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, 2, pp. 609—622.

DOI: http://doi.org/10.1111/j.1365-246X.2009.04456.x

Geophysical Journal International

Geophys. J. Int. (2010) **180,** 609–622 doi: 10.1111/j.1365-246X.2009.04456.x

Holocene palaeomagnetic secular variation recorded in multiple lake sediment cores from eastern Finland

Eeva Haltia-Hovi,[1,2] Norbert Nowaczyk[2] and Timo Saarinen[1]

[1]*Department of Geology, University of Turku,* 20014 *Turku, Finland. E-mail: eemaha@gfz-potsdam.de*
[2]*Deutsches GeoForschungsZentrum GFZ, Telegrafenberg,* 14473 *Potsdam, Germany*

Accepted 2009 November 11. Received 2009 November 9; in original form 2008 November 19

SUMMARY

Holocene palaeomagnetic secular variation (PSV) in inclination and declination recorded in the sediment remanent magnetization of two small lakes, Lake Lehmilampi (63°37′N, 29°06′E) and Lake Kortejärvi (63°37′N, 28°56′E) in eastern Finland is presented. As an outcome of systematic coring, eight cores, 300–753 cm in length, were investigated. All samples (Lehmilampi $n = 1320$, Kortejärvi $n = 943$) were subjected to palaeo- and mineral magnetic analyses. The directions of the characteristic remanent magnetization (ChRM) were obtained from progressive alternating field demagnetization of the natural remanent magnetization (NRM) followed by principle component analysis. The younger sections of the sediment columns in the studied lakes are annually laminated, providing detailed chronologies for dating PSV features back to 5100 cal. BP. The underlying older sections of the cores were dated by palaeomagnetic pattern matching in respect to varve-dated Lake Nautajärvi PSV data (Ojala & Saarinen 2002), thus yielding a composite age model covering nearly the whole Holocene epoch. Average sedimentation rates ranging from ∼0.68 to 0.74 mm yr^{-1} enabled recording of changes in the geomagnetic field at decadal resolution. The carriers of remanence are dominantly magnetite of stable single-domain to pseudo-single-domain grain size, accompanied by magnetic minerals of harder coercivity. The sediments from both lakes exhibit strong and stable single-component magnetizations nearly throughout the whole cores. The sediment magnetization lock-in delay is estimated to range between 80 and 100 yr. PSV data were transformed into time-series and subsequently stacked to comprise North Karelian stack, and Fisher statistics were used to calculate mean directions together with the 95 per cent confidence level (α_{95}). A comparison of declination and inclination features of the North Karelian stack with previously published data expresses remarkable similarity, therefore confirming the similar source behind the changes in the NRM directional records. The high quality of the PSV data extracted from Lehmilampi and Kortejärvi, in terms of dating as well as amplitude reconstruction, have a high potential to improve existing and future geomagnetic field models.

Key words: Environmental magnetism; Palaeomagnetic secular variation; Europe.

1 INTRODUCTION

Averaged over 10^4 yr, the geomagnetic field resembles the field of a dipole, aligned along the rotational axis of the Earth. On shorter timescales, non-dipolar components of the geomagnetic field become more significant (e.g. Courtillot & Le Mouël 1988; Merrill & McFadden 2003). The palaeomagnetic secular variation (PSV) of the Earth's magnetic field can be recorded as a remanent magnetization in marine and lake sediments, lava flows, or baked archaeological objects (Verosub *et al.* 2001; Le Goff *et al.* 2002; Kovacheva *et al.* 2004; Herrero-Bervera & Valet 2007).

Directional changes of natural remanent magnetization (NRM) recorded in organic-rich lake sediments during the Holocene have been studied in order to obtain continuous high-resolution records of secular variation, extending the records of geomagnetic field behaviour far beyond instrumental measurements (e.g. Mackereth 1971; Creer *et al.* 1972; Stober & Thompson 1977; Verosub *et al.* 1986; Readman & Abrahamsen 1990). In order to construct a palaeosecular variation record of good quality, several prerequisites need to be satisfied. Sedimentation must be continuous and sedimentation rates high to reconstruct a high-resolution palaeosecular variation record. The record must have a robust chronological control, and the age of the primary magnetization unequivocally established. For example, dissolution of primary magnetic minerals and/or formation of secondary magnetic minerals in anoxic depositional environments can compromise the usefulness of the record unless the different components can be reliably dated (e.g. Ron *et al.* 2007). Moreover, directional records can be physically distorted during coring and/or sampling. Through using multiple records preferably from different sites the reliability of a PSV record can be both verified and improved (Barton & McElhinny 1981; Turner & Thompson 1981; Haverkamp & Beuker 1993; Brandt *et al.* 1999; Snowball & Sandgren 2002; Ojala & Tiljander 2003; Vigliotti 2006; Snowball *et al.* 2007).

Annually laminated, that is, varved lake sediments provide vital continental archives of changes in palaeo-environment and palaeoclimate. Their inherent annual chronology provide an attractive opportunity to date precisely palaeosecular variation during the Holocene (Sprowl & Banerjee 1989; Saarinen 1998; Stockhausen 1998; Ojala & Saarinen 2002; Snowball & Sandgren 2002; Ojala & Tiljander 2003), overcoming the problems related to radiometric dating of sediment organic matter (Oldfield *et al.* 1997; Barnekow *et al.* 1998; Wohlfarth *et al.* 1998). Moreover, reliably dated PSV master records provide a rapid means of dating homogenous sediments (Saarinen 1999).

In this study, eight sediment cores of Holocene age from two adjacent small lakes, Lake Lehmilampi and Lake Kortejärvi located in eastern Finland, were subjected to detailed palaeomagnetic investigations in order to produce regionally applicable PSV master curves of mean inclinations and declinations, with associated 95 per cent confidence limits. Mineral magnetic analyses provide information on the lake development histories and the characteristics of the magnetic carriers. The younger sediment sections in the basins are continuously varved, providing an excellent chronological control over the obtained palaeosecular variation data. The stacked ChRM inclination and declination data were finally qualitatively compared with PSV data from North and West Europe to validate the geomagnetic origin of the record.

2 ENVIRONMENTAL SETTING

Lake Lehmilampi (for short, we will use the Finnish name Lehmilampi: location 63°37′N, 29°06′E, size 15 ha, 95.8 m above sea level) and Lake Kortejärvi (for short, Kortejärvi: location 63°37′N, 28°56′E, size 23 ha, 105.3 m above sea level) are two small boreal lakes located in Northern Karelia (Fig. 1). Sedimentation in Lehmilampi and Kortejärvi started approximately 11 000 yr ago while they were submerged by Lake Pielinen (for short: Pielinen, 892 km^2, 93.7 m above sea level) in its ancient extent. Lehmilampi and Kortejärvi became isolated owing to postglacial crustal rebound and resultant shore displacement in the northern parts of Pielinen. Among others, these lakes were located during a systematic survey for lakes with annually laminated sediments (Ojala *et al.* 2000). Lehmilampi and Kortejärvi are located in glacially carved depressions in northwest-southeast direction. The lake catchments have undulating topography, with hills characterized by bedrock outcrops and till deposits and the intervening depressions by fine sediments accumulated in the ancient Pielinen. Maximum difference of height between water table and maximum topographical peak is 50 and 80 m in the catchments of Lehmilampi and Kortejärvi, respectively, enabling an abundant supply of fine detrital matter during spring flooding following the rapid snowmelt. The pronounced seasonality of sediment sources driven by the climatic regime and the stratification of the water column causing low concentration of dissolved oxygen concentration in the deepest parts of the basins are essential for the formation and preservation of varves (O'Sullivan 1983; Saarnisto 1986). The area is a part of the Archean Fennoscandian shield and the main rock types are granitoids and their migmatitic variants (Luukkonen 2005). The average temperature in January and July is −10 and +16 °C, respectively (Helminen 1987).

3 FIELD WORK AND SUBSAMPLING

Several long sediment cores have been obtained from Lehmilampi (core prefix LL) and Kortejärvi (core prefix KJ) between the years from 2004 to 2007 for varve and palaeo- and mineral magnetic analyses (Fig. 1). Long sediment cores were recovered in one piece during spring, while the lake surface was frozen using a stationary piston corer (core length ∼300 cm) and a modified Kullenberg corer, that is, PP-corer (core length ∼750 cm) (Putkinen & Saarelainen 1998). Sediments were cored into plastic liners (inner diameter from 5 to 6.5 cm). Cores were not azimuthally oriented, but care was taken to avoid rotation of the coring gear during sediment penetration. To secure the varve record up to the present, the upper *ca.* 30 cm of

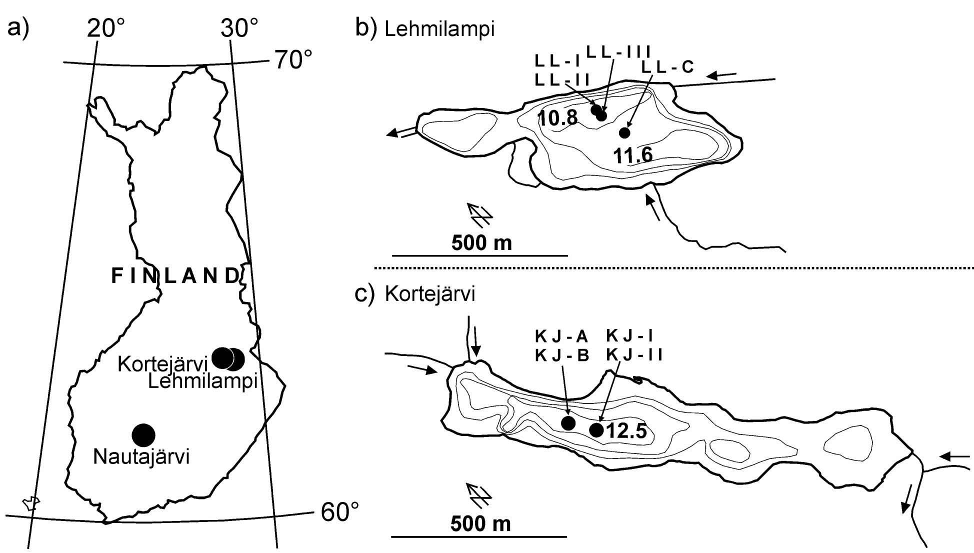

Figure 1. (a) Locations of the investigated lakes Lehmilampi and Kortejärvi. Location of Nautajärvi, whose varve-dated PSV patterns were used to date the older sediments in Kortejärvi and Lehmilampi, is shown as well. Coring sites are shown in the sketches of (b) Lehmilampi and (c) Kortejärvi together with water depth information.

Table 1. General information on the sediment cores investigated in this study.

