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Post-glacial sedimentation rate and patterns in six lakes of the Kokemäenjoki upper watercourse, Finland

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Sediment distribution and accumulation in a chain of five lakes and Pääjärvi, southern Finland for the last ca. 10 000 years were investigated using acoustic sounding profiles. Lake bathymetry, catchment relief, geology and locations of input creeks and ditches have a critical effect on sedimentary dynamics in the study lakes. These factors cause considerable within-lake variation in the sediment depositions. Typically, the majority of accumulating matter and nutrients are removed from the flow system in sedimentation pools, which are seldom evident on bottom topography alone. However, detailed geological study can provide this information. The physical properties of long sediment sequences from each lake were investigated and dated using a palaeomagnetic dating method. The long-term sediment composition in the study lakes appeared to be more dependent on regional environmental factors, i.e. climate, whereas the rate of sedimentation was connected with soil types and land use in the immediate catchment area.

Introduction

The objectives of the NUTRIBA project (Nutrients from River Basins — Experimental and Modelling Approach) funded by the Baltic Sea Research Programme (BIREME) of the Finnish Academy were to identify and quantify important processes and mechanisms for nutrient pathways, cycling, transformation and retention within selected water bodies of the Kokemäenjoki drainage basin in central-southern Finland. A chain of five lakes (hereafter called the NUTRIBA lake chain), located in the upper areas of the Kokemäenjoki drainage basin, was selected as an intensive study site in the NUTRIBA project. This paper presents results of sedimentological and palaeolimnological investigations of the NUTRIBA lake chain.

An understanding of the sedimentary dynamics within an individual lake or a chain of lakes requires remote characterization of the thickness and distribution of sediment deposits (Scholz 2001). This kind of information is needed when investigating the role of lakes as sinks and sources of organic and inorganic material, as well as nutrients, carbon, phosphorus and nitrate. The primary focus of the present study was to provide a comprehensive outline of sedimentation in the NUTRIBA lake chain using echo-sounding profiles. Here we discuss how lake bathymetry, the geological setting and hydrological factors control sedimentation dynamics in the NUTRIBA lake chain. This background

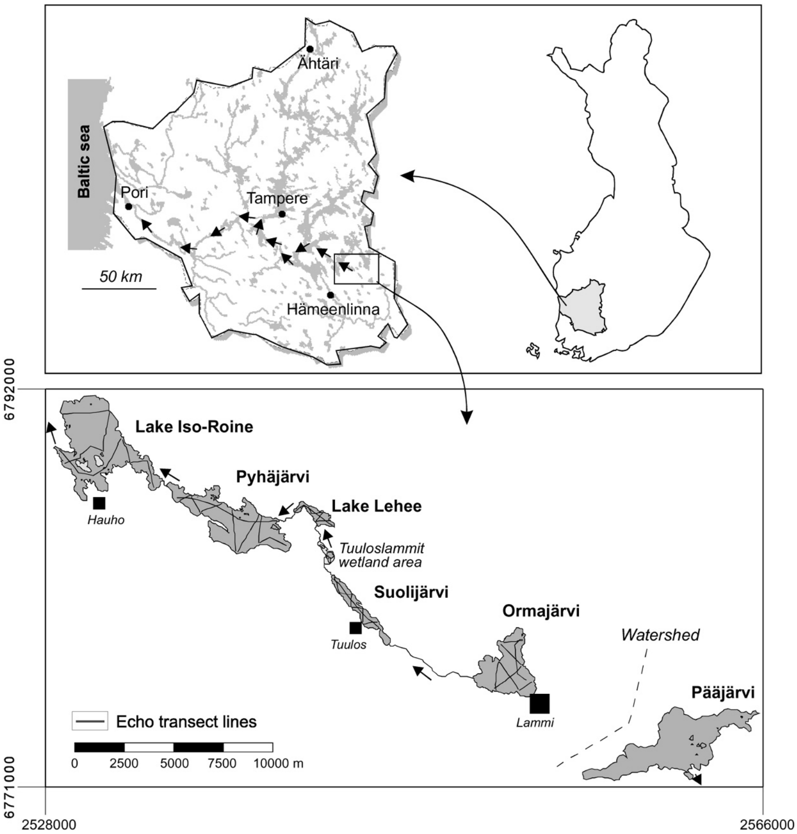

Fig. 1. The NUTRIBA lake chain is located in the upper area of the Kokemäenjoki drainage basin, southern Finland (Finnish grid).

will assist other process studies included in the NUTRIBA project, such as the transportation and retention of nutrients and related biogeochemical processes (Rask *et al.* 2004).

The second focus was to investigate long-term fluctuations in the sedimentation rate and total carbon accumulation in the NUTRIBA project lakes. To this aim, long sediment cores were retrieved at sites that according to the echo-sounding survey represent continuous sedimentation since the lakes were isolated from the Baltic basin around 10 000 years ago. These sediment sequences were dated using a palaeomagnetic dating method (e.g., Thompson and Oldfield 1986, King and Peck 2001).

Materials and methods

Study area

The NUTRIBA lake chain is located in central-southern Finland on the upper area of the Kokemäenjoki basin (total river catchment area of 26 820 km^2), some 150 km inland from the estuary of the River Kokemäki (Fig. 1). The lake chain drains towards the northwest from Ormajärvi (94.1 m a.s.l.) to Lake Iso-Roine (84.1 m a.s.l.), and is composed of five morphometrically and limnologically different lakes. The locations and characteristics of the study lakes are presented in Table 1. In addition, Pääjärvi, located on the other side of the local watershed and draining to the southeast, was used as a reference site for the sedimentary study of the NUTRIBA lake chain.

The Pre-Quaternary geology of the NUTRIBA lake chain area is characterized by mica- and veined gneiss on the east and south side, and granodiorite and porphyritic granodiorite in the northwestern corner. The NW–SE orientated basins of the lakes Iso-Roine and Pyhäjärvi were formed in a fracture zone between these two bedrock blocks (Matisto 1976). The structure of the bedrock is a principal factor in lake-catchment relief and sedimentation dynamics of lakes

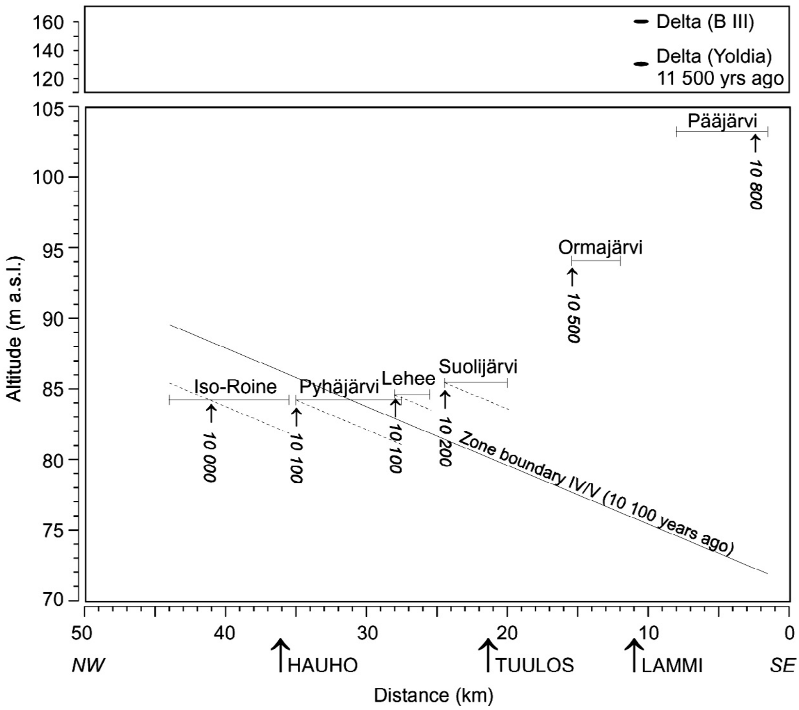

Fig. 2. Delta levels of the Baltic Sea stages B III–Yoldia Sea and the isolation of the NUTRIBA lake chain. Transgression and regression of lakes are parallel to Pollen Zone Boundary IV/V (*see* Sauramo 1949).

