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Zillén, Lovisa

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PO Box 117  
221 00 Lund  
+46 46-222 00 00

# LUNDQUA Thesis 50

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Setting the Holocene clock using varved lake sediments in Sweden

*Lovisa Zillén*

## **Avhandling**

att med tillstånd från Naturvetenskapliga Fakulteten vid Lunds Universitet för avläggandet av filosofie doktorsexamen, offentligen försvaras i Geologiska institutionens föreläsningssal Pangea, Sölvegatan 12, Lund, fredagen den 17 oktober kl. 10.15.

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**Lund 2003**  
**Lund University, Department of Geology, Quaternary Sciences**

# Setting the Holocene clock using varved lake sediments in Sweden

By

Lovisa Zillén

This thesis is based on a synthesis and four papers. The four papers are listed below and presented as appendices I-IV. The papers are reprinted with permission from Elsevier Science Ltd. (Appendix II) and Arnold Publishers (Appendix IV).

**Appendix I:** Zillén, L., Snowball, I., Sandgren, P. & Stanton, T. 2003: Occurrence of varved lake sediment sequences in Värmland, west central Sweden: lake characteristics, varve chronology and AMS radiocarbon dating. *Boreas* 4, 000-000.

**Appendix II:** Zillén, L., Wastegård, S. & Snowball, I. 2002: Calendar year ages of three mid-Holocene tephra layers identified in varved lake sediments in W central Sweden. *Quaternary Science Reviews* 21, 1583-1591.

**Appendix III:** Zillén, L. Century-scale Holocene geomagnetic field variations and apparent polar wander paths reconstructed from varved lake sediments in Sweden. *Unpublished manuscript*.

**Appendix IV:** Snowball, I., Zillén, L. & Gaillard, M.J. 2002: Rapid early-Holocene environmental changes in northern Sweden based on studies of two varved lake sediment sequences. *The Holocene* 12, 7-16.



Joint Swedish and Finnish fieldwork on the ice covered Lake Kälksjön, Värmland, west central Sweden, March 2002. Retrieving a sediment piston-core for palaeomagnetic measurements.

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"The farther backward you can look, the farther forward you are likely to see" (Winston Churchill).

## Introduction

Reconstructions of changes in Earth systems help us to understand the past, the present and to make confident prognoses about the future. Due to the observed global temperature rise that characterised the majority of the 20th century AD an important scientific and political priority has become to establish the significance of human activity on the climate system, which requires that the full range of natural variability is also known.

Lakes and their catchments respond physically, chemically and biologically to climate and environmental changes and these responses are recorded in the lake sediments. Oldfield (1977) pointed out that lake sediments contain a variety of proxy environmental and climate indicators that precede the time range of instrumental observations and that studies of these sediments form an integrated insight into ecosystem variations on all time-scales.

Dating of geological materials, such as lake sediments, is fundamental in order to understand the natural and cultural changes that took place in the past. It is a crucial and often a delicate task in all studies of past environmental changes, particularly those that aim to reconstruct *rates of change*, to construct an accurate chronology. A range of dating methods and techniques with various degree of resolution and precision are available to the researcher. Table 1 shows the limits and error estimates associated with commonly used absolute and relative dating methods that can be applied in Holocene studies. All of these dating methods require the presence of at least one specific sediment component: for example, the vast majority of Holocene palaeoclimate and palaeoenvironmental investigations of lake sediments have relied on time-scales based on measurements of the  $^{14}\text{C}$  content of organic material. However, this dating method can be biased a range of factors, e.g. unknown secular variations of  $^{14}\text{C}$  in the atmosphere (Pilcher, 1991), unknown limnic  $^{14}\text{C}$  reservoir effects and uncertainties arising from inferred ages derived from interpolation between individually dated levels. Due to the analytical errors associated with  $^{14}\text{C}$  measurements Holocene age/depth models based on this technique are often restricted to a centennial scale resolution or less.

This thesis is based on studies of Holocene annually laminated (or varved) lake sediments in

Sweden. The word varve defines sediments where seasonally deposited layers (or laminae) of variable composition and colour represent an annual cycle of sediment accumulation (Renberg, 1981a). Ideally free of interpolation, continuous varved lake sediment sequences provide researchers with high-precision calendar year time-scales that cover the majority of the Holocene (Table 1) and these are considered to be excellent archives in studies of past changes (e.g. O'Sullivan, 1983; Saarnisto, 1986; Snowball *et al.*, 1999). Varved lake sediments also have the advantage over non-varved sediments in that they provide (i) unsmoothed data series, (ii) the possibility to identify rates of past changes at an annual, possibly seasonal resolution and (iii) the potential to be calibrated against modern instrumental records of climate parameters, such as precipitation, temperature and river discharge (e.g. Hughen *et al.*, 1996; Sander *et al.*, 2002).

Current palaeoclimatologic research is to a large extent focused on the influence of recurrent high-frequency features of the climate system, such as the North Atlantic Oscillation (e.g. Rogers, 1977; Hurrell, 1995) and solar variability (e.g. Beer, 2000; Bond *et al.*, 2001), which possess frequencies of about 7 and 11 years, respectively. Exploration of these short-term changes requires that environmental changes must be quantified on increasingly shorter time-scales; shorter than the resolution that conventional radiocarbon dating can offer (Table 1). Furthermore, high-resolution palaeoarchives with annual to decadal resolution are needed to extend the records of these features of the climate system back into the past, before the instrumental period. Current palaeoclimatology also requires that geographically separated proxy archives are correctly dated and synchronized, which enables leads and lags in environmental response variables to be established and analysed.

In the absence of high-resolution palaeointensity records, it has long been assumed that the production rates of cosmogenic nuclides, such as  $^{14}\text{C}$  and  $^{10}\text{Be}$ , in the atmosphere are modulated only by long-term changes ( $>10^3$  yr) in the strength of the Earth's geomagnetic field (Mauzaud *et al.*, 1994; Bond *et al.*, 2001; Björck *et al.*, 2001). However, such an assumption may lead to the misinterpretation of nuclide records in terms of solar forcing and climate changes. Recent studies suggest that short-term ( $10^2$  yr) geomagnetic field changes have taken place during the Holocene and that these would have affected the production of cosmogenic nuclides (Snowball & Sandgren, 2002; Ojala & Saarinen, 2002; St-Onge *et al.*, 2003). Thus, it is essential to reconstruct the Earth's magnetic field at a century-scale

Table 1. Absolute and relative dating methods available for Holocene lake sediments

Dating methods for lake sediments	Time range yr (last 11 500 yr)	Resolution yr	Precision yr
<i>Absolute dating methods</i>			
Isotopic chronometers <sup>210</sup> Pb	10-200	1- 10 <sup>1</sup>	~ ± 10
<sup>14</sup> C	200 - 11 500	10 <sup>1</sup> -10 <sup>3</sup>	~ ± 50 - 500
Amino acid racemization	150 - 11 500	10 <sup>2</sup> - 10 <sup>3</sup>	~ ± 500 - 1000
Varve counting	1 - 11 500	1 - 10 <sup>1</sup>	~ ± 100 - 300
<i>Examples of relative dating methods</i>			
Tephra isochrones	1 - 11 500	10 <sup>2</sup> - 10 <sup>3</sup>	~ ± 100 - 500
Biostratigraphy	1 - 11 500	10 <sup>2</sup> - 10 <sup>3</sup>	~ ± 100 - 500
Paleomagnetic secular variations	150 - 11 500	10 <sup>2</sup> - 10 <sup>3</sup>	~ ± 100 - 500
Isotopic isochrones <sup>137</sup> Cs	1-50	10 <sup>1</sup>	~ ± 1 - 5

temporal resolution (or better). Due to these above-mentioned requirements in modern palaeoclimate, palaeoenvironmental and palaeomagnetic studies, improved chronological control has become an international research priority in studies of the Holocene.

The quality and quantity of palaeoclimate and palaeoenvironmental reconstructions have increased significantly as a result of the analyses of different archives that possess continuous and independent calendar year time-scales. Excellent examples include the studies of the Greenland ice-cores (e.g. Grootes *et al.*, 1993; Alley *et al.*, 1997b) and the construction of regional dendro-climatological time-series from tree-ring data (e.g. Fritts, 1976; Briffa *et al.*, 1992, 1998). However, despite the knowledge that research based on calendar year time-scales can provide exceptional records of past changes, the geographical distribution of continuous Holocene varved lake sediments in Sweden is unknown and the potential uses of these sequences have not been fully explored.

This doctoral thesis was initiated to discover new varved lake sediment sequences in the province of Värmland, west central Sweden, to explore the environment in which these sediments (if found) were formed and evaluate their potential value as chronological archives in Holocene research.

### Aims of the doctoral thesis

The aims of this thesis were to:

1. Locate and recover new varved lake sediment sequences in the province of Värmland, west central Sweden (Appendix I).
2. Identify the climatic and environmental prerequisites for the formation of varves and provide a tool for finding annually laminated sedimentary

archives in boreal environments in Sweden (Appendix I).

3. Construct high-precision incremental varve chronologies validated by alternative and independent dating methods (Appendix I).

4. Search for, identify and assign calendar year ages to Icelandic tephra isochrones in the varved lake sediments (Appendix II).

5. Reconstruct the behavior of the Earth's geomagnetic field in the province of Värmland prior to instrumental observations based on calendar year time-scales (Appendix III).

6. Study Holocene climate variability and rate of changes on a high temporal scale by focusing on a selected time window (i.e. the so-called "8.2 ka cold event"; Appendix IV).

### Clastic-biogenic varves in Fennoscandia

This thesis focus on biogenic-clastic varved lake sediments. Due to various environmental prerequisites for the formation and preservation of varves\* in lake sediments in Fennoscandia (see next chapter), such sediments have only been reported in southern and central Finland (e.g. Saarnisto, 1986; Ojala *et al.*, 2000) and in northern Sweden (e.g. Renberg, 1981a, 1982, 1986; Petterson, 1996; Snowball *et al.*, 1999, 2002; Appendix I).

### A review

#### Sweden

Stålberg (1923) and Granlund (1931) made the first pollen analytical studies of varved lake sediments in Sweden during the early 20th century. During

\* From this point on, the term varve (unless stated otherwise) refers to biogenic-clastic varves.

the 1970's, Renberg (1976) studied chemical laminations and Digerfeldt *et al.* (1975) used X-ray techniques to enhance the detection of varves. Pioneer studies of the mineral magnetic and palaeomagnetic properties of clastic varves in Sweden were carried out by Ising (1942) and Granar (1958). These have recently been continued on varves in northern Sweden by Mörner & Sylwan (1989), Snowball *et al.* (1999) and Snowball & Sandgren (2002).

The majority of work on Swedish varved lake sediments that cover more than the last few hundred years has been conducted on three sites located in the vicinity of the city of Umeå in the province of Västerbotten, northern Sweden (i.e. Lake Kassjön, Lake Sarsjön and Lake Frängsjön). Studies of these sequences have improved our knowledge about regional vegetation development, climate-lake interactions and ecosystem response to the introduction of agriculture in Västerbotten (Segerstöm, 1990; Anderson *et al.*, 1995, 1996). Research on varve thickness, different physical parameters and various sediment components (e.g. minerogenic matter, organic matter and biogenic silica) within the varves and their relation to climate have been improved by using image analysis on sediment sequences from this area (Pettersson, 1999). Varved sediments have also been used to reconstruct the atmospheric deposition of heavy metals (e.g. Renberg *et al.*, 1994, 2000) and the influence of acidification on lake sediment chemistry (Renberg, 1985).

Prior to this thesis, environmental investigations of Swedish varved lake sediment sequences older than 6300 cal. BP were sparse. Exceptions are studies of the shoreline displacements along the Swedish east coast in northern Sweden (Renberg & Segerström, 1981; Renberg, 1981b), a comparison between a floating varve chronology and AMS dates in the Abisko area, northern Sweden (Barnekow *et al.* 1999) and a mineral magnetic study of Lake Sarsjön (Snowball *et al.* 1999).

### *Finland*

Early works of varved lake sediments in Finland were performed by Simola (1977) and Saarnisto *et al.* (1977) who studied annual laminations and diatom succession in Lake Lovojärvi. Saarnisto (1975) introduced the freeze-coring technique (i.e. frozen finger technique; Shapiro, 1958) to Fennoscandia, which made it possible to recover the uppermost unconsolidated sediments of the sequences and improve studies of the recently deposited sediments.

As a result of systematic fieldwork (e.g. Ojala *et al.*, 2000) varved lake sediments have been more frequently reported in Finland than in Sweden. Ojala *et al.* (2000) explored the preconditions for the formation of biogenic-clastic varved lake sediments by studying the geological, geomorphological and morphometric properties of Finnish lakes. This work led to the discovery of thirteen continuously annually laminated Holocene lake sediment sequences in the central and southern part of the country.

Most studies of varved lake sediments in this region are focused on Late Holocene environmental change, e.g. Grönlund & Asikainen, (1992), who studied the introduction of early agriculture and slash-and-burn cultivation cycles in eastern Finland. More recent studies on varve thickness and physical parameters have been performed by Tiljander *et al.* (2002) and Ojala & Francus (2002). Over the last 10 year period, a number of papers have concentrated on palaeomagnetic analyses e.g. Saarinen (1994, 1998, 1999), Ojala & Saarinen (2002) and Ojala & Tiljander (2003).

### **Formation**

Varved lake sediments are the result of several physical, chemical and biological processes (O'Sullivan, 1983) in combination with suitable climatic, environmental and topographical conditions. Biogenic-clastic varves consists of alternating layers of autochthonous organic (e.g. algae and diatoms) and allochthonous mineral material. Special types of varves can also occur consisting of e.g. calcium carbonates (calcareous varves) and iron hydroxides/sulfides (ferrogenic varves).

The annual sedimentation cycle in biogenic-clastic varves is represented by three or four (depending on the presence of an autumn layer) seasonally deposited laminae i.e. (i) a light coloured spring laminae of allochthonous mineral matter that is transported in suspension by inflowing streams to the lake during relatively short periods of maximum river discharge, (ii) a light brown summer laminae of autochthonous organic material, (iii) a light coloured autumn laminae of allochthonous mineral matter, which may be deposited after high river discharge caused by heavy autumn rainfall events and (iv) a dark brown winter lamina of fine-grained autochthonous organic material, which is deposited during calm conditions when the lake is ice covered (e.g. Pettersson 1996). A sedimentological model that explains the cyclic deposition of the different seasonal components in

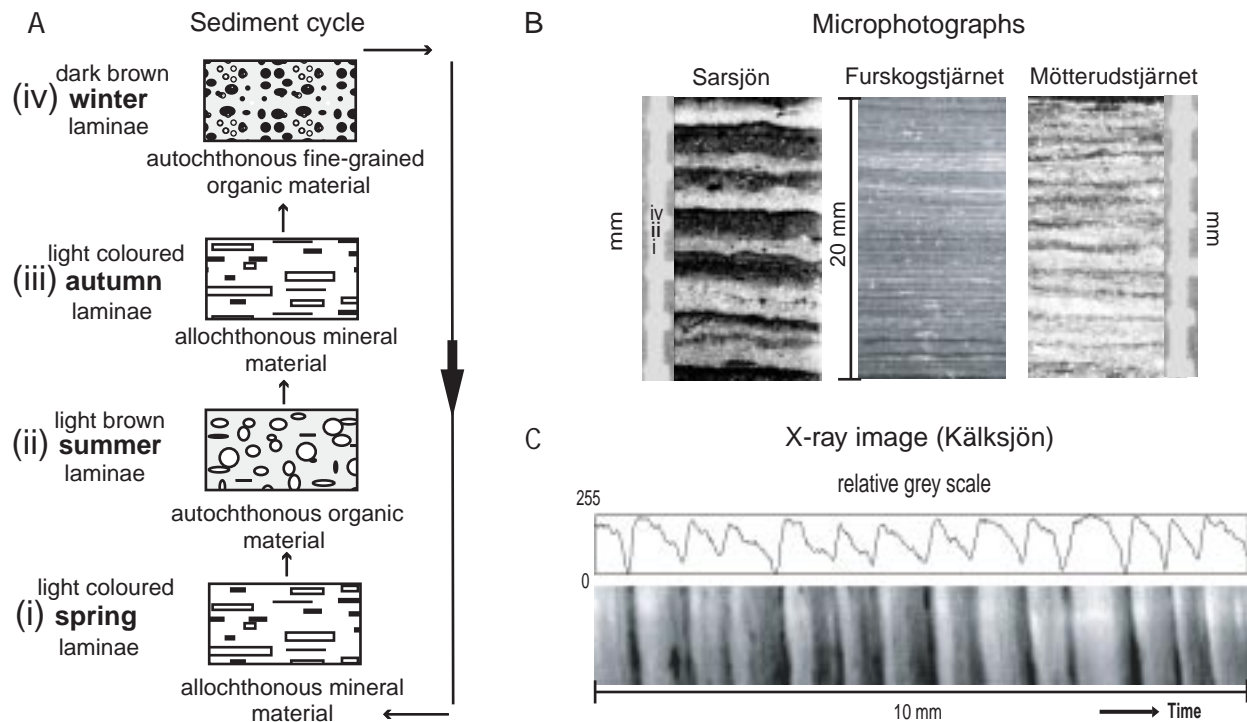


Fig. 1. (A) Schematic model explaining the sediment cycle of the seasonally deposited lamina in biogenic/clastic varves (see text for more details). (B) Microphotographs of biogenic/clastic varves from Sarsjön, northern Sweden, Furskogstjärnet and Mötterudstjärnet, west central Sweden. The different laminae which constitute a general varve, spring, summer, and winter laminae, are labelled as in Fig. 1A. (C) An X-ray image of varved lake sediments from Kälksjön. The varves are clearly defined by the relative grey scale values, which are expressed in a 0-255 scale. Note that a thin light coloured autumn layer is present in some varves.

varves is presented in Figure 1 together with photographs and an example of an X-ray image of varves found in Sweden.

