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Devoke Water and Loch Sionascaig: recent environmental changes and the post-glacial overview

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Diatoms from postglacial sediments of two oligotrophic lakes, one in northwest England and one in northwest Scotland, have been examined. Apart from the decline of alkalinity in the early post-glacial period at both sites, the only evidence for further increase in acidity occurs in the post-1900 sediments of Devoke Water (Cumbria). There has been no such change in Loch Sionascaig, in a region of lower acid deposition in northwest Scotland.

Introduction

The aquatic ecosystem is a reflection of the state of both the terrestrial and atmospheric environment, with catchment soils (where sufficient) intervening as buffers or ion-exchange mechanisms. The state of the lakes is therefore indicative of wider environmental conditions. Within the last *ca.* 150 years, there have been considerable changes to many of the lakes in the U.K., Scandinavia and elsewhere (Johnson 1982). Many considered as oligotrophic, undisturbed systems have recently become more acidic and no longer support certain plants and animals, especially fish.

Recent changes in many lakes that apparently result from increasing air pollution have to be considered within the context of the long-term changes in post-glacial history as a whole, to observe which has the greater influence and to assess the likelihood of lake recovery. We have made an analysis of the most recent sediments of two oligotrophic lakes for which earlier post-glacial records were already available, Devoke Water (Evans 1961) and Loch Sionascaig (Pennington *et al.* 1972), and have compared the modern rates and extent of change with previous changes.

Methods

Cores of the upper 1 m of sediment were collected from Devoke Water, in 1985, and Loch Sionascaig, in 1986, by using a Mackereth minicorer. These were collected from the mid-lake area in 9 m, and towards the eastern end in 21 m of water, respectively. Site locations and characteristics are given in Battarbee & Renberg (this symposium).

Radio-isotope analyses were done by Appleby *et al.* (this symposium) and diatom analysis has followed the methods in Haworth (1984). The nomenclature follows Hartley (1986) and Surface Water Acidification Project (SWAP) guidelines (Munro *et al.*, this symposium). A more detailed methodology appears in Haworth and Atkinson (in preparation).

Material for the long-core studies by Evans (1961) and Haworth (Pennington *et al.* 1972) was collected by using the 6 m Mackereth corer. Despite problems of sampling the upper sediment by using this corer, and the incomplete description of methods, the stratigraphy outlined by Evans clearly includes these upper sediments; 20 cm was assumed lost from the top

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of the Loch Sionascaig core. In figures 1 and 2, sample levels in the upper 1 m have been adjusted to match with the later minicores. Evans' diatom counts were expressed as concentrations per mg dry mass of sample and his data have been recalculated as percentages (figure 1). His pH classifications have been changed here to conform with SWAP guidelines and units. The pH categories are as used in our investigation of the 1986 minicore.

