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Holocene Varved Lake Sediments as Records of Palaeoenvironmental Change and Geomagnetic Palaeosecular Variation in Eastern Finland

by

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Abstract

This dissertation discusses Holocene palaeoenvironmental and palaeomagnetic secular variation (PSV) records reconstructed from sediments preserved in Lake Lehmilampi (63º37´N, 29º06´E) and Lake Kortejärvi (63º37´N, 28º56´E) in eastern Finland. Several piston and freeze cores were obtained from both lakes for varve and magnetic analyses. Sediment samples were impregnated in low-viscosity epoxy and physical parameters of varves, including varve thickness and relative grey-scale values, were recorded using x-ray densitometry combined with semiautomatic digital image analysis. On average, varve records of Lehmilampi and Kortejärvi cover 5122 and 3902 years, respectively. Past solar activity, as estimated by residual ^{14}C data, compares favourably with varve thicknesses from Lehmilampi during the last 2000 years. This indicates the potential of clastic-organic varves to record sensitively climatic variations. Bulk magnetic parameters, including magnetic susceptibility together with natural, anhysteretic and isothermal remanent magnetizations, were measured to describe mineral magnetic properties and geomagnetic palaeosecular variation recorded in the sediments. Main stages in the development of the investigated lakes are reflected in the variations in the mineral magnetic records, sediment lithology and composition. Similar variations in magnetic parameters and sediment organic matter suggest contribution of bacterial magnetite in the magnetic assemblages of Lehmilampi. Inclination and relative declination records yielded largely consistent results, attesting to the great potential of these sediments to preserve directional palaeosecular variation in high resolution. The PSV data from Lehmilampi and Kortejärvi were stacked into North Karelian PSV stack, which may be used for dating homogenous lake sediments in the same regional context. Reconstructed millennial variations in relative palaeointensity results are approximately in agreement with those seen in the absolute palaeointensity data from Europe. Centennial variations in the relative palaeointensity, however, are influenced by environmental changes. Caution is recommended when using varved lake sediments in reconstructing relative palaeointensity.

Contents

List of original articles

This thesis arose out of an original project entitled “Palaeointensity of the Earth’s Magnetic Field during the Last 10 000 Years”, planned out by T. Saarinen and funded by Academy of Finland (grant n:o 205805).

The thesis is based on the following four original papers:

I Haltia-Hovi, E., Saarinen, T., Kukkonen, M., 2007. A 2000-year record of solar forcing on varved lake sediment in eastern Finland. Quaternary Science Reviews 26, 678-689. *Reprinted with permission from Elsevier.*

II Haltia-Hovi, E., Nowaczyk, N., Saarinen, T., Plessen, B., 2009. Magnetic properties and environmental changes recorded in Lake Lehmilampi (Finland) during the Holocene. Journal of Paleolimnology 43, 1-13. *Reprinted with permission from Springer.*

III Haltia-Hovi, E., Nowaczyk, N., Saarinen, T., 2010. Holocene palaeomagnetic secular variation recorded in multiple lake sediment cores from eastern Finland. Geophysical Journal International 180, 609-622. *Reprinted with permission from John Wiley and Sons.*

IV Haltia-Hovi, E., Nowaczyk, N., Saarinen, T. Environmental influence on relative palaeointensity estimates derived from Holocene varved lake sediments in eastern Finland. *Manuscript submitted to Physics of the Earth and Planetary Interiors.*

In Papers I-IV, E. Haltia-Hovi (EHH) was responsible for sediment sample preparations and varve counting. However, the sediment preparation of the sixteen subsamples from the reference cores in Paper I was shared with M. Kukkonen, who also measured the long-core magnetic susceptibility of these cores. Magnetic data in Papers II-IV were measured by EHH under the guidance of and partly in cooperation with N. Nowaczyk (NN) at Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Germany. NN was responsible for the hysteresis analyses and the application of the Fisher statistics to the palaeomagnetic data in Paper III. B. Plessen was in charge of the measurements of total organic carbon for Paper III at GFZ. EHH was responsible for interpreting the data and writing the Papers I-IV. The Papers I-II and IV were commented by T. Saarinen and II-IV by NN.

1. Introduction

1.1. Varved lake sediments, their formation and occurrence

Meaningful investigation of the different palaeoenvironmental proxy parameters recorded in sediment stratigraphies requires reliable and precise dating. Incremental dating techniques allow the construction of chronologies on annual basis, upon which they can either be fixed to the present or form floating chronologies. The materials that can be used in such incremental techniques include tree rings, ice cores, corals, speleothems and annually laminated sediments (Walker, 2005). Due to their high temporal resolution, extending to a seasonal level, annually laminated sediment sequences provide one of the most detailed terrestrial archives for the study of rapid palaeoenvironmental changes (Brauer et al., 2008). Varved sediments can be deposited and preserved in lacustrine and restricted marine basins, yielding continuous, high-resolution sediment records that carry an inherent absolute chronology. Precisely dated long varve records can potentially yield detailed palaeoclimatic records, which can be correlated and synchronized with other climatic proxies such as $\delta^{18}O$ derived from Greenland ice cores (Andrén et al., 1999). The term annual lamination is used in this thesis interchangeably with varve, which originates from the Swedish word *varv*, meaning a cycle, turn or lamina. The term was originally coined in this context by the Swedish geologist de Geer (1912), who investigated the retreat of the Fennoscandian ice sheet using outcrops of glaciolacustrine clastic varves in Sweden, and has later been extended to cover the wide spectrum of annually laminated sediments.

As discussed by O´Sullivan (1983) and Saarnisto (1986) and later expanded on by Petterson (1996), Larsen et al. (1998), Ojala et al. (2000) and Zillén et al. (2002), the prerequisites for the deposition and preservation of varves of various types in lakes include a combination of factors, which can be reduced to 1) seasonal changes in the character of depositing sediment, and 2) absence of post-depositional disturbances. Depending on climatic setting and catchment type, varves are comprised of different components, such as biogenic, ferric, calcareous, and clastic (Zolitschka 1991; Renberg, 1981a; Hsü and MacKenzie, 1985; Hughen et al., 2000). The basic clastic-organic varve structure encountered in the Fennoscandian boreal brown-water lakes is typically composed of alternating pairs of light (clastic) and dark-coloured (organic) laminas that are clearly visible to the eye and attributable to the recurring seasonal climatic cycle in the northern parts of the temperate zone (Petterson et al, 1999; Tiljander et al., 2002). Suitable basin morphometry and short water overturn period in spring and autumn contribute to the development of oxygen deficiency in the hypolimnion, so that varved sediments are likely to be found in mero- or dimictic lakes. High autochthonous productivity contributes to rapid consumption of dissolved oxygen through the decomposition of organic matter, contributing to a low oxygen concentration in the lake bottom waters. Human-induced eutrophication due to nutrient loading has been shown in many cases to initiate varve deposition (Grönlund et al., 1986; Lüder et al., 2006).

All laminations observed in sediments found in different depositional environments do not record an annual sedimentation cycle but may result from e.g. turbidity currents and other pulses of detrital matter (Lambert and Hsü, 1979; Simola and Tolonen, 1981; Hagadorn et al., 1995). Therefore, the seasonal character of sediment laminations must be verified. This can be accomplished by sediment trap studies in order to monitor the seasonal association of specific sediment types depositing in the lake bottom and to connect the changes to seasonal climatic and limnologic processes (Simola, 1981; Anderson and Dean, 1988; Leeman and Niessen, 1994; Chu et al., 2005). The seasonal character of sediment laminations can also be validated by correlation of the microfossil stratigraphy of the individual laminas to an established seasonal succession of diatom blooms and pollen taxa (Terasmae, 1963; Simola, 1979; Lotter, 1989). Optimally, the validity of varve chronology is confirmed by comparing it with results from other soft sediment dating techniques in order to detect possible errors in varve counting or unnoticed sediment hiatuses. Radiocarbon (^{14}C) analyses, either conventional or AMS (Accelerator Mass Spectrometry), have been widely applied for this purpose (e.g. Tolonen, 1980; Goś}lar et al., 1989; Wohlfarth et al., 1993; Aardsma, 1996; Oldfield et al., 1997;

Brauer and Casanova, 2001; Zillén et al., 2003). The fidelity of chronologies obtained from recent varved sediments has been validated by short-lived radiogenic isotopes such as ^{137}Cs and ^{210}Pb (Saarinen, 1998; Lima et al., 2005). Crosschecks against independently dated marker horizons, such as tephra layers (Zillén et al., 2003), can also serve to increase the reliability and precision of chronological framework. In some cases, geomagnetic palaeosecular variation (PSV) records have been applied in the verification of varve chronologies (Ojala and Tiljander, 2003; Stanton et al., 2010).

