CHEMOSTRATIGRAPHY OF THE HOLOCENE SEDIMENTS OF LAKE TYÖTJÄRVI IN SOUTHERN FINLAND AND ITS LIMNOLOGICAL SIGNIFICANCE

PENTTI ALHONEN

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The significance of some chemical elements during the limnological history of Työtjärvi, a small oligohumic lake in southern Finland, is discussed. Sedimentary chlorophyll, organic matter, phosphorus, iron, manganese, magnesium, aluminium, zinc, copper, sodium, potassium and calcium were determined from the sediment core investigated, and their stratigraphical distribution was interpreted in terms of limnology. Sodium, potassium, aluminium, magnesium and, possibly also, calcium can be used as indicators of the intensity of erosion during the developmental history of Lake Työtjärvi, especially since the first signs of land use in the catchment of the lake. In contrast, the sedimentary chlorophyll, phosphorus and Fe/Mn ratio throw light on the typological development of Lake Työtjärvi, adding more details to earlier biostratigraphical results.

By applying the trophic terminology it can be concluded that Lake Työtjärvi was eutrophic in its early stages during the Preboreal and Boreal periods, but that it rapidly became increasingly dys-oligotrophic at the beginning of the Atlantic period as a result of the ombrotrophic development in the adjacent bog, Varrassuo. The eutrophication associated with prehistoric land use in the catchment was the second conspicuous change in the limnological history of Lake Työtjärvi. It was not, however, continuous, and the lake remained dys-oligotrophic. The most recent change in the limnology of the lake has been the fall of the water colour, probably due to acid precipitation of anthropogenic origin.

Key words: paleolimnology, lake sediments, chemical composition, stratigraphy, eutrophication, Holocene, Lake Työtjärvi, Hollola, Finland.

Pentti Alhonen: Department of Geology, University of Helsinki, Snellmaninkatu 5, SF-00170 Helsinki, Finland.

Introduction

The purpose of this paper is to discuss the significance of some chemical elements during the limnological history of the small lake Työtjärvi (60° 59N and 25° 28E) situated in a shallow basin on top of the First Salpausselkä, about 10 km west of the town of Lahti. Varrassuo, a concentric raised bog immediately to the east of the lake, is connected with it by a narrow channel. Thus it is clear that the limnology of Työtjärvi is basically controlled by the development of this bog.

In an earlier investigation (Alhonen et al. 1977; Donner et al. 1978), the biostratigraphy of Lake Työtjärvi was compared with that of the adjoining bog using radiocarbon dated cores sampled from their sediments. Being the most representative and the best of its kind, this study site as a whole is well suited for showing the close relationship that can exist with the geological depositional structure of the catchment, including the climatic development (temperature and moisture), and human activities. Similarly both Työtjärvi and Varrassuo are a good example of an intimate relationship between lacustrine and terrestrial biota. In this paper I have also tried to interpret physico-chemical conditions in the water column during the developmental history of Lake Työtjärvi. The sedimentary concentrations of chemical variables appear to be to some extent comparable to limnological features in the hypolimnetic water of a lake.

Limnological characters of the lake

Limnologically Lake Työtjärvi is now an oligohumic lake. According to recent observations, the water colour in the epilimnion has decreased from 80 to 50 mg Pt l^{-1} (Table 1). The lake is characterized by groundwater seepage. Formerly it had no outflow, but at the turn of the century, the level of Lake Työtjärvi was lowered by about 2 m when a channel was dug through the narrow ridge damming it in the south (Donner et al. 1978).

Lake Työtjärvi is about 1 km in diameter. The average water depth is 1—2 m, but near the north-eastern shore there is a depression with water 7 m deep. The littoral zone is poor in macrophytes.

Some limnological data on Lake Työtjärvi are given in Table 1. It is seen that the chemical oxygen demand (COD) of epilimnetic water has varied during the observations time form 10 to 13 mg O_2 l^{-1}. Total N concentrations range from 0.41 to 0.84 mg l^{-1} and those of total P from 0.016 to 0.045 mg l^{-1}. The values are clearly low. No measurements of phytoplankton primary productivity are so far available, but palaeolimnological data show a trend towards greater productivity in the lake since the beginning of the Subatlantic Chronozone (Donner et al. 1978). This typological development has been occasional. A more significant change in the limnology of Lake Työtjärvi has been the change in water colour in recent years. This may be due to acid precipitation of anthropogenic origin.

