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Palaeolimnological changes related to acid deposition and land-use in the catchments of two Norwegian soft-water lakes

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This is a palaeolimnological study of two Norwegian soft-water lakes, one receiving high, the other low, deposition of sulphur and nitrogen compounds. At the site with low acid deposition inferred pH has oscillated between 5.6 and 5.9 and there is little evidence of atmospheric contamination. At the site with high acid deposition, many centuries of stability are followed by a rapid acidification from pH around 5 in 1900 to the present (1986) level of pH 4.4. In this lake, the sedimentary record indicates a close connection between acid deposition and recent lake acidification.

Introduction

The objective of this study was to reconstruct the recent pH history of two lakes with similar catchments, one (Verevatn) subjected to high and the other (Röyrtjörna) to low deposition of sulphur and nitrogen compounds and to compare their histories in relation to acid deposition and land-use. Sedimentary concentrations of carbonaceous particles, trace metals, polycyclic aromatic hydrocarbons (PAH) and sulphur were recorded to assess the timing and magnitude of the deposition of airborne pollutants. Pollen analysis and documentary research were employed to study shifts in land-use. Analyses of sedimentary remains of chironomids, cladocerans, chrysophytes, and diatoms were used to document changes in lake acidity and lake history.

Both lakes have similar granitic, forested (*Picea abies* and *Pinus sylvestris*) catchments susceptible to acidification. However, Röyrtjörna is somewhat less sensitive to acid deposition as indicated by its higher calcium content. The distance between the lakes is *ca.* 730 km in a NNE–SSW direction. Verevatn (Aust-Agder) is located near Birkenes, an SNSF Experimental Catchment (established by the Norwegian research project 'Acid precipitation – effects on forest and fish'), and Röyrtjörna (Nord-Trøndelag) near a Surface Water Acidification Project (SWAP) experimental catchment. Further details about lake locations and other characteristics are given in Battarbee & Renberg (this symposium).

Methods

Both lakes were cored at the point of maximum lake depth by using freezing techniques (Renberg 1981) to retrieve the top *ca.* 30 cm of sediment; a Russian sampler was used for the deeper sediments. Details of analytical procedures are given in Stevenson *et al.* (1987). The sediment chronology is based on radiocarbon (Laboratoriet för isotopgeologi, Stockholm) and on ^{210}Pb dating (El-Daoushy, this symposium). Reconstructions of past lake pH from the fossil diatom assemblages were based on weighted averaging (Birks *et al.*, this symposium).

Results

(*a*) *Röyrtjörna*

Concentrations of spheroidal carbonaceous particles (SCP) can be used to detect geographical and temporal differences in deposition and to study deposition history (Wik & Natkanski, this symposium). In Röyrtjörna, particle concentrations are extremely low. No particles were detected below 6 cm in the sediment core. The maximum concentration of 1.6×10^3 particles gds^{-1} occurred at 1.5 cm from the sediment surface, corresponding to the early 1970s.

The concentration–depth profiles show that there is very little contamination by trace metals and no change in sulphur concentrations. Overall, the chemical results confirm that this site has received very little deposition of atmospheric contaminants.

Betula pollen and charcoal suggest the start of some human influence in the catchment of Röyrtjörna already at *ca.* 45 cm (H. I. Høeg, unpublished results). From 29 cm up to 5 cm there are definite pollen indications of land-use (*Rumex*, *Artemisia*, *Hordeum*, *Plantago lanceolata*, *Secale*, *Centaurea cyanus*). No primary land-use indicators were recorded in the top 4 cm of sediment.

The cladoceran remains show a stable community during the whole period. Acid sensitive planktonic *Daphnia* species were common in all samples, but the number of species was low compared with non-acid lakes in southern Norway. This may be related to climatic differences associated with latitude (J. P. Nilssen & S. Sandøy, unpublished results) rather than to differences in water quality.

The profiles of individual diatom taxa and of pH preference groups indicate small oscillations in lake acidity in the 75 cm long core. Diatom-based reconstructions of past pH indicate that the total range of the inferred pH values is 0.3 pH units from 5.6 to 5.9. The lack of recent acidification at this site is confirmed by the result of chrysophyte scale analysis (Cronberg, this symposium), which shows that the indifferent (= circumneutral) taxa *Mallomonas crassisquama* and *M. caudata* dominate the assemblage in the uppermost sediment (cf. Verevatn).

