

Diatom and Metal Stratigraphy of a Small and Shallow Lake in Southern Finland

MARTIN LODENIUS, TIMO RAUKOLA, ALI SOLTANPOUR-GARGARI,
ESA TULISALO, & HEINZ-RUDOLF VOIGT

Department of Biological and Environmental Sciences, POB 27, FIN-00014
University of Helsinki, Finland (martin.lodenius@helsinki.fi)

Vertical distribution of diatoms and metals in sediments reveal pollution history

Accepted April 23, 2008

Abstract: A sediment sequence of 52 cm in length was cored from the deepest point (1.5 m) of Lake Sandöträsket, SW Finland (59° 52' N, 23° 10' E) close to a steel plant. The frequency of diatom species and the concentrations of ten elements (Ca, Cd, Cu, Hg, Fe, Mg, Mn, Ni, Pb and Zn) and organic matter were studied. The isolation from the Litorina Sea (now the Baltic Sea) about 3100 years ago was clearly seen in the distribution of diatom species. However, the Cs dating revealed that the upper sediment layers were mixed. The diatom stratigraphy indicates small or moderate changes in pH and trophic status of the lake. The metal distribution was similar for many metals with many fold higher concentrations near the surface compared to the lowest layers. There were strong correlations between metals except for Ca and Mg. Metal concentrations were compared to other lacustrine and marine sediments from the same area. The diatom and metal stratigraphies indicate anthropogenic influence.

Key words: sediment, diatom stratigraphy, metal, paleolimnology

INTRODUCTION

After the last ice age Finnish lakes have been isolated from the sea due to the elevation of earth's surface and generally undergone a change of typology caused principally by the soil development of the surrounding catchment, climate and human activities around a lake. Recent sediments of lakes are affected by nutrient load from the catchment, air or/and from anthropogenic activities. The paleolimnological development of lakes can be traced from the sediment stratigraphy by using different indicators (e.g. Seppä & Tikkanen 1998; Seppä et al. 2000). Diatoms are used in biostratigraphic research to give versatile information about past conditions of lakes. For instance pH, trophic state, water level, transparency, oxygen condition, nitrogen, phosphorus, metal proportions and pollution

have been studied by methods and statistical constructions resting on diatoms (e.g. Anderson et al. 1986; Huttunen & Meriläinen 1986; Lockhart et al. 2000; Cattaneo et al. 2004) to infer past chemical and environmental conditions in lakes. Diatoms have specific tolerance ranges to different environmental variables (salinity, temperature, light, nitrogen, phosphorus and metal concentrations etc.). Being within the tolerance range of a certain variable does not necessarily mean that a taxon in an assemblage is abundant, but can often be limited by another variable (e.g. Sancetta 1999). The relative abundance of diatoms is used in this study. In very shallow water bodies like the one studied here, in estuaries and coastal waters the sediment stability may be destroyed by wind activity, which can lead to frequent resuspension of bottom sediments (Sullivan 1999). The relative abundance of diatom life forms (planktonic or benthic-epiphytic) in a sediment core can often reveal past fluctuations in water level. In shallow closed clear water lakes the diatoms often strongly reflect fluctuations in water level cause by climate (Wolin & Duthie 1999).

EXPERIMENTAL

Lake Sandöträsket is a small (approximately 1 km²) and shallow (max. depth 1.5 m) lake that rests 12 m above the present sea level (59° 52' N, 23° 10' E, Fig. 1). The lake was a bay of the Litorina Sea until 3100 BP when it was isolated to a lake (prof. Matti Tikkanen, University of Helsinki, personal communication) and is surrounded by pine forest on permeable sandy deposits. The present quality of the water is good. At the time of sampling the conductivity was 48.5 µS/cm and pH 7.2. Past measurements performed in autumns of the years 1984–1988 (Helminen, 1989) gave following values: alkalinity (0.07–0.14 mmol/l), pH (5.8–6.5), colour (10–30 mg Pt/l) and phosphorus (7–20 µg/l). The lake has been influenced by emissions from the nearby steel plant at Koverhar since 1961. The emissions have included large amounts of Fe, Ca and S and smaller amounts of trace metals. The emissions of Cd from the iron and steel plant at Koverhar have been reduced significantly since the 1970's (Voigt 2003). Sampling was carried out from the deepest point (1.5 m) with a gravity corer (inner diameter = 6 cm) on July 14th 1998.

The metal concentrations from Sandöträsket were compared to results from surface sediment samples obtained by an Birge-Ekman sampler from Byviken (1.5 m) and Krogarviken (2.5 m) and to results published previously: Gennarbyviken (2 m; Voigt 2000), Storfjärden (35 m; Voigt 2003) and Western Gulf of Finland (60 m; Leivuori 1998).

For determination of diatoms, organic matter was oxidized by a mixture of H₂O₂ and water (1:2) of fresh sample (1 cm³) in 60 °C overnight. The diatom suspension was separated from minerogenic matter by repeated suspending and decanting. A dried drop on a glass slide was mounted on fluid Depex, then covered by a cover slip and dried. For every slide (level) at least 300 taxon units were counted (e.g. Vuorinen et al. 1986). The diagram was drawn by those taxa surpassing 1% at every level. The diatom species were identified mainly after Mölder & Tynni (1967–73), Tynni (1975–80) and Germain (1981). The species were grouped into the pH-ecological categories (Table 1) following mainly Hustedt (1930, 1937–39). The taxa appearing in the diatom frequency diagram cover more than 90% of all counted units.



Fig. 1: Study areas; 1 Sandöträsket, 2 Byviken, 3 Krogarviken, 4 Storfjärden, 5 Gennarbyviken-Kila, 6 Koverhar steel plant

Table 1. The most abundant diatom taxa present in the sediment core of Lake Sandöträsket. alk=alkaliphilic, ind=indifferent, ac=acidiphilic, F=freshwater, B=brackish, M=marine, b=benthic, e=epiphytic, p=planktonic, according to Hustedt (1937-39) and Alhonen (1972) In cases where a taxon is given by a genus the abbreviations concern the majority of taxa found in a genus in question.