Iso-Roine and Pyhäjärvi. The Pääjärvi area is composed of granodiorite, amphibolite, granite and mica gneiss (Laitakari 1980).

The Quaternary geology of the study area is characterized by Salpausselkä I and Salpausselkä II (SS I and SS II) ice-marginal formations, formed due to the re-advance of the continental ice-sheet during the Younger Dryas event between 12 250 and 11 590 years ago (Saarnisto and Saarinen 2001). Pääjärvi is located between SS I and SS II and was revealed from under the ice approximately 11 700 years ago. Soon after, around 11 500 years ago, the drainage of the Baltic Ice Lake caused a sudden lowering of the water level in the Baltic basin that can be detected as multiple delta top-set levels (160 m a.s.l. for the Baltic Ice Lake and 130 m a.s.l. for the Yoldia Sea) in the Lammi area. The Ormajärvi area was deglaciated more or less simultaneously with the drainage of the Baltic Ice Lake. The other basins of the NUTRIBA lake chain became exposed from under the retreating ice between 11 400 and 11 200 years ago. The NUTRIBA lake chain and Pääjärvi were isolated from the Yoldia Sea (Fig. 2). Pääjärvi was isolated 10 800 years ago and Ormajärvi approximately 300 years later (10 500 years ago). The rest of the NUTRIBA lakes then became isolated during a 200-year period from 10 200 (Suolijärvi) to 10 000 years ago (Lake Iso-Roine) (Sauramo 1958, Donner 1964, Saarnisto 1971a).

Post-glacial land uplift in the area caused considerable tilting of lake basins since their isolation. The tilting approximately corresponds with the NW–SE gradient of the Yoldia shoreline at the Pollen Zone Boundary IV/V of Sauramo

Table 1. Characteristics of the NUTRIBA chain lakes and Pääjärvi (Finnish grid).

Lake	Location	Altitude (m)	Area (ha)	Max. depth (m)	Mean depth (m)
Pääjärvi	6774145/ 3399335	102.9	1344	85	14.8
Ormajärvi	6778528/ 3390636	94.1	653	31.4	8.5
Suolijärvi	6782061/ 3382955	85.4	203	10.4	4.7
Lehee	6787098/ 3380901	84.6	104	4.1	1.4
Pyhäjärvi	6786958/ 3376520	84.2	949	35	10.1
Iso-Roine	6792295/ 3369455	84.1	3087	73	7.2

(1949) around 10 000 years ago (*see* e.g., Saarnisto 1971b). Only the NW part of Lake Iso-Roine has been regressive (Fig. 2).

Quaternary deposits of the area are heterogeneous. Eskers exist on both sides of the lake chain, being NW–SE orientated and partly abutted to the research lakes. Fringe areas of these eskers are typically covered by shore deposits, for example in the Ormajärvi–Pääjärvi watershed boundary area. Silt and sandy silt deposits are also clustered in the Ormajärvi–Pääjärvi area. The western and central parts of the research area mainly consist of till, and there are clay deposits around the Tuuloslammit wetland area. Some bedrock outcrops are found on the north side of Lakes Iso-Roine and Pyhäjärvi, as well as minor peat accumulations in the depressions between bedrock outcrops and till formations (Kae 1978, Kukkonen and Haavisto-Hyvärinen 1986). Approximated proportions of the main soil types of immediate catchments of the study lakes are as follows: Ormajärvi: 50% glaciofluvial material, 30% till, 20% fine-grained deposits; Suolijärvi: 30% glaciofluvial material, 30% till, 10% bedrock outcrops, 30% fine-grained deposits, minor peat deposits; Lake Lehee: 60% fine-grained deposits, 40% till, several bedrock outcrops; Pyhäjärvi: 80% till, 10% glaciofluvial material, and the remaining 10% with bedrock outcrops, fine-grained and peat deposits; Lake Iso-Roine: 60% till, 10% bedrock outcrops, 10% glaciofluvial material, 20% fine-grained deposits and peat deposits; Pääjärvi: 50% till and bedrock outcrops, 25% glaciofluvial material, 25% fine-grained deposits.

The study area is located within the Southern Boreal vegetation zone and the dominant tree species are pine and spruce (Alalammi 1987). Three municipal centres — Lammi, Tuulos and Hauho — are located in the area (Fig. 1.), while scattered settlements are common on the shores of the study lakes. Silt and clay areas near Ormajärvi and Suolijärvi are actively cultivated, as well as areas on the south side of Lakes Lehee and Pääjärvi.

The present day local climate is continental, with a mean annual precipitation of about 600–650 mm, of which approximately one third is snow. The annual mean temperature is ca. +4 to +5 °C, the warmest months being June and July and the coldest January or February. The study lakes are ice-covered for a period of four to five months, usually from mid-December until late April (Alalammi 1987).

Acoustic sounding and studies of long sediment cores

The thickness and distribution of post-glacial sediments in the NUTRIBA lakes were investigated with a FURUNO FE 881 MK 2 echo sounder in August 2004. Locations of survey lines for acoustic sounding profiles were based on experience gained in previous studies in the boreal landscape (Pajunen 2000, 2004) and reconnaissance of topographic and bathymetric maps. For example, we gathered a total of 11.2 km of acoustic sounding profiles from Ormajärvi, which has an area of 6.5 km^2. This data was then analysed with a surface mapping system (Golden Software Inc, SURFER®) in order to calculate the volume and 3D distribution of post-glacial gyttja and/or clay-gyttja deposits. Also some statistical characteristics, such as variance of the sediment thickness, were calculated.

Coring of the long sediment profiles (a duplicate set of cores from each of the NUTRIBA chain lakes) was targeted on the basis of acoustic sounding profiles at locations that were considered to best represent the sedimentary environment of each study lake. Coring was carried out with a heavy piston corer (Putkinen and Saarelainen 1998). Up to nine metres long parallel cores were taken from the same locations and stored for control and later use. All the cores were stored in a cold room (+4 °C).

The sediment cores were opened in the laboratory, their surfaces were cleaned, and they were logged for sediment stratigraphy and volume magnetic susceptibility (Bartington MS2E1 surface scanning sensor). In addition, the cores were sampled for loss on ignition (LOI) at 1 cm resolution (+550 °C for 2 hours). LOI was then used to estimate the accumulation rate of carbon in each lake following the formula of Håkanson and Jansson (1983).