(*b*) *Verevatn*

The carbonaceous-particle profile begins with a 4 cm tail of low values followed by a marked increase at 7 cm. At 3 cm there is a distinct peak value of 59×10^3 particles gds^{-1}, which corresponds to the early 1970s.

The analyses show that this site is strongly contaminated by atmospheric pollutants. Lead contamination started earlier than zinc. Zinc increases around 11 cm depth and, although there is a small increase in lead at 17 cm, the main increase is at 13 cm. The sulphur and PAH profiles are similar to the trace metals, with the increase in concentration around 10 cm (Rippey, this symposium).

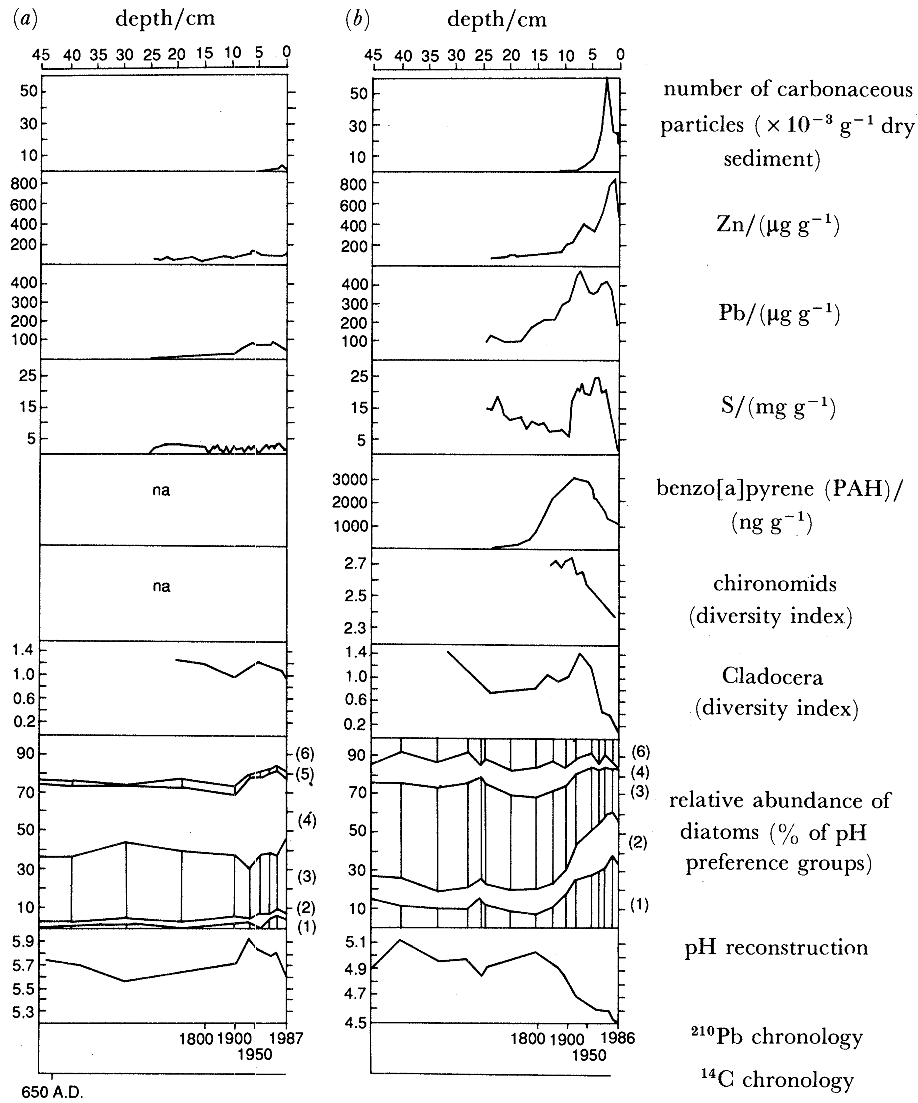

FIGURE 1. Stratigraphy of selected parameters from (*a*) Röyrtjörna and (*b*) Verevatn; na, not available; (1) acidobiontic, (2) acidobiontic/acidophilous, (3) acidophilous, (4) indifferent, (5) alkaliphilous, (6) unknown. Reconstruction of pH is from diatom-based estimates.

Pollen analysis indicates almost continuous agricultural land-use in the vicinity of Verevatn from 175 cm up to the sediment surface (H. I. Høeg, unpublished results). Above 37 cm there are indications of increased agricultural activity but the samples reflect considerable variation in intensity. The profiles of *Hordeum*, *Avena*, *Triticum*, and *Secale* suggest that the most intensive periods were from 21 cm to 15 cm and from 11 cm to 6 cm.

