Holocene sedimentary history of annual laminations of Lake Korttajärvi,central Finland

Mia Tiljander

Academic dissertation

To be presented with permission of the Faculty of Science
of the University of Helsinki, for public criticism
in the Lecture Room E204 of Physicum, Kumpula,
on October 27th, 2005, at 12 o'clock

Publications of the Department of Geology D5
Helsinki 2005

PhD-thesis No. 185 of the Department of Geology, University of Helsinki

Supervised by:
Professor Matti Saarnisto
Geological Survey of Finland
Espoo, Finland

Professor Juha Karhu
Department of Geology
University of Helsinki

Reviewed by:
Doctor Atko Heinsalu
Institute of Geology
Tallinn University of Technology, Estonia

Docent Aarno Kotilainen
Geological Survey of Finland
Espoo, Finland

Opponent:
Doctor Achim Brauer
GeoForschungsZentrum Potsdam
Germany

Cover: Lake Korttajärvi in summer 2004

ISSN 1795-3499
ISBN 952-10-2158-6 (paperback)
ISBN 952-10-2159-4 (PDF)
http://ethesis.helsinki.fi/

Helsinki 2005
Yliopistopaino

Mia Tiljander: Holocene sedimentary history of annual laminations of Lake Korttajärvi, central Finland, University of Helsinki, 2005, 29 pp., University of Helsinki, Publications of the Department of Geology D5, ISSN 1795-3499, ISBN 952-10-2158-6, ISBN 952-10-2159-4 (pdf-version).

Abstract

An 11.6 m long sediment sequence from Lake Korttajärvi was studied to establish a high-resolution chronology, to interpret physical and mineral magnetic properties, to explain Holocene environmental changes and to test if a climate signal is present in the stable isotope records from lake organic matter. The sediment sequence of Lake Korttajärvi is annually laminated (varved). A varve is composed of lamina sets that are deposited during the yearly sedimentation cycle. In the case of Lake Korttajärvi, varves are clastic-biogenic and have a graded bedded structure. The varve year begins when a light mineral lamina deposits in the spring. The mineral lamina becomes gradually mixed with organic matter in summer and autumn. At the end of the varve year (winter) black organic matter deposits under the ice cover. Variations in the basic varve structure exist. The varved sediment sequence covers almost the whole Holocene. The first varves were deposited 9590 years ago when the lake basin isolated from the Ancylus Lake of the Baltic basin. This first independent lake period lasted 430 years. After that, the lake became a part of the larger lake complex of Ancient Lake Päijänne for over 2700 years. The varve formation continued during the large lake period, although the varve structure was more complicated. Lake Korttajärvi became an independent lake basin for the second time 6400 years ago due to the formation of a new outlet and the lowering of the water level of the Ancient Lake Päijänne. The formation of annual lamina has continued to the present day.

The chronology for Lake Korttajärvi was established by counting varves. The sediment sub-samples were embedded with epoxy, X-rayed and counted with a semi-automatic computer program developed for tree-ring analyses. The digital technique allows high-resolution image analysis. Digital varve counting was used to obtain an exact thickness and number of varves, relative X-ray density and proxies that describe the amount of mineral and organic matter. Comparing this high-resolution data to other physical proxies enabled the discovery of changes in the sedimentation process. The accuracy of the dating was confirmed by comparing paleomagnetic measurements of sediment cores from Lake Korttajärvi to two independently dated long varved sediment sequences in central Finland. Mineral magnetism was used to identify deposited magnetic mineral matter.

Periodicity is typical for the sedimentation of the recent lake phase. Mineral- and organic-matter-rich periods alternate in time periods from decades to centuries. The clearest climate-dependent time period is the Medieval Warm Period, AD 980-1250. The sedimentation rate was low and the deposited material was highly organic. Other organic-matter-rich periods existed in 1846-1704 BC, 1688-1486 BC and AD 140-220. Evidence of the most recent cooling period, the Little Ice Age is not clear in the Lake Korttajärvi record, but two periods with increased mineral matter deposition exist in AD 1580-1630 and AD

1650-1710. The natural sedimentation is disturbed since cultivation increased in the area after the early 18th century. Other periods rich in mineral matter indicate severe climate conditions: 3061-3037 BC, 1877-1848 BC and 907-875 BC. The 900 BC-event happened approximately concomitant with the abrupt climate cooling in western Europe. The climate in Scandinavia is highly dependent on the North Atlantic Oscillation (NAO). The air pressure difference between Iceland and the Azores affects the direction of the westerlies and therefore has an influence on the weather in northern Europe.

The high resolution chronology was utilized in carbon and hydrogen isotope studies. Analyses were made from the lake organic matter which is mainly formed of autochthonous organic matter mixed with a minor component of terrestrial plant debris. $\delta^{13}C$ and δD values both show an increasing trend since the early Holocene. $\delta^{13}C$ values reflect the isotopic composition of dissolved inorganic carbon (DIC), which is the source of carbon for aquatic plants, and fractionation effects associated with carbon fixation. The long-term trend of increasing $\delta^{13}C$ values during the Holocene is probably related to a decreasing content of DIC, leading to lower discrimination against ^{13}C in algal carbon fixation. δD values are dependent on local precipitation, evaporation, temperature and hydrological conditions of the lake. The rise of the early Holocene temperature is reflected in increasing δD values by + 9‰, and a local positive shift in δD by + 9‰ in AD 1050-1150 indicate a notable temperature rise during the Medieval Warm Period.

Contents

List of publications

This study is based on the following four papers.

I. Tiljander, M., Ojala, A., Saarinen, T. and Snowball, I. 2002. Documentation of the physical properties of annually laminated (varved) sediments at a sub-annual to decadal resolution for environmental interpretation. *Quaternary International* 88, 5-12.

II. Ojala, A.E.K. and Tiljander, M. 2003. Testing the fidelity of sediment chronology : comparison of varve and paleomagnetic results from Holocene lake sediments from central Finland. *Quaternary Science Reviews* 22, 1787-1803.

III. Tiljander, M., Saarnisto, M., Ojala, A.E.K. and Saarinen, T. 2003. A 3000-year palaeoenvironmental record from annually laminated sediment of Lake Korttajärvi, central Finland. *Boreas* 32 (4), 566-577.

IV. Tiljander, M., Karhu, J. and Kauppila, T. Holocene records of carbon and hydrogen isotope ratios of organic matter in annually laminated sediments of Lake Korttajärvi, central Finland. Submitted to *Journal of Paleolimnology* .

M. Tiljander and A.E.K. Ojala shared equally the writing of Paper I. The interpretation presented in Paper I is based on data produced by M. Tiljander and T. Saarinen. I. Snowball produced the hysteresis data. A.E.K. Ojala wrote most of the text of Paper II and produced data from two lakes. M. Tiljander was responsible for the data of Lake Korttajärvi and background research. Both authors were responsible for data combination and figures. M. Tiljander was responsible for the data and writing of Paper III in guidance of M. Saarnisto. A.E.K. Ojala and T. Saarinen involved in method development. M. Tiljander and J. Karhu participated in planning and writing of Paper IV. M. Tiljander produced the isotope data, and T. Kauppila was responsible for the diatom reconstructions.

1 Introduction

Annually laminated (varved) lake sediments offer a great opportunity for a high-resolution analysis in paleoenvironmental studies. Varved lakes provide the most accurate dated sediment samples for further paleolimnological studies. Accurate chronology gives exactness to vegetation history, land use and human impact studies in a given area. Also, studies of lakes natural evolution become more accurate when varved sediments are used. Long varved lake sediment sequences are needed for further research because precisely dated lake sediment stratigraphies are fundamental and necessary for the interpretation of paleoclimatic records and their correlation (Brauer and Negendank 2004). Annually laminated lakes have been recorded especially in North America, Fennoscandia, Central Europe, East Africa and Japan (O'Sullivan 1983; Fukusawa 1999).

Laminations are formed by a seasonal rhythm of sedimentation composed of horizontally bedded layers which differ in composition and texture, appearing in two or more layers (Saarnisto 1986; Ojala 2001). The structure of varves is preserved in certain basins due to several factors: 1) sheltered, even and deep basin (> 8 m), 2) at least one inlet and outlet, 3) reasonably high discharge from the drainage area, 4) lack of post-depositional disturbance. Varved lakes are often temperature or chemically stratified and many have protracted seasonal anoxia in the hypolimnion and therefore little bioturbation (Saarnisto 1986). Oxygen deficiency can be caused naturally or by cultural eutrophication leading to the formation of black sulphide layers (Salonen et al. 1990). In some Finnish lakes, after the beginning of intensive cereal cultivation, soaking of fibre plants (hemp, flax) increased markedly and many small lakes were eutrophicated and even polluted, leading to permanent anoxia in deep lake basins (Huttunen and Meriläinen 1979).

