RHYTHMICALLY LAMINATED SUBLITTORAL LAKE SEDIMENTS IN AN EUTROPHICATED BAY

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The annual rhytmic lamination of sediments is a widely known and throughly studied feature, but observations have mostly been made on core samples obtained from the deepest part of a lake basin or from a depth of at least 15 m. In Olkkolanlahti Bay and northern Tiirinselkä, which are hypertrophic water bodies and parts of the large lake Päijänne (Central Finland), clearly stratifed sediments have been found in the sublittoral zone at water depths of 1.2 and 2.2 m. All of the sediment cores obtained here exhibit light and dark laminae with varying diatom abundance. They may therefore be regarded as rhythmical laminations. Their thickness (±20 mm per couplet) was considerable in comparison to most laminae recorded in annually laminated sediments.

Key words: lake sediments, laminations, genesis, biostratigraphy, diatom flora, Holocene, Olkkolanlahti, Lake Päijänne, Jämsä, Finland.

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Introduction

In summer 1987 a study was conducted by the Finnish Pulp and Paper Research Institute (Pogreboff 1989) to investigate the changes in water macrophyte vegetation in the neighbourhood of Kaipola Paper Mill (United Paper Mills Ltd). The Olkkolanlahti Bay and northern Tiirinselkä are part of the large lake Päijänne, Central Finland (Fig. 2). The large amounts of detritus and bark debris observed both on the bottom and the water surface near to the shore line caused interest in the rate of infilling, and in the way in which the sediments accumulated and consolidated. A sample taken by an »expressly made» sediment corer from the bottom at a point where the water was 0.8 m deep showed that the sublittoral sediments were rhythmically laminated, with alternating green and grey layers of considerable thickness (Fig. 1).

Laminated lake sediments reported in earlier studies, for example the detailed discussion by Saarnisto (1986), have usually been observed at a depth of more than 15 m. However in a study of the Freshwater Reservoir of Uusikaupunki the water depth in Velhovesi was mainly 2.5—3 m and in the sediment samples occured black sulphide spots and stripes conspicuously before an exposure to air (Hinneri 1974).

The dark layers represent usually autumn and winter periods and light layers summer periods. The minerogenic material in the light layers is

Fig. 1. A sediment sample obtained in July 1987. Photo Peter Vihra.

probably transported by the spring floods after the ice has melted (Saarnisto et al. 1977). In many lakes black sulphide gyttja can also occur in summer and it indicates a reducing sedimentary environment with microbial decomposition of biogenic matter, sulphide reduction and dissolution of iron from minerals and polluting particulate matter (Vuorinen et al. 1986). The continued deposition of black sulphide gyttja in the hypolimnion area can indicate a permanent or intermittent oxygen deficiency (Alhonen 1986).

Dark laminae are also produced in meromictic lakes by the mass mortality of photosynthetic anaerobic bacteria in late autumn, when the mixolimnion, its lower part in particular, is mixed with surface water containing oxygen (Dickman 1979). The anaerobic bacteria live in the lower mixolimnion most of the year. They multiply in summer and die with the sudden intrusion of oxygen. Dark laminae can form very rapidly (in 1 to 2 weeks) and may account for a large proportion of the annual autotrophic production. On the bottom of the lake the detritus forms a thin organic-rich layer containing ferrous sulphide.

It has been widely believed that shallow water sediments are affected by agencies such as erosion by waves and ice, and the irregularity of erosion and accumulation zones caused by permanent changes in water level and bioturbulence, which thus interfere with the lamination process. Our observations indicate that this is not always the case.

Also seasonal variations in diatoms have been studied in detail but not in sublittoral bottom sediments. It is therefore not self-evident that the biostratigraphical (diatom) changes in sublittoral lamina could be interpreted as annual ones, and that they are undependend on other mechanisms such as water level fluctuations and littoral forces.

Research area and ecological background

The Bay Olkkolanlahti lies near to the town of Jämsä, Central Finland (Fig. 1). It is part of Tiirinselkä, an open lake part of Middle Päijänne, which is the central basin of a large watercourse system. Until the late 1970s Päijänne was becoming increasingly hypertrophic, but nowadays a great part of the waterbody is recovering (Granberg et al. 1986, Heinonen et al. 1988). The middle part is recovering more slowly because of heavy pollution by two papermills, a sawmill, and agricultural and municipal sewage. Tiirinselkä receives water from the river, about 3 km northeast of the sampling site which has a mean discharge rate of 15—20 m^3/s. There are also two smaller rivers inflowing when together discharge less than 1 m^3/s. The total watershed of Tiirinselkä covers about 1500 km^2 (Granberg et al. 1986).