Documentary records show that the catchment contains no farms but certain areas were previously utilized as outlying fields. A study based on statistical records and interviews shows a sharp decline in the utilization of the outlying fields (used for the gathering of fodder and for grazing) during the period 1865–1985 (Timberlid 1990).

The chironomid stratigraphy encompassing the period from *ca.* 1800 to 1986 can be divided into three phases defined by differences in faunal stability, diversity, productivity, survival rate and species composition (Brodin, this symposium). Only the diversity index is shown here.

Phase I (*ca.* 15–7 cm, *ca.* 1800–*ca.* 1940) is characterized by environmental stability with no clear trends in the faunal parameters. Phase II (7–3 cm, *ca.* 1940–*ca.* 1975) represents severe acidification indicated by marked decreases in all measured parameters. Phase III (3–0 cm, *ca.* 1975–1986) reflects a stable continuation of the severe pH depression reached during the last part of Phase II.

Below about 6 cm the cladoceran analysis shows quite stable conditions with the acid sensitive *Daphnia longispina* present at all levels. But from 6 cm to the surface species number and diversity decrease markedly. The upper samples show a very poor planktonic community dominated by one species, *Bosmina longispina*. As in Lilla Öresjön (Renberg *et al.*, this symposium) the acidobiontic littoral cladoceran *Acantholeberis curvirostris* (Sandøy & Nilssen, this symposium) increased in abundance in the most recent sediment.

Chrysophyte analysis revealed major changes in species composition in the top *ca.* 5 cm of the core. Stable *Mallomonas crassisquama* dominance in the lower sediments is abruptly replaced by marked increases in the acid tolerant *Mallomonas lychenensis*, *M. canina*, *M. hamata*, and *Synura echinulata*.

The sedimentary diatom assemblages show little change from level to level in the lower part of the core. Most of the systematic shifts take place after *ca.* 1900 A.D. (10 cm) when a marked increase in the proportion of acidobiontic taxa starts. Although the stratigraphic shifts for each individual taxon are moderate it is evident from figure 1 that the total assemblage reflects a significant recent pH decline in Verevatn. Diatom-inferred pH values reflect the floristic changes by indicating stable conditions until about 1900 when pH started to decrease from pH 5 to 4.5 at the top of the core (1986). Measured lake pH in February 1986 was 4.4.

Discussion

The pattern in deposition of airborne pollutants in Norway is clearly reflected by the sedimentary concentrations of carbonaceous particles, trace metals, polycyclic aromatic hydrocarbons and sulphur in the two study lakes. Röyrtjörna, situated far from polluting sources, has very little contamination compared with that of Verevatn at Birkenes, which is an area of maximum deposition of sulphur in Norway (Dovland *et al.* 1976) and a region with many acidified lakes (Henriksen *et al.* 1988).

For both lakes there is good agreement between the ecological inferences from the sediment stratigraphy of chironomids, cladocerans, chrysophytes and diatoms. There are only minor faunal and floristic shifts within the Röyrtjörna core indicating stable ecological conditions during the period under study. The diatom-based pH reconstructions reveal minor oscillations within a range of 0.3 pH units, but no consistent trend. This pattern in the pH estimates may be related more to pollen-inferred land-use changes than to acid deposition, which is very low at this site. The pH estimates increase during the most intensive land-use period. The succeeding decrease, starting around 1900 A.D., may reflect a trend back to pH conditions that prevailed before the onset of notable land-use.

At Verevatn the biostratigraphy of chironomids, cladocerans, chrysophytes and diatoms indicates stable conditions until shortly after 1900 A.D. Since then, there has been a rapid decrease in the pH of the lake to the present level, which is markedly lower than any estimate of past pH. At Verevatn there is no systematic relation between pollen-inferred shifts in land-use and reconstructed lake pH. In this lake there is a striking similarity between the sediment profiles of air pollutants and biological remains. The pH-related biological changes show a slight time lag relative to the onset of air pollution as recorded in the sediments. The same stratigraphic pattern in air pollution and environmental change has been reported from several other lakes in this geographical region (Berge 1979, 1985; Davis & Berge 1980) including hill-top lakes with virtually no catchments and hence no influence from past or present land-use (Birks *et al.*, this symposium).

The available palaeolimnological evidence thus points to acid deposition as the most likely cause for the recent rapid acidification of Verevatn, a site typical of other acidified soft-water lakes in southernmost Norway.

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