## Criteria for the formation and preservation of varves

### Climate

Varved lake sediments tend to form in regions with a climate characterised by strong seasonal contrasts. Boreal environments in Fennoscandia are marked by seasonal shifts in atmospheric conditions and the climate in this region is characterised by low winter temperatures (which causes snow accumulation and the freezing of lake surfaces, see Fig. 2), rapidly increasing spring temperatures (which causes snowmelt floods and maximum river discharge peaks during spring), relatively high summer temperatures (which support primary productivity within the lake) and occasionally, intense autumn storms (which produce a river discharge peak that almost equals the spring discharge).

It has been recognised that the concentration of

sediments in suspension in streams and rivers is strongly related to the intensity of river discharge in both small and large catchments in Fennoscandia (Tikkanen, 1990; Sander *et al.*, 2002). The highest concentrations occur during spring snowmelt when the daily annual river discharge rate reaches maximum values (Tikkanen, 1990; Sander *et al.*, 2002). Figure 2 also displays the seasonal variation in river discharge, which is the driving mechanism for the formation of spring layers (and occasionally autumn layers) in varved sediments.

### Lake morphometric properties

A prerequisite for the preservation of varves is the absence of significant post-depositional disturbance, primarily in the form of bioturbation, and water movements created by currents and winds. Varves, therefore, tend to be found in relatively deep stratified lakes where vertical mixing of the water column is limited and anoxic conditions prevail in the hypolimnion, which restricts the presence of a bottom fauna and flora (e.g. O'Sullivan, 1983; Saarnisto, 1986; Petterson, 1996). In addition, lakes that are deep relative to their surface area are more



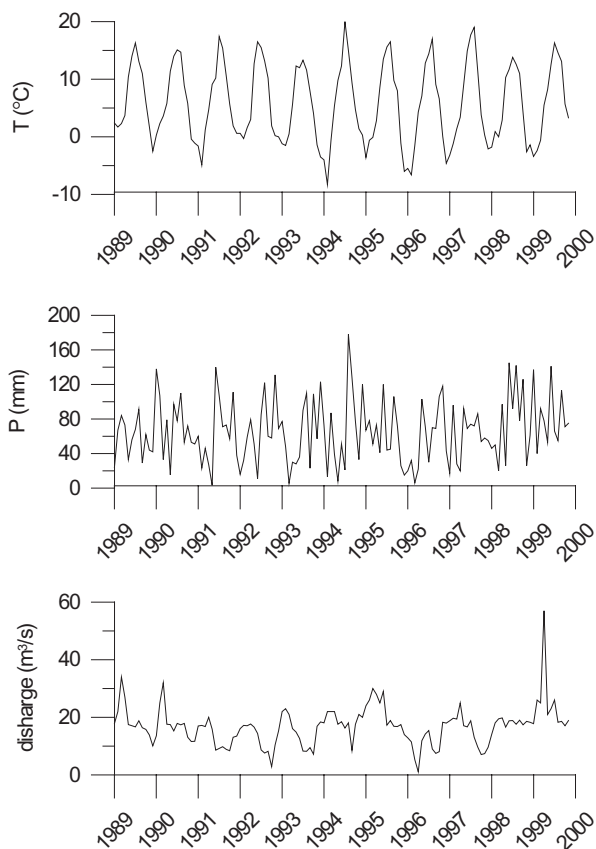


Fig. 2. Diagrams showing a) mean temperature, b) mean precipitation, and c) mean river discharge rates for years AD 1989-2000 obtained from Djurskog and Lennartsfors meteorological and hydrological stations in the province of Värmland, west central Sweden. The seasonal variability in these parameters are characteristic for boreal regions in Fennoscandia i.e. low winter temperatures, rapid increasing temperatures during spring, relative high temperatures during summer, high winter precipitation in the form of snow and maximum river discharge rates during spring. These variables are the driving mechanisms for the formation of varves in lake sediments in Fennoscandia.

likely to experience permanent or seasonal stratification and to contain varved sediments than shallower lakes. A model, after Larsen *et al.* (1998), that describes the relationship between lake surface area/maximum water depth and the occurrence of laminated and varved sediments, is presented in Appendix I.

Varve formation and preservation are also favoured by lake morphometry variables, such as, a medium slope gradient (which restricts slumping) and shape, where a circular basin with a flat and broad lake bottom provides a low energy environment and a large area for sediments to accumulate (e.g. O'Sullivan, 1983; Saarnisto, 1986; Appendix I).

### Lake catchment properties

The fine-grained mineral matter that constitutes the spring layers and occasionally the autumn layers, seen in Figure 1, primarily originates from stream bank erosion during periods of maximum river discharge (Pettersson, 1999; Snowball *et al.*, 1999). Thus, the presence of fine-grained mineral material in the lake catchment area favours the formation of distinct and visible spring and autumn layers in varves (Renberg, 1982; Ojala *et al.*, 2000; Appendix I). Lakes with varved sediments are often found in areas located below the ancient highest coastline (HC) or in large post-glacial lake areas, where such sediments were previously deposited (Ojala *et al.*, 2000; Appendix I).

Other factors that favour the formation are (i) the presence of at least one inflowing stream in the catchment, which ensures the supply of enough elastic material during the spring and autumn to form distinct mineral layers (Appendix I) and (ii) the relief of the lake catchment, which can influence the maximum water depth required for varves to accumulate. A more sheltered location of a lake basin decreases the effective wind fetch and prevents vertical mixing of the water column (Ojala *et al.*, 2000).

### Study areas

Five varved lake sediment sequences in Sweden (i.e. Furskogstjärnet, Mötterudstjärnet, Kälksjön, Sarsjön and Frängsjön) have been studied in this thesis (Fig. 3). The majority of the analytical work presented is based on two sites (Furskogstjärnet and Mötterudstjärnet) in the province of Värmland, west central Sweden (Appendices I, II, and III).

### Värmland

Värmland was initially selected as the main study area because (i) the province meets the geological and environmental criteria to contain varved lake sediments, (ii) it lies within the present-day sensitive *Limes Norrlandicus* ecotone (Fries, 1948; Fig. 3) i.e. a zone that would be sensitive to and rapidly react to climate and environmental changes and (iii) this area would be appropriate for a comparison with similar studies in northern Sweden i.e. it would be the southern point in a north-south climatic gradient study.

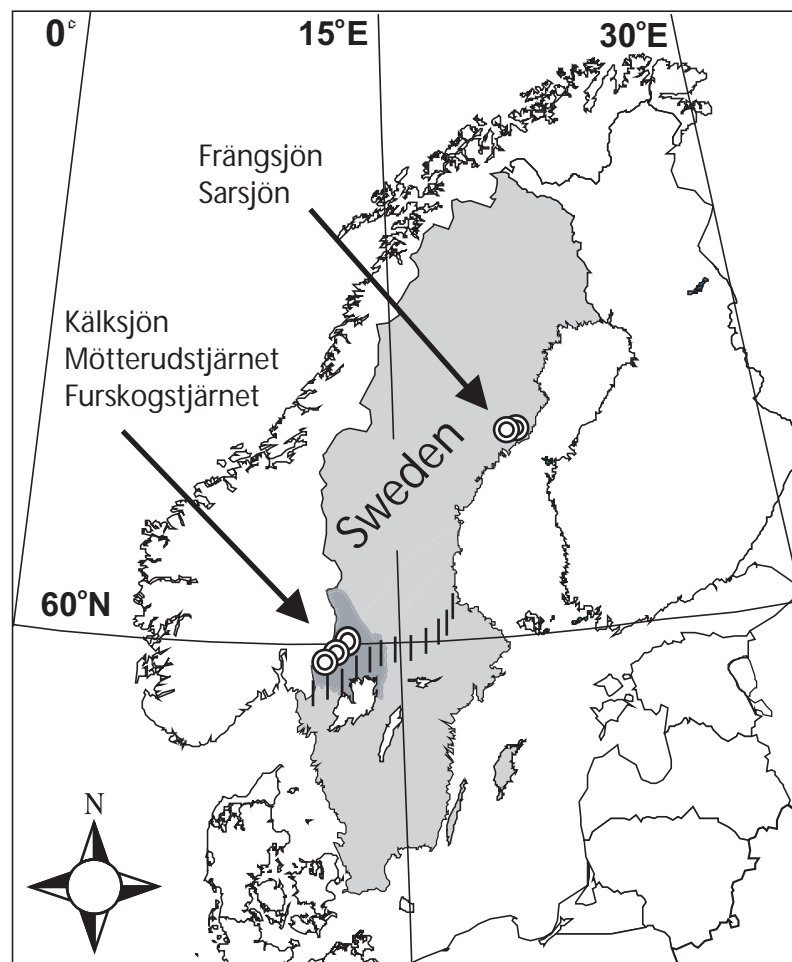


Fig. 3. Map showing the location of the study sites in northern and west central Sweden (the major research area i.e. the province of Värmland in dark shade). The present-day location of the vegetation and climatic transition zone *Limes Norrlandicus* is shown as a dashed line (Fries, 1948). This zone is the borderline between the Boreo-Nemoral (to the south) and South Boreal (to the north) vegetation zones. The latter is dominated by a conifer forest of spruce (*Picea abies*), pine (*Pinus silvestris*), and birch (*Betula pubescens*), with scattered occurrence of temperate deciduous trees such as oak (*Quercus robur*), hazel (*Corylus avellana*), elm (*Ulmus glabra*), lime (*Tilia cordata*) and ash (*Fraxinus excelsior*) at the borderline. The Boreo-Nemoral zone is dominated by conifer forest (see above) with significant amounts of temperate deciduous trees (see above).

### Geology

Värmland can be divided into three major bedrock regions, i.e. (i) a western part which is dominated by grey granite and granodiorite, (ii) a central part dominated by red orthogneiss and (iii) an eastern part dominated by grey to grey-reddish granite (Värmland granite; Lindh & Gorbatshev, 1998). The Mylonit shear zone, which extends from central Värmland to the province of Halland, southwest Sweden, is the main structural element and forms the boundary between the western and central Värmland bedrock areas (Lindh & Gorbatshev, 1998). The dominant bedrock morphology in the central and northern parts of the province is characterised by NNW-SSE orientated valleys, the largest being up to c. 3 km wide and 400 m deep

(Lindh & Gorbatshev, 1998). Minor fault lines, trending both parallel and perpendicular are often associated with larger faults. Southern Värmland is a Precambrian peneplain, where only low ridges of bedrock rise above the peneplain.

The province has experienced several stages of the Baltic Sea development (Börck, 1995). The HC is c. 165 and c. 200 m a.s.l. in southern and northern Värmland, respectively. Quaternary deposits of glacial and post-glacial marine/lacustrine clay and silt are common below the HC (Lundqvist, 1958). The glacial clay has a maximum thickness of c. 20 m and is generally covered by 2-3 m of post-glacial clay and silt. Sediments above HC are dominated by sandy- and silty tills. Glaciofluvial sand and gravel are frequently found in the valleys, often deposited as eskers (Lundqvist, 1958).

### Lake properties, lake catchment characteristics, vegetation and climate

Lake properties and catchment statistics of Furskogstjärnet, Mötterudstjärnet and Kälksjön are presented in Table 2. The three basins were once part of the Ancient Lake Vänern (Björck, 1995) when isostatic land uplift and drainage of the Ancient Lake Vänern through the Göta Älv outlet (Björck, 1995) transformed the sedimentary basins into individual freshwater lakes. Areas close to the lake margins are dominated by silty and clayey soils, which are presently used as arable land. Sandy and silty till covers the remainder of the catchment areas. These areas are mostly forested, although there are some scattered fens and bogs. Intensive human impact in the lake catchments started after *c.* AD 1850 when the lumber industry expanded and the construction of drainage ditches in Sweden intensified.

The water profiles measured in late winter (February/March) are characterised by gradual oxygen depletion with depth and a density increase (temperatures close to 4°C; Fig. 4). This condition is believed to prevail during most of the year, except for a few weeks during spring and autumn when the temperature change and lake waters experience seasonal turnover. The lakes are thus seasonally stratified (dimictic), with associated anoxia in the waters below the thermocline (i.e. in the hypolimnion).

The regional vegetation is dominated by a conifer forest of spruce (*Picea abies*), pine (*Pinus silvestris*), birch (*Betula pubescens*) and alder (*Alnus glutinosa*), with scattered occurrence of temperate deciduous trees, such as, oak (*Quercus robur*), lime (*Tilia cordata*), hazel (*Corylus avellana*), elm (*Ulmus glabra*) and ash (*Fraxinus excelsior*).

At the study sites, the period AD 1961-1990 was characterised by a mean January temperature of -5°C, a mean July temperature of 16°C, a mean annual precipitation of *c.* 800 mm and a mean annual maximum snow depth during the winters of 50 cm (data from the Swedish Meteorological and Hydrological Institute, SMHI). The surfaces of relatively small lakes in Värmland are frozen from the beginning of December to the beginning of May (data from SMHI).

### Västerbotten

Appendix IV is based on a study of two varved lake sediment sequences (Sarsjön and Frängsjön) in the province of Västerbotten, northern Sweden.

### Geology

The bedrock in this province mainly consists of granites, pegmatites and slates. Rapakivi granite and dolorite-dikes are common in the central part of the province (<http://www.sgu.se/kartpubl/index.htm>).

The bedrock has an undulating morphology and is characterised by NW-SE orientated fault lines. The coastal areas were once part of the Ancylus Lake and glacial/post-glacial clay and silt were widely deposited below its highest limit (Granlund, 1943).

Wave washed sediments, such as gravel and sand, are frequently found on hill slopes below the HC. Glaciofluvium was often deposited in the form of eskers, which are frequently found in the NW-SE oriented valleys. The HC in the study area is located at *c.* 280 and 220 m a.s.l., in the eastern and western part, respectively. Above this limit the bedrock is covered by sandy tills, fens and bogs (Granlund, 1943).

Table 2. Lake and lake catchment properties of the five studied sites referred to in the present study

	Furskogstjärnet	Mötterudstjärnet	Kälksjön	Sarsjön	Frängsjön
location (lat.; long.)	59°23'N 12°05'E	59°38'N 12°40'E	60°08'N 13°03'E	64°02'N 19°36'E	64°01'N 19°42'E
altitude (m a.s.l.)	137.3	89	98	177	163
area (ha)	33	13	30	10	7
catchment area (ha)	800	300	400	350	120
maximum depth (m)	14.2	9.4	14.2	7.3	7.1
post-isolation sediment thickness (m)	3.6	3.85	6.45	4.3	4.5
mean varve thickness (mm)	0.38	0.41	0.68	0.48	0.51
post-isolation sediment sequence (calendar years BP 1950)	9555 ± 141	9282 ± 172	?	8879 ± 190	8616 ± 190

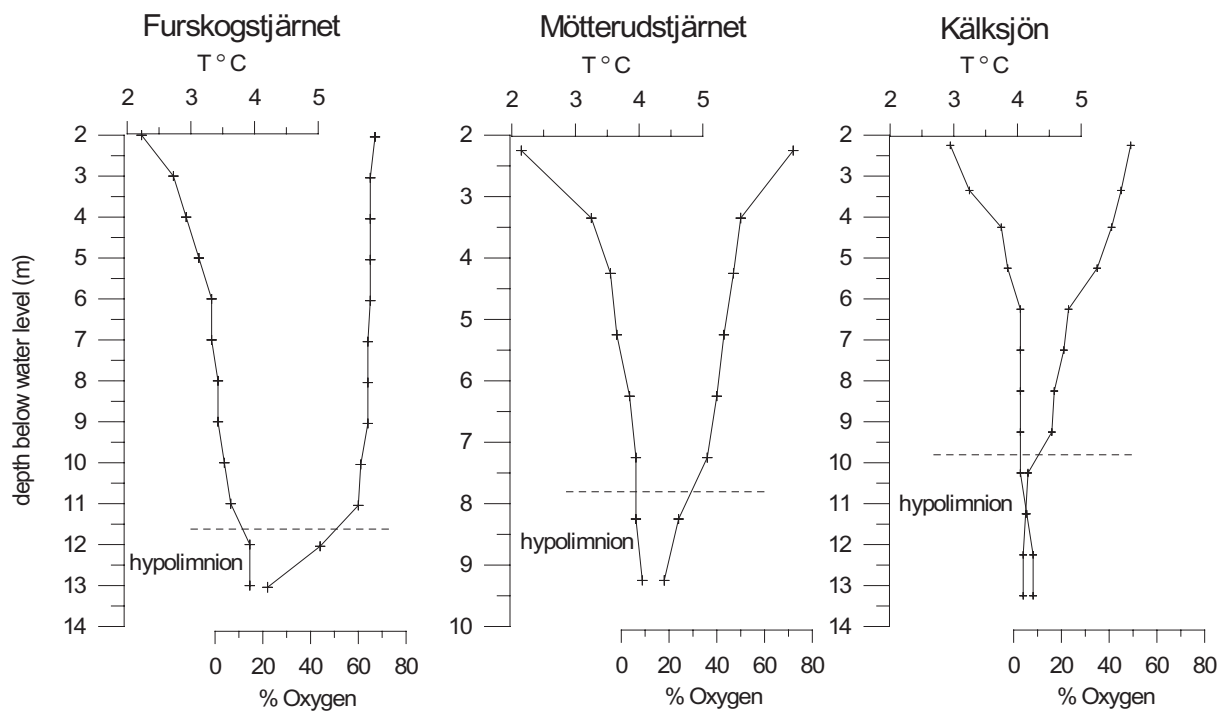


Fig. 4. Water profiles of temperature and oxygen concentration obtained from Furskogstjärnet, Mötterudstjärnet and Kälksjön during winter. The water profiles are characterised by decreasing oxygen concentrations towards the bottom of the lakes, where the temperatures are close to 4°C. The non-homogenised water columns indicate that the waters are stratified, which lead to seasonal anoxia in the hypolimnion. Anaerobic bottom conditions are a prerequisite for the formation of varves.