The sediment sequences from lakes Ormajärvi, Suolijärvi, Pyhäjärvi, Iso-Roine and Pääjärvi were dated with palaeomagnetic dating method (Thompson and Oldfield 1986, King and Peck 2001). Palaeomagnetic dating of soft sediments is based on the assumption that small magnetic grains (or their magnetic domains) orient parallel to the Earth's prevailing magnetic field during or soon after settling on a lake floor. This orientation remains unchanged under suitable undisturbed conditions when particles are covered by continuous sedimentation. Sediment deposits therefore possess records of natural remanent magnetization (NRM). NRM consists of three main elements, declination, inclination, and intensity that define the direction and strength of the palaeomagnetic field. The relatively high sedimentation rate (ca. 0.5 to 2 mm yr^{-1}) and suitable age (ca. 10 000 years) of typical northern European lakes enables them to record fluctuations in palaeosecular variation (PSV) of the Earth's magnetic field. These fluctuations can be used as a relative dating method in lacustrine and marine environments (Snowball and Sandgren 2002, Ojala and Tiljander 2003). However, there are several prerequisites that need to be fulfilled before palaeomagnetic dating can be applied. First, the magnetic signal of the sediments under investigation must truly reflect the NRM (*see* AF (alternative field) demagnetization technique in, e.g., King and Peck 2001) and the NRM data must be reasonably stable. Second, a well-dated local reference curve (i.e. master curve) must be available for comparison and the resolutions of the studied and reference curves must be of similar order.

In this study, sediment sampling into 7 cm^3 plastic cubes for palaeomagnetic measurements and testing of the stability of the NRM followed Ojala and Tiljander (2003), and results from the NUTRIBA chain lakes were compared with the varve-dated reference curve of Nautajärvi, which clearly meets the criteria mentioned above (Ojala and Tiljander 2003). NRM was measured with a 2G-Enterprises SRM-755R tri-axial SQUID magnetometer. The obtained NRM curves were visually matched with the Nautajärvi reference curves, labelling the major characteristics of declination and inclination following Creer *et al*. (1976). Age–depth transformations for the NUTRIBA chain lakes and Pääjärvi sediment sequences were based on positively identified patterns of the NRM signal.

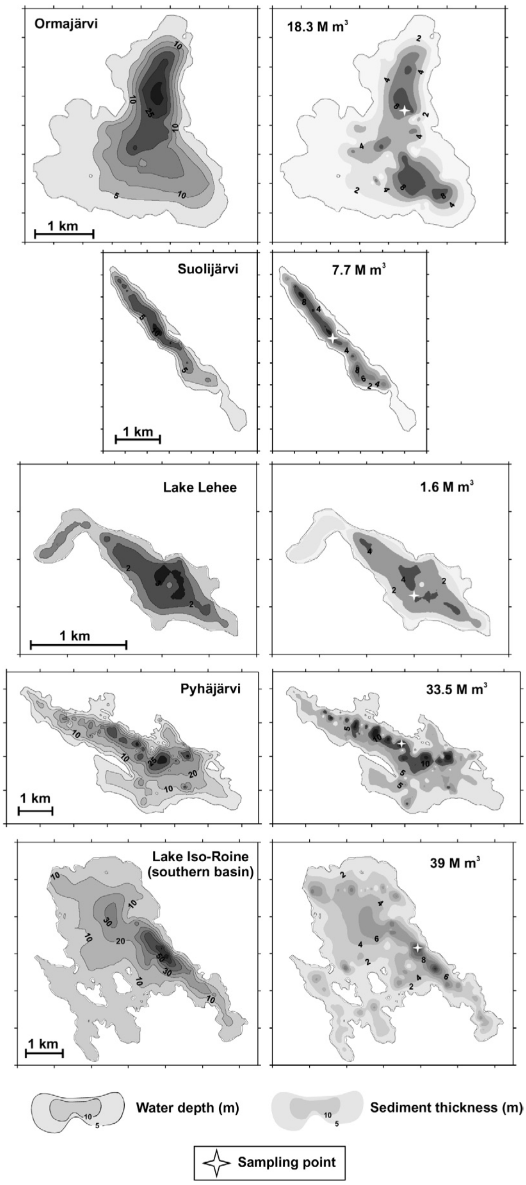

Fig. 3. Bathymetric maps (left) and thickness and regional distribution of the post-glacial sediments (right) in the NUTRIBA chain study lakes.

Results

Distribution of sediment in the NUTRIBA chain lakes

According to its bathymetry, Ormajärvi appears as a single basin lake (Fig. 3). Sediment studies, however, indicate that there are two distinct sedimentation areas in north and SE parts of the lake. In both sedimentation areas the post-glacial sediments are over 8 m thick. Sediment layers in other parts of Ormajärvi are thinner. For example, around the outflow area of the lake the thickness of the post-glacial sediment deposits is only 1 to 2 m. Due to this variation, the variance of the sediment thickness is relatively high, 6.9 m. The average sediment thickness in Ormajärvi is 2.7 m and the total amount of gyttja is 18.3 million m^3.

Suolijärvi is an oblong flow-through lake with a maximum depth of 10 m. The deepest basin is located in the central area of the lake, being attenuated like the lake itself. The most significant sediment accumulation areas are determined by the lake bathymetry, and the thickest sediment layers are found in the central basin of the lake. It is also noticeable that the outflow end of the lake has a clearly more important role as an accumulation area than the inflow end. The total amount of post-glacial sediments in Suolijärvi is approximately 7.7 million m^3 and the maximal thickness of sediment bed is almost 11 m, whereas the average thickness of the sediment is 3.7 m. Due to the morphology of the lake and the low amount of sediment at the input end, the variance of the sediment thickness is significant, being 9.5 m.

Many locations in Lake Lehee were filled with sediments up to its maximum level of accumulation during post-glacial times. The maximum sediment thickness in the deepest area of the lake is 4.8 m, while the mean thickness of the sediment layer is only 1.6 m and the variance 1.3 m. The total volume of post-glacial sediment in Lake Lehee is 1.6 million m^3.

Pyhäjärvi is the second largest isolated basin in the NUTRIBA lake chain. The maximum thickness of the post-glacial sediment (15.8 m) was detected in the NE part of the lake. This accumulation area formed in a fracture zone of the bedrock and is bounded by steep, 10–15 m high cliffs above the shoreline. Altogether, there are four to five accumulation depressions in the same NW–SE oriented fracture zone, in which sediment layers over ten metres thick exist. Due to the relatively small area of these basins, the mean thickness of the sediment in Pyhäjärvi is 3.4 m and the variance is 8.4 m.

Lake Iso-Roine differs from the other NUTRIBA chain lakes not only because of its size but also because it is a part of a larger water body. In addition to the NUTRIBA lake chain, Iso-Roine collects drainage from a northern waterway. In this study, however, we have concentrated on the southern part of Iso-Roine, which is an immediate recipient of the waters of the NUTRIBA lake chain. The same fracture zone that traverses along Pyhäjärvi also forms the main accumulation area in Iso-Roine. The thickest sediment layers (maximum 16.7 m) lie in a well-restricted basin over 70 m deep (Fig. 3). The central area of Iso-Roine comprises a rather large accumulation area in which the sediment thickness is 5 to 8 m. This area is also located in the fracture zone. The average thickness of postglacial sediments in Lake Iso-Roine is only 2.8 m and the variance is 5.4 m.

Sediment stratigraphy, loss on ignition (LOI) and magnetic susceptibility (MS)

Lithostratigraphical division of the long sediment profiles from NUTRIBA chain lakes is based on physical sediment properties and visual characteristics, which are presented in Fig. 4.