Material and methods

Chemical analyses were made on the core sampled and described by Donner et al. (1978). It was taken with a Livingstone sampler from the 7 m depression, which was first located with the help of echo sounding profiles (Fig. 1). The lithostratigraphy of the core was as follows: 0—185 cm brown mud, 185—190 cm grey clay-mud, which is deposited in grey silty clay (see Donner et al. 1978, Fig. 9). Lake Työtjärvi was emerged from the Baltic during the drainage of the Baltic Ice Lake to the level of Yoldia Sea about 10 200 years ago (Donner 1967). Thus, organic sediments began to form in the Työtjärvi basin after this remarkable and rapid environmental change.

Table 1. Some limnological properties of Lake Työtjärvi. Values measured at 1 m.

Date	Temperature (°C)	Oxygen concentration (mg/l)	Specific conducticity (mS/m + 25°C)	Chemical oxygen demand (mg O_2/l)	pH	Colour (mg Pt/l)	Total P (mg/l)	Total N (mg/l)
19. 8. 1982	17.5	8.4	2.2	13	6.3	80	0.045	0.41
29. 3. 1983	0.6	10.1	3.2	11	5.8	70	0.016	0.68
3. 4. 1984	0.9	5.5	3.1	12	5.5	50	0.036	0.84
29. 8. 1984	14.0	9.8	2.2	10	6.1	50	0.040	0.50

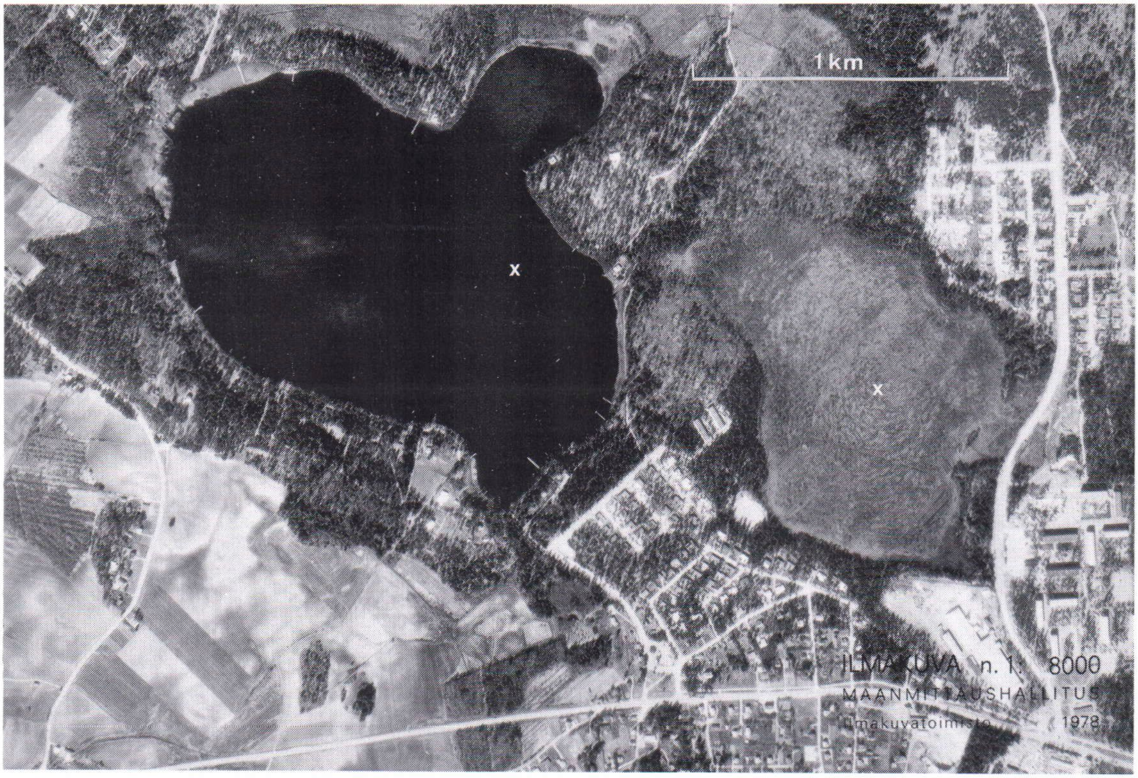

Fig. 1. Air photograph (No 75162:31, Map sheet 213312) of Työtjärvi and Varrassuo showing the sampling site in the lake (published with the permission of the Survey Office).