The development of suitable equipment for coring continuous lake sediments sequences (Livingstone 1955; Mackereth 1958), together with the development of the freeze coring technique (Shapiro, 1958; Saarnisto, 1975; Wright, 1979; Renberg, 1981b) allowed the recovery of undisturbed varved sediment sequences extending up to the present, and gave an impetus to investigations of postglacial, organic-rich varved sediments also in Finland. Modern varved lake sequences are known to exist in diverse environments over a broad geographical range. Certain regions in the Northern Hemisphere, including Fennoscandia (Saarinen, 1998; Snowball et al., 1999; Ojala and Saarinen, 2002), the Alps and the crater lakes of the West Eifel volcanic field, have been subject to intensive research (e.g. Leeman and Niessen, 1994; Brauer et al., 2001), as have parts of North America (Tian et al., 2005) and Japan (Kitagawa and van der Plicht, 2000). This reflects the concentration of research in these areas, of course, but also the climatic gradient in these latitudes that is favourable for inducing seasonal changes in sediment sources. Lacustrine varve records have also been investigated in other regions, such as in the eastern Mediterranean (Wick et al., 2003), Africa (Pilskaln and Johnson, 1991), South America (Boës and Fagel, 2008) and China (Zhou et al., 2007).

1.2 Lake sediments as palaeomagnetic archives

The geomagnetic field results from the fluid motion in the iron-rich outer liquid core of the Earth, and its direction and strength are changing constantly on wide temporal and spatial scales. When averaged over timescales from 10^4 to 10^5 years, the configuration of the geomagnetic field approaches a dipole placed at the center of the Earth tilted approximately 11° with respect to the axis of rotation (Merrill and McFadden, 2003). The part of the geomagnetic field of internal origin remaining after the removal of the main geocentric dipole field is called the nondipole field, which principally reflects the more localized sources in the Earth´s magnetic field (Constable, 2007).

Magnetite (Fe_3O_4) is a ferrimagnetic mineral with a strong magnetic moment, and it is a common accessory mineral in rocks and sediments. Past changes in the magnetic field can be preserved in natural materials containing iron oxides in the form of natural remanent magnetization (NRM). Magnetite particles disintegrated from their source rocks are ultimately transported to depositional basins such as lakes. During their descent through water column, magnetite particles become aligned according to the contemporaneous magnetic field, acquiring depositional remanent magnetization (DRM). This orientation can be preserved in lake sediments, allowing the reconstruction of geomagnetic palaeosecular variations. Such records allow the investigation of geomagnetic variations in the past, improving the understanding of the processes in the outer core, and the correlation of geological records from different settings. The study of the past configurations of the Earth’s magnetic field preserved in natural archives is called palaeomagnetism. Due to their high sensitivity and rapidity of measurements, superconducting rock magnetometers have become the principal instruments of palaeomagnetic research during the last three decades.

Following Mackereth (1971), palaeomagnetic investigations based on organic-rich Holocene lacustrine sequences have continued ever since, and the patterns of geomagnetic palaeosecular variation (PSV) have become well established at several sites in Europe, North America and Japan. In the majority of the palaeosecular variation studies, sediment dating is based on ^{14}C analyses of organic matter (Stober and Thompson, 1977; Barton and McElhinny, 1981; Turner and Thompson, 1981; Readman and Abrahamsen, 1990; Brandt et al., 1999; Frank et al., 2002; Vigliotti, 2006). Bulk ^{14}C analyses are known to be prone to errors for several reasons, including sediment resuspension, low carbon concentrations in the sediment, scarcity of terrestrial macrofossils, old carbon reservoir effects and contamination

(Olsson, 1979; Tolonen, 1980; Olsson, 1991; Wohlfarth et al., 1998). These problems can be avoided by using the precise chronology of varved sediments, as they provide an independent method for dating PSV (Saarinen, 1998; Stockhausen, 1998; Ojala and Saarinen, 2002; Snowball and Sandgren, 2002; Ojala and Tiljander, 2003). The identification of similar patterns in the directional variation curves allows dating of homogenous sediments by comparison to an independently dated PSV master curve obtained in the same regional context (Saarinen, 1999; Virtasalo et al., 2006).

Besides palaeosecular directional records, lake sediments may preserve records of relative variations in the geomagnetic palaeointensity. The basic assumption of reconstructing relative palaeointensity is that the NRM of the sediment is in linear relation to the concentration of magnetic minerals and the geomagnetic field strength of the time of deposition. Normalization of NRM records by different concentration-sensitive parameters, commonly κ (magnetic susceptibility), ARM (anhysteretic remanent magnetization) and SIRM (saturation isothermal remanent magnetization), is assumed to isolate the geomagnetic signal in the NRM. Reconstructing relative palaeointensity requires strictly uniform mineral magnetic properties (Tauxe, 1993), and variations in the concentration, mineralogy and grain size of magnetic minerals very often complicate the establishment of reliable relative palaeointensity estimates. Sometimes it is found that the original signal has been partly overwritten or completely destroyed by postdepositional changes, for instance, authigenic production of new magnetic phases such as iron sulphides or diagenetic dissolution of iron oxides (Snowball and Thompson, 1992; Nowaczyk et al., 2001). Careful investigation of the mineral magnetic properties, and possibly also other physical parameters of sediments such as grain size variations and lithology, can provide essential information for estimating the reliability of a relative palaeointensity record.

1.3 Mineral magnetic assemblages as palaeoenvironmental proxies

Variations in the characteristics and concentration of magnetic minerals in sediments can response sensitively to palaeoenvironmental changes (Thompson et al., 1980; Thompson and Oldfield, 1986; Verosub and Roberts, 1995; Evans and Heller, 2003). Employment of magnetic measurements as part of palaeoenvironmental studies has increased rapidly since the 1970's. Measurement of low-field volume-specific magnetic susceptibility (κ), an in-field measure, represents the most frequently employed mineral magnetic parameter in palaeoenvironmental studies, usually interpreted as reflecting variations in the concentration of magnetite and enabling quick correlation of sediment cores (Thompson et al., 1975; Nowaczyk, 2001). Measurements of laboratory-installed remanences, such as ARM and SIRM, can be applied to characterize mineral magnetic assemblages in more detail. In a magnetic assemblage dominated by magnetite, κ, ARM and SIRM are biased to reflect a specific group of magnetic grain size, which mirrors the number of magnetic domains. Alone, or expressed as interparametric ratios, these different parameters can be employed to characterize variations in magnetic mineralogy and granulometry.

At the outset of environmental magnetism it was assumed that magnetic minerals originate solely from catchment erosion, and they remain unchanged in sedimentary sequences. With time and increasing information from different lakes, it became clear that several processes may be complicating the initial simple hypothesis. These include: 1) Post-depositional diagenetic changes of the original magnetic minerals (Snowball and Thompson 1990; Jelinowska et al., 1997; Stockhausen and Zolitschka, 1999; Nowaczyk et al., 2001), 2) Authigenic formation of magnetic minerals such as an iron sulphide greigite (Fe_3S_4) (Snowball and Thompson, 1990), and 3) Bacterial production of SPM and SD sized magnetite (and sometimes greigite) (Frankel et al., 1979). Advantages of mineral magnetic measurements include their rapidity, minimal need of sample preparation, and, in many cases, magnetic analyses are non-destructive and leave the sediment intact for other analyses. However, interpretation of the results is usually not unequivocal, and information on the sediment physical, biostratigraphical and geochemical characteristics are necessary for a more complete understanding of the observed variations and mechanisms behind them.

1.4 Objectives of the thesis

This study was initiated in order to produce high-resolution data on relative geomagnetic palaeointensity variations recorded in varved lake sediments. The reconstructions of past solar activity are based on investigations of cosmogenic isotopes, such as ^{14}C and ^{10}Be. Production rates of cosmogenic isotopes are modulated by the combined effects of solar activity and geomagnetic field strength. Therefore, precisely dated high-resolution relative palaeointensity data would be of great value in such reconstructions.

Lake Lehmilampi (hereinafter referred to as Lehmilampi) and Lake Kortejärvi (hereinafter referred to as Kortejärvi) in north Karelia were chosen for this purpose by T. Saarinen. In the beginning, facilities and equipment for study of varved sediments were established at the Department of Geology. As a result of these efforts, varve chronologies were reconstructed for Lehmilampi and Kortejärvi. In the next stage of the study, high-resolution geomagnetic palaeosecular variation records were reconstructed and dated in part by the independent varve chronologies to produce high-resolution palaeomagnetic master curves. In the final stage of the study follows the discussion on relative palaeointensity records and their reliability.

