The eutrophication of Lake Årungen as interpreted from paleolimnological records in sediment cores

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SAMMENDRAG

I løpet av dette århundret har Årungen ved Ås i Akershus fylke gjennomgått en omfattende endring i trofigrad. Innsjøen har utviklet seg fra en mesotrof (lite næringsrik) til en hypertrof (ekstrem næringsrik) tilstand. Første del av denne utviklingen kan karakteriseres som en eutrofiering betinget av moderat tilførsel av næringsstoffer fra landbruk og husholdningskloakk.

I løpet av de siste 30 år har det vært en stadig økt næringstilførsel både fra landbruk og spesielt fra urenset kloakk. Dette har ført innsjøen over i en hypertrof tilstand.

Denne utviklingen er vist ved et omfattende studium av sedimentkjerner fra innsjøens dypeste, sentrale område. Disse paleolimnologiske undersøkelsene omfatter radioisotop-analyser, tungmetallanalyser, kjemiske analyser av organisk materiale og næringsstoffer, samt en undersøkelse av kiselalgeskall (diatomeer) som er bevart i sedimentet.

ABSTACT

During this century Lake Årungen, SE Norway, has undergone a trophic development. The initial phase of this development can be characterized as an eutrophication caused by a moderate agricultural and sewage loading, changing the lake from a state of mesotrophy to a state of eutrophy. During the last c. 30 years there has been a further increase in the agricultural loading and a heavy increase in the untreated sewage loading changing the lake into a hypertrophic state. This development is demonstrated by the results of an extensive study of sediment cores from the deepest central part of the lake. The paleolimnological records comprise radioisotope analyses, determinations of heavy metals, chemical investigation on organic matter and nutrients, and finally investigation on diatom frustules preserved in the sediment.

1. INTRODUCTION

Sediments that accumulate in a lake basin represent an integration of materials imported from the lake's drainage area and materials produced within the lake, all of which are subject to differential transport by currents and turbulence and capable of being modified by biological and chemical activities (see Frey 1969). Consequently the sediments contain information on the history of lakes and their corresponding drainage areas. The «reading» of this history can be more or less successful, depending both on the consistency of the «language» it is written in and our ability in interpreting the «language» (see Frey 1974).

The aim of the present study is to interpret the recent ecological changes of Lake Årungen, SE Norway. This is performed by analysing some selected chemical components and biological remains in sediment cores from the deepest central part of the lake. The study comprises data on the organic matter, nutrients, heavy metals and the relative abundance and diversity of diatom frustules preserved in the sediment. The sediments have been dated by radiological methods. The input of several elements to the sediment have been calculated.

2. MATERIALS AND METHODS

The lake studied. Lake Årungen is situated about 25 km southeast of Oslo, Norway. The lake's surface area is 1.2 km^2, its maximum length 3.0 km and its maximum depth 13.2 m. Of the drainage area (52 km^2) approximately 50% consists of cultivated areas and 40% of forest. During the last c. 30 years the lake has received an increased loading of domestic waste water and agricultural run-off. As a consequence the lake has reached a hypertrophic stage in a development characterized by high levels of nutrients, heavy blooms of phytoplankton and extremely low Secchi-disk transparencies. During periods of thermal stratification the hypolimnion rapidly turns anaerobic and the sulhide produced is precipitated as Fe-sulphides. Further details about the lake have been given by Skogheim (1978 a, 1979 a).

Core sampling and core treatment. In April 1978 when the lake was covered with ice, two parallel sediment cores of 50 cm length were obtained with a gravity duplo-corer (Skogheim 1979 b) using acrylic tubes (44 mm I.D.). The sampling site was at maximum depth (13.2 m) in the central flat bottom area of the lake basin.

The cores were extruded from the sampler and divided into sections of 1 cm thickness within 16—20 hours after sampling (stored overnight at 4°C in a dark room). One core was used for radiological dating and the other was used for the chemical and biological analyses.