In varved sediments the seasonal or annual cycles of sedimentation are usually observed as colour changes. In biogenic varves a white diatom-rich layer is formed in spring and summer followed by gradually darker more organic horizons having a black humus layer at the top of the varve (Saarnisto 1986). The narrow black bands composed of organic matter can also contain chrysophyceaen cysts (Battarbee 1981). In pure organic varves, the internal varve structure is often not clearly visible to the naked eye (e.g. Tolonen 1980). In clastic-organic varves, the white (light) layer is composed of fine-grained mineral matter and is deposited in early spring during the relatively short snow melt period, when inflowing streams are transporting in suspension clay, silt and fine sand particles from the catchment into the lake basin (Renberg 1981a; Ojala et al. 2000). The mineral layer is often graded bedded. During summer, autochthonous organic production increases and organic matter deposits on the lake bottom. The thickness of the organic matter layer varies depending on the length of the productive season. The finest, almost black, organic matter settles during winter, under the ice cover. Sometimes, heavy rain or storms can cause a thin separate mineral layer in the varve. In addition to biogenic and clastic-organic annual laminations, calcite bearing varves (e.g. Kelts and Hsü 1978) and pure clastic varves (e.g. Sturm 1979) also exist. Late-glacial varves are good examples of the last category.

Kukkonen and Tynni (1970) described diatom-rich varves from the sediments of Lake Pyhäjärvi. This was the first study on Holocene varved lake sediment in Finland. The active study period of Holocene varved lake sediments in Finland started in 1972, when Matti Saarnisto brought here the freeze-coring technique, introduced by Shapiro (1958), and further developed by H. E. Wright Jr. in the late 1960's (Wright 1980; Saarnisto 1986). The method has been successfully used in paleolimnological research ever since (e.g. Renberg 1981b). The coring technique has been developed further, but the Russian peat corer is still a useful basic corer. The Livingstone type piston corer with aluminium rods is practical in the field and useful for 2-3 m long cores. The Kullenberg corer, and especially the modified PP-corer (Putkinen and Saarelainen 1998), which was used in this study, is practical for long, continuous sediment cores, up to 10 m.

Applying improved searching methods, annually laminated lake sediments turned out to be more common than was believed (Saarnisto 1985). In the 1970-80's several Finnish lakes were known to be varved (e.g. Kukkonen and Tynni 1970; Saarnisto et al. 1977; Simola 1977; Tolonen 1978; Appleby et al. 1979; Huttunen and Meriläinen 1979; Huttunen 1980; Tolonen 1980; Simola and Lodenius 1982; Saarnisto 1985, 1986). Later, several lakes with varved sediment were used for paleolimnological investigation (e.g. Grönlund 1995; Saarinen 1998; Pitkänen and Huttunen 1999; Ojala 2001; Kauppila 2002) and as a result of systematic searching, new sites with varved sediments were identified (Ojala et al. 2000).

This thesis is composed of four papers: Paper I, methodology for documenting and counting varves, Paper II, testing the accuracy of the chronology, Paper III, presenting a paleoenvironmental study of the last 3000 years and Paper IV, documenting the Holocene evolution of carbon and hydrogen isotope ratios in organic matter. In addition, the varve counts of the present author have been utilized in describing image analysis techniques (Saarinen and Petterson 2001), in a diatom-based past lake water quality study (Kauppila 2002), in paleoecological pollen and diatom investigations (Grönlund and Vuorela 2000; Eriksson 2002) and in a shoreline displacement study of the Baltic basin (Ojala et al. 2005).

2 Study site

Lake Korttajärvi is located in central Finland (62˚20’N, 25˚41’E, 94.4 m asl.) about 10 km north from the town of Jyväskylä (Figure 1). Lake Korttajärvi is the central lake of the Tourujoki watercourse. Three small rivers flow into it from the southwest, north and northeast. This two-basin lake has only one outlet, to the south from the northern basin. Waters enter through lakes Alvajärvi and Palokkajärvi, finally reaching Lake Päijänne, one of the biggest lakes in Finland. The mean annual discharge of Lake Korttajärvi is 2.1 m^3 s^{-1} with a 0.3 month residence time (Palomäki 1996). Lake Korttajärvi is a temperature stratified dimictic lake with a full overturn in spring and autumn. It has an ice-cover during the five winter months. The area of the lake is 0.45 km^2 and the maximum depth is 12.5 m. The lake was quite badly polluted by waste waters in the 20th century, but since the loading of polluted waters stopped in the late 1970’s, the quality of the water has improved.

The annual laminations of Lake Korttajärvi were discovered in 1997 by Timo Saarinen and the lake was cored, reaching over 7 m laminated sediment. During subsequent years several parallel cores were taken (Table 1). The most intensive fieldwork season was winter 1999. Because of the high deposition rate (~ 1.2 mm year^{-1}), the uniform laminated sediment sequence is long, causing technical difficulties for the coring. In 2001, the beginning of the varve formation was reached at the depth of 11.6 m. All the sediment cores for this study were taken from the southern basin, although test samples have shown that the sediments in the northern basin are also laminated.

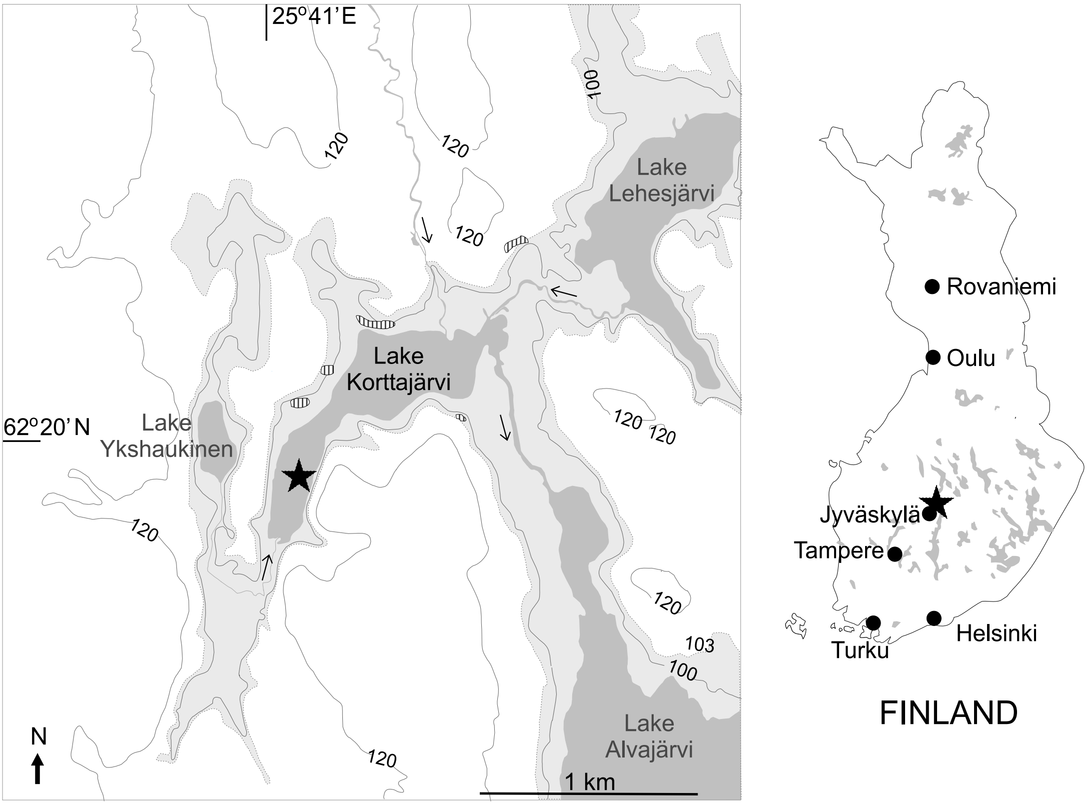

Figure 1. Present Lake Korttajärvi and the adjacent lake and river systems (dark grey) and the area of the Ancient Lake Päijänne (light grey). Stone Age sites are shown as striped areas. The black star marks the coring site. The solid black lines indicate elevations in meters above sea level.

The lake basin has twice been an independent small lake. Lake Korttajärvi basin isolated from the Anculys Lake of the Baltic basin 9590 varve years ago, when the varve formation began. For the next 430 years, Lake Korttajärvi was an independent lake. The next 2760 years Lake Korttajärvi was a part of the Ancient Lake Päijänne and 6400 varve years ago Lake Korttajärvi isolated and the present lake basin was formed. This interpretation is based on this study and studies made by Saarnisto (1971 a, b, pers. comm. 2001) and Ojala et al. (2005).