The oldest radiocarbon date from the 180—188 cm depth of its lithostratigraphy is 9020 ± 190 B.P. (Donner et al. 1978, Appendix II).

Before the chemical analyses all sediment samples were homogenized and dried. The organic matter is expressed as percentage of loss on ignition. The sample was first combusted at 550°C for two hours. Iron and manganese were determined from acid-diqested samples ($HC1 + HNO_3$) with Atomic Absorption Spectrophotometry and phosphorus was determined spectrophotometrically after oxidizing with $HC1O_4$. The sedimentary cholorophyll was analysed spectrophotometrically from acetone extract following the method described by Vallentyne (1955). For the analytical methods of sodium, potassium, calcium, magnesium, aluminium, zinc and copper see Vuorinen et al. (1983).

Results

The results of the chemical analysis of the sediment core from Lake Työtjärvi are given in Fig. 2 and Table 2.

Organic matter

The Työtjärvi core shows a clear and consistent rise in the content of the organic matter towards the highest value (82 %) at a depth of 100 cm. From this peak the concentrations decrease up to the sediment surface, with the exception of a small rise at a depth of 10 cm. The loss on ignition value of the surface sediment is 54 %.

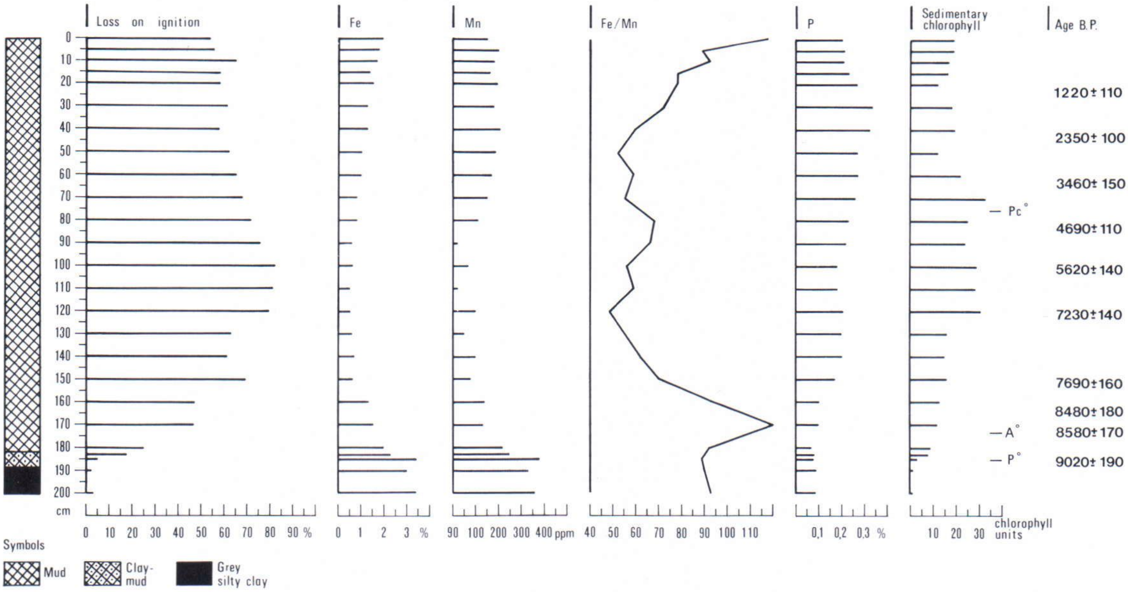

Fig. 2. Työtjärvi: Vertical distribution of loss on ignition, Fe, Mn, Fe/Mn, P and sedimentary chlorophyll in the core investigated. Radiocarbon dates from Donner et al. (1978, Appendix II). P°, A° and Pc° are the rational limits for the *Pinus, Alnus* and *Picea* pollen curves.

Iron

The highest Fe content was recorded from the basal part of the core. From a depth of 185 cm (the first stratigraphical level of brown mud) there is a sharp decrease towards the minimum values in the middle part of the profile. A slight increase in the Fe curve is seen in the uppermost samples.

