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Preconditions for the formation of annually laminated lake sediments in southern and central Finland

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The geological and geomorphological settings of annually laminated sediments in Finnish boreal lakes in southern and central Finland were investigated. The purpose of the study was to identify the key sedimentary environmental factors of the morphometric features and catchment sediment types that control varve deposition in lakes. Altogether nearly 300 lakes were surveyed, of which 180 basins were cored. 35 of the cored lakes were found to contain partially laminated and 13 completely laminated sediments. Statistical analyses of the lake dataset, which also includes 15 previously located lakes composing varved sediments, show that two groups of lakes are more favourable for the formation of varves than others. The first group includes the majority of previously located varved lakes and is characterized by small-sized, relatively deep basins in glaciofluvial deposits. The second group is characterized by fairly equal proportions of till, bedrock and fine-grained sediment in the catchment, and it is more dependent on the shape of the catchment and basin itself than maximum depth and lake area. These lakes are located in the distal part of Younger Dryas end moraines or in the areas of ancient lake complexes or ice-lakes, and commonly comprise clastic-organic laminae couplets.

Introduction

Annually laminated (varved) sediments are invaluable archives for palaeoecological reconstructions. They can be precisely dated and provide a high resolution record for studies of environmental change. All laminated sediments do not necessarily reflect annual cycles of sedimentation (Saarnisto 1986). However, in the boreal environment, characterized by strong seasonal contrasts of ice cover, spring floods, summer stratification, algae blooms and autumn storms, the annual cycle is the principal cause of rhythmic sedimentation in lakes. Nevertheless, the annual nature of laminated sediments has to be determined in each occurrence from the structural and compositional elements of the sediments (Simola 1992).

The study of laminated lake sediments in Finland began in 1975 when Saarnisto introduced a new coring technique (crust-freeze coring) to sample loose surface sediments. Earlier, Kukkonen and Tynni (1970) had identified annually laminated sediments from Pyhäjärvi. Tolonen (1978) was the first to use varved sediments for palaeoecological reconstructions in Finland with a study of 6 200 varves in Lake Ahvenainen. More recently, Grönlund (1995) reconstructed land-use history from 13 varved lake sequences in eastern Finland, and Saarinen (1999) used varved sediments to reconstruct secular variations of the Earth's magnetic field, which can be used for palaeomagnetic dating. Annually laminated sediments have also been used in studies of climate change (Itkonen and Salonen 1994), chronometry (Saarnisto 1985, Ojala and Saarnisto 1999), pollution reconstruction (Kansanen and Jaakkola 1985) and erosion history (Sandman *et al.* 1990). A total of nearly 30 varved sites had been located and studied in Finland before the present study (Table 1) (Fig. 1). Only a few of these contain sediments laminated throughout the entire sequence.

During the past two decades Renberg and his co-workers (e.g. Renberg 1978, Renberg 1982, Petterson *et al.* 1993) described the basic structure of varves in various Swedish Boreal lakes. Varves are formed in a depositional cycle of minerogenic material in spring, particulate organic material (plants, algae, etc.) in summer and a thin, fine-grade and dark-coloured organic winter layer. Lower boundaries of the minerogenic laminae are sharp and the amount and the grain size of the mineral matter decrease upward, grading to darker organic material. This type of varves are commonly found in dimictic lakes with a substantial input of silt or clay during spring floods. Seasonal anoxia in the hypolimnion of these lakes is instrumental in preventing the sediments from being disturbed by bioturbation (Petterson 1996). Saarinen (1998) described a similar type of varve structure in Pohjajärvi, a lake in Central Finland.

During the past few years, several authors (e.g. Grönlund 1995, Salonen *et al.* 1997) showed that numerous lakes, with different morphometrics and various geomorphic settings, contain laminated sediments in the Finnish Boreal zone. Nevertheless, the conditions favourable to the formation of long and continuous accumulation of distinct varve sequences are still rare.

Lakes containing varved sediments exhibit a number of common characteristics. In this paper we discuss those characteristics based on a systematic survey of lakes that were found to contain indications of laminated sediments in Finland. On the basis of the selected geomorphic and catchment characteristics, we then discuss the geological context in which those lake basins were initially formed, following the last deglaciation in Finland.

Methods

Map reconnaissance

Prior knowledge of varve accumulation, the reconnaissance topographic (some containing bathymetric information) and surficial geological maps (published by the Geological Survey of Finland), and increasing information of the appearance of varved sediments in lakes allowed us to focus our work on a few main areas, from where nearly 300 lakes, with the minumum depth of > 5 meters, were targeted for the field study (Fig. 1). Lakes lying high above present day sea level were preferred, because they were isolated from early Baltic Sea phases, and probably contain a sediment record extending to the Weichselian deglaciation. The size of the target lakes varied from a few ha to some hundreds ha. On the basis of earlier studies (e.g. Saarnisto 1986, Petterson 1996), lakes with large peat bogs in their catchment were avoided and lakes with fine-grained sediments in their catchment and substantial inflow were preferred.