Ormajärvi

The section from 644–602 cm (sediment depth) consists of laminated clay gyttja with visually noticeable layers of coarser mineral matter. In the lower part of this section the stripes are 1 to 4 mm thick, but in the upper part of the section they are approximately 1 mm. The amount of organic matter appears to increase upwards. This can be also observed in the LOI, which increases evenly from 5% to 15% in this section. The MS, on the other hand, decreases from 15×10^{-5} to 10×10^{-5} SI.

The 602–0 cm section consists of gyttja which is variably laminated for most of the sequence. The sediment structure between 602–587 cm is laminated with approximately 1 mm thick layers. The 587–506 cm subsection is also laminated, but the maximum layer thickness is 2 mm, and the organic rich layers are generally thicker

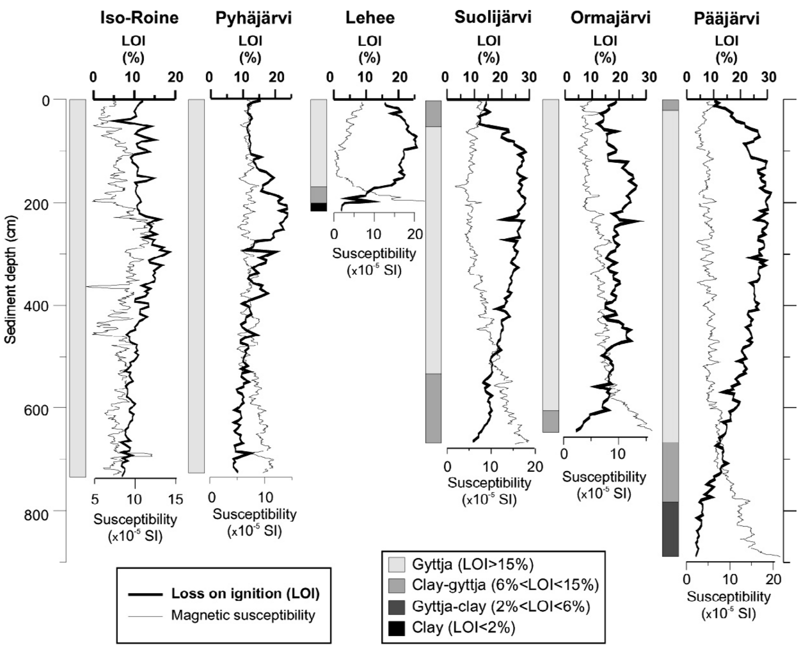

Fig. 4. Magnetic susceptibility and LOI measurements of sediment sequences from the NUTRIBA chain lakes and Pääjärvi. Stratigraphical units of each record are presented on the left side of each panel.

than the mineral rich ones. In the 506–387 cm subsection the laminations are again thinner and sediment contains vivianite as macroscopic precipitates. Laminae become even thinner upwards between 506 and 387 cm, and coarser mineral matter is present in the structure. In the 387–221 cm subsection the laminations are thick: 1 to 4 mm in the lower part of this subsection and up to 6 to 8 mm in the top part. The laminae are very thin (< 1 mm) and uniform between 221–191 cm, whereas the 191–183 cm subsection is disturbed. This section is rich in vivianite, which can be seen as a maximum in the MS. The 183–162 cm subsection is laminated (1 to 2 mm), but the 162–139 cm subsection is again disturbed. The maximum value of LOI was measured in this subsection. LOI decreases in the subsection 139–114 cm and the structure is homogenous. In the 114–0 cm subsection, 1–3 mm laminations rich in sulphides occur between 114–88 cm, while the subsection 88–79 cm contains no sulphide banding. The subsection from 79 cm to the sediment surface is laminated (3 to 8 mm), and is increasingly sulphide rich and loose upwards in sediment. A 1-cm-thick silty clay layer exists at the sediment depth of 26 cm, coinciding as a peak in the MS.

In general, the sediment LOI increases upwards from 15% to 25% between 602 and 160 cm, then decreases to 12% (in the sequence 160–70 cm) and increases again to nearly 20% at the sediment surface. There is a LOI maximum feature at the depth of 480–430 cm, which is not detectable in the visual sediment structure. MS decreases upwards, being 8×10^{-5} SI at the sediment depth of 580 cm, and then decreases to 4×10^{-5} SI at the sediment surface. Short-term fluctuations in MS appear related to the variation in mineral matter concentration.

Suolijärvi

The section 685–518 cm consists of clay gyttja. In the subsection 685–640 cm the amount of organic matter strongly increases and the first laminations gradually appear. There is a strong increase in LOI and decrease in MS. Between 640–518 cm, MS decreases from 16×10^{-5} to 10×10^{-5} SI and LOI increases to 15%. The structure in this subsection is laminated, but the laminations are irregular and distorted.

The sediment section 518–60 cm consists of gyttja. Throughout the subsection 518–423 cm there are irregular laminae with 1 to 3 mm thick mineral rich layers and less than 1 mm thick organic-rich layers. The thickness of laminations remains the same upwards in the 423–252 cm subsection, being up to 3 mm at the top contact. Laminations are disturbed. The subsection 252–239 cm is a transition zone where the organic matter content increases and the structure becomes homogenous. The subsection 239–60 cm is formed from homogenous gyttja. The MS decreases to 4×10^{-5} SI by 252 cm and then remains rather stable ($4–6 \times 10^{-5}$ SI). LOI increases up to approximately 28% by 252 cm and remains at this level up to the 60 cm level.

The section 60–0 cm, as well as the lowest section of the core, consists of clay gyttja. The sediment is mostly without structure, except for a few irregular laminations. The subsection from 60–25 cm contains fairly large amounts of sulphides in comparison to the more minerogenic subsection 25–0 cm. MS increases from 4×10^{-5} to 8×10^{-5} SI towards the sediment surface, whereas LOI decreases to 12%.

Lake Lehee

The section from 220–200 cm consists of homogenous clay with a sharp upper contact.

The 200–175 cm section is clay gyttja in which the amount of mineral matter decreases upwards, which can be seen in the sediment structure as well as in the LOI increasing from 5% to 20%, and MS decreases from 40×10^{-5} to 5×10^{-5} SI.

The sediment section 175–0 cm consists of gyttja. The structure of the subsection 175–17 cm is homogenous. Maximum of LOI (40%) is present between 90–70 cm. The 17–0 cm subsection consists of from very dark, massive and sulphide-rich gyttja.

Pyhäjärvi

The Pyhäjärvi core (726–0 cm) is gyttja throughout. The 726–530 cm subsection is composed of distorted, laminated sediment with 1 to 4 mm thick layers. The sediment colour varies, and darker, organic-rich layers can be seen as MS minima and LOI maxima. There is a homogenous section between 530–292 cm, with occasional thin laminations. The subsection 292–270 cm consists of more compact, homogenous sediment. Laminations again appear in the subsection 270–190 cm. The upper part of the section consists of < 1 mm layers, while in the lower part laminations are thicker (1 to 2 mm) and accompanied by a few homogenous, 1 to 2 cm thick layers. The 190–140 cm subsection is laminated, and layers are less than 2 mm thick. Between 140 cm and the surface the sediment is composed of homogenous detritus gyttja. In the Pyhäjärvi core, LOI increases upwards from 8% to 24% between the bottom of the core and 220 cm, and then decreases to 12% at the sediment depth of 10 cm. LOI then increases again towards the sediment surface. MS decreases from 12×10^{-5} to 6×10^{-5} SI in the subsection 720–530 cm. Between 530 cm and the sediment surface MS varies between 5×10^{-5} and 9×10^{-5} SI.