Lake	Core	Coring tool	Core length (cm)	Water depth (m)	Coring time	No. of subsamples
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	8.54	3/2007	256
Kortejârvi	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

the sediment column was carefully sampled using a Limnos gravity corer (Kansanen *et al.* 1991), designed to preserve the water-sediment interface pristine. Immediately after raising the Limnos sediment core to the frozen lake surface, a mini-sized wedge-shaped freeze core was cored from it, a technique developed at the Department of Geology, University of Turku (Saarinen & Wenho 2005). For transportation the 750-cm-long cores were cut and sealed in the field into three *ca*. 250-cm-long separate sections. Coring was carried out in the deepest basin areas except for the core LL-C, which was cored from a shallower water depth in order to investigate the influence of water depth on magnetic properties and varve preservation. Information on the eight cores investigated in this study is summarized in Table 1.

The core sections were transported to the Department of Geology, where they were stored in a cold room at 5 °C before opening. In the laboratory, all the cores were carefully opened lengthwise. After opening, the top 25 cm of the core KJ-I became perforated with tiny holes caused by methanogenesis, questioning its suitability for palaeomagnetic investigations. The sediment surface of the split core was levelled and covered with plastic film. Magnetic volume susceptibility (κ) was measured on the split cores at 2 mm intervals using an automatic long-core measurement system built at the Department of Geology. The system is equipped with a Bartington MS2 susceptibility meter attached to a MS2E high-resolution sensor. The obtained magnetic susceptibility logs were used for core correlation and for the estimation of bulk sediment compositional changes in the cores.

Sampling for palaeo- and mineral magnetic analyses was carried out along the central axis of the core. Two different types of polystyrene cubic boxes with volumes of *ca*. 6 and 8 cm^3 were used during the course of this study. Sampling boxes were inserted at about 2.5 cm intervals oriented in respect to the core top, leaving a few millimetres space between the cubes in order to reduce sediment deformation. Core KJ-B was exceptionally sampled on trial with an overlap to increase the resolution. Discrete samples were stored in airtight plastic containers in the cold room up to three weeks before the measurements started.

4 PALAEO- AND MINERAL MAGNETIC MEASUREMENTS

All bulk measurements on discrete samples were made in the Laboratory for Palaeo- and Rock magnetism of the Helmholz Centre Potsdam, German Research Centre for Geosciences. Low-field volumetric magnetic susceptibility (κ) was measured using an AGICO Kappabridge KLY-3S for the majority of the samples. Data for cores LL-C, KJ-I, and KJ-II was obtained with a newly developed Variable Field Susceptibility Meter (VFSM) from Magnon GmbH, Germany, cross-calibrated to the KLY-3S. Directions and intensity of the NRM were measured from all the samples with a fully automated 2G SRM-755 DC-SQUID cryogenic long-core magnetometer equipped with an in-line three-axis alternating field (AF) demagnetization system. To investigate the stability of the NRM and to reveal possible secondary overprints, all samples were AF-demagnetized in ten progressive steps from 0 to 100 mT with remaining NRM vectors measured after each demagnetization step. Anhysteretic remanent magnetization (ARM) was imprinted with a single-axis 2G Enterprises 600 AF demagnetizer equipped with an additional direct current (DC) coil, using a maximum AF field of 100 mT superimposed with a 0.05 mT steady field along the *z*-axis of the sample. ARM was measured with the cryogenic long-core magnetometer. ARM is expressed as anhysteretic susceptibility (κ_{ARM}) by normalizing the ARM by the strength of the steady field. Demagnetization of ARM was accomplished in 5–6 steps at peak AF amplitudes up to 50 and 65 mT, respectively, which was sufficient to determine the median destructive field of the ARM (MDF_{ARM}) of all the samples. Isothermal remanent magnetization (IRM) was produced with a 2G Enterprises 660 pulse magnetizer using a field of 1 T, defined here as the saturation IRM (SIRM), and the acquired remanence was measured with a Molyneux Minispin spinner magnetometer in two positions. The maximum field of 1 T can only partially saturate magnetic components of higher coercivity, if present in samples. After SIRM acquisition, a reverse field of 100 mT ($IRM^{0.1T}$) was imprinted in the samples in order to determine an *S*-ratio $[0.5\times(1\text{-}IRM^{-0.1T}/IRM^{1.0T})]$. 19 pilot samples from Kortejärvi (core KJ-A) were selected for detailed mineral magnetic analyses. A small specimen (*ca*. 20 mg) of air-dried sediment was mixed with glue to form a small pellet. An alternating gradient force magnetometer (MicroMag, Princeton Measurements) was used to obtain acquisition curves of isothermal remanent magnetization (aIRM) in a field range from 2×10^{-3} to 2.0 T in 61 steps, and to determine hysteresis properties. The latter was also done for further 37 pilot samples from core KJ-II.

The measured magnetic parameters in combination with the calculated interparametric ratios provide proxies of relative variations in the mineral magnetic assemblages indicative of palaeoenvironmental changes (Thompson & Oldfield 1986; Evans & Heller 2003). Basically, these parameters are not uniquely diagnostic but can be indicative of different aspects of the magnetic grains. Parameters basically sensitive to the concentration of ferrimagnetic minerals include κ, κ_{ARM} and NRM. Being an in-field measure, κ can be biased by diamagnetic and paramagnetic contributions, if the concentration of ferrimagnetic minerals is low. κ_{ARM} responses sensitively the concentration of stable single-domain (SSD) sized magnetite in the sediment (King *et al.* 1982; Maher 1988). Besides a concentration-sensitive parameter, NRM can be controlled by the strength of the geomagnetic field during the time of the acquisition of the remanence. MDF_{ARM} is a measure of coercivity, which varies in response to magnetic grain size and mineralogy. The concentration-independent ratio of SIRM/κ mirrors relative variations in magnetic grain size, with higher values implying finer grain sizes. In addition, high values ($\sim$70 kA m^{-1}) of SIRM/κ have been shown to indicate the presence of the iron sulphide greigite (Fe_3S_4) (Snowball & Thompson 1990). The *S*-ratio is a widely used parameter to estimate the relative proportions of low and high coercivity magnetic minerals in the sediments, with high (low) *S*-ratios values indicating dominance of low (high) coercivity fractions (Frank & Nowaczyk 2008). It should be noted that the reliability of mineral magnetic ratios is limited if the sediment magnetic properties are not dominated by magnetite but include a variable magnetic assemblage.

5 ESTABLISHMENT OF CHRONOLOGY

The upper sediments in the basins of Lehmilampi and Kortejärvi are annually laminated (Fig. 2). This interpretation is based on freeze corer sampling in consecutive years of field working between the years 2004 and 2007 and the visual observation of a building of a new set of clastic-organic laminas each year. Methods of sediment preparations, X-ray densitometry and digital image analysis applied in order to establish varve chronology are described in Haltia-Hovi *et al.* (2007, see also references therein). Varve counting was proceeded as deep in the sediment as varves could be clearly identified and it was repeated three times for both lakes in order to obtain an estimate of the reliability of the varve counting. Varve chronologies were calibrated to the year 1950, which represents the year 0 BP.

For the deeper, non-varved sediments (approximately $\geq$380 cm) in Lehmilampi and Kortejärvi, chronology was established by palaeomagnetic pattern matching in respect to Lake Nautajärvi PSV record (in short: Nautajärvi; 61°48′N, 24°41′E) (Ojala & Saarinen 2002). Nautajärvi has a highly precise varve chronology covering the last 9898 $\pm$ 100 yr. Based on the behaviour of pilot samples during AF demagnetization, Nautajärvi NRM data was considered to be cleaned after a single AF demagnetization step at 20 mT, which was then used for the final data. The palaeomagnetic correlation procedure was carried out in the following steps: (1) the cores LL-I and KJ-I were selected as representative reference cores from each lake, (2) bulk magnetic susceptibility (κ), which shows visually similar patterns in all the cores from the same lake, was used to transfer the data from the other cores to the depth scale of the reference cores, (3) the ChRM (characteristic remanent magnetization) in inclination and declination of the reference cores were assigned relative ages by matching visually similar PSV patterns present in Nautajärvi inclination and declination data. Ages between the tie-points were linearly interpolated and (4) the relative time scale (age versus depth) of the reference cores were applied to date the rest of the cores. Palaeomagnetic pattern matching can be prone to subjective and equivocal correlations between the palaeomagnetic features, but due to the largely similar morphology in the different palaeomagnetic records, this was considered as best approach to establish a complete chronology for the North Karelian data.

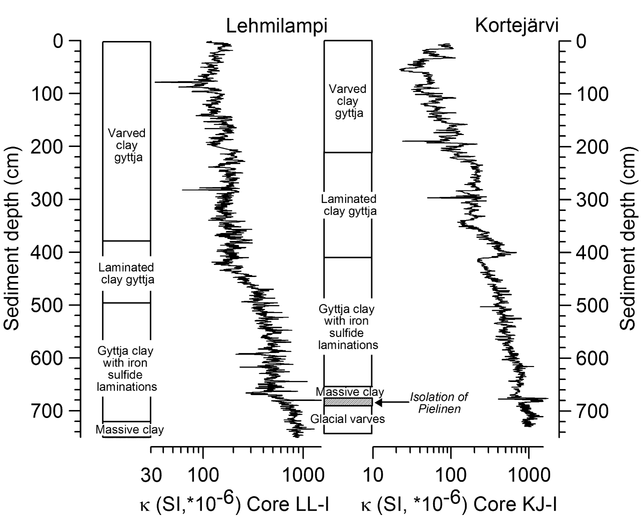

Figure 2. Schematic lithological columns for the recovered sediments from Lehmilampi and Kortejärvi together with high-resolution magnetic susceptibility ($\kappa \times 10^{-6}$) measured with a Bartington MS2E sensor at 2-mm intervals.