Radiological analyses. The ^{137}Cs analyses were performed and reported by Augustson et al. (1978). The ^{210}Pb-analyses were performed by Dr. Eakins et AERE, Harwell, England, using the method outlined by Pennington et al. (1976). The authors of the present paper are responsible for interpretations of the results. The analyses ware performed on freeze-dired samples.

Chemical analyses. Immediately upon extrusion of the sediment from the core the redox potential (Eh) and pH were measured (with a Radiometer PHM 26) by placing the electrodes in the centre of each sediment section. The ammonia was measured with an ORION gas-sensitive electrode (Model 95—10) in a suspension of wet sediment. Subsamples of wet sediment were used for determination of water content (dried at 105°C for 24 hours). Other subsamples of wet sediment were freeze-dried and the following analyses were performed, on a dry weight (D.W.) basis.

Amounts of organic carbon (C), total nitrogen (N) and total sulphur (S) were determined using a Carlo Erba Elemental Analyzer Mod. 1106. Duplicate analyses were performed. Total nitrogen includes a fraction of ammonia from the interstitial water. The inorganic nitrogen in the sediment, which was measured as ammonia in the wet sediment, was invariably close to about 10% of total nitrogen. 2 g samples of dry sediment were autoclaved in 15 ml of 1:1 conc. HNO_3 and the non-silicate fractions of Fe, Mn, Zn, Cu, Pb, Hg, Co, Cd, Cr, were analysed by atomic absorption spectrophotometry (Perkin-Elmer Mod. 303). Total phosphorus (P) was determined as orthophosphate (Murphy and Riley 1962) in the same solutions.

Alkali-soluble silicate was determined according to Tessenow (1975). Sedimentary chlorophyll degradation products were analysed by a procedure slightly modified after Vallentyne (1955). Analyses were performed on wet samples and the absorbance of the acetone extracts were scanned in the spectral region 750 to 350 nm (Shimazdu Spectrophotometer Mod. 210). Concentrations are calculated in arbitrary units according to Vallentyne (1955) on the basis of dry weight and organic carbon.

Diatom counting. 0.1 g freeze-dried sediment from each sample stratum was treated with a mixture of conc. H_2SO_4 and sat. $KMnO_4$ to remove organic matter. The purfied material was suspended in 10 ml of distilled water and a 50 μl subsample was mounted on glass slides using Coumarone mounting medium (R.I. = 1.63). Between 100—111 frustules were counted in each sample.

Species identification followed Hustedt (1930), Huber-Prestalozzi (1942), Cleve-Euler (1951—1955), and Patrick and Reimer (1966).

3. RESULTS

Radiological dating. Based on ^{137}Cs analyses (Fig. 1) a mean sedimentation rate of 8.4 ± 0.4 mm/year was calculated for the period 1954—1978 (Augustson et al. 1978). The similarity between the patterns of ^{137}Cs-activity in the sediment (Fig. 1 A) and the atmospheric fall out of ^{137}Cs in the actual geographical region (Fig. 1 B) provide a reasonable basis for the estimation of the sedimentation rate. Bioturbation or wind-induced resuspension does not seem to have caused a redistribution of ^{137}Cs in the core and the calculated sedimentation rate appears to form a reliable average for the period 1954—1978. The sedimentation rate during this period is regarded as constant, judged from the fact that the lake have been in a state of hypertrophy during this period (Skulberg 1969, Skogheim 1978 a).

The sedimentation rate for the period 1900—1950 was calculated to 3.4 mm/year as a mean value from the ^{210}Pb-analyses. During this period the sedimentation rate is not expected to have been constant, but rather to have exhibited a gradual increase. However, the ^{210}Pb analyses were unfortunately too few to give evidence for a gradual change in the sedimentation rate.