ABBREV	TAXON	pH-ECOLOGY	HABITAT
Anem ser b	Anomoeoneis serians var brachysira (Breb.) Hustedt	ac	F b/e
Anem exilis	Anomoeoneis exilis (Kütz.) Cleve	alk	F b/e
Eunotia	Eunotia spp.	ac	F b/e
Pinnularia	Pinnularia spp.	ind	F b/e
Nav pupula	Navicula pupula Kützing	ind	F b/e
Nav radiosa	Navicula radiosa Kützing	ind	F b/e
Nav rad ten	Navicula radiosa var tenella	ind	F b/e
Frust rh sax	Frustulia rhomboides var saxonica (Rabenh.) De Toni	ac	F b/e
Tab fenestr	Tabellaria fenestrata (Lyngb.) Kützing	ind/ac	F(B) p
Fragilaria	Fragilaria spp.	alk	F(B) b/e
Cymb cesat	Cymbella cesatii (Rabenh.) Grunow	ind	F b/e
Cymb rest	Cymbella spp.	alk/ind/ac	F b/e
Stauron anc	Stauroneis anceps Ehrenberg	ind	F b/e
Neidium	Neidium spp.	alk/ind	F b/e
Nitzschia	Nitzschia spp.	alk	B b/e
Epithemia	Epithemia spp.	alk	F/B/M b/e
Gram marin	Grammatophora marina (Lyngbye) Kützing		M b/e
Campylod	Campylodiscus clypeus Ehrenberg	alk	M/B b/e
Achn kr	Achnanthes austriaca var helvetica	alk/ind	F b/e
Achn lev	Achnanthes levanderi Hustedt	alk/ind	F b/e
Achnantes	Achnanthes spp.	alk/ind	F b/e
Tab flocc	Tabellaria flocculosa (Roth) Kützing	ac	F b/e

The taxonisation was not detailed in some cases. The unidentified taxa were grouped to the genus. The identification problems were due to abrasion and dissolution of diatoms especially in deeper sediments caused, probably, by winds and currents (Denys & de Wolf 1999) in this shallow and isolated lake. The samples taken at certain intervals contain fossil diatom assemblages that represent large time scales (up to hundreds of years) of sedimentation.

For element analyses the samples were dried, homogenized and digested in conc. HNO₃. Elements were determined by AAS (flame, electrothermal and cold vapour techniques; Varian SpectraAA400 and Milestone DMA-80; Tervahattu et al. 2001). Organic matter for fresh samples (1 cm³) was determined by measuring the loss on ignition. ¹³⁷Cs dating was carried out for 14 samples by a beta counter.

Our results for a standard reference sample (NIST SRM 8704 Buffalo River Sediment) were lower than the certified values (in brackets) for some metals because these are total concentrations obtained after lithium metaborate combustion. Our results were: Ca 2.2 ± 0.02% (2.6 ± 0.08%), Mg 1.2 ± 0.02% (1.2 ± 0.02%), Fe 3.2 ± 0.07% (3.97 ± 0.10%), Mn 480 ± 7.2 mg/kg (544 ± 21 mg/kg), Zn 390 ± 2.0 mg/kg (408 ± 15 mg/kg), Pb 129 ±

8.2 mg/kg (150 ± 17 mg/kg), Cd 3.1 ± 0.28 mg/kg (2.94 ± 0.29 mg/kg), Ni 40 ± 1.5 mg/kg (42.9 ± 3.7 mg/kg).

RESULTS AND DISCUSSION

Dating and sedimentation rate

The isolation from the sea can be seen at 45 cm from the diatom distribution (described in following paragraph). Although the advantage of studying diatom assemblages from fossil sediments is the large time scale (Snoeijs 1999) the sediments are all the time affected by physical and biological processes (bioturbation, mixing). Mixing of sediment strata is a common phenomenon in the Gulf of Finland (Kankaanpää et al. 1997). In the studied lake we can expect that both physical and biological mixing processes have been considerable. Characteristics and organic matter distribution in the sediment core are presented in Fig. 2. The distribution of ^{137}Cs shows elevated values from 22 cm to the surface which clearly indicates mixing of the sediment layers in the shallow lake. Consequently, no exact chronology can be determined for this sediment core. Supposing from the ^{137}Cs distribution that the maximum at 12 cm corresponds to the year 1986 (Chernobyl disaster), then the rate at the top of the core is as much as about 1 cm/a. With the exception of the topmost (0–16 cm) part of the core, the sedimentation rate has obviously been very low: approximately 0.1 mm/a. This is significantly lower than values reported for accumulation areas in the Gulf of Finland (Kankaanpää et al. 1997).

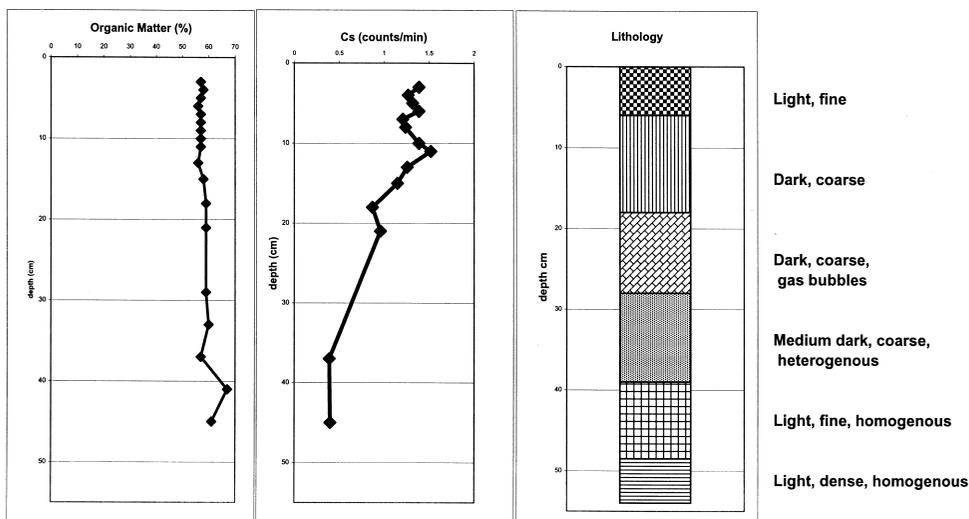


Fig. 2: Organic matter (% of dry wt), ^{137}Cs concentrations and visual characteristics of the sediment core