### Lake properties, lake catchment characteristics, vegetation and climate

Lake and lake catchment characteristics for Sarsjön and Frängsjön are presented in Table 2. Both lakes are situated under the HC of the ancient Ancylus Lake. The dominant Quaternary deposit around the lakes is post-glacial clay, which forms the basis of arable land. Both lakes are dimictic with seasonal anoxia in the hypolimnion (Pettersson, 1999).

Sarsjön and Frängsjön are situated in the present-day boreal vegetation zone, which is dominated by spruce (*Picea abies*), pine (*Pinus silvestris*) and birch (*Betula pubescens*) and with alder (*Alnus incana*) present on wet soils. Regional pollen diagram indicate that significant human disturbance in the coastal areas began at *c.* AD 1200, while the more inland areas around Sarsjön and Frängsjön were not disturbed significantly by humans (in the form of forest clearance) until AD 1700-1900 (Segerström, 1990).

During the period AD 1961-1990, the climate in the vicinity of Umeå was characterised by a mean January temperature of -10°C, a mean July temperature of 15°C, a mean annual precipitation of *c.* 700 mm and a mean annual maximum snow depth during the winters of 70 cm (data from SMHI).

The surfaces of small lakes are frozen from the beginning of November to the middle of May (data from SMHI).

## Materials and methods

### Sediments

The post-isolation sediment sequences consist of varved brown/grey fine-detritus gyttja-clays and gyttja-silts, which extend to *c.* 9500 and to *c.* 9000 cal. years BP\* in west central Sweden and northern Sweden, respectively (Table 2). The five post-isolation sediment sequences have a thickness of approximately 4 m, except in Kälksjön, where it has a thickness of *c.* 6.5 m (Table 2).

### Localisation and collection of varved lake sediments

A database containing information about lake morphometry (maximum depth, maximum depth/average depth ratio and water volume) of about 1500 lakes in Värmland was obtained from SMHI and

\* Throughout the thesis, cal. years BP means calendar years BP 1950

used in a selective process in which varved lake sediments possible could be found (Appendix I). This procedure also involved the classification of lake catchment properties, by using topographic and Quaternary deposit maps and subsequent reconnaissance fieldwork.

After the final step in the selective process, continuous sediment sequences were collected from the deepest area of the ice-covered lake surfaces during the late winters of AD 1999, 2000 and 2001. A 5 m long fixed piston corer operated with rods and cables (Aaby & Digerfeldt, 1986) was used to collect sediments for palaeomagnetic measurements. The piston cores were not oriented to an azimuth during coring. Great care was taken to avoid rotation during operation and to ensure that the cores penetrated vertically into the sediment.

In addition to the piston cores a 1.5 m long and 75 mm diameter Russian corer (Jowsey, 1966) was used to recover complete sediment sequences, with an overlap of 0.5 m between individual sections. As the uppermost sloppy sediments could not be retrieved with the Russian core the topmost c. 40 cm were collected with a freeze corer (Renberg & Hansson, 1993). Catchment soil samples (stream bank and soil horizons samples) were collected during summers. These samples were subject to mineral magnetic analyses for a comparison with lake sediment mineral magnetic properties.

## Chronology

Continuous varve chronologies with cumulative  $\pm$  error estimates were established for Furskogstjärnet, Mötterudstjärnet and Frängsjön sediment sequences by following the guidelines in Lotter & Lemcke (1999), Petterson (1999) and Snowball *et al.* (1999). The Sarsjön varve chronology was constructed by Snowball *et al.* (1999). Varve counts were performed by two people on the Russian cores and the freeze cores by using an Aniol electronic tree-ring measuring system and a Leica/Zeiss stereo microscope. Photographs of the varves were taken using the same microscope and a Nikon COOLPIX-950 digital camera. X-ray radiographs of varves were obtained from 12 x 10 x 0.5 cm sediment blocks embedded with epoxy (Clark, 1988; Lamoureux, 1994). Relative grey-scale was obtained using the freeware image analysis programme "Scion Image".

Contiguous 2 cm sediment slices were cut from the Russian core sequences obtained from Furskogstjärnet and Mötterudstjärnet and sieved through a mesh width of 0.25 mm. AMS (Accelerator Mass Spectrometry)  $^{14}\text{C}$  dating was

performed on various terrestrial plant macrofossils that did not pass through the sieve (i.e. bark and needles of *Pinus sylvestris*, fruits and catkins scales of *Betula pubescens*, unidentified leaves and unidentified mosses). Measurements were performed at the Radiocarbon Dating Laboratory, Lund University. Calibration of  $^{14}\text{C}$  years into calendar years was made using atmospheric data from Stuvier *et al.* (1998) and the Oxcal calibration program v3.5, Bronk Ramsey (1998); using default values; cub r:4 sd:12 prob usp[chron].

## Tephra analyses

Contiguous 1 cm<sup>3</sup> sediment samples from the Russian cores recovered from Furskogstjärnet and Mötterudstjärnet sediment profiles were extracted and used for tephra identification. Each sample was treated with a density-separation technique (Turney, 1998) to concentrate possible rhyolitic glass shards. The mineral particles with a density between 2.3 and 2.5 g/cm<sup>3</sup> were mounted in Canada balsam on a microscope slide and visually analysed with a polarising microscope at 200-400 x magnification. Samples with observed tephra shards were prepared for microprobe analysis and subsequent analytical procedures following Dugmore *et al.* (1995a). Microprobe analyses were performed at the Department of Geology and Geophysics at Edinburgh University.

## Palaeomagnetic and mineral magnetic analyses

Samples for palaeomagnetic analyses were taken out at an interval of 3 cm between the center of adjacent samples from two piston profiles from Furskogstjärnet and Mötterudstjärnet using standard sampling boxes. The Natural Remanent Magnetisations (NRM's) and Anhysteretic Remanent Magnetisations (ARM's) were measured using a 2G-Enterprises model 755-R SQUID magnetometer equipped with an automatic three-axis alternating field (AF) demagnetisation system. ARM was induced in a peak-alternating field (AF) of 100 milli Tesla (mT) with a controlled direct current (DC) bias field of 0.05 mT. The remanent magnetisation of eleven pilot samples from each sediment sequence were measured after progressive AF demagnetisation at 0, 5 and then at 10 mT increments up to a maximum AF of 100 mT. Based on the results from the pilot measurements, the remaining samples were measured after stepwise AF demagnetisation at 0, 5, and 40 mT.

The palaeomagnetic data sets were statistically filtered using the method described by Björck *et al.* (1987). Virtual geomagnetic pole positions were calculated from the directions of the magnetic field according to Butler (1992) and the IADP99 computer program (Torsvik *et al.* <http://www.ngu.no/geophysics/>).

Bulk magnetic susceptibility ( $\kappa$ ) was measured every 4 mm with a Bartington Instruments MS2E1 magnetic susceptibility high-resolution surface scanning sensor coupled to a TAMISCAN automatic logging conveyor.

Initial susceptibility ( $\chi_{in}$ ) was measured with a Geofyzica Brno KLY-2 "Kappabridge". The samples were magnetised with a Redcliffe 700 BSM pulse magnetiser in a field of 1 Tesla (T), assumed to magnetically saturate the sample, and then the saturation isothermal remanent magnetisation (SIRM) was measured with a Molspin Minispin magnetometer. SIRM and  $\chi_{in}$  were measured on the same samples that were used for NRM and ARM analyses and on contiguous 1-cm samples obtained from Russian cores. ARM measurements were also performed on the consecutive 1-cm samples.

Magnetic hysteresis loops were measured with a Princeton Measurements Corporation alternating gradient magnetometer (AGM M-2900) on consecutive 5-mm thick subsamples of fresh sediments cut from the Russian sediment cores. These subsamples were then dried and weighed and the hysteresis properties of the dried samples were remeasured. The ferrimagnetic component was found to saturate below 300 mT, why a slope correction was applied between 380 and 500 mT, which allowed the high-field magnetic susceptibility ( $\chi_{hf}$ ) of the paramagnetic component to be determined and the magnetic hysteresis properties of the ferrimagnetic component to be calculated i.e. saturation magnetisation ( $M_s$ ), saturation remanent magnetisation ( $M_{RS}$ ), coercivity ( $B_0)_C$  and coercivity of remanence ( $B_0)_{CR}$ .

Catchment samples were wet-sieved through a mesh of 63  $\mu\text{m}$  prior to analyses. This procedure was performed to provide a sediment fraction that was more likely to be representative of the mean mineral grain size of the silt and clay rich sediments.

The dry mass of each sample (palaeomagnetic, mineral magnetic, and catchment samples) was measured after oven drying at 40°C.

All palaeomagnetic and mineral magnetic analyses were performed in the Palaeomagnetic and Mineral Magnetic Laboratory in the Department of Geology, Lund University.

### Pollen analyses

A 1 cm<sup>3</sup> volume sampler was used to take 2 cm<sup>3</sup> sediment samples at intervals of c. 75 years from the Sarsjön and Frängsjön sediment sequences. The pollen slides were prepared following conventional methods (Berglund & Ralska-Jasiewiczowa, 1986), which included the addition of exotic marker grains (Lycopodium spores) for pollen concentration and accumulation rate (influx) calculations. Pollen and spores were identified using reference literature (Moore *et al.*, 1991; Reille, 1992; Erdtman *et al.*, 1961) and by comparison with reference slides at the Department of Geology, Lund University. Pollen percentage diagrams were constructed using TILIA and TILIA-GRAPH programs (Grimm, 1991). Ninety five percent confidence limits of the true concentration of pollen grains and influx values (grains cm<sup>-2</sup>yr<sup>-1</sup>) were calculated according to Maher (1981).

### Geochemistry

Total organic carbon (TOC) of the Sarsjön and Frängsjön sediment sequences were measured with a LECO RC-412 multiphase carbon determinator on 1 cm samples taken at an interval of 4 cm. Prior to the analyses, a tungsten ball mill was used to homogenise the samples, as only c. 0.1-0.2 mg was used for the analyse. These were then subsequently dried at 105°C and placed in a dessicator.

Total carbon (T) and nitrogen (N) analyses of the Furskogstjärnet and Mötterudstjärnet sediment sequences were measured with a sample interval of 2 cm on a LECO CHN-900 micro multi-elemental determinator at the Institute for Baltic Sea Research, Rostock, Germany. The analyses were performed on homogenised and dried samples. Prior to analyses, sub-samples were weighed (c. 10 mg) and placed in tin capsules. Standards (70.0 % C and 10.0 % N) were analysed before, during and after sub-sample measurements to account for drift.

## Summary of papers

### Paper I

Zillen, L., Snowball, I., Sandgren, P. & Stanton, T. 2002: Occurrence of varved lake sediment sequences in Värmland, west central Sweden: lake characteristics, varve chronology and AMS radiocarbon dating. *Boreas* 4, 000-000.

This paper presented the results of a survey of lakes in Värmland, which was carried out with an aim to find continuous varved lake sediment sequences covering the majority of the Holocene. It was the first study in Sweden where the identification of recognisable preconditions for the formation and preservation of varved lake sediments were systematically considered prior to fieldwork.

By following a selective process based on previous studies in Canada (Larsen *et al.*, 1998) and Finland (Ojala *et al.*, 2000) three new varved sites were discovered in this province (i.e. Furskogstjärnet, Mötterudstjärnet and Kälksjön). The sequences of Furskogstjärnet and Mötterudstjärnet were detected and recovered in 1999. The Kälksjön site was discovered during a second field survey in 2001 and the sediment sequence was recovered in 2002.

The three lakes were found to have several common lake morphometric properties and lake catchment characteristics, such as maximum water depth, maximum water depth/lake surface area ratio, catchment soil types, altitude and number of inflows, as also recognised by the previous studies. It could be concluded that the methods outlined by Larsen *et al.* (1998) and Ojala *et al.* (2000) are applicable also in boreal environments in Sweden. It could also be concluded that potential regions for varved lake sediments in Sweden are, (i) areas below the HC along the east coast, (ii) the mid-Swedish lowlands, i.e. the area below the HC that extends from Gothenburg in the west to Stockholm in the east, (iii) the large post-glacial lake areas in northern and southern Scandinavian mountains, and (iv) the post-glacial lake areas in the South Swedish Uplands.

The aim was then to construct high-precision varve chronologies based on these sediments and to compare the varve chronologies to radiocarbon time-scales. Varve chronologies with calculated  $\pm$  error estimates were established by varve counting performed by two people on both sediment sequences. The varve chronology in Furskogstjärnet extends back to  $9555 \pm 141$  cal. years BP ( $\pm 1.48$  %) and in Mötterudstjärnet to  $9282 \pm 172$  cal. years BP ( $\pm 1.85$  %). These are at present the longest

geological records with an annual resolution known to exist in Sweden. The error estimates of these sequences are of the same magnitude as the Holocene section of the Greenland ice cores (i.e.  $\pm 1$ %; Alley *et al.*, 1997a, 1997b), varve chronologies from Finland (i.e. between  $\pm 1$  % and  $\pm 3$  %; Ojala & Saarnisto, 1999; Ojala & Saarinen, 2002) and varve chronologies in northern Sweden (i.e.  $\pm 2$ %; Snowball *et al.*, 1999, 2002).

Terrestrial plant macrofossil remains from ten levels in both sediment sequences were radiocarbon dated by the AMS technique. In Furskogstjärnet, the calibrated  $^{14}\text{C}$  dates deviated significantly from the varve based time-depth curve at several levels. In Mötterudstjärnet, a fully reasonable time-depth model based on the  $^{14}\text{C}$  dates yielded significantly older ages in the lower part of the sequence compared to the varve chronology. These older ages suggest that Mötterudstjärnet was isolated from Ancient Lake Vänern at *c.* 9700 cal. BP, which is not in agreement with early-Holocene lake stratigraphy records based on radiocarbon dating from the same area (Wastegård, 1995), nor with varved-based PSV record from northern Sweden and central Finland. The time-depth curves based on varve counting were supported by tephrochronology and correlation between palaeomagnetic secular variation curves obtained from varved sites in Fennoscandia.

An important conclusion of this paper is that the time-scales based on the varved lake sediments are more accurate and precise than those obtained from radiocarbon dating of terrestrial plant macrofossils. This suggests that radiocarbon based age/depth models derived for lake sediment sequences should in the absence of varves be treated with caution and preferably be supported by other dating techniques.

### Paper II

Zillén, L., Wastegård, S. & Snowball, I. 2002: Calendar year ages of three mid-Holocene tephra layers identified in varved lake sediments in west central Sweden. *Quaternary Science Reviews* 21, 1583-1591.

Tephra (volcanic ash) deposits are excellent isochrones for the correlation of geographically separated geological archives and can be used as a relative dating tool (e.g. Dugmore *et al.*, 1995b). Holocene Icelandic volcanic eruptions have distributed tephra particles over a wide area of northern and central Europe.