Manganese

The manganese content falls from the lower part of the lithostratigraphy. However, upwards the manganese content rises steadily. Thus, its stratigraphical distribution is similar to that of iron. The levels of total manganese appear to be somewhat higher than those of iron in the upper part of the profile.

Fe/Mn ratio

The deposition of iron and manganese is regulated by changes in the oxygen content in the hypolimnetic water of a lake. Thus, their stratification in sediments, and especially their ratio, reflects variations in redox conditions in the water phase.

In the lower part of the Työtjärvi profile the Fe/Mn ratio is high (90—120), but it decreases steadily towards its minimum value of 48 at a depth of 120 cm. The ratio clearly rises from a depth of 50 cm up to the sediment surface. The reason for this may be that manganese was dissolved and thus removed to the hypolimnion.

Phosphorus

In the sediment stratigraphy of Lake Työtjärvi the phosphorus content seems to be associated with that of iron and manganese showing a slight increase up to 30 cm depth in the core. Thereafter it decreases towards the sediment surface.

Table 2. Contents of sodium, potassium, calcium, magnesium, aluminium, zinc and copper in the core investigated.

Depth (cm)	Na (ppm)	K (%)	Ca (%)	Mg (%)	Al (%)	Zn (ppm)	Cu (ppm)
1	318	0.19	0.56	0.87	2.00	273	28
10	172	0.14	0.50	0.26	1.92	191	23
20	3550	0.15	0.44	0.29	1.92	127	28
30	3100	0.13	0.54	0.30	1.88	124	21
40	6350	0.14	0.53	0.30	2.01	98	26
50	1710	0.13	0.57	0.28	1.91	111	18
60	5290	0.12	0.48	0.26	1.91	98	23
70	4000	0.12	0.45	0.23	1.90	120	19
80	3330	0.13	0.37	0.24	2.06	79	19
90	348	0.10	0.35	0.21	1.81	100	22
100	151	0.07	0.38	0.20	1.73	163	22
110	950	0.07	0.36	0.17	2.09	96	27
120	1170	0.09	0.40	0.18	1.72	129	23
130	394	0.15	0.39	0.24	1.86	130	25
140	843	0.13	0.42	0.25	2.06	143	31
150	422	0.10	0.41	0.18	1.63	111	25
160	755	0.18	0.43	0.29	1.53	324	25
170	482	0.19	0.41	0.34	1.46	268	29
180	560	0.52	0.51	0.71	2.00	180	30
190	546	0.51	0.75	1.10	2.65	92	29
200	607	3.13	0.70	1.63	2.88	99	34

Sedimentary chlorophyll

The highest content of sedimentary chlorophyll in the Työtjärvi core occurs between depths of 70 and 120 cm. In the topmost samples a slight increase of the chlorophyll content can be seen. Its whole chemostratigraphy seems mainly to be related to that of the organic matter.

Sodium and potassium

The analytical results of sodium and potassium are listed in Table 2. The highest sodium values are found at 20—80 cm. Below this depth the sodium content shows a clear minimum, after which it fluctuates considerably without any definite trend. The distribution of potassium in the Työtjärvi sediments basically follows that of sodium.

Calcium and magnesium

The vertical distribution of calcium and magnesium is presented in Table 2. There are no great variations in the contents of these elements during the Holocene history of Lake Työtjärvi. The analytical results show only that the content of calcium and especially that of magnesium falls slightly from basal silty clay to organic sediments.

Aluminium

The aluminium content of the sedimentary sequence of Lake Työtjärvi is presented in Table 2. Except for a slight increase in the uppermost 80 cm the content of aluminium varies little in this core. Hence, the stratigraphical distribution of this element may well be associated with the mineral product of environmental erosion.

Zinc and copper

The analytical results of Zn and Cu are presented in Table 2. The concentration of zinc increases rapidly in the lower part of the lithostratigraphy, showing a maximum (324 ppm) at a depth of 160 cm. The rise in zinc content can be seen in the topmost part of the Työtjärvi core. The stratigraphical distribution of copper is, in contrast, quite featureless.