Coring

Coring of the target lakes was mainly carried out with a 0.5 or 1.0 meters long Russian peat corer (Jowsey 1966), operated with a series of two-meter long rigid aluminium rods and designed for fast and reliable lake sediment sampling down to a water depth of 25 meters. If the water depth exceeded 25 metres, a wedge-shaped crust-freeze corer (model Renberg 1981, length 150 cm, width 12 cm) or a modified Kajak sampler (Kajak 1966) was used. The crust-freeze corer is used to sample loose material at the sediment–water interface in order to ensure the continuity of the laminated structure to the present day deposits. Coring was normally conducted at the deepest point of the lake or close to river mouths, if they were considered to correspond to a sediment accumulation zone.

For the purpose of statistical treatment, maximum water depth, lake area, altitude and catchment properties were surveyed for each of the cored lakes. In addition cored sediment sequences

Table 1. New lakes, selected for further studies, and previously located Finnish lakes, found to contain varved sediments. Previously located varved sequences are all related either to large and deep lakes depositing seasonally variable amounts of minerogenic matter or to small meromictic lakes depositing diatom-rich layers alternating with black humus-rich winter layers (Saarnisto 1986). Calcareous varves have not been found in Finnish lakes (based on Saarnisto 1986).

	Area (ha)	Maximum depth (m)	Nature of varves	Number of varves	Catchment type	References
Previously studied varved lakes						
Ahvenainen	7.8	19	B/d	6 174	GF	Tolonen 1978
Lampellonjärvi	9.7	10	B/d	> 3 372	GF	Tolonen 1980
Lovojärvi	4.8	17.5	B/d	4 929	GF	Saarnisto *et al*. 1977
Pääjärvi	1 342	87	B/d, C	> 800	H	Simola & Uimonen-Simola 1983
Polvijärvi	185	35	B/d	?	T, FG	Simola 1983
Taka-Killo	2.8	25	B/d	1 506	GF, P	Huttunen 1980
Pyhäjärvi	1 290	68	B/d	3 700	H	Kukkonen & Tynni 1970
Valkiajärvi	7.8	25	C, B	8 700	T, BR	Saarnisto 1985
Pohjajärvi	3.6	20	C	3 200	T, FG	Saarinen 1998
Päijänne	8 560	95	B/d	450	H	Itkonen & Salonen 1994
Hännisenlampi	?	?	B	?	?	Vuorinen 1978
Laukunlampi	8.4	26	B/d	?	GF	Battarbee 1981
Kissalammi	4.7	15	B	5 500	GF	Tolonen 1981
Heinälampi	3.2	8	C	~ 2 600	FG, T	Sandman *et al.* 1990
Likolampi	1.04	11	B	390	GF	Grönlund *et al.* 1986
Sotkulampi	3	9	?	3 700	T, FG	Grönlund *et al.* 1990
Suurjärvi	780	32	B	3 600	H	Grönlund *et al.* 1990
Pitkälampi	30	20	?	700	FG, T	Grönlund 1995
Mustikkalampi	5	12	B	~ 2 000	H	Grönlund *et al.* 1990
Tervalampi	2	10.5	B	~ 4 200	GF	Grönlund *et al.* 1990
Varved lakes discovered within this research and selected for further studies						
Alimm. Savijärvi	8	8	C	~ 8 800	FG, BR	
Nautajärvi	13	19.5	C	n.d.	FG, BR	
Valkeajärvi	25	7.1	C	7 200	FG,BR, GF	
Pitkäjärvi	65	13.5	C/B	n.d.	T,FG	
Vaskunjärvi	40	16.4	C	n.d.	T, FG, BR	
Ristijärvi	21	18.5	C	n.d.	T, FG, BR	
Kortejärvi	25	12	C/B	n.d.	T, FG, BR	
Lehmälampi	13	11	C/B	n.d.	T, FG, BR	
Kalliokourunjärvi	15	11.2	B	n.d.	H	
Korttajärvi	25	12.4	C	n.d.	T, FG	
Suujärvi	10	12	B	~ 4 000	GF	

Catchment type: T = till, P = peat, GF = glaciofluvial, BR = bedrock, FG = fine-grained,H = heterogeneous.
Nature of varves: B = biogenic (/d = diatom), C = clastic-org.
Number of varves: n.d. = not determined.