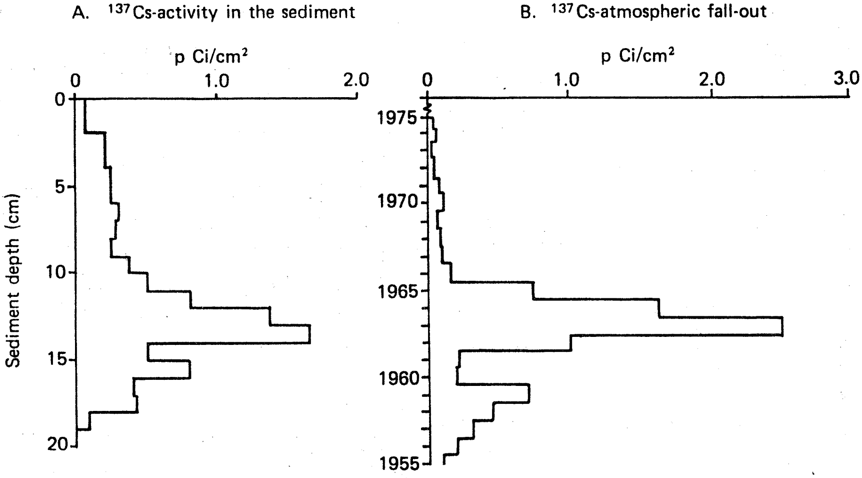

Fig. 1. A. *Depth profile of* ^{137} *Cs-activity in a sediment core from Lake Årungen.*
B. ^{137} *Cs-activity in atmosphere fall-out at the same location (Data from Auguston et al. 1978).*

Chemical analyses. The predominant inorganic component of the sediment is clay (c. 75%). A minor contribution of silt is also present. The organic matter contributes less than 14% to the dry weight. The topmost 25 cm of the core is black because of layers of FeS. Data on the source of the sediment, distributions and interrelationships of chemical components in the sediments of this lake are given by Skogheim (1978 a).

pH in the sediment varied between 6.95 and 6.60, but there was no clear vertical pattern. Redox potential decreased from about —200 mV in the surface to a fairly constant level of c. — 400 mV at 5 cm and further down in the sediment. Reduction of sulphate and production of methane are taking place in the lower part of this sediment.

The vertical variations of organic carbon, total phosphorus and total nitrogen, the C/N ratio, sedimentary chlorophyll, the pigment ratio E 410/E350, alkali-soluble silicate, and the diversity of diatoms are shown in Fig. 2.

Organic carbon increases upward from c. 23 cm (corresponding to approximately 1945) to the top of the sediment. This coincides with the apperance of the Fe-sulphide layers and the onset of the eutrophication.

Organic carbon and total nitrogen are closely correlated ($r = 0.99$, $n = 29$, $p < 0.001$), but there is also a change in the quality of the organic matter as seen in the C/N ratio. There is a steady decrease in the C/N-ratio from the lower part of the sediment towards the surface.

Total phosphorus and organic carbon exhibit similar vertical variations ($r = 0.64$, $n = 29$, $p < 0.01$). The variation in total phosphorus is within a factor of 3; surprisingly low in fact, compared with other hypertrophic lakes (cf. Bengtsson

