 cm^3 samples), and the number of glassy tephra particles (glass shards) exceeding 20 µm in size were counted. At Klocka Bog, tephra concentrations were calculated by adding a known amount of *Lycopodium* spores.

Levels containing tephra particles were then re-sampled and subjected to an acid digestion procedure (Dugmore et al., 1992). Generally ca 2-4 cm^3 of sediment or peat is sufficient, but in the peat profiles from Klocka Bog, greater volumes of peat (20-45 cm^3) were needed in order to obtain sufficient concentrations of glass shards for electron probe microanalysis (EPMA). Mineral residues from Klocka Bog were not subjected to sieving or heavy liquid separation, except for the sample at 3-4 cm in profile 1, where the high minerogenic content made separation using sodium polytungstate necessary. All samples from Lake Stentjärn and Lake Spåime were sieved through an 18 µm mesh and treated with the heavy liquid separation method (Turney, 1998). Liquid densities of 2.3 and 2.5 gcm^{-3} were used. Samples containing minerals and/or organic matter that masked the tephra particles during microscopy, such as high concentrations of iron oxides, were treated with the CBD (citrate–bicarbonate–dithionite) method (Mehra and Jackson, 1960), and samples with high concentrations of biogenic silica (diatoms, phytoliths) were treated with sodium hydroxide (Rose et al., 1996). Quantitative geochemical analyses were performed on samples from Klocka Bog, using a wavelength dispersive spectrometer (WDS) electron microprobe at the Department of Geology and Geophysics, Edinburgh University. The analyses of the samples from Klocka Bog were carried out on a Cambridge Instruments Microscan V microprobe operating at 20 kV accelerating voltage, 5 mm beam diameter, and a 15 nA beam current. Slides were scanned systematically for superficial grains. Quantitative analyses of shards with volcanic glass compositions were then undertaken in WDS mode. Before each WDS analysis the beam was centred by "burning" a hole in the araldite resin and the beam current was determined by the insertion of a Faraday cup into the path of the beam. Nine major elements were measured, with a counting time of 10 s per pair of elements. The beam was covered during spectrometer movement to minimize mobilization of alkali elements. The samples from Lake Stentjärn were analysed with a Cameca SX100 electron microprobe equipped with 5 vertical WD Spectrometers. Ten major elements were measured with a counting time of 10 seconds. An accelerating voltage of 20 kV and a beam strength of 10 nA (all other samples), determined by a Faraday cup were used, with a rastered beam over an area of 10×10 µm to reduce instability of the glass and subsequent sodium loss. Calibration was undertaken using a combination of standards of pure metals, simple silicate minerals and synthetic oxides, including andradite. These were used regularly between analyses to correct for any drift in the readings. A PAP correction was applied for the effects of X-ray absorption (Pouchou and Pichoir, 1991).

Radiocarbon dating

The chronologies of the stratigraphic sequences from Lake Spåime, Lake Stentjärn and Klocka Bog were primarily based on AMS radiocarbon dating of terrestrial, macroscopic plant remains. Macrofossils were preferably collected from narrow stratigraphic intervals to optimize the chronological precision, which generally resulted in samples spanning 4-40 mm, and only in a few cases as much as 60 mm. Samples were wet-sieved (125 or 250 µm mesh) with a fine jet of water and rinsed in de-ionized water. Delicate plant remains of terrestrial origin were picked from the sieve residue and dried in glass vials at 105 °C, followed by standard pre-treatment and analysis at the radiocarbon dating laboratories at Lund University and Uppsala University, Sweden, and Poznán University, Poland. The material used for dating of the Klocka Bog peat sequences predominantly consisted of moss remains, mainly *Sphagnum* sp. All material used for dating was carefully treated to avoid contamination by dust and mould (Wohlfarth et al., 1998). The reported radiocarbon ages were converted to calibrated ages based on the IntCal98 calibration data set (Stuiver et al., 1998), using the OxCal version 3.5 radiocarbon calibration software.

Plant macrofossil analysis

The sediment successions from Lakes Spåime and Stentjärn were divided into 2-3 cm thick, contiguous samples and processed using standard techniques (cf.

Wasylikowa, 1986). Samples were wet-sieved through a 125 or 250 mm mesh, generally after being soaked in 5% sodium hydroxide overnight. Sieve residues were examined under a binocular microscope at ×50 magnification, and plant remains were determined to species level where possible following Beijerinck (1947) and Tomlinson (1985), and by comparison with reference collections. Sample volumes generally ranged from 35 cm^3 to a maximum of ca 300 cm^3 except in the lowermost part of the Lake Stentjärn sequence where only one core segment was used for analysis, yielding sample volumes of 10-30 cm^3. Major plant macrofossil taxa are expressed as concentrations per unit volume of wet sediment, whereas less frequently recorded taxa were expressed as numbers of macrofossils per sample.

Pollen analysis

Pollen analysis was applied to 2 cm^3 volume samples at 36 levels from Lake Spåime, and at 30 levels from Lake Stentjärn. Samples were prepared according to method A described by Berglund and Ralska-Jasiewiczowa (1986), complemented by treatment with 40% hydrofluoric acid of samples rich in minerogenic material. *Lycopodium* tablets were added to allow calculation of pollen concentration and pollen accumulation rates (influx). The samples were mounted in glycerol and pollen grains were counted using a Leica light microscope at ×400 and ×1000 magnification. Plant taxonomy and identification of pollen and spores follow Florin (1969) and Moore et al. (1991). Comparisons were made with pollen reference collections at the Department of Physical Geography and Quaternary Geology, Stockholm University. At least 500 tree pollen grains were counted at each level, except for a few of the lowermost samples where pollen concentrations were low. Pollen grains of *Betula* were treated as a single taxon, including both *B. nana* and *B. pubescens*. Pollen diagrams were constructed using the TILIA and TILIA GRAPH 2 programs (Grimm, 1992).

Cuticle analysis

Attempts were made to identify subfossil leaf fragments, preferably to species level, by searching for cuticle remains with preserved epidermal features. Samples from Lake Spåime were treated and analysed using a light microscope at ×400 magnification as described by Lamme (2000). Samples from Lake Stentjärn were treated as described in the macrofossil analysis section, i.e. samples were sieved using a 125 mm mesh, and residues were screened under a binocular microscope at ×50 magnification. Subfossil cuticle remains were then analysed using a Leica light microscope at ×400, and epidermal features were identified using reference samples and an epidermis key (Westerkamp and Demmelmeyer, 1997). Reference samples were created by bleaching of modern leaves in sodium hypochlorite until the epidermis became transparent or dissolved. The cuticles from both sides of the leaves were then removed and mounted in glycerol. However, no results from the cuticle analysis could be used to enhance the results of the macrofossil analysis since the concentration of subfossil leaf remains in the two lake sediment sequences was generally low, and only leaf fragments that were sufficiently well preserved to allow macrofossil identification could be used for cuticle analysis.

Summaries of papers

During the course of this project, several researchers have contributed with various analyses, and have also been involved as authors. The author of this thesis has performed the following work included in the papers below (see also Table 1):
Paper I. Led the fieldwork, produced the sediment stratigraphic, pollen, plant macrofossil, and tephrochronological data, handled the integration and presentation of results, and led the discussion.
Paper II. Led the fieldwork, performed stratigraphic subsampling and tephrochronological analyses, prepared samples for EPMA and radiocarbon dating, compiled and presented the results, and led the discussion.
Paper III. Led the fieldwork, produced the peat humification data, handled the integration and presentation of results, and provided the main part of the discussion.
Paper IV. Participated in complementary fieldwork, performed a cryptotephra screening, assisted with cuticle analysis, and provided minor contributions to the discussion.

Paper I

Bergman, J., Hammarlund, D., Hannon, G., Barnekow, L. and Wohlfarth, B., 2005: Deglacial vegetation succession and Holocene tree-limit dynamics in the Scandes Mountains, west-central Sweden: stratigraphic data compared to megafossil evidence. *Review of Palaeobotany and Palynology 134,* 129-151.

The aim of this paper was to obtain and analyse high-resolution records of plant macrofossils, magnetic susceptibility, and total carbon content, complemented by pollen data, from the lake sediment sequence at Lake Stentjärn (987 m a.s.l.), in west-central Sweden. Holocene vegetational and environmental changes were reconstructed from the data, with particular emphasis on the deglacial establishment of terrestrial vegetation and subsequent tree-limit ecotonal dynamics. The stratigraphic results obtained were designated for comparison with local megafossil data. A short-lived pioneer flora with *Geum rivale*, *Dryas octopetala*, *Empetrum nigrum*, *Ledum palustre*, *Saxifraga* sp., *Salix* spp. and *Oxyria digyna* established locally following deglaciation at ca 10,500 cal yr BP. The pioneer flora was probably out-competed by expanding grass-communities, and possibly establishing *Betula pubescens*, at ca 10,300 cal yr BP. The abrupt vegetational change may be related to the climatic perturbation recorded at this stage in several proxy records across the North Atlantic region (e.g. Björck et al., 2001). Subsequent local expansions of *Betula pubescens* at ca 9800 cal yr BP and *Pinus sylvestris* at ca 9200 cal yr BP were followed by a temporary retraction of the birch tree and stand-limits, and a permanent retreat of the pine tree-limit between 8500 and 8000 cal yr BP, accompanied by declining aquatic productivity and increasing catchment erosion. A gradual decrease in forest density initiated at ca 6000 cal yr BP led to a retreat of the birch tree- and stand-limits at ca 3500 cal yr BP, followed by possible persistence of scattered trees in the catchment until ca 2000 cal yr BP. A mosaic heath vegetation dominated by *Empetrum* and *Betula nana* developed at ca 3500 cal yr BP. The stratigraphic data obtained from Lake Stentjärn were compared with records of radiocarbon-dated subfossil wood remains (megafossils), primarily collected from the study area during recent decades (e.g. Kullman, 1995; Kullman and Kjällgren, 2000). A general conformity was revealed between plant macrofossil data and pollen accumulation rates. A comparison between non-stratigraphic megafossil data and pollen influx/plant macrofossil records also revealed a high level of consistency of the inferred tree-limit variations for *Pinus sylvestris*, *Betula pubescens* and *Alnus incana*. The long-term decline of the pine tree-limit, as inferred by the megafossil data, is closely correlated with the stratigraphic plant macrofossil record from ca 9200 to 8200 cal yr BP, clearly indicating synchronous high-elevation pine growth in the study area and in the lake catchment at ca 1000 m a.s.l. The tree birch plant macrofossil record also correlated well with the megafossil data during the time period 8000-5000 cal yr BP, indicating tree birch growth at ca 1000 m a.s.l. in the study area and in the lake catchment. However, during approximately 9800-8500 cal yr BP, the birch megafossil data set does not match with the plant macrofossil record, which indicates tree birch growth of forest density in the lake catchment. The discrepancy likely depends on unfavourable preservation conditions for birch wood at this time. The stratigraphic alder records display a strong temporal correlation with the megafossils, although the alder megafossil record fails to reconstruct the spatial patterns of mid-Holocene alder growth. Possibly, no or few sites with suitable preservation conditions for alder megafossils existed at the lake catchment elevation. Chronological control was established by radiocarbon dating of terrestrial macrofossils and geochemical identification of a tephra horizon originating from the Icelandic Askja-1875 eruption. Two other tephra horizons detected in the sediment sequence were not geochemically analysed, but the inferred ages of ca 3000 and 6900 cal yr BP, suggested a correlation with the Hekla-3 and Lairg A tephras.

Paper II

Bergman, J., Wastegård, S., Hammarlund, D., Wohlfarth, B., Roberts, S. J., 2004: Holocene Tephra horizons at Klocka Bog, west-central Sweden: aspects of reproducibility in sub-arctic peat deposits. *Journal of Quaternary Science 19*, 241-249.

This paper presents a study aimed at investigating the potential of Holocene tephrostratigraphy in the study area of western Jämtland, where several Holocene tephra horizons, presumably of Icelandic origin, were previously detected by Persson (1966, 1971) during pioneering tephrochronological investigations. Glassy tephra particles at several levels originating from Icelandic volcanic eruptions were recorded in two ca 2.32 and 2.36 m thick peat profiles at Klocka Bog, an ombrotrophic peat deposit in western Jämtland. Predominantly rhyolitic volcanic ash particles were recorded at a total of eight stratigraphic levels in the profiles. Tephra shard concentrations were calculated by adding a known amount of *Lycopodium* spores to peat samples of known volume. Peat profiles 1 and 2, located ca 150 m apart, were radiocarbon dated at seven and six individual levels, respectively. Samples containing tephra shards were subjected to quantitative geochemical analysis on a wavelength dispersive spectrometer (WDS) electron microprobe. Five of the detected tephra horizons were geochemically correlated with the Askja-1875, Hekla-3, Kebister, Hekla-4, and Lairg A tephras, respectively. Radiocarbon dating of these tephras broadly agrees with previously published ages from Iceland, Sweden, Germany, and the British Isles (e.g. Larsen et al., 1999; Boygle, 1998; van den Bogaard and Schmincke, 2002; Pilcher et al., 1996). The identification of the Lairg A tephra demonstrates a more widespread distribution than previously thought, extending the usefulness of Icelandic Holocene tephrochronology further north into west-central Scandinavia. The long-lasting snow cover in the region is hypothesized as a factor that may be responsible for fragmentary tephra deposition patterns in northerly located peat deposits, whereas the general large-scale distribution of tephras is likely related to seasonal wind dynamics of the lower stratosphere (Lacasse, 2001).

Paper III

Bergman, J. and Hammarlund, D.: Recurrent episodes of increased effective humidity during the late Holocene inferred from mid-Swedish peat deposits and lake sediments. *Manuscript submitted to Quaternary Science Reviews.*

In this paper, palaeoecological and sediment stratigraphic records from two peat profiles from Klocka Bog, located in the boreal vegetation zone, and two alpine lake sediment sequences from the central Scandes Mountains have been evaluated for significant mid to late Holocene environmental changes. Records of climatic humidity inferred from peat humification data (DOH) from Klocka Bog were compared to a local chironomid-inferred mean July temperature reconstruction and records of total carbon content, magnetic susceptibility, and pollen influx of *Pinus*, *Betula*, and *Alnus* from the two lake sediment sequences. Chronological constraints were obtained by radiocarbon dating of moss remains, terrestrial plant macrofossils and geochemical identification of cryptotephra horizons originating from Icelandic volcanic eruptions of known ages (App. I and II). The individually normalized DOH records exhibit millennial-scale trends, which are not significantly correlated ($p<0.05$), except during the periods 6500-4000 cal yr BP and 2100-0 cal yr BP, most likely due to changes in peat composition (dominance of *Sphagnum* or fen plants such as *Carex*) and microform distribution within the peat deposit. The discrepancy between the two records between 4000 and 2100 cal yr BP may be related to internal variability in the development and distribution of hummock, lawn, and pool microforms, or simply the complex nature of the peat humification process (e.g. Caseldine et al., 2000). The arboreal pollen influx data sets derived from the two adjacent lake sequences display significant dissimilarities between sites, which partly are explained by climate-driven sedimentary changes, mirrored by the respective lake catchment properties. Especially the high and generally increasing tree-pollen accumulation rates at ca 6000-2000 cal yr BP in the lower of the two lakes, may reflect enhanced influx by melt-water, possibly following pollen deposition on increasingly late-melting snow cover. The time periods between 5800-4800 cal yr BP, and 1800 cal yr BP until the present, are recognised as periods increasing climatic humidity, probably reflecting major rearrangements of the atmospheric circulation pattern across the northern North Atlantic and adjacent land areas. Although the ultimate forcing is not known, these perturbations may be expressions of long-term equivalents of the decadal-scale modes of climate variability known as the North Atlantic Oscillation. Also, potential mechanisms that influence Holocene climate variability are discussed, as reconstructions of atmospheric radiocarbon production rates show maximum values during both episodes of increased effective humidity identified here, which theoretically could be related to reduced solar activity.

Paper IV

Hammarlund, D., Velle, G., Wolfe B. B., Edwards T. W. D., Barnekow, L., Bergman, J., Holmgren, S., Lamme, S., Snowball, I., Wohlfarth, B. and Possnert, G. Palaeolimnological and sedimentary responses to Holocene forest retreat in the Scandes Mountains, west-central Sweden. *The Holocene 14*, 862-876.

This paper presents a multi-proxy study based on analyses performed on sediments accumulated during the last 10,700 years in Lake Spåime, a small, hydrologically open water body in the low alpine zone of the Scandes Mountains, west-central Sweden. The lake is located at 887 m a.s.l., above the present-day forest-limit at ca 800 m a.s.l. The subalpine forest in the Sylarna-Storulvån area is dominated by mountain birch, whereas the lake catchment vegetation consists mainly of heath communities with dwarf shrubs, willows, grasses, sedges, and alpine herbs. The study aimed to evaluate (1) the nature of climate changes that forced the late-Holocene lowering of altitudinal tree-limit in the region, the timing of which is known from prior studies based on radiocarbon-dating of subfossil wood, and (2) the impact of these vegetational changes on the aquatic ecosystem. Based on plant macrofossil, pollen, geochemical, chironomid, and mineral magnetic analyses of lake sediments the Holocene environmental response was reconstructed. Arboreal pollen and plant macrofossil data confirm the persistence of tree growth, probably at forest den-sity, in the lake catchment at least from ca 9700 cal yr BP until ca 3700 cal yr BP. When the woodlands dominated by tree birch dispersed, the heath community plants *Empetrum nigrum* and *Betula nana* expanded significantly in the lake catchment. *B. pubescens* plant macrofossils indicate a complete retraction of remaining tree birch specimens from the elevation of the lake around 600-500 cal yr BP. Although growing-season temperature is commonly believed to be the dominant factor driving forest- and tree-limit variations in the region, a chironomid-based reconstruction of mean July air temperature suggests that local deforestation during the late Holocene was not accompanied by a significant cooling. The tree-limit retreat was more likely caused by increasing effective moisture and declining length of the growing season. The ecohydrological response of Lake Spåime to this combination of climatic and vegetational changes included a decline in primary productivity, as indicated by an abrupt decrease in sediment organic matter content, while associated increases in organic $\delta^{13}C$, $\delta^{15}N$, and C/N point to diminished fluxes and altered balance of catchment-derived nutrients following deforestation. The decline in aquatic productivity is also marked by a distinct change in the mineral magnetic properties, from a high magnetic concentration assemblage dominated by fine-grained magnetite of biogenic origin to one dominated by background levels of coarse-grained detrital magnetite.

Additional results

Tephrochronological data from lake sediments

The tephrochronological studies presented in App. I and II were carried out at Lake Stentjärn and Klocka Bog, but a largely similar investigation was also conducted at Lake Spåime. The tephra screening performed on the sediment sequence from Lake Spåime revealed the presence of tephra shards at several stratigraphic levels (mid- to late Holocene). However, high concentrations of biogenic silica (diatoms, phytoliths etc.) at most levels prevented an estimation of tephra shard concentration without additional laboratory treatment. Other problems encountered were the high amounts of iron oxide and hydrated iron oxides that formed mainly during the ashing procedure. Despite attempts to remove the iron oxides, using the CBD (citrate–bicarbonate –dithionite) method (Mehra and Jackson, 1960), and to dissolve the biogenic silica using a technique involving sodium hydroxide treatment (Rose et al., 1996), further studies were considered unrealistic due to the large sample volumes needed for more precise analyses in relation to the limited amount of sediment available. Due to the stratigraphically wide sampling of the tephra screening and the generally high concentrations of biogenic silica and "waste minerals", little hint was provided as to the actual concentration and age of the potential cryptotephra horizons, although the most likely candidates probably are the Hekla-4, Kebister, and Hekla-3 tephras.

The data from Lake Stentjärn indicated three mid- to late Holocene tephra horizons (App. I). The interpolated ages of the two lower of these fall within published age intervals of the Lairg A (Pilcher et al., 1996) and Hekla-3 tephras (van den Bogaard et al., 2002), respectively. Only the youngest cryptotephra horizon yielded sufficient EPMA results for correlation with a known eruption and North Atlantic tephra isochrone (Askja-1875). The EPMA data for the Askja-1875 tephra identified at Lake Stentjärn are listed in Table 2 and plotted in Fig. 7.

SiO_2	TiO_2	Al_2O_3	FeO_{tot}	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Total
72.55	0.881	13.048	3.732	0.152	0.729	2.889	3.696	2.422	0.198	100.297
72.279	0.606	15.113	2.578	0.049	0.456	3.270	3.616	2.104	0.168	100.240
73.663	0.698	12.814	2.952	0.096	0.489	2.396	3.451	2.593	0.167	99.318
72.985	0.800	12.500	3.231	0.087	0.636	2.394	3.902	2.286	0.145	98.965
71.629	0.931	12.857	3.447	0.090	0.732	2.429	3.811	2.447	0.196	98.569
71.941	0.833	12.783	3.225	0.040	0.665	2.562	3.919	2.424	0.168	98.561
71.75	0.839	12.613	3.599	0.062	0.705	2.618	3.684	2.319	0.188	98.376
71.61	0.748	12.465	3.610	0.127	0.717	2.695	3.149	2.157	0.140	97.418
72.30	**0.79**	**13.02**	**3.30**	**0.09**	**0.64**	**2.66**	**3.65**	**2.34**	**0.17**	**98.97**

Table 2. Geochemical analysis results (EPMA) obtained on eight tephra shards from the youngest tephra horizon (Askja-1875 AD) encountered in the Lake Stentjärn sediment sequence. Mean values are printed in bold. The MgO/FeO_{tot} ratios are plotted in Fig. 7, whereas the EPMA methodology is described in the methods section and in Appendix II.

Loss-on-ignition data from Klocka Bog

LOI percentages in the lowermost parts of the two peat profiles (prior to ca 6000 cal yr BP) were lower than in the upper parts (Fig. 8), which may suggest focusing of aeolian material during the early Holocene. However, the most likely explanation is local dominance of phytolith-producing plants, such as *Carex* sp., *Equisetum* sp., *Eriophorum* sp., and *Phragmites australis* (Fredlund and Tieszen, 1997; Delhon et al., 2003), at the early stage of the bog development. Dominance of macroscopic remains of Cyperaceae was observed in the lower parts of the peat profiles, and during tephra screening, high concentrations of biogenic silica, mainly phytoliths, were recorded. This suggests that fen-like conditions dominated at the sampling sites during a majority of the early Holocene, probably alternating with periods of forest vegetation. Subfossil remains of mainly *Pinus sylvestris* (e.g. Lundqvist, 1969), but also thermophilous trees such as *Tilia cordata* (Kullman, 1998b), have been found in the lowermost parts of the peat deposit. High concentrations of phytoliths have been observed previously in Scandinavian peat sequences dominated by *Carex* sp. (Björck et al., 1994).

At the top of the two peat profiles, LOI records indicate an episode of low organic content (Fig. 8), corresponding to a 1-2 cm thick layer with high minerogenic content, clearly visible to the naked eye. This layer of unsorted sandy silt most probably reflects one or several historical flooding events related to high (catastrophic) discharges of the Handölan and Enan Rivers. Northern and central Sweden experienced several warm springs and

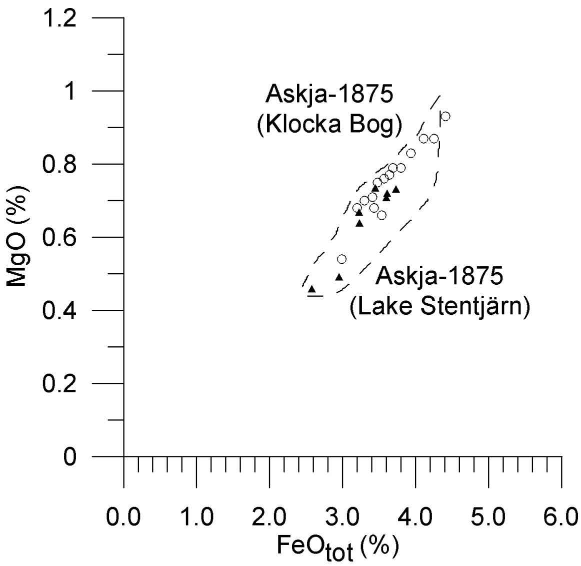

Fig. 7. Binary plot with major oxide data (MgO versus FeO_{tot}) of Askja-1875 tephra shards from Lake Stentjärn and Klocka Bog. Values are expressed as weight percentages. The field indicated by a dashed line shows the main geochemical distribution of the Askja-1875 tephra in Iceland and Sweden (Oldfield et al., 1997; Larsen et al., 1999).

summers during the 1930's (Alexandersson, 2002), and especially in 1934 and 1938 considerable flooding events were reported from the northern and central part of Sweden (Swedish Meteorological and Hydrological Institute; www.smhi.se). As inferred from the chronology of profile 1 (App. II), the single or multiple silt deposition event seem to have occurred during the early 20th or the late 19th century, and may be related primarily to the spring flood of May 5th, 1934, which according to local historical sources caused a serious flooding of Lake Ånnsjön (H.

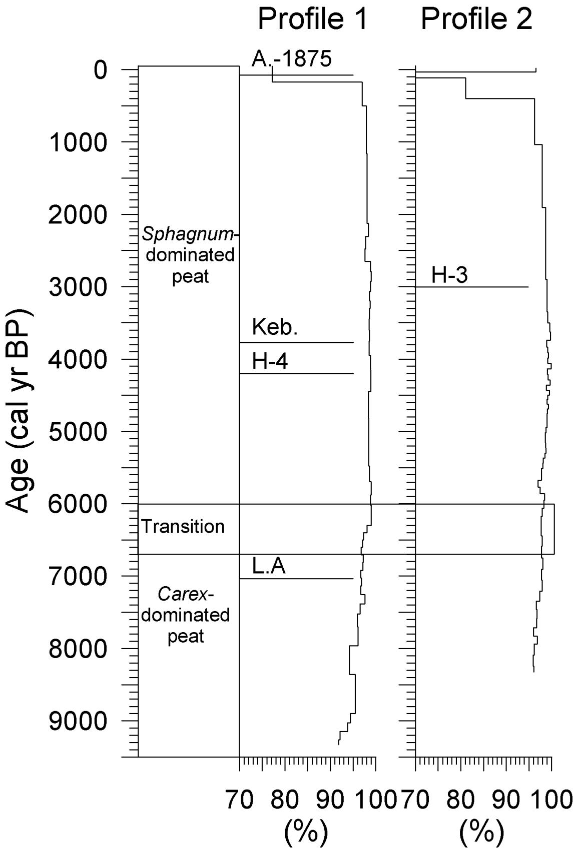

Fig. 8. Loss-on-ignition (LOI) data from profile 1 and 2 at Klocka Bog expressed as percentages of organic matter content in relation to total dry weight. The approximate transition zone from Carex to Sphagnum-dominated peat is indicated by solid lines. Tephra horizons are indicated by horizontal lines (App II).

Strandberg, Handöl, pers comm.). It is possible that the highest Holocene lake levels occurred during recent centuries, but based on the present data, it seems more likely that silt layers originating from possible earlier flooding events are absent at the sampling sites due to the gradual erosion of the peat deposit. If previous floods only reached a limited distance in-land across the bog surface, which slopes towards the lake at a gradient of 5-10 m per 1000 m, the persistent erosion may have prevented earlier flooding event layers to be preserved for more than a few centuries.

Discussion

Tephrochronological studies

The possibility to geochemically correlate distal tephra horizons across the North Atlantic region is a remarkable step forward in securing high-precision chronologies for terrestrial, marine, and ice-core archives. With the development and refinement of geochemical microprobe analysis techniques (EPMA) during the 1980's and 1990's, researchers could determine "geochemical fingerprints" for individual tephra horizons encountered, and hence identify and correlate them with corresponding proximal layers, e.g. on Iceland. The documentation of especially Icelandic tephra deposits in terms of geochemistry, geographical extension, and correlation to historical and pre-historical eruptions is well under way (Larsen et al., 1999; Haflidason et al., 2000; Larsen et al., 2001). Recent studies in Sweden (e.g. Zillén et al., 2002; Gunnarson et al., 2003; Wastegård et al., 2003; Wastegård, 2005) have led to the discovery of several Holocene tephra horizons in peat and lake sediment sequences. The vast majority of Scandinavian tephras found to date are all invisible to the naked eye (so-called cryptotephras; cf. Turney et al., 2004) and can only be detected trough combustion techniques and microscopy. Most of the recent studies include main oxide EPMA data, which makes it possible to correlate most tephras with high confidence to Icelandic eruptions.

Although the age assignments of the Holocene tephra marker horizons encountered have not been significantly improved as a consequence of this study, important knowledge about the distribution of cryptotephras in north-western Europe have been obtained. It could for example be shown that the early Holocene Lairg A tephra had a much more northerly distribution than previously known. In order to improve the age determination of distal pre-historic tephras, high-precision chronological control is essential, and approaches involving annually laminated lake sediments, ice core archives, and high precision wiggle-matching of radiocarbon dates, seem at present as the most promising ways forward. However, it is equally important to gain increased understanding of small- and large-scale dispersal processes of tephras and of the mechanisms involved in the deposition of distal ash particles in different geological archives, such as peat and lake sediments. Without understanding of the meteorological, sedimentological, and post-depositional processes affecting tephra incorporation, tephrochronology cannot be used for detailed correlations between the growing number of local and regional Holocene palaeoclimatic and palaeoenvironmental data sets, which all are needed as the Holocene climate history grows increasingly complex and more detailed descriptions of short-term climatic fluctuations emerge. Within this project, problems related to post-depositional processes, such as snow-cover conditions, and their impact on tephrostratigraphic data have been discussed (App. II). The probability of finding Icelandic tephra horizons in Scandinavian geological archives (mainly peat) generally increases towards the west (Persson, 1971), since the local tephra fallout depends on prevailing local atmospheric conditions. Tephra fallout is much more likely to occur in areas with high precipitation rates, since approximately 99 % of all distal tephra deposition is estimated to take place in association with local rainfall, so called "wet deposition" (Langdon and Barber, 2004). A similar pattern is probably also valid for the British Isles, where tephras are widespread, but predominantly found in the oceanic north-west and west, i.e. in areas with high annual precipitation rates (cf. Chambers et al., 2004; Langdon and Barber, 2004). Based on the same argumentation, one might speculate whether late Holocene climatic change towards wetter and more oceanic conditions, has led to more favourable conditions for tephra fallout in north-western Europe, thus resulting in higher frequencies of tephra horizons during the later part of the Holocene. As for the regional (North Atlantic) distribution of Icelandic distal tephras derived from explosive eruptions, these seem largely controlled by the seasonal strength of the westerlies and easterlies in the lower stratosphere (Lacasse, 2001; App. II).

Implications for the local deglaciation history

Mountain peaks, such as Sylarna, Blåhammarfjället, and Snasahögarna, probably formed nunataks already at the Pleistocene-Holocene transition or even earlier (Kullman and Kjällgren, 2000; Fig. 9a). The oldest high-elevation megafossil recovered from the Sylarna massif (ca 1200 m a.s.l.) yielded an age of 11,000-10,500 cal yr BP (Kullman and Kjällgren, 2000). Mount Enkälen and the adjacent Lakes Stentjärn and Spåime (Fig. 2) were likely deglaciated during the same time period, since the onset of accumulation of organic material in the lake basins dates to ca 10,700-10,500 cal yr BP (Fig. 9b; App. I and IV). The Storulvån valley probably became ice free around 10,000-9900 cal yr BP (Fig. 2, 9c) and the northernmost part of the Handölan valley at ca 9900-9800 cal yr BP (cf. Segerström and von Stedingk, 2003). A large ice-dammed lake (Storlis-sjön) was subsequently formed in the Lake Ånnsjön depression. This basin probably drained to the east around 9500-9300 cal yr BP (Fig. 9d), after which organic accumulation began at Klocka Bog.

High-elevation megafossils: remnants of forest or extreme outliers?

The very high-elevation megafossils of pine and birch from the southern parts of the Scandes Mountains (e.g. Kullman and Kjällgren, 2000; Kullman, 2002a, 2004a), which have yielded Late Weichselian and early Holocene ages are probably remnants of trees that grew in climatically favourable positions, with a reliable (annually consistent) snow cover on the early deglaciated nunataks. The snow conditions at the growth sites are possibly the key to understanding the occurrence of these finds. As discussed by Kullman (2004a), tree remains found at this elevation (above ca 1000 m a.s.l. for pine, and 1300 m a.s.l. for tree birch in the Sylarna-Storulvån area) were possibly preserved by overriding glaciers or incorporated in expanding perennial snow fields. On the other hand, the megafossils may also initially have been buried in small pools and hollows, as reliable and optimal snow conditions for tree growth are generally found in intermediately sloping terrain, such as around small hollows and depressions, which suggests that the very sites where high-elevation tree growth could be sustained, also supplied the locations where the wood could be preserved. If the prevailing climatic conditions during the early Holocene (11,500-10,300 cal yr BP) indeed were warmer and/or drier than at present, the high-elevation trees could benefit from soil moisture supplied by the melting snow beds during summer. Glaciers may thus have overridden the peat or sediments that accumulated in the hollows at a later stage (Kullman, 2002a), such as after 8500 cal yr BP (see below). This argument is more important for explaining the high-elevation tree birch remains, since pine wood generally decomposes at a much slower rate. Hence, subfossil tree remains found at high altitudes do not necessarily represent as many individuals as megafossils found at lower elevations. The high-elevation tree remains may thus more closely reflect outliers at or above the tree-limit, whereas the rest of the "mid-elevation" (ca 1000-700 m a.s.l.) Holocene megafossil data (mainly excavated from peat hollows above the present-day forest-limit) probably reflects tree vegetation of fo-rest density. According to Kullman (1995) and Kullman and Kjällgren (2000) average megafossil

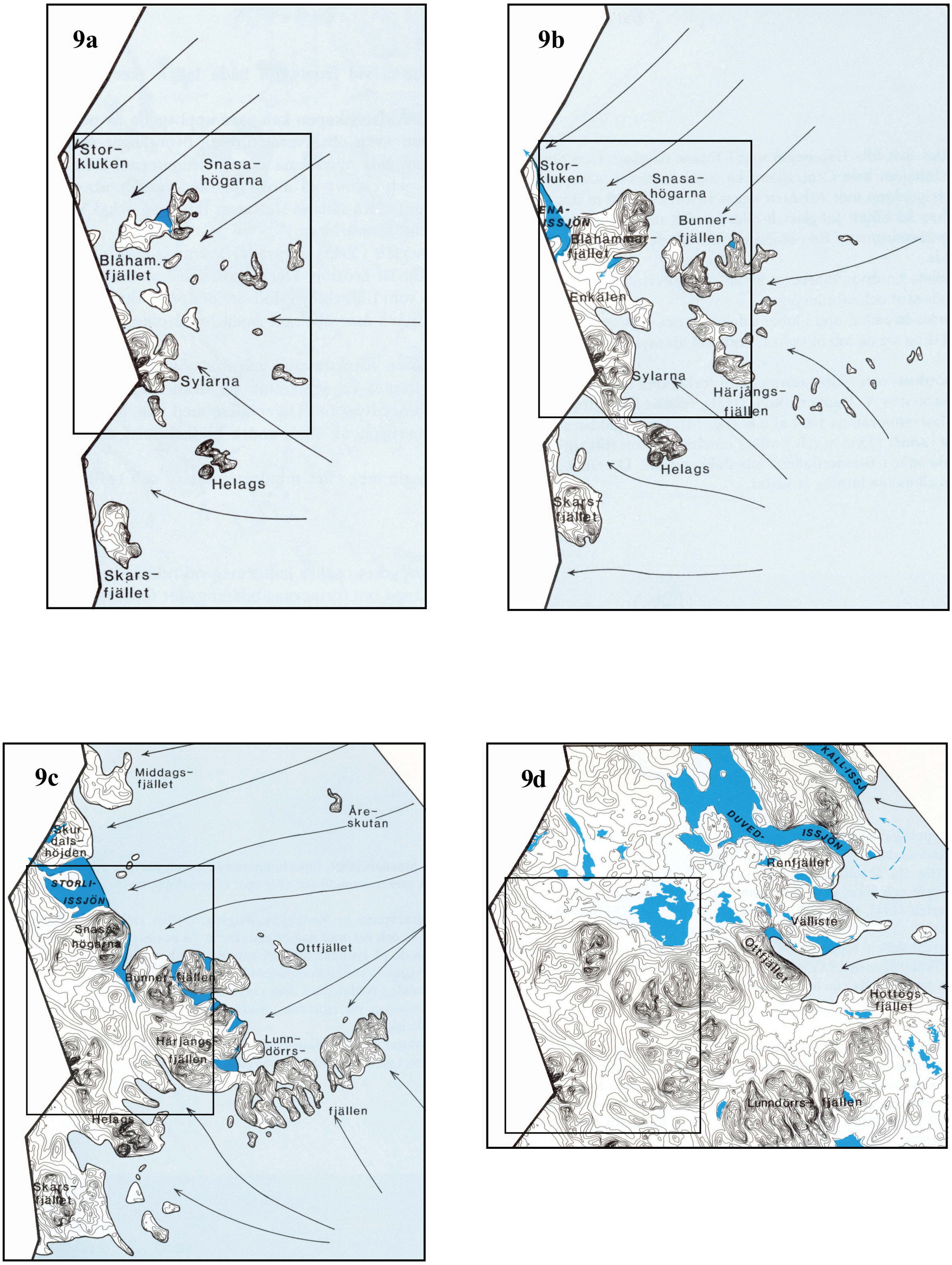

Fig. 9. Deglaciation maps of the study area (from Borgström, 1989), with contour lines at 25 m. Maps a-d show a tentative reconstruction of the deglaciation of western Jämtland. Age assignments are based on radiocarbon-dated levels for the onset of organic accumulation at various sites. 9a) Onset of the Holocene (ca 11,500 cal yr BP). 9b) Deglaciation of Mount Enkälen and the southern part of the Handölan valley between 10,700 and 10,500 cal yr BP. 9c) Deglaciation of the Storulvån valley, south of Snasahögarna at 10,000-9900 cal yr BP. 9d) After the drainage of the ice-dammed lake (Storli-issjön) in the Ånnsjön area at 9500-9300 cal yr BP, Lake Ånnsjön received its present-day shape, but was located further east because of the earlier isostatic recovery in the west.

finds can be considered to represent small stands, or enclaves of 3-10 trees. Since this definition is relatively close to the definition of *forest* according to Matthews et al. (2001; Fig. 5), the majority of the megafossil data can be regarded as broadly reflecting forest density.

The Holocene climatic and environmental development

The establishment of mid-elevation forest 10,500-8500 cal yr BP

Due to the ongoing local deglaciation, the study area can be considered as a glacial or proglacial environment during the early part of this period. Therefore, sedimentary records derived from this area may have been affected, and possibly dominated by related sedimentary processes, rather than by climate. However, the continued presence of snow-bed community plants, such as *Salix herbaceae* and *S. polaris* suggests high rates of winter precipitation after ca 10,300 cal yr BP. This is in general accordance with the elevated magnetic susceptibility values at Lake Stentjärn, and extended distributions of Norwegian mountain glaciers (Nesje et al., 2001; Fig. 10). The summers were probably relatively warm during this period, as suggested by the chironomid-inferred temperature reconstruction from Lake Spåime, the presence of e.g. *Ledum palustre* and the local presence of *Hippophaë* (App. I), which prefers mean July temperatures above 10 °C (Table 3). The abundance of subfossil *Geum rivale* seeds at Lake Stentjärn also suggests favourable early summer conditions, consistent with the presence of *Potamogeton* sp., which prefers mean July temperatures above 8 °C (App. I; Table 3).

The possible climatic perturbation at ca 10,300 cal yr BP recorded in the Lake Stentjärn vegetation proxy records (App. I; Fig. 10) correlates well with the onset of the Erdalen event, an episode of glacier expansion at ca 10,300-9700 (-9500) cal yr BP, which is evident in Norwegian glacier status records (Dahl and Nesje, 1996; Matthews et al., 2000, 2005; Nesje et al., 2001). This event may also be associated with cooler and more humid conditions inferred from lake sediment records on the Faroe Islands (Björck et al., 2001; Hannon et al., 2003), in northern Norway (Husum and Hald, 2002; Seppä et al., 2002a) and in the Alps (Haas et al., 1998; Heiri et al., 2003). However, due to chronological uncertainties and the proglacial sett-ing of the sediment record, the proxy data from the study area cannot be regarded as conclusive evidence for the occurrence of such a climatic event, or for its environmental impact. The Lake Spåime TC record shows that organic accumulation only started after the termination of the Erdalen event (App. IV), which is a well recorded feature in palaeo-climatological proxies displayed in Fig. 10. The reason for this could possibly be the presence of decaying bodies of stagnant glacier ice in the catchment (Borgström, 1989), or simply high amounts of winter precipitation associated with the Erdalen event. Tree birch expanded to forest density in the two lake catchments at ca 9800-9700 cal yr BP (Fig. 11), largely synchronous with the local high-elevation birch growth inferred from megafossils (Kullman, 2004a). The expansion of *Betula pubescens* along the Scandinavian west coast generally took place within a few hundred years. In the central Troms region, northern Norway, the tree birch expansion is dated to ca 9900 cal yr BP

Minimum mean July temp. (°C)	Plant species	Reference
9-11	*Pinus sylvestris*	Aas and Faarlund (1988)
>12	*Pinus sylvestris*	Iversen (1954)
8-10	*Betula pubescens*	Aas and Faarlund (1988)
>10 (12)	*Betula pubescens*	Iversen (1954)
>10 (11-12)	*Hippophaë rhamnoides*	Kolstrup (1980)

Table 3. Estimates of minimum mean July temperatures, or minimum mean summer temperatures for relevant plant species. Ecological data were derived from Iversen (1954), Kolstrup (1980), and Aas and Faarlund (1988).

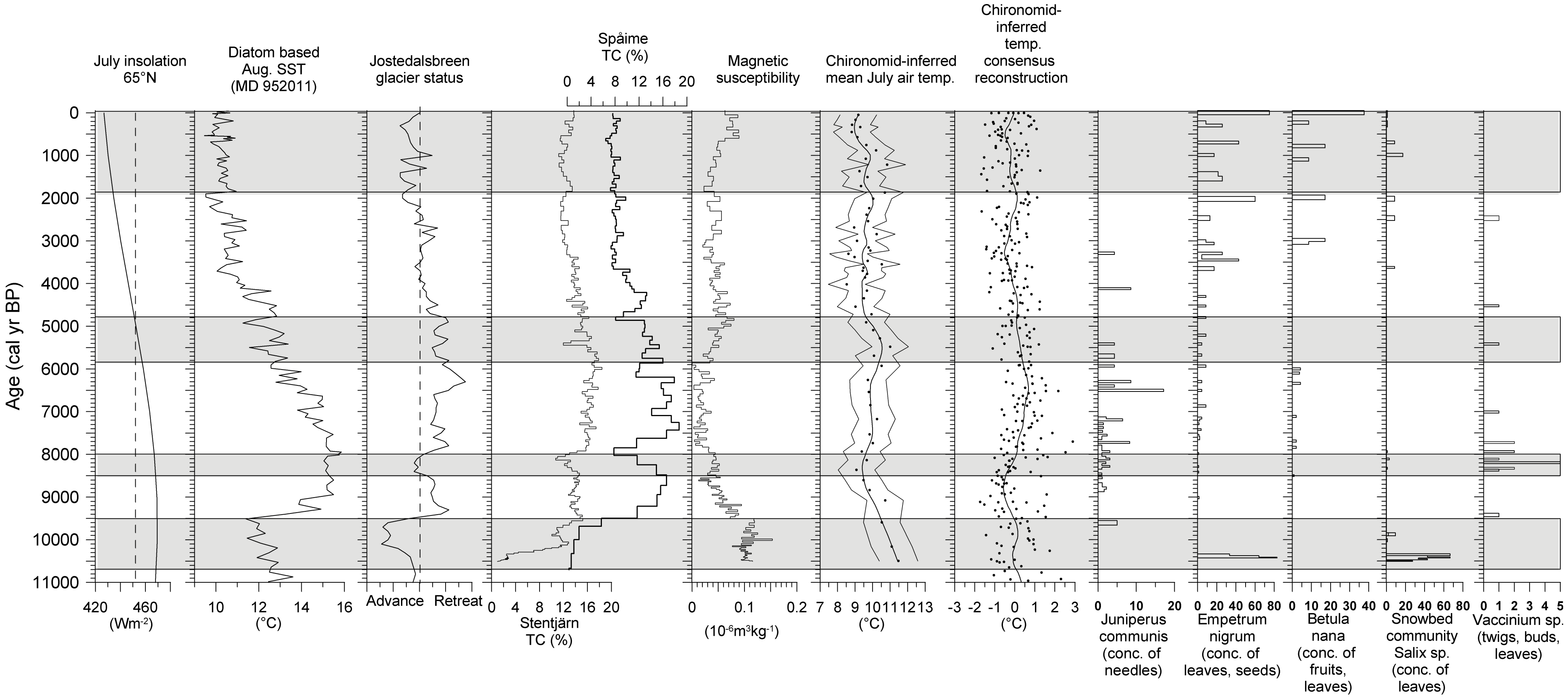

Fig. 10. Comparison of sediment stratigraphic and palaeoecological data from Lakes Spåime (App. IV), and Stentjärn (App. I) with some previously published solar forcing calculations and proxy records. These include July insolation index (solid line) and mean Holocene July insolation (dashed line) for 65 °N (Berger and Loutre, 1991), a diatom-based temperature reconstruction from marine core MD 952011 in the Norwegian Sea (Birks and Koç, 2002) and a glacier status record relative to modern conditions (dashed line) for the Jostedalsbreen ice cap in south-western Norway, inferred from composite glaciolacustrine sediment data (Nesje et al., 2001). Two chironomid-inferred reconstructions of mean July air temperatures are included, one from Lake Spåime (App. IV) and one consensus temperature reconstruction extracted from six lake sediment sequences in western Scandinavia (Velle et al., 2005a). Shaded zones indicate periods of markedly dynamic climatic conditions (App. II and III). All data are plotted without adjustment for isostatic uplift.

(Jensen et al., 2002), and in the Dovre Mountains in central Norway to 10,500-9900 cal yr BP (Eide, 2003), with the earliest expansions occurring at high elevation. In the Setesdal valley, southern Norway, tree birch probably expanded already at ca 10,800 cal yr BP, simultaneously in the southern and northern parts of the valley (Eide, 2003). The lack of migratory lags between these widespread tree birch expansions indicates expansions from local populations at high altitudes, which were triggered by climatic factors such as the development of optimal snow and soil conditions following deglaciation. As shown in Fig. 11 and 12, the elevation of the early Holocene macrofossil and megafossil data is overestimated due to isostatic recovery, and this needs to be taken into account in interpretations of the climatic and environmental conditions.

The TC record from Lake Spåime, which at this stage was likely influenced by catchment erosion, may reflect decreasing winter precipitation around 9500 cal yr BP, which is consistent with decreasing magnetic susceptibility values at Lake Stentjärn. Norwegian mountain glaciers retreated significantly or disappeared completely at this time, probably due to decreasing winter precipitation in combination with high ablation-season temperatures. Winter precipitation probably continued to decrease until ca 8600 cal yr BP. The first appearance of *Vaccinium myrtillus* at Lake Stentjärn may also reflect such a development, i.e. thinner snow cover. At ca 9200 cal yr BP pine established as a major element of the forest in the study area, which is synchronous with the pine expansion in the Dovre Mountains (Eide, 2003). The expansion of pine at all elevations in the study area (e.g. Kullman and Kjällgren, 2000, Fig. 11) may be related to increasing summer temperatures, as suggested by the sea-surface temperature reconstruction of Birks and Koç (2002). The chironomid-inferred summer temperature reconstruction from Lake Spåime, as well as corresponding Norwegian chironomid records indicate the opposite development (Fig. 10). However, as discussed by Velle et al. (2005a, 2005b) chironomid-based summer temperature reconstructions may be biased by other processes, particularly during the early Holocene. A successive thinning of the snow cover is likely to have had a significant positive impact on the density of pine in the tree-limit ecotone, promoting an expansion, although the high-elevation pine growth appears less pronounced when compensated for land uplift (Fig. 12). Thus, the high-altitude occurrence of pine may not have been solely controlled by summer temperature. As demonstrated by Aas and Faarlund (1988) and Eide (2003), pine established in the southern Norwegian mountains at 10,000-9600 cal yr BP and spread according to Iversen (1954) from Late Weichselian refugia in Denmark.

A temporary cooling at 8500-8000 cal yr BP

A lowering of the pine and birch tree- and forest-limits took place in the study area after ca 8500 cal yr BP (Fig. 11), probably as a response to lowered summer temperatures (Fig. 10). Generally, *Betula pubescens* and *Pinus sylvestris* require mean summer temperatures of 8-10 °C and 9-11 °C, respectively (Iversen, 1954; Aas and Faarlund, 1988), but these climatic requirements differ somewhat depending on the degree of oceanicity. In the coastal areas of western Scandinavia slightly higher summer temperatures are required, as compared to more continental areas, where the accumulated heat is greater due to lower cloudiness and larger diurnal temperature ranges (Odland, 1996). The relationship between pine growth and the oceanic/continental climate gradient has also been investigated along a west-east transect across the study area (Linderholm et al., 2003), yielding concordant results. This may suggest that mean summer temperatures (June-August) fell below 8-9 °C at the elevation of Lake Stentjärn, on the assumption that the tree-limit descended to a level slightly below the lake catchment, which is in reasonably good agreement with the chironomid-inferred reconstruction of mean July air temperature from Lake Spåime. *Vaccinium* sp. possibly expanded after 8500 cal yr BP at Lake Stentjärn, due to changing snow conditions, as this taxon is generally favoured by intermediate snow cover. Glaciers in the Scandes Mountains expanded during this period, probably partly as a result of the decreasing ablation season temperature (Nesje et al., 2001). This episode, termed the Finse event, was probably related to the transient cooling episode around 8200 cal yr BP, which is widely recognized around the North Atlantic (Alley et al., 1997; von Grafenstein et al., 1998; Hammarlund et al., 2003, 2005; Magny et al., 2003). Previous evidence of this temporary cooling has been obtained from glaciolacustrine sediments in other parts of the Scandes Mountains (Karlén, 1976; Karlén, 1988; Dahl and Nesje, 1994; Nesje and Dahl, 2001; Nesje et al., 2001). Vegetation responses supposedly

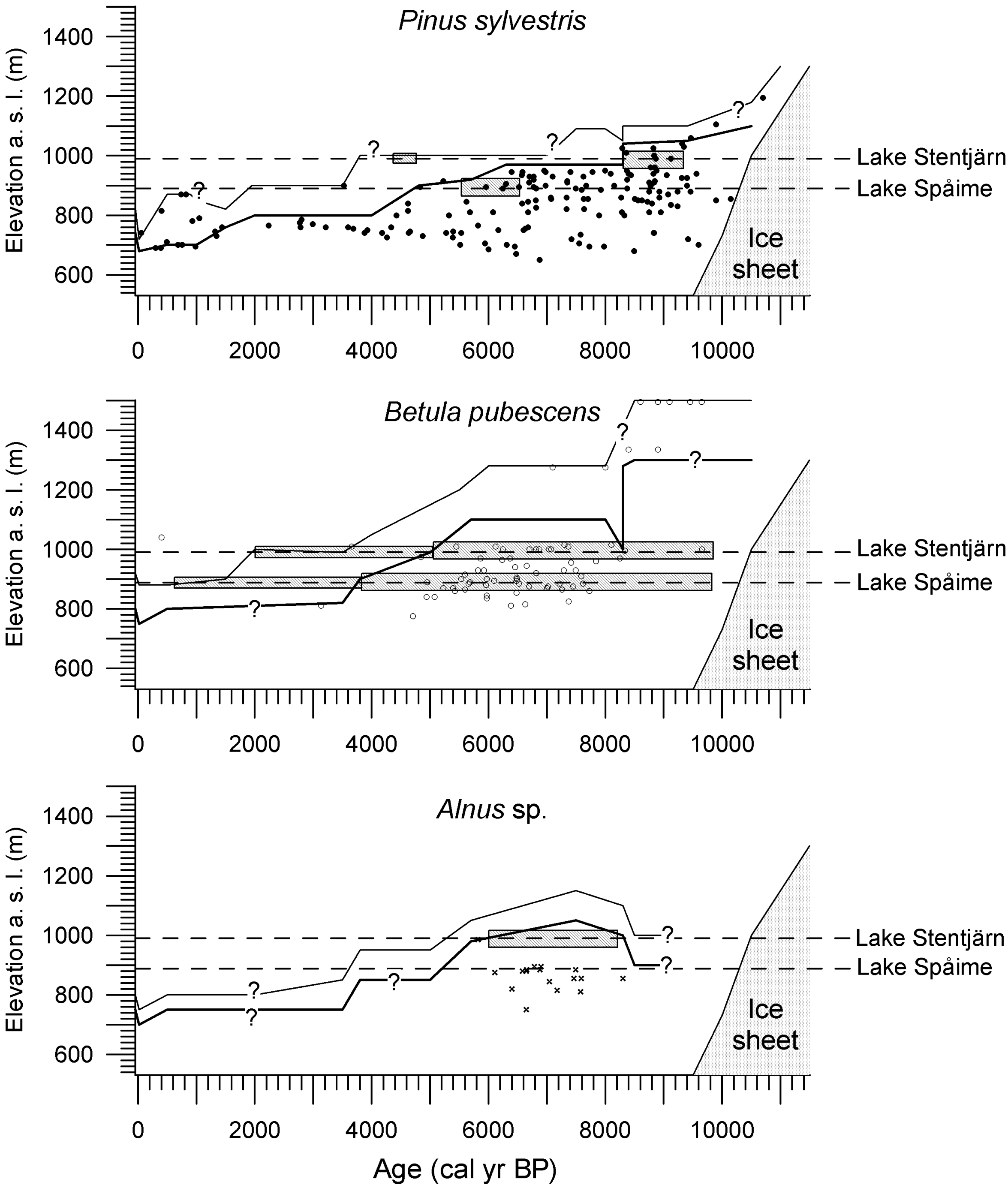

Fig. 11. Hypothetical reconstructions of Holocene tree-limits (thin curves) and stand-limits (thick curves) of Scots pine (Pinus sylvestris), mountain birch and/or downy birch (Betula pubescens ssp. czerepanovii/Betula pubescens ssp. pubescens), and grey alder/alder (Alnus incana/Alnus glutinosa). Stand-limits (or enclave-limits) can be considered as the upper altitudinal growth limit for stands of trees of a specific species (3-10 trees) at approximate forest density (cf. Kullman, 1994, 1995). Published radiocarbon-dated finds of subfossil wood (megafossils) are indicated by dots and include 161 samples of Pinus sylvestris (Lundquist, 1959, 1969; Kullman, 1980, 1987, 1988, 1989, 1995; Kullman and Kjällgren, 2000), 64 samples of Betula pubescens (Kullman, 1988, 1989, 1995) and 17 samples of Alnus incana (Kullman, 1988, 1995), all collected within a continuous mountain area of ca 8000 km^2 (Kullman, 1995). The maximum distance of individual megafossil samples from Lake Stentjärn is ca 50 km. Radiocarbon ages of all megafossils were converted to calibrated ages based on the IntCal98 calibration data set (Stuiver et al., 1998). Age estimates are expressed as most probable intercepts with the calibration curve within 95.4% probability envelopes (App. IV). Wide and narrow shaded bars indicate presence of macrofossils in the sediment sequences of Lakes Spåime and Stentjärn interpreted as reflecting forest-density and tree-limit density vegetation, respectively. The elevations of Lakes Spåime and Stentjärn are indicated by dotted lines, and the inferred extent and retreat of the Fennoscandian ice sheet in the study area are included. All data are uncorrected for land uplift and plotted against present-day elevation above sea level.

coupled to this event have also been detected in pollen records from south-central Norway (Barnett et al., 2001), northern Sweden (Snowball et al., 2002), central Europe (Tinner and Lotter, 2001) and Estonia (Veski et al., 2004). It is worth noting that the onset of the climatic deterioration as recorded at Lakes Stentjärn (App. I) and Spåime (App. IV) was initiated at ca 8500 cal yr BP (Fig. 10), well before the 8200 cal yr BP cold event as recognized in Greenland ice-cores (Alley et al., 1997). This development is consistent with the hypothesis of a broad climate anomaly at ca 8600-8000 cal yr BP encompassing the distinct cold event around 8200 cal yr BP, as recently proposed by Rohling and Pälike (2005). The prolonged period of cooling, which may be related to reduced solar output, seems to reflect mainly summer conditions, while the event itself, which is assumed to reflect a catastrophic release of melt-water to the North Atlantic from Laurentide glacial lakes (Barber et al., 1999), is more evident in winter-dominated proxies (Rohling and Pälike, 2005).

At ca 8100-8000 cal yr BP temperatures increased again, although the climatic conditions probably did not resemble those prior to 8500 cal yr BP, since *Pinus sylvestris* did not fully re-colonize the catchment of Lake Stentjärn. Pollen influx values reached maximum levels at ca 7500 cal yr BP (App. I and III), corresponding to the onset of the Holocene thermal maximum (see below). However, the long-term Holocene trend of declining seasonality, with the added effect of land uplift (Fig. 10, 11 and 12), prevented pine from reclaiming its tree- and stand-limit positions from prior to the 8200 cal yr BP cold event. As suggested by megafossil evidence from the area (Kullman and Kjällgren, 2000), the pine tree-limit continued to decline subsequent to the recovery of the birch tree-limit at ca 8000 cal yr BP.

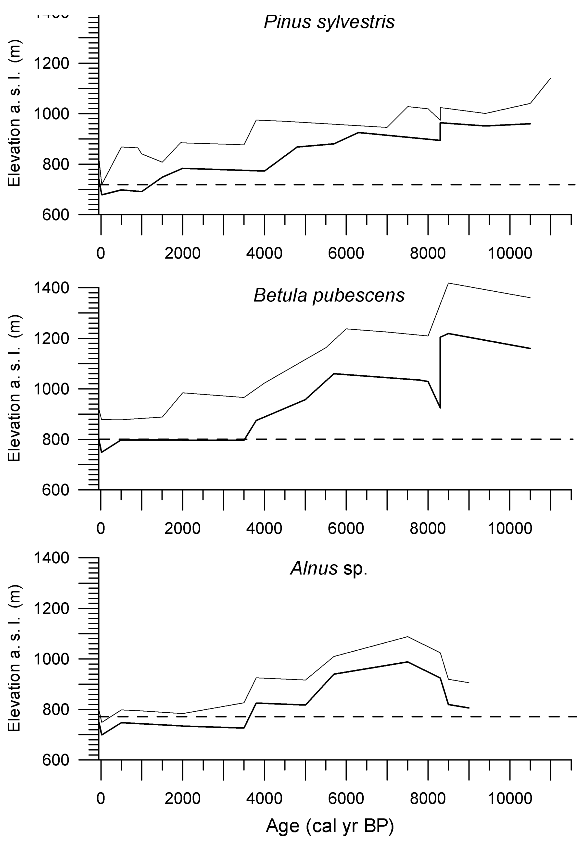

Fig. 12. Reconstructions of stand- and tree-limits for pine, tree birch, and alder, corrected for land uplift. The horizontal lines represent approximate present-day stand-limits in the study area of Pinus sylvestris, Betula pubescens ssp. czerepanovii, and Alnus incana, respectively. Stand-limits (or enclave-limits) can be considered as the upper altitudinal growth limit for stands of trees of a specific species (3-10 trees) at approximate forest density (cf. Kullman, 1994, 1995). The appearance of slightly advancing stand- and tree-limits during periods of stable uncorrected values (cf. Fig. 11) is an artefact of the uplift correction.

The Holocene thermal maximum 8000-5800 cal yr BP

An increase in summer temperature took place around 8000 cal yr BP, as shown by an altitudinal expansion of *Alnus* sp. into the tree-limit ecotone (Fig. 11 and 12). The increase in *Alnus* pollen influx to maximum values around 7500-7000 cal yr BP (App. I and III), coincides with a clear peak in the frequency of *Alnus incana* megafossils (Fig. 11; Kullman, 1995) and elevated *Alnus* pollen frequencies at Lake Spåime (App. IV), probably reflecting relatively mild winters and springs. Summers were relatively warm during this period and winter precipitation possibly reached a Holocene minimum. The regional significance of this pattern is demonstrated by the retreat or disappearance of Norwegian mountain glaciers (Nesje et al., 2001; Fig. 10). According to pollen-based temperature reconstructions from northern Finland (e.g. Seppä and Birks, 2001, 2002), mean July temperatures were low during the earliest part of the Holocene, supposedly because of strong North Atlantic oceanic influence, followed by a maximum between 8000 and 6500 cal yr BP (ca 1.8-1.6 °C higher than at present). Generally, marine records from the Norwegian Sea and terrestrial records from northern Fennoscandia imply a distinct

Holocene thermal maximum (HTM) at ca 7500-5500 cal yr BP (Barnekow, 1999b; Snowball et al., 2004), consistent with reconstructions of tree-limit changes along altitudinal transects from the northern part of the Scandes Mountains (Barnekow, 1999a). The presence of *Alnus* sp. at this stage may indicate prevailing wet, oceanic conditions, whereas a wide range of data from northern Fennoscandia points to dry conditions during the HTM (Snowball et al., 2004). However, oxygen-isotope data from northern Sweden imply a relatively moist oceanic climate regime that successively graded into more continental conditions between ca 10,000 and ca 6500 cal yr BP (Hammarlund et al., 2002). Such a long-term decrease in effective humidity is consistent with the decline in *Alnus* pollen influx values during the course of the HTM. In addition, the diatom-based SST reconstruction from the Norwegian Sea by Birks and Koç (2002) suggests declining temperatures throughout this time period (Fig. 10).

Initiation of late Holocene climatic instability 5800-4800 cal yr BP

Shortly after 6000 cal yr BP *Alnus* sp. disappeared from the lake catchments, most likely as a result of the long-term decline in summer insolation (Berger and Loutre, 1991; Fig. 10), and possibly in combination with the development of unfavourable soil conditions, i.e. podzolisation and paludification (Kullman, 1992). Stands of alder likely remained along the valley below the forest-limit (Fig. 11), as indicated by the Lake Spåime pollen influx values (App. III). Between 6000 and 5500 cal yr BP, peat humification (DOH) records from Klocka Bog respond to a significant and widespread change in climatic humidity towards cooler and/or wetter conditions (App. III). Norwegian glaciers expanded after ca 6000 cal yr BP following a period of general retreat or absence (Nesje et al., 2001), thus suggesting lowered summ-er temperatures (Velle et al., 2005a). According to Calvo et al. (2002) and Koç et al. (1993) a significant drop in SST took place at ca 5500 cal yr BP, largely synchronous with the expansion of glaciers in western Norway (Fig. 10). TC records from Lakes Spåime and Stentjärn indicate a general decline in lacustrine organic productivity at this stage, which is largely synchronous with the retreat of birch-dominated forest (Fig. 11). A similar development, i.e. retreating pine and birch tree-limits, took place synchronously in southern Norway (Eide, 2003). Pollen records from Lake Spåime show elevated poll-en influx values of pine and tree birch at this time (App. III), persisting until 1800-1400 cal yr BP. These trends may indicate enhanced erosion of catchment soils and a successive opening of the forest. In addition, cooler and wetter springs may have induced pollen deposition on late-melting snow beds, and subsequent fluvial transport by meltwater to this open-basin lake (App. III).

Establishment of the alpine vegetation zonation 4800-1800 cal yr BP

A continued general cooling trend characterizes the later part of the Holocene, although slightly more variable climatic conditions and less consistent patterns were recorded at ca 5000-2000 cal yr BP (Fig. 10). The abundance of *Juniperus communis* macrofossils during earlier periods were followed by a declining trend after ca 5500 cal yr BP and the complete disappearance shortly after 3500 cal yr BP, which may indicate unfavourable snow conditions for juniper in the increasingly wind-exposed terrain, as this species requires reliable snow conditions for protection against winter desiccation.

The retreat of forest from the catchment of Lake Spåime occurred at ca 3700-3500 cal yr BP (Fig. 11). The regional forest-limit was probably suppressed by increasing net precipitation, to a large extent due to the influence of late-melting snow cover (App. I, III and IV; Kullman, 1995). The lack of firm evidence for declining summer temperatures at this stage based on some reconstructions (Rosén et al., 2001; Calvo et al., 2002; App. IV) suggests that increasing summer humidity may have enhanced the cooling effects. However, a consensus reconstruction of mean July temperature based on chironomid data from Lake Spåime and five other sites in southern Norway exhibits a cooling trend during the period of tree-limit retraction in the study area (Fig. 10). Increasing climatic variability during the later part of the Holocene may also have contributed to a lowering of alpine tree-limits. Subsequent to the disappearance of trees from catchment of Lake Stentjärn, submerged mosses colonized the lake. This may indicate that the limnic ecosystem passed a threshold in trophic status, triggered by the vegetational and climatic change at ca 3500 cal yr BP. These changes occurred during an episode of pronounced cooling and/or increased humidity as suggested by numerous proxy records from north-western Europe (Anderson et al., 1998; Snowball et al., 1999; Nesje et al., 2001; Seppä et al., 2002b; Hammarlund et al., 2003). Thus, around 3500 cal yr BP the establishment of "near-modern" climatic conditions took place with increased growth-season effective humidity and late snowmelt, which heavily influenced the vegetation and shaped the vegetation zonation that characterizes the Scandes Mountains today. An establishment of dry to fresh low-alpine heaths took place, dominated by *Empetrum nigrum*, *Betula nana*, and snow-bed community *Salix* species in depressions (Fig. 10). The heath vegetation is favoured by intermediate snow cover for protection against frost desiccation, but is sensitive to overly deep snow and the subsequently shortened growth season due to delayed snowmelt. Since the density and distribution of the field and shrub layer in the low-alpine zone is largely controlled by snow conditions, the climatic shift around 3500 cal yr BP probably brought late snowmelt as a consequence of colder springs, which supplied the heath plants *E. nigrum* and *B. nana* with optimal snow conditions.

Decreasing climatic stability 1800 cal yr BP- present
DOH data from Klocka Bog (App. III) and chironomid data from Lake Spåime indicate the onset of a second episode of increased effective humidity and lowered summer temperatures at or slightly after 2000 cal yr BP, following a brief period of relatively warm and/or dry summer conditions (App. III; Fig. 10). At ca 600 cal yr BP, these conditions were probably accompanied by increased winter precipitation, which is clearly reflected by elevated magnetic susceptibility values at Lake Stentjärn and a further expansion of Norwegian mountain glaciers (Nesje et al., 2001; Fig. 10). At this stage, *Betula pubescens* disappeared completely from the catchment of Lake Spåime, as indicated by the absence of tree birch macrofossils and a decline in birch pollen influx (App. IV; Fig. 11). These environmental and vegetational changes are probably associated with a cooling during the Little Ice Age (cf. Moberg et al., 2005), which apparently led to a significant lowering of the regional tree-limit in the study area. Palaeotemperature estimates based on various proxy records from Fennoscandia suggest a cooling of ca 1 °C as compared to present-day conditions (Snowball et al., 2004), which is in good agreement with the chironomid-inferred reconstruction from Lake Spåime. According to Matthews et al. (2000), the most extensive late Holocene phase of expanding mountain glaciers occurred during the Little Ice Age. Since approximately the 1930's, the regional tree-limits of pine, birch, and spruce have advanced around 100-150 m (cf. Kullman, 2000b, 2001, 2002b). These vegetational responses are probably associated with the end of the Little Ice Age and the subsequent warming, which may have been amplified as a consequence of increased anthropogenic emissions of greenhouse gases during recent decades (Kullman, 2001).

Methodological conclusions – vegetational reconstruction

1. Holocene changes in the altitudinal distribution of alpine plant communities and ecotones may form a basis for detailed climatic and environmental reconstructions. Snow cover regimes, summer soil moisture conditions, and summer temperature are among the parameters that can be estimated. The advantage of using plant macrofossil data sets in combination with palynological data cannot be overestimated. High-resolution plant macrofossil analysis based on large sample volumes enables detection of short-term climatic changes.
2. Plant macrofossil data sets obtained from lake sediments provide semi-quantitative information on changes in tree-limit and forest-limit positions, largely consistent with local megafossil evidence after ca 9500 cal yr BP. High-elevation megafossils from the earliest part of the Holocene probably reflect scattered trees in sheltered positions. As a whole, the position of the forest-limit depends on edaphic conditions, snow cover and summer temperature, whereas tree-limits are mainly determined by summer temperature.

Palaeoclimatic conclusions

1. As revealed by stratigraphic records from lake sediments and peat deposits in the study area, the Holocene climate history of the central Scandes Mountains appears to be linked to sub-millennial-scale variations in North Atlantic ocean and atmospheric dynamics superimposed on long-term orbital-driven trends in solar insolation.
2. Apparent discrepancies between early Holocene high-elevation tree growth and palaeotemperature estimates inferred from other proxies remain to be resolved. However, the early Holocene establishment of pine at high altitudes suggests high summer

temperatures as a result of enhanced solar irradiance, and relatively high amounts of winter precipitation. Semi-perennial snow beds likely provided moisture during the initial part of the growing season. Moderately cold winters, characterized by abundant precipitation and cloudiness, probably reflect enhanced zonal circulation and cyclonic activity.

3. Rapid responses of the tree-limit ecotone to a transient episode of mainly lowered summer temperatures are evident at ca 8500-8000 cal yr BP.

4. The periods 9500-8500 and 8000-6000 cal yr BP may have been characterized by warm and relatively dry summer conditions, during which thermophilous vegetation could be supported at high elevations. The present data do not allow for assessment of the timing of maximum Holocene thermal conditions.

5. A widespread synchronous vegetation response took place at 3700-3500 cal yr BP, probably brought about by increased growth-season effective humidity and late snowmelt, which heavily influenced the vegetation and shaped the vegetation zonation that characterizes the Scandes Mountains today. Heath community plants dominated by *Empetrum nigrum* and *Betula nana* expanded, mainly in response to late snowmelt and formed the characteristic low to mid alpine vegetation zones.

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Svensk sammanfattning

Under den geologiska period som kallas kvartärtiden (de senaste 2,6 miljoner åren) har flera istider (glacialer) och mellanistider (interglacialer) avlöst varandra enligt ett mönster där glacialerna varar i ungefär 100000 år och mellanistiderna i ca 10000 år. Under istiderna täcktes stora landområden på norra halvklotet, bl.a. Skandinavien, av väldiga inlandsisar. Då den senaste mellanistiden, kallad *Holocen*, började för 11500 år sedan, blev klimatet återigen varmare och de flesta inlandsisarna på norra halvklotet smälte undan, förutom på t.ex. Grönland. Det relativt varma klimat som har rått under Holocen har dock inte varit helt stabilt, vilket man tidigare trott. Det har förekommit både gradvisa och plötsliga klimatförändringar. Det är mycket viktigt att förstå hur det naturliga klimatet utvecklats och förändrats under Holocen om man vill kunna förutsäga framtidens klimat, något som under 1900-talets senare del blivit allt mer aktuellt genom de uppmärksammade utsläppen av växthusgaser, vilka anses ha orsakat en global uppvärmning. Innan frågor kring den eventuella mänskliga påverkan på klimatet och dess framtida konsekvenser kan besvaras krävs det att vi lär oss mer om de naturliga långsiktiga och kortsiktiga svängningarna i klimatsystemet.

Inom mitt avhandlingsarbete har jag huvudsakligen rekonstruerat naturliga miljöförändringar under de senaste 10500 åren genom studier av geologiska arkiv, som sjösediment- och torvlagerföljder, där organogent och minerogent material ackumulerats i sedimentära/stratigrafiska sekvenser. I området kring Sylarna och Storulvån i västra Jämtlandsfjällen har sjöarna Spåime (887 m ö.h.) och Stentjärn (987 m ö.h.), belägna på kalfjället ovanför dagens fjällbjörksbälte, undersökts med målet att rekonstruera de alpina vegetationsförändringarna. I den skandinaviska fjällkedjan förekommer, liksom i de flesta bergsområden, en tydlig vegetationszonering där vegetationen förändras avsevärt med stigande höjd över havet. Huvudsakligen beroende på att lufttemperaturen är lägre på hög höjd, men också på grund av att totala nederbörden och andelen snönederbörd generellt ökar med höjden. Fjällvegetationens zonering, och särskilt trädgränserna, är således mycket känsliga för klimatförändringar då de återspeglar de ingående vegetationselementens klimatiska toleransgränser. På så sätt utlöser ofta eventuella klimatförändringar tydliga förändringar i vegetationens sammansättning och rumsliga utbredning, vilka i sin tur kan rekonstrueras med hjälp av paleoekologiska metoder, såsom pollenanalys och analys av makroskopiska växtrester (makrofossil). Liksom den terrestra vegetationen, påverkas även sjöar direkt av klimat- och miljöförändringar, vilka registreras fysiskt, kemiskt och biologiskt i sedimentlagerföljdernas geologiska arkiv.

Tidigare paleoekologiska studier från undersökningsområdet har framför allt varit baserade på fynd av subfossila trädrester (t.ex. stubbar och stammar) i icke-stratigrafiska lägen, s.k. *megafossil*, vilka visat att huvudsakligen trädslag som björk, tall och al tidigare under Holocen växt på betydligt högre höjd än i modern tid. Pollen- och makrofossilanalyserna utförda på sedimentlagerföljderna från Spåime och Stentjärn indikerar att en kortlivad flora dominerad av humleblomster, fjällsippa, kråkbär, skvattram, bräckor, viden och fjällsyra etablerade sig i landskapet under isavsmältningen (deglaciationen), som inträffade ca 10500 år före nutid. Deglaciationsfloran ersattes en kort tid senare, kring 10300 år före nutid, av expanderande grässamhällen och för ca 9800 år sedan etablerades björkskog på hög höjd i undersökningsområdet. Analyser av koncentrationen magnetiska mineral och den totala andelen kol i sedimenten från Stentjärn och Spåime, indikerar att perioden mellan 10300 och 9500 år före nutid troligtvis karakteriserades av hög snönederbörd. Denna klimatsituation fördröjde sannolikt etableringen av tall i undersökningsområdet, vilken expanderade först något senare, kring 9200 år före nutid. Den tidigholocena björk- och tallskogen blev dock relativt kortlivad. Kring 8200 år före nutid blev klimatet kallare och tallgränsen retirerade från Stentjärns dräneringsområde. Kring 8000 år före nutid blev klimatet återigen varmare och björkskogen expanderade återigen, denna gång tillsammans med al. Tall återetablerade sig dock aldrig på högre höjd, men växte på lägre nivåer och i dalgångarna. Vid ca 5800 år före nutid, efter en period av relativt varmt klimat, blev vårarna troligtvis kallare i kombination med ökande humiditet, vilket resulterade i att trädgränserna för både björk och al började dra sig nedåt, och skogen tunnades ut. Kring 3500 år före nutid upplöstes mer eller mindre skogen i sjöarnas dräneringsområden, och endast enstaka fjällbjörkar återstod fram till ca 2000 år före nutid. I höjd med Spåimesjön växte enstaka björkar ända fram till 600-500 år före nutid, då de sista träden retirerade ned i dalen, troligtvis p.g.a. det kallare klimat som rådde under Lilla Istiden. Vid en jämförelse mellan de stratigrafiska vegetationsdata (pollen- och makrofossildata) insamlade under doktorandprojektet, och de tidigare publicerade megafossilfynden, framstår det tydligt att resultaten av de olika metoderna överensstämmer med varandra. De skillnader som förekommer i resultaten kan till stor del förklaras genom att megafossilen bevaras dåligt i olika delar av området, vilket leder till att megafossilfynden kan ge en något inkomplett bild av trädskiktets utbredning i tid och rum.

För att kunna rekonstruera de vegetations- och klimatförändringar som inträffat i området under Holocen, krävs noggrann datering av de geologiska arkiv varifrån paleoekologiska data extraheras. Kronologierna i de torv- och sjösedimentsekvenser som undersökts inom projektet har företrädesvis baserats på kol-14-datering av terrestra växtmakrofossil uttagna från lämpliga stratigrafiska nivåer. Men även andra dateringsmetoder har använts inom projektet. Tidigare undersökningar från Klockamyren (526 m ö.h.), en mosse belägen i barrskogszonen väster om Ånnsjön, har indikerat att flera lager av isländsk vulkanisk aska, *tefra*, finns inkorporerade i torvlagerföljden. Lager eller horisonter av tefra kan användas som likåldriga nivåer (isokroner) för att korrelera och datera olika geologiska arkiv, tex i Nordatlantaområdet, och på så sätt upprätta en s.k. *tefrokronologi*. Flera horisonter av mikroskopiska askpartiklar lokaliserades i två profiler från Klockamyren, och flera av askhorisonterna kunde kopplas geokemiskt till de isländska vulkanutbrotten Askja-1875, Hekla-3, Hekla-4 Kebister och Lairg A. Tre isländska tefrahorisonter påträffades även i Stentjärns lagerföljd, varav den översta korrelerades geokemiskt med Askja-1875.

Som ett led i arbetet med att studera de holocena lokala förändringarna i klimatisk humiditet i västra Jämtland, har även Klockamyrens grundvattenfluktuationer rekonstruerats genom mätningar av torvlagerföljdens humifieringsgrad (nedbrytningsgrad). Humifieringsgraden reflekterar generellt grundvattennivån i mossen under sommarhalvåret då det torvbildande växtmaterialet (huvudsakligen mossor) på en viss nivå avsätts. Grundvattennivån i sin tur varierar med sommarnederbörden och temperaturen. Humifieringsanalyser från de två profilerna i Klockamyren indikerar att under perioderna 5800-4800 år före nutid, och efter 2000-nutid var klimatet i området mycket fuktigt under somrarna.

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