Lake Iso-Roine

The entire core of Lake Iso-Roine (731–0 cm) also consists of gyttja. The basic structure is laminated gyttja. In the subsection 731–370 cm laminations are broken by 2 to 10 cm thick homogenous layers. In the upper part of the core such mixed layers do not exist, but the lamination structure itself is rather distorted. Laminations are broken, bent and heavily stretched. LOI increases from 8% to 16% between 731–300 cm, and then decreases to 6% at the sediment depth of 40 cm. Between 40 cm and the sediment surface, LOI again slightly increases. MS increases up to 12×10^{-5} SI at the sediment depth 240 cm. Between 240 cm and the sediment surface, MS decreases to 8×10^{-5} SI. The high-frequency variability of LOI and MS reflect changes in sediment stratigraphy, but minima and maxima are not comparable to changes in the macroscopic sediment structure.

Pääjärvi

The 887–780 section is composed of gyttja clay. This section consists of regularly laminated 2–20 cm subsections and structureless, 3 to 10 cm thick subsections. LOI increases upwards from 3% to 6% and MS decreases from 23 to 12×10^{-5} SI in this section. One of the homogenous subsections can be seen as an MS maximum peak at the sediment depth of 780 cm.

The section 780–665 cm is composed of laminated clay gyttja, and LOI increases and MS decreases upwards.

Sediment between 665–30 cm consists of gyttja, the structure of which is laminated, probably composed of true varves (i.e. annual laminations), as discussed by Simola and Uimonen-Simola (1983) and Itkonen and Salonen (1994). The thickness of laminae varies between 0.5–8 mm, but is mainly about 2 to 4 mm throughout the sediment profile. Laminations are distorted and twisted in many parts of the sediment sequence. It was therefore impossible to construct a reliable varve chronology from this particulate core. LOI increases upwards up to 32% at 180 cm and then decreases to 19% at the sediment depth of 30 cm. The MS decreases to approximately 5–10 $\times$ 10^{-5} SI at the sediment depth of 600 cm, and fluctuates in this range up to the sediment depth of 30 cm.

The section 30–0 cm is again composed of clay gyttja. The sediment is loose, containing large amounts of sulphides, and the structure is mixed and distorted. LOI continues to decrease and MS increases in this uppermost section.

Palaeomagnetic dating

Ojala and Tiljander (2003) demonstrated that the PSV of the Earth's magnetic field as represented in sediment sequences with clastic-organic varves, such as Nautajärvi, provides regionally applicable reference curves for palaeomagnetic correlation and age control in Fennoscandia. The palaeomagnetic record of Nautajärvi, extending back to ca. 10 000 years (with the estimated error of < 1% in the varve chronology), was used here as the main reference curve in dating the NUTRIBA chain sediment cores. The distance between the Nautajärvi reference site and the NUTRIBA chain lakes is less than 100 km and they have a relatively similar LOI, susceptibility and a rate of sedimentation, all promoting PSV curve correlations between records.

Randomly selected samples were submitted for stepwise AF demagnetization in order to test the stability of the NRM and investigate the magnetic carriers of the remanence. All the test samples, for example sampling cube 46 from the depth of 146 cm in the Pyhäjärvi core, exhibited a strong and stable primary component of the NRM direction. In addition, the AF demagnetization behaviour of the sample suggests that fine-grained single domain (SD) and pseudo-single domain (PSD) magnetite is the dominant carrier of the remanence (King *et al.* 1982, Thompson 1986). Similar results were obtained from lakes Nautajärvi, Korttajärvi and Alimmainen Savijärvi sediments by Ojala and Tiljander (2003).

Characteristics of NRM inclination and relative declination of the NUTRIBA chain lakes are correlated with the Nautajärvi reference curve in Fig. 5. The declination and inclination values vary roughly between ±40° and 60–80°, respectively, in the NUTRIBA chain lakes, which correspond well with recent studies from Fennoscandia (e.g., Snowball and Sandgren 2002, Ojala and Tiljander 2003). It appears that the declinations possess slightly more noise than the inclination datasets, but they still exhibit almost all of the major declination features (f, e, g', h, i) typically found in northern hemisphere records. In particular, a rapid westerly swing of declination (f to e) occurring between 800 and 570 BC is well represented in the NUTRIBA chain lakes, as well as a smooth maximum feature 'h' at around 4800 BC (*see* Ojala and Tiljander 2003). Patterns of inclination variation in the NUTRIBA lakes are also very consistent with the Nautajärvi reference curve over the last ca. 10 000 years. Particularly well-pronounced maximum features ε' and λ, which were detected from the study lakes, can be anchored to the varve dates 570 BC and 6385 BC, respectively. The minimum features κ (at 4250 BC) and μ (at 6855 BC) of inclination are also well represented in the NUTRIBA cores, and even many of the minor features, such as β, δ, ζ, η, and ι are evident and comparable with the Nautajärvi reference curve.

Altogether, 14 to 22 PSV curve features were used to anchor the sediment sequences of the NUTRIBA chain lakes to the varve-dated Nautajärvi palaeomagnetic reference curve. The age–depth transformation presented in Fig. 6 is based on these fixed sediment depths in each of the study lakes. Furthermore, fluctuations in