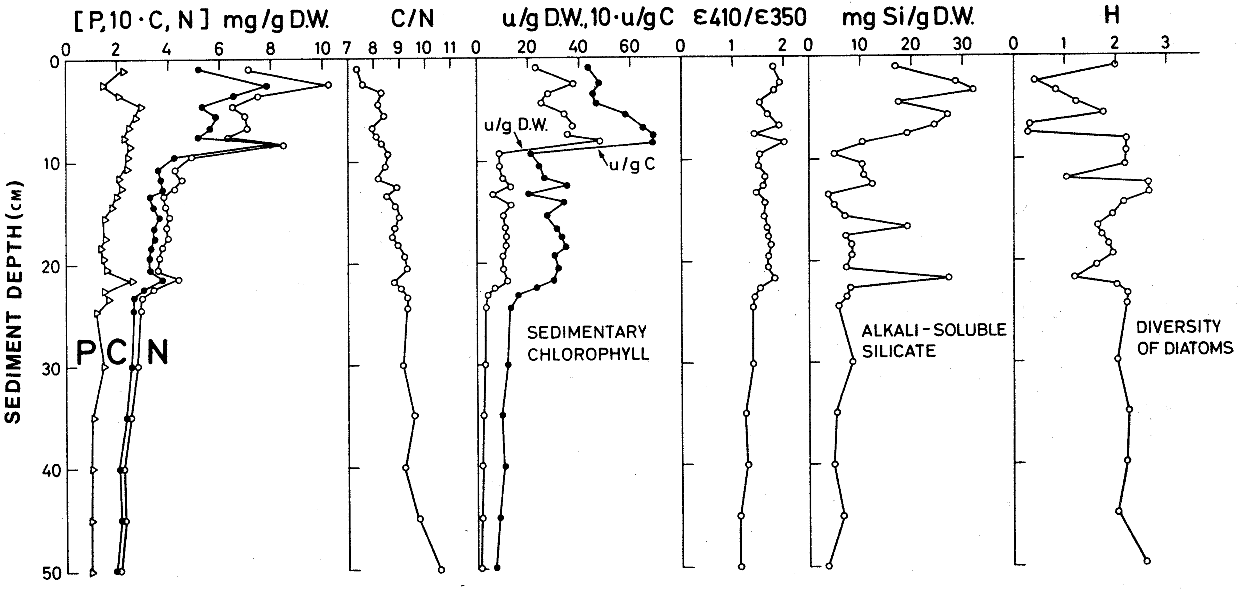

Fig. 2. *Vertical variation in organic matter (OC, TN), nutrients (TP), the ratio C/N, sedimentary chlorophyll degradation products, the pigment ratio* E_{410}/E_{350} *(see the text alkali-soluble silicate (Alk-Si), and the diversity index of diatoms.*

and Fleischer 1971, Bengtsson and Persson 1978, Skogheim 1976).

Sedimentary chlorophyll degration products, calculated on both dry weight- and organic carbon-basis, exhibit two increases, first at approximately 1950 and then a second increase at approximately 1965. This development is closely related to that of organic carbon.

The pigment ratio E_{410}/E_{350} (absorption at respective wave-lengths in nm in acetone extract) is here applied to indicate a shift in the ratio autochthonus/allochthonus origin of organic matter (Gorham 1961). The variation in this ratio is the inverse of that of the C/N ratio.

Alkali-soluble silicate is taken as a measure of amorphous silicate in order to quantify the amount of diatom frustules. An oscillating pattern appears during the last c. 30 years. The sedimentation of diatoms seems to be high, in particular during the last decade.

The vertical variations of sulphur and some selected metals are shown in Fig. 3. Iron, a major element in the sediment, has lower values and an oscillating pattern during the last c. 30 years. The concentrations of the metals zinc, mercury, copper, lead and cadium seem to be increasing during the last c. 30 years, whereas manganese, cobalt and chromium show little or no vertical variation. Sulphur, mainly as sulphides (Skogheim, unpubl.) has a vertical variation clearly indicating that the eutrophication period is characterized by an anaerobic hypolimnion and the precipitation of FeS and other metal sulphides.