Lake Korttajärvi is also an interesting site archeologically, since Stone Age quartz tools were found from five places near the Lake Korttajärvi shoreline (T. Sepänmaa, pers. comm. 1998) (Figure 1).

Laminations in the sediment of Lake Korttajärvi studied by backscattered electron microscope images (BSEI-images) show a graded bedded structure of the mineral grains within a varve indicating that the structure originated from variations in the rate of sedimentation. The annual nature was determined by comparing photographs taken from the freeze-core samples (coring years 1997 and 1999, see Figure 3 in Paper III). The varves are clastic-organic, with a basic structure consisting of 1) light spring laminae consisting of mineral matter, 2) darker summer and autumn laminae composed of mineral matter and organic matter and 3) nearly black winter lamina made of organic matter.

Table 1. Analyses made from the cores.

Core	Coring tool	Depth (cm)	Analyses
A97	PP-corer	0-727	X, D, P, S, L, PA
JKO99	freeze corer	0-40	**V**, Photo, D, PH, CH
99a	piston corer	0-178	E, S
99b	piston corer	0-170	$\delta^{13}C$, δD, S
99c	piston corer	0-170	P, S
99d	piston corer	0-180	L, S
99e	piston corer	0-179	V, E, X, P, S, M, H
99h	piston corer	90-220	**V**, E, X, S
99hu1	piston corer	0-250	D, PH, CH, S
HU99	PP-corer	0-895	**V**, E, P*, $\delta^{13}C$, δD, C_{LECO},N_{LECO}, S
A01	PP-corer	0-873	V, E, X, D*, S, M, PA
B01	PP-corer	643-1160	**V**, E, X, D*, P, L, $\delta^{13}C$, δD, C_{LECO},N_{LECO}, S, M, PA

* only individual samples

V=varve counts

(The chronology is based on the cores shown by **V**)

E=epoxy blocks

X=X-rays

Photo=photographs

D=diatoms

P=pollen

PH=sediment phosphorus fractionations

CH=geochemistry

L=loss on ignition

$\delta^{13}C$=carbon isotope ratio

δD=deuterium isotope ratio

C_{LECO}=total carbon

N_{LECO}=total nitrogen

S=susceptibility

M=mineral magnetism

PA=paleomagnetism

H=hysteresis

3. Methods

3.1 Sampling

The first samples were cored in winter 1997 with a PP-corer. The whole 7.27 m long core was laminated. Further sampling was done in January 1999 when several parallel cores (max 2.5 m) were taken (Table 1). In April 1999, almost 9 m of the sediment was cored, but the lowermost level of the varve formation was not reached. Finally, in 2001, the homogeneous clay under the varved sediments was reached at the depth of 11.6 m. The coring was carried out in two separate cores with a 2.3 m overlap. In each sampling, cores were cut to 2-2.5 m long pieces for transportation. Cores were not allowed to freeze and they were stored in a cold room at 4°C. The freeze-corer was used twice in 1997 and 1999 to study the undisturbed surface of the sediment (Figure 3 in Paper III).

3.2 Sub-sampling

In the laboratory, the susceptibility was first measured from the unopened cores with a Bartington equipment sensor MS2C at a 2 cm resolution. Then the cores were divided into halves and the sediment surface was cleaned with a glass slide. The sediment surface was covered by a plastic film and the susceptibility was measured from the sediment surface at a 5 mm resolution (sensor MS2E1). Cores from which different analyses were performed during the study are listed in Table 1.

Overlapping sub-samples for varve counting were taken using aluminium trays (1x1x12cm). Samples were placed in plastic vessels holding 5 to 6 samples at a time. A modified water-acetone-epoxy exchange method was used. Sediment pore water was removed with acetone and replaced by epoxy resin (see Paper I). Thereafter the epoxy resin treated samples were dried in an oven. The extra epoxy was removed with a saw and exactly 2 mm thick slices were separated (first sawed and then polished with sandpaper) for X-ray images and further for varve counting.

A half of each core was used for paleomagnetic sampling. Polystyrene cubes (7 cm^3) were pressed perpendicularly to laminae into the levelled and trimmed sediment surface at a 2.5-3 cm resolution leaving 0.5-1 cm sediment in between. Cores were not oriented to the geographical north, leaving variation in declination to be expressed in relative terms. Samples for hysteresis analysis were taken from the 2 mm thick epoxy blocks (see Paper I).

Pollen, diatoms, and loss-on-ignition (LOI) as well as phosphorus and other geochemical parameters were analyzed in independent studies (Grönlund and Vuorela 2000; Eriksson 2002; Kauppila 2002) and the sampling of those studies are therefore not discussed here.

Samples for isotopic measurements ($\delta^{13}C$, δD) and determination of total C and N were taken form the same core from which the blocks for the varve counting were taken. A sample covering 10 years was taken after every 500 years (22 samples). More detailed sampling, with an interval of 50 to 100 years, was performed to cover the time period AD 500-2000 (22 samples).

3.3 Varve chronology

The varve counting was done from 12 cm long epoxy blocks. X-ray radiographs were taken from the 2 mm thick slices sawn from the epoxy blocks (equipment: Philips constant potential MG 102L). Aluminium and glass calibration wedges, to be used in calibration of separate X-ray films, were placed beside the samples. X-ray negatives were scanned to produce grey-scale images for a semi-automatic varve counting program (DendroScan), which was originally developed for tree-ring studies. Every varve boundary was confirmed from the polished epoxy blocks under a binocular microscope. With this method the varve counting was stored in digital form. The procedure is described in more detail in Paper I.

Creating a reliable chronology from sediment sequences, when the total extension exceeds 10 m (which is the maximum length of a core by the corer), requires analyses from parallel cores. The main chronology was determined from a freeze-core (JKO99) and from two longer cores (HU99 and B01, AD 1985-4586 BC and 4587-7590 BC respectively). Parallel cores were used to count varves from the cut-point gaps and disturbed parts of the main cores.

When the piston corer is used, the top of the sediment is often missed or disturbed. The uppermost varve of the core HU99 was determinated by comparing the photo of the freeze-core to the X-ray image of the uppermost epoxy embedded sediment block. The last analyzed year of the chronology is the uppermost varve of core HU99, AD 1985.

The whole chronology was established similarly, fitting the following block to the previous one. The first annual lamination (varve) of the Korttajärvi sediment sequence was deposited in 7590 BC (i.e. 9590 years before year 2000). The chronology created by counting the varves was supported by paleomagnetic studies (Paper II).

3.4. Documenting varves

Image analysis techniques were used for varve counting (as described in 3.3.). The varve counting program also produced laminae thickness data and relative X-ray density data. The output consists of percentage grey-scale values that were translated into corresponding density grey-values (0-255). When the X-ray negatives were scanned with a resolution of 1000 dpi, a 0.5 mm thick layer contained approximately 20 data points. The method is described in more detail in Paper I. The relative annual X-ray density value (average of each varve), light sum (LS=the sum of the grey-values) as well as dark sum (DS=255*number of counts - LS) are illustrative in studying sedimentation changes.

The scanning electron microscope (SEM; JEOL-5900) was used in internal varve studies (Paper I). The size of the mineral grains and the deposition structure were determinated. The identification of the mineralogy of individual grains is possible, but extremely time consuming.

3.5. Mineral- and paleomagnetic measurements

Mineral magnetic properties indicate the nature of the accumulating material, especially the concentration and grain size variation of the magnetic mineral material. Comparison of different parameters provides additional information on the sediment stratigraphy.

Susceptibility is the most commonly used magnetic parameter, because the measurement is fast and easy and can be carried out without disturbing the sediment. Susceptibility is particularly useful in comparing parallel cores. Commonly, highly minerogenic lake sediments have reasonably high susceptibility values, the quality of magnetic minerals also being dependent on the local drainage area and bedrock. In this study, susceptibility was measured from all cores (except cores A97 and JKO99). First from unopened cores with a Bartington equipment sensor MS2C and immediately after opening the core with sensor MS2E1 (see Chapter 3.2.). Susceptibility was also measured from polystyrene cubes with a KLY-2 instrument (Geofizika Brno).

The intensity of natural remanent magnetization (NRM), declination and inclination were measured by tri-axial squid magnetometer (2G Enterprise SRM-755R). The samples were then cleaned using alternating field (AF) demagnetization, by submitting samples to a 20 mT AF field. The AF demagnetization removes less stable components of the remanent magnetization leaving the more stable components (Thompson and Oldfield 1986). While analyzing NRM remanence, every 20th sample was exposed to a stepwise AF field to test the magnetic stability and strength of the remanence (Saarinen 1996).

In an anhysteric remanent magnetization (ARM) the remanence was produced by subjecting the sample to a strong (100 mT) alternating field, which was smoothly decreased to zero in the presence of a weak steady field (0.05 mT). ARM intensity is particularly sensitive to fine magnetic grain sizes (Snowball 1995).