Geographically, the area is known as the Jämsä River valley. It consists of open, rolling countryside, with exposed rocky summits rising to an altitude of 100 m above the lake level. The soils are formed of Ancylus clay and silts (Virkkala 1954). Both the landscape and the soil type are unusual in the Päijänne region. Records of eutrophile (terrestrial) plants found in the area (Virkkala 1954, Koskinen 1964) and the presence of alkaline dark rocks in the Päijänne region, suggest that the glacigenic soils near Olkkolanlahti may be rich in nutrients and that its initial trophic status is high.

The conditions in Tiirinselkä have been monitored regularly since the 1960s by the Centre for Environment Research at Jyväskylä University (Granberg et al. 1986). Since 1982 no essential reduction has been observed in primary production, which is about 30 g/m^2 causing lowered oxygen concentration and temporary oxygen depletion. Water samples are rich in bacteria, and turbidity is high. High biological oxygen demand (BOD) spreads southwards, beyond Tiirinselkä. According to a model published by Kylä-Harakka (1981), loads of 10 t BOD/d and 40 k P/d are too great (Granberg et al. 1986). Bottom fauna, zooplankton and phytoplankton species indicate that organisms which benefit from waste water and eutrophication thrive in Tiirinselkä. The redox potential in Tiirinselkä sediments was below zero (Granberg et al. 1986), but this observation applies only to the central part of the bay.

During the summer 1987 a botanical survey of water and littoral macrophytes in Olkkolanlahti and in the northern most part of Tiirinselkä was conducted (Pogreboff, 1989). The Päijänne watercourse has a south-north orientation and while the snow and ice cover of the watershed thaw unsynchronously, the spring flood does not reach the central basin until June-July — the natural high water season. Owing to the rainy and cold summer, in July 1987 the water level in Päijänne was exceptionally high: at the end of the month it was about 40 cm above normal (i.e. the mean July water level in 1961—80). Water turbidity was high — the depth at which the Secchi disc was visible was 0.5—0.9 m, and the suspended solid content of the water column was 55—70 mg/l. The presence of laminated sediments in the littoral zone was observed at the same time.

According to the isobathic map Olkkolanlahti and northern Tiirinselkä possess bottoms of irregular shape: the 3-m depth zone dominates and there is a sharp fall from 3 to 6 m. There are four deep hollows below the 20-m isobath. Although quite small, they have steep slopes. The maximum depth, 34 m, is close to the place where we collected our sediment core. A map of Olkkolanlahti with the February 1990 sampling site marked on it is shown in Figure 2.

Kaipola paper mill started in 1954. It was modernised for the first time in 1964, after which five paper machines with a daily output of more than 1000 t of newsprint and magazine paper went in operation. The mill was modernised for the second time in the 1980s. A new paper mill went into production in 1987, and current capacity is 500 000 t/a. The pulping process is thermomechanical and the main product is light coated printing paper (Jensen 1988).

Production of groundwood pulp made it necessary to store spruce logs in water (Anon. 1965). Up to 40 per cent of the wood for Kaipola paper mill and Olkkola saw mill is transported by floating. The water area used for log storage at Kaipola mill is 40 ha; the area at Olkkola sawmill is smaller. The consequences of floating and storage are visible all along the shore, with numerous logs anchored in gyttja, abundant detritus produced by luxuriant littoral stands of *Glyceria maxima* and bark debris (Fig. 3). In 1987, new ponds for biological effluent treatment were built close by Olkkola sawmill.

Fig. 4 shows monthly water level data recorded at Kalkkinen, the site of the outflow from Päijänne, during the 1980s, and the duration of the ice cover on the lake placed on profile of sam-