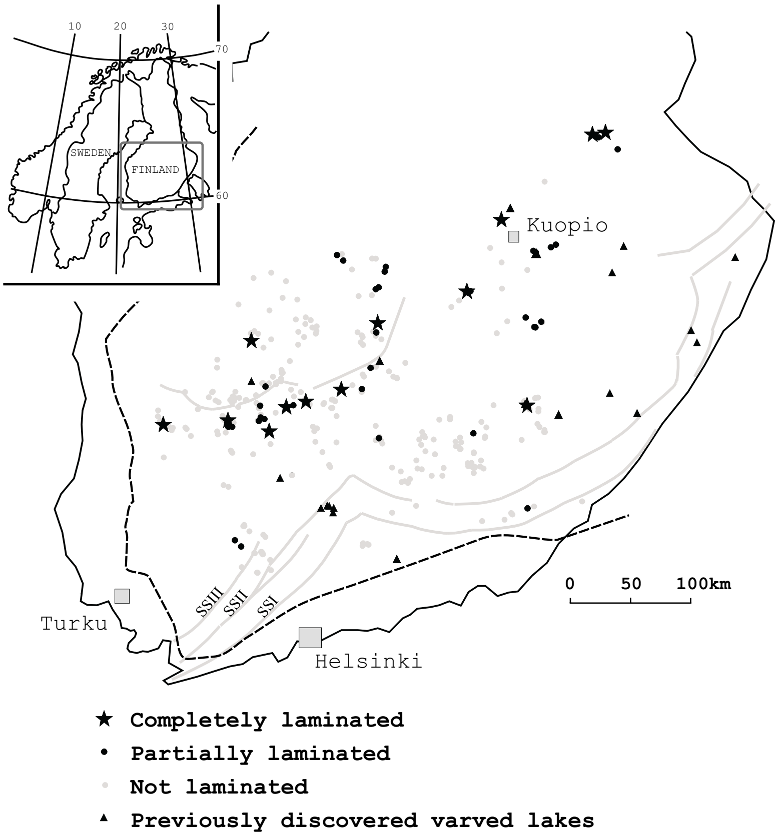

Fig. 1. Regional distribution of previously located lakes with annually laminated sedimentsand lakes cored within this research during winters 1997–1999. Note that no lakes with varved sedments have thus far been located in northern Finland. Figure includes Younger Dryas end moraines (grey lines), and the highest Litorina Sea shore-line (dotted line) according to Eronen and Haila (1990).

were classified as:

1. not laminated (or massive),
2. partially laminated, or
3. completely laminated (meaning laminated throughout the entire core).

Partially laminated sequences include those that were only laminated either in the top or in some other section of the core and those for which it was not possible to core through the entire sequence. Sequences containing recent formations of black iron sulphide layers, commonly formed as a result of human activity in the watershed, were classified as not laminated.

Promising lakes were selected for further detailed studies on the basis of the sediment composition, lamination structure, vertical continuity of the laminae and location and altitude of the lake.

Statistical treatment of lake data

The variables included in the lake dataset were: altitude, maximum depth, lake area; and areal-percentage of the catchment soil types classified as: till, peat, glaciofluvial sediments, fine-grained material and bedrock. These variables were recorded for 195 lakes including the 15 previously discovered varved lakes (Table 1) and the 180 lakes cored within this project. However, the present dataset, although useful for the present analysis, cannot be considered as representative of all Finnish lakes, because it does not include large lakes, and because it does not result from a random sampling process. Large lakes, due to their more complicated and variable limnic sedimentary environment, would not be suitable for this kind of statistical treatment and were therefore not included, even though several authors (e.g. Kukkonen and Tynni 1970, Itkonen and Salonen 1994) showed that isolated deep basins within them can contain varved sequences.

Two statistical approaches were used to examine the relationships between the selected variables and varve accumulation. The first approach, cluster analysis, measures similarities and differences between objects (Swan and Sandilands 1995), in this case different morphometric features and lake catchment properties. A Ward's method cluster analysis, using Euclidean distances as the dissimilarity measure, was applied to the dataset.

The second approach, factor analysis, was used to determine if the total variation in the dataset could be represented by a smaller number of factors. Factor loadings were normalised with the Varimax method (Jongman *et al.* 1995). The lakes were then plotted against the factor scores in order to examine their distribution in fewer, interpretable dimensions.

Results

Altogether 279 lakes were surveyed in southern and central Finland during the winters 1997–1999. Approximately one third of these lakes turned out to be too shallow or to have an unsuitable sedimentary environment for varve accumulation. The remaining 180 lakes (Fig. 1) were cored with the purpose of locating new annually laminated sequences. Descriptive statistics of the lake dataset, composed of previously located varved lakes and lakes cored within this research, are presented in Table 2. The average lake lies at an altitude of 105 m a.s.l., has a surface area of 10 to 20 hectares and a maximum depth of 10 meters.

Altogether 48 new basins were found to contain laminated sediments, and 13 of these sequences were laminated uninterruptedly throughout the entire sequence. The majority of these new lakes, as well as all of the previously studied varved lakes, are located either in the distal part of Central Finland End Moraine or near eskers and other glaciofluvial deposits. Laminated sequences included both biogenic and clastic structures, with a typical laminae thickness ranging between 0.3 and 1.0 mm.

Based on a cluster analysis, the lake dataset was divided into five groups (Fig. 2).

Cluster I (9 lakes): characterized by fairly large lakes (area 100 to 300 ha) with heterogeneous and till-dominated surficial sediments in their catchment.

Cluster II (23 lakes): composed of lakes that have abundant (> 80%) glaciofluvial deposits in their catchment, are small in size and have a variable maximum depth (4 to 26 m).

Cluster III (38 lakes): lakes characterized by a catchment dominated by till and by variable morphometric features and surface area.

Table 2. Descriptive statistics of the lake dataset composed of 195 lakes that were either cored in this study or have previously discovered to contain varves.