The aim of the study was to find and identify

tephra particles in the varved lake sediment sequences in Värmland, geochemically correlate them to the Icelandic tephra stratigraphy and assign them calendar year ages. Prior to this study, three mid-Holocene tephra horizons of Icelandic origin (i.e. Hekla-4, Kebister/Hekla Selsund and Hekla-3) had been identified in peat deposits in the same province by Boyle (1998). Although these tephra horizons had been precisely geochemically identified, temporal control had been limited to radiocarbon dating (e.g. Dugmore *et al.*, 1995a, 1995b; Pilcher *et al.*, 1995; Boyle, 1998; Wastegård *et al.*, 2001)

Three intermediate to rhyolitic Icelandic Holocene tephra layers, Hekla-3, Kebister (Hekla-Selsund) and Hekla-4 were identified in Furskogstjärnet and Mötterudstjärnet. Calendar year ages were assigned to these tephra layers based on the varve chronology obtained from Furskogstjärnet, because when this paper was published the Mötterudstjärnet varve chronology was not yet fully established. However, the number of years between the tephra horizons was calculated according to varve counts conducted on both varved sediment sequences. The varve ages were estimated to  $3295 \pm 95$  cal. years BP for Hekla-3,  $4030 \pm 103$  cal. years BP for Kebister and  $4390 \pm 107$  cal. years BP for Hekla-4. The age difference between Kebister and Hekla-4 was estimated to  $400 \pm 40$  varve years (previously estimated to *c.* 200 (calibrated  $^{14}\text{C}$  years), between Hekla-3 and Hekla-4 to  $1135 \pm 55$  varve years (previously estimated to *c.* 1100 calibrated  $^{14}\text{C}$  years) and between Hekla-3 and Kebister to  $708 \pm 20$  varve years.

The ages obtained from the Furskogstjärnet sequence were supported by the calibrated radiocarbon dates obtained by interpolation between AMS-dated levels ( $2\sigma$  range). The varve ages were compared with previously reported radiocarbon dates from Iceland, Sweden and the British Isles. Considering the age-error estimates associated with the varve chronology and calibrated  $^{14}\text{C}$  ages, the ages of Kebister and Hekla-4 were in agreement with former investigations. However, the varve age of Hekla-3 was found to be older (by *c.* 200 varve years) than previously suggested.

### Paper III

Zillén, L.: Century-scale Holocene geomagnetic field variations and apparent polar wander paths reconstructed from varved lake sediments in Sweden. Unpublished manuscript.

Palaeomagnetic measurements of sediment samples can be used to reconstruct records of the Earth's geomagnetic field and these reconstructions provide a useful correlation and relative dating tool that can be applied to suitable sedimentary archives (Saarinen, 1999). However, the vast majority of former Holocene palaeomagnetic investigations on lake sediments have relied on time-scales based on radiocarbon  $^{14}\text{C}$ -dating (e.g. Turner & Thompson, 1981; Hanna & Verosub, 1989; Løvlie *et al.*, 1999; Gogorza *et al.*, 2000) or prehistoric records derived from discontinuous palaeomagnetic studies of archeological materials (Pesonen *et al.*, 1995) and volcanic rocks (Merrill & McElhinny, 1983).

Prior to this study continuous palaeomagnetic secular variation (PSV) records had been constructed for northern Sweden (Mörner & Swydan, 1985; Snowball & Sandgren, 2002) and Finland (Saarinen, 1999; Ojala & Saarinen, 2002). This palaeomagnetic study of Mötterudstjärnet and Furskogstjärnet was undertaken to extend the network of PSV records in Fennoscandia. The paper also presented a compilation of reconstructed palaeointensity records from Fennoscandia, which were compared to records of global dipole moment. This comparison was done to explore the influence of short-term ( $<10^2$ - $10^3$  yr) geomagnetic field variations on the production rates of cosmogenic nuclides, such as  $^{14}\text{C}$  and  $^{10}\text{Be}$ , in the atmosphere. These nuclides have a wide range of geophysical applications, including dating, element cycling and the identification of climate forcing (Mauzued *et al.*, 1994; Bond *et al.*, 2001; Björck *et al.*, 2001).

AF demagnetisation measurements and mineral magnetic analyses showed that stable single domain magnetite was the dominant carrier of a stable natural remanent magnetisation (NRM). The mineral magnetic analyses also demonstrated that the sediments meet the uniformity criteria for palaeointensity reconstructions. NRM measurements were performed on duplicate sediment cores obtained from both sediment sequences. The results were statistically filtered and used to produce smoothed regional PSV records with 95 % confidence limits. Statistically significant changes in declination and inclination were compared to similar PSV curves from northern Sweden, Finland and the UK.

The good chronological control of the sediment profiles from Värmland provided the opportunity to discuss the age discrepancies between these geographically separated PSV curves. Age discrepancies of up to 700 years between these sites can be ascribed to an unknown combination of lock-in effects, inconsistent definitions of troughs and



peaks in the PSV curves, chronological uncertainties and possible a westward drift of the non-dipole field.

Virtual geomagnetic pole (VGP) positions covering the last *c.* 9000 calendar years were reconstructed to visualize the behavior of the geomagnetic vector, using the stacked directional data obtained from both west central and northern Sweden. The VGP record demonstrates that the North Magnetic Pole has changed its position over time, e.g. at *c.* 4400 BC it was positioned close to the New Siberian Islands in eastern Siberia, and at *c.* 850 BC it was close to the island of Novaja Zemlja, at a latitude of *c.* 75°. The reconstructed VGP record ends at *c.* AD 1850 close to the present geomagnetic North Pole.

VGP's were dominated by an anticlockwise path around the rotation axis, which suggests that the source of secular variation during most of the Holocene has been the main dipole field. This behaviour could have been caused by wobbling of the field axis as it precessed anticlockwise around the Earth's rotation axis (Turner & Thompson, 1981). The VGP paths also provide valuable information that can be used to assess regional records of <sup>10</sup>Be flux, e.g. to the Greenland ice-sheet.

Relative palaeointensities obtained from the Swedish and Finnish sites were calibrated against compiled global dipole moments and used to calculate global average cosmogenic nuclide production rates. There was a good agreement between the relative intensity records, calibrated dipole moments, and the long-term trend seen in the compiled global dipole moments (e.g. Yang *et al.*, 2000). This agreement supports the argument that the long-term Holocene intensity trend of the geomagnetic field in Fennoscandia has been unaffected by non-dipole influences. By applying a fifth degree function (Wagner *et al.*, 2000) to the calibrated palaeointensity data sets, global average nuclide production rates for <sup>14</sup>C were calculated. Short-term changes in calculated <sup>14</sup>C production rates corresponded to an equivalent change in measured  $\Delta^{14}\text{C}$  in tree rings (Stuvier *et al.*, 1998).

This study provided a detailed picture of past changes in the direction and intensity of the geomagnetic field in Fennoscandia. It also revealed that short-term (<10<sup>2</sup>-10<sup>3</sup> yr) geomagnetic field modulation must be taken into account when interpreting the reconstructed production rates of cosmogenic nuclides, i.e. that short-lived changes in atmospheric concentrations of e.g. <sup>14</sup>C and <sup>10</sup>Be, cannot necessarily exclusively be attributed to solar variability.

## Paper IV

Snowball, I., Zillén, L. & Gaillard, M.J. 2002: Rapid early-Holocene environmental changes in northern Sweden based on studies of two varved lake sediment sequences. *The Holocene* 12, 7-16.

The aim of this paper was to study regional climate and environmental changes during the early Holocene based on studies of two varved lake sediment sequences in northern Sweden (Sarsjön and Frängsjön). A high-field magnetic susceptibility record obtained from the Sarsjön sequence had previously identified a significant period of increased catchment erosion between 8050 and 7650 cal. years BP (Snowball *et al.*, 1999). It was suggested that the enhanced erosion was driven by increased snow accumulation in the catchment during extended winters, which was released during the spring snow melt.

After taking into account chronological dating uncertainties, this period was considered synchronous to the "8.2 ka cold event", recorded as a  $\delta^{18}\text{O}$  excursion in the Greenland ice-cores (von Grafenstein, *et al.*, 1998) and a period of increased glacial activity in the Scandinavian mountains (Karlén, 1976; Dahl & Nesje, 1994). It has also been suggested that this climatic event was caused by a marked change in the North Atlantic ocean circulation, possibly forced by increased meltwater influx from the Laurentide ice-sheet (Klitgaard-Kristensen *et al.*, 1998). However, due to an unknown early Holocene marine radiocarbon reservoir effect, the exact timing of the meltwater influx and its strength had been debated (Barber *et al.*, 1999; Hu *et al.*, 1999).

To reconstruct the regional environmental response to this cooling event, high-resolution measurements of high-field magnetic susceptibility, total organic carbon content and pollen analyses (both percentage and influx values) were performed on both sediment sequences. Emphasis was also invested to evaluate the exact timing and duration of this climate anomaly. The palaeoenvironmental data sets, with temporal frameworks based on two independent varve chronologies, indicate that a 300-year long period of distinctly colder climate, with enhanced winter snowfall, affected the boreal forest ecosystem in this region between *c.* 8050 and *c.* 7650 cal. years BP. This interval was characterised by an increase in mineral matter accumulation, which is assumed to represent a proxy record for winter snow accumulation, a distinct low in TOC and SIRM (the latter considered to reflect a change in the abundance of magnetotactic bacteria) and a statistically

significant decrease in total pollen influx (TPI; predominantly pine, birch and alder). The reduced TPI values are interpreted as a combination of both low individual tree pollen production and less dense regional vegetation cover (with the former being the most important). Low early and late summer temperatures and increased frequency of frost between *c.* 8050 and *c.* 7650 cal. years BP are proposed to be the most likely causes of the response seen in the pollen records. Notable increases in the influx of deciduous tree species (primarily oak and hazel) and TPI values suggest that a rapid change to warmer conditions occurred between 7650 and 7550 cal. years BP.

Given dating errors associated with the varve chronologies and the Greenland ice-core time-scales, the cold interval was considered to reflect the regional (possibly global) climatic cooling, often referred to as the "8.2 kyr BP cooling event". However, the younger age (8050-7650 cal. years BP) of the cold event in northern Sweden did not support the hypothesis of forcing by the sudden drainage of Laurentide glacial lakes into the North Atlantic, unless a minimal 300-year delay in ocean-atmospheric coupling was accepted.

In conclusion, this study contributes to a complex picture of early Holocene climate and environmental change, in response to deglaciation of the Northern Hemisphere. It highlighted the pitfalls that can occur by "wobble-matching" of early Holocene proxy climate records across the North Atlantic region and the assignment of calendar year ages to events that may have been spatially restricted or metachronous. It stressed the importance of the development and validation of independent calendar year chronologies at a regional scale and that varved lake sediment sequences in Fennoscandia could play an important role in this context.

## Additional results

Unpublished records of variations in physical and geochemical properties of the Furskogstjärnet and the Mötterudstjärnet sediment profiles, plus refined calendar year ages of the three Holocene tephra layers are presented in this section. The additional results are interpreted in terms of environmental changes and contribute to the improvement of Holocene geochronology.

## Mineral magnetic analyses

Figure 5 shows the variation of the mineral magnetic properties in Furskogstjärnet and Mötterudstjärnet sediment sequences and trends over the past *c.* 9000 calendar years BP.

The trends in SIRM and  $\chi_{in}$  in both sediment profiles are similar and characterised by values ranging between 5-30 mAm<sup>2</sup>kg<sup>-1</sup> (Furskogstjärnet) and 5-20 mAm<sup>2</sup>kg<sup>-1</sup> (Mötterudstjärnet), which is in the upper range of values typical for natural samples dominated by ferrimagnetic minerals (Thompson & Oldfield, 1986). The isolations of the sedimentary basins, at *c.* 9555 cal. years BP and *c.* 9282 cal. years BP in Furskogstjärnet and Mötterudstjärnet, respectively, are marked by peaks in SIRM and  $\chi_{in}$ , due to a high concentration of magnetic minerals in the associated clay/silt layer. With regards to the post-isolation sediments, maximum SIRM and  $\chi_{in}$  values exist between *c.* 8000 and 6000 cal. years BP in Furskogstjärnet and between *c.* 7200-5600 cal. years BP in Mötterudstjärnet. These early-mid peak values are followed by a long-term decreasing trend towards the Late Holocene. The last *c.* 1300 cal. years BP are characterised by high values similar to those of the varved sediments that formed before 6000 cal. years BP.

All samples have a positive  $\chi_{hf}$ , which ranges between  $4.7 \times 10^{-8}$  -  $1.5 \times 10^{-7}$  m<sup>3</sup>kg<sup>-1</sup> (Furskogstjärnet) and  $4.0 \times 10^{-8}$  -  $1.8 \times 10^{-7}$  m<sup>3</sup>kg<sup>-1</sup> (Mötterudstjärnet). These values are characteristic for iron bearing paramagnetic minerals, such as, amphiboles, biotites, ilmenites, pyroxenes and olivines (Thompson & Oldfield, 1986). The  $\chi_{hf}$  records display high-frequency variations, where peak values often are associated with troughs in the ferrimagnetic concentration parameters SIRM and  $\chi_{in}$ . High  $\chi_{hf}$  values in the early Holocene are followed by a relatively long period of moderately lower values characterised by a decreasing trend towards the Late Holocene between 7600-3200 cal. years BP. The last 3200 (Furskogstjärnet) and 3000 years (Mötterudstjärnet) are characterised by increased values and relatively higher-frequency variations.

Magnetic grain size parameters (i.e.  $M_{RS}/M_S$  and  $(B_0)_{CR}/(B_0)_C$ ) show low variability in the post-isolation sediments, which indicates a quite uniform magnetic grain size distribution, where values of *c.* 0.5 ( $M_{RS}/M_S$ ) and *c.* 1.5 ( $(B_0)_{CR}/(B_0)_C$ ) are typical of fine-grained SSD magnetite (Maher, 1988). Low  $M_{RS}/M_S$  and high  $(B_0)_{CR}/(B_0)_C$  ratios exist in the oldest part of the sequences (i.e. between 9500-9000 cal. years BP and 9300-8500 cal. years BP in

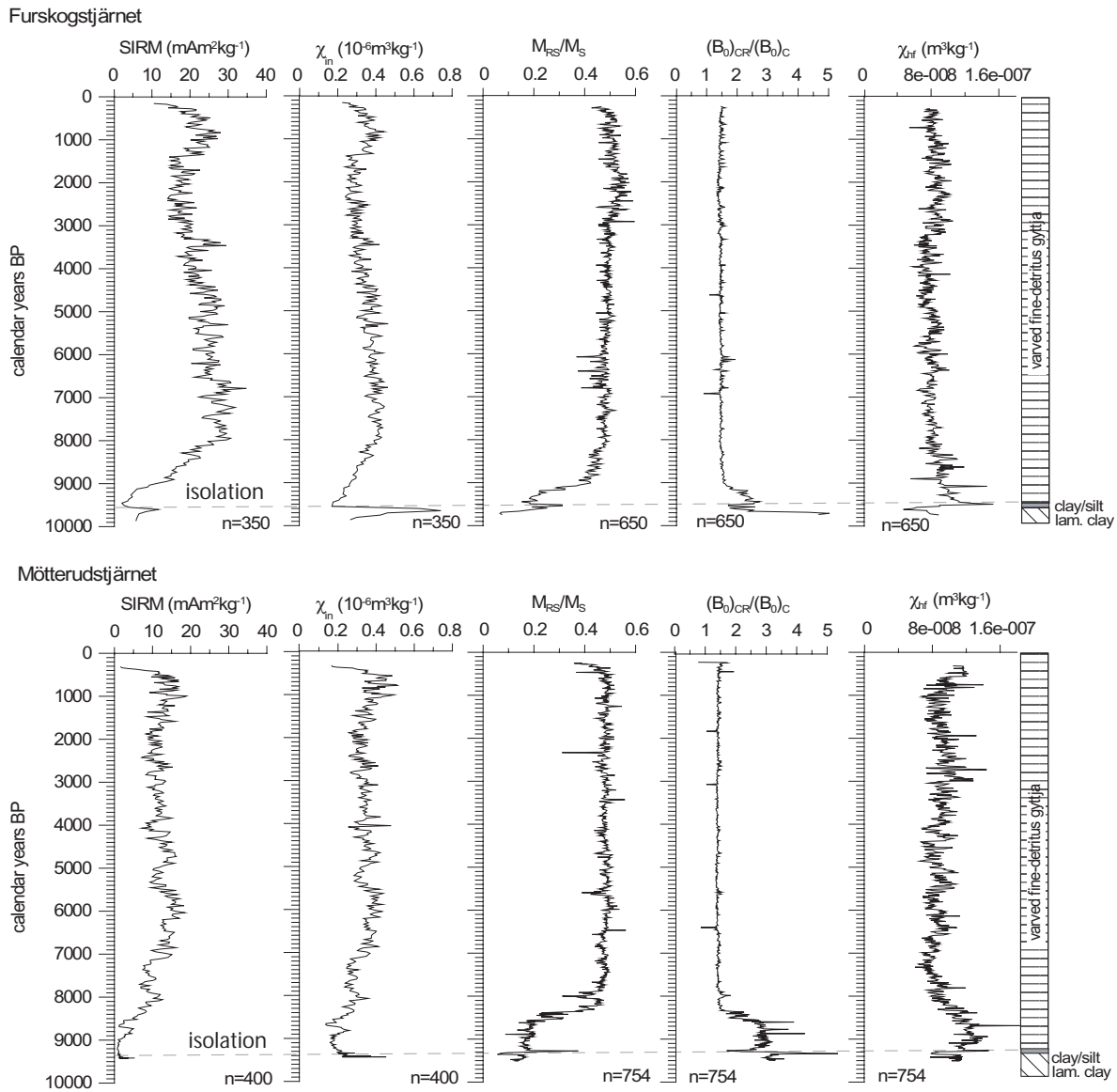


Fig. 5. Down core plots of mineral magnetic parameters showing concentration ( $\chi_m$  and SIRM), magnetic grain size parameters ( $M_{RS}/M_S$  ratios and  $(B_r)_{CR}/(B_r)_C$  ratios), and high-field (paramagnetic) susceptibility ( $\chi_{HF}$ ) variations in Furskogstjärnet and Mötterudstjärnet sediment sequences covering the last c. 9500 years.