Discussion

The stratigraphical geochemistry of Quaternary lake sediments, especially that of the Holocene, has been used mainly to demonstrate (1) erosional processes caused by various factors, and (2) hypolimnetic exchange of different substances as a function of oxygen saturation depletion in the mud/water interfaces. More attention should be paid to the stratigraphical importance of certain chemical variables such as phosphorus, nitrogen and the Fe/Mn ratio, when estimating the long-term trophic fluctuations of a lake. As pointed out by Edmondson (1969) the evaluation of ancient water chemistry from sediments seems to be the most difficult part of palaeolimnology. However, this should not prevent attempts to interpret lithostratigraphical results in terms of limnology as fully as possible. The interpretation of changes in all chemical variables naturally depends on a dated sediment sequence with a calculated rate of sedimentation. We must be able to follow the typological fluctuations within a reliable geochronology.

The geochemically investigated core from Lake Työtjärvi was dated with help of a number of radiocarbon dates. They were used to draw the curve for the rate of sedimentation (Donner et al. 1978, Fig. 12). It decreased in the lowermost part of the lithostratigraphy being then rather even (average 0.20 mm yr^{-1}). A slight increase in the sedimentation rate is seen in the topmost part of the core. The Holocene chronostratigraphy with chronozones (Mangerud et al. 1974) is also based on radiocarbon dating.

Organic matter

Loss on ignition is often used to estimate the content of organic matter in lake sediments. Its accumulation can be considered as an indicator of lake productivity as a function of time or increasing input of allochthonous organic matter (and humus substances) to the lake. The organic matter in lake sediments is both authochthonous and allochthonous. Thus, the interpretation of the stratigraphical distribution of the organic matter in sediment cores may by difficult or even erroneous (see excellent discussion by Mackereth 1966).

Digerfeldt (1972) showed that serious misinterpretations arose because of the prosedure used for calculating the content of organic matter in sediment during the Holocene development of Lake Trummen in southern Sweden. According to him, the sedimentary organic matter content should be calculated by determining its annual deposition. However, the organic content determined per dry matter as loss on ignition values also refers to minerogenic deposition. Later, Digerfeldt (1975) compared the geochemical results from the sediment profile of Ranviken, a bay in Lake Immeln, with those of Lake Trummen. The low organic sedimentation with low productivity during the oldest Holocene chronozones seems to be inconsistent with the results from Lake Trummen. The development of Lake Trummen was similar to that of Lake Työtjärvi during the Preboreal period.

Hjelmroos-Ericsson (1981) used the calculated annual deposition of organic matter to show the productivity of Lake Wielkie Gacno in Poland (cf. Digerfeldt 1972). There were only small variations in the loss on ignition values during the greater part of its Holocene development. Kansanen and Jaakkola (1985) demonstrated that increases in the content of organic matter might be due to an elevated level of primary production in the recent history of Lake Vanajavesi, but that they might also reflect increased input of allochthonous organic matter consisting mainly of extractives from soils or peaty material (humic substances) to the lake. This was particularly true in the preindustrial layers.

As seen in Fig. 2 the amount of organic material in the Työtjärvi core increases to the Subboreal maximum; thereafter the values are commonly over 50 %. If the input of minerogenic matter to the lake has remained constant, the rise in the organic component is due to increasing allochthonous humus from the adjoining mire Varrassuo (see Fig. 1). Limnological development such as this is typical of progressive dystrophication (e.g. Lake Kyrösjärvi: Alhonen 1967, Lake Telkko: Alhonen 1970, Lake Prästsjön: Renberg 1976). This interpretation seems to be supported by the diatom stratigraphy of Lake Työtjärvi. Alkaliphilous diatoms clearly dominate in the bottom of the core, but higher up they are replaced by acidophilous forms such as *Melosira distans* and its variety *lirata* (Donner et al. 1978, Figs. 10 and 15).

The low content of organic matter during the early Atlantic period in the limnological history of Lake Työtjärvi could, however, also be attributed to the simultaneous increase in mineral matter due to the transgressive water level resulting from a moist climate. Abundant deposition should then be associated with the increased supply of minerogenic matter from reworking of the sandy shores and from the catchment.

The discussion above shows clearly that the curves of sedimentary organic matter, even when interpreted in different ways, do not readily lead to a solution concerning the origin of the matter. In the case of Lake Työtjärvi, the coloured organic matter of its water and its proportion in the chemical composition of sediments are highly significant factors. Analytical research should therefore be focused on sestonic, colloidal and soluble organic matter. Because soluble humus substances could be biologically active and possibly take part in nutritional chains of waters, they might also be included in palaeolimnological research of lake sediments.