	Mean	Median	Min.	Max.	Std. Dev.	Std. Error
Altitude (m a.s.l.)	106.3	105.0	60.0	185.0	21.1	1.5
Area (ha)	24.9	11.0	1.0	300.0	47.4	3.4
Maximum depth (m)	10.6	9.0	2.0	36.0	6.5	0.5
Catchment (%)						
till	33.9	30.0	0.0	95.0	28.8	2.1
peat	4.1	0.0	0.0	85.0	8.8	0.6
glaciofluvial	17.4	0.0	0.0	100.0	30.6	2.2
bedrock	18.4	10.0	0.0	85.0	20.2	1.5
finegrained	26.1	25.0	0.0	100.0	23.4	1.7

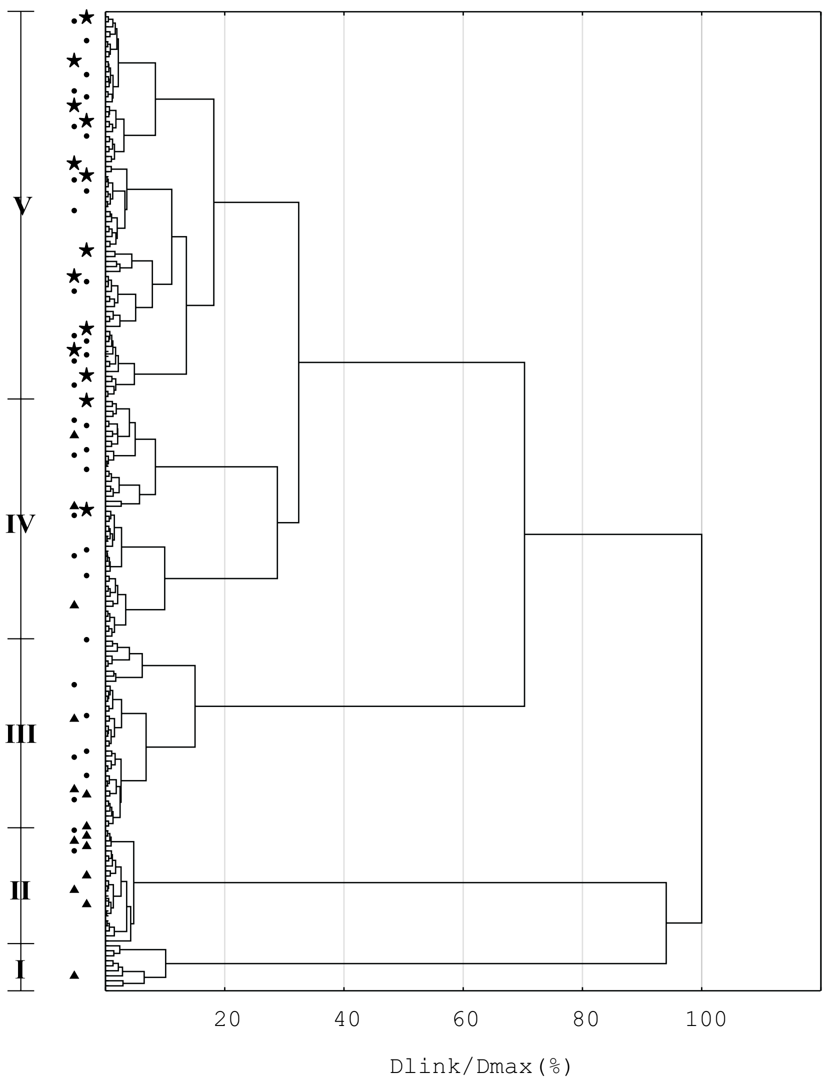

Fig. 2. A Ward's method linkage cluster analysis (Euclidean distances) for the lake dataset. Lakes are divided into 5 different clusters marked on the left-hand side (key: *see* Fig. 1).

Cluster IV (48 lakes): includes lakes that are relatively shallow (5–10 m), small in size (~10 ha) and have an abundance (> 50%) of fine-grained sediments in their catchment.

Cluster V (77 lakes): lakes have a variable surface area (3 to 100 ha), are located at lower altitudes and have a more heterogeneous catchment coverage composed of approximately equal proportions of fine-grained material, till and bedrock outcrops. Cluster V includes the majority of the partially and completely laminated sequences newly discovered here.

Factor analysis reduced the total variation in the lake dataset to three statistically significant factors that explain almost 70% of the variation (Fig. 3 and Table 3). Factors 1 and 3 have high loading of geologic characteristics, namely catchment sediment types, whereas factor 2 has two strong positive morphometric variables, namely depth and size. Low loading of factor 1 characterizes bedrock and fine-grained deposits in the catchment, whereas high loading reflects peat deposits and higher altitude. Loading of factor 3 characterizes either till or glaciofluvial deposits as they appear in opposite sides in the figure therefore excluding each other.