6 RESULTS

6.1 Sediment lithostratigraphy and lake development

Due to their similar development history, sediments from Lehmilampi and Kortejärvi express similar visual lithostratigraphy reflecting different lake phases. Fig. 2 shows high resolution magnetic susceptibility down-core logs of the reference cores from Lehmilampi (LL-I) and Kortejärvi (KJ-I) together with schematic sediment columns. Both lakes show a sediment succession from (1) light grey silty clays with glacial varves to (2) massive grey clay sediments, changing then to (3) gyttja clays with black iron sulphide banding, which gradually changes with increasing organic accumulation into (3) conspicuously laminated clay gyttja sediments and finally into (4) clastic-organic varved gyttja sediment. The glacial varves formed during the glaciolacustrine phase of Pielinen (Miettinen 1996). The lower limit of the glacial varve unit was not retrieved in the coring. The thickness of the glacial varves (0.9 cm on average) decreases upcore, recording the wasting of the Fennoscandian ice sheet. Between 50 and 213 glacial varves were counted in this unit depending on the terminal depth of the core. The PSV data from the glacial varves are not discussed here because of the large scatter in the data different from core to core. Glacial varves end abruptly with the sedimentation of a distinct layer of sediment with mixed coarse and fine sediments, marking the end of the ice lake phase and the isolation of Pielinen, which took place approximately 11 000 cal. yr BP (Saarnisto 1971; Hyvärinen 1973; Miettinen 1996). The massive clays and gyttja clays with sulphide banding overlying this horizon represent sediments deposited in ancient Pielinen. Accumulation of organic matter increases with the approaching isolation of the lakes, and the sediments become distinctly laminated with alternating layers of detrital and organic matter. This transitional laminated sediment unit grades finally into clastic-organic varves, brought about by high organic productivity in association with oxygen deficit in the lake deep basins. Thereon, the varve records continue consistently until present in both lakes. Based on the combination of visual changes in sediment composition, mineral- and palaeomagnetic records and varve counting, isolation of Kortejärvi and Lehmilampi took place approximately at 7000 and 5100 yr BP, but the exact level of isolation is undefined. The uppermost 120 cm of core LL-C (sediment column not shown here) obtained from a shallower water depth consists of brownish homogenous sediment due to the improved oxygenation of the sediment. Vivianite [$Fe^{2+}{}_3(PO_4)_2 \cdot 8H_2O$], an authigenic hydrated iron phosphate, was occasionally observed as macroscopic concretions throughout the laminated parts of the sediment columns, but more frequently in the varved gyttjas. Formation of vivianite is indicative of the reducing environment with dissolved iron in the pore waters and a high amount of phosphorus derived from the decomposition of organic matter (Anderson & Rippey 1988).

6.2 Varve chronology and the sediment accumulation rates

On average, Lehmilampi and Kortejärvi varve chronologies cover 5122 and 3902 yr, corresponding to the sediment depth of 358 and 315 cm, respectively. The precision of varve counting is high, and the cumulative counting error for the whole varved sequence is estimated as +104 (+2.1 per cent) and −114 (−2.2 per cent) varves for Lehmilampi and for +60 (+1.5 per cent) and −59 (1.5 per cent) varves for Kortejärvi. Counting error estimates expressed in 100-yr intervals visualize in detail the slight variations in the reliability of varve counting (Fig. 3).

As the magnetic measurements and varve studies were made on different cores, the chronologies were transferred as follows. The relative maximum X-ray density, extracted from digital image analysis of the varves, is related to the clastic component in each varve, and it shows nearly identical variations with magnetic susceptibility (κ). Smoothing the relative maximum X-ray density value with a 21-yr running average was sufficient to average out the high-frequency variations in for easier fit with the bulk data from the discrete samples. As an example, in Fig. 4 are plotted bulk κ data obtained from two cores (KJ-I and KJ-A) from Kortejärvi dated with the smoothed relative maximum X-ray density data, showing the similarity of the curve patterns in the different records. Similar correlation has been

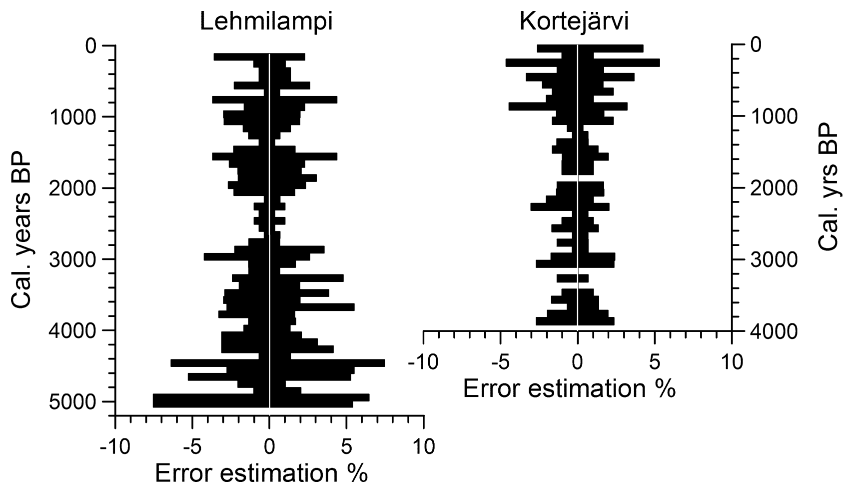

Figure 3. Error estimates of varve counting for Lehmilampi and Kortejärvi sediments in 100-yr intervals plotted against time.

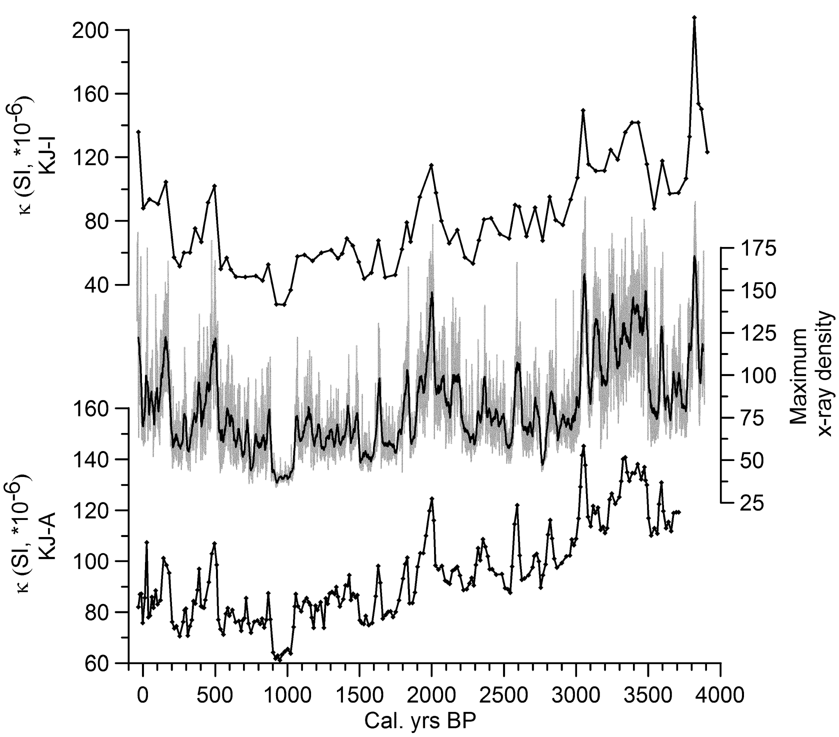

Figure 4. Transferring of Kortejärvi varve chronology by using the relative maximum X-ray density (annual data shown in grey) smoothed with a 21-yr running average (black line) and the bulk magnetic susceptibility ($\kappa \times 10^{-6}$) derived from the discrete palaeomagnetic samples. Both κ and maximum X-ray density are mainly controlled by the lithogenic contribution to the sediments and yield similar records, enabling transfer of the chronology.

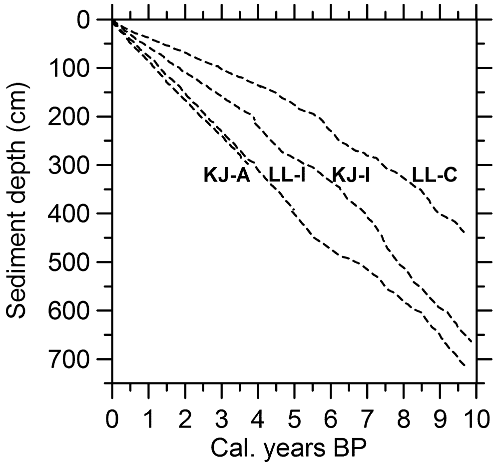

Figure 5. Sediment age versus depth of selected sediment cores from Lehmilampi (cores LL-I and LL-C) and Kortejärvi (cores KJ-I and KJ-A). In general, sedimentation has proceeded steadily in both lakes, but different coring sites show variable sedimentation rates.

established between the bulk κ and relative maximum X-ray density data obtained from Lehmilampi (Haltia-Hovi *et al.* 2009). The independent varve chronology and dating obtained by palaeomagnetic pattern matching were merged into a composite age model for Lehmilampi and Kortejärvi.

Sedimentation has proceeded relatively linearly in both lakes during the Holocene with a mean accumulation rate of 0.74 mm yr^{-1} in Lehmilampi and a slightly lower rate of 0.68 mm yr^{-1} in Kortejärvi. Sedimentation rate was more rapid in the second coring site of Kortejärvi (KJ-A) with 0.80 mm yr^{-1} (Fig. 5). In the upper ~130 cm of the core LL-C sedimentation rate was approximately 0.34 mm yr^{-1}. Sedimentation rates in the older sediments show some more variations, which are probably caused by the development history of the lakes with changing sediment sources and inflow routes. On average, the resolution of PSV data ranges between 20 and 30 yr per sample.

6.3 Mineral magnetic characteristics and carriers of remanence

Mineral magnetic properties and their palaeoenvironmental interpretation from Lehmilampi (core LL-I) have been presented in Haltia-Hovi *et al.* (2009). To compare effortlessly the mineral magnetic characteristics of Lehmilampi and Kortejärvi (Figs 6a-d), selected magnetic parameters of Lehmilampi (core LL-I) are again presented here and discussed briefly together with the core LL-C. The cores KJ-II and KJ-A are representative of the mineral magnetic properties of Kortejärvi.

Mineral magnetic properties are similar in both lakes up to 7500 cal. BP, when the two basins were still submerged by the waters of the ancient Pielinen. These detrital sediments are characterized by high concentration of ferrimagnetic minerals and decreasing magnetic grain size with time. IRM acquisition measurements up to 1 T from Lehmilampi core LL-I showed that the sediments are nearly saturated by 0.3 T, indicating that ferrimagnetic mineral(s), probably magnetite, is the main magnetic mineral with some contribution of canted antiferromagnetic minerals (Haltia-Hovi *et al.* 2009). Variations in organic matter (expressed as total organic carbon in wt per cent) parallels mass-normalized κ_{ARM}, interpreted to mirror enhanced biogenic production of SSD sized magnetite in the post-isolation sediments during climatically favourable periods, such as the Medieval (Haltia-Hovi *et al.* 2009). Magnetic properties of the core LL-C (Fig. 6b) are largely similar to the core LL-I (Fig. 6a) until 4000 cal. BP, when varves gradually disappear and sediment becomes homogenous gyttja clay. Magnetic grain size becomes coarser and the proportion magnetically harder minerals increases, as indicated by the decreasing values of SIRM/κ, MDF_{ARM}, and also the *S*-ratio, which is affected by the grain size variations instead of being diagnostic of magnetomineralogy. This change in magnetic properties when shifting from varved to homogenous gyttja clays in Lehmilampi is tentatively interpreted to reflect the presence (absence) of fossil magnetosomes, SSD ferrimagnetic particles, in varved (homogenous) sediments. Magnetotactic bacteria proliferate in weakly anoxic conditions, and the mineral magnetic properties in LL-C during the last ~4500 yr are probably dominated by coarser detrital magnetite from the catchment instead of *in situ* produced biogenic ferrimagnetic grains.