2. Study sites

Lehmilampi (63º 37´N, 29º 06´E, size 15 ha, 95.8 m a.s.l.) and Kortejärvi (63º37´ N, 28º 56´ E, size 23 ha, 105.3 m a.s.l.) are small boreal lakes located in the municipalities of Nurmes and Valtimo, respectively, in Northern Karelia, eastern Finland (Fig. 1). Lehmilampi has two inlets and one outlet, and is the headwater lake in its water system, while Kortejärvi has two inlets and two outlets and is situated in the middle of a chain of lakes. The waters of both lakes drain eventually into the northern end of Lake Pielinen (hereinafter Pielinen, size ~870 km^2), which is one of the largest lakes in Finland. Its waters have regressed several tens of kilometres during the Holocene due to more rapid postglacial crustal uplift rate in the northern end of the lake (Miettinen, 1996). The laminated sediment sequences preserved in Lehmilampi and Kortejärvi were initially discovered during an intensive survey for such sequences carried out in central and southern Finland (Ojala et al., 2000; Ojala, 2001). The catchments of Lehmilampi and Kortejärvi are similar in composition, comprising of bedrock outcrops on hilltops, hillslopes covered by thin layer of till, and fine sediments i.e. silt and clay in low-lying areas. Catchment reliefs are steep, resulting in maximum altitude differences of 50 and 80 meters in Lehmilampi and Kortejärvi between water table and maximum topographical peak, respectively, promoting the supply of detrital matter to the lake basins. The climate is temperate with distinct seasonal temperature contrast, and the mean February and June temperatures are -10ºC and +16ºC, respectively, and the annual mean temperature is 2º (Helminen, 1987). No continuous limnological data are available for these lakes, but the chemical and physical data collected from Lehmilampi by Finnish environmental authorities (three measurement occasions between the years 1975 and 1998) show that the lake is thermally stratified, and the hypolimnion is anoxic (dissolved oxygen 1.2 mg/l). The pH is slightly acidic (value 6.3) throughout the water column (data collected from the Finnish environmental information system Hertta).

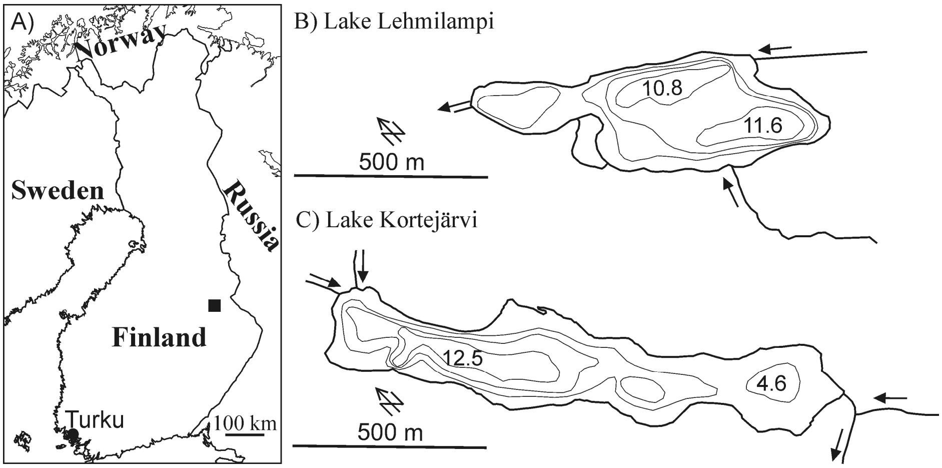


Figure 1. A) Black square in the general map shows the location of lakes, B) Lehmilampi and C) Kortejärvi with bathymetric lines. Numbers in B) and C) denote maximum depth of the basins in meters.

3. Methods

3.1 Coring

Long sediment cores were obtained from Lehmilampi and Kortejärvi in the spring between the years 2004 and 2007 for varve studies and magnetic analyses using the lake ice as a coring platform (Table 1). Coring was concentrated in the deepest area of the basin, except for one core obtained from the shallower middle part of Lehmilampi (LL-C). The sediment for the varve analyses was taken using a lightweight rod-operated piston corer through a plastic casing into plastic liners of 250 cm in length and 5 cm in diameter with a generous overlap of 150 cm. With this equipment the upper 500 cm from the sediment–water interface was retrieved from Lehmilampi. In Kortejärvi, the coring proceeded to a depth of 350 cm below the lake floor, where compacted detrital sediments deposited at the time of isolation hindered penetration of the corer. The water-saturated loose surface sediments may become disturbed when using e.g. piston corers, so these were collected by freeze coring technique (Fig. 2) (e.g. Saarnisto, 1975; Saarinen and Wenho, 2005). Two parallel sediment sequences were obtained from both lakes to bridge the cutting points between core sections and possible coring-induced sediment disturbances. A modified Kullenberg piston corer (Putkinen and Saarelainen, 1998) was mainly used to obtain long sediment cores from the two lakes for palaeomagnetic analyses. With a core barrel length of ~750 cm and an inner diameter of 5.0 cm, this type of corer was able to penetrate into the more consolidated deeper sediments by means of weights of up to 300 kilogrammes. Two sediment cores were taken from Kortejärvi using a larger-diameter hand-operated piston corer (core length ~300 cm, inner diameter 6.5 cm). None of the cores was azimuthally oriented, but care was taken to avoid rotating the coring gear during sediment penetration. The cores were stored in a cold room (5°C) at the Department of Geology before opening.

Investigations	Lake	Core	Coring tool	Length (cm)	Water depth (m)	Coring time	N:o of samples
Varve analyses							
	Lehmilampi	**A1**	**Piston corer**	**0-240**	**10,80**	**3/2004**	
		B3	**Piston corer**	**150-394**	**10,80**	**3/2004**	
		C	**Piston corer**	**270-498**	**10,80**	**3/2004**	
		LL-III	**PP-corer**	**0-753**	**10,80**	**3/2007**	
		Several mini ice fingers	**Limnos corer and freezing technique**	**0-20**	**10,80**		
	Kortejärvi	**B1**	**Piston corer**	**0-235**	**11,86**	**3/2004**	
		B3	**Piston corer**	**150-327**	**11,86**	**3/2004**	
		A2	**Piston corer**	**150-347**	**11,86**	**3/2004**	
		Several mini ice fingers	**Limnos corer and freezing technique**	**0-20**	**11,86**		
Magnetic analyses							
	Lehmilampi	**LL-I**	**PP-corer**	**0-748**	**10,80**	**2/2006**	**317**
		LL-II	**PP-corer**	**0-749**	**10,80**	**2/2006**	**330**
		LL-III	**PP-corer**	**0-753**	**10,80**	**3/2007**	**301**
		LL-C	**PP-corer**	**0-631**	**8,50**	**3/2007**	**256**
	Kortejärvi	**KJ-I**	**PP-corer**	**0-717**	**11,54**	**3/2007**	**280**
		KJ-II	**PP-corer**	**0-747**	**11,54**	**3/2007**	**305**
		KJ-A	**Piston corer**	**0-300**	**12,05**	**4/2006**	**228**
		KJ-B	**Piston corer**	**0-304**	**12,05**	**4/2006**	**130**

Table 1. Information on sediment cores obtained from Lehmilampi and Kortejärvi investigated in the thesis.

Figure 2. Freeze cores taken from Kortejärvi in March 2004 with two types of ice fingers. The length of the "mini ice finger" on the left is ca. 20 cm. Note the undisturbed water-sediment interface (Photo courtesy of T. Saarinen)

3.2 Sediment preparation and impregnation in epoxy

Sediment cores were opened in the laboratory. The sediment surfaces of the opened halves of the core were cleaned and covered with cling film to prevent drying and oxidizing of the sediment surface. Visual comparison of piston cores with the freeze cores revealed that approximately 5 cm of sediment corresponding to 10 to 20 years was missing from the topmost piston cores. For the construction of the varve chronology the sediments were impregnated in low-viscosity epoxy using the water-acetone-epoxy impregnation method (Lamoureux, 1994; Pike and Kemp, 1996; Lotter and Lemcke, 1999; Tiljander et al., 2002). Impregnation in epoxy solidifies the soft sediment, preserves fine sediment structures and allows the preparation of standard sized samples. Sediment preparation and impregnation procedures employed in this study are described in Paper I. The epoxy components included nonenyl succinic anhydride (NSA), vinyl cyclohexene dioxide (VCD or ERL 4221), diglycidyl ether of polypropylene glycol (DER 736) and dimethylaminoethanol (DMAE) (manufacturers Structure Probe Inc. and PolySciences Inc.) in the proportions quoted by Tiljander et al. (2002). The success of impregnation was generally good. Occasionally, the epoxy did not penetrate to the core of the subsample, which remained soft and sticky. This caused trouble later on in the sample preparations, when samples were to be cut and polished into standard size slabs for radiography. Moreover, after several months of storage, some of the thin slabs and surfaces of the blocks were prone to twisting and cracking.