Diatom stratigraphy

The sediment core of lake Sandöträsket is characterized by diatom assemblages that are typical for a nutrient poor long-term acidification process. The deep alkaliphilic flora gradually changes from *Epithemia-Fragilaria-Achnantes* assemblage to more acidic *Achnantes-Cymbella-Anomoeoneis-Eunotia* (Battarbee et al. 1999). Towards the surface (about 19 cm upwards) the assemblage changes again and becomes more alkaliphilic. In many shallow lakes where light can easily penetrate to the bottom, periphyton can dominate primary production and provide information about littoral zone responses to the trophic changes (Hall & Smol 1999). The clearest feature in the stratigraphy of Lake Sandöträsket is the high number of periphytic (mainly benthic) diatoms which are attached to substrata. Many of these diatoms could even be classified as aerophilic (e.g. Hustedt 1930, 1937–39, Mölder & Tynni 1967–73).

The increased occurrence of *Tabellaria fenestrata* and *Eunotia spp.* in the middle of the core of the studied lake most likely indicates a period of higher water-level connected with lower pH caused by climate and catchment soil. To infer the dependence between metals and diatoms, stable conditions that can resist confusing outer influence e.g. acidification in a lake are needed. We could not detect any clear response of diatoms to metals.

Another typical feature of the core is the high number of pH-indifferent species throughout the sequence (Fig. 3). This seems to be an indication of few or minor changes of pH, and, probably, also of the trophic status of the lake, which has mostly been mesotrophic. Towards the surface, still, the inferred pH rises and the trophic status changes, but not to the point that the lake could be classified as eutrophic. The isolation of Lake Sandöträsket from a former sea stage is seen at the horizon 45–46 cm at the latest by the clear decline of *Campylodiscus clypeus*, an indicative species of the lagoon stage of Finnish lakes, when they isolated from the Litorina stage of the Baltic (e.g. Snoeijjs 1999). The marine species *Grammatophora marina* has disappeared at this horizon and it has been substituted by slightly brackish *Epithemia spp.* Two *Achnanthes* species and *Fragilaria spp.* are indicative of the alkaline and nutrient rich nature of the isolated lake (e.g. Huttunen & Meriläinen 1983).

Additionally, the sediment has changed from clay-gyttja to gyttja. Upwards many pH-indifferent species like *Navicula radiosa var radiosa*, *Navinula pupula* and *Pinnularia spp.* dominate, indicating a pristine clear water (e.g. Mölder & Tynni 1967–73). At the horizon 35–36 cm humic substances and reduced transparency seem to have been present in the water, as indicated by the clear appearance of *Anomoeoneis serians var brachysira* and *Frustulia rhomboides var saxonica* (Anderson et al. 1986). The simultaneous *Pinnularia spp.* drop confirms the change. At 21–28 cm the slightly acidit *Eunotia spp.* are at their highest concentration. *Tabellaria fenestrata*, the only predominantly planktonic species, is at its highest and the epiphytic *Cymbella cesatii* and *Achnanthes spp.* are at their lowest concentration, indicating that water level and transparency have been higher than previously. The development of the lake seems to have been natural long-term acidification up to the horizon 21–22 cm. From the horizon 19–20 cm upwards the state of the lake seems to be different indicating, probably, man's influence around the lake.