Cored lakes show two main groups, plus several outliers, when plotted against the factor scores

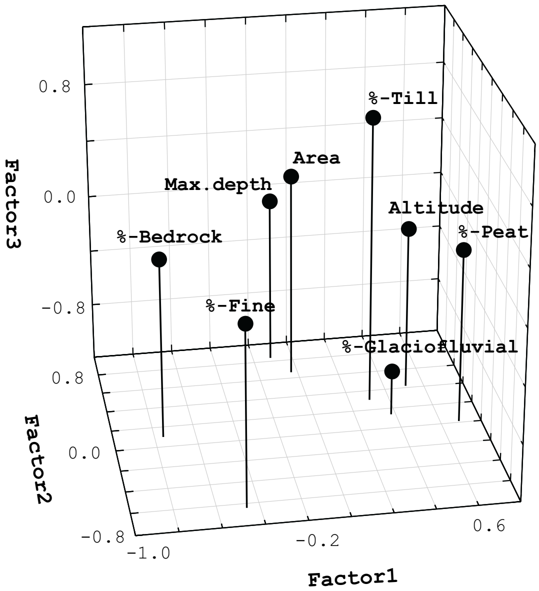

Fig. 3. Factor analysis (Extraction: Principal components, Rotation: Varimax normalised) lessens the 8 variables of the dataset down to three statistically significant factors. Factors 1 and 3 are loaded with catchment sediment types, whereas factor 2 has two strong variables, depth and size. Factor loadings are marked in Table 3.

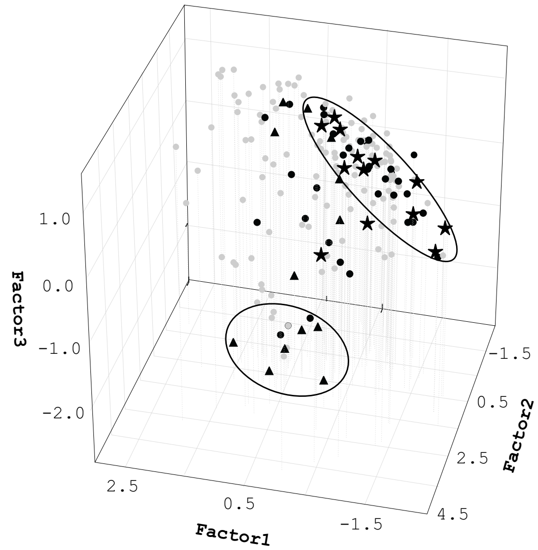

Fig. 4. Factor scores of cored and previously located varved lakes plotted against peat/bedrock (Factor 1), depth-area/fine-grained (Factor 2) and till/glaciofluvial (Factor 3) factors (key: *see* Fig. 1).

(Fig. 4). The first group, in the foreground, contain a smaller number of lakes and includes most of the previously located lakes with varved sequences. The shape of the second group is elongated as scores of the factors 3 and 1 increase simultaneously. The centre of this group contains the majority of the new lakes that were found to contain laminated sediments.

Discussion

On the basis of earlier studies and the present lake dataset, low-productivity, dystrophic lakes with peatlands in the watershed are not favourable for the formation and preservation of varved sediments. These lakes, which commonly occur in the forested boreal areas, have a low organic productivity, and sediments consist mainly of allochthonous organic particulate material. Here is usually a high rate of bioturbation in the water-sediment interface and the annual rhythm is not preserved in the sediment.

The geographical distribution of lakes with laminated sequences is the first indication of a close relationship between the surficial geologic setting and the accumulation of varves in lakes. The occurrence of varved sediment cannot be explained by a straightforward depth-area relationship (Fig. 5). It is dependent on various interacting sedimentary environmental factors, such

Table 3. Factor loadings of 3 statistically significant factors obtained from the lake dataset. They explain nearly 70% of the variabilities in the whole dataset. Factor 1 = peat/bedrock, Factor 2 = depth-area/fine-grained and Factor 3 = till/glaciofluvial.

	Factor 1	Factor 2	Factor 3
Altitude	0.510	0.419	–0.044
Area	–0.032	0.663	0.244
Maximum depth	–0.110	0.839	–0.029
%-till	0.301	0.303	0.820
%-peat	0.691	0.013	0.034
%-glaciofluvial	0.378	0.137	–0.882
%-bedrock	–0.758	0.098	0.069
%-fine-grained	–0.463	–0.641	0.069
Expl. Var.	1.774	1.850	1.522
Prp. Total	0.222	0.231	0.190

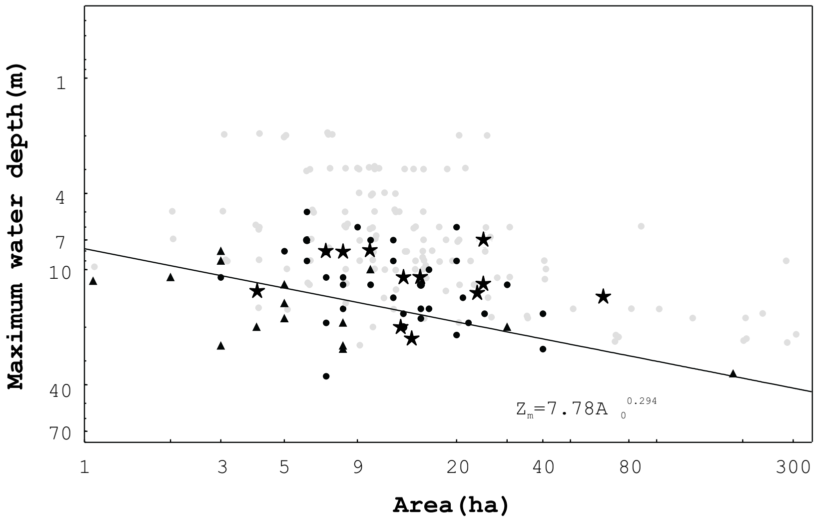

Fig. 5. The relationship between maximum depth of the water and lake area for the Finnish lakes cored within this research and previously discovered to compose varved sediment. The equation $Z_{m1} = 7.78A_0^{0.294}$, (Z_{m1} = a shallowest maximum depth in meters where a lake can compose laminated sediments and A_0 = lake surface area in hectares) was used by Larsen and MacDonald (1993) to distinguish lakes with laminated sediments from those with massive sediments. The curve was re-examined later by the authors (Larsen *et al.* 1998) (key: *see* Fig. 1).

as lake basin and catchment morphometry and catchment sediment types, as shown earlier by Larsen *et al.* (1998) in North American lakes.