3.3 Radiography of sediment samples

Radiography of sediment enables rapid, non-destructive scanning and recording of sediment structures, which are not always visible to the naked eye. Since the densities, thicknesses and the atomic numbers of the sediment constituents determine their ability to absorb X-rays (Hamblin, 1962; Axelsson and Händel, 1972), X-ray radiography is especially well suited for documenting thin (<0.1 mm) clastic-organic varves with distinct density contrast between the different seasonal laminas (Saarinen and Saarnisto, 1998). The sample slabs were radiographed at the Department of Geology using a Soredex Mamex x-ray device, originally designed for mammography, with a focus spot size of 0.1 mm and a focal distance of 50 cm. Sediment subsamples were placed above the Agfa Structurix DW/D7 film, and radiographs were taken with an exposure time of 5×5 seconds and the settings adjusted to 8 mA and 20kW. These values were chosen after testing with different settings, because they produced radiographs where sediment laminations appeared distinctively. A calibration wedge made of cover glass slips was x-rayed with each set of samples for later adjustment of the grey scale values throughout the varve record (Fig. 3). The films were developed manually. In the case of Kortejärvi a pre-existing set of radiographs from a reconnaissance survey was also available, and this was utilized as well.

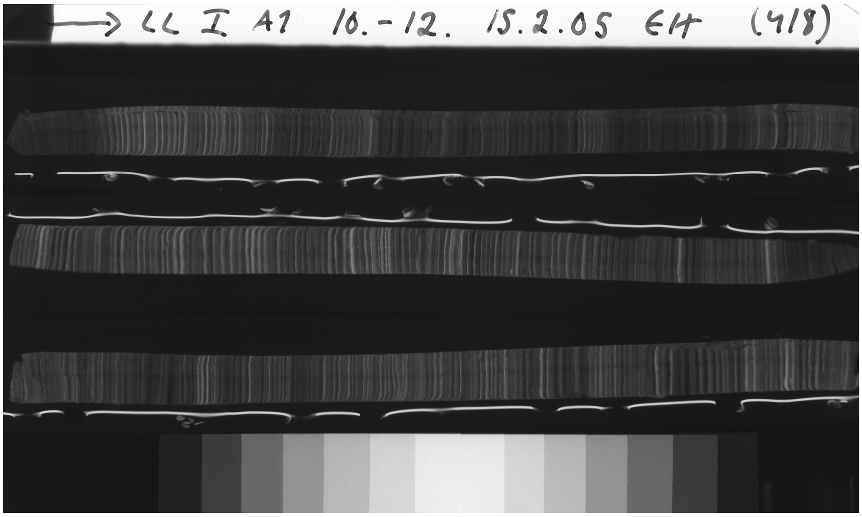


Figure 3. Radiograph from Lehmilampi showing three subsamples and a calibration wedge. More dense spring mineral laminas appear as light and organic laminas as dark.

3.4 Digital image analysis and varve counting

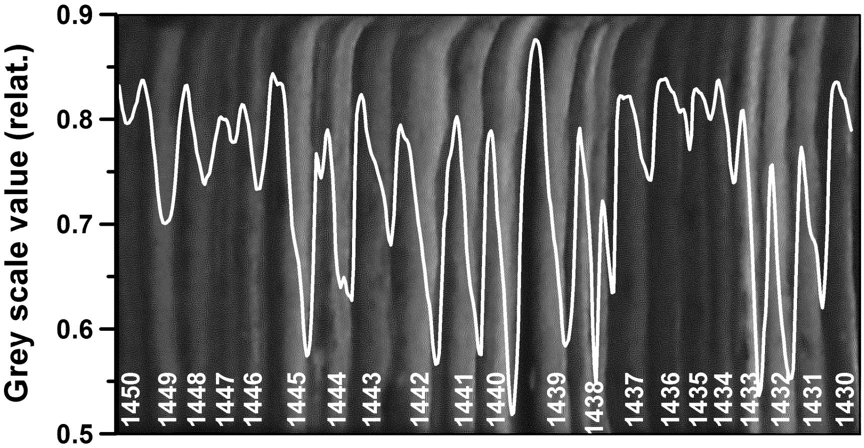
Petterson et al. (1999) investigated the relationship between varve grey-scale values, derived from image analysis, and sediment compositional changes in the annually laminated sediments of Lake Kassjön (Sweden). They emphasized the potential of image analysis as a tool for the rapid collection of high-resolution thickness and proxy compositional information on clastic-organic varves in palaeoenvironmental studies. In previous studies investigating clastic-organic varves, sediment radiography in combination with digital image analysis have become an established method for collecting seasonal data from clastic-organic varves (Saarinen and Petterson, 2001; Tiljander et al., 2002; Ojala, 2004). Sets of x-ray images from Lehmilampi and Kortejärvi were scanned with a resolution of 1000 dpi using a commercial flatbed scanner (Canon 9900F). The individual radiographs were adjusted to the same arbitrary frame of reference of grey scale values using the calibration wedge in order to produce a continuous grey-scale record. Varve counting procedure is described in more detail in Paper I. Counting of varves was continued as deep as the varve structure could be identified. Marker horizons such as prominent clastic layers were noted, and the varves between these markers were counted three times to estimate the counting error, after which average number of varves was counted for each section. The counting time, in which the number of varves was closest to the average was taken to represent as the most probable number of varves in that section. These sections were combined into a composite varve record for Lehmilampi and Kortejärvi, and the following varve parameters were calculated using the program *Lustot.BAS* by. T. Saarinen from the relative grey scale data in order to characterize composition of a single varve:

- Light sum (LS): Sum of all grey values
- Dark sum (DS): 255*number of pixels - LS
- Mean X-ray density: Sum of all grey values / n:o of pixels
- Varve thickness (VT): N:o of pixels*0.0254 mm
- MIN: Minimum x-ray density value in each varve
- MAX: Maximum x-ray density value in each varve

LS and DS are determined by the thickness and composition of each lamina within a varve, and increased LS (DS) values denote increased accumulation of mineral (organic) matter. Mean x-ray density describes the average varve composition. MAX (MIN) quantifies the highest (lowest) grey scale value in varve. Example of an x-rayed sample from Lehmilampi with associated varve data is given in Fig. 4.

3.5 Magnetic measurements

Long-core low-field magnetic susceptibility was measured at 2.0 mm intervals along the split cores on an automatic long-core measurement system built at the Department of Geology, using a Bartington MS2 susceptibility meter attached to 2E point-reading sensor. These high-resolution down-core magnetic susceptibility logs were used for initial core correlation and for a quick estimate of the variations in the concentration of magnetite. The cores were sampled at ca. 2.5 cm intervals into transparent polystyrene cubic boxes, with an orientation arrow showing the direction



Year (AD)	LS	DS	N:o of pixels	Mean x-ray density	VT (mm)	MIN	MAX
1445	1323	5817	28	47,24	0,71	39,78	55,41
1444	687	2883	14	49,05	0,36	45,67	51,31
1443	1625	7555	36	45,15	0,91	39,40	49,37
1442	1570	7355	35	44,87	0,89	42,79	47,89
1441	1408	6752	32	44,01	0,81	41,77	45,62
1440	2029	9191	44	46,12	1,12	39,93	55,49
1439	2273	9457	46	49,42	1,17	43,99	56,74
1438	886	3959	19	46,65	0,48	41,26	51,59
1437	1327	6323	30	44,22	0,76	40,42	48,99
1436	951	4149	20	47,55	0,51	39,14	52,43
1435	962	4903	23	41,82	0,58	37,61	46,56
1434	1011	4599	22	45,97	0,56	44,24	48,58

Figure 4. X-ray density curve from Lehmilampi between the years AD 1430 and 1450 and the associated varve data for a selected period of 12 years. See text for the explanations of the parameters.

of the z-axis. During the course of the study two types of boxes were used, with inner volumes of 6.4 cm^3 and 7.9 cm^3 (manufacturers Semadeni and Caubère). The samples were stored sealed in plastic vessels in a moist condition for up to three weeks in a cold room at 5ºC before the measurements.