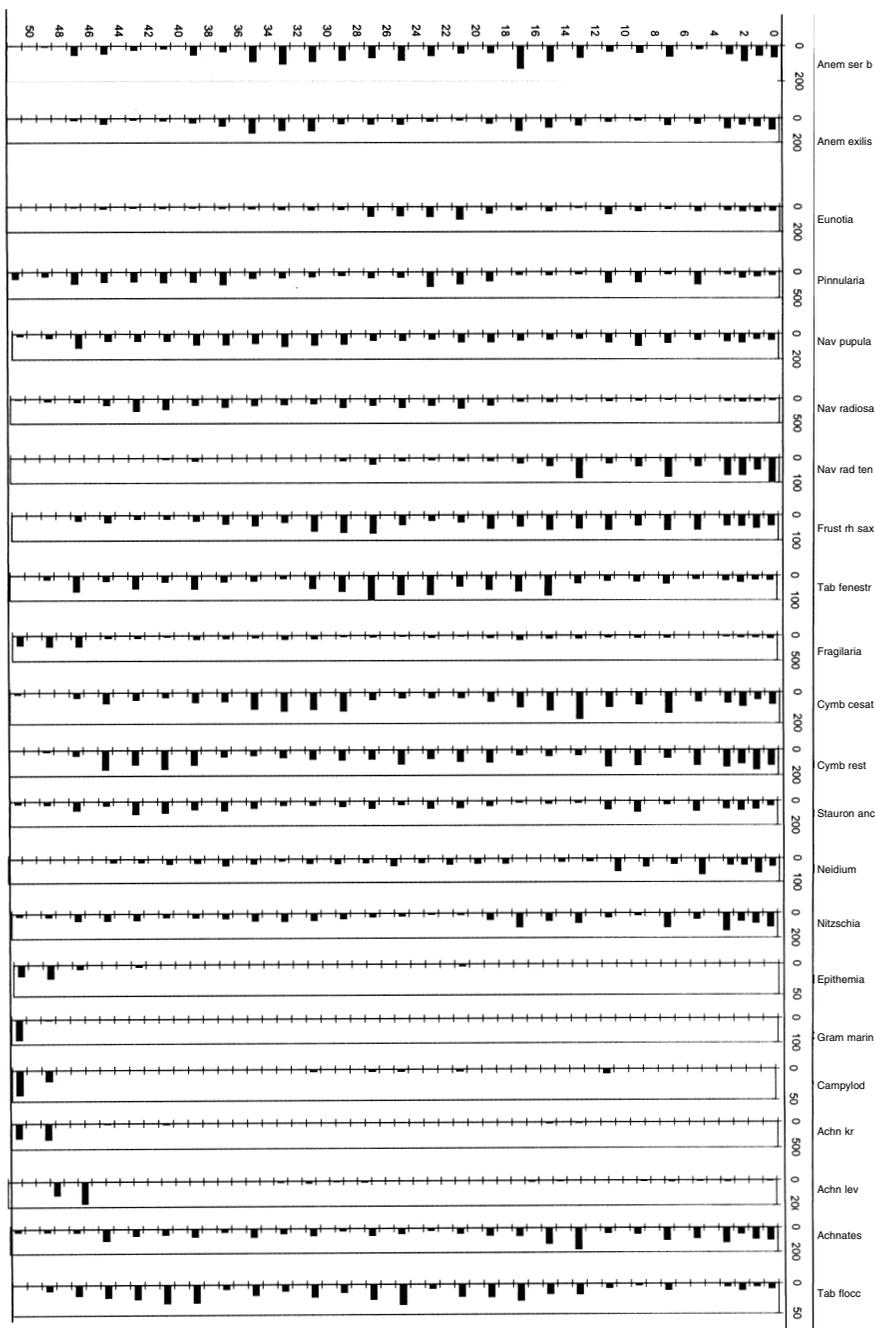


Fig. 3: Occurrence of diatom taxa at different depths of the core (for abbreviations see Table 1; please note the different scales for different species)

There are greater diatom anomalies in more recent layers indicating more rapid changes than before. Epiphytic species (e.g. *Cymbella* spp. and *Achnanthes* spp.) become more abundant. *Navicula radiosa* var *radiosa* is substituted by the variety *N. radiosa* var *tenella*. The alkaliphilic species (eg. *Nitzschia* spp.) become more abundant at 9–10 cm. From this level upwards the changes indicate an increased nutrient load to the lake, probably connected with dust emissions. Also the numbers of epiphytic and aerophilic 6 species (eg. *Stauroneis anceps*) increase. In the surface layers (0–4 cm) the conditions seem to be more stabilized. Industrial dust emissions (especially Ca and Fe) from the nearby Koverhar steel works may, to some degree, have influenced Lake Sandöträsket to a more productive and alkaline level.

Stratigraphy of metals and organic matter

The core history may be interpreted in the light of the known history of the pollution source in order to verify the dating. Reshaping of the profiles can occur for instance because of diagenetic processes such as biomixing and remobilisation under suitable redox conditions (Lockhart et al. 2000; Shotbolt et al. 2006). Towards the surface the enrichment values for most trace metals are at least three fold the background values at approximately 30 cm (Fig 4). For Zn, Cd, Ni, Pb, Hg, Cu an increasing trend can be seen from the lowest layers to approximately 10 cm. This development is connected to increase of pH and decrease of transparency, which changes can be interpreted from the diatom flora. Towards the surface the concentrations of trace metals decrease. Fe stays at the same level but Mn drops at 10–5 cm indicating a more anoxic period similar to that in some small acidic and polluted lakes in south Finland (Tolonen & Jaakkola 1983). Fe and Mn are sensitive to redox conditions. The Fe contamination is still up to 5 fold smaller than in Lac Dufault in Canada, a lake influenced by mining in the catchment (Cattaneo et al. 2004). For Ca, Mg and organic matter the vertical profiles are rather even.

Organic matter: The profile (Fig. 2) is typical for lacustrine sediments with about 60% organic matter almost throughout (0–46 cm) of the sediment core. The level is rather steady through the whole core except for a peak at 41 cm after the isolation from the sea.

Fe has a low mobility in granitic weathering (Harriss & Adams 1966). Additionally, the catchment area of the lake is flat, and hardly brings large amounts of minerogenic matter to the lake. The diagram (Fig. 4) is consistent with the graph of loosely bound Fe forms of e.g. Lake Lippajärvi (Vuorinen et al. 1986). Steady increase is seen from brackish environment (52 cm) to 12 cm with the exception of an increase at the uppermost layer which may be caused by emissions from the steel factory.

Mn has an intermediate mobility in granitic weathering. Mn seems to be mostly in loosely and moderately bound forms and behaves almost the same way as Fe: steady increase from brackish environment (52 cm) until a drop at 10–5 cm, then increase to the present but with a stronger maximum in the uppermost layer. Also

Cu follows almost the same behaviour as Fe: steady increase from brackish environment to 12 cm. Then the level is even with a peak at 3 cm.

Zn follows the form and magnitude of eg. Lippajärvi core (Vuorinen et al. 1986). There is a steady increase from brackish environment (52 cm) to 7–12 cm with decreasing concentrations upwards. **Cd** follows closely the distribution of Zn.