Isolation of Kortejärvi took place around 7000 cal. BP, and this event is paralleled with deposition of organic and detrital laminations, increased concentration of magnetic minerals and somewhat coarser magnetic grain size washed from the newly shaped catchment (Fig. 6c). Magnetic grain size shows rapid shifts after isolation, and the two prominent peaks in SIRM/κ centred at 5000 and 4000 cal. BP occur simultaneously with nearly black organic matter and abundant vivianite observed in the sediment. These may suggest increased organic productivity and *in situ* formation of magnetic minerals. In parallel with the start of varve formation in the core KJ-I, mineral magnetic characteristics indicate decreasing magnetic concentration and coarsening grain size. The drop in *S*-ratio at 2200 cal. BP is clearly visible in the IRM acquisition curves, where specimens are not saturated by the field of 2.2 T (Fig. 7). This suggests significant contribution of canted antiferromagnetic minerals in the magnetic assemblage, such as hematite (Fe_2O_3) and/or goethite (α-FeOOH), an iron hydroxide (Chaparro *et al.* 2006). However, the magnetic characteristics in the two coring sites in Kortejärvi are different during the last 4000 yr (*cf.* 6c, 6d). Visualized in the Day plot (Day *et al.* 1977), specimens from KJ-A are tightly clustered slightly above the mixing lines by Parry (1980, 1982) and Dunlop (2002), suggesting highly uniform mineralogy and significant proportion of submicron-sized SSD magnetite in the magnetic assemblage, whereas samples from KJ-II show a more variable grain size distribution and larger contribution from multidomain (MD) particles (Fig. 8). Such a large difference is not likely to result from differences in the incoming catchment material, because the lake is supplied by inflows originating from a small area and the initial detrital magnetic assemblages are assumed to be similar. Instead, the differing magnetic properties are proposed to result from the contribution of fossil magnetosomes to the sediment giving rise to the uniform magnetic properties of KJ-A and its parallel KJ-B (not shown). Sediment deposition rate is slower in the coring site represented by the cores KJ-I and KJ-II, so they do not represent the centre of sediment accumulation in the basin. However, the sediments in the two coring sites are visually comparable and were interpreted visually to be thoroughly varved during the last 4000 yr. Possibly, the different parts of the basin have depositional environments with slightly different characteristics in terms of the ambient geochemical environment and oxygen availability, thereby influencing the magnetic parameters.

6.4 NRM demagnetization and characteristic remanent magnetization

The intensity of the NRM is variable in the studied sediments, ranging between 7 and 453 mA m^{-1} in Lehmilampi and between

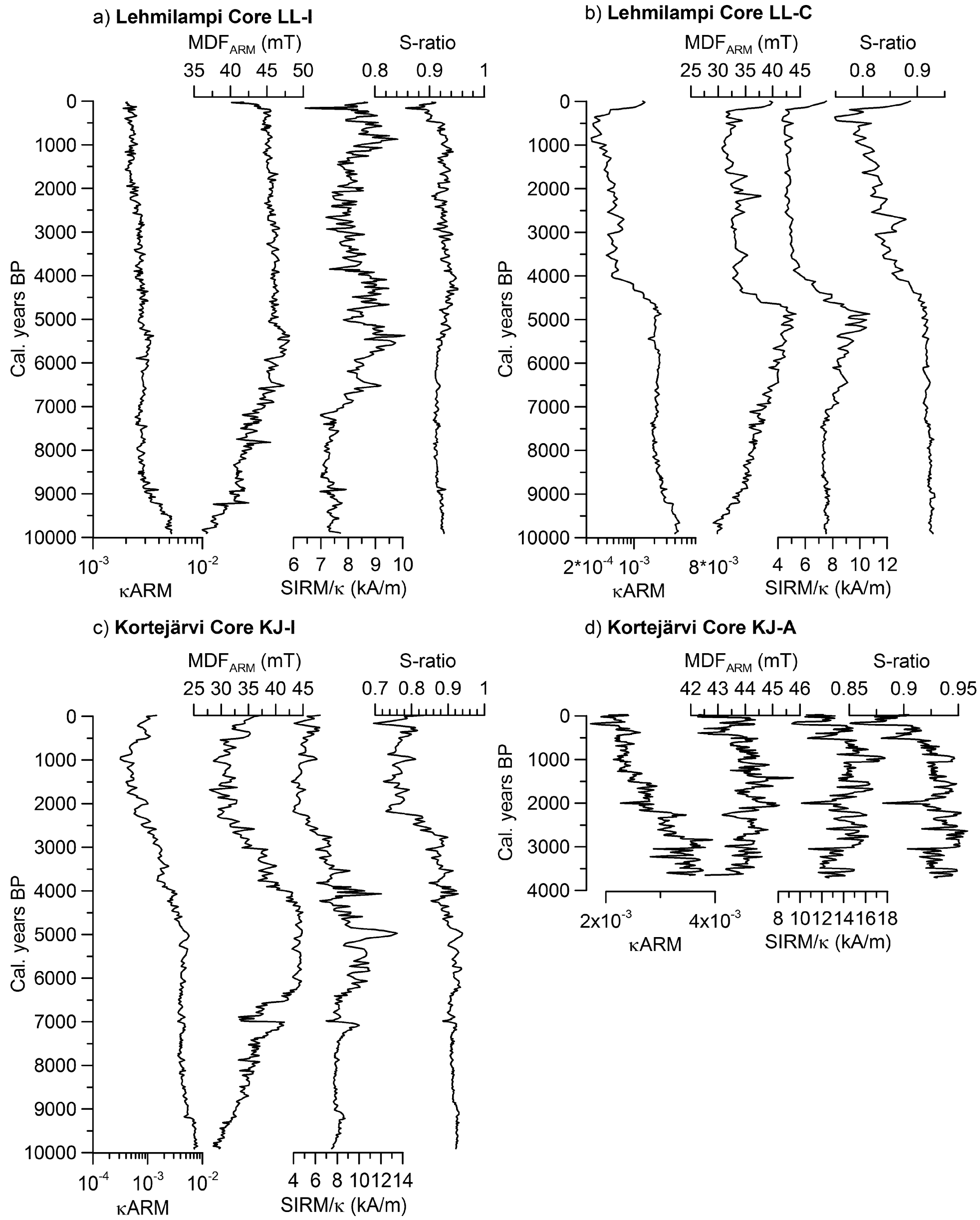

Figure 6. Selected mineral magnetic parameters for Lehmilampi (a and b) and Kortejärvi (c and d), indicative of relative changes in magnetic grain size and mineralogical changes: κ_{ARM}, $\mathrm{MDF}_{\mathrm{ARM}}$, SIRM/$\kappa$, and *S*-ratio. See text for further explanation of the interpretation of the parameters.

6 and 400 mA m^{-1} in Kortejärvi (Fig. 9). These values are in the same range as the results published earlier from other Fennoscandian varved lake sediments (Saarinen 1998; Ojala & Saarinen 2002).

Changes in orientation and intensity of the NRM signal are visualized in vector endpoint plots (Fig. 10). Representative curves showing results of AF demagnetization of NRM have sigmoidal shape indicating that the magnetic carrier is fine-grained magnetite (Fig. 11). Some samples carried a small soft magnetic overprint, which was removed by the AF demagnetization steps of 15–20 mT. At least five successive AF-demagnetization steps were subjected to principal component analysis (Kirschvink 1980) in order to determine the characteristic remanent magnetization (ChRM) of the samples. Most of the samples display only very small angular changes during the demagnetization procedure, indicating stable single-component palaeomagnetic directions which are interpreted to represent the primary magnetization of the sediments.

Inclination and declination of the eight cores are plotted versus depth in Figs 12(a) and (b). The laminations in the cores were observed to lie perpendicular to the liner wall, indicating vertical penetration of the corer into the sediment layers. Therefore, inclinations observed relative to the axis of the cores are interpreted to represent the true inclination relative to the bedding plane of the sediments. ChRM inclination shows a downward decreasing trend in the records and the values vary between 50° and 85°, fluctuating around the predicted value of 75.3° for an axial geocentric dipole field for the coring site (Fig. 12a). The ChRM declination data in the lower two core segments were rotated in relation to the uppermost section to constitute a continuous declination record. The resulting mean declination values of the composite cores were then set to arbitrary zero. The maximum range of the characteristic declinations is about ±40° with comparable amplitudes found in all eight cores (Fig. 12b). Some spurious data points (<1 per cent of the total

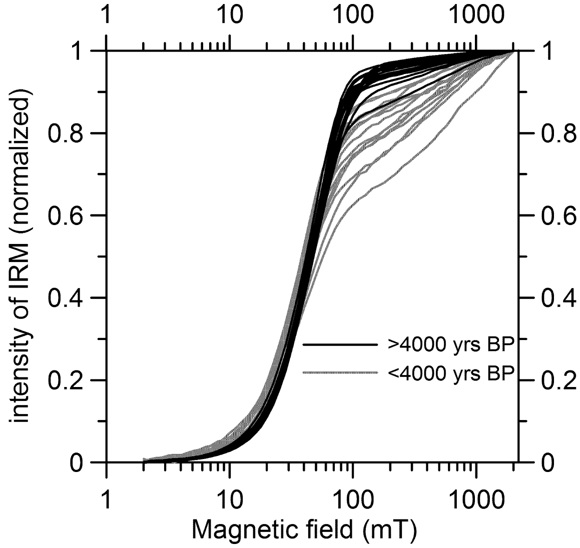

Figure 7. Curves of acquisition of IRM of 37 subsamples from the core KJ-II. Maximum applied field was 2.2 T. The sediments deposited during *ca*. the last 4400 yr (grey lines) are of harder remanence compared to the sediments deposited >4400 yr BP (black lines), indicative of significant proportion of antiferromagnetic minerals in the sediments.

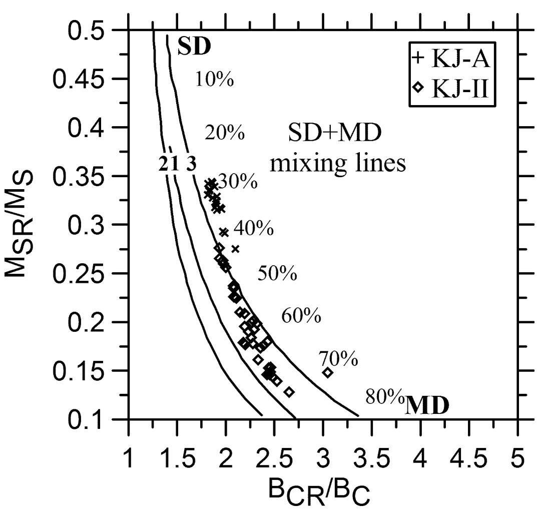

Figure 8. Hysteresis parameters for the KJ-I (diamonds) and KJ-A (crosses) pilot samples in Day plot (Day *et al.* 1977), M_{rs}/M_s = saturation remanence to saturation magnetization and B_{cr}/B_c = coercivity of remanence to coercive force. Mixing lines 1 and 2 by Dunlop (2002) and the line 3 by Parry (1980, 1982).

data) located mainly in the core cutting points and in the topmost water-saturated sediments were removed because of unusually large scatter with no counterpart found in the other cores. In addition, the uppermost 500 yr of the core KJ-I were left out as well due to the very large scatter present in ChRM directions caused by mechanical deformation of magnetic alignment due to methanogenesis after opening the core. The slower sediment deposition rate in the shallower coring site of Lehmilampi as represented by the core LL-C gives rise to the somewhat smoothed record.