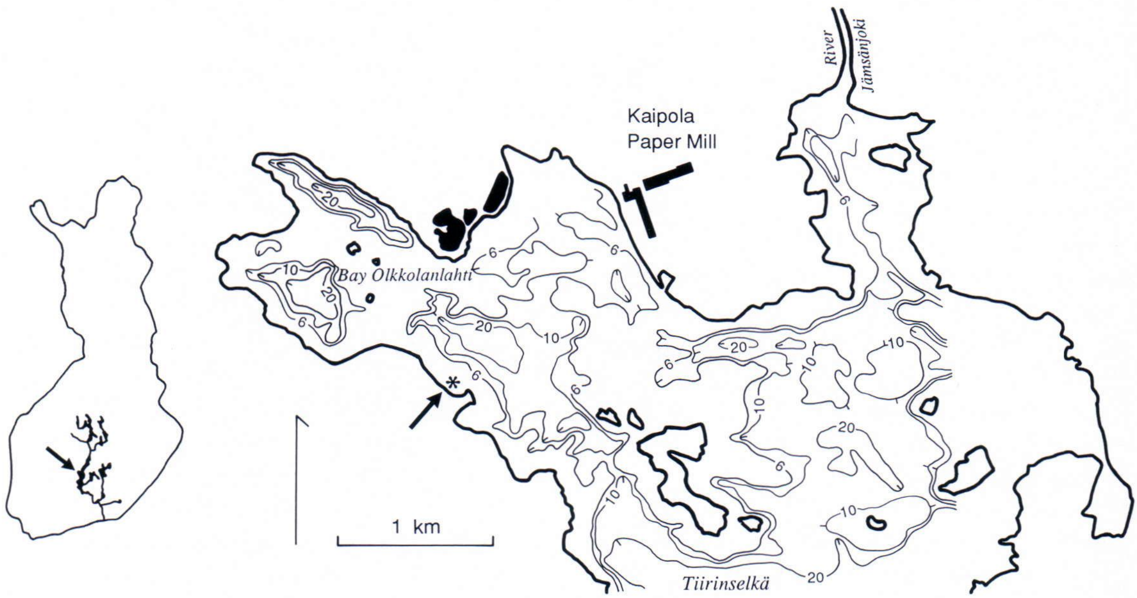

Fig. 2. Map showing the site the sediment samples were taken from, the immediate vicinity and the isobathic curves of northern Tiirinselkä. The »0» isobath has an absolute elevation of 77.8 m above the sea level. Topographic base map 1:50 000, No 21442, Kaipola. National Board of Survey.

pling site. The data is obtained from Monthly Hydrological Reports, 1981—1990 (The National Board of Waters and Environment).

The maximum-minimum amplitude is 1.5 m, but the amplitudes of minimum and maximum data during the 1980s (the breadth of grayish zone) are about 0.6 m. Also marked is the point of the sediment coring in 1987. Note that when the sediment samples were taken in February 1990 the water level was 0.7 m below the diagram-0 (the mean water level in July 1987). As these samples were taken through the ice cover, from under water 1.2 and 2.2 m deep, it is clear that the sites had not been exposed to air or to erosion by the action of ice or waves.

According to observations in winter time the Jämsänkoski river water, oxygen poor and rich in organics, spreads all over the Tiirinselkä in the epilimnion causing oxygen depletion. There is no doubt, that springfloods like that can temporary erodate the river banks and bottom. But it seems doubtfully, that this mechanism could explain our observation. The natural suspended solid content in Jämsä river water is about 1.6 mg/l (measured above Jämsänkoski) changes to 11.8 mg/l measured in the estuary of the river — below the towns Jämsänkoski and Jämsä, Jämsänkoski paper mill and clay soil land area (Granberg 1986). In summer 1987 the solids content, suspended in the water of the lakes sublittoral zone was about 50—70 mg/l (Pogreboff 1989).

Methods

Field methods

Sediment samples were taken with a Livingstone-type corer from the littoral zone in February 1990. The ice was about 30 cm thick. The corer, equipped with a Plexiglass barrel (10 cm diameter), raised the upper 0.8 m-section of sediment from depths of 1.2, 1.6 and 2.2 m. All cores were stored at +4°C until analysed.

Fig. 3. A view of the shore line near the winter 1990 sampling site. Photo Peter Vihra.

Laboratory methods

The samples taken from sites with water depths of 1.2 and 2.2 m were determined for dry weight and organic content from the weight loss at 110° and 550°C. Quantitative diatom analyses were carried out on cores taken from depths of 1.2 and 1.6 m, treated with 20% H_2O_2 and decanted to enrich the amounts of diatoms. At least 250 frustules were counted from each of the slides made from light diatom-rich layers using × 100 magnification. Slides made from gradually darkening horizons were poor in diatoms and at least two from each sample were counted.

Results

A light diatom-rich layer, which also contained large amounts of minerogenic material, was followed by a brownish green sequence terminating at a black layer. Black layers also occurred quite often in light layers. Vivianite grains were found within some of the black and brownish green layers.

In light-grey layers the water content was 54.2% and the loss on ignition 3.8%; the corresponding values for the dark humus rich layers were 70.2% and 6.8%. The total number of coupled layers (dark and light) was about 38 in an 80-cm-long core sample, which makes an average of 21 mm per couplet.