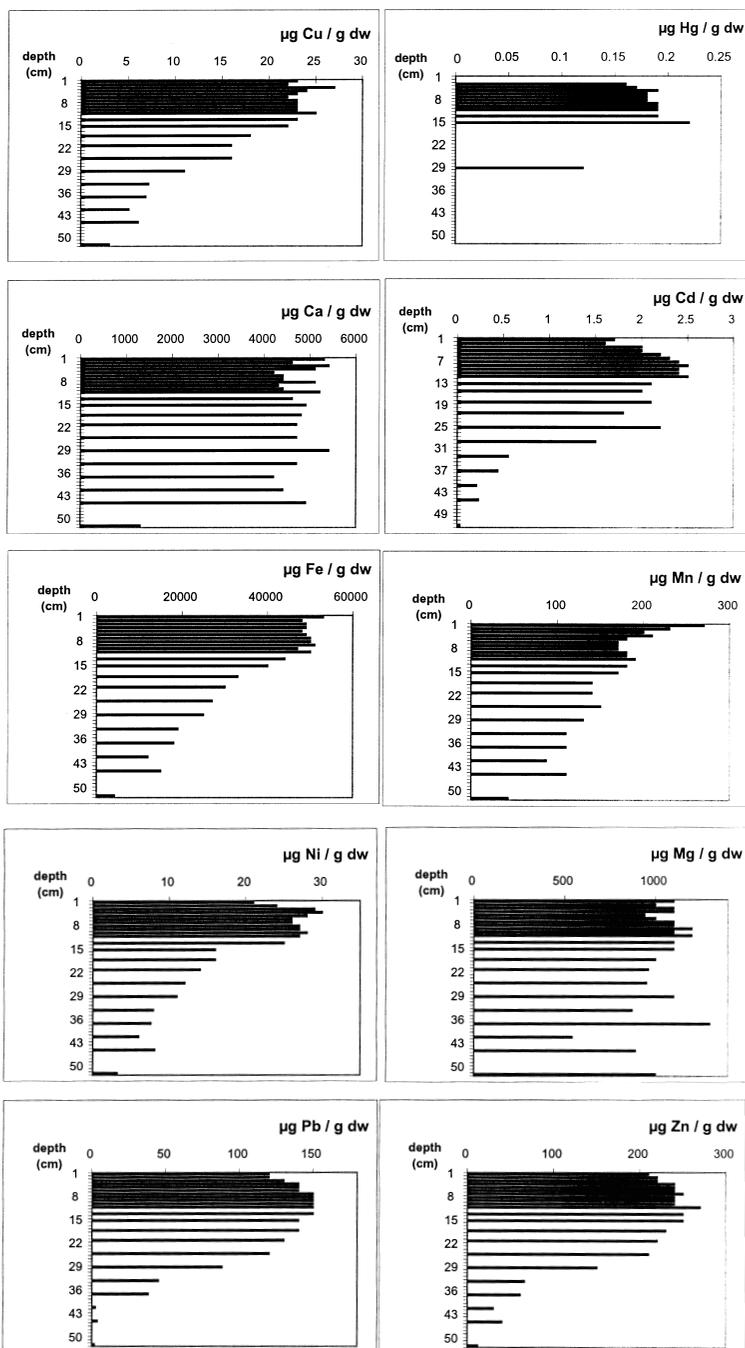


Fig. 4: Metal concentrations ($\mu\text{g/g dry wt}$) in the sediment core

Ni shows steady increase from brackish environment (52 cm) to 4 cm. Then the concentrations decrease. Also for **Pb** there is a steady increase from brackish environment to 7–12 cm. Upwards from that the concentrations decrease.

Mg shows a rather stable level of concentrations in the whole sediment core. The minimum at 41 cm corresponds to the maximum of organic matter indicating that Mg is originated not only from organic matter in loosely bound forms but also from minerogenic moderately bound forms.

Ca follows organic matter in accordance with most studies of Finnish lakes. Ca seems to be mostly in exchangeable and loosely bound forms. The concentrations are low in brackish environment (52 cm), thereafter they stay at a rather stable level.

Hg: The form of Hg is affected by redox conditions in altering mobilities (Lockhart et al. 2000). Low sedimentation rates can alter Hg sediment profiles by remobilisation and diffusion (Gobeil et al. 1999). The profile show increase from 45 cm to 21 cm, thereafter there is a slight decrease (no samples from the surface).

Fe/Mn and **Cu/Zn** ratios are indicators of redox fluctuations. According to the ratios (Fig. 5) oxygen depletion is seen at about 10–5 cm but the situation has improved thereafter. A clear Fe/Mn rise connected with anomaly of redox value was measured from the surface sediment of the highly polluted Gallträsket, S. Finland (Tolonen & Meriläinen 1983). There the trace metals were clearly higher than in Sandöträsket, but Fe and Mn were clearly lower indicating worse anoxic condition. The Fe/Mn ratio in Sandöträsket was usually higher than in the Laajalahti Bay near Helsinki (Vaalgamaa 2004).

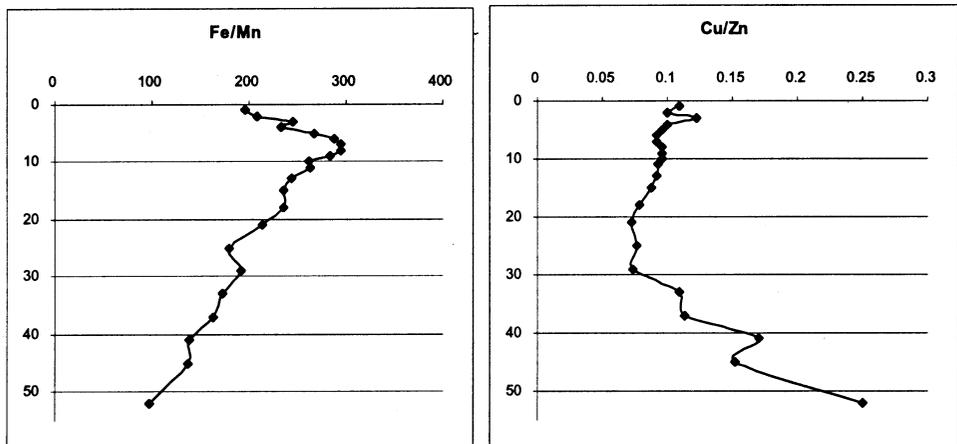


Fig. 5: Fe/Mn and Cu/Zn ratios in the sediment core, y axis depth in cm

Metal levels

Mean values of heavy metal concentrations in sediment cores from the lake Sandöträsket and the central depth of Tvärminne Storfjärden, NE off the Tvärminne peninsula are presented in Table 2. There is a clear decline of Fe, Mn, and Cu by depth (time) in the sediments. For Zn and Cd the decline is pronounced only for the periods following the

deepest sample (50 cm). In the sediments from the depth in Storfjärden a similar distinct decline by depth (time) may be calculated only for Zn and Cd, while the values for Fe and Cu show a decline for the periods following the deepest sample (50 cm). For Mn there is a clear increase in Sandöträsket while the lowest value was recorded at the surface of the sediment from Storfjärden.