The same samples which were used for paleomagnetic analyses were also used for mineral magnetic analyses. Measurements for isothermal remanent magnetization (IRM) and saturation isothermal remanent magnetization (SIRM) were analyzed in order to study the carrier of the magnetism. The same samples submitted for NRM demagnetization were also submitted for stepwise IRM acquisition. The remainder of the samples were directly measured in a 1 T field to get the

SIRM value. Later, all samples were exposed to reverse 100 mT fields for IRM. S-ratio, calculated by dividing a backfield IRM value by the SIRM value, was used to study the nature of magnetic minerals. Low values (near -0.8) indicate soft magnetic minerals, like magnetite or greigite, whereas high values (>0) indicate hard magnetic minerals, like hematite or pyrrhotite (Snowball 1995).

3.6. Stable isotopes

Samples covering 10 years of sedimentation were first washed in 1 M HCl at 60 °C for 2 hours to remove all carbonate minerals. A 0.5 g aliquot was dried and C and N concentrations were analyzed by either the LECO CHN-600 analyzer or the VARIO MAX CN Elemental analyzer. The HCl-washed sample was further used for bulk analysis of the isotopic composition of carbon. To study the pure organic matter of the sediment, kerogen was extracted from the HCl-washed sediment using HCl-HF dissolution. 2 mg of kerogen was used for analysis of the isotopic composition of carbon and hydrogen. The precise method is described in Paper IV. Isotope compositions were determined using a Finnigan MAT 251 mass spectrometer.

4. Results

4.1. Review of papers

4.1.1. Paper I

The basic aim of studying annually laminated lake sediments is to identify environmental changes that happened in the lake and its drainage basin at high-resolution. This paper presents new developments in varve analysis techniques for documentation of varved sediments and describes a method to digitize physical properties of annually laminated lake sediments. Also, the modified water-acetone-epoxy exchange method was elaborated. Microstratigraphical investigations give detailed information about internal varve composition and structure. The paper also includes an example of comparison between physical and mineral magnetic measurements in lake sediment studies.

Only well preserved sediment sequences provide continuous and reliable records for accurate chronologies. Sampling began from carefully defined coring sites that were selected on the basis of several factors such as lake morphometry, watershed topography, influx and outflow. Parallel cores were needed to replicate varve analysis and to cover the cut-points of the long cores. 2.5-3 m was a maximum practical length for core transportation.

Sub-sampling was done in the laboratory. Susceptibility was measured from the cores before sampling. 12 cm long, 1 cm thick and wide sub-samples with at least 1 cm overlap were taken using aluminium trays, which were pressed into the sediment and used to transport sub-samples into the plastic vessels for the water-acetone-epoxy exchange to better preserve the internal structure of the sub-samples. Sediment pore water was removed with acetone and replaced by epoxy resin. The embedding was done in a desiccator under low pressure. After the epoxy resin treatment, samples were dried in an oven. The extra epoxy was sawed away and exactly 2 mm thick slices were separated (first sawed and then polished with sandpaper) for X-raying.

Image analysis techniques were used for varve counting, laminae thickness measurements and characterizing detailed varve structure. The X-ray negatives were scanned to produce bitmap computer images (tiff) containing 1-255 grey-scale values to be used in the DendroScan program. The grey-value 0 (black) was used to define the path by drawing a line perpendicular to the varve structures and the program identified the grey-values along the path and recorded the varve boundaries. A 0.5 mm thick layer contained approximately 20 data points. The program output consisted of percentage grey-scale values that were translated into corresponding density grey-values. In varve counting, the final control was made by the author, by confirming the varve structure comparing the polished sample under the microscope and the picture from the computer screen. A major advantage of using this time-consuming computer program is the ability to store the data in digital form: varve/laminae thickness, X-ray density and the varve count. Two illustrative parameters, light sum and dark sum, were easily calculated from the grey-value data. According to the interpretation, the LS indicates the strength of the spring flood (mineral matter accumulation) and the DS indicates the intensity of organic matter accumulation, mainly the lake-internal productivity.

A SEM was an accurate tool in detailed internal varve studies. The annual deposition cycle of clastic-organic varves was shown on the basis of the graded bedded structure of deposited mineral grains.

The uppermost first meter of the Lake Korttajärvi sediment sequence was used as an example of combining physical and mineral magnetic proxies. The increased erosion rate above the core-depth of 38 cm is reflected in X-ray density and varve thickness as well as increased values of magnetic mineral concentration and grain-size. Also, the increased amount of organic matter between 93 and 78 cm is reflected in diminished magnetic mineral concentration and grain size.

Magnetic properties can provide information about sediment provenance or the presence of authigenic magnetic minerals in the sediment. Mineral magnetism is also a relatively fast method to obtain information about sediment composition compared to the above-mentioned time-consuming image analysis methods.

The most detailed information about the sediment composition is obtained by combining all possible proxies and focusing in more detail on those core sections where rapid changes are identified.

4.1.2. Paper II

The accuracy of the Lake Korttajärvi varve chronology was tested by comparing it to two long independent varve chronologies. All three lakes deposit annual clastic-biogenic varves and have a very similar structure. Varve counts from lakes Alimmainen Savijärvi and Nautajärvi were done by author Ojala and from Lake Korttajärvi by author Tiljander. Varve counts from Lake Alimmainen Savijärvi were performed from fresh sediment surface and photographs, whereas in the case of Lake Nautajärvi and Lake Korttajärvi embedded sediment blocks and an image analysis program as described in Paper I were used. The Lake Alimmainen Savijärvi record covers 10,295 ± 340 varves, Lake Nautajärvi 9898 ± 97 varves and Lake Korttajärvi 9590 ± 103 varves (cumulative counting error ± 3%, ± 1% and ± 1% respectively). The accuracy of the chronologies was tested by comparing paleomagnetic measurements. All the lakes are within a small geographical area (less than 100 km apart) and should therefore reflect synchronous changes in paleosecular variation (PSV).

Patterns of declination and inclination at the three sites are consistent and within the error of the varve chronologies. The linear trend was removed from the Lake Alimmainen Savijärvi and Lake Korttajärvi declination records because of the distortion of the original data due to tube twisting during penetration into the sediment. Inclination data was used for combining the three lakes in order to assemble a “Finnish master curve”. Declination was not used because of the linear correction. The UK master curve and Swedish stacked data were compared to Lake Nautajärvi declination, indicating that the UK master curve correlates well except the period of 6000-2000 BC and the Swedish stacked data seems to be 400 to 500 years younger in sediments older than 5000 BC.

Comparison of the three lakes to each other as well as to the UK master curve and Swedish stacked data, confirms the reasonable reliability of the chronologies. Inclination features from the originally inferior chronology of Lake Alimmainen Savijärvi deviate from Lake Korttajärvi and Lake Nautajärvi inclination features by 100-200 years. Lake Korttajärvi and Lake Nautajärvi equate well with one another, deviation being less than 100 years based on different inclination features (despite 105 and 215 year deviations in features κ and λ, 6500-4000 BC). In the inclination feature μ (7000-6800 BC) the deviation is only 45 years indicating that the 150-year error in Lake Korttajärvi varve chronology (Ojala et al. 2005) is restricted to the interval 5500-4500 BC and the final isolation from the Baltic basin took place at the time when the varve formation began in 7590 BC.

Altogether, these results encourage the use of paleomagnetic results from these lakes or the “Finnish master curve” for comparison when dating homogeneous lake and marine sediments in Finland.

4.1.3. Paper III

The study of the last 3000 years is based on high-resolution varve analyses (varve thickness and X-ray density). These physical analyses together with meteorological and historical data were utilized to describe environmental changes in the Lake Korttajärvi area. Alternating long-lasting mineral-matter- and organic-matter-rich periods reflect environment and climate conditions. The sediment sequence is analyzed by dividing it into different time periods. The climate interpretation is based on the fact that colder winter means increased snow cover and more intense spring flooding and thus mineral matter influx into Lake Korttajärvi. Accordingly, cooler and shorter summer results in lower primary production and therefore less organic matter in the sediment.

Characteristic of the first millennium BC were cyclical changes in the sedimentation. Organic-matter-rich periods lasted 44, 64, 70, 72 and 148 years and mineral-matter-rich periods 25, 32, 35 and 36 years. The most intensive period of catchment erosion during the millennium was

970-875 BC, and was contemporaneous with the abrupt change to cooler climate at middle latitudes of the Northern Hemisphere (van Geel et al. 1996) and Southern Hemisphere (van Geel et al. 1996, 2000).