Magnetic measurements were made in the Laboratory for Paleo- and Rock Magnetism at the Helmholtz Centre Potsdam, German Research Centre for Geosciences. The following bulk magnetic parameters were measured from all samples:

1) Low-field magnetic susceptibility (κ)

2) Natural remanent magnetization (NRM) and its demagnetization in alternating field (AF) in ten steps up to 100 mT

3) Anhysteretic remanent magnetization (ARM) using a maximum AF field of 100 mT superimposed with a 0.05 mT steady field, and its AF demagnetization up to 50 or 65 mT

4) Isothermal remanent magnetization (IRM) using a maximum field of 1000mT and backfield of -100mT

Detailed information on all the measurements and instrumentation can be found in Papers II and III. Calculation of interparametric ratios using the concentration-dependent parameters κ, ARM and SIRM allowed inferences to be drawn regarding the relative changes in magnetic mineralogy and grain size.

3.6 Total organic carbon

Total organic carbon (TOC) quantifies the content of organic matter in sediment. Organic matter can be derived from allochthonous and autochthonous sources, and value of TOC is determined by the balance between the input and degradation of organic matter (Meyers and Teranes, 2001). A subsample for analysing TOC concentration was taken from each sample of the core LL-I (*n*=317) from Lehmilampi. For determination of TOC, ca. 3 mg of sample was weighted in an Ag-capsule and few drops of 20% hydrochloric acid were added. Samples were heated for 3 h at 75°C, and finally they were wrapped up in the Ag-capsules. Analysis of elemental content was performed with Carlo Erba elemental analyzer (NC2500). The reproducibility for replicate analyses is 0.2 %.

4. Results

4.1 Sediment records of Lehmilampi and Kortejärvi

The 750-cm long sediment sequences of Lehmilampi and Kortejärvi express similar development history, i.e. from part of a large lake complex into a small lake. The lowermost sediments cored from Lehmilampi and Kortejärvi contain clay varves which were deposited in Pielinen ice lake. The base of sediment unit with glacial varves was not retrieved. Sediments predating isolation from Pielinen are characterized by black sulphide laminated gyttja clays, and concentration of organic matter is low (TOC ≤ 3%, Paper II). Using sediments cored from two sub-basins of Pielinen, Vasamaselkä and Purjeselkä, Simola (1984) suggested that the black laminations result from some process having longer duration other than annual. The characteristics and origin of these rather irregular sulphide laminations were not established in the present study. Attempts to count these laminations with available techniques were hindered by 1) rapid oxidation of the sediment surface and virtual disappearance of laminations, 2) laminations were not clear in x-ray densitometry.

Sulphide laminated sediments grade into more regularly laminated sediment together with increasing concentration of organic matter. Sediments contain pale and thick silty laminas, which alternate with organic brown layers. These sediments were interpreted to have been deposited during isolation. The uppermost sediments cored from Lehmilampi and Kortejärvi record a striking succession of light (clastic) and dark (organic) laminations extending to sediment depth of ~400 cm and ~350 cm. The seasonally contrasting climatic regime, with cold winters and warm summers, induces rhythmic variations in sources of sediment. Fine sediments are transported to lake basins in the spring, when approximately half of the yearly runoff is discharged following snowmelt (Kuusisto, 1984). The resulting detrital lamina grades into a layer of fine organic matter derived from autochthonous productivity during open water season. Low concentration of dissolved oxygen in the hypolimnetic waters allows the preservation of conspicuous clastic-organic varves in Lehmilampi and Kortejärvi. Direct evidence of the annual nature of the laminations was obtained by ice-finger sampling in consecutive years and observing the building up of a similar set of laminas each year. Apparently, sediments preserved in the deepest parts of the basins of Lehmilampi and Kortejärvi contain an unbroken sequence of annual laminations extending until the present. A mean number of 5122 and 3902 varves were counted in the sediments of Lehmilampi and Kortejärvi, respectively. Cumulative calculation errors in varve counting are estimated as +104 (+2.1 %) and−114 (−2.2 %) varves for Lehmilampi and +60 (+1.5 %) and −59 (-1.5 %) for Kortejärvi (Paper III). Such continuous varve deposition reflects stability of hypolimnetic conditions and absence of slumping, which has ensured the preservation of high resolution varve records extending from the Middle Holocene until present. Consistency of sediment deposition in the northern deep basin of Lehmilampi was demonstrated by high-resolution logs of magnetic susceptibility measured from a set of eight reference cores (Paper I).

Varve quality is not constant throughout the sediment sequences, but varies from perfect to moderate, as reflected in variations in the error estimates (Paper III). Several factors contribute to the quality of varves. Occasional periods of better oxygenation of the lake bottom can cause poorer varve preservation by benthic fauna spreading to formerly uninhabited deep basin areas. Microbial methanogenesis and degassing in strongly reducing environments may destroy varve structure. Moreover, sediment deformation during coring and subsampling, which is common when preparing soft sediments, can also reduce the precision of varve counting. Varve counting is a subjective procedure, and subjectivity becomes even more important when varve structure differs from the usual set of detrital and organic lamina. For example, the virtual absence of the spring laminas in the sediments deposited during the High Mediaeval (1000 and 700 yrs BP) made locating varve boundaries difficult. In the impregnated and polished sediment blocks this period is dark blackish brown. Varve counting could be carried out during the Mediaeval and sediment sections with similar characteristics by adjusting the contrast and brightness of the scanned radiographs, which made distinguishing varve boundaries easier. On one hand, counting error reached a maximum of 7.5 % in organic-rich sediments deposited >4400 yrs BP in Lehmilampi. On the other hand, largest difficulties in varve counting of Kortejärvi took place in the sediments deposited during the last 300 years (Paper III), where sedimentation is characterized by frequent pulses of mineral matter. Varve quality in these subrecent sediments was probably also degraded by degassing, because sediment surface became perforated after core opening. It should be noted that small calculation error also indicates consistent interpretation of the varve boundaries in the sediment section under investigation, not necessarily the preciseness of the result itself.

4.2 Review of the papers I-V

4.2.1 **Paper I**: *Haltia-Hovi, E., Saarinen, T., Kukkonen, M., 2007. A 2000-year record of solar forcing on varved lake sediment in eastern Finland. Quaternary Science Reviews 26, 678-689.*

Precisely dated high-resolution natural archives provide valuable information on climatic and human histories far beyond the era covered by direct measurements, improving comprehension of past environments and climates. The article presents a high-resolution varve record covering the last 2000 years from Lehmilampi. A sediment core was impregnated in low viscosity epoxy to preserve the fine varve details. X-ray densitometry and semi-automatic digital image analysis were applied in collecting data on the number, thickness and mean x-ray density of the varves. The precision of the varve counting is fairly high, reflecting the high quality of the varves, and the counting error for the core analysed was estimated as -2.2% (44 varve years) and +2.3% (46 varve years) for the last 2000 years. Analysis of varve properties revealed by digital image analysis revealed that the accumulation of organic matter (described by DS) closely follows the varve thickness, which ranges between 0.25 and 2.92 mm during the last 2000 years. Conspicuously similar patterns were found in the visual comparison of varve thickness record with residual $\Delta^{14}C$ over the last 2000 years (Reimer et al., 2004). A preliminary interpretation was proposed that varve thickness is controlled by solar forcing. This implies that, under ideal conditions, clastic-organic varve sequences respond sensitively to changes in larger-scale climate variables and not merely to local conditions. The mediating link between varve thickness and solar forcing was not established, however, and further investigations were proposed.

4.2.2 **Paper II**: *Haltia-Hovi, E., Nowaczyk, N., Saarinen, T., Plessen, B., 2009. Magnetic properties and environmental changes recorded in Lake Lehmilampi (Finland) during the Holocene. Journal of Paleolimnology 43, 1-13.*

This paper presents the Holocene history of Lehmilampi as revealed by bulk mineral magnetic analyses, including χ, ARM and IRM, in combination with total organic carbon (TOC) data. The varve chronology was extended to cover the last 5122 years and the deeper sediments not covered by varve chronology were dated in respect to the palaeomagnetic master curve FENNOSTACK (Snowball et al., 2007). The general development history of Lehmilampi could be rapidly documented from the bulk magnetic measurements. Lehmilampi became isolated from Pielinen approximately 5100 cal. yrs BP. The two lake phases differ in terms of the mineral magnetic properties of the sediments, notably the magnetic grain size variations. The magnetic carrier is most likely magnetite, with some contribution from haematite. Organic content in the sediment increases rapidly with isolation, reflecting increasing nutrient levels in the basin. According to the interparametric ratios responding to relative shifts in magnetic grain size (χ_{ARM}/SIRM and SIRM/χ_{LF}), magnetic grain size decreases with isolation. Variations in magnetic grain size correspond to those in the concentration of organic matter, interpreted to reflect an authigenic source of magnetic minerals, that is, bacterial fossil magnetosomes contributing to the post-isolation magnetic properties. The variations in the input of fine magnetite, i.e. the production of magnetosomes, in Lehmilampi are assumed to be regulated by lake productivity, and ultimately by climate.