Final inclination and declination data of the eight cores are plotted against time in Figs 13(a) and (b). These data were merged into a stack to obtain a PSV record representative of the local geomagnetic field behaviour. Based on the composite age model, the ChRM directions were transformed into time-series by linear interpolation between correlative features and recalculated into equal 10-yr time intervals and then vectorially stacked. Fisher statistics (Fisher 1953) were applied to calculate mean directions and α_{95} values in order to quantify the statistical reliability of the palaeomagnetic data. Latin and Greek letters label prominent declination and inclination features, respectively, following the nomenclature by Turner & Thompson (1981) for the UK master curve. Finally, a 150-yr triangular moving average was applied to the mean directional data to smooth the high-frequency variations. The PSV stack was named North Karelian stack after its area of origin.

7 DISCUSSION

7.1 Comparison of the North Karelian PSV stack with PSV records from other regions

The excellent capability of clastic-organic varved lake sediments to record PSV features was first demonstrated in Finland by Saarinen (1998) and since then, palaeomagnetic investigations using varved sediments have been successfully carried out in Sweden and Finland. These relatively organic-rich sediments with high sedimentation rates in steady depositional environments present in small boreal lakes seem to comprise ideal material for reconstructing PSV features of the geomagnetic field, yielding highly repeatable directional records as shown also in the present study. This became possible due to the application of a fully automated long-core cryogenic magnetometer adapted for discrete samples.

The reliability of the North Karelian stack was tested by comparing it with selected PSV records from northern and western Europe (Figs 14a and b). These include the (1) Nautajärvi PSV record (61°48′N, 24°41′E; Ojala & Saarinen 2002), (2) Lake Pohjajärvi in eastern Finland (62°82′N, 28°04′E; Saarinen 1998), (3) FENNOSTACK, a palaeomagnetic varve-dated stack combining data from seven Finnish and Swedish lakes (57°–64°N, 12°–24°E; Snowball *et al.* 2007), comprising the Nautajärvi PSV record and (4) the stacked PSV record from three lakes in United Kingdom (53°–56°N, 2°–4°E; Turner & Thompson 1982). Because the PSV features older than 5100 and 3900 yr BP recorded in Lehmilampi and Kortejärvi sediments, respectively, are dated in relation to the Nautajärvi PSV record, their temporal dimensions are not considered. The North Karelian stack clearly possesses the major maxima and minima in inclination (γ–μ) and declination (*d*–*j*) as seen in other records, indicating that the same sources of the Earth's magnetic field are dominating these records. This reflects the high quality of the North Karelian stack, suggesting that the obtained directional patterns are faithful recordings of the geomagnetic field variations over the last 10 000 yr. The North Karelian stacked declination shows higher amplitude variations (±25°) than the FENNOSTACK, and resembles more the amplitudes of the Nautajärvi record, indicating the directional swings have not been subdued due to stacking. The pattern in the UK palaeomagnetic stack is very similar to that found in all of the Fennoscandian records, but features older than 4200 yr BP yield older ages of up to 750 yr than those found in FENNOSTACK. Snowball & Sandgren (2002) discussed the temporal differences between Swedish varve-dated palaeomagnetic data and the UK stack, and concluded that dating of UK data is compromised by old carbon when using ^{14}C dating on the bulk sediment samples. The declination feature labelled 'j' is more prominent in the North Karelian stack compared to the reference data, providing a clear marker feature for the Early Holocene.

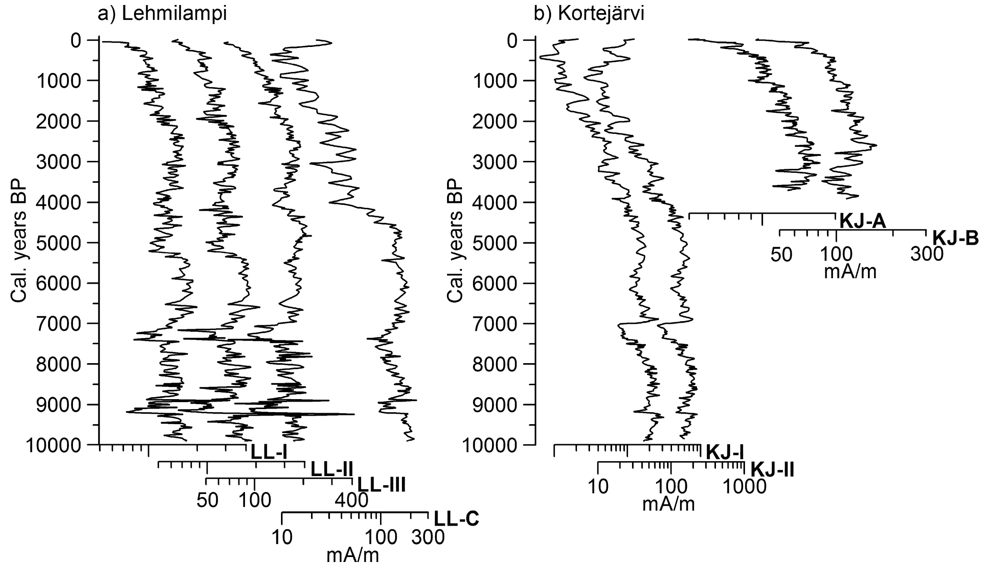

Figure 9. Natural remanent magnetization (NRM) as a function of time as measured from discrete samples from (a) Lehmilampi and (b) Kortejärvi. Note the variable scaling of the *x*-axes.

The features in the palaeosecular variation record of Lake Pohjajärvi yield younger ages in the range of 100–200 yr, which may be related to more rapid lock-in time and/or underestimation of varve number when counting varves on fresh sediment surface (Lotter & Lemcke 1999).

The most conspicuous shift in declination during the Holocene occurs between 2820 and 2300 cal. BP between the features 'f' and 'e', with the coeval steep inclination feature 'ε' centred at 2600 cal. BP. This indicates an exceptional rapid clockwise movement of the virtual geomagnetic north from the northeast to the northwest with respect to the study area. With the aid of the precise varve chronology, the rate of change is reconstructed in detail. Similar feature has been reported in several other studies extending from northern Siberia (Frank *et al.* 2002) to Iceland (Kristjánsdóttir *et al.* 2007), providing a stratigraphic feature to geographically wide areas in the Northern Hemisphere.

7.2 Sediments of Lehmilampi and Kortejärvi as recorders of palaeosecular variation

Obviously, the mean inclination of 70.9° appears too shallow by *ca*. 5° than would be expected by an axial geocentric dipole inclination for the site. The origin of the bias in inclination is difficult to establish in the absence of precise knowledge of the details of the remanence acquisition (Levi & Banerjee 1990; Tauxe 2005). Depositional remanent magnetization (DRM) is assumed to cause inclination lowering, because the physical alignment of magnetic particles is influenced by, for example, factors related to the size and shape of the magnetic particles and the horizontality of the depositional surface, and is not controlled solely by the configuration of the magnetic field. On the other hand, post-depositional remanent magnetization (pDRM), which takes place after a certain critical level of sediment dewatering and solidification has been reached, may produce a more faithful recording of the inclination. In the case of pDRM, the palaeomagnetic record is lagging the sediment age. Alternatively, the 'too shallow' inclinations may also represent a true geomagnetic feature due to non-dipolar contributions to the time-averaged field. Time intervals of varying length have been proposed as the lock-in delay of magnetic moments in varved lake sediments. Nearly syndepositional remanent magnetization was proposed by Ojala & Saarinen (2002), whereas an intermediate estimate on the lock-in delay of *ca*. 80–100 yr was suggested by Saarinen (1999) and Snowball & Sandgren (2002). Stockhausen (1998) estimated a magnetization lock-in delay of ~150 yr in the diatomaceous varved gyttjas in the maar lakes in western Germany. Taking into account the error estimates in varve counting, the simultaneousness of the declination maximum 'f' in the declination in North Karelian PSV stack in comparison with FENNOSTACK and Nautajärvi data, all coming from a restricted geographical area, suggests largely similar magnetization lock-in times and the fidelity of the individual varve chronologies. Post-depositional sediment disturbances are minimal in the absence of bioturbation in these varved and therefore poorly oxidized sediments. Determination of the exact magnetization lock-in depth and time is not possible, however, because the sediments close to the water–sediment interface are frequently disturbed during coring and therefore palaeomagnetic data cannot be extracted from them. Nevertheless, the sediment lock-in depth is approximated here by observations on varve thickness in the mini ice wedges. Varves in the water-sediment interface are thick, but they quickly become thinner due to the relatively rapid sediment deposition rates causing loss of water and consolidation. In Lehmilampi and Kortejärvi thick water-saturated varves are found in the uppermost *ca*. 5–10 cm from the water–sediment surface, corresponding to a time interval of *ca*. 20–50 yr in these lakes, which may approximate the sediment lock-in depth and time. This simple estimate, which is in close agreement with those presented earlier for Fennoscandian varved lake sediments, should be taken into account when considering when age of the palaeomagnetic features.