During the Roman period there was in AD 140-220 an 80-year-long period in the Lake Korttajärvi area when organic matter deposition and the sedimentation was similar to that during the Medieval Warm Period (MWP), interpreted as milder climate condition. After this period, a clear mineral matter – organic matter varve structure existed, until the beginning of the MWP.

The MWP, AD 980-1250, was an exceptional period. The MWP is characterized by thinly laminated varves rich in organic matter, almost lacking the mineral pulses (i.e. spring floods), indicating mild climatic conditions. This period was interrupted by a colder period from AD 1115-1145, dominated by mineral-matter-rich varves. The sediment deposited during the MWP was highly organic and dark brownish in colour. Based on pollen and diatom studies (Kauppila 2002), the MWP was a two-stage event. AD 980-1100 was warm and dry, a cold spell (AD 1115-1145) interrupted the warm trend and the following period AD 1145-1220 was again warm and even drier than the first stage.

The interpretation of the Little Ice Age (LIA) from the varve properties of Lake Korttajärvi is not straightforward, possibly because of the accelerating catchment erosion since AD 1720 caused by human activities, and the interpretation of the paleoclimate is no longer reliable. Because of the increased land use in the area, the sedimentation rate has accelerated, however, two severe climate periods existed in AD 1580-1630 and AD 1650-1710, just before the major catchment erosion events. Both periods indicate higher mineral matter accumulation (thick varves and high average X-ray density value) and thus probably severe climate periods.

In the 20th century the thickness of the varves increases towards modern times and exceptionally thick varves can be connected to human activities (ditching, road construction etc.).

Climate variations together with other environment factors control sedimentation processes. The climate conditions in the North Atlantic tightly control the climate in Scandinavia. During a negative NAO (North Atlantic Oscillation) index, westerlies are weak and cold air masses spread from east and north, whereas during a positive NAO index strong westerlies bring wet and warm air masses (Hurrell 1995). The LS (mineral matter index) shows the same trend as the positive wintertime NAO index (Luterbacher et al. 2002) in AD 1500-1760.

4.1.4. Paper IV

Stable isotopes were used to reconstruct changes in paleoenvironment and paleoclimate. A case of interest was also to identify the previously observed climate signals (Paper III). Carbon and hydrogen isotope ratios were analyzed from HCl-HF extracted residue representing the sediment organic matter (kerogen). Carbon isotope ratios were also analyzed from HCl-washed sediment. The Holocene period was analyzed at a 500 year resolution and the most recent 1500 years (AD 500-2000) at 50-100 year resolution.

In Lake Korttajärvi the C/N ratio is 11-15, indicating that the organic matter is mainly autochthonous mixed with a distinct component of terrestrial plant debris, as phytoplankton has a C/N ratio of 4-10 and land plants have C/N values above 20 (Meyers 1994).

The isotopic composition of carbon in lake organic matter reflects the isotopic composition of the carbon source, DIC (dissolved inorganic carbon), used by the algae in photosynthesis, and the effects of fractionation associated with the photosynthetic carbon fixation. Changes in productivity, temperature, lake water pH and diagenesis can also affect the $\delta^{13}C$ values of the sedimentary organic matter.

Hydrogen in lake organic matter is derived from the hydrogen of the lake water. δD values can be used as a climate indicator because lake plants and algae use the lake water that is locally precipitated and thus correlated with local mean annual temperature.

The $\delta^{13}C_{HCl\text{-}HF}$ values show a long-term increasing trend from -31.6 to -29.2‰. Diatom-inferred pH values indicate that the lake was neutral during the Ancient Lake Päijänne period

(7160-4400 BC) and became more acidic towards modern times. Acidification has changed the lake towards a less productive direction. It is likely that the proportion of DIC decreased during the Holocene leading to decreasing discrimination against ^{13}C in algal carbon fixation and higher $\delta^{13}C$ values.

Hydrogen isotope values of kerogen are affected by the local climate. It has been estimated that the temperature in southern Finland rose approximately 3 °C from the early Holocene until 4000 BC (Heikkilä and Seppä 2003). Based on the δD - temperature relation of the present day precipitation (Kortelainen and Karhu 2004), the temperature rise would indicate a 14‰ increase in the δD values, which can be compared to the measured δD change of 9‰ in kerogen. Another local maximum of 9‰ in kerogen δD values exists during the Medieval Warm Period.

4.2. Chronology and physical properties of varves

The 11.6 m long sediment sequence of Lake Korttajärvi is continuously varved. The varve structure varies, but remains clear, even when Lake Korttajärvi was a part of the Ancient Lake Päijänne. The varve counting was made basically from two main cores, HU99 and B01 (Table 1), where the varves were best preserved. The top of the sediment sequence was dated by counting varves from the freeze core. Varves were also counted from other cores (Table 1), and parallel cores were especially important in dating the main cores cut-points gaps and in some places where the varve structure was disturbed. Altogether, 9590 varves were counted.

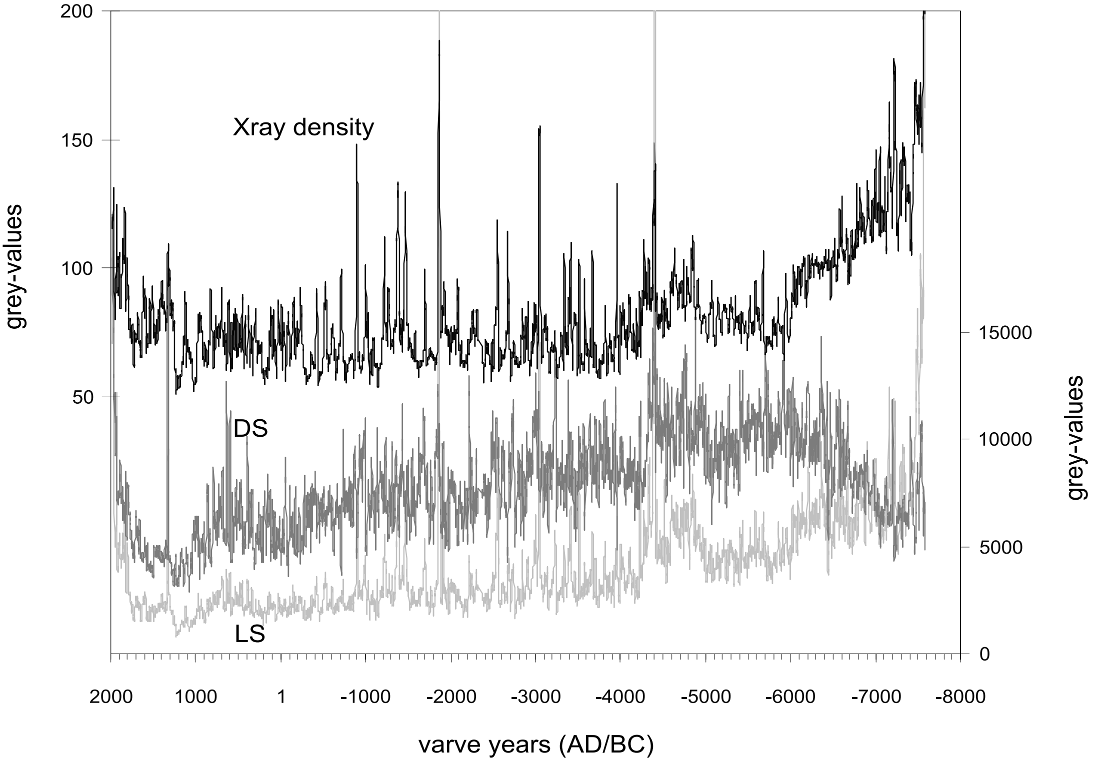

Figure 2. The annual average grey-value (X-ray density) together with the LS (sum of annual grey-values) and the DS (LS_{max}-LS).

The development of the varve formation is seen in Figure 2. High average X-ray density values and equal values of LS and DS indicate that the deposited material was mainly minerogenic. The amount of organic matter started to increase gradually. By the visual interpretation from the polished epoxy blocks, varves deposited before 7450 BC were light and contained coarse mineral matter laminae covered by brownish organic matter. 7450-7185 BC varve structure was still clear, containing light → brownish orange → grey → black (occasionally: light → brownish orange → grey → brownish orange → black) laminae.