The present study leads to the recognition of two types of environmental conditions that promote varve formation within smaller Finnish Boreal lakes. The first type, within glaciofluvial deposits, is dominated by autochthonous processes and has a low mineral matter influx. The second type, controlled by allochthonous processes, occurs in till and bedrock areas and is characterized by higher mineral matter influx.

Lakes in glaciofluvial deposits

In this group, laminated sediments are found in deep, stratified clear water lakes, typically lying within eskers or their outwash plains (80% to 100% of the catchment is covered with glaciofluvial deposits). The majority of the previously discovered lakes with varves (e.g. Lake Laukunlampi, Battarbee 1981) are found in such an environment. These lakes appear mainly in cluster II and show a separate group when plotted against factor scores (Fig. 4). They have high negative loading of factor 3 and positive loading of factors 1 and 2, indicating that the shape and maximum water depth of basins are the most critical requirements for the formation of varves in these lakes. Varved sediments occur quite commonly when the lake area is less than 10 hectares and water depth more than 15 meters.

The occurrence of varved sequences in these cluster II lakes, and in a few small and deep "kettle-hole" lakes (e.g. Valkiajärvi; Saarnisto 1985) appearing in cluster III and having heterogeneous or till-dominated catchment, is usually related to the fact that the water mass is permanently stratified (*meromictic*). Such lakes are often the highest basins in their drainage area and have no significant inflow (Saarnisto *et al.* 1977, Saarnisto 1985). The sediment often exhibits thin biogenic (often diatom-rich) laminae structure and is seldom laminated throughout the entire Holocene sequence.

Lakes in till and bedrock areas

This group includes the majority of lakes with partially or completely laminated sediment se-