As expected, the diatom analyses showed that the species were mainly lacustrine, alkaliphilic, littoral forms. Exceptionally there also occurred abundant *Tabellaria fenestrata* and T. *flocculosa,* which are commonly regarded as slighty acidophilic species. As the relatively fragile frustrules of *Tabellaria* are divided into several easily identifiable septa they occur in samples in greater abundance than the other diatoms (Simola and Tolonen 1980).

The darker layers contained very few diatom species, and the number of diatoms was low. Typical species were *Tabellaria fenestrata,* T. *flocculosa, Aulacoseira granulata* and A. *islandica* (Fig. 5). In contrast, the light layers incorporated a great variety of diatom species, for example A. *italica,* A. *distans* and the strains *Surirella, Eunotia, Navicula, Pinnularia, Tetracyclus* and *Gyrosigma* as well as the above-mentioned diatoms. It was not possible to establish the an-

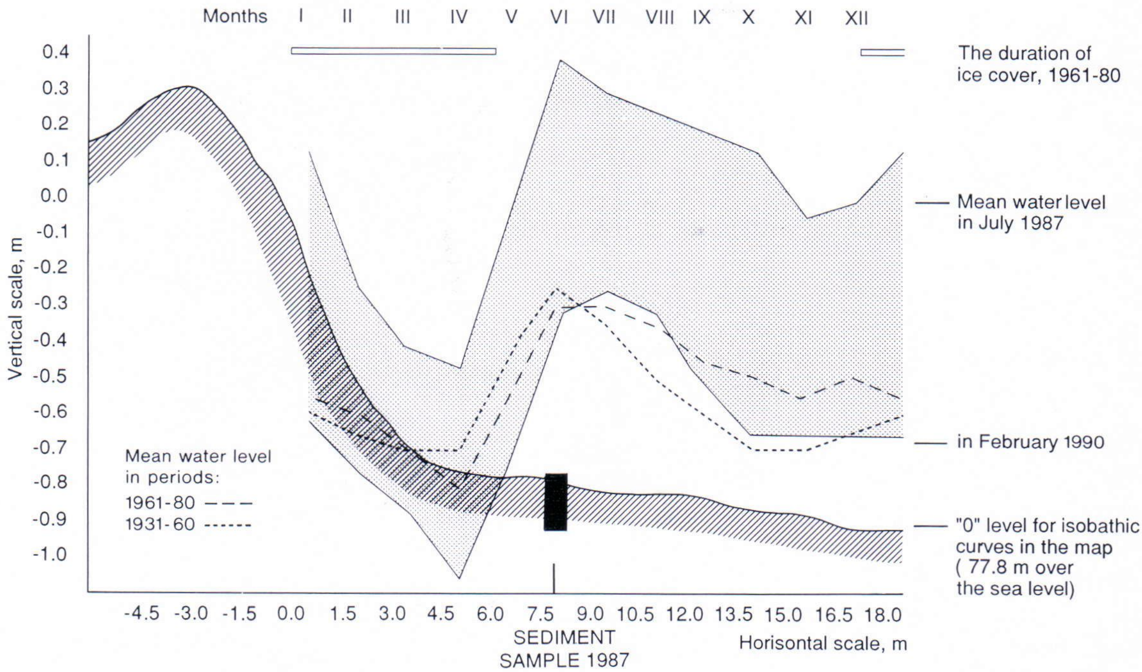

Fig. 4. The water level in Päijänne during the 1980s (grayish area) has been considerable higher as compared with previous long term observations (yy 1931—60 and 1961—1980). During that period also the spring floods in Jämsä river were exceptionally high and accompanied by temporary rising of water discharge up to 100 m^3/s (Granberg, pers. comm).

nual diatom maxima in detail with the methods used.

Discussion

According to Simola (1979), the sedimentation maximum begins in spring before the vernal diatom bloom, and diatoms occur mainly in the light summer layers. The dark winter layers with more organic matter are poor in diatoms. Simola also suggests that organic material drifts from the littoral zone during the autumnal overturn. His samples were taken from the deepest part of the lake. Thus in our cores the greenish brown sequence following the black sulphide layer could represent vernal sedimentation.

According to Saarnisto (1985), dark organic material increases as winter approaches, when the sulphur and vivianite content of the sediment is at its highest. The minerals are formed under reducing conditions, when phosphate and ferrous ions have reached saturation point (Simola et al. 1981).