The amount of the depositing organic matter increased until 6000 BC and stabilized for a thousand years. Accelerating sedimentation is seen in increasing X-ray density values as well as in LS and DS (Figure 2) and in varve thickness (Figure 6 in Paper II). During the Ancient Lake Päijänne stage (7160-4400 BC) varve

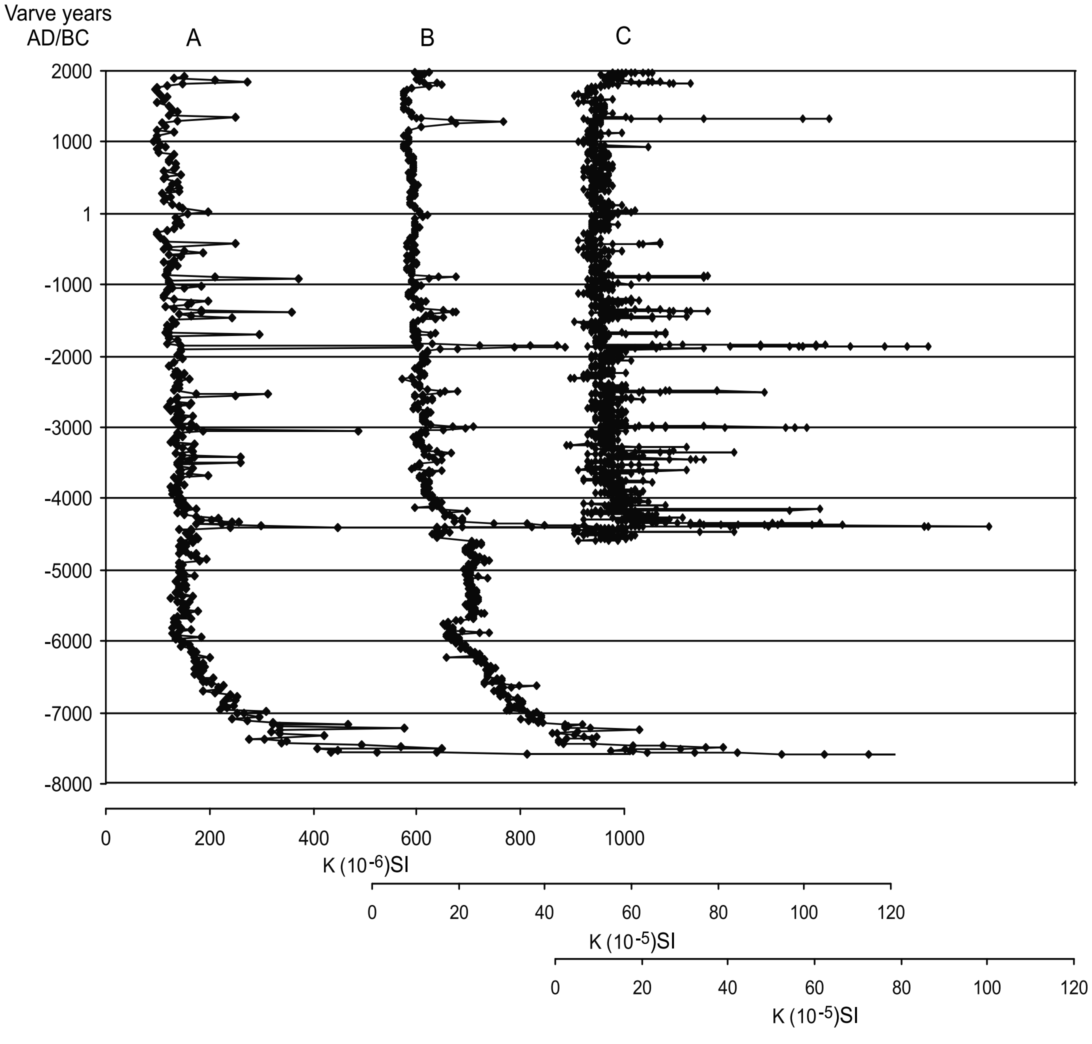

Figure 3. Magnetic susceptibility values measured from parallel sediment cores of Lake Korttajärvi with different time resolution and equipment. A was measured from paleomagnetic cubes of core B01 (7590 to 4573 BC) and core A01 (4543 BC to AD 2000) with the KLY-2 instrument. B was measured from the cores B01 (7590 BC to 4597 BC) and HU99 (4540 BC to AD 2000) with the Bartington equipment sensor MS2C. C was measured from core HU99 with the Bartington equipment sensor MS2E1.

structure was complex, but the rhythm of annual sedimentation is clear in detailed X-ray density data where the light mineral lamina at the bottom and a black lamina at the top are clear, but the laminae structure in between varies. The internal varve structure is light → dark grey → black or light → black → brownish orange → black (getting gradually darker upwards).

The most drastic event in Lake Korttajärvi happened 4400 BC, when the lake isolated form the Ancient Lake Päijänne. Changes in the sedimentation pattern can be seen in X-ray density (Figure 2), susceptibility (Figure 3), varve thickness (Figure 6 in Paper II) and in mineral magnetic properties (Figure 6). As seen in Figure 2, it took 200 years for the varve composition to settle. The internal varve structure contained at least three laminae (light → brownish orange → black). Sometimes the internal placement of laminae varies, but the varve year always ends with the black lamina. Similar varves were also deposited before the isolation period. The brownish orange shade is probably caused by iron precipitated as iron hydroxides or iron sulphides (black), which is common in Fennoscandian varved lake sediments (Renberg 1981b). The present day varve structure is more uniform (light → dark → black) and characteristic are mineral- and organic-matter-rich periods lasting decades to centuries. Based on the X-ray density data (Figure 2), exceptional mineral-matter-rich periods occurred around 3050 BC, 1860 BC and 890 BC, the clearest organic-matter-rich period was AD 980-1250 and the increasing sedimentation started in AD 1720.

4.3. Mineral magnetic properties

The resolution of the susceptibility measurements appears to be important. As seen in Figure 3, the sparsest resolution, measurements from the polystyrene cubes, gives the clearest curve, showing the main trends and peaks of mineral matter. Measurements from unopened cores with a Bartington equipment sensor MS2C at 2 cm resolution show a very similar susceptibility curve to measurements from the cubes. A difference is found in curve B during a period of a higher susceptibility, 5681-4645 BC, measured from core B01. The shift in scale is exaggerated due to

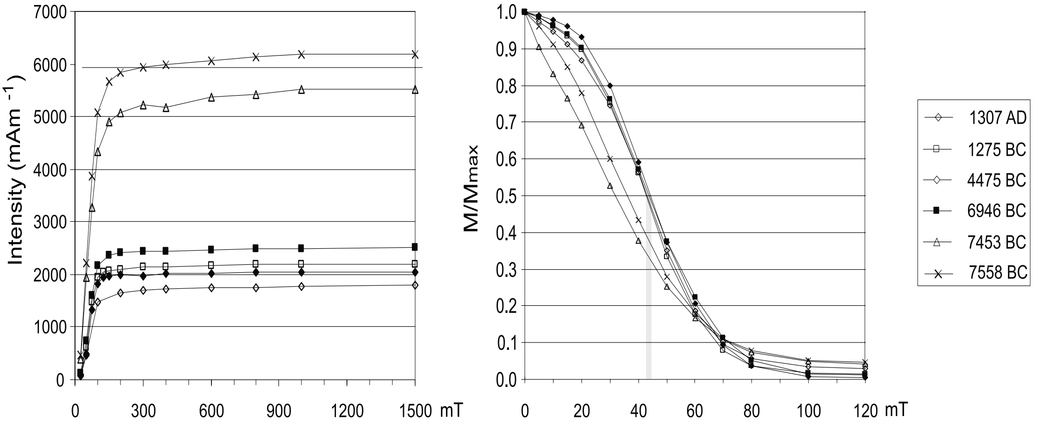

Figure 4. IRM acquisition (left) and NRM AF-demagnetization behaviour (right) from selected samples.

combination of the two cores HU99 and B01. The finest resolution, measured at 5 mm resolution by scanning the fresh (covered by a plastic film) sediment surface using a Bartington equipment sensor MS2E1, is the most accurate, including more sensitive variation.

In Lake Korttajärvi each sample cube contains approximately 20-30 years. IRM acquisition and the stepwise NRM demagnetization (Figure 4) indicate that the depositing magnetic material has been uniform during the sedimentation process, except for the very beginning of the sedimentation (the two oldest samples from the clay layer). Despite the oldest samples, the carrier of the remanence is magnetite, because SIRM is reached under a 200 mT field, the medium destructive field (MDF) varies between 42-46 mT and samples are completely demagnetized in the 100 mT magnetic field. The clayey bottom of the sediment sequence also contains a harder magnetic component. The same pattern is noted in Lake Nautajärvi (Ojala and Saarinen 2002). Also, the Day-plot (Day et al. 1977) based on hysteresis parameters from the topmost first meter of the sediment sequence (Paper I) indicates that the carrier of the remanece is fine grained PSD (pseudo single domain) magnetite (Figure 5).