Variations in the concentration of magnetic minerals in lake sediments can be regulated by the detrital influx derived from the catchment (Jelinowska *et al.* 1997; Stockhausen & Zolitschka 1999). Interpreting mineral magnetic records simply in terms of detrital influx can be misleading, because magnetic minerals of authigenic and/or biogenic origin are being discovered in an increasing number of studies. Greigite (Fe_3S_4), a metastable iron sulphide phase,

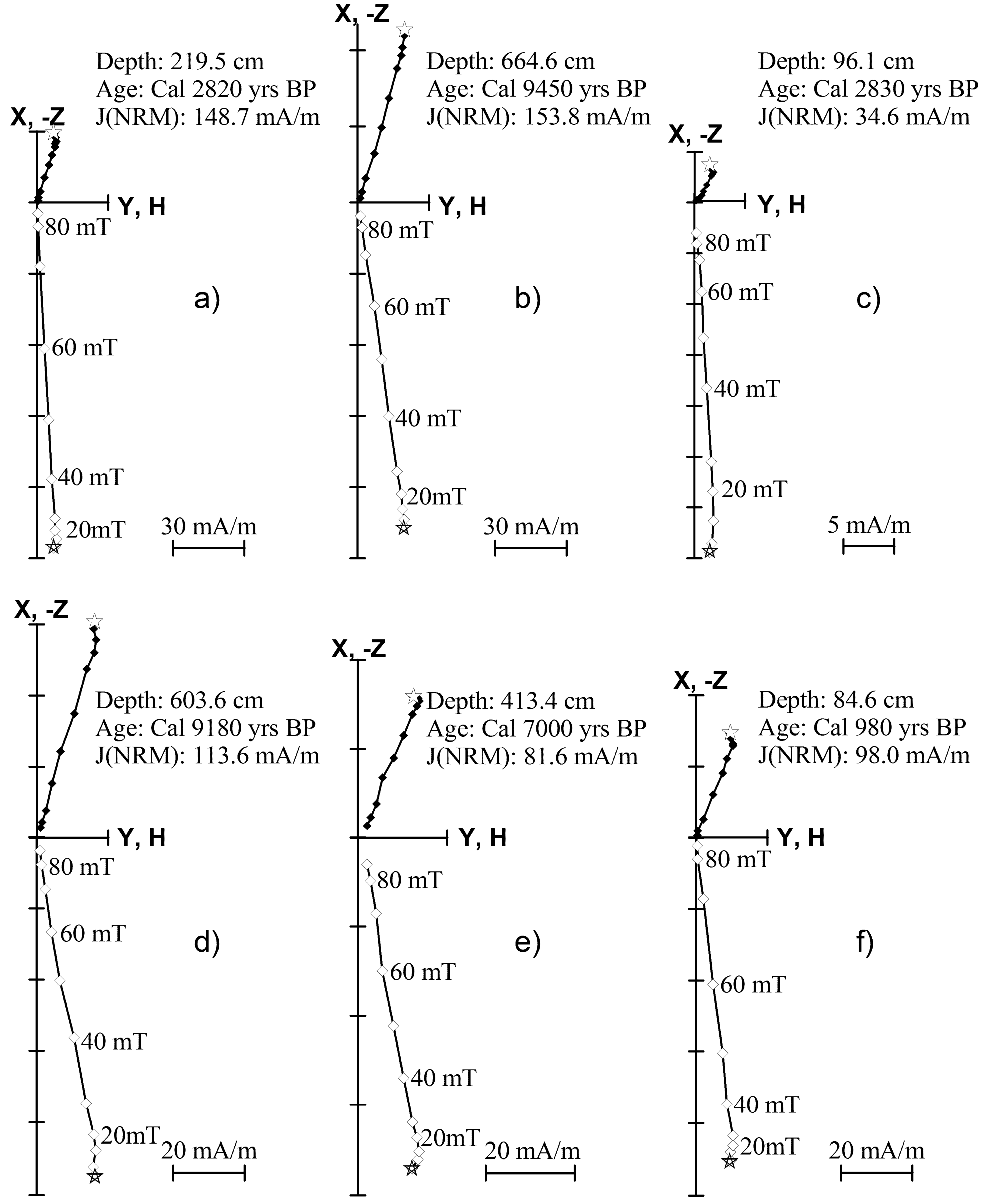

Figure 10. Orthogonal vector plots of six representative samples showing the behaviour of NRM vectors during alternating field demagnetization. Filled (open) symbols denote the projections to the horizontal (vertical) plane. Stars denote the original NRM. These results indicate stable, single-component magnetizations after the removal of the soft remanence present in some samples after the 15–20 mT demagnetization step.

can form in organic-rich, anoxic environments where bacteria reduce sulphate for their metabolism (Ariztegui & Dobson 1996; Vigliotti *et al.* 1999). As a ferrimagnetic mineral, greigite may carry a stable chemical remanent magnetization, but the time of the remanence acquisition must be determined if sediments are to be investigated for palaeomagnetism (Hallam & Maher 1994; Rowan & Roberts 2005; Babinszki *et al.* 2007). Oxygen concentration has been low in the deepest parts of the investigated basins probably throughout the history of these lakes, as evidenced by the thoroughly laminated/banded sediment columns. Lake productivity increased rapidly after isolation in Lehmilampi and Kortejärvi, inducing increased accumulation of organic matter in the lake bottom. Nevertheless, the magnetic results presented from Lehmilampi and Kortejärvi sediments do not indicate that greigite is contributing in these sediments. There was no acquisition of a gyroremanent magnetization during AF demagnetization, high values in the ratios SIRM/κ (>40 kAm^{-1}) or in M_R/M_s (>0.5), which are diagnostic for the presence of greigite (Snowball & Thompson 1992; Roberts 1995; Snowball 1997; Ron *et al.* 2007). An increasingly reported source of ferrimagnetic minerals in lake sediments are biogenically produced ferrimagnetic crystals of stable single domain size. These magnetosomes are produced by magnetotactic bacteria for their orientational purposes in their search for a suitable habitat. Upon bacterial death, the fossil magnetosomes can become excellent recorders of the geomagnetic field in the bottom sediments (Winklhofer & Petersen 2007). Using Swedish lake sediments, Snowball (1994) showed that the intensity of NRM in the sediment was changing in line with the organic matter content, confirming the bacterial origin of the stable single domain sized magnetic carriers with transmission electron microscopy (TEM), showing chains of magnetosomes. The high values in MDF_{ARM} in Lehmilampi and Kortejärvi especially in the varved sediment sections indicate similar mineralogy

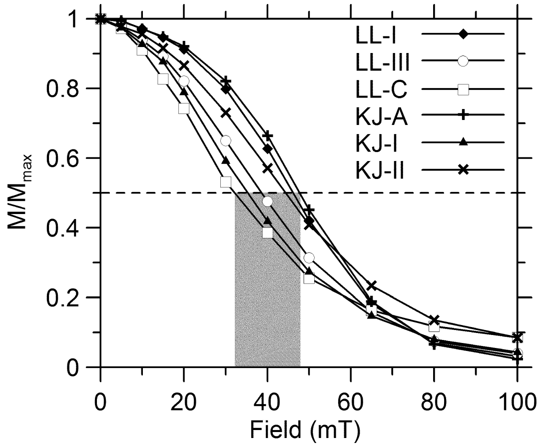

Figure 11. NRM intensity versus AF peak amplitudes of six samples with from Lehmilampi and Kortejärvi. Samples are the same as presented in Fig. 10.

and magnetic grain size of the magnetic carriers in these lakes. The characteristic remanent magnetization is thoroughly well defined in these lakes, yielding reproducible results, despite the changes in the sediment and mineral magnetic characteristics.

The high-resolution and precisely dated palaeomagnetic data presented here is evidently of high quality, such as needed as precise input data for geomagnetic field models. The quality of these models strongly depends on the precision in dating, the temporal resolution, and amplitudinal reliability of each individual input record, especially when it comes to analyse geomagnetic field behaviour largely exceeding the time interval covered by satellite missions and geomagnetic observatory recordings, as here described for the Holocene. However, geomagnetic field models need input from all over the globe in order to provide representative and correct information on dipolar as well as multipolar variability. Therefore, the North Karelian stack is another piece of a mosaic describing the variations of the geodynamo in time and space.

8 CONCLUSIONS

A comprehensive palaeo- and mineral magnetic investigation of a total of eight cores from Lehmilampi and Kortejärvi in Finnish Karelia showed that the sediments in these lakes retain a reliable palaeomagnetic record for the last 10 000 yr. Progressive AF demagnetization of the NRM and subsequent principle component analysis proved that the remanence can be characterized by a stable single-component magnetization. Mineral magnetic analyses showed that the remanence carrier is mainly magnetite in the stable single domain to pseudo single domain size range. The fairly small errors in varve counting in the independent varve chronologies of Lehmilampi (±2.2 per cent) and Kortejärvi (±1.5 per cent) imply that PSV features in the younger parts of the sediment sequences have been precisely dated. The reliability of the records presented in this study is expressed in the remarkable similarity of interlake data and the agreement found in the comparison with other records. Lehmilampi and Kortejärvi PSV data were stacked into North Karelian stack, in which all the main inclination and declination minima and maxima are recorded as in previous studies from the area. The data from the investigated eight cores is of high quality and thus they can serve as a reference record for dating homogenous sediments in nearby regions. In addition, the North Karelian stack has high potential for improving geomagnetic field models analysing the field variability during the Holocene.

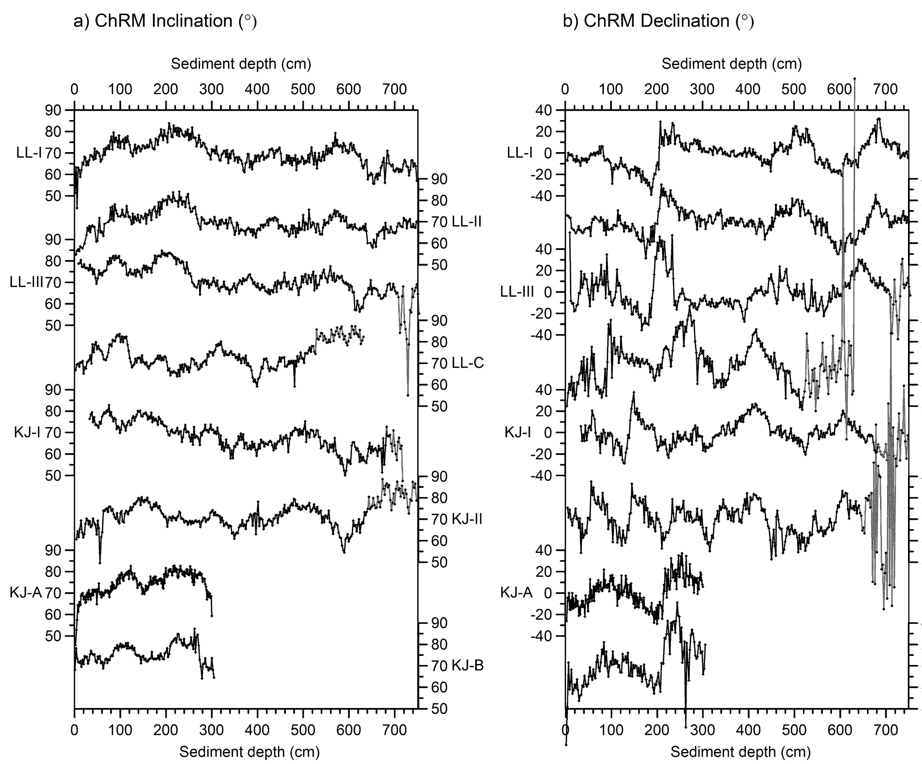

Figure 12. (a) ChRM inclinations of Lehmilampi and Kortejärvi cores plotted against time. ChRM inclinations for the cores are: LL-I: 69.8°, LL-II: 69.5°, LL-III: 71.7°, LL-C: 72.3°, KJ-I: 69.3, KJ-II: 70.8°, KJ-A: 75.0°, KJ-B: 76.2°. (b) ChRM declinations (corrected) of Lehmilampi and Kortejärvi.