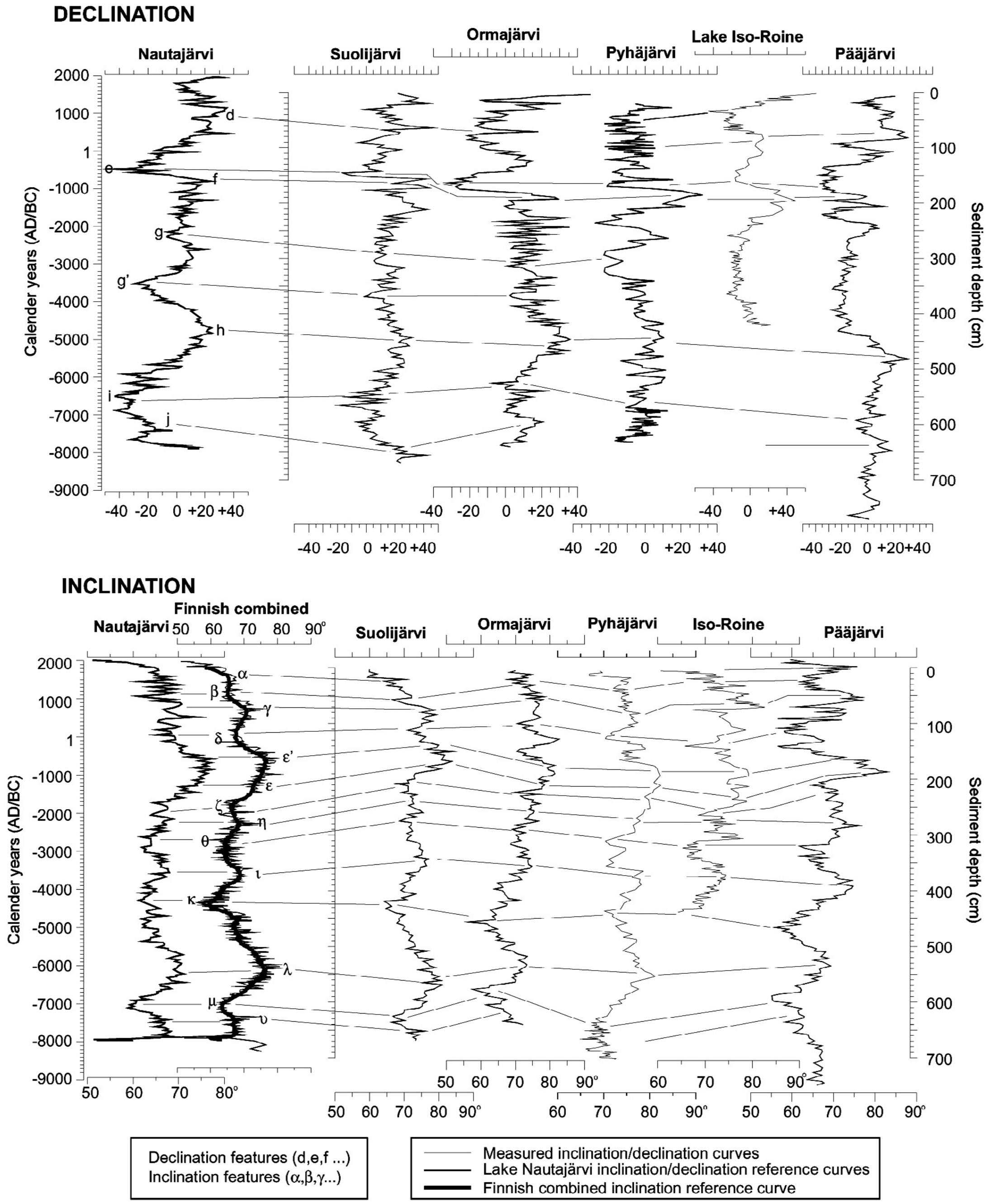

Fig. 5. Matching of the magnetic records of the study lakes with the palaeosecular, declination and inclination curves of the varve-dated Nautajärvi reference curves and Finnish combined inclination curve (Ojala and Tiljander 2003).

the rate of sedimentation presented in Fig. 7 are based on the age–depth transformations. In lakes Ormajärvi and Suolijärvi the ca. 6.5-m-long sediment sequences extend back to about 7800 BC, whereas the Pyhäjärvi record covers some centuries less, and the Pääjärvi record a few centuries more. The Pääjärvi sequence is also two metres longer than those of the three above-mentioned lakes. The 7.3-metre-long sediment record of Lake Iso-Roine, having a considerably higher rate of sedimentation than the other NUTRIBA lakes, extends only to 4300 BC.

Discussion

Sediment accumulation

Ormajärvi

In Ormajärvi there are two main sedimentation basins (Fig. 3). Naturally, the most important accumulation area is located in the deepest part of the lake on the north side, but due to the presence of Lammi village, a sewage plant and a dairy, all located on the SE side of the lake, the focus of sedimentation has partly changed. The sediment thickness in the SE accumulation area is almost equal to that in the northern area, but it can be presumed that recent accumulation has been faster in this part of the lake. The artificial lowering of Ormajärvi in 1824–1831 (Anttila 1967) has probably caused considerable lake-shore erosion and re-deposition of sediment. As a consequence, a silty clay layer can be detected at a sediment depth of 26 cm. According to this horizon, the sedimentation rate during the last 180 years was approximately 1.5 mm a^{-1}, even in the northern basin.

These two accumulation areas trap the majority of allochthonous and autochthonous matter in Ormajärvi. Sedimentation in the outlet area of the lake, as well as in southwestern parts, is minor. This naturally results from the shallowness of the area, but also from the north–south orientated moraine ridge, which is a continuation of the cape on the north side of the lake. This ridge sedimentologically separates the outlet area of the lake from the rest of the basin. Also the location of cultivated land in east and north sides of the lake determines the main source of allochthonous influx into the basin.

Suolijärvi

In Suolijärvi the main accumulation area is closely connected with the lake bathymetry, mainly due to the simple form of the lake basin. Sedimentation has concentrated in the deepest part of the outlet end of the lake. However, because of the even bathymetry, land uplift probably changed the sedimentation pattern in Suolijärvi during the last ca. 10 000 years (Fig. 2) (Sauramo 1958, Saarnisto 1971a). The area of highest accumulation, as well as shoreline, has slowly transferred towards the southeast, and this development will probably continue.

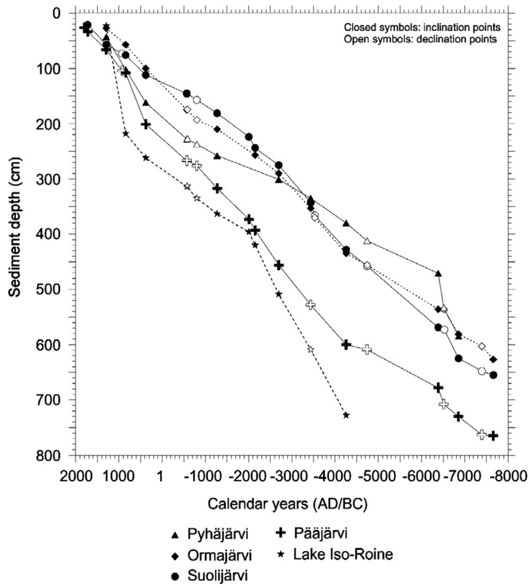

Fig. 6. Palaeomagnetic age–depth transformation for the five investigated sediment sequences. Lakes Iso-Roine and Pääjärvi had the highest rate of sedimentation, while rates in Ormajärvi, Pyhäjärvi and Suolijärvi were equal.

At the moment the shallow area at the southeast end of the lake is a transportation area, and stable accumulation does not occur. One of the main sources of the mineral matter yield into Suolijärvi is the silty area between Ormajärvi and Suolijärvi. Although the mineral load from Ormajärvi itself is rather small, due to the sediment dynamics of the lake, the Ormijoki erodes mineral matter from this silty area and transports it into Suolijärvi.

Lake Lehee

Lake Lehee is a shallow flow-through lake with the theoretical retention time of approximately 35 days only. Its sedimentation dynamics is straightforward; there are no areas of stable

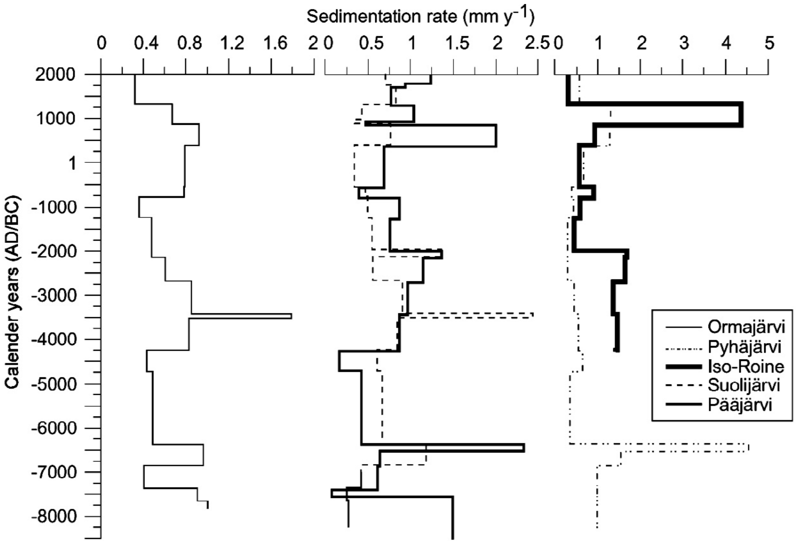

Fig. 7. The rate of sedimentation (in mm yr^{-1}) varied considerably in the investigated lakes during the last ca. 10 000 years.