Table 2. Calculated mean values of heavy metal concentrations (mg/kg d. wt) in sediment cores from the lake Sandöträsket and the central depth of Tvärminne Storfjärden, NE of the Tvärminne peninsula (Voigt 2003).

Deep/Metal	Fe	Mn	Zn	Cu	Cd
Sandöträsket 10 cm	50 000	250	220	22	2.1
25 cm	28 000	150	220	16	2.4
50 cm	4 200	43	15	3	0.03
Storfjärden 10 cm	42 000	380	170	45	0.89
25 cm	42 000	720	180	48	0.43
50 cm	37 000	570	110	35	0.23

The sediments from the central depth (35 m) in Tvärminne Storfjärden are considerably younger than those from lake Sandöträsket, due to different sedimentation rates; 0.1 mm/a for Sandöträsket (this study), and 1.0 mm/a for a depth (mean 42 m) intensively studied (Nuorteva 1994), in the sea area 20 km SE off the city of Hanko-Hangö respectively. Additionally, the erosion effects of local bottom currents, bioturbation activity by abundant benthic animals are all capable of thoroughly mixing the uppermost few centimeters of sediment (Winterhalter 1992). Furthermore, the mobility and transportation of elements by currents from even long distances, as in the Gulf of Finland (Leivuori 1998), should be considered carefully when comparing sediment cores of different origins (Vallius 1999).

The values of Fe and Cd are both high in the lake Sandöträsket compared to the other investigated water bodies in the neighbourhood (Table 3). For Mn the mean value corresponds well with the values from the shallow waters in Gennarbyviken-Kila and the shallow waters around Tvärminne (Krogarviken and Byviken), but it is considerably lower than the corresponding values for the depths (Storfjärden and the Western Gulf of Finland). For Zn the obtained value from Sandöträsket is higher than in the sediments of the shallow bays (Gennarbyviken-Kila, Krogarviken and Byviken), where the concentrations of Zn are clearly lower than in Sandöträsket. With the exception of the

shallow Kila bay in Gennarbyviken, the obtained concentrations of Hg are all of the same order of magnitude.

Table 3. Mean concentrations (mg/kg d.wt.) of selected heavy metals from the surface sediments (<10 cm) of the lake Sandöträsket (peninsula of Hanko-Hangö, SW Finland), the isolated large Gennarbyviken water reservoir (N of Hanko-Hangö peninsula; Voigt 2000), two shallow coastal bays around the Tvärminne peninsula (Krogarviken, Byviken), the central depth of Tvärminne Storfjärden (Voigt 2003), and the main depth of the Western Gulf of Finland (Leivuori 1998)

Site (depth)	Fe	Mn	Zn	Cu	Cd	Hg
Sandöträsket 1.5 m	50 000	250	220	22	2.1	0.08
Gennarbyviken-Kila (2 m)	31 000	300	90	30	0.65	0.02
Krogarviken (2.5 m) & Byviken (1.5 m)	20 000	180	70	23	0.50	0.05
Storfjärden (35 m)	42 000	380	180	45	0.89	0.07
Western Gulf of Finland (60 m)	43 000	510	180	33	0.36	0.06

The high concentrations of Fe in the sediments of the Sandöträsket may be explained by the activity of the iron and steel plant in the neighbourhood at Koverhar, where the activity began in 1961. The same explanation may be valid also for the occurrence of Zn and Cd, which metals have been emitted from the plant (Voigt 2003). The mean concentration of Cu in the sediments of Sandöträsket corresponds well to means calculated from other fresh water lakes in Finland, e.g. the Kitka Lakes (25 and 21 mg/kg, respectively; Myllymaa et al. 1985), and Finnish headwater lakes (mean 18.4 mg/kg; Verta et al. 1990). The higher concentrations of Zn in the sediments of the lake Sandöträsket in contrast to the brackish water environment (Storfjärden, Western Gulf of Finland), may be explained by the selective concentration of Zn and Cd in the sediments of freshwater reservoirs (Pita and Hyne 1975).

The Cd concentrations here are of the same order of magnitude as the mean concentrations calculated for the surface sediments of Tvärminne Storfjärden in the 1970's (3 mg/kg d.wt), at the time when the cadmium emissions from the steel plant at Koverhar were still considerably high. The turbidity in the shallow lake may influence the occurrence of metals analysed from the sediments, leading to a broad variation of the results depending on the behaviour of the metals in the labile environment. The complex mechanism of release of buried metals from the sediments into the bottom water makes the interpretation of the obtained results even more problematic.

Correlations

The occurrence of diatom species often correlate positively with each other but in lake Sandöträsket diatoms were not found to have any significant correlations with depth or

metals (Table 4). We found strong negative correlations with depth and the metals Fe, Zn, Cu, Mn, Cd, Ni, Pb and Hg, which emphasizes anthropogenic influence.

Table 4. Correlation coefficients (Pearson) and p-values (N = 14) between depth, metals and organic matter (OM). No significant correlations were found for Ca and Mg

	Depth	Cd	Cu	Fe	Hg	Mn	Ni	OM	Pb
Cd	-0.957 0.000								
Cu	-0.966 0.000	0.967 0.000							
Fe	-0.971 0.000	0.943 0.000	0.980 0.000						
Hg	-0.832 0.000	0.901 0.000	0.856 0.000	0.767 0.001					
Mn	-0.929 0.000	0.921 0.000	0.979 0.000	0.971 0.000	0.771 0.001				
Ni	-0.949 0.000	0.911 0.000	0.973 0.000	0.988 0.000	0.738 0.003	0.981 0.000			
OM	0.767 0.001	-0.680 0.007	-0.752 0.002	-0.785 0.001	-0.470 0.090	-0.772 0.001	-0.778 0.001		
Pb	-0.951 0.000	0.983 0.000	0.954 0.000	0.911 0.000	0.932 0.000	0.897 0.000	0.877 0.000	-0.696 0.006	
Zn	-0.943 0.000	0.984 0.000	0.966 0.000	0.917 0.000	0.942 0.000	0.917 0.000	0.888 0.000	-0.677 0.008	0.990 0.000

Metals often correlate with other metals but not with Ca or Mg. Organic matter correlate negatively with most metals ($r = -0.7 \dots -0.8$), with the exception of Ca (+0.47). In a study from European marshlands (Callaway et al. 1998) Zn, Cu, Cd, Ni and Pb correlated with each other but not with Fe or Mn indicating, probably, diagenesis caused by redox-conditions. In our study, evidently unfavourable redox-conditions may have been limited to some periods.