4.2.3 **Paper III**: *Haltia-Hovi, E., Nowaczyk, N., Saarinen, T., 2010. Holocene palaeomagnetic secular variation recorded in multiple lake sediment cores from eastern Finland. Geophysical Journal International 180, 609-622.*

This paper presents directional palaeosecular variation (PSV) records, or inclination and relative declination, as preserved in the sediments of Lehmilampi (n=1320) and Kortejärvi (n=943) during the Holocene. The original NRM was carefully demagnetized in ten steps in all the samples, and the direction of the characteristic remanent magnetizations (ChRM) was determined by progressive alternating field demagnetization of the natural remanent magnetization (NRM) followed by principle component analysis. After the removal of the occasional and small viscous overprint, the sediments from both lakes display strong, stable single-component magnetizations almost throughout the core lengths. Sediment in Kortejärvi preserves an unbroken series of clastic-organic varves covering the last 3902 years until present, and varve chronology was constructed for Kortejärvi using similar methods as for Lehmilampi. The older sediment sections in both lakes were dated by palaeomagnetic pattern matching in relation to the varve-dated PSV data for Lake Nautajärvi (Ojala and Saarinen, 2002), yielding a composite age model. According to the mineral magnetic investigations, remanence is predominantly carried by a magnetite of pseudo-single-domain grain size, accompanied by minerals with a harder coercivity, most likely haematite. The fairly high sedimentation rates (0.35 to 0.75 mm/yr) ensure high resolution in the recording of changes in the geomagnetic field. The PSV data from Lehmilampi and Kortejärvi were stacked and Fisher statistics were applied to calculate the mean directions together with 95% confidence intervals ($\alpha95$) and precision parameters (k) to produce a North Karelian PSV stack.

Comparison of the declination and inclination features of the North Karelian stack with previously published data for Great Britain and Fennoscandia points to remarkable similarity with respect to time and amplitude, confirming the same geomagnetic origin behind the changes recorded in the palaeosecular directional variations.

4.2.4 **Paper IV**: *Haltia-Hovi, E., Nowaczyk, N., Saarinen, T. Environmental influence on relative palaeointensity estimates derived from Holocene varved lake sediments in eastern Finland.* Submitted to Physics of the Earth and Planetary Interiors.

This paper presents relative palaeointensity (RPI) estimates derived from four sediment cores from Lehmilampi and Kortejärvi extending from the Middle Holocene up to the present. These cores were selected from a set of eight cores (Paper III) on the basis of their apparently uniform mineral magnetic properties, which is an important prerequisite for successful determination of RPI. Three RPI estimates were calculated from each core by normalizing NRM with different concentration-dependent parameters (NRM_{30mT}/κ, NRM_{30mT}/ARM_{30mT}, and $NRM_{30mT}/SIRM_{1000mT}$) to isolate the geomagnetic RPI signal in the sediment. Different normalizations produced curves of similar millennial amplitudes and trends, but higher frequency variations are different. However, RPI estimates are dependent on their normalizing parameters and respond to variations in magnetic grain size and sediment composition, indicating unremoved environmental imprint. $NRM_{30mT}/SIRM_{1000mT}$ from Lehmilampi is least coherent with its normalizer, and three cores using this RPI estimate from Lehmilampi were stacked in order to compare the millennial trends with other relative and absolute palaeointensity records from Europe. Comparison shows that the different records agree fairly well, suggesting that sediments from Lehmilampi record the general trends of geomagnetic palaeointensity changes.

5. Discussion

5.1 Palaeoenvironmental development interpreted from mineral magnetic records

Major changes in lithostratigraphy and shifts in mineral magnetic characteristics trace of the main stages in the histories of Lehmilampi and Kortejärvi (Paper II and III). Concentration of magnetic material is highest in the glacial varves, and magnetic susceptibility ranges from 800 to 1800 (SI, 10^{-6}). Such a high values are probably caused by abundant magnetite in the glacially scoured material. Volume-specific concentration of magnetic minerals in the sediments decreases rapidly during the Early Holocene, and a general decreasing trend continues during the Holocene. In the light of mineral magnetic evidence, sediments accumulated in Pielinen record a stable phase in lake development history. Unequal isostatic uplift has tilted the basin of Pielinen during the Holocene and exposed former lake bottom for tens of kilometres northwest of Pielinen (Virkkala, 1949; Hyvärinen, 1966; Miettinen, 1996; Saarnisto, 2000). Regression of Pielinen led to the gradual isolation of Kortejärvi and Lehmilampi approximately 7000 yrs BP and 5100 yrs BP, respectively. Gradually stabilizing depositional environment and increasing primary production in the closing small suboxic basins gave rise to the start of formation of distinct clastic-organic varves. The shift in lithostratigraphy recording the change from a part of a large lake complex into small boreal lake is evident in mineral magnetic parameters, particularly in magnetic grain size. Mineral magnetic parameters reflect rapid changes in the post-isolation sediments. These may be interpreted in terms of a combination of environmental factors, including changes in the influx of detrital magnetic minerals, production of organic matter and interconnected production of bacterial magnetite and, possibly, dissolution of magnetite. Mineral magnetic properties in the two coring sites of Kortejärvi basin show unexpectedly differing characteristics (Paper III). Such difference in magnetic grain-size, concentration and mineralogy between two coring sites in the same basin may suggest 1) partial dissolution of magnetic minerals in the coring site represented by the cores KJ-I and KJ-II, and 2) authigenesis of ferrimagnetic minerals by biomineralization in coring site represented by cores KJ-A and KJ-B. In the case of Lehmilampi, magnetic grain size changes in response to changing organic matter content (TOC) in varved sediments. This was tentatively interpreted as indicating authigenic production of single domain-sized magnetosomes by magnetotactic bacteria in phase with lake productivity. A similar relationship between the percentage of organic matter in the sediment and enrichment of the magnetite concentration has been detected in earlier studies on homogenous and varved lake sediments in Sweden, as shown by TEM and/or mineral magnetic analyses recording variations in the production of authigenic magnetosomes (Snowball, 1994; Snowball et al., 1999; Snowball et al., 2002).

Increase in the concentration of magnetic minerals during the last few hundred years probably reflects human-induced land use changes, such as slash-and-burn cultivation in the catchments of these lakes, which exposes soils and amplifies natural rates of erosion. Slash-and-burn technique was widely used in eastern Finland between the 17th and 20th centuries (Grönlund, 1991; Pitkänen and Huttunen, 1999). Logging and farming in the surroundings of Lehmilampi and Kortejärvi has increased the input of mineral matter to lakes. In addition, a railway line was built close to Kortejärvi in the early 1920´s, which is visible as increased accumulation of mineral matter recorded in the deposition of varves with thick spring laminas. Ongoing pollen analyses from the sediments of Lehmilampi will give more detailed information on the beginning of human settlement and its continuity in northern Karelia (personal communication, A. Augustsson, University of Kalmar).