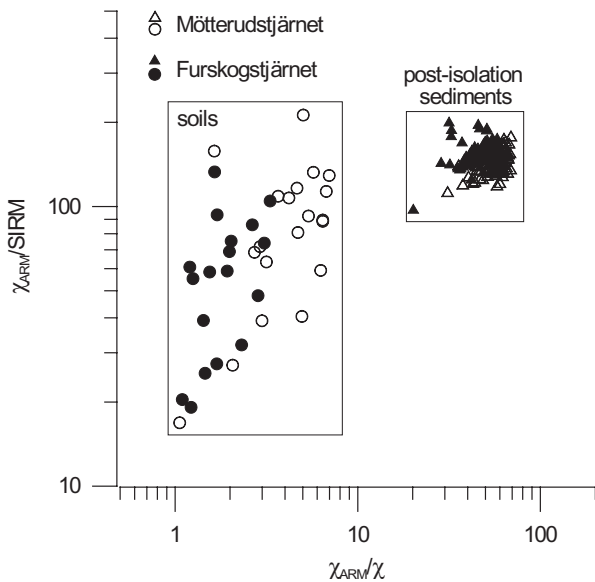


Fig. 6. Biplots of  $\chi_{ARM}/SIRM$  versus  $\chi_{ARM}/\chi$  obtained from mineral magnetic measurements of post-isolation sediments and catchment samples from Furskogstjärnet and Mötterudstjärnet. The biplot demonstrates that the post-isolation sediments form a distinct cluster characterised by high  $\chi_{ARM}/SIRM$  values indicative of a fine grain size distribution of ferrimagnetic SSD magnetite. The catchment samples display a clear divergence from the respective post-isolation samples, which demonstrates that the magnetic properties of the post-isolation sediment sequences are not dominated by allochthonous mineral magnetic grains.

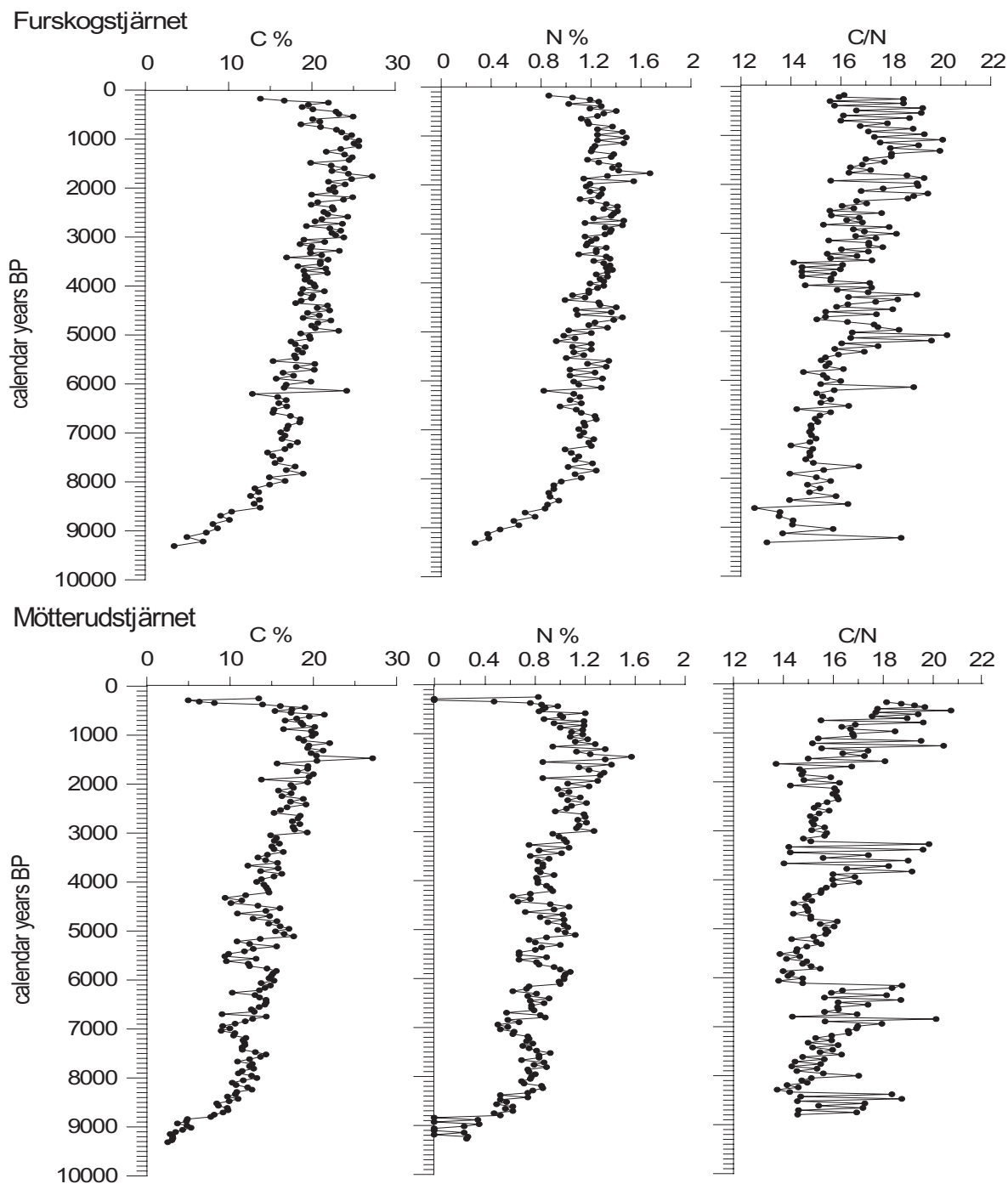


Fig. 7. Down core plots showing the temporal variation in total concentration of total carbon (C) and total nitrogen (N) in Furskogstjärnet and Mötterudstjärnet post-isolation sediment sequences. Also down core plots of C/N ratios.

Furskogstjärnet and Mötterudstjärnet, respectively) indicating the addition of larger multi-domain grains.

Biplots of  $\chi_{\text{ARM}}/\text{SIRM}$  and  $\chi_{\text{ARM}}/\chi_{\text{in}}$  are presented in Figure 6 to demonstrate the variance in mineral magnetic properties between catchment soil types (material  $< 63 \mu\text{m}$  from stream banks and soil horizons) and post-isolation sediments. The post-isolation sediments are characterised by high  $\chi_{\text{ARM}}/\text{SIRM}$  values. In contrast, magnetic properties of the catchment materials are characterised by low  $\chi_{\text{ARM}}/\text{SIRM}$  and  $\chi_{\text{ARM}}/\chi_{\text{in}}$  values.

### Carbon and nitrogen

Total carbon (C) and nitrogen (N) percentages obtained from Furskogstjärnet and Mötterudstjärnet are presented in Figure 7. Both C and N percentages are characterised by a long-term increasing trend. Maximum values exist during the last *c.* 3500 years, except in the uppermost sediments (the last *c.* 1500 years), which show low values. Mean C and N concentrations are moderately higher in Furskogstjärnet (i.e. C = 18% and N = 1.1%) in

Table 3. Calendar year ages and interpolated radiocarbon dates of the Hekla-3, Kebister and Hekla-4 tephra obtained from varved lake sediments in this study. Fu = Furskogstjärnet, Mö = Mötterudstjärnet.

Tephra layers	Fu	Fu cal. BP (2 $\sigma$ )	Mö	Mö cal. BP (2 $\sigma$ )
	varve age	interpolated	varve age	interpolated
Hekla-3	3295 $\pm$ 95	3350 $\pm$ 300	3150 $\pm$ 71	2800 $\pm$ 200
Kebister	4030 $\pm$ 103	4050 $\pm$ 400	3925 $\pm$ 86	3600 $\pm$ 300
Hekla-4	4390 $\pm$ 107	4400 $\pm$ 435	4350 $\pm$ 90	4200 $\pm$ 300

comparison to Mötterudstjärnet (i.e. 13% and 0.8%, respectively). High C percentages are often associated with peak values in SIRM and  $\chi_{in}$ .

C/N ratios in both sediment profiles vary between *c.* 13 and 21. In Furskogstjärnet sediments the C/N ratio gradually increases towards the present, whereas the C/N profile of Mötterudstjärnet is characterised by an increasing trend in sediment post-dating *c.* 1500 calendar years BP. The remaining part of the Mötterudstjärnet sediment sequence is characterised by relative stable values ranging between *c.* 15-16, interrupted by distinct peaks (C/N ratios of *c.* 20), centered around 8500, 6500, and 3500 cal. years BP.

### Refined tephrochronology

In Appendix II, calendar year ages and interpolated radiocarbon  $^{14}\text{C}$  ages were determined for three mid-Holocene tephra deposits identified in Furskogstjärnet and Mötterudstjärnet, i.e. Hekla-3, Kebister, and Hekla-4. However, the varve ages were only calculated from the calendar year time-scale obtained from Furskogstjärnet. The now completed counting of the varves in Mötterudstjärnet produce ages of 3150  $\pm$  71 cal. BP (Hekla-3), 3925  $\pm$  86 cal. BP (Kebister) and 4350  $\pm$  90 cal. BP (Hekla-4). These ages of Kebister and Hekla-4 are in good agreement with those obtained from Furskogstjärnet (see Table 3). However, the Mötterudstjärnet varve age assigned to Hekla-3 is 145 years younger than the age obtained from Furskogstjärnet.

### Significance of additional results

#### *Mineral magnetic and geochemical properties*

Based on a comparison between the magnetic properties of lake sediments and catchment materials Snowball *et al.* (2002) concluded that the magnetic properties of the post-isolation varved sediments found in Sarsjön, Frängsjön and

Furskogstjärnet are dominated by ferrimagnetic stable single-domain (SSD) magnetite produced by magnetotactic bacteria (i.e. magnetosomes). The same conclusion was reached (in Appendix III) for the Mötterudstjärnet post-isolation varves.

The relatively high SIRM and  $\chi_{in}$  values, and the clear difference between the magnetic properties of the catchment soil samples and the post-isolation sediments shown in Figure 6, provide additional evidence that a within-lake process has increased the concentration of SSD magnetite in the sediments. Snowball *et al.* (2002) also showed that a positive linear relationship exists between the concentration of SSD magnetite and the content of total organic carbon. Based on this close correlation it can be assumed that the SSD magnetite produced by magnetotactic bacteria is a function of the supply of organic carbon in the lake sediment (e.g. Snowball *et al.*, 2002). The additional results in Figures 5, 6 and 7 provide further evidence of a post depositional process that increased the concentration of SSD magnetite in the varved lake sediments.

The  $\chi_{hf}$  values, which are independent of the concentration of ferrimagnetic minerals (such as SSD magnetite), indicate that the glacial and post-glacial clay covering the lake catchments forms the primary source of allochthonous mineral material in the lake sediment sequences. As stated in Appendix IV, it is argued that more positive  $\chi_{hf}$  values reflect higher accumulation rates of fine-grained clastic catchment materials derived from stream bank erosion, predominantly during periods of maximum river discharge rates associated with the spring snow melt flood (Snowball *et al.*, 1999; Appendix IV). This conclusion is supported by Sander (2003), who showed that there is a positive power relationship between the annual varve thickness and maximum annual daily discharge in clastic varves in the River Ångermanälven Estuary, central Sweden. Sander (2003) also demonstrated that the reconstructed snowmelt flood could be correlated to the average accumulated winter precipitation. With the exception of events caused by abrupt fluvial channel adjustments, it is most likely that a similar connection also exists between

the concentration of paramagnetic clay minerals (as reflected in the  $\chi_{\text{hf}}$ ) and maximum annual discharge rates in biogenic-clastic varves in relative small sedimentary basins in Fennoscandia. Although the data presented here is smoothed over an average period of 4-5 years, it is likely that the high-frequency variations in the 9500 year-long data sets form a proxy-record of accumulated winter precipitation. The  $\chi_{\text{hf}}$  record could be interpreted as a winter climate proxy, where higher values reflect cold and extended winters with deeper snow packs, and lower values reflect milder and shorter winters with decreased accumulated solid winter precipitation.

However, it can be argued that the supply of eroded material and its fluvial transport was also affected by the length and intensity of the spring snowmelt period, the severity of the winter and the thickness of ground frost. Rapid snowmelt caused by rapidly increasing temperatures during spring would produce distinct peak river discharges, while slow snowmelt would cause more blunt discharge peaks.

The only way to better understand the possible connections between physical properties of varve sedimentary records and environmental/climate change is to calibrate environmental proxies against modern instrumental records of climate parameters. However, due to significant human influence in the studied lake catchments over the past 200 years, which has increased the supply of sediment, it is not possible to perform a calibration exercise between the physical properties of the varves and local/regional climate records, as was performed for the larger Ångermanälven catchment by Sander *et al.* (2002).

Total C and N percentages can demonstrate the downcore variations in primary organic productivity (mostly algae) within the lake, which is favoured by nutrient availability (silica, phosphorous and nitrate) light, climate and water temperature (e.g. Rhee & Gotham, 1981). These variables can be used as a proxy-indicators of climate change in lakes unaffected by human induced eutrophication, where high values suggest that climate conditions were warmer in the past, when limnic productivity was higher (e.g. Batterbee, 2000).

C/N ratios can reflect an approximate state of resistance of organic compounds to decomposition, where higher ratios commonly occur in organic materials which are more resistant (Wetzel, 1983). In general, allochthonous terrestrial organic detritus has C/N ratios between *c.* 45:1 and 50:1, while autochthonous limnic organic materials have C/N ratios of about 12:1 (Wetzel, 1983).

Theoretically, changes of organic matter source should be detectable by changes in sedimentary C/N ratios (e.g. Meyers & Ishiwatri, 1993; Das, 2002).

The C/N ratios in both sediment profiles vary between 12:1 and 21:1, which suggest that the organic compounds of the post-isolation sediments are dominated by autochthonous organic material. On the basis of the C/N ratio it has been estimated that planktonic matter forms between *c.* 42% (C/N ratio 21:1) and 75% (C/N ratio 12:1) of the organic matter pool of the lake sediments (Punning & Tõugu, 2000). However, the nitrogen cycle in lakes is complex and major losses of nitrogen can occur via denitrification and outflow (Wetzel, 1983). In particular anaerobic decomposition of sediment organic matter can result in considerable loss of nitrogen in the form of  $\text{N}_2$  (Wetzel, 1983). The inconsistent results in C/N ratios between the two sediment profiles seen in Figure 7 imply that these are affected by local environmental factors or/and internal lake processes rather than regional climate.

It is notable that maximum SIRM values correspond to lower C/N ratios in Furskogstjärnet between *c.* 8000-6000 cal. years BP. High SIRM values reflect elevated concentrations of SSD magnetite (magnetosomes produced by anaerobic bacteria) and could indicate more reduced conditions. This opposite trend in SIRM and C/N records is not so pronounced in Mötterudstjärnet, where much lower SIRM values suggest that the environment at the water/sediment interface was not as reduced as in Furskogstjärnet. The latter may have promoted a burrowing bottom fauna and consequent mixing of sediments, which could explain why the varves in Mötterudstjärnet sediment sequence are less well preserved during certain intervals.

The decreasing long-term trends in the  $\chi_{\text{hf}}$  records as seen in Figure 5 were most probably caused by a gradual landscape stabilisation and reduced effect of sediment focusing after the isolation. Thus, high  $\chi_{\text{hf}}$  values in sediment deposited prior to *c.* 8000 calendar yr BP in Mötterudstjärnet in comparison to Furskogstjärnet (Fig. 5), can be explained by higher contribution of clay minerals from catchment erosion during the initial period after the isolation (i.e. isolated at  $9282 \pm 172$  cal. years BP, which is *c.* 300 years later than Furskogstjärnet). The same trend can be seen in the magnetic susceptibility record from Lake Kassjön, northern Sweden, which was isolated at *c.* 6400 cal. years BP (Pettersson, 1999).

## *Tephrochronology*

The final counts of the varves in Mötterudstjärnet lead to a refinement of the ages of the tephra layers previously published in Appendix II. The calendar year age of Hekla-4 has now been estimated to  $4370 \pm 99$  (previously  $4390 \pm 107$ ), Kebister to  $3980 \pm 95$  (previously  $4030 \pm 103$ ) and Hekla-3 to  $3220 \pm 83$  (previously  $3295 \pm 95$  cal. years BP). Note that these final ages and their age error estimates all overlap with those ages obtained earlier.