and continuous accumulation. The thickest sediment layers, a maximum of ca. 4 metres, are located in the central area of the lake at the water depth 4 metres. A north–south orientated bedrock groundsill between the main basin and the western basin of the lake effectively separates these two sub-basins. Most of the processes related to sediment dynamics have focused on the SE part of the lake. However, sediment accumulation is in an unstable state and the sediment is subject to continuous erosion, transportation and re-deposition. The basin of Lake Lehee has filled to the maximum with sediments and much of the incoming load of organic and mineral matter drifts into the Kopsjoki and then towards Pyhäjärvi. The Tuuloslammit wetland area also has an important role in this part of the NUTRIBA chain. It effectively filters the mineral matter load between lakes Suolijärvi and Lehee. However, the Tuuloslammit area probably adds to the proportion of organic matter in the total input. Lake Lehee receives inflow also from the north, but small basins of lakes Kuoruejärvi, Okslammi and Takanen effectively retain the suspended load of mineral and organic matter from this inflow.

Pyhäjärvi

The sedimentation dynamics of Pyhäjärvi are much more complex than the smaller lakes of the NUTRIBA chain. The northwest–southeast orientated bedrock fracture zone (Matisto 1976) forms a series of accumulation pools along the north side of the lake. Due to land uplift, the focus of sedimentation changed in post-glacial times towards the southeast (Sauramo 1958, Saarnisto 1971b). It is probable that the thickest layers located in the western part of the fracture zone were mainly deposited soon after the isolation of the basin, and the present accumulation in these pools is minor as compared with the situation immediately after isolation. The main accumulation area for the matter drifting from the upper NUTRIBA lakes is nowadays in the deepest pool in the NE part of the lake. According to this inflow, the pool gains material from heavily cultivated areas on the eastern side of the lake, which accelerates the sedimentation even more.

In addition to the fracture zone, a further geological factor is important in the sedimentation dynamics of Pyhäjärvi. A northwest–southeast orientated esker on the south side of Pyhäjärvi partly fills this side of the lake depression with shore deposits. The same esker, which can be seen as a long cape, continues through the lake and separates the southwestern pool from the rest of the lake. This basin is an independent accumulation pool that collects the matter transported to the lake from southwestern inlets.

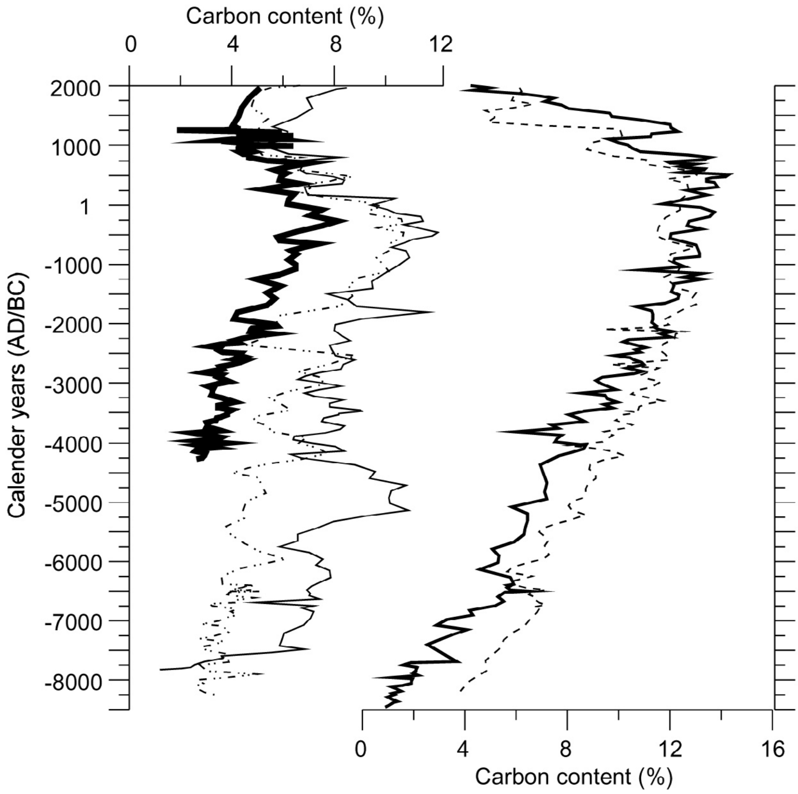

Fig. 8. Comparisons of sediment carbon stratigraphies in the NUTRIBA chain lakes and Pääjärvi. Note the upwards decreasing trend in every record and obvious, relative decline during the last ca. 1500 years.

Lake Iso-Roine

The same fracture zone that is characteristic of Pyhäjärvi is also a principal feature determining the sedimentation pattern and dynamics of Lake Iso-Roine. The deepest point of the lake, 76 metres (Fig. 3), is in the fracture zone. This depression, the area of which is rather small as compared with the size of the entire lake, collects the majority of the matter drifting via the NUTRIBA lake chain. It probably also collects a significant amount of the matter transported to the lake from the northern water system. The sedimentation rate in this pool is far greater than other accumulation areas of Lake Iso-Roine, and the sediment thickness in this basin is almost 16 metres, while the average sediment thickness in the lake is only 2.8 m. Large shallow and microtopographically variable areas at the outlet end of the lake contain only a minor amount of sediments. In addition to the major accumulation basin, the fracture zone as a whole is a rather important accumulation area, especially in the central part of the fracture. Lake Iso-Roine was artificially lowered during 1821–1826 (Anttila 1967), which may have caused temporary changes in the sedimentation pattern of the lake. However, the role of the deepest pool as an accumulation area of the lake is essential.

Fluctuations in sedimentation rate and carbon content

The detailed rate of sedimentation and sediment carbon content (%) in the NUTRIBA chain lakes and in Pääjärvi during the last ca. 10 000 years are illustrated in Figs. 7 and 8. These results are based on the LOI analysis and palaeomagnetic dating of the sediment cores. As observed in the acoustic sounding profiles, there are exceptionally thick post-glacial sediment deposits in the deepest part of Lake Iso-Roine basin. In this depression, the rate of sedimentation ranged between 0.4 and 4 mm yr^{-1} during the last ca. 6000 years, being on average around 1.0 mm yr^{-1}. These results emphasize the importance of this single sedimentary basin as a sink and store of bulk sediment and nutrients within the whole southern basin of Lake Iso-Roine. In comparison, the rate of sedimentation in the other sedimentary pools of the NUTRIBA lakes has fluctuated between 0.3 and 2.0 mm yr^{-1} (ca. 0.6 mm yr^{-1} on average), which is comparable to the average sedimentation rates in lakes of the Finnish Boreal zone (e.g., Pajunen 2004).

Compared with Lake Iso-Roine, Pyhäjärvi has a fairly stable rate of sedimentation, which may result from the fact that there are several separate sedimentary pools, removing the affects of the regional and temporal variations in sedimentation. The post-glacial gyttja is also more evenly spread in Ormajärvi and Suolijärvi than in Lake Iso-Roine. Nevertheless, all these lakes exhibited considerable temporal fluctuations in the rate of sedimentation during the past approximately 10 000 years.