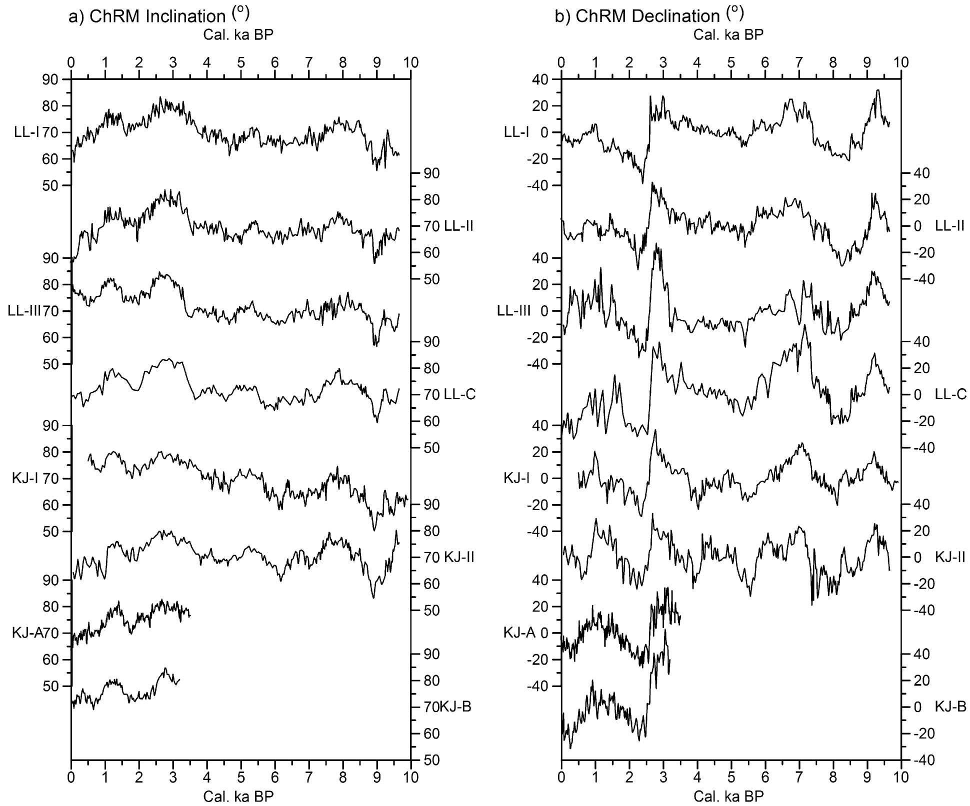

Figure 13. Final inclination and declination data of the eight cores plotted against time. (a) ChRM inclinations, (b) ChRM declination.

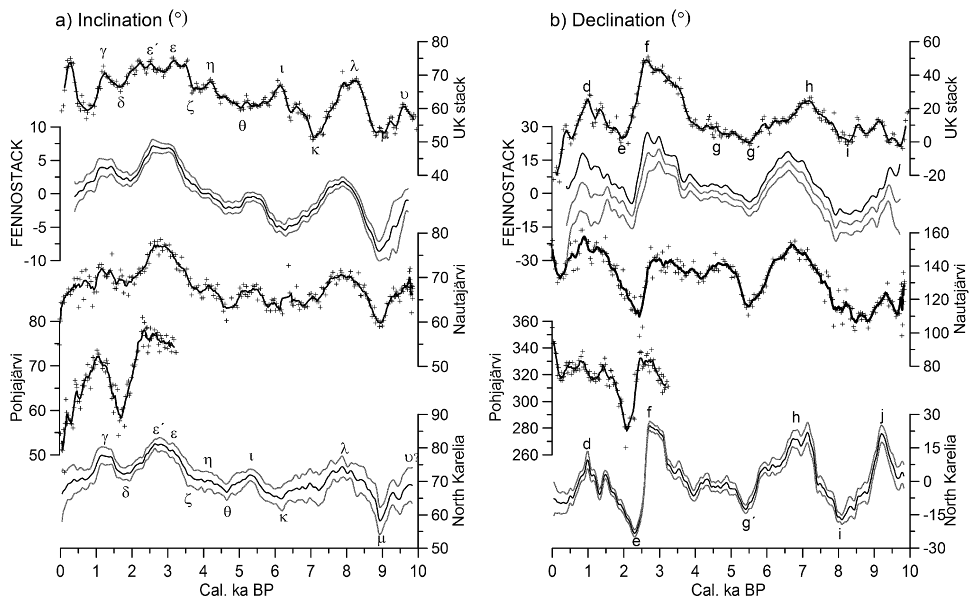

Figure 14. (a) Inclinations and (b) declinations of the North Karelian stack (this study) compared with PSV results from the following studies: Nautajärvi, Pohjajärvi, FENNOSTACK, and UK (see text for references). Nomenclature of inclination and declination minima and maxima follows that of Turner & Thompson (1981). In FENNOSTACK, inclination is expressed as deviations from the core average and 95 per cent confidence limits. The UK, Nautajärvi and Pohjajärvi data are also expressed as a 5-point running average (black line). In the North Karelian stack and FENNOSTACK declinations are expressed as deviations from the core average. Associated 95 per cent confidence limits are plotted with the North Karelian data and FENNOSTACK. UK data was downloaded from the National Geophysical Data Center (http://www.ngdc.noaa.gov/geomag/paleo.shtml).

ACKNOWLEDGMENTS

This study was funded by the Academy of Finland (Grant no. 205805), K.H. Renlund Foundation and The Centenary Foundation of Kymi Corporation. Jean-Pierre Valet, Mark Dekkers and an anonymous reviewer are acknowledged for their constructive criticism and valuable comments helping to improve the manuscript. I. Snowball and A. Ojala are thanked for kindly sharing their datasets. S. Putkinen (Geological Survey of Finland), H. Wenho, E. Puoskari and Helgi Páll Jonsson (Department of Quaternary Geology, University of Turku) are thanked for their participation in field working. H. Wenho and S. Nyman are thanked for their contribution in sediment subsampling.

REFERENCES

Anderson, N.J. & Rippey, B., 1988. Diagenesis of magnetic minerals in the recent sediments of a eutrophic lake, *Limn. Oceanogr.,* **33,** 1476–1492.

Ariztegui, D. & Dobson, J., 1996. Magnetic investigations of framboidal greigite formation: a record of anthropogenic environmental changes in eutrophic Lake St. Moritz, Switzerland, *The Holocene,* **6,** 235–241.

Babinszki, E., Márton, E., Márton, P. & Kiss, L.F., 2007. Widespread occurrence of greigite in the sediments of Lake Pannon: implications for environment and magnetostratigraphy, *Palaeogeogr., Palaeoclimatol., Palaeoecol.,* **252,** 626–636.

Barnekow, L., Possnert, G. & Sandgren, P., 1998. AMS 14C chronologies of Holocene lake sediments in the Abisco area, northern Sweden–a comparison between dated bulk sediment and macrofossil samples, *J. Quat. Sci.,* **120,** 59–67.

Barton, C.E. & McElhinny, M.W., 1981. A 10 000 yr geomagnetic secular variation record from three Australian maars, *Geophys. J. R. astr. Soc.,* **67,** 465–485.

Brandt, U., Nowaczyk, N.R., Ramrath, A., Brauer, A., Mingram, J., Wulf, S. & Negendank, J.F.W., 1999. Palaeomagnetism of Holocene and Late Pleistocene sediments from Lago di Mezzano and Lago Grande di Monticchio (Italy): initial results, *Quat. Sci. Rev.,* **18,** 961–976.

Chaparro, M.A.E., Sinito, A.M., Bidegain, J.C. & de Barrio, R.E., 2006. Magnetic studies of natural goethite samples from Tharsis, Huelva, Spain, *Geofís. Int.,* **45,** 219–230.

Courtillot, V. & Le Mouël, J.L., 1988. Time variations of the earth's magnetic field: from daily to secular, *Ann. Rev. Earth planet. Sci.,* **16,** 389–476.

Creer, K.M., Thompson, R. & Molyneux, L., 1972. Geomagnetic secular variation recorded in the stable magnetic remanence of recent sediments, *Earth planet. Sci. Lett.,* **14,** 115–127.

Day, R., Fuller, M. & Schmidt, V.A., 1977. Hysteresis properties of titanomagnetites: grain-size and compositional dependence, *Phys. Earth planet. Inter.,* **13,** 260–267.

Dunlop, D.J., 2002. Theory and application of the Day plot (M_{rs}/M_s versus H_{cr}/H_c). 2. Application to data for rocks, sediments, and soils, *J. geophys. Res.,* **107,** B32057, doi:10.1029/2001JB000487.

Evans, M.E. & Heller, F., 2003. *Environmental Magnetism–Principles and Applications of Enviromagnetics. International geophysics series,* Vol. 86, 299 pp. Academic Press, Boston.

Fisher, R.A., 1953. Dispersion on a sphere, *Proc. R. Soc. Lond., Ser. A,* **217,** 295–305.

Frank, U. & Nowaczyk, N., 2008. Mineral magnetic properties of artificial samples systematically mixed from haematite and magnetite, *Geophys. J. Int.,* **175,** 449–461.

Frank, U., Nowaczyk, N.R., Negendank, J.F.W. & Melles, M., 2002. A paleomagnetic record from Lake Lama, Northern Central Siberia, *Phys. Earth planet. Int.,* **133,** 3–20.

Haltia-Hovi, E., Saarinen, T. & Kukkonen, M., 2007. A 2000-year record of solar forcing on varved lake sediment in eastern Finland, *Quat. Sci. Rev.,* **26,** 678–689.

Haltia-Hovi, E., Nowaczyk, N., Saarinen, T. & Plessen, B., 2009. Magnetic properties and environmental changes recorded in Lake Lehmilampi (Finland) during the Holocene, *J. Paleolimn.,* in press, doi:10.1007/s10933–009-9309-8.

Hallam, D.F. & Maher, B., 1994. A record of reversed polarity carried by the iron sulphide greigite in British early Pleistocene sediments, *Earth planet. Sci. Lett.,* **121,** 71–80.

Haverkamp, B. & Beuker, T.H., 1993. A palaeomagnetic study of maarlake sediments from the Westeifel, in *Paleolimnology of European Maar Lakes. Lecture Notes in Earth Sciences,* Vol. 49, pp. 349–365, ed. Negendank, J.F.W. & Zolitschka, B., Springer, Heidelberg.

Helminen, V.A., 1987. Lämpöolot, in *Atlas of Finland*, *Climate,* pp. 4–10, ed. Alalammi, P., National Board of Survey and Geographical Society of Finland, Helsinki (in Finnish).

Herrero-Bervera, E. & Valet, J.P., 2007. Holocene paleosecular variation: from dated lava flows on Maui, *Phys. Earth planet. Int.,* **161,** 267–280.