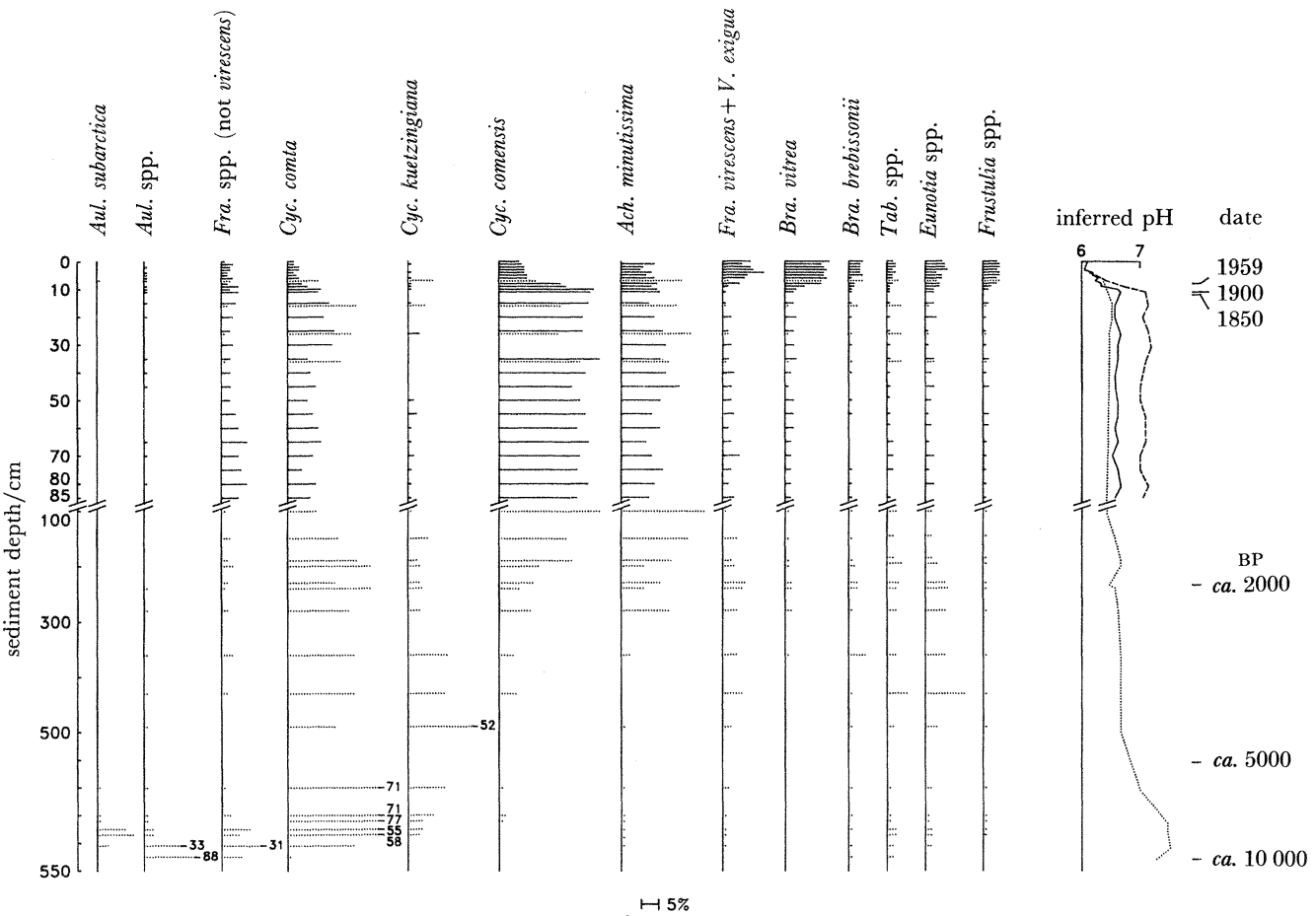

FIGURE 1. Devoke Water. Percentages of major diatom taxa and the inferred pH with the recent minicore (0–85 cm) superimposed upon a recalculation of the 1959 profile of the whole Post-glacial. Depths below 90 cm relate to long-core stratigraphy, whereas those above 90 cm relate to minicore stratigraphy and long-core samples have been adjusted accordingly. Diatoms: (.....), 1959 long core and (—), 1985 minicore. Inferred pH: (.....), Index B calculation of 1959 profile and (—), Index B calculation of 1985 profile; (------), weighted averaging of 1985 profile. Dates according to ^{210}Pb and ^{14}C. (*Aul.*, *Aulacoseira*; *Fra.*, *Fragilaria*; *Cyc.*, *Cyclotella*; *Ach.*, *Achnanthes*; *Bra.*, *Brachysira*; *Tab.*, *Tabellaria*.)

RESULTS

Devoke Water is an oligotrophic lake in a glacial hollow on the western fells of Cumbria, close to the coast; this raises the salt content slightly whereas alkalinity is low (table 1). Pennington (1964, 1984) showed that the now treeless catchment supported woodland until clearances by Bronze Age and subsequent farmers. The sharp rise in *Calluna* pollen, together with an increase in the iodine:carbon ratio is interpreted, by her, as the increased input of humus during the Romano-British period. Soil erosion was such that there was a tenfold increase in sediment accumulation above the Elm Decline. Evans (1961) found a high proportion of alkaliphilous

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Table 1. Characteristics of Devoke Water, southwest Cumbria and Loch Sionascaig, northwest Scotland

lake	Devoke Water	Loch Sionascaig
grid reference	SD 163972	NC 120140
altitude/m	233	73
length/km	1.2	4.8
surface area/ha[a]	34	517
drainage area/ha[a]	305	4000
maximum depth/m	14	66
mean depth/m	4	18.5
distance from the sea/km	8.5	4.0
local geology	Borrowdale volcanics and granite	Lewisian gneiss Torridonian sandstone
vegetation	rough grass and bracken	blanket bog and deer grass
soils	shallow and peaty	peat
sodium/(μeq l^{-1})	231	363
calcium/(μeq l^{-1})	108	73
magnesium/(μeq l^{-1})	79	101
potassium/(μeq l^{-1})	10	14
chloride/(μeq l^{-1})	272	433
sulphate/(μeq l^{-1})	111	71
nitrate/(μeq l^{-1})	15	4
alkalinity/(μeq l^{-1})	< 50	50–100
pH	6.3	6.6