Iron, manganese and their ratio

Iron and manganese have rather similar chemical behaviour in lakes. As summarized by Hutchinson (1957), the vertical distribution of iron is reflected in the similar distribution of redox potentials. If the oxygen curve is orthograde, there is no marked enrichment in iron. But if the mud surface is reduced, ferrous Fe tends to diffuse into the water column. Manganese is remobilized more easily than iron. Therefore the Fe/Mn ratio can be used as an indicator of oxygen conditions in the hypolimnion during the limnological development of a lake.

It is known that iron and manganese are related to the content of organic matter; humic substances in particular are able to retain iron in solution (Ryhänen 1964). The stratigraphical distribution of Fe and Mn in the sediments of Lake Työtjärvi probably reflects the nature of the organic matter in the lake and the depositional conditions in its hypolimnion. Both curves (see Fig. 2) fall gradually, but the organic content in the sediments increases simultaneously.

This phenomenon can be interpreted as an indication of the dystrophication process in Lake Työtjärvi (cf. also Alhonen 1967, 1971). A similar trend has been found by Renberg (1976) in the sediments of Lake Prästsjön (cf. also Digerfeldt 1972, 1975). Moreover, in the chemostratigraphy of Lake Pyhäjärvi, the iron deposited during its dystrophic stage shows a minimum, whereas the humus leached from bogs in the environment shows a clear maximum (Kukkonen and Tynni 1970).

It can be assumed from the Fe/Mn ratio that, during the Middle Holocene, Lake Työtjärvi was stratified with orthograde oxygen distribution. It is also possible that, at its initial stage (during the late Preboreal and Boreal periods), the oxygen curve was to some extent clinograde during the summer stratification, because the Fe/Mn-ratio is high enough (Gorman and Swaine 1965). A similar trend can be seen in the upper part of the chemostratigraphy, where the ratio again implies clinograde oxygen distribution. It seems probable that small hypolimnetic deficits occurring in the stratification at that time refer to the incipient slash-and-burn culture. Ryhänen (1968) has pointed out that allochthonous humus substances are biologically activated, consuming oxygen as increasing amounts of nutrients are transported to the lake by leaching as a result of the activity of this prehistoric culture. The biostratigraphical evidence supports the view that this loading may have been important for the natural economy of Lake Työtjärvi.

Phosphorus and sedimentary cholorophyll

Phosphorus has a dominant function in lake metabolism. Its stratigraphical distribution can, therefore, be interpreted to show palaeoproductivity of lakes, but it is also known that humus in the water column is able to stabilize phosphorus in the form of humus iron complexes (cf. Ohle 1963).

Although the phosphorus curve of lake sediments may be used as a criterion of enrichment, its content appears to be a poor indicator of eutrophication (e.g. Kansanen and Jaakkola 1985). The highest values of P in the Työtjärvi core, however, coincide with prehistoric eutrophication.

Sedimentary cholorophyll derivatives, such as phosphorus, have been used as indicators of palaeoproductivity conditions during the limnological history of a lake (e.g. Wetzel 1970; Sanger and Gorham 1972; Alhonen 1972; Gorhan et al 1974; Kansanen and Jaakkola 1985). However, low oxygen levels in the hypolimnion favour pigment preservation (see Gorhan et al. 1974). It is possible that a part of the chlorophyll content during the Middle Holocene history of Lake Työtjärvi is of secondary origin. But then again the chlorophyll content is generally low in allochthonous organic matter (Gorhan and Sanger 1975). The slight rise in the uppremost 20 cm of the Työtjärvi core can probably be attributed to eutrophication of the lake.

Sodium, potassium, magnesium, calcium and aluminium

Both sodium and potassium are associated with the mineral fraction of the lake sediments (see Mackereth 1966, Fig. 9). Their contents may therefore be regarded as representing variations in the rate of erosion in the geological environment of a lake. Thus, there is a close relationship between the mineral content of the sediment and the sodium and potassium content of the minerogenic matter; this is clear from the observations of Mackereth (1966, Fig. 10). It can be seen that the content of alkali metals in the mineral fraction diminishes gradually with the decline in the total mineral content of the lake sediment. Its minerogenic component is directly related to the intensity of erosion, and the stratigraphical variations in the gross composition of lake sediments are thus related to fluctuations in erosion in the catchment. But if these elements show very little variation in the sediment profiles one may conclude that the minerogenic component has remained constant and that the composition of the sediments is mainly controlled by variations in the deposition of organic matter.