Diatom analysis

The relative abundance (%frustules) of the dominant diatom species are shown in Fig. 4. The small centric diatom *Stephanaodiscus hantzschii* Grunow, indicative of highly polluted waters (Håkanson 1976), increases suddenly at approximately 1945 and later exhibits large variations with peaks of up to an abundance of 92%. At 7—8 cm depth (i.e. about 1970) there was a sudden decrease in *S. hantzschii* counteracted by the sudden appearance and high frequency of *Melosira granulata* var. *angustissima* Muller, another species indicative of highly eutrophic habitats (Kalbe and Werner 1974, Stoermer and Ladewski 1976). *Melosira italica* subsp. *subarctia* Müller, which is indicative of more aligotrophic conditions (Shear et al. 1976, Schelske and Stoermer 1972) showed a pronounced decrease at c. 25 cm depth, which corresponds to the onset of eutrophication. *Fragilaria crotonensis* Kitton, indicative of eutrophication (Moss 1972, Stoermer et al. 1978, Stockner 1972) was relatively abundant at 15—25 cm depth, which corresponds to the first part of the eutrophication period (c. 1950—1960).

The peak of *Synedra* spp. at approximately 1895 (40 cm depth) was caused by *S. ulna* var. *danica* (Kutz) Grunow, a typically planktonic form (Hustedt 1930). Other species of *Synedra* present were *S. rumpens* Kutzing, *S. rumpens* var. *familiaris* Kutzing, *S. acus* Kutzing and *S. delicatissima* Kutzing.

The increase of *Nitzschia* spp. during the last c. 20 years is maily dominated by *N. palea* (Kutz) W. Smith, a species which tolerates extremely enriched waters (Hustedt 1930, Cholonky 1968). Other species of this genera *N. acicularis* (Kutz.), W. Smith, *N. kutzingina* (Kutz.) W. Smith, and *N. holsatica* (Kutz.) W. Smith.

Asterionella formosa Hassal disappeared at the same time as *S. hantzschii* and *F. crotonensis* showed sudden increase at 25 cm depth (c. 1950). The last record of

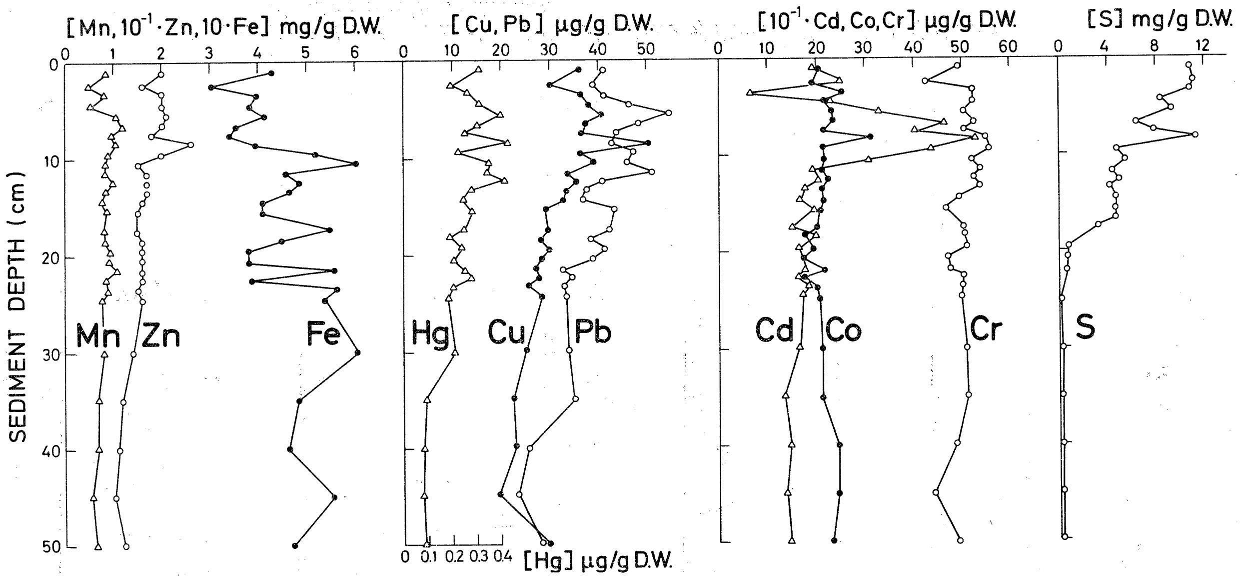

Fig. 3. *Vertical variation in some selected metals (Mn, Zn, Fe, Hg, Zn, Cu, Pb, Cd, Cr) and sulphur (S). All concentrations are given on the dry weight basis (D.W.).*