## **Discussion**

### **Occurrence of varved lake sediments in Sweden**

Prior to the publication of Appendix I, varved lake sediment sequences spanning the majority of the Holocene had only been reported from southern and central Finland (e.g. Ojala *et al.*, 2000) and northern Sweden (e.g. Petterson, 1996; Snowball *et al.*, 1999). The three varved sites identified in Värmland extends the network of high-resolution calendar year time scales in Fennoscandia and these are, so far, the most southerly located. However, varved lake sediments extending more than 9500 years back in time have been reported in central Europe. For example, the varved lake sediment sequences (biogenic-carbonate varves) of Lake Holzmaar, west Germany, (Hajdas *et al.*, 1995; Zolitschka, 1998), Lake Gosciadz, central Poland (Ralska-Jasiewiczowa *et al.*, 1998), Lake Soppensee, Switzerland (Hajdas, *et al.*, 1993) and Lake Meerfelder Maar, west Germany (Brauer *et al.*, 2000) extend back to *c.* 13000-13800 cal. years BP. However, the sediments in Lake Gosciadz, Lake Meerfelder Maar and Lake Soppensee are not varved in the upper parts and these varve chronologies are floating. Recently, a partly varved sediment sequence has been found in Sarup Sø in Denmark (Rasmussen *et al.*, 2002). These varves are also of the biogenic-carbonate type.

The discovery of the three varved sedimentary basins in Värmland was facilitated by knowledge of the prerequisites for the formation of varves in lake sediments in Canada (i.e. clastic varves, Larsen *et al.*, 1998) and in Finland (Ojala *et al.*, 2000). The results presented in Appendix I, show the importance of systematically considering the topographical, environmental and geological conditions of a selected area. One must consider that the maximum water depth was, due to

equipment limitations, set to 17 m. It cannot, therefore, be excluded that varves could be found in deeper lakes further to the south.

Visual comparison between the varves found in northern and west central Sweden indicates that the varves in the more southerly sites have less distinct spring layers than the sites further north. Furthermore, visual comparison of the varves in the three sediment sequences in Värmland, show such a north-south gradient in the varve composition. The Furskogstjärnet sediment profile, which is the most southerly located site, has the highest total carbon content and the thinnest average varve thickness. Given the basic model of varve formation (Appendix I) it can be argued that this property is due to a thinner winter snow cover and a less intense river discharge during spring. Based on this argument it is possible that the South Swedish Uplands is the southern limit where biogenic-clastic varves could be found in Sweden.

The number of lakes known to contain varved sediments in Fennoscandia has increased substantially over the past five years (e.g. Ojala *et al.*, 2002, Appendix I). These sites now form an ideal material base that can be used to improve the Holocene chronology of this region.

### **Varve chronologies: limitations and potentials**

In addition to the discovery of new sites with varved lake sediments in Värmland, this thesis has focussed on chronological aspects and applications. Multiple dating methods, i.e. varve counting, AMS radiocarbon dating, tephrochronology and palaeomagnetic correlations were applied to two main sites, which make it possible to compare the errors associated with them.

#### *Varve chronologies and associated error estimates*

Prior to the establishment of a varve chronology it is necessary to confirm that the varves actually are annual and that the individual laminae fit into a sedimentological model that explains the annual cycle of sedimentation (Saarnisto, 1986; Lotter & Lemcke, 1999). It is also essential to perform varve counts on undisturbed sediments (Saarnisto, 1986; Lotter & Lemcke, 1999). Furthermore, the statistical confidence in a varve chronology increases if several people perform repeatable varve counts (Saarnisto, 1986; Lotter & Lemcke, 1999) and if the varve chronology is supported and validated by other independent dating methods

(Hajdas *et al.*, 1995, Zolitschka *et al.*, 2000).

The varve chronologies presented in this study meet these above criteria. This study presents a sedimentological model that explains the cyclic sedimentation in biogenic-clastic varves (Ojala & Francus, 2002), which is supported by the contemporary observations of varve formation. Microscopic investigations show that the varves from Värmland possess components and a general structure that are similar to biogenic-clastic varves found in Finland (Ojala *et al.*, 2000) and northern Sweden (e.g. Petterson, 1996; Snowball *et al.*, 1999). Sediment traps could provide detailed information about the exact timing of the formation of seasonal laminae and improve inferences made about past changes in varve composition. However, such work would require at least 2-3 decades of observations to provide statistically treatable data.

Every varve chronology contains errors and it is essential to estimate the errors associated with a varve chronology as they reflect its quality and its application (Lotter & Lemcke, 1999). It is notable that the counting of the Frängsjön varves undertaken by Renberg & Segerström (1981) produced an isolation age of  $8616 \pm 190$  cal. years BP. The divergence to the one presented in Appendix IV, which yielded in an isolation age of  $8617 \pm 190$  cal. years BP, is only a single year. The error estimates of the varve chronologies,  $\pm 1.48\%$  in Furskogstjärnet,  $\pm 1.85\%$  in Mötterudstjärnet, and  $\pm 2.1\%$  in Sarsjön and Frängsjön, are of the same magnitude as varved sequences in Finland ( $\pm 1-2\%$ , Ojala & Saarinen, 2002) and the Holocene sections of the Greenland ice-cores ( $\pm 1\%$ , Alley *et al.*, 1997a, 1997b). In general, varve chronologies based on various varved lake sediments have an accuracy of *c.*  $\pm 3\%$  (e.g. Zolitschka, 1998; Hughen *et al.*, 1996; Ojala & Tiljander, 2003) and it is rare that a single varve chronology possesses an error estimate below  $\pm 1\%$ . The relatively low error estimates associated with the varve chronologies presented in this study clearly indicate that they are of good quality.

Based on preliminary palaeomagnetic data (Stanton, unpublished) and correlation to the Furskogstjärnet and Mötterudstjärnet PSV curve (Appendix IV), the Kälksjön varves began to form *c.* 8800 calendar years ago and the sediment accumulation rate must have been, on average, double that of the earlier discovered sites in Värmland. Further studies of Kälksjön are likely to improve the chronological precision and accuracy of the tephrochronology and palaeomagnetic secular variation master curve presented in Appendix II and Appendix III, respectively.

The identification of tephra isochrones should make it possible to synchronise the two independent varve chronologies from Värmland and, therefore, assess differences in the varve chronologies. Due to the extraction and concentration techniques, however, the Hekla-3 and Hekla-4 tephra layers could not be geochemically identified in Mötterudstjärnet. On the other hand, it was argued that the two other micro-tephra layers found in the Mötterudstjärnet profile were at similar stratigraphic positions and most likely corresponded to the same eruptions as the micro-tephra found in Furskogstjärnet (Appendix II).

Given the errors associated with the varve chronologies, Hekla-4 and Kebister show almost identical calendar year ages in both profiles, i.e.  $4390 \pm 107$  and  $4350 \pm 90$  (Hekla-4),  $4030 \pm 103$  and  $3925 \pm 86$  (Kebister) in Furskogstjärnet and Mötterudstjärnet, respectively, whereas the calendar year age of Hekla-3 displays a divergence of 145 years between the two independent time-scales (i.e. Furskogstjärnet suggests an older age,  $3295 \pm 95$  cal. years BP, in comparison to Mötterudstjärnet varve chronology,  $3150 \pm 71$  cal. years BP). However, the latter ages are within the calculated error estimates of both chronologies at the respective time-interval (i.e.  $\pm 95$  and  $\pm 71$ , respectively) where Hekla-3 were identified.

It would be beneficial to search for these tephra horizons in other varved sites in northern and central Europe, particularly the sediment sequences in Lake Gosciadz, central Poland (Goslar *et al.*, 1989, 2000), Lake Soppensee (Hajdas *et al.*, 1993) and Lake Meerfelder Maar (Brauer *et al.*, 2000) in Germany. This exercise would open the possibility to synchronise regional environmental proxy records, assess the differences between varve chronologies and tie floating varve chronologies to the Fennoscandian series. Further effort should be made to search for additional tephra horizons in the Värmland sites. This would not only provide the possibility to synchronise a wider interval of the calendar year-time scales in this region but also promote the construction of a varved-based Northwest European tephrochronology, which could be used to synchronise terrestrial, marine and ice-core stratigraphies. Potential Holocene Icelandic tephra deposits for this task are e.g. Hekla-5 (*c.* 6800-7100 cal. BP), Glen Garry (*c.* 1940-2320 cal. BP), Landnán (AD 870's), Hekla-1 (AD 1104), Askja (1875) and Hekla (AD 1947; Stefan Wastegård, pers. commun.).



*Varve chronology versus radiocarbon time-scale*

The AMS radiocarbon dates on various terrestrial macrofossil remains found in the sediment of Furskogstjärnet were scattered around the varve based time/depth curve. If the outliers are excluded, a time-depth curve based on interpolated AMS radiocarbon dated levels does not diverge significantly from the chronology based on varve counts. In the case of Mötterudstjärnet, a similar time-depth curve derived from interpolated AMS radiocarbon dates would lie within the error estimates of the varve chronology, except in sediments deposited prior to *c.* 8000 cal. BP, where the AMS radiocarbon dates would suggest older ages (Appendix I). The radiocarbon analyses imply that Mötterudstjärnet was isolated between 9700-10000 cal. BP ( $2\sigma$  range), which is 500- 800 cal. years older than the estimated varve age of the isolation.

As stated in Appendix I, it seems impossible that Mötterudstjärnet, which is situated at an altitude 50 m lower than Furskogstjärnet, and only 50 km apart, could have been isolated around 9700 cal. BP, unless the age of the isolation of Furskogstjärnet ( $9555 \pm 141$  calendar years BP) is quite inaccurate. Also, when correlating the independent PSV records presented in Appendix III based on varved lake sediments in northern Sweden and Finland (Snowball & Sandgren, 2002; Ojala & Saarinen, 2002; Ojala & Tiljander, 2003), the results demonstrate that Mötterudstjärnet must have been isolated more recently than 9500 calendar years BP. Unless the varve chronologies from all the other Fennoscandian sites display too young ages in the older parts of the sediment sequences, there is no logical reason to question the varve age of the isolation of the Mötterudstjärnet sediment profile. On the other hand, lock-in effects introduce unknown errors in the ages of the PSV features, which may also be biased by drifting of non-dipolar geomagnetic field features (discussed in Appendix III).

There is no obvious explanation for the seemingly too old radiocarbon dates in comparison to the varve chronologies in the lower part of the Mötterudstjärnet sediment sequence. A possible explanation is that the apparently too old dates are due to the redeposition of organic remains from the littoral zone to the deepest part of the lake or that the macrofossils were stored in the terrestrial environment before deposition. Even though the AMS  $^{14}\text{C}$  measurements were performed on delicate macrofossil remains, which should decompose

relatively fast in an oxic environment, there are examples from northern Sweden of 1200 year old sub-fossil trees preserved on dry ground (Grudd *et al.*, 2002).

*Palaeomagnetic correlation and dating*

Palaeomagnetic secular variation trends do not provide direct age estimates. However, once a master PSV curve has been independently dated, it has the potential to be applied to sites elsewhere, at least at a regional scale (radius *c.* 1000-2000 km; Thompson & Oldfield, 1996). The fidelity of such a regional master curve depends on the dating technique applied on the geological strata. The varved-based PSV records in Fennoscandia provide excellent reference curves for regional palaeomagnetic correlations and age transference.

As demonstrated in Appendix III, the four PSV curves from Fennoscandia and the UK show almost identical changes during the Holocene, with differences in the ages of inclination and declination features resolved to within the error estimates associated with the varve chronologies. However, the results presented in Appendix III showed that age divergences up to 700 years exist between the PSV features from northern and west central Sweden in sediments deposited between *c.* 4000-5000 calendar years BP. The potential causes of such a discrepancy are now discussed.

The ages assigned to the palaeomagnetic features may be affected by other problems than those associated with errors in the varve chronologies. These problems include variable sampling resolution (*c.* 100 years in the present study and in Ojala & Tiljander, 2003), uncertainties regarding the definition of features, unknown lock-in delay of the NRM (Tauxe, 1993; Snowball & Sandgren, 2002) and potential drift of the non-dipolar geomagnetic field (Turner & Thompson, 1981). However, it is not practical to improve the sampling resolution because the palaeomagnetic measurements are performed on standard sized cubic samples (internal volume of  $7 \text{ cm}^3$ ). Use of smaller sampling cubes would increase the surface area to volume ratio of the samples, with the result that a proportionally larger volume of the sample would be disturbed and the signal to noise ratio would increase. U-channel measurements (e.g. Brachfeld *et al.*, 2000) reduce disturbance caused by discrete sampling, but the current measuring techniques smooth the palaeomagnetic signal over several centimeters. Given the operation of common magnetometers, there appears to be no practical means of improving the sampling resolution.

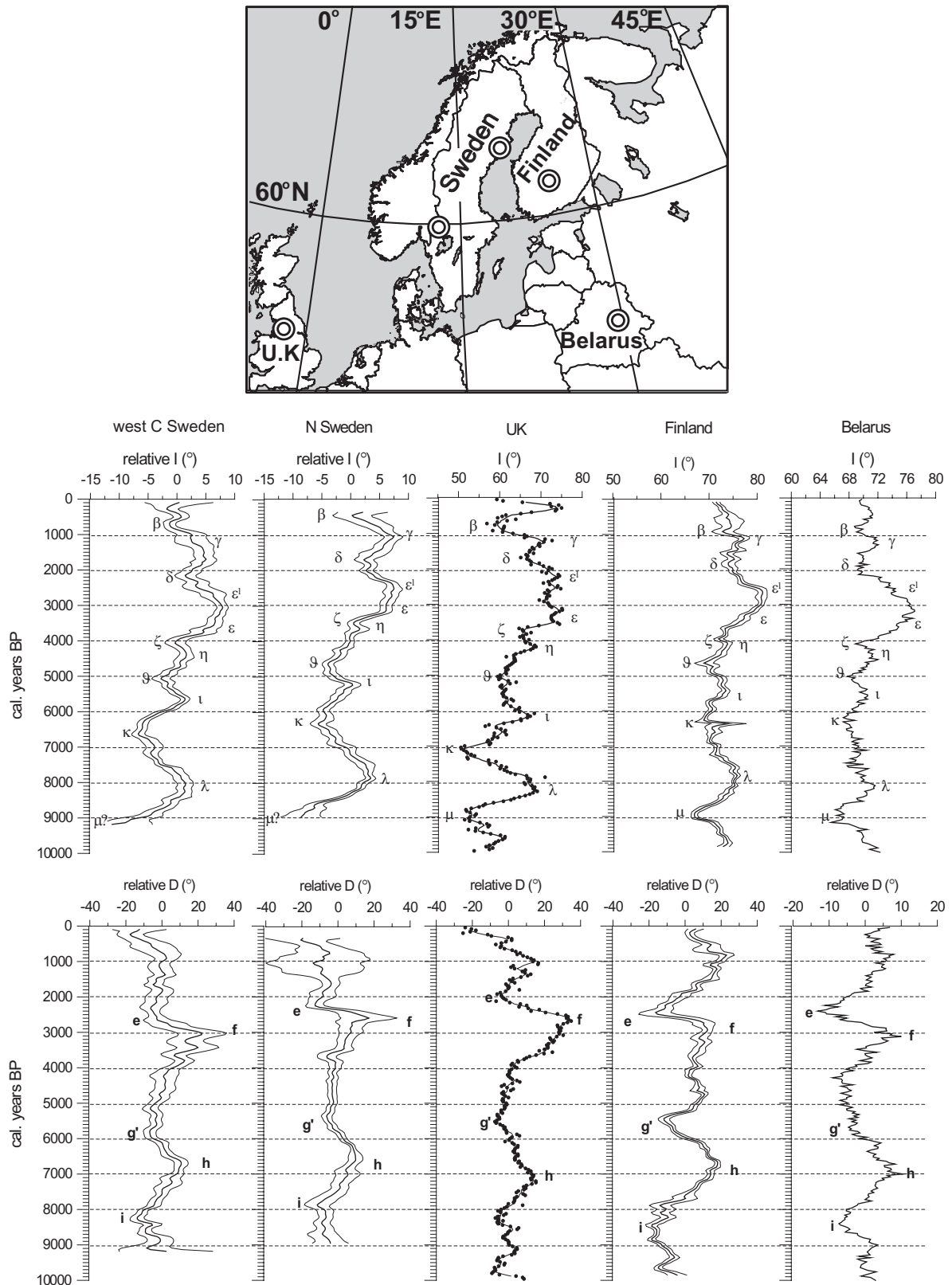


Fig. 8. Spatial distribution of the regional inclination and declination changes reconstructed from west central Sweden, northern Sweden, Finland and Belarus. The figure demonstrates that there is a good coherency between the Fennoscandian varve-based directional PSV records and the  $^{14}\text{C}$  dated record from Belarus and that almost identical directional changes have occurred over an area that covers c.  $30^\circ$  longitude and c.  $10^\circ$  latitude.