Hyvärinen, H., 1973. The deglaciation history of Fennoscandia–recent data from Finland, *Boreas,* **2,** 85–102.

Kansanen, P.H., Jaakkola, T., Kulmala, S. & Suutarinen, R., 1991. Sedimentation and distribution of gamma-emitting radionuclides in bottom sediments of southern Lake Päijänne, Finland, after the Chernobyl accident, *Hydrobiologia,* **222,** 121–140.

King, J.W., Banerjee, S.K., Marvin, J.A. & Özdemir, Ö., 1982. A comparison of different magnetic methods for determining the relative grain size of magnetite in natural materials: some results from lake sediments, *Earth planet. Sci Lett,* **59,** 404–419.

Kirschvink, J.L., 1980. The least-squares line and plane and the analysis of palaeomagnetic data, *Geophys. J. R. astr. Soc.,* **62,** 699–718.

Kovacheva, M., Hedley, I., Jordanova, N., Kostadinova, M. & Gigov, V., 2004. Archaeomagnetic dating of archaeological sites from Switzerland and Bulgaria, *J. Archaeol. Sci.,* **31,** 1463–1479.

Kristjánsdóttir, G.B., Stoner, J.S., Jennings, A.E., Andrews, J.T. & Grönvold, K., 2007. Geochemistry of Holocene cryptotephras from the North Iceland Shelf (MD99-2269): intercalibration with radiocarbon and palaeomagnetic chronostratigraphies, *The Holocene,* **17,** 155–176.

Jelinowska, A., Tucholka, P. & Wieckowski, K., 1997. Magnetic properties of sediments in a Polish lake: evidence of a relation between the rock-magnetic record and environmental changes in Late Pleistocene and Holocene sediment, *Geophys. J. Int,* **129,** 727–736.

Le Goff, M., Gallet, Y., Genevey, A. & Warmé, N., 2002. On archeomagnetic secular variation curves and archeomagnetic dating, *Phys. Earth planet. Int.,* **134,** 203–211.

Levi, S. & Banerjee, S., 1990. On the origin of inclination shallowing in redeposited sediments, *J. geophys. Res.,* **95,** 4383–4389.

Lotter, A.F. & Lemcke, G., 1999. Methods for preparing and counting biochemical varves, *Boreas,* **28,** 243–252.

Luukkonen, E., 2003. *Geological Map of Finland. Sheet 4321 Nurmes,* Geological Survey of Finland, Espoo.

Mackereth, F.J.H., 1971. On the variation in direction of the horizontal component of remanent magnetisation in lake sediments, *Earth planet. Sci. Lett.,* **12,** 332–338.

Maher, B., 1988. Magnetic properties of some synthetic submicron magnetites, *Geophys. J.,* **94,** 83–86.

Merrill, R.T. & McFadden, P.L., 2003. The geomagnetic axial dipole field assumption, *Phys. Earth planet. Int.,* **139,** 171–185.

Miettinen, A., 1996. Pielisen jääjärven kehityshistoria (The history of the Pielinen ice lake), *Terra,* **108,** 14–19. (in Finnish, with English abstract)

O'Sullivan, P.E., 1983. Annually-laminated lake sediments and the study of Quaternary environmental changes–a review, *Quat. Sci. Rev.,* **1,** 245–313.

Ojala, A.E.K. & Saarinen, T., 2002. Palaeosecular variation of the Earth's magnetic field during the last 10000 years based on the annually laminated sediment of Lake Nautajärvi, central Finland, *The Holocene,* **12,** 391–400.

Ojala, A.E.K. & Tiljander, M., 2003. Testing the fidelity of sediment chronology: comparison of varve and paleomagnetic results from Holocene lake sediments from central Finland, *Quat. Sci. Rev.,* **22,** 1787–1803.

Ojala, A.E.K., Saarinen, T. & Salonen, V.-P., 2000. Preconditions for the formation of annually laminated lake sediments in southern and central Finland, *Boreal Environ. Res.,* **5,** 243–255.

Oldfield, F., Crooks, P.R.J., Harkness, D.D. & Petterson, G., 1997. AMS radiocarbon dating of organic fractions from varved lake sediments: an empirical test of reliability, *J. Paleolimn.,* **18,** 87–91.

Parry, L.G., 1980. Shape-related factors in the magnetization of immobilized magnetite particles, *Phys. Earth Planet. Int.,* **22,** 144–154.

Parry, L.G., 1982. Magnetization of immobilized particle dispersions with two distinct particle sizes, *Phys. Earth Planet. Int.,* **28,** 230–241.

Putkinen, S. & Saarelainen, J., 1998. Kullenbergin näytteenottimen uusi kevennetty malli, *Geologi,* **50,** 22–23. (in Finnish)

Readman, P.W. & Abrahamsen, N., 1990. Geomagnetic Secular Variations from Holocene Lake Sediments of Sorø Sø, Denmark, *Phys. Earth planet. Int.,* **62,** 4–18.

Roberts, A.P., 1995. Magnetic properties of sedimentary greigite (Fe_3S_4), *Earth planet. Sci. Lett.,* **134,** 227–236.

Ron, H., Nowaczyk, N.R., Frank, U., Schwab, M.J., Naumann, R., Striewski, B. & Agnon, A., 2007. Greigite detected as dominating remanence carrier in Late Pleistocene sediments, Lisan formation, from Lake Kinneret (Sea of Galilee), Israel, *Geophys. J. Int.,* **170,** 171–131.

Rowan, C.J. & Roberts, A., 2005. Tectonic and geochronological implications of variably timed magnetizations carried by authigenic greigite in marine sediments from New Zealand, *Geology,* **33,** 553–556.

Saarinen, T., 1998. High-resolution palaeosecular variation in northern Europe during the last 3200 years, *Phys. Earth planet. Int.,* **106,** 301–311.

Saarinen, T., 1999. Palaeomagnetic dating of Late Holocene sediments in Fennoscandia, *Quat. Sci. Rev.,* **18,** 889–897.

Saarinen, T. & Wenho, H., 2005. *Minijääsormi sekä muita uusia ja vanhoja ideoita järvisedimentin talvikairaukseen. Geologian tutkijapäivät 14.-15.3.2005, Turku,* Congress Abstract Book, pp. 72–73. (in Finnish).

Saarnisto, M., 1971. The history of Finnish lakes and Lake Ladoga, *Commentationes Physico-Mathematicae, Soc. Sci. Fenn.,* **41,** 371–388.

Saarnisto, M., 1986. Annually laminated lake sediments, in *Handbook of Holocene Palaeoecology and Palaeohydrology,* pp. 343–370, ed. Berglund, B.E., Wiley, New York.

Snowball, I.F., 1994. Bacterial magnetite and the magnetic properties of sediments in a Swedish lake, *Earth planet. Sci. Lett.,* **126,** 129–142.

Snowball, I.F., 1997. Gyroremanent magnetization and the magnetic properties of greigite-bearing clays in southern Sweden, *Geophys. J. Int.,* **129,** 624–636.

Snowball, I., Zillén, L., Ojala, A., Saarinen, T. & Sandgren, P., 2007. FENNOSTACK and FENNORPIS: Varve dated Holocene palaeomagnetic secular variation and relative palaeointensity stacks for Fennoscandia, *Earth planet. Sci. Lett.,* **255,** 106–116.

Snowball, I. & Sandgren, P., 2002. Geomagnetic field variations in northern Sweden during the Holocene quantified from varved lake sediments and their implications for cosmogenic nuclide production rates, *The Holocene,* **12,** 517–530.

Snowball, I. & Thompson, R., 1990. A stable chemical remanence in Holocene sediments, *J. geophys. Res.,* **95,** 4471–4479.

Snowball, I. & Thompson, R., 1992. A mineral magnetic study of Holocene sediment yields and deposition patterns in the Llyn Geirionydd catchment, north Wales, *The Holocene,* **3,** 238–248.

Sprowl, D.R. & Banerjee, S.K., 1989. The holocene paleosecular variation record from Elk Lake, Minnesota, *J. geophys. Res.,* **94,** 9369–9388.

Stober, J.C. & Thompson, R., 1977. Magnetic remanence acquisition in Finnish lake sediments, *Geophys. J. R. astr. Soc.,* **57,** 727–739.

Stockhausen, H., 1998. Geomagnetic palaeosecular variation (0–13000 yr BP) as recorded in sediments from three maar lakes from the West Eifel (Germany), *Geophys. J. Int.,* **135,** 898–910.

Stockhausen, H. & Zolitschka, B., 1999. Environmental changes since 13,000 cal. BP reflected in magnetic and sedimentological properties of sediments from Lake Holzmaar (Germany), *Quat. Sci Rev.,* **18,** 913–925.

Tauxe, L., 2005. Inclination flattening and the geocentric axial dipole hypothesis, *Earth planet. Sci. Lett.,* **233,** 247–261.

Thompson, R. & Oldfield, F., 1986. *Environmental Magnetism,* 227 pp. Allen & Unwin, London.

Turner, G.M. & Thompson, R., 1981. Lake sediment record of the geomagnetic secular variation in Britain during Holocene times, *Geophys. J. R. astr. Soc.,* **65,** 703–725.

Turner, G.M. & Thompson, R., 1982. Detransformation of the British geomagnetic secular variation record for Holocene times, *Geophys. J. R. astr. Soc.,* **70,** 789–792.

Verosub, K.L., Mehringer, P.J., Jr. & Waterstraat, P., 1986. Holocene Secular Variation in Western North America: Paleomagnetic Record From Fish Lake, Harney County, Oregon, *J. geophys. Res.,* **91**(B3), 3609–3623.

Verosub, K.L., Harris, A.H. & Karlin, R., 2001. Ultrahigh-resolution paleomagnetic record from ODP Leg 169S, Saanich Inlet, British Columbia: initial results, *Mar. Geol.,* **174,** 79–93.

Vigliotti, L., 2006. Secular variation record of the Earth's magnetic field in Italy during the Holocene: constraints for the construction of a master curve, *Geophys. J. Int.,* **165,** 414–429.

Vigliotti, L., Capotondi, L. & Torii, M., 1999. Magnetic properties of sediments deposited in suboxic-anoxic environments; relationships with biological and geochemical proxies, in *Palaeomagnetism and Diagenesis in Sediments, Geol. Soc. Spec. Publ.,* Vol. 151, pp. 71–83, ed. Tarling, D.H. & Turner, P., The Geological Society, London.

Winklhofer, M. & Petersen, N., 2007. Paleomagnetism and Magnetic Bacteria, in *Magnetoreception and Magnetosomes in Bacteria, Microbiol. Monogr,* Vol. 3, pp. 255–273, ed. Schüler, D., Springer, Berlin Heidelberg.

Wohlfarth, B., Skog, G., Possnert, G. & Holmquist, B., 1998. Pitfalls in the AMS radiocarbon-dating of terrestrial macrofossils, *J. Quat. Sci.,* **13,** 137–145.