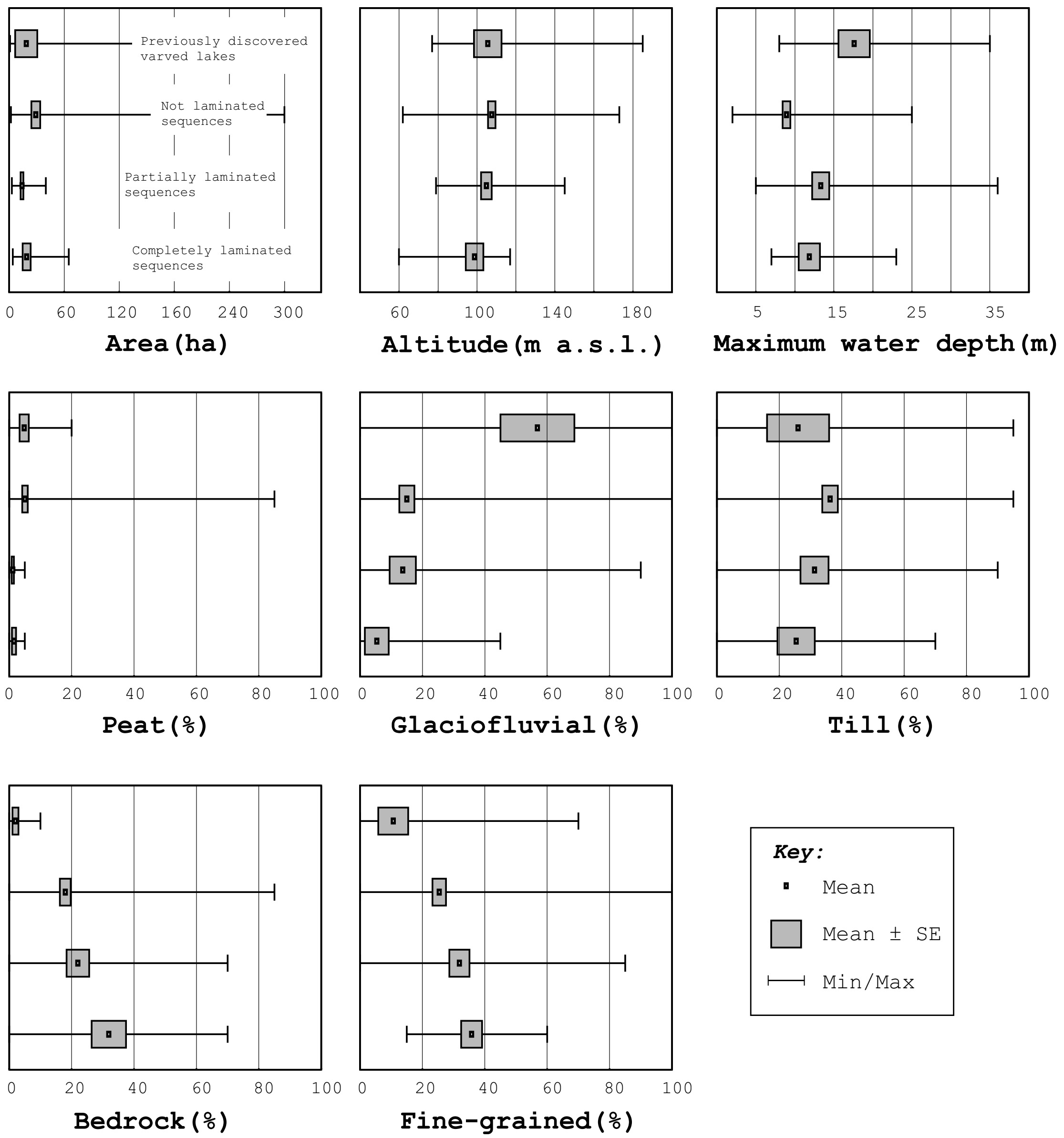

Fig. 6. Properties of the limnic sedimentary environments for the previously discovered varved lakes and non-laminated, partially laminated and throughout laminated lakes cored within this research.

quences discovered. These lakes appear in cluster V. They have a negative loading of factor 2 and simultaneously increasing loadings of factors 1 and 3. These lakes are located at lower altitudes (average of about 100 m a.s.l.) than the first group, and their catchment is characterized by fairly equal proportions (20% to 40%) of till, bedrock and fine-grained material (mainly silt) (Fig. 6). Alimmainen Savijärvi (Fig. 7) is a typical example of this type of a lake. The catchments of these lakes supply sufficient fine-grained material to form clastic-organic varves (*see* Introduction) (Fig. 8), when suitable morphometric requirements are met. However, a relatively high stream discharge is required in order to transport the material from the catchment into the lake.

Lakes containing sediments composed of clastic-organic laminae couplets are typically located

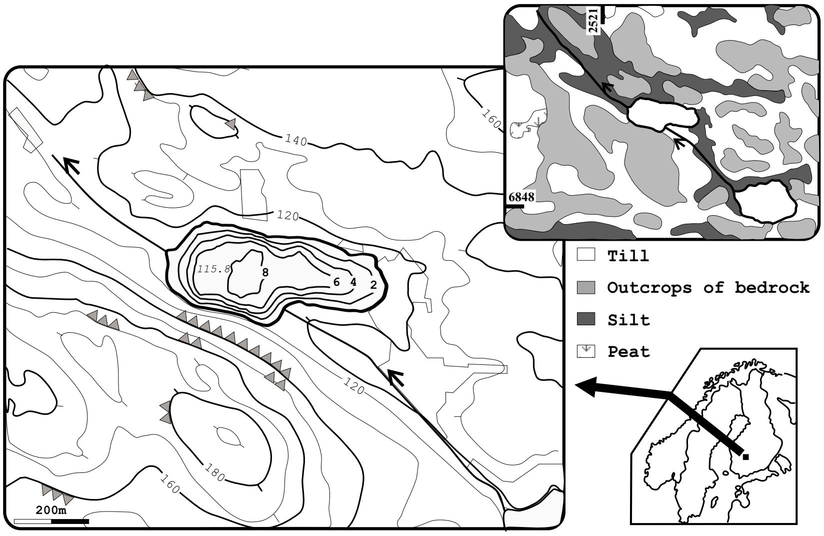

Fig. 7. The topography of the Alimmainen Savijärvi watershed is variable with steep cliffs on the south side and more plain ground, with some arable land, on the north and east side. Lake basin bathymetry is characterized by a plain accumulation depth (> 8 m). The catchment (right-hand side figure) is composed of equal areas of till, silt, and outcrops of quartz-feldspar schist bedrock.

in the distal part of large morainic features (e.g. Alimmainen Savijärvi; Fig. 7) or were isolated from ancient lake complexes or ice-lakes (e.g. Korttajärvi). Morphometrically, the accumulation of varves in this environment is more dependent on the shape of the basin and the catchment topography than the maximum water depth and lake surface area. In the areas of numerous bedrock outcrops, lakes usually follow closely the bedrock topography and therefore often contain suitable, elongated, relatively deep basins for varve accumulation. For example in Alimmainen Savijärvi (maximum water depth 8.1 m, lake area ~7 ha) the sediment is very evenly distributed in a fairly level, 8 meters deep, oval-shaped basin, and the same “marker-horizons” are detectable in all cores within that basinal area (Fig. 7).

The presence of fine-grained material in the catchment seems to control the formation of laminae through several interacting physical ways. Allochthonous input of minerogenic matter leads to the formation of a clastic lamination in the first place, it supplies nutrients for biological production, and increases the sedimentation and compaction rates, as a function of the size and the topography of the watershed. Increased rates of sedimentation and compaction result in thicker, sharper and more coherent laminae (Renberg 1981), all improving varve identification and counting.