Figure 6 presents magnetic parameters that depend on the magnetic mineral concentration and grain size. The magnetic concentration is dependent on the deposited magnetic minerals and their amount in the sediment. Four peaks (in NRM, ARM and SIRM) stand out indicating higher magnetite concentration: AD 1330, 1870 BC, 4400 BC and 5400-5000 BC. All the high magnetic pulses are connected to thicker mineral matter varves. SIRM/susceptibility ratio records an overall increase of finer magnetite grain size between 6000-5000 BC and even finer grained magnetite deposited in 5400-5000 BC. This can be correlated to the increased erosion in the catchment area as a result of the rising water level of the Ancient Lake Päijänne. However, the same kind of reduction in magnetite grain size exists in AD 1000-1200, during medieval times, when the erosion was negligible. The S-ratio indicates that the minerogenic sediment of Lake Korttajärvi is basically composed of soft magnetic material (i.e. magnetite). The highest S-ratio value is -0.67. The ARM/SIRM ratio is also an indicator of magnetite grain size. Low ARM/SIRM values in the early Holocene are a result of high SIRM values and therefore due to the increased magnetic concentration.

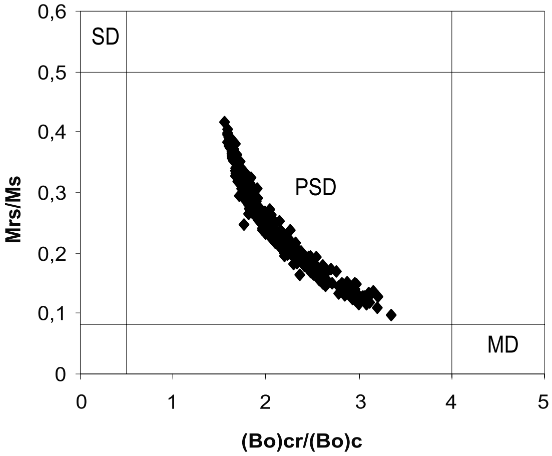

Figure 5. A Day-plot from the hysteresis measurements of the topmost first meter of the sediment sequence. The plot presents the grain size and shape of the magnetic mineral grains: SD (single domain grains), PSD (pseudo single domain grains) and MD (multi domain grains).

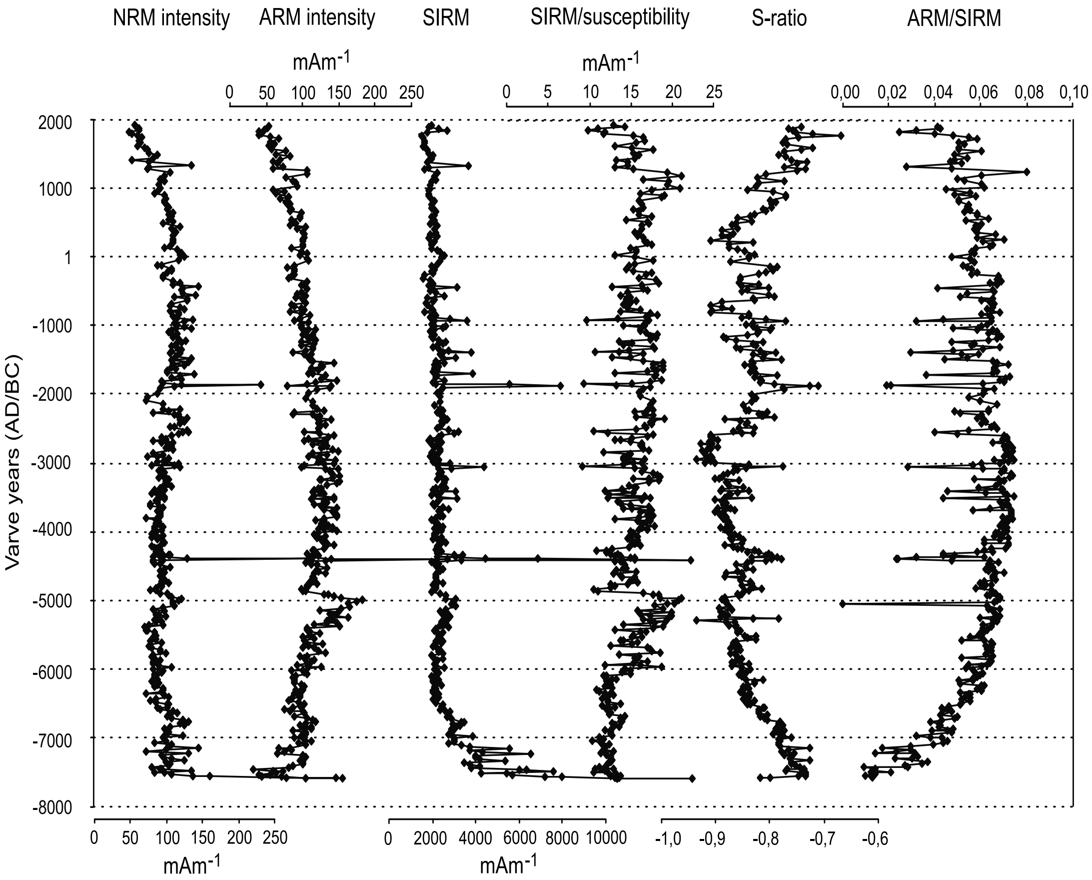

Figure 6. Mineral magnetic properties (NRM intensity, ARM intensity, SIRM, SIRM/susceptibility, S-ratio, ARM/SIRM) of the sediments from Lake Korttajärvi.

5. Discussion - Evolution of the Lake Korttajärvi

The first annual laminations in Lake Korttajärvi were deposited in 7590 BC, when the lake basin isolated from the Ancylus Lake. The isolation point was confirmed by a change of the diatom assemblage (Ojala et al. 2005). Lake Korttajärvi was an independent lake basin for 430 years (7590-7160 BC). Water level changes caused occasional disturbances in the sediment structure just before and after the end of the independent lake phase. Varve structure was simple before 7450 BC and still clear in sediments deposited 7450-7185 BC even though more internal variation existed. According to pollen analysis by Eriksson (2002), *Alnus* arrived in the area in 7160 BC (Figure 7), which coincides with the end of the first independent lake phase. The early landscape was dominated by grasses and by *Pinus* and *Betula* forest (Figure 7). The lake water was neutral according to diatom-based pH (Paper IV).

During the mid Holocene, when Lake Korttajärvi was part of the Ancient Lake Päijänne for 2760 years, the varve formation continued even though the internal structure of the varves was complicated. The complicated varve structure between c. 5500 and 4500 BC caused an assumption of a 150-year error in the chronology in an earlier study (Ojala et al. 2005). The error, however, is not true because the deviation in paleomagnetic results appears to be restricted only to the interval with the complicated varve structure. Mineral magnetic studies indicate that fine grained magnetite was deposited during 6000-5000 BC. According to pollen analysis, the amount of Quercetum Mixtum (QM) group increase clearly indicates the long and warm mid-Holocene. The pH was close to neutral during the Ancient Lake Päijänne stage. The increasing trend in the carbon content, $\delta^{13}C_{HCl-HF}$ values and δD values is clear. The early Holocene warming is seen as a distinctive increase in the δD values of kerogen in 7160-4400 BC (Paper IV).

The isolation from the Ancient Lake Päijänne took place in 4400 BC (4410-4380 BC). This affected the varve formation for the next 200 years. Alternating mineral- and organic-matter-rich periods (decades to centuries) were characteristic of this second independent lake phase (4400 BC-present). During severe climate periods thicker varves rich in mineral matter were deposited and during milder climate periods the mineral laminae were thin and varves were highly composed of organic matter. A cold spell in 907-875 BC was an intensive period of catchment erosion and accumulation of thick clastic varves. This event could indicate an abrupt climate change c. 2500-2800 years ago also observed in other studies (van Geel et al. 1996, 2000; Hakala et al. 2004). An even bigger event occurred in 1877-1848 BC. This event lasted 29 years, during which thick clayey varves were deposited. One more intense period of deposition of mineral-matter-rich varves happened in 3061-3037 BC. Those events are most probably related to changes in drainage conditions. Organic-matter-rich periods existed in 1688-1486 BC and 1846-1705 BC. They are characterised by a lower than average grey-value indicating weak spring flooding.

After the isolation, an overall acidification trend started in Lake Korttajärvi (Paper IV). The long-term gradual decreasing trend in the diatom-inferred pH and P_{tot} values indicate a gradual change towards more acidic and unproductive conditions. This could have decreased the availability of DIC to aquatic plants and affected the fractionation of carbon isotopes during carbon fixation which is seen as higher $\delta^{13}C_{HCl-HF}$ values (Paper IV). The acidification trend continued until AD 1600. The pollen record (Figure 7) does not show significant changes, except the arrival of the *Picea* in the area in 3730 BC (Eriksson 2002).