5.2 Climate signal recorded in the varves of Lehmilampi

Several studies employing different palaeoclimatic proxies have shown that the Holocene climate, once considered as a climatically stable epoch, has undergone rapid shifts (e.g. Alley et al., 1997; Bond et al., 2001; Mayewski et al., 2004; Snowball et al., 2004). The physical parameters of varves can potentially carry high-resolution signals of these variations, which can expand our knowledge of past climate shifts and their rates of change, as well as help us to put into perspective the present warming trend and the mechanisms behind it. Establishing the actual relation between varve parameters and climate would provide the key to interpreting the wealth of information that is carried in long varve records. This remains a challenge, because of the complex response of lakes to external forcing on sedimentation, e.g. climate-controlled effects on catchment erosion and the transportation of detrital grains into the lake. Nevertheless, many studies have successfully shown that the characteristics of recent varves, especially variations in varve thickness, vary sensitively in response to climatic parameters when calibrated against local instrumental meteorological and hydrological data (Itkonen and Salonen, 1994; Leeman and Niessen, 1994; Hughen et al., 2000; Romero-Viana et al., 2008). Instrumental climatic data are localized in character, however, and are available only for the very recent past, so that climatic proxies with an annual resolution are invaluable in order to extend our understanding of climate variability back beyond the measurement era. The influence of solar forcing on climate has been suggested in several studies of palaeoclimatic data from different sources (Denton and Karlén, 1973; Grove and Switsur, 1994; Vos et al., 1997; van Geel et al., 1999; Bond et al., 2001). Varve thickness measurements obtained from the Lehmilampi sediments during the last 2000 years showed that the varve thickness appears to be changing fairly well in phase with the variations in solar activity, as represented in the residual ^{14}C variations (Reimer et al., 2004), although some leads and lags are evident (Fig. 5). During the last 2000 years, the thinnest and nearly entirely organic varves were deposited in the High Mediaeval period between 11th and 13th century. The virtual absence of detrital matter during this time period can be interpreted as warmer winter temperatures and/or minor wintertime precipitation, resulting in weak spring floods. Moreover, different palaeoenvironmental proxies, including buried soils and δ^{13}C from *Pinus* cellulose, from Khibiny Mountains in Kola Peninsula indicate a dry and warm High Mediaeval and reduced winter precipitation followed by cooling of climate (Kremenetski et al., 2004). A completely different but very interesting approach was adopted by Berggren et al. (2010), who isolated ^{10}Be signal in the sediments of Lehmilampi during the last 100 years and successfully compared it with sunspot number data, indicating the sensitivity of sedimentation in Lehmilampi to variations in solar activity.

Human impact and its duration on the lake catchment are unresolved, and whether a signal of purely climatic origin has been established remains an open question. For example, the suggested linkage between varve thickness in Lehmilampi and ^{14}C residual record (Reimer et al., 2004) clearly deviate during the Maunder Minimum, i.e. between the late 17th and mid-18th century, which may reflect human-induced catchment disturbance, causing an imbalance between the regional climate and response of the lake. Nevertheless, the relation between organic accumulation and climate is still an interesting one, as shown by Ojala et al. (2008), who found coherent trends in the thickness of the organic laminas in clastic-organic varve couplets and the length of growing season as inferred from pollen-based temperature reconstructions during the Holocene. The results obtained from Lehmilampi highlight the value of this clastic-organic varve record as a proxy indicating larger-scale climatic conditions, encouraging further studies in this field. X-ray densitometry combined with digital image analysis is particularly applicable tool in the study of seasonally resolved records, where year-by-year sampling of fine laminations is very laborious. However, this technique records only density variations in varves and omits the microstratigraphy, which can reveal more discreet variations for a more precise climatic interpretation. A calibration of clastic-organic varve parameters against meteorological and hydrological observational data would be needed in order to understand the reflection of climate in varves on longer timescales. Then, full use of the potential climate data recorded in high-resolution clastic-organic varves could be possible (Jones et al., 2009).

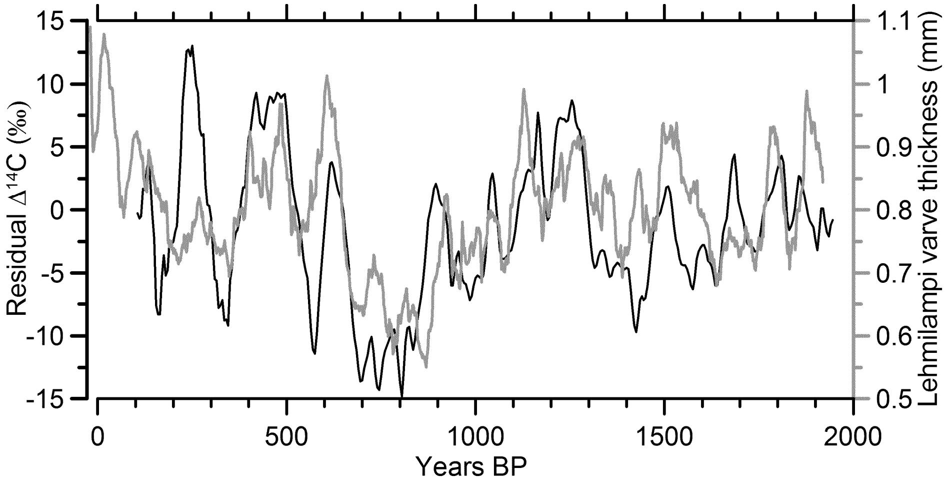


Figure 5. Varve thickness of Lehmilampi (grey line) smoothed with 51-yr running average and $\Delta^{14}C$ residuals (Reimer et al., 2004).

5.3 Palaeosecular variation records of Lehmilampi and Kortejärvi

The results regarding the directional components of palaeosecular variation in Lehmilampi and Kortejärvi showed clearly consistent patterns during the Holocene. (Paper III) The ten-step NRM demagnetization procedure of all the samples and subsequent determination of the characteristic directional components by principal component analysis were carried out in the most detailed way published so far for Fennoscandian lake sediments in order to isolate the stable component of the magnetization. Such a detailed investigation was made possible by the use of a fully automated cryogenic long-core magnetometer adapted for measurements on discrete samples, in which eight samples could be processed at a time. The uniformity of the palaeosecular variation records in Lehmilampi and Kortejärvi and their similarity with other published PSV records from Europe attests to the excellent ability of these sediments to record directional palaeosecular variations in high resolution. This is due to the relatively high sediment deposition rates and absence of post-depositional disturbance of the sediment. Therefore, magnetization lock-in time is likely to have been short in these sediments, as longer lock-in times would induce larger-scale smoothing of amplitudes. Nevertheless, the palaeosecular variation records obtained from lake sediments are inevitably altered during the remanence acquisition processes in the sediment, bearing a filtered record of the original geomagnetic signal.

Mean ChRM inclinations (*I*) in most of the cores are somewhat too shallow, ranging from 69.3º to 72.3º, as compared with the expected geocentric axial dipole value for the site of 75.3º. Inclination flattening is frequently found in lake sediments (King, 1955; Tauxe, 2005), and the deviations detected in these sediments are in the same range as the previously published values for Fennoscandian varved lake sediments (Saarinen, 1998; Ojala and Saarinen, 2002; Ojala and Tiljander, 2003). Inclinations shallower than expected may result from tilting of the corer during sediment penetration, compaction in the deeper sediments or non-dipolar field contributions, but it is also possible that the geocentric axial dipole model is not applicable at high northern latitudes (Stockhausen, 1998).

The reconstructed PSV data for the younger sediment sections, i.e. the independently dated last ~5000 years in Lehmilampi and ~3900 years in Kortejärvi, can be used as a master curve for dating homogenous sediments in the same regional context, provided that the sediments under investigation hold a reliable palaeosecular variation record. The use of palaeomagnetic data for core correlation and the relative dating of lake sediments have been discussed by several authors, such as Creer (1982), King et al. (1983), Løvlie (1989), Lund (1996) and King and Peck (2001). The well-known declination (*D*) feature "f" (Turner and Thompson, 1981) is centred in Lehmilampi around 2620±40 yrs BP and in Kortejärvi between 2650±45 yrs BP (KJ-A) and 2720±40 yrs BP (KJ-I), when interpreting the easternmost peak in the *D* just before the rapid westerly movement of the vector as the feature "f". This feature is present in all the PSV records in the same regional context, defined by a radius of 1000-2000 kilometres, and provides a clear chronostratigraphic feature for correlating records in the same region. However, positioning of a particular feature on a palaeosecular variation curve showing high-frequency variations is fairly subjective, increasing the uncertainty of dating of the target curve.

5.4 Constraints on obtaining relative palaeointensity estimates

High-resolution relative palaeointensity records have published from several Fennoscandian clastic-organic varved sequences (Saarinen, 1998; Ojala and Saarinen, 2002; Snowball and Sandgren, 2002; Snowball et al., 2007), and it has been common practice to normalize the natural remanent magnetization (NRM) by anhysteretic remanent magnetization (ARM). Using ARM as normalizing parameter is supported by the fact that it is particularly sensitive to the concentration of single-domain and fine pseudo-single domain grains, which carry the stable palaeomagnetic information in the magnetic assemblage (Levi and Banerjee, 1976; King et al., 1983). Despite the apparently ideal mineral magnetic properties of the Lehmilampi cores selected for reconstructing variations in RPI, different normalizations of NRM from Lehmilampi and Kortejärvi produced ambiguous results. Sediment compositional variations controlling mineral magnetic properties express co-variation with the proposed RPI estimates.