CONCLUSIONS

The isolation from the sea was clearly observed in the diatom community. The lagoon stage of the studied lake of the sea is indicated at 47–48 cm by the species *Campylodiscus clypeus* when the marine *Grammatophora marina* had already vanished. At approximately 45–46 cm the lake stage begins, but it was probably influenced by occasional brackish water by floods. The diatoms indicate no dramatic changes since the isolation and they follow the natural long-term development up to about 19 cm. The diatom assemblage has been mostly benthic throughout the history of the lake indicating that light has been able to penetrate to the lake bottom. The rise of the only predominantly planktonic diatom *Tabellaria fenestrata* in the middle of the core probably indicates a higher water level

period. The assemblage changes at about 19 cm and more alkaliphilic species begin to dominate. This change is most likely not affected by climatic warming or acid rain (Sorvari et al. 2002), but it is connected with nutrient inputs by dust and traffic and metal pollution from the near-by steel plant. If a more anoxic period can be deduced inversely, then the highest value of Fe/Mn at about 10–5 cm could be a sign of oxygen depletion. In these reduced conditions, Mn has escaped from sediment to water. For most metals there is an increase in concentration up to 10–15 cm and often a decrease thereafter. Influence from the steel factory can be seen in the Fe and Mn concentrations in the upper most layer. No significant connection was found in the occurrence of diatoms and metals.

ACKNOWLEDGEMENTS

We are indebted to Mr Kurt Andersson and Mr Jarkko Hintsala for assistance in sampling and analysing. We also want to thank prof. Högne Jungner, University of Helsinki, for Cs dating of the samples.

REFERENCES

- Alhonen, P., 1972: Gallträsket: The geological development and palaeolimnology of a small polluted lake in Southern Finland. *Commentationes Biologicae (Soc. Sci. Fennica)* 57: 1–34.
- Anderson, D.S., Davis, R.B., Berge, F., 1986: Relationships between diatom assemblages in lake surface sediments and limnological characteristics in southern Norway. In: Smol, J.P., Battarbee, R.W., Davis, R.B., Meriläinen, J. (Eds.), *Diatoms and Lake Acidity*, Dr W. Junk Publishers, Dordrecht: 97–113.
- Battarbee, R.W., Charles, D.F., Dixit, S.S., Renberg, I., 1999: Diatoms as indicators of surface water acidity. In: Stoermer, E.F., Smol, J.P. (Eds.): *The diatoms: Applications for the environmental and earth sciences*. Cambridge: 85–127.
- Callaway, J.C., Delaune, R.D., Patrick, W.H. Jr., 1998: Heavy metal chronologies in selected coastal wetlands from northern Europe. *Marine Pollution Bulletin* 36: 82–96.
- Cattaneo, A., Couillard, Y., Wunsam, S., Courcelles, M., 2004: Diatom taxonomic and morphological changes as indicators of metal pollution and recovery in Lac Dufault (Québec, Canada). *Journal of Paleolimnology* 32: 163–175.
- Denys, L., de Wolf, H., 1999: Diatoms as indicators of coastal paleoenvironments and relative sea-level change. In: Stoermer, E.F., Smol, J.P. (Eds.), 1999: *The Diatoms: Applications for the Environmental and Earth Sciences*, Cambridge: 277–297.
- Eronen, M., 1974: The history of the Litorina Sea and associated holocene events. *Societas Scientiarum Fenniae, Communicationes Physico-Mathematica* 44: 79–195.
- Germain, H., 1981: *Flore des diatomées*. Société nouvelle des éditions Boubée, Paris: 444 pp.
- Gobeil, C., Macdonald, R.W., Smith, J.N., 1999: Mercury profiles in sediments of the Arctic Ocean basins. *Environmental Science and Technology* 33: 4194–4198.
- Hall, R.I., Smol, J.P., 1999: Diatoms as indicators of lake eutrophication. In: Stoermer, E.F., Smol, J.P. (Eds.), 1999. *The Diatoms: Applications for the Environmental and Earth Sciences*. Cambridge: 128–168.
- Harriss, R.C. & Adams, J., 1966: Geochemical and mineralogical studies on the weathering of granitic rocks. *American Journal of Science* 264, 146–173.
- Helminen, O., 1989: Pienten järvien happamoitumisesta Länsi-Uudellamaalla 1984–1988. *Länsi-Uudenmaan vesiensuojeluyhdistys r.y. Julkaisu* 7: 38 pp.
- Hustedt, F., 1930: *Bacillariophyta (Diatomeae)*. In: Pascher, A. (ed.), *Die Süßwasserflora Mitteleuropas*. Gustav Fischer Verlag, Jena: 466 pp.