An overview of the limnological properties of this group of lakes is uncertain, because no year round data is available for any of the lakes. Nevertheless, during the winter coring period, some of the lakes containing varved sediments were observed to have an inverse thermal stratification and higher pH, conductivity and anoxia near bottom waters, suggesting dimixis. In dimictic lakes, strong winter and summer stratification and the absence of oxygen in the bottom waters prevent bioturbation, the major cause of sediment disturbance, in deep basins. This periodic stratification is caused and enhanced by several facts (Wetzel 1983, Petterson 1996):

1. Short overturn periods (or even incomplete overturns) in Fennoscandian climate, especially in the spring, when a rapid warming of the surface waters enhances the stratification of the water column while the lower waters remain considerably colder.
2. Sheltered location of the lake basin with a minimum effective wind fetches. Even though catchment topography was not included as a quantitative variable in the dataset, the presence of numerous bedrock outcrops in the watershed appears to be an important factor, since these lakes are sheltered by the high relief bedrock topography. If, however, the catchment is dominated by a more continuous till and fine-grained cover with less bedrock outcrops, then lakes are usually less sheltered, which leads to increased importance of water maxi-

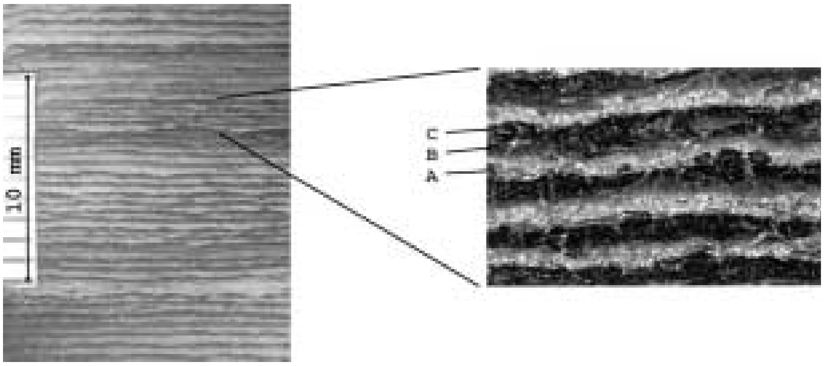

Fig. 8. Clastic-organic varves in Alimmainen Savijärvi have an average thickness of about 0.45 mm. The left-hand side figure is taken from the fresh sediment surface, whereas the right-hand side figure is taken through a polarization microscope with crossed nicols (approximately 2300 BP). Varve structure is threefold: minerogenic matter (A), particulate organic matter (B) and fine-grained organic matter (C).

mum depth in the accumulation of varves. Minimum water depth found to accumulate varved structure was 7 meters (Valkiajärvi, Virrat), a figure comparable to that for Swedish lakes (Petterson 1996).
3. High summer organic productivity and decomposition of organic material (autochthonous and/or allochthonous) leading to the depletion of oxygen in the lower waters soon after the overturn period.

One other factor that also promotes the formation of varved sediments in small or mid-sized Finnish lakes is a plain sediment depression, a depth where an anoxic conditions arise and which is also the area most likely to maintain a high rate of continuous sedimentation. However, the depression should be wide enough and not have steep slopes to prevent sediment slumping and turbidity currents from the littoral zone which may disturb the sequence.

Recent systematic searches for varved sequences in Finland, as well as in Sweden and Estonia, during the past few years have resulted in a series of varved sequences, potentially useful for investigating long-term and rapid environmental changes. The ongoing work with these new sequences is targeted to apply and to develop prior sampling techniques (epoxy embedding) and physical varve analysis methods (e.g. varve counting, density measurements based on X-ray images, varve-thickness analysis, grain-size analysis based on SEM back-scatter images, magnetic measurements) (Snowball *et al.* 1999, and M. Tiljander, A.E.K. Ojala, T. Saarinen and I. Snowball, unpubl.) in order to identify past climatic changes reflected in varved sediments (e.g. Merkt 1971, Clark 1988, Lamoureux 1994, Cooper 1998, Francus 1998, Saarinen and Saarnisto 1998, Lamoureux 1999, Petterson 1999). Fast and repeatable physical measurements provide an excellent basis for the study of chemical and biological proxies which may be either time or money consuming.

Conclusions

1. The lake dataset shows that lakes containing partially or completely laminated sequences are frequent in the Finnish Boreal zone, and exhibit a number of common geomorphic and geologic characteristics.
2. The occurrence of varved sediments in lakes cannot be explained by a straightforward depth-area relationship. It is dependent on various interacting sedimentary environmental factors, such as basin and catchment morphometry, catchment sediment types.
3. Within smaller lakes, varves are found in two geologic and geomorphic settings. The first one occurs within glaciofluvial deposits, whereas the second one occurs in till and bedrock areas.
4. In catchments dominated by glaciofluvial de-

posits the occurrence of varves is usually connected with permanently stratified water mass, and the sediment often exhibits biogenic laminae.

5. In catchments dominated by till and bedrock outcrops the accumulation of varves is more dependent on the shape of the basin and catchment topography, than lake maximum depth and area. The influx of minerogenic matter increases the sedimentation and compaction rate and leads to the formation of clastic laminae in the first place. The majority of lakes with partially or completely laminated sediments, in this study, represent this kind of lake environment.

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