There was no clear common trend in the rate of sedimentation in the NUTRIBA chain lakes, but of particular interest are a few simultaneously occurring peaking values in the sediment accumulation. The first occurred after the isolation of the lakes from the Baltic Sea, around 6500–7000 BC. This intensification in deposition can be seen in Ormajärvi, Suolijärvi, Pyhäjärvi and Pääjärvi and may be related to rapid land uplift in the area or a rapid change in the palaeohydrology of the watercourse, such as the formation of new channels between the study lakes. The more recent increase in the rate of sedimentation at around AD 500–1500 is probably related to anthropogenic activities in the area: first slash-and-burn agriculture and then increased arable cultivation (Huttunen and Tolonen 1977, Huttunen 1980). The results would suggest that the onset of the large-scale anthropogenic activities was not synchronous throughout the study area. Also lake-level lowering during the 19th and 20th centuries influenced NUTRIBA chain lakes, most probably causing noticeable variation in sedimentation, although these variations may not be precisely connectable to results of this study. Erosion volume and suspended material transport, as well as the temporary variations in water quality in the Lammi area, were studied earlier by Tikkanen *et al.* (1985) and Tikkanen (1990). According to these studies, up to 40 g m^{-2} annually can be transported into Pääjärvi. It seems clear that even short-term, small-scale changes in the immediate catchment area of a lake can cause significant variability of the seasonal-annual sedimentation. However, such changes can only be detected in lakes that compose varved sediments (e.g., Ojala and Alenius 2005).

In any case, such fluctuations in the rate of sedimentation in the NUTRIBA chain lakes during the last thousands of years make a significant difference when calculating the long-term natural retention of bulk sediment, carbon and nutrients in single basins or in a chain of lakes. In general, changes in the rate of sedimentation would appear to be dependent on local forcing factors (cultivation, basin development, sediment focusing) rather than regional climatic factors during the last ca. 10 000 years. However, long-term fluctuations in sediment composition (Fig. 8) in the NUTRIBA lake chain (and Pääjärvi) open up possibilities to investigate common larger-scale environmental factors that drive changes in lake-catchment sedimentary dynamics. This can be seen particularly well in the consistency of the carbon content curves of Suolijärvi and Pääjärvi, which are located on opposite sides of the watershed. Their carbon contents had increased from the isolation horizons to ca. 750 AD (12%–14%), and then declined towards the present day.

These results suggest that a millennial-scale trend in sediments composition is driven more by regional forcing factors that are regulating the allochthonous *vs.* autochthonous sediment accumulation in these lakes. The results, however, may be biased by an ontogenetic development of each basin, especially during the last 2000 years.

The trend in carbon accumulation in lakes Iso-Roine, Pyhäjärvi and Ormajärvi differs from that in Suolijärvi and Pääjärvi. In these three lakes, the carbon content had increased upwards from ca. 5% at 8000 BC to over 10% at around 250 BC. It then declined to 5% by 1000 AD, after which it increased again towards the present day. All studied cores indicate a general increase in LOI and a decrease in magnetic susceptibility towards the present day until the AD/BC boundary. Obviously, this results from millennial-scale decrease in catchment erosion and the transportation of allochthonous mineral matter into the study lakes, which is seen as an increasing trend in carbon content. During the last ca. 2000 years, however, the trend in Suolijärvi and Ormajärvi was opposite, likely due to expansion of agricultural people in the Lammi area (Huttunen and Tolonen 1977, Huttunen 1980). Simultaneously, with the increase of catchment erosion due to human activities the relative proportion of catchment-derived carbon also increased (Simola 1992).

Significantly, carbon content in this study was estimated according to Håkanson and Jansson (1983), and these values are therefore only reliable when the original value of LOI is over 10%. It would also be possible to estimate the millennium-scale total dry matter and carbon accumulation rates (g m^{-2} a^{-1}) and storages from the presented results. For example, Pajunen (2004) roughly estimated these in the study of 140 Finnish lakes, whereas Ojala and Alenius (2005) calculated them in detail from the Nautajärvi varved sediment sequence. However, sedimentation environment in NUTRIBA lakes is rather complicated and calculations mentioned above, carried out on single coring locations could only provide rough estimations of lake-scale carbon or dry matter accumulation.

What is therefore causing this clear trend in the sediment and relative carbon accumulation in the NUTRIBA lake chain records? A millennial-scale shift in palaeohydrology is one possible explanation. It is known that spring is the period of the most intensive runoff in this environment, and it is controlled by the presence of snow storage in winter, the water equivalent of snow in the spring, and the rapidity of the snowmelt in spring (e.g., Kuusisto 1984). Catchment erosion and transportation of allochthonous material are, therefore, also highest during the spring. A climatic shift towards milder and wetter winters could have lessened the spring maximum discharge peaks, and thus catchment erosion, causing the pattern seen in the NUTRIBA lakes. Possibly also tilting of the watershed towards the slowest land uplift direction have had a long-term effect on sedimentation in the NUTRIBA chain lakes.

Changes in catchment overburden may be another possible explanation. A decreasing trend in the sediment yield, partially caused by reworking of the mineral matter in the lake-catchment system, is very typical for lakes that have undergone a transition from larger lake complexes (or ice-lakes) into smaller isolated basins (e.g., Saarnisto 2000). It has been suggested from Nautajärvi that the primary stabilization of the catchment may take over a thousand years, but in fact a slowly decreasing supply of erodable material in the drainage system is actually seen throughout the entire evolution of the basin (Ojala and Alenius 2005). This may also be the case in the NUTRIBA chain lakes. Moreover, stabilization of the dispersal of vegetation around the exposed lake affects the transportation of allochthonous material into these basins, but surely could not have an influence over thousands of years. The most recent change (around AD 500–1500) was, as mentioned, due to increased human activities in the area that have intensified catchment erosion, delivering more allochthonous mineral matter into these lakes. Artificial lowering of the lakes clearly has an effect on the sediment quality, such as the clayed layer at the depth of 26 cm in Ormajärvi. Overall, it is likely that a combination of these factors is forcing the changes in sedimentation detected in the NUTRIBA lake chain, but the magnitude of the effect of each factor can not be discussed on the basis of results presented in this paper only.

Conclusions

1. Millennial-scale fluctuations in the sediment composition in the NUTRIBA chain lakes and in Pääjärvi indicate that there were considerable changes in their sedimentation environment during the last 10 000 years. Changes are due to, e.g., catchment stabilization after the lake isolation and anthropogenic activities.
2. The functionality of palaeomagnetic dating in different types of lakes in the NUTRIBA chain provides a key to understanding the sedimentation development as a whole. However, changes in the sedimentation rate and sediment composition do not necessarily correlate.
3. The long-term changes in the composition of sediment (organic *vs.* mineral matter) seem

to be more dependent on larger scale environmental factors, whereas the sedimentation rate is strictly connected with changes in the ontogenetic development of each basin.

4. Long lake sediment cores are highly important in environmental research as well as in regional quaternary geological research. A single "background" sample seldom provides all the information needed for environmental policymaking. However, it is important to link data obtained from surface sediment samples with long core results to indicate the past and present state of surface water bodies.
5. In addition to lake bathymetry, the information provided by echo sounding or ground-penetrating radar sounding is almost essential to successful sediment sampling.

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