Snowball (1997) observed that the NRM of greigite bearing palaeomagnetic samples embedded in epoxy was not altered by the embedding technique. This method could be used to improve the resolution of palaeointensity measurements, but probably not directional measurements due to alignment problems.

It is also difficult to assess the exact timing of the NRM acquisition in the varved sediment records due to the lack of NRM data from the unconsolidated uppermost sediments. Such data has been used to identify the observed westerly declination swing at AD 1840 in western Europe (Thompson & Oldfield, 1986). In order to identify the westward drift of non-dipolar geomagnetic fields it is necessary to obtain high-resolution data series from sites along the same latitude covering several tens of degrees of longitude (Turner & Thompson, 1981).

Despite the problems discussed above, the good agreement between the Fennoscandian PSV records during the majority of the Holocene shows that there is potential to construct a super-regional PSV master curve on a calendar year time-scale for this region, which can be used as a relative dating tool.

To demonstrate the spatial distribution of the regional PSV variations, Figure 8 displays inclination and declination curves from central Sweden (Appendix III), northern Sweden (Snowball & Sandgren, 2002), Finland (Ojala & Saarinen, 2002) and a recent record from Belarus (Lake Naroch; Nourgaliev *et al.*, 2003). There is a good agreement between the Fennoscandian varve-based directional PSV records and the record from Belarus (based on PSV correlation's and radiocarbon dating; Fig. 8), which demonstrates that synchronous PSV changes occurred over a relatively large area (i.e. covering *c.* 30 degrees longitude and *c.* 10 degrees latitude) and that the independent PSV curves reflect at least regional (1000 km > radius < 2000 km) changes rather than geomagnetic field variability on a local scale (radius < 1000 km). These results also indicate that no significant westward drift has taken place in the region covered by these records during the majority of the Holocene. However, the chronological uncertainties ( $\pm 100$ -200 yr) and the sampling resolution (*c.* 100 yr) still don't allow us to totally exclude a relatively fast westward drift (*c.* 0.4 degrees longitude per year), as recorded over the period of instrumental observations (Thompson & Oldfield, 1986).

## Holocene climate and environmental changes

It is unknown to what extent the two Holocene  $\chi_{hf}$  records based on the varved lake sediments reflect changes in local lake sediment focusing (which may also be affected by local environmental changes rather than climate) or regional climate forcing. Even so, it is interesting to discuss the entire data sets in terms of climate variability and put them in the context of other independently dated records of Holocene environmental changes in Northwest Europe and the North Atlantic region.

Considering the error estimates associated with the independent varve chronologies the Värmland varve data sets display similar high-frequency variability throughout the Holocene (Fig. 9). After a *c.* 300-year long period of positive  $\chi_{hf}$  values centered at *c.* 7800 cal. BP (this interval is discussed separately in the next section), negative  $\chi_{hf}$  values, and high C percentages (Fig. 9), are interpreted as a response to a regional atmospheric warming at *c.* 7500 cal. BP. This relatively rapid warming (Appendix IV) signals the onset of the Holocene Thermal Maximum (HTM; *c.* 8000-5500 cal. years BP), which is characterised in Northwest Europe by relatively high solar insolation, high atmospheric temperatures and dry conditions. The HTM caused the retreat of glaciers in the Scandinavian mountains (e.g. Dahl & Nesje, 1994; Snowball & Sandgren, 1996; Nesje *et al.*, 2001), high sea surface temperatures in the North Atlantic (e.g. Koç *et al.*, 1993), a pine tree-line *c.* 300-400 m higher than today in northern Sweden (Kullman, 1999; Barnekow, 2000) and increased atmospheric temperatures (1°C) as recorded by pollen analyses (e.g. Seppä, 1996; Seppä & Birks, 2001) and chironomid reconstructions (Korhola *et al.*, 2002).

Two *c.* 500-year long periods of increased catchment erosion, which can be interpreted as a response to colder climate conditions with increased winter snow accumulation are centered at approximately 6300 and 5300 cal. BP in both varved records that span the HTM (Fig. 9). The oldest of these coincides with one of the major ice-rafting episodes in the North Atlantic identified by Bond *et al.* (1997), a distinct cooling phase around 5800 cal. BP as record from a tree-line lake in northwest Finland (Korhola *et al.*, 2002), increased sea-salt and dust deposition on Greenland (O'Brien *et al.*, 1995) and certain glacier advances in northern Sweden (Karlén & Kuylentierna, 1996). These two periods also correspond to equivalent intervals of increased erosion recorded in the Sarsjön and Frängsjön sediment sequences (Snowball *et al.*, 1999; Appendix IV).

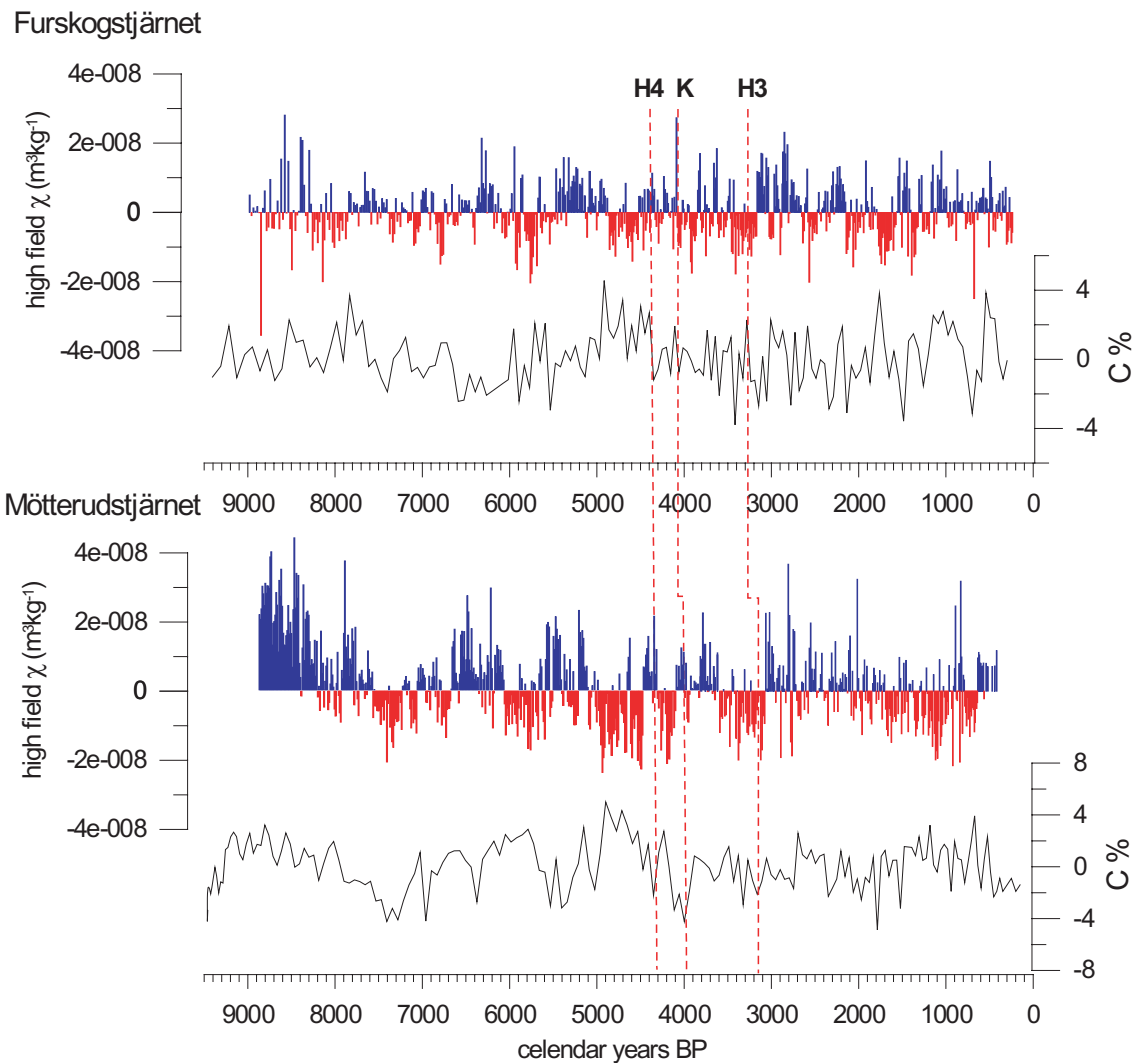


Fig. 9. Temporal variance of the  $\chi_{hf}$ , and total carbon (C) percentages from Mötterudstjärnet and Furskogstjärnet sediment sequences. The data sets are plotted around 5-degree polynomial fits in order to highlight the presence of higher frequency variations. Locations of tephra layers Hekla-4 (H4), Kebister (K) and Hekla-3 (H3) are marked by dashed lines.

Late Holocene climate development in Fennoscandia has been characterised by decreasing temperatures and more moist conditions (Snowball *et al.*, in press). In Scandinavia, the start of this period (c. 4000-3500 cal. BP) was marked by tree-line declines in the Scandinavian mountains (Barnekow, 2000) and glacier advances (Nesje & Kvamme, 1991). A particularly rapid transition to a more variable climate at c. 3700 cal. BP was recognised in the Sarsjön  $\chi_{hf}$  record by Snowball *et al.* (1999), although the regional applicability of this single data set was unknown. The Furskogstjärnet and Mötterudstjärnet sediment data sets indicate an abrupt increase in catchment erosion and subsequent high-frequency variations at c. 3200 cal. BP, which almost coincides with the Hekla-3 tephra (Fig. 9). The rapid transition at c. 3700 cal. BP in the Sarsjön and Frängsjön  $\chi_{hf}$  data sets is thus not recorded in the Värmland  $\chi_{hf}$  records.

However, the period between c. 4000 and 3500 cal. BP in Furskogstjärnet and Mötterudstjärnet sediment sequences is characterised by relatively high  $\chi_{hf}$  values, which could correspond to the transition noted in the varved sites in northern Sweden.

During the historical period, high C percentages and low  $\chi_{hf}$  exist between c. 1200-800 cal. BP in both sediment sequences (Fig. 9), which coincides with the climate anomaly known as the Medieval Warm Period (MWP, or Medieval Climate Anomaly- MCA), when temperatures were probably c. 0.5-0.8 °C higher than today (e.g. Briffa *et al.*, 1990). Without further influx calculations it is not possible to determine if such changes in C percentages were caused by increased organic productivity or the reduced mineral matter transport to the sedimentary basins during the MCA. However, Ojala (2001) suggested that low

concentration of mineral material reflect phases of low erosion and high rates of organic accumulation, as recorded in varved sediments in Lake Nautajärvi, Finland. The Nautajärvi sediment sequence also has a very low content of minerogenic matter between c. 1000 AD and 1200 AD, which was probably caused by attenuated spring floods.

It should be pointed out that erosion records of the historical period are difficult to interpret due to significant human impact. In fact, the onset of impact in the lake catchments in west central Sweden is not fully investigated. Further analyses are required to detect traces of human impact in the sediments of Furskogstjärnet and Mötterudstjärnet.

### *The "8200 cal. BP climate anomaly"*

According to Appendix IV, a 300-year long period of distinct colder climate prevailed in northern Sweden, centered at 7800 cal. BP, which probably corresponds to the so-called "8.2 ka cold event" recorded in the Greenland ice-cores (Grootes *et al.*, 1993). This climatic event has also been reconstructed from pollen analyses of lake sediments in southern Germany and Switzerland, where it has been dated to c. 8200 cal. BP based on  $^{14}\text{C}$  radiocarbon measurements and varve counts (Tinner & Lotter, 2001). Figure 10 shows high-field magnetic susceptibility data covering the time interval between 8500 and 6500 cal. BP obtained from four Swedish varved sediment profiles (i.e. Furskogstjärnet, Mötterudstjärnet, Sarsjön and Frängsjön).

In Furskogstjärnet and Mötterudstjärnet, an equivalent period of increased erosion, as recognised in the  $\chi_{\text{hf}}$  records from Sarsjön and Frängsjön, can be seen between c. 7850 and 7500 cal. BP (most pronounced in the Mötterudstjärnet sediment sequence). This c. 300-year long period is also represented by distinctly low C percentages (Figs. 7 and 9) and decreased values in SIRM (which indicate reduced concentrations of magnetosomes; Fig. 7). The magnetic hysteresis data (Fig. 5) indicate a larger magnetic grain size, which would have been caused by enhanced catchment erosion.

The two local data sets from west central Sweden are thus in agreement with the previous two records presented in Appendix IV. According to the interpretation carried out in Appendix IV, these data indicate a period of distinctly colder climate, with enhanced winter snowfall centered at c. 7800 cal. BP. Do these data truly reflect the same cold event as registered in the Greenland ice cores, with age discrepancies due to errors in any of the chronologies, or do they reflect a regional

Scandinavian event and possibly a time-transgressive response of the climate system?

Given that the age-error estimates associated with the four varve chronologies are approximately  $\pm 150$ –200 years, and that the uncertainty of the most up-to-date Greenland ice-core time-scale is c.  $\pm 100$  years, it can be argued that the 300-year long climatic cooling identified in the varved sediments represents the major Holocene climate event that is registered as a negative oxygen isotope ( $\delta^{18}\text{O}$ ) excursion in Greenland, and in Lake Ammersee, southern Germany (von Grafenstein *et al.*, 1998). It should be noted that the Lake Ammersee oxygen isotope excursion was initially radiocarbon dated to c. 7900 cal. BP (von Grafenstein *et al.*, 1998). However, the radiocarbon date closest to the event was considered to be erroneous (i.e. it had a high  $\delta^{13}\text{C}$  value) and the oxygen isotope data were "wiggle matched" to the Greenland  $\delta^{18}\text{O}$  record.

On the other hand, several other European reconstructions indicate that a climate shift took place around 7800 cal. BP and that, given the dating uncertainties, they can also be considered to have taken place during the "8.2 ka cold event" registered in the Greenland ice cores. For example, palaeoenvironmental reconstructions based on multi-site studies of Holocene peat deposits in northern England and western Ireland (Barber *et al.*, 2003; Hughes & Barber, 2003) and a single-site study of a Holocene peat archive in northern England (Hughes *et al.*, 2000) suggest that the most significant change during the Holocene was a transition from fen-peat to bog-peat at c. 7800 cal. BP. The age of this fen-bog transition was determined by interpolation between radiocarbon dated levels and by a series of regression models fitted to the radiocarbon dates. The transition was interpreted as a major shift to more humid climatic conditions, probably connected to the "8.2 ka cold event" (Hughes *et al.*, 2000; Barber *et al.*, 2003; Hughes & Barber, 2003). Peat stratigraphic studies in Scotland (Tipping, 1995) and lake level studies in the Jura Mountains of France (Magny, 1992) also point to a phase-shift to wetter and colder conditions around 7700 and 7800 cal. BP, respectively.

The rapid warming (within 75 years) at the end of this cold event, as recorded by e.g. increasing TPI and pollen influx values of temperate deciduous trees (Appendix IV), is interesting since the *rate of change* was probably of the same magnitude as the predicted temperature rise (1.4–5.8 °C) for the next 100 year due to global warming (<http://www.ipcc.ch>).