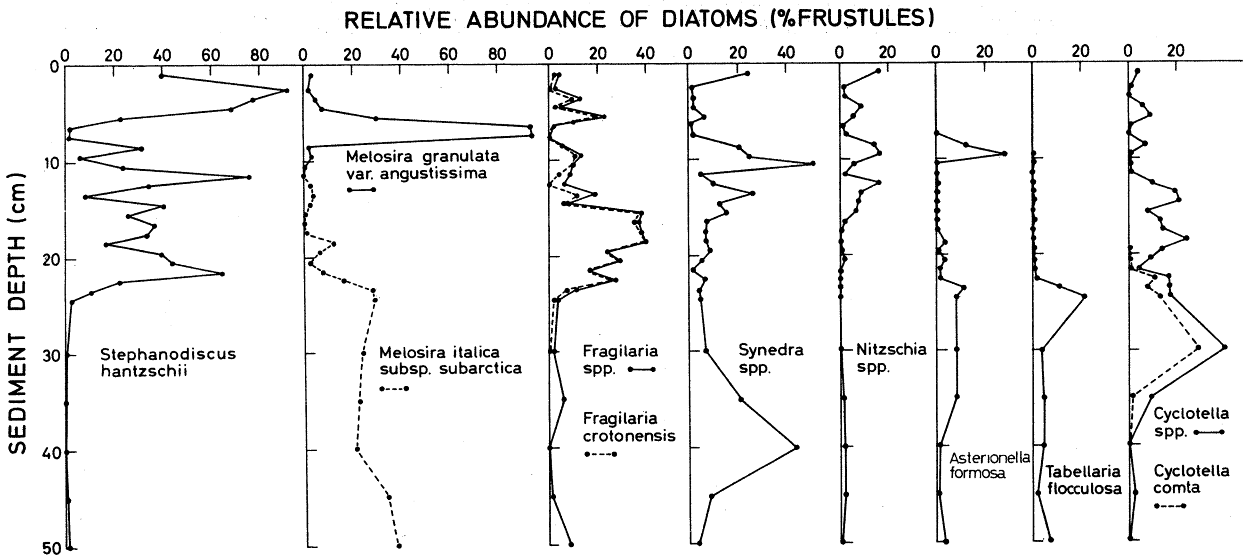

Fig. 4. *Vertical variation in the relative abundance of diatoms (frustules) of the most abundant planktonic diatoms.*

this species was the peak at 7—8 cm depth (c. 1965).

Tabellaria flocculosa (Roth) Kutzing, showed a similar trend as *A. formosa* and *M. italica* subsp. *subartica* and almost disappeared at 25 cm depth.

There is a peak of *Cyclotella comta* (Ehr.) Kutzing, at 30 cm depth, but above c. 20 cm depth this species is not recorded. The species found in the lower part of the core are mainly *C. comta, C. kutzingina* Thwaites and *C. stelligera* Cleve & Grunow. In the depth interval 10—20 cm (c. 1950—1965) the dominant species of this genus were *C. stelligera, C. pseudostelligera* Hustedt and *C. menhegiana* Kutzing. Above 10 cm depth (after 1965) *C. pseudostelligera* was the dominant *Cyclotella*-species.

Diversity index (H) is estimated by the Shannon's function (Shannon 1948):

$$H = - \sum_{i=1}^{i=s} (n_i/n \,.\, \ln (n_i/n)$$

where n_i is the number of individuals in the i-th species, n is the total number of individuals and s the number of species. A sudden drop in H may be observed (Fig. 2) at approximately 1950. More recently the diversity index oscillates, tending to lower values.