Magnesium is also associated with the minerogenic matter of lake sediments and readily leached from the catchment. Therefore it should be an indicator of both erosion and allochthonous input, because Mg in lakes tends to be precipitated with humus colloids (Koljonen and Carlson 1975). Simola (1983) showed a clear relationship between the content of magnesium and ditching for peatland drainage during the recent history of Polvijärvi, a lake in North Karelia.

According to Mackereth (1966), calcium is not so clearly associated with minerogenic erosion products and is more readily leached from soils than is magnesium. It has also been demonstrated that a fall in the pH of water greatly accelerates the passage of Ca into solution (e.g. Hanson et al. 1982; Tolonen and Jaakkola 1983). A temporary increase noted in the content of calcium and magnesium in the pale grey gyttja layer in the lithostratigraphy of Lake Iidesjärvi (Vuorinen et al. 1983, Fig. 5) may also be interpreted as an erosion product possibly due to a rise in the water level (Alhonen 1981, p. 105).

The highest values of sodium and potassium in the Työtjärvi core refer to input of allochthonous minerogenic matter from the catchment due to forest clearance by the slash-and-burn method during the Iron Age (500 BC-AD 1200) in the catchment (cf. Donner et al. 1978, p. 277).

The trend of aluminium, which is associated with the minorogenic matter of lake sediments, and has therefore also been used as an erosion indicator, is much the same as that of sodium and potassium in the core investigated.

Zinc and copper

The geochemical cycles of these metallic elements in lake waters have received little attention in Finnish limnology and palaeolimnology. Increases in epilimnetic copper content have been recorded in the autumnal circulation possibly owing to oxidation of sulphide in the surface sediments as oxygen reaches the deeper parts of the hypolimnetic water (see Hutchinson 1957, Fig. 214). As enriched heavy metals, however, copper and zinc seem to indicate cultural eutrophication (Kemp et al. 1976; Vuorinen et al. 1983; Kansanen and Jaakkola 1985). In non-polluted lakes their contents are rather low, depending on the bedrock of the catchment. In the Iidesjärvi core, zinc and copper have similar stratigraphical distributions (Vuorinen et al. 1983, Figs. 4 and 7).

In the Työtjärvi core zinc seems to be associated with the eutrophication cycle in the upper part of the lithostratigraphy, presumably bound to the solid particles derived from intensified erosion in the environment. The zinc content may also be related to the dystrophication of Lake Työtjärvi and have remained in solution, because its stratigraphical behaviour resembles that of iron and manganese (cf. Mackereth 1966).

Conclusions

In the above discussion on the stratigraphical distribution of chemical variables investigated from the Työtjärvi core it has been assumed that certain elements reflect the limnochemical composition of the lake during its limnological history. Although precipitated into the sediment by different mechanisms, sodium, potassium, aluminium, magnesium and, possibly also, calcium can be used as indicators of erosion rate in the drainge area of Lake Työtjärvi, particularly since the first signs of land use are in the surroundings of the lake. In the chemostratigraphy of the Työtjärvi sediments the contents of chlorophyll and possibly also phosporus and the Fe/Mn ratio seem to give useful information on the typological development of this lake and thus add to what is known from earlier biostratigraphical studies (see Donner et al. 1978).

In trophic terminology it can be said that Lake Työtjärvi was more or less eutrophic in its initial phase during Preboreal and Boreal periods, but at the beginning of the Atlantic period, just after 8000 BP, the typological development of the lake became rapidly dys-oligotrophic owing to ombrotrophic changes in the Varrassuo bog (cf. Donner et al. 1978). It can be concluded that diminishing light conditions in this brown water stage limited phytoplankton productivity, even though there are numerous physico-chemical variables that also affect primary production in Finnish lakes. The Subatlantic eutrophication caused by prehistoric land-use in the lake environment was a second dramatic change in the limnological history of Lake Työtjärvi. This dyseutrophy (or chtonio-eutrophy *sensu* Järnefelt e.g. 1953) does not appear to have been continuos, and the lake remained dys-oligotrophic in its limnological type.

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