- Hustedt, F., 1937–39: Systematische und Ökologische Untersuchungen über die Diatomeenflora von Java, Bali und Sumatra. *Archiv für Hydrobiologie Suppl.* 15: 131–177, 187–295, 393–506, 638–790; *Suppl.* 16: 1–155, 274–394.
- Huttunen, P., Meriläinen, J., 1983: Interpretation of lake quality from contemporary diatom assemblages. *Hydrobiologia* 103: 91–97.
- Huttunen, P., Meriläinen, J., 1986: Applications of multivariate techniques to infer limnological conditions from diatom assemblages. In: Smol, J.P., Battarbee, R.W., Davis, R.B., Meriläinen, J. (eds.), *Diatoms and Lake Acidity*, Dr. W. Junk Publishers, Dordrecht: 201–211.
- Kankaanpää, H., Vallius, H., Sandman, O., Niemistö, L., 1997: Determination of recent sedimentation in the Gulf of Finland using Cs-137. *Oceanologica Acta* 20: 823–836.
- Leivuori, M., 1998: Heavy metal contamination in surface sediments in the Gulf of Finland and comparison with the Gulf of Bothnia. *Chemosphere* 36: 43–59.
- Lockhart, W.L., Macdonald, R.W., Outridge, P.M., Wilkinson, P., DeLaronde, J.B., Rudd, J.W.M., 2000: Tests of the fidelity of lake sediment core records of mercury deposition to known histories of mercury contamination. *Science of the Total Environment* 260: 171–180.
- Myllymaa, U., Saarelainen, J., Hyvönen, P., 1985: Nutrient and metal concentrations in the surface sediment layers of the Kitkajärvi lakes. *Publications of the Water Research institute, National Board of Waters, Finland* 62: 20–53.
- Mölder, K., Tynni, R., 1967–73: Über Finnlands recente und subfossile Diatomeen I–VII. *Bulletin of the Geological Society in Finland* 39, 199–217, 40, 151–170, 41, 235–251, 42, 129–144, 43, 203–220, 44, 141–149, 45, 159–179.
- Nuorteva, J., 1994: Topographically influenced sedimentation in Quaternary deposits – a detailed acoustic study from the Western part of the Gulf of Finland. *Geological Survey of Finland, Report of Investigation* 122: 1–88.
- Pita, F.W., Hyne, N.J., 1975: The depositional environment of zinc, lead and cadmium in reservoir sediments. *Water Research* 9: 701–706.
- Sancetta, C., 1999: Diatoms and marine paleoceanography. In: Stoermer, E.F., Smol, J.P. (Eds.), 1999. *The Diatoms: Applications for the Environmental and Earth Sciences*, Cambridge: 374–388.
- Seppä, H. & Tikkanen, M., 1998: The isolation of Kruunuvuorenlampi, southern Finland, and implications for Holocene shore displacement models of the Finnish south coast. *Journal of Paleolimnology* 19: 385–398.
- Seppä, H., Tikkanen, M. & Shemeikka, P., 2000: Late-Holocene shore displacement of the Finnish south coast: diatom, litho- and chemostratigraphic evidence from three isolation basins. *Boreas* 29: 219–231.
- Shotbolt, L., Hutchinson, S.M., Thomas, A.D., 2006: Sediment stratigraphy and heavy metal fluxes to reservoirs in the southern Pennine uplands, UK. *Journal of Paleolimnology* 35: 305–322.
- Snoeijs, P., 1999: Diatoms and environmental change in brackish waters. In: Stoermer, E.F., Smol, J.P. (Eds.), 1999. *The Diatoms: Applications for the Environmental and Earth Sciences*, Cambridge: 298–333.
- Sorvari, S., Korhola, A., Thompson, R., 2002: Lake diatom response to recent arctic warming in Finnish Lapland. *Global Change biology* 8: 171–181.
- Sullivan, M.J., 1999: Applied diatom studies in estuaries and shallow coastal environments. In: Stoermer, E.F., Smol, J.P. (Eds.), 1999. *The Diatoms: Applications for the Environmental and Earth Sciences*. Cambridge: 34–351.
- Tervahattu, H., Lodenius, M., Tulisalo, E., 2001: Effects of the reduction of cement plant pollution on the foliar and bark chemical composition. *Boreal Environment Research* 6: 251–259.
- Tolonen, K., Jaakkola, T., 1983: History of lake acidification and air pollution studied on sediments in South Finland. *Annales Botanici Fennici* 20: 57–78.
- Tolonen, K., Meriläinen, J., 1983: Sedimentary chemistry of a small polluted lake, Gallträsk, S. Finland. *Hydrobiologia* 103: 309–318.
- Tynni, R., 1975–1980: Über Finnlands rezente und subfossile Diatomeen VIII–XI. *Geol. Survey Finland, Bull.* 274, 1–55 (1975), 284, 1–37 (1976), 296, 1–55 (1978), 312, 1–93 (1980) + tables.
- Vaalgamaa, S., 2004: The effect of urbanisation on Laajalahti Bay, Helsinki City, as reflected by sediment geochemistry. *Marine Pollution Bulletin* 48: 650–662.
- Vallius, H., 1999: Heavy metal deposition and variation rate within a sedimentary basin in central Gulf of Finland. *Chemosphere* 38, 1959–1972.

- Verta, M., Mannio, J., Iivonen, P., Hirvi, J.-P., Järvinen, O., Piepponen, S., 1990: Trace metals in Finnish headwater lakes – Effects of acidification and airborne load. In: Kauppi, P., Anttila, P., Kenttämies, K. (Eds.): Acidification in Finland. Springer Verlag, Berlin, Heidelberg: 883–908.
- Vuorinen, A., Alhonen, P., Suksi, J., 1986: Palaeolimnological and limnogeochemical features in the sedimentary record of the polluted lake Lippajärvi in southern Finland. *Environmental pollution (Series A)* 41: 323–362.
- Voigt, H.-R., 2000: Water quality and fish in two freshwater reservoirs (Gennarby and Sysilax) on the 35 SW coast of Finland. *Acta Universitatis Carolinae, Environmentalica* 14: 31–59.
- Voigt, H.-R., 2003: Tvärminnen alueen eräiden pohjapintasedimenttien ja pohjaeläinten raskasmetallipitoisuuksia. [Heavy metal concentrations of bottom sediments and bottom fauna in the Tvärminne area]. *Ympäristö ja Terveys* 34 (6): 39–41.
- Winterhalter, B., 1992: Late-Quaternary stratigraphy of Baltic Sea basins – a review. *Bulletin of the Geological Society of Finland* 64: 189–194.
- Wolin, J.A., Duthie, H.C., 1999: Diatoms as indicators of water level change in freshwater lakes. In: Stoermer, E.F., Smol, J.P. (Eds.), 1999. *The Diatoms: Applications for the Environmental and Earth Sciences*. Cambridge: 183–204.