4. DISCUSSION

Presentation of the vertical patterns of a single parameter in a sediment core on dry a weight basis (Figs. 2 and 3) may lead to serious misinterpretations if the sedimentation rate varies (cf. Digerfeld 1972). In Table 1 the loading of various components to the sediments are given as mean values for three periods.

Table 1. *Average loading («net deposition») of dry material, organic carbon (C), total nitrogen (N), total phosphorus (P), amorphos silicate (Alk-Si), sulphur (S), sedimentary chlorophyll degradation products (SCDP, relative units, see text for explanation) and selected metals (Fe, Mn, Zn, Cu, Pb, Co, Cd, Hg) to the sediments at 13 m lake depth in Lake Årungen.*

Sediment depth interval	*Years*	*Dry material* gdw/m^2 · year	*C*	*N*	*P*	*Alk Si*	*S*	*SCDP* mu/m^2 · year	*Fe*	*Mn*	*Zn*	*Cu*	*Pb*	*Cr*	*Co*	*Cd*	*Hg*
			g/m^2 · year						g/m^2 · year			mg/m^2 · year					
0—20 cm	1955—1978	2620.0	103.9	12.3	4.85	29.8	12.43	40.0	111.4	2.17	0.43	85.1	108.0	128.2	93.6	5.88	0.67
20—30 »	1925—1955	1839.0	51.7	5.7	2.74	16.0	0.47	9.5	98.4	1.52	0.28	50.4	63.3	92.1	37.8	3.18	0.38
30—40 »	1895—1925	2079.1	51.7	5.6	2.47	12.8	0.14	5.5	117.1	1.80	0.27	52.7	71.4	111.5	46.6	3.24	0.25

The sedimentation rate of wet sediment during the mesotrophic period was relatively high (3.6 mm/year) due to the high percentage of agricultural areas in the drainage area leading to a relatively high level of inorganic erosion (mainly clay). The sedimentation of dry material during the period 1895—1955 was 1955 g/m^2 · year on average.

The sedimentaion of wet sediment during the last c. 25 years (uppermost 20 cm) was apparantly higher, 9.2 mm/year. However, if the water content of the sediment is taken into consideration the sedimentation rate of dry material during the period covered in the uppermost 20 cm of the sediment is only slightly higher (2620 g/m^2 · year) than below 20 cm depth.

It should be kept in mind that all discussions on sedimentaion rate in this paper refer to maximum lake depth which is not representative of the whole lake. This is shown in an earlier paper (Skogheim 1978a) on the sedimentation rate of copper in Lake Årungen as a function of lake depth. There are certain characteristic differences in vertical distribution of the various components. Organic carbon, total nitrogen, total phosphorous and diatom remains (Alk-Si) show an approximate doubling of the sedimentation relative to the mesotrophic period. There is a fivefold increase in the sedimentation of chlorophyll degradation products which may indicate the higher level of biomass of phytoplankton. However, this component is also very sensitive to enhanced conditions for preservation during the eutrophic/hypertrophic stage with an anaerob hypolimnion (Gorham and Sanger 1971). Consequently, evidence of eutrophication cannot be deduced solely on the basis of sedimentation of chlorophyll degradation products.

Gorham (1961) suggested that the pigment ratio E 410/E 350 rises with increasing lake fertility. As can be seen in Fig. 3 this ratio is significantly higher in the sediment layer deposited after c. 1950. This is in accordance with the increasing importance of autochthonous sources of organic matter during the eutrophication. However, factors as e.g. enhanced preservation of pigments and higher abundance of Cyanophyta may contribute to the change in the pigment ratio at c. 1950.

The continuous decrease in the C/N ratio during the eutrophication also suggests an increasing importance of autochthonous sources of organic matter, but as for pigments, an enhanced preservation during anaerobic conditions will reduce the indicative value of this ratio.