The results from Lehmilampi and Kortejärvi suggest that RPI estimates reconstructed from varved lake sediment sequences may be biased by unremoved environmental influences (Paper IV). Preservation of varves requires low concentration of oxygen in the deep basin, and reducing conditions combined with relatively high deposition rates of organic matter may lead to selective dissolution of magnetic minerals. However, mineral magnetic parameters of the cores selected for reconstructing RPI did not explicitly indicate dissolution of magnetite. The underlying variations in magnetic grain size and sediment composition may compromise the reliability of these relative palaeointensity estimates, but the favourable comparison with the patterns of dipole moments reconstructed using archaeomagnetic data (Pesonen et al., 1995; Kovacheva et al., 2009) suggests that the effect is not excessive and the millennial variations in relative palaeointensity are mainly controlled by changes in geomagnetic dipole field. When employing RPI data obtained from varved lake sediments, such as estimating the contribution of intensity variations in geomagnetic field to cosmogenic nuclide production rates in order to estimate past variations in solar activity (Snowball and Sandgren, 2002), these possible subtle imprints should nevertheless be considered and corrected for, if possible.

Stacking of various RPI estimates from different settings may smooth out local variations in RPI records, but it is also possible that sediment cores from a geographically restricted area such as Fennoscandia reflect similar variations controlled by the same climate regime. In Figure 6 is plotted TOC record (reversed scale) from Lehmilampi together with FENNORPIS and Lake Nautajärvi RPI data from the last 4000 years. The different records display similar features, which may suggest a partially common climatic origin of the environmental imprint in the records. Interpretation of a TOC record is not simple, because sediment TOC concentration is influenced by several factors (Meyers and Teranes, 2001). Most certainly Lehmilampi TOC is controlled by local environment as well, but it has congruent features with climatic proxies from the Northern Atlantic and areas surrounding it. The period of higher intensity between 2800 and 2200 yrs BP coincides with low organic content. Approximately during this time period is recorded an IRD event in the North Atlantic (Bond et al., 2001) and increased concentration of dust and sea salt in Greenland ice cores (O´Brien et al., 1995), which may be recorded in Lehmilampi as suppressed lake productivity. Possibly, remanence acquisition is influenced by climate, which controls sediment and mineral magnetic characteristics. It is suggested that the presence of environmental imprints should be considered more carefully in future studies when attempting to reconstruct relative palaeointensities from varved lake sediments.

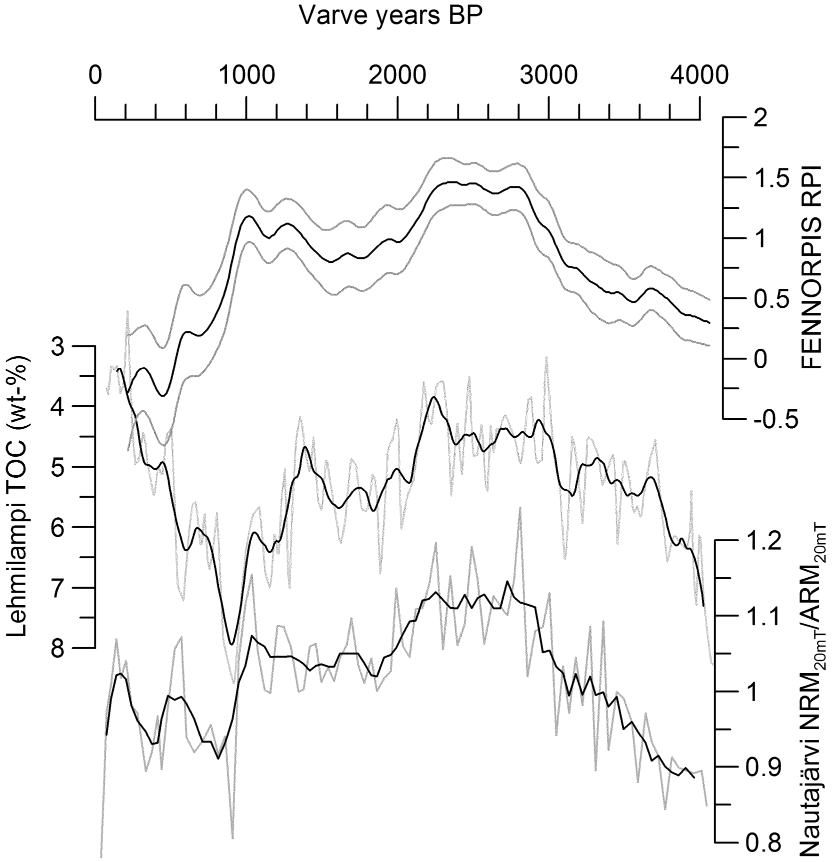


Figure 6. FENNORPIS and Lake Nautajärvi RPI estimates and TOC measured from Lehmilampi. The different records display similarities, which may reflect a partly similar climatic modulation of the variations.

6. Conclusions

1. Post-isolation sediments of Lehmilampi and Kortejärvi contain an unbroken series of clastic-organic varves encompassing the last 5122 and 3902 years, respectively.

2. Variations in varve thickness in Lehmilampi during the last 2000 years show correspondence with solar activity, as deduced from the ^{14}C residual data, suggesting climatic control over sedimentation. Varve thickness and composition shows changes coinciding with the Mediaeval Climate Anomaly (11-13th centuries) and the subsequent Little Ice Age. This indicates the potential of clastic-organic varves to respond sensitively to larger-scale climatic variations.

3. Bulk mineral magnetic characteristics respond to palaeoenvironmental processes and changes. In combination with other sedimentological data, main stages of lake development can be quickly outlined.

4. The directional palaeosecular variation records are well preserved and consistent, confirming the excellent capability of these sediments to record palaeosecular variations. Varve-dated palaeosecular variation records from Lehmilampi and Kortejärvi can be used as master records for dating homogenous sediments.

5. Centennial variations in relative palaeointensity estimates reconstructed with conventional normalization techniques are imprinted by environmental influences mainly linked with changes in the concentration of sediment organic matter. Relative palaeointensity estimates from varved lake sediments should be treated with caution, unless they are shown to be free of environmental influences.

7. Supplementary information: Radiocarbon dating

In an attempt to validate varve chronology for Lehmilampi, radiocarbon analyses were carried out at the Radiocarbon Laboratory in Poznan, Poland. Terrestrial plant macrofossils were searched for by sieving the sediment material in slices of 1 cm through a 0.05 mm mesh under running tap water. Unfortunately, it turned out to be difficult to find suitable material for dating, as macrofossils were scarce, even though the catchment is densely vegetated by boreal mixed forest. The very few, sporadic individual fruits of birch did not contain enough dry organic material for accelerator mass spectrometry (AMS) dating. Two pine needles found at depths of 100 cm and 244 cm in the sediment, corresponding to varve ages of ~779 AD and ~954 BC, were submitted for AMS dating, and bulk sediment samples were taken from three depths. Total organic carbon was used for dating in the two deeper samples. The radiocarbon ages were calibrated to calendar ages using CalPal online (Cologne Radiocarbon Calibration & Paleoclimate Research Package, http://www.calpal-online.de/). Unfortunately, radiocarbon dating of these sediments was not very successful (Table 2). Only the uppermost macrofossil dated by AMS yielded an age fairly close to the varve age, but the rest of the ^{14}C dates turned out to be excessively old. This is assumed to be due to the complex history of the lake, causing the redeposition of older carbon and making radiocarbon dating an unsuitable technique for the sediments.

Sample depth	Sample code	Sample material	^{14}C age	Cal. ^{14}C age	Varve age* Palaeomagnetic age**
LL 100.0 cm	Poz-18359	Pine needle	1305+/- 30 BP	710+/-40 cal AD	779 AD*
LL 244.0 cm	Poz-18360	Pine needle	2985+/-35 BP	1222+/-64 cal BC	954 BC*
LL 400-401.0 cm	Poz-18404	Bulk sample	5210+/-40 BP	4018+/-33 cal BC	3100 BC**
LL 500-504.5 cm	Poz-18361	Bulk sample/TOC	8340+/-50 BP	7417+/-63 cal BC	4800 BC**
LL 600-604.5 cm	Poz-18362	Bulk sample/TOC	10970+/-60 BP	10947+/- 99 cal BC	8500 BC**

Table 2. Radiocarbon age determinations for Lehmilampi

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In der Tiefe ist es einsam

Eeva Haltia-Hovi
In Berlin, May 2010

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