Early pollen of *Hordeum* c. 2000 years ago (Figure 7) indicates early cultivation at the area (Grönlund and Vuorela 2000). An organic-matter-rich interval existed in AD 140-220. The high organic accumulation indicates warm climatic conditions during this period (Paper III).

The most distinctive climate period in the whole sediment sequence is the Medieval Warm Period in AD 980-1250 (Paper III). This organic-matter-rich period started and ended abruptly. The concentration of the mineral matter was negligible

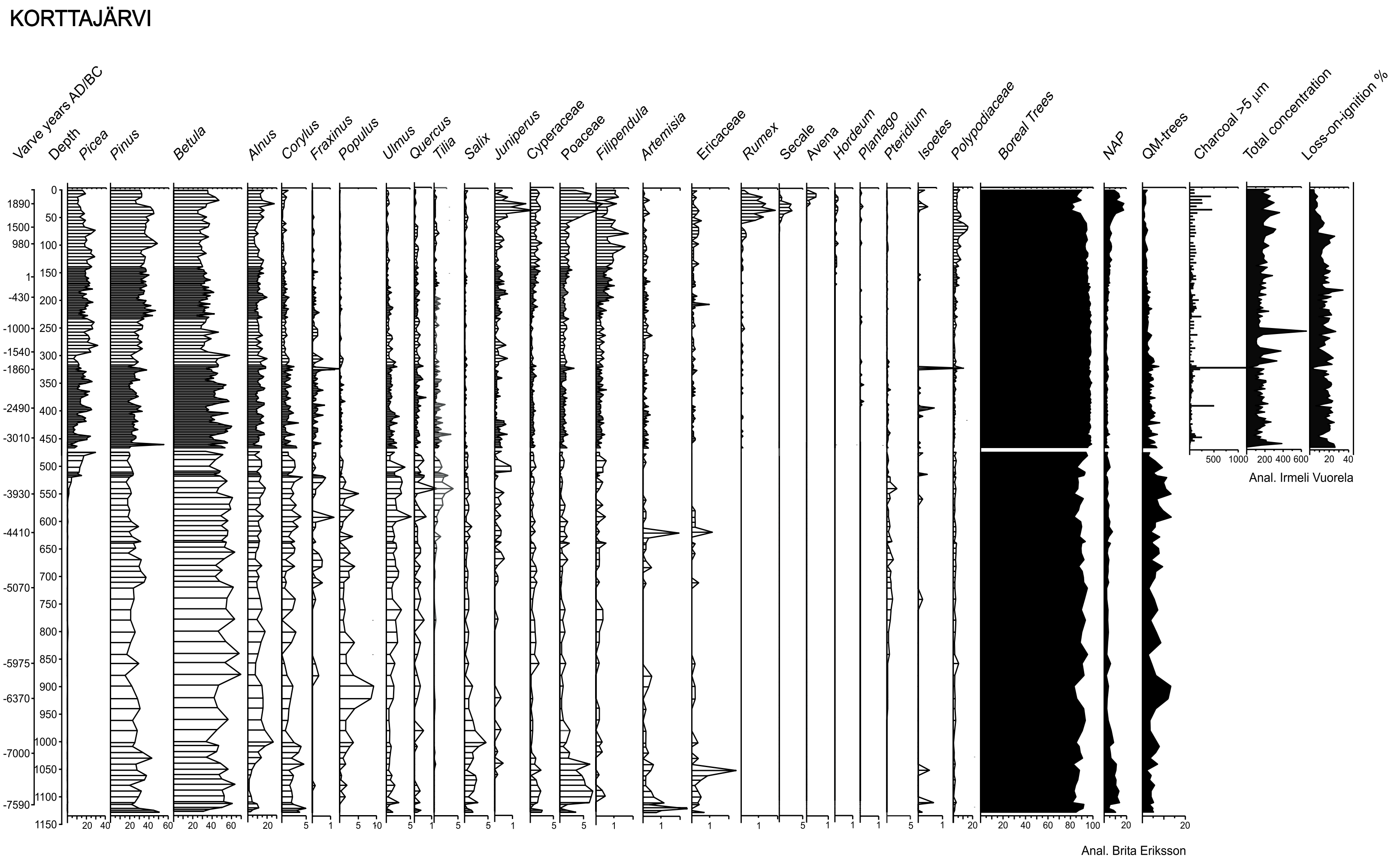

Figure 7. A combined pollen diagram covering the Holocene analyzed by Irmeli Vuorela and Brita Eriksson. Samples are from Lake Korttajärvi core B01 (7590 to 5200 BC) and A97 (5070 BC to the present).

and the deposited magnetic material was very fine grained magnetite. δD values of kerogen indicate a notable rise in the temperature (Paper IV).

After the Medieval Warm Period, the year AD 1326 is an exceptionally thick clay varve and therefore found in all magnetic measurements as a higher magnetite concentration. Intensive cultivation started in the area in AD 1580 (Paper III) at the same time that the anthropogenic alkalization period started in AD 1600 (Paper IV). The Little Ice Age was not identified, but two mineral-matter-rich periods in AD 1580-1630 and AD 1650-1710 possibly provide evidence for the Little Ice Age. Since the early 18th century, the sedimentation has clearly been affected by increased human impact and therefore not useful for paleoclimate research.

6. Conclusions

Varved lake sediments are important for paleoenvironmental and paleoclimate studies. Lake sediments have the advantage of creating long-core (millennial), continuous records from the same site. By embedding sub-samples with epoxy and using image analysis techniques, it is possible to obtain detailed information about the internal varve structure. Digitally stored data also permits re-examination, detailed core to core correlation and the ability to study in detail specific core sections where changes have been identified. The annual sedimentation cycle provides an accurate chronology, which is the basis for the following conclusions.

1. A combination of several physical proxies (varve thickness, X-ray density, LOI, mineral magnetism, organic matter $\delta^{13}C$ and δD) provides accurate information about sedimentological, environmental and climatic changes within the sediment sequence.

2. The development of Lake Korttajärvi can be divided into three lake phases: 1) An independent lake 7590-7160 BC, 2) a part of a large lake complex 7160-4400 BC and 3) an independent lake 4400 BC to present.

3. Lake Korttajärvi sediments record a long-term gradual change to more acidic and less productive conditions, based on variations in diatom-inferred pH and diatom-inferred P_{tot} and organic matter content. The increasing trend in the isotopic composition of carbon is closely related to this change.

4. The Medieval Warm Period in AD 980-1250 is the most distinctive climate period in the whole sediment sequence identified by changes in sediment colour, X-ray density, varve thickness, LOI, as well as the isotopic composition of hydrogen in kerogen. The period is characterized by a sharp drop in the mineral-matter sedimentation rate.

5. Evidence for the Little Ice Age is not clear in the record. Two minor cooling periods in AD 1580-1630 and 1650-1710, can be observed based on X-ray density and varve thickness data, which may be related to the Little Ice Age.

6. X-ray density and varve thickness data give some indications for other mild climate periods in 1846-1705 BC, 1688-1486 BC and AD 140-220 and severe climate periods in 3061-3037 BC, 1877-1848 BC and 907-875 BC.

7. Acknowledgements

I am most grateful to my supervisor Matti Saarnisto, who gave me the possibility to work in his research group. His endless interest to this study, encourage and support is highly appreciated. Juha Karhu as my isotope supervisor helped me a lot, allowed me to work in the stable isotope laboratory and arranged the working facilities at the late stage of the study. Timo Saarinen is thanked for teaching the basics of the lake sediment studies and paleomagnetism.

Special thanks belong to Antti Ojala, with all the help, teamwork and fruitful discussions, as well as reading and making comments on my writings. Tommi Kauppila deserves greatest thanks for never-ending time for making analyses and giving valuable advices. Ian Snowball is also thanked for the co-operation with varve studies.

Likewise, I want to thank Arja Henttinen for advices, support and technical help in the stable isotope laboratory and Matti Leino for explains and help with the SQUID. Ale Grundström together with Seppo Putkinen and his team were a great help in field work. Brita Eriksson, Tuulikki Grönlund, Irmeli Vuorela and Teija Alenius are thanked for the data of pollen and diatom studies. The official reviewers Atko Heinsalu and Aarno Kotilainen are acknowledged for their comments on the manuscript. And thank you, all my other colleagues for discussions of science and every day life.

I am grateful for the working facilities of the Geological Survey of Finland where all the analyses and three of four papers were written. The Academy of Finland (grants SA47047 and SA44074), the University of Helsinki and the Graduate School in Geology (Veli-Pekka Salonen) are acknowledged for the finance of this work.

I was also privileged to join workshops financed by LAMSCAN (a Nordic Arctic Research Programme – NARP) and HOLIVAR (a part of ESF - European Science Foundation).

Finally, I want to thank the most important people of my life, my family: Mika, Ville and Venla. Thank you for the patience, support and understanding during the years.

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