Conclusions

In this study black sulphide layers, often with vivianite grains, were found in all cores. This indicates that anaerobic conditions prevail on the bottom of northern Tiirinselkä at least part of the year, even in the littoral zone. Typical indicators of eutrophication; *Aulacoseira islandica* ssp. *helvetica* and *Cyclotella radiosa* were present. Because the cores taken from the littoral zone of Olkkolanlahti exhibit black and brownish green layers followed by a diatom-rich light layer, these samples has been considered as rhythmically laminated lake sediments.

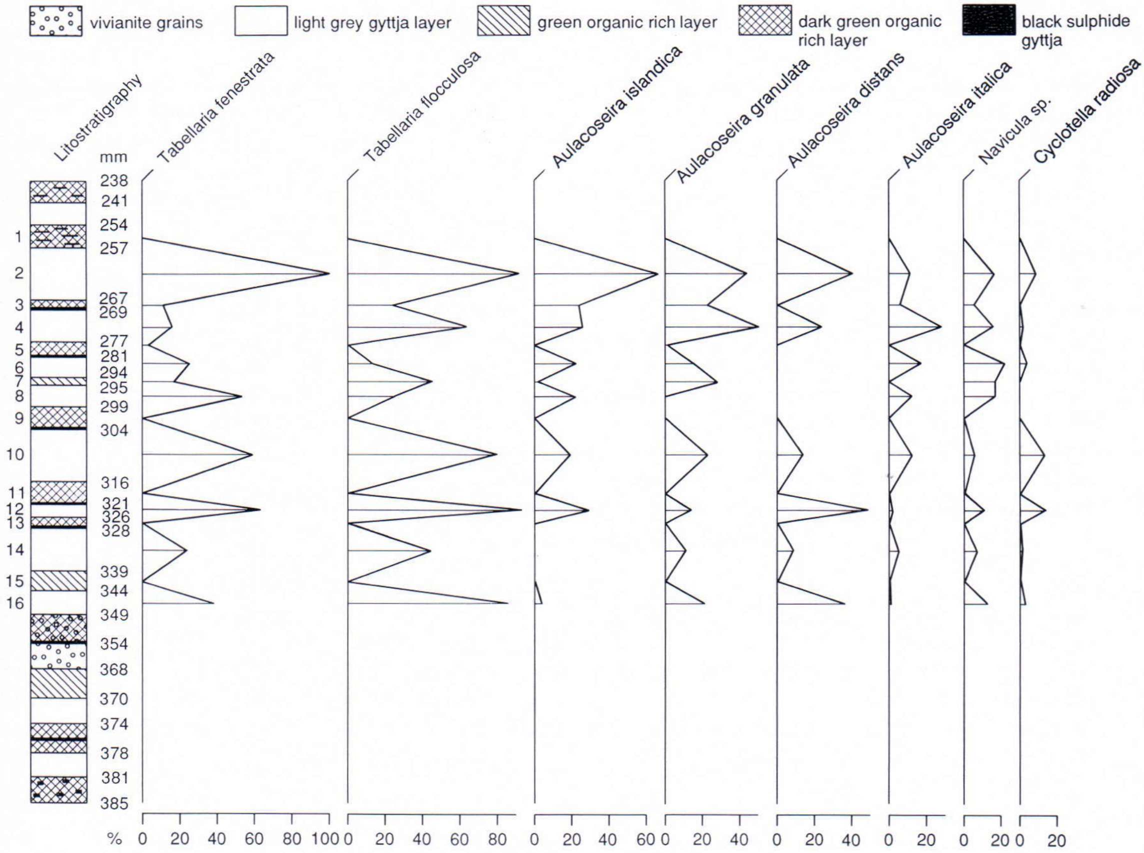

Fig. 5. Schematic litho- and diatom stratigraphy of the results from c. 10 cm long part of the core taken at 1.6 m depth. The percentages of diatoms are given in relative amounts/cm^3 wet sediment.

Rhythmical lamination can also arise as a result of water level changes in Päijänne. During spring and autumn floods, turbidity and the suspended solids content of the water column are high. Oxygen fluctuations can then also affect bottom sediments, and diatom rich, minerogenic layers may be formed. A sudden influx of oxygenated water rapidly produces dark laminae owing to the mass mortality of anaerobic bacteria in the water. When the water level falls, oxygen-poor conditions dominate, even in the sublittoral zone and on the surface of the bottom sediments, and can cause deposition of diatom-poor, organic-rich sequences.

Our observations indicate that clearly rhythmical lamination can exist even in a lakes sublittoral zone. In this description we could not with certainity explane their periodicity or origin. Obviously more detailed work including radiometric measurements should be done to explain their origin.

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