[a] 1 ha = 10^4 m^2.

taxa in the immediate post-glacial sediment (table 2, figure 1), mainly *Melosira* (*Aulacoseira*) and *Fragilaria* spp., and suggested that there had been a pH of about 7.0. These taxa declined *ca.* 5000 BP and again just above the horizon that Pennington (1964) ascribes to the Romano–British period. *Cyclotella kuetzingiana* and *C. comta* are abundant throughout the early post-glacial period and circumneutral (= indifferent) diatoms, such as *C. comensis* and *Achnanthes minutissima*, increased steadily in the latter part of the Post-glacial, as in other Cumbrian lakes (Haworth 1985). Evans found little change in the upper part of the core except for some increase in acidic taxa at the surface. Our Index B inferred pH profile (Renberg & Hellberg 1982) of the 1959 core data suggests that the pH of lake water in the immediate Postglacial was about 7.7 but that this declined during the next 5000 years, to pH about 6.7. There was a further drop to 6.5 (figure 1) and then 6.4 in the upper sample, close to the measured pH of 6.3 in 1959.

The close interval analysis of the 1985 1 m core shows that there was little change in diatom percentages below 12 cm with circumneutral taxa dominant, especially *Cyclotella comensis*, *C. comta* and *Achnanthes minutissima* (figure 1). A significant percentage of alkaliphilous taxa was present throughout the profile, e.g. *Fragilaria*, *Nitzschia* and *Asterionella* spp. but this declined, above 12 cm, where more acidic taxa such as *Brachysira vitrea* and *Fragilaria virescens* increase by 20% (table 2, figure 1). The profile inferred from Index B shows that the earlier pH was about 6.6 but there has been a slight but distinct decrease to about 6.35 above 10 cm. The similar calculation based upon the weighted averages of each taxon according to the SWAP calibration set (Birks *et al.*, this symposium) produces a similar profile but infers a higher pH of about 7.0 below 10 cm, where the *Cyclotella* percentage is markedly higher. ^{210}Pb dating identifies the 1959 horizon at 7.5 cm, which has an inferred pH of 6.3, the same as measurements at that time. The pH declined to 6.1 above this. The ^{210}Pb profile of this core suggests a

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discontinuity at 9 cm with a loss of a section representing up to 50 years, or about 9 cm; calculations to date the profile (figure 1) have therefore been made with reference to ^{137}Cs and ^{241}Am analyses (Appleby *et al.*, this symposium). The pH decline at 10 cm is estimated at about 1900, whereas 9 cm is dated as 1954.

Loch Sionascaig is a large, irregularly shaped lake on the coastal foreland of northwest Scotland, surrounded by bare rock and peatbog. Here, as in Devoke, there is a high NaCl content (table 1). Pennington *et al.* (1972) found that the sedimentary record differed from other U.K. sites in that there was a very gradual transition between the late-glacial and Post-glacial. This study also indicated early peat formation and the decline of the local pine forest at *ca.* 4000 BP.

The diatom assemblages of the core from this site reflect these changes (figure 2) as alkaline taxa declined, and circumneutral ones increased, well before 8500 BP (table 2), which is earlier than elsewhere in the U.K. (Haworth 1985). This change also predates the maximum extension of birch–hazel woodland but coincides with the base of the *Calluna* and *Sphagnum* profiles signifying the onset of peat formation. *Cyclotella comensis*, *C. kuetzingiana* and *Achnanthes minutissima* predominate thereafter, *C. kuetzingiana* increasing as *A. minutissima* decreases. *Aulacoseira* spp. are best represented at the time of the Elm Decline and the expansion of peat. The dominant form, *A. subarctica*, may be up to 5% of the sample between 8500 BP and the present, especially between 6000 and 4000 BP. The diatom-inferred pH declined from more than 7.7 at 10000 BP to less than 6.5 about 8000 BP with little further change, even at the pine decline (Pennington *et al.* 1972). This emphasizes the rapid decline in alkaliphilous taxa at the end of the late-glacial. Although percentages of acidic taxa increased, with a maximum of about 20% at the level of peat expansion at *