The most pronounced increase in sedimentation rate among the parameters is that of sulphur as sulphide which increased from hardly detectable values to approximately 12.4 gS/m^2 year. This is the most significant sign of the shift to an anaerobic metabolism in the sediments and hypolimnion during the eutrophication. The increase in the concentrations of the heavy metals Zn, Cu, Pb, Cd, Hg, and to a smaller extent Cr and Co may to some degree be explained by the precipitation of metal sulphides. However, the organic matter should also provide improved conditions for the retention of the metals during the eutrophic period. There is no increase in the sedimentation of iron. This metal is in excess, relative to sulphide in the lake sediments.

The sequence of diatom changes during the first three quarters of this century are rather straightforward concerning the appearance of species with various environmental demands compared with the trophic change of the lake ecosystem caused by the increase in external loading:

I The predominant change during the first quarter of the century was the increase in the abundance of planktonic species in relation to benthic species of genus *Navicula, Eunotia* and *Achnanthes.*

The period was dominated by *Melosira italica* subsp. *subarctica* a common species in mesothrophic and oligotrophic lakes. During this period there was a small but invariable abundance of «mesotrophic» species such as *Asterionella formosa* and *Tabellaria flocculosa,* and there was a peak of *Synedra ulna* var. *danica,* a planktonic species of circumneutral fresh waters (Patrick and Reimer 1966).

II The second quarter of this century may be characterized as a period of mesotrophy and eutrophication and is, with respect to diatoms, similar to the preceeding period, except for the presence of a pronounced maximum of *Cyclotella comta.* Both *A. formosa* and *T. flocculosa* were present, but they diminished suddenly at the end of the period together with *C. comta, S. ulna* var. *danica* and *M. italica* subsp. *subarctica.*

III The last period, the eutrophic/hypertrophic period, is very different from the previous one because of the reduction of a number of «mesotrophic» spesies at the transition of period II/III and the marked increase of *Stephanodiscus hantzschii.* At the same time there is a very pronounced increase in *Fragilaria crotonensis,* a species characteristic of high nutrient levels. Such shifts in species of diatoms have been experienced in several lakes undergoing trophic development. For example, Stockner and Benson (1967) reported an increase in *F. crotonensis* and a decrease in *M. italica* subsp. *subarctica* due to nutrient enrichment in Lake Washington. Stockner (1972) put forward the hypothesis that an increase of *A. formosa* appears to be related to agricultural influence, while an increase of *F. crotonensis* corresponds to sewage input to lakes. The observed shift in the diatom community at det passage of mesotrophy to eutrophy is very significant and agrees well with the known shift from a moderate agricultural/sewage loading to an increased agricultural loading and a very heavy sewage (untreated) loading from approximately 7000 persons. The extreme abundance of *M. granulata,* var. *angustissima* at approximately 1965, a species indicative of highly eutrophic habitats suggests the beginning of the hypertrophic period. *Nitzschia palea,* a species which tolerates extremely enriched water, also appears in the hypertrophic period.

Stockner (1972) developed a lake classification scheme for dimictic temperate lakes by means of the A/C-ratio (frustules of Araphidineae/frustules of Centrales). This ratio does not reflect the trophic change of Lake Årungen, primarily because of the sudden rise in abundance of the small centric *S. hantzschii* at c. 1950 and the later high abudance of this species. This confirms the findings of Brugam (1979) that *S. hantzschii* is more reliable indicator of eutrophication than the A/C-ratio, in particular in lakes with high surface concentrations of total phosphorous.

The diversity index H (Fig. 2) can be used with some caution to indicate the stability of the diatom community. A vertical pattern emerges: a) relative invariability in the diversity in the mesotrophic/eutrophic period until c. 1950, indicating a relatively high degree of stability in the diatom community, b) generally lower diversity and greater fluctuations in the topmost sediment representing the period after c. 1950. This indicates larger instability in the eutrophic/hypertrophic state.

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