Besides eventual age discrepancies due to errors in the chronologies, or a possible time-transgressive

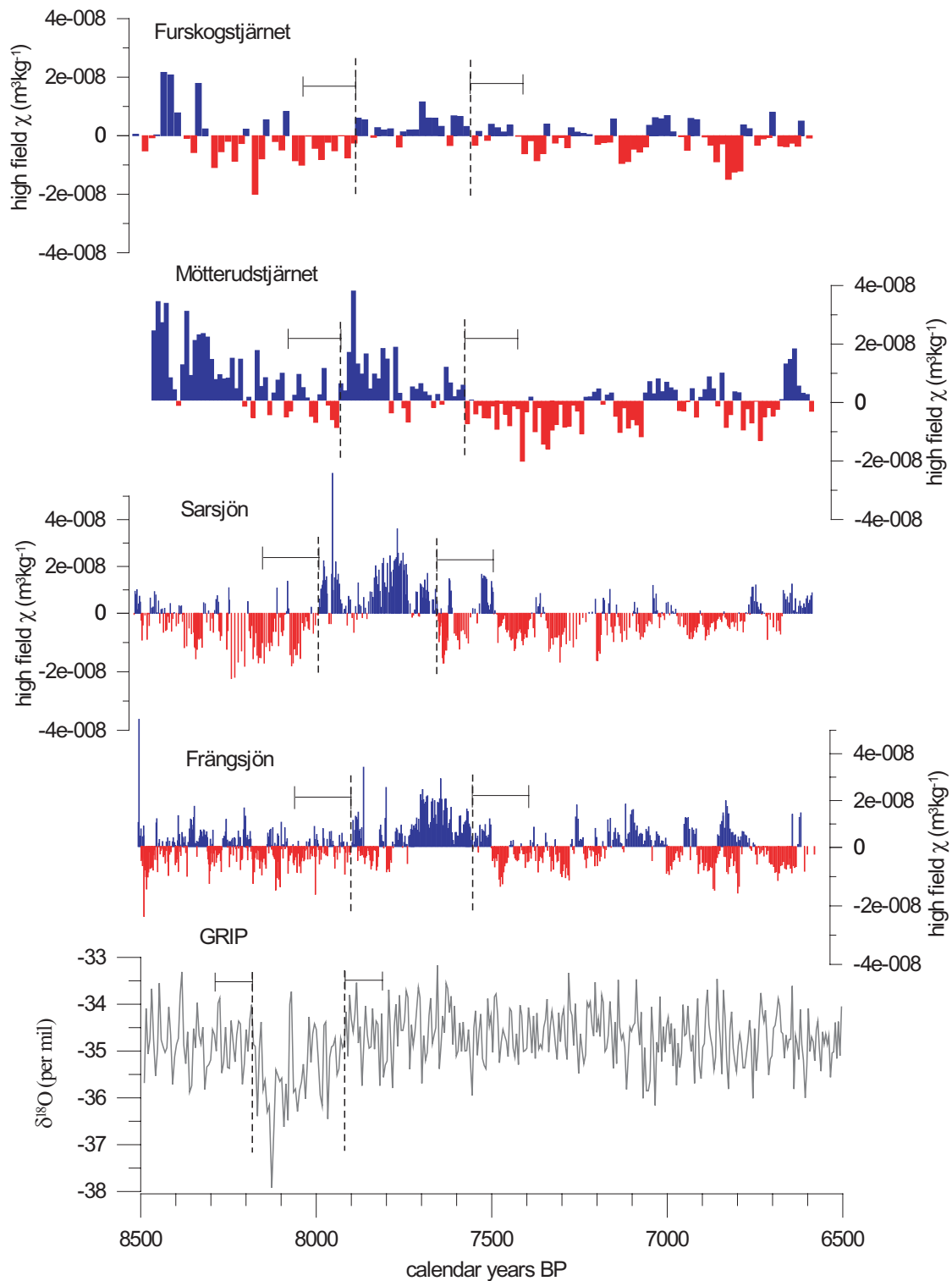


Fig. 10. Temporal variations in high-field magnetic susceptibility covering the time interval of the so-called "8.2 ka cold event" obtained from all four Swedish varved sediment profiles presented in this study (i.e. Furskogstjärnet, Mötterudstjärnet, Sarsjön, and Frängsjön). The records show that a 300-year long period of increased erosion (i.e. positive  $\chi_{hf}$  values) existed in west central and northern Sweden centered at c. 7800 cal. BP. The lower curve shows the  $\delta^{18}O$  record from the Greenland ice-core (GRIP). The error uncertainties associated with each independent calendar year time-scale are marked as error bars.

climate response, there are two possible scenarios that could explain the observed age divergence of the "8.2 ka cold event".

First, due to the deglaciation of the northern Hemisphere, it is possible that the early Holocene was unstable over a wide geographical area and that several local and uncorrelated century-scale climatic shifts existed between the start of the Holocene and 7500 cal. BP (Snowball *et al.*, in press). Second, as pointed out by Alley *et al.* (1997), some of the data sets from the Greenland ice-cores indicate that the event is part of a longer-lived anomaly from *c.* 9.0 to 7.8 ka, where the 8.2 ka deviations are more anomalous in records of local conditions (i.e. temperature and snow accumulation) than in regional wind-blown indicators (dust and sea salt), suggesting that the Greenland climate stabilized earlier relative to other regions.

It is impossible to determine leads and lags of proxy climate indicators until geological archives have been synchronised at several different stratigraphic levels at a temporal resolution better than the periodicity/frequency of the climatic events under study. This precision has not yet been achieved for spatially separated archives of the Early Holocene and the cause(s) of the so-called "8.2 ka cold event" remain(s) open to speculation. Even through the most precise geochronologies produced for the Holocene exist at northern high latitudes, particularly in northern Europe, it has not been possible to determine the trigger mechanism for this event. It can only be proposed that considerable effort should be invested in the development and validation of synchronised independent calendar year chronologies at a regional scale.

## Conclusions

- Three new varved lake sediment sequences were identified in the province of Värmland, west central Sweden. Based on knowledge of common lake morphometry properties and lake catchment characteristics, this thesis identifies geographical regions in Sweden that are likely to contain lakes with varved sediments.
- Furskogstjärnet and Mötterudstjärnet varve chronologies are the first in Fennoscandia to be validated by other independent dating methods (AMS radiocarbon measurements of terrestrial macrofossil remains, tephra isochrones and palaeomagnetic correlations). This thesis demonstrates that varved lake sediments have a wide

range of applications and that they are suitable geological archives with respect to chronological control and reliability.

- Icelandic tephra horizons were geochemically identified within 1-cm horizons, corresponding to *c.* 20 years, in the varved lake sediments in Värmland. The varve chronologies obtained from the Furskogstjärnet and Mötterudstjärnet sediment sequences were used to assign calendar years ages to Holocene tephra isochrones with a precision better than  $\pm 110$  varve years. Calculation of the number of years between individual tephra layers was performed with a precision of  $\pm 20$ -55 years.
- The palaeomagnetic secular variation curves presented in this thesis (both directions and intensity) can be used to date Holocene sedimentary sequences in Northwest and Central Europe (i.e. from the UK in the west to Belarus in the east). The accuracy of the method is limited by the errors associated with the varve chronologies (i.e.  $\pm 1$ -2%), sampling resolution (50-100 years), definition uncertainties and possible lock-in effects. Comparison between the PSV curves in this study and previously obtained records in Northwest Europe suggests that no significant westward drift of the non-dipole field occurred during the majority of the Holocene. If one accepts that the palaeomagnetic secular variations presented in Appendix IV reflect the behaviour of the geomagnetic dipole it can be concluded that the North Magnetic Pole has significantly changed its position during the Holocene. The apparent polar wander paths can be used to assess records of  $^{10}\text{Be}$  flux to the Greenland ice-sheet. Palaeointensity records show statistically significant short-term ( $10^2$ - $10^3$  yr) variations, which suggests that the century scale production of cosmogenic nuclides in the atmosphere, such as  $^{14}\text{C}$  and  $^{10}\text{Be}$ , has not exclusively been modulated by the solar magnetic field.
- The varve-based  $\chi_{\text{hf}}$  data presented in this thesis were interpreted as a winter climate proxy. The  $\chi_{\text{hf}}$  records display high-frequency variability throughout the Holocene, which corresponds to dated records of Holocene environmental changes in Northwest Europe and the North Atlantic region. A 300-year long period of distinctly colder climate conditions centred at *c.* 7800 cal. BP is recorded in four varved lake sediment sequences in Sweden. This event had a major impact

on the regional vegetation in northern Sweden where the boreal forest was seriously stressed, i.e. pollen production declined and/or trees died or did not reproduce. Considering dating uncertainties, this climate shift corresponds to a major Holocene climate anomaly, the so-called "*8.2 ka cold event*". Improved chronological control is still required to determine the causes of such events and the response of spatially separated archives of Early Holocene environmental change.

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## Svensk sammanfattning

Under kvartärtiden (den geologiska period som omfattar de senaste ca 2,6 miljoner åren) har klimatet på Jorden varierat dramatiskt. Långa perioder (ca 100 000 år) av istid med stora inlandsisar som täckte Skandinavien, Ryssland, Sibirien, Grönland och Nordamerika har periodiskt avbrutits av kortare perioder (ca 10 000 år) av varmare klimat, så kallade interglacialer. Holocen är den senaste interglaciala perioden som började för ca 11 500 år sedan och som sträcker sig fram till nutid. Under denna period immigrerade dagens flora och fauna in på tidigare nedisade områden och högre civilisationer utvecklades.

På grund av de ökande utsläppen av växthusgaser, under 1900-talets andra hälft, har klimatfrågorna blivit allt viktigare. Har vi en ökande växthuseffekt eller är det en naturlig klimatförändring vi ser? För att kunna svara på den frågan, och för att kunna göra tillförlitliga prognoser för framtiden måste vi veta hur klimatet varierar naturligt sett ur ett långt tidsperspektiv, dvs under hela vår nuvarande värmeperiod.

Sjöar och dess dräneringsområden reagerar fysiskt, biologiskt och kemiskt på förändringar i den yttre miljön och dessa reaktioner kan registreras i sjösediment. Sjösediment är därmed utmärkta geologiska arkiv från vilka man kan rekonstruera klimat- och miljöförändringar, mycket längre tillbaka i tiden än vad som är möjligt genom historiska källor (ca 500 år tillbaka i tiden) eller instrumentala observationer (ca 100 år tillbaka i tiden). Fundamentalt i studier av dessa naturliga arkiv är att kunna tidsbetämma (datera) förändringar med hög precision och noggrannhet. Utan en robust kronologi är det omöjligt att förstå de naturliga och kulturella förändringar som ägt rum.

Att dektektera snabba och kortvariga klimatvariationer, så som den nordatlantiska oscillationen (NAO) och solfläckarnas eventuella påverkan på klimatet, vilka har en cyklisitet på 7 respektive 11 år, har vidare gjort det nödvändigt att använda geologiska arkiv med en mycket hög tidsupplösning, allra helst en årlig sådan. Det är också betydelsefullt att studera hur korttidsvariationer ( $10^2$  år) i Jordens magnetfält har påverkat inflödet av kosmisk strålning till atmosfären och därmed även produktionen av kosmiska nuklider, så som  $^{14}\text{C}$  och  $^{10}\text{Be}$ , vilka har flertalet geofysiska applikationer bl a inom datering, studier av grundämnescykler och identifiering av klimatvariationer. Att förbättra den kronologiska kontrollen har därför blivit en viktig

forskningsuppgift i studier av Holocena klimat- och miljöförändringar.

Flertalet undersökningar av sjösediment baserar sina tids/djup-modeller på kol-14-dateringar av organiskt material. Tids/djup-modeller baserade på denna metod är ofta begränsade till en tidsupplösning på mer än hundra år och innehåller ofta flera svårbestämbara felkällor.

I min avhandling har jag studerat årslaminerade (eller varviga) sjösediment och deras potential som tidsskalor i studier av Holocen. Varviga sjösediment består av säsongsmässigt (vår, sommar, höst och vinter) avsatta lager (eller laminae) av växlande organiskt- och oorganiskt material där tre till fyra laminae (beroende på om ett höstlamina deponerats eller ej) tillsammans utgör sedimentationen under ett år (eller ett varv). Varven kan liknas vid trädringar i ett träd där en sommarring och en vinterring representerar tillväxten under ett år. Genom att räkna de individuella varven kan man skapa en kontinuerlig kronologi, sk varvkronologi, med hög precision och tidsupplösning.

Den geografiska utbredningen av varviga sjösediment i Sverige är relativt okänd. Tidigare studier har bara utförts på tre kända varviga sedimentsekvenser i Sverige (Sarsjön, Frängsjön och Kassjön), vilka alla är belägna i norra Sverige i utkanten av Umeå. En målsättning med avhandlingen har därför varit att finna fler svenska sjöar med varviga sjösediment.

Genom att följa en urvalsprocess som presenteras i avhandlingen, där bl a sjöars limnologi, morfologi och dräneringsområden bedömts, så har tre nya varviga sedimentprofiler identifierats i Värmland (Furskogstjärnet, Mötterudstjärnet och Kälksjön). Denna undersökning presenterar även andra geografiska områden med hög potential att inrymma sjösediment av denna typ och ett schema för att hitta sådana sedimentprofiler i Sverige.

I min avhandling har jag upprättat varvkronologier för två av lokalerna i Värmland. Resultatet från varvräkningen visar att Furskogstjärnet och Mötterudstjärnet sedimentsekvenser är  $9555 \pm 141$  respektive  $9282 \pm 172$  kalenderår gamla, vilket gör dem till de äldsta kända geologiska arkiv med en årlig upplösning i Sverige.

Vulkaniska asklager (tefralager) är utmärkta isokroner (likåldriga nivåer) som kan användas för att korrelera olika geologiska arkiv och att datera sedimentsekvenser. Under Holocen har vulkanutbrott på Island släppt ut och spridit tefrapartiklar över stora områden av Europa. Tre isländska tefralager, nämligen Hekla-4, Kebister och Hekla-3, har geokemiskt identifierats inom ett 1cm

intervall, vilker motsvarar ca 20 år, i de två varviga sedimentsekvenserna från Värmland. Baserat på varvkronologierna har kalenderår (varvår) angivits på dessa ovärderliga isokroner, med en precision bättre än ca  $\pm 110$  år.

Moderna observationer av Jordens magnetfält visar att den magnetiska nordpolen har förflyttat sig 1100 km sedan år 1850. Sedan 1970 har hastigheten accelererat och rör sig nu med en fart av ca 40 km per år. Likaså har mätningar visat att magnetfältets styrka minskat kontinuerligt de senaste 150 åren. Detaljerade geomagnetiska studier av de varviga sjösedimenten visar att dagens situation inte är unik, utan att den magnetiska nordpolen ständigt har ändrat position under Holocen och att Jordens magnetfält varierat i styrka.

Om variationer i Jordens magnetfält presenteras på en tidsskala kan de användas till att åldersbestämma geologiska arkiv. Geomagnetiska variationer presenterade i avhandlingen visar liknande svängningar i jämförelse med andra studier utförda i Storbritannien, Finland och Vitryssland, vilket demonstrerar att fluktuationerna är regionala och att de därmed kan användas till att datera Holocena sedimentarkiv i nordvästra och centrala Europa.

Jordens magnetfält skyddar oss från solvinden och annan kosmisk strålning. I interaktionen mellan Jordens magnetosfär och den kosmiska strålningen produceras kosmiska nuklider, så som  $^{14}\text{C}$  och  $^{10}\text{Be}$ . Magnetiska intensitetsmätningar av sedimentsekvenserna visar att Jordens magnetfält under Holocen varierat med en relativ hög frekvens (ca  $10^2$ - $10^3$  år), vilket tidigare inte var känt. Dessa korttidsfluktuationer i jordens magnetfält har påverkat produktionen av kosmiska nuklider i atmosfären, vilket innebär att växlingar av halten  $^{14}\text{C}$  och  $^{10}\text{Be}$  i geologiska arkiv inte enbart kan tillskrivas variationer i solvinden. Fortsatta geomagnetiska studier av geologiska arkiv med hög tidsupplösning kommer att öka vår kunskap om potentiella länkar mellan solfläckor och klimatet.

Baserat på sedimentprofilerna från två av de tidigare kända varviga lokalerna i norra Sverige (Sarsjön och Frängsjön) studerades den regionala klimatutvecklingen under tidig Holocen. Syreisotopundersökningar av iskärnor på Grönland har visat att under denna period inträffade en snabb klimatförsämring (ca 6-8 °C kallare över Grönland) centrerad runt ca 8200 kalenderår före nutid. Avhandlingen visar att den regionala vegetationen i norra Sverige reagerade snabbt (inom 75 år) på denna klimatförsämring och att skogen utsattes för allvarlig stress i form av att pollenproduktionen avtog och att trädtheten minskade. I denna studie daterades händelsen till 7800 kalenderår före nutid.

## Slutsatser

- Tre nya varviga sjösedimentsekvenser har identifierats i Värmland. Två av dessa är hittills de äldsta kända geologiska arkiv med en årlig upplösning i Sverige.
- Furskogstjärnet och Mötterudstjärnet varvkronologier är de första i Skandinavien att bli värderade av flera oberoende dateringsmetoder (kol-14-datering, tefrakronologi och geomagnetiska korrelationer). Avhandlingen visar att varviga sjösediment kan erbjuda en rad tillämpningar i studier av Holocen och att de är utmärkta geologiska arkiv med hänseende till kronologisk kontroll och tillförlitlighet.
- Tre isländska tefralager har geokemiskt identifierats inom ett 1cm intervall, vilket motsvarar ca 20 år, i två varviga lokaler i Värmland. Baserat på kalenderår-tidsskalorna från Furskogstjärnet och Mötterudstjärnet har dessa daterats med en precision bättre än  $\pm 110$  år.
- De geomagnetiska kurvorna presenterade i avhandlingen kan användas till att datera Holocena sedimentarkiv i nordvästra och centrala Europa. Resultat visar att den magnetiska nordpolen har förflyttat sig betydande avstånd under de senaste ca 9000 åren. Denna studie presenterar statsiktiskt säkerställda korttidsvariationer i Jordens magnetfält, vilket visar att högfrekventa fluktuationer i produktionen av kosmiska nuklider ( $^{14}\text{C}$  och  $^{10}\text{Be}$ ) i atmosfären inte enbart kan tillskrivas förändringar i solens aktivitet.
- En 300-år lång klimatförsämring, centrerad runt 7800 kalender år tillbaka i tiden, är registrerad i fyra årslaminerade sedimentsekvenser i Sverige. Denna snabba klimatförändring hade en stor inverkan på den regionala vegetationen i Västerbotten, d v s skogen utsattes för allvarlig stress. Denna studie bidrar till ökad kunskap om den komplexa klimatutvecklingen i norra hemisfären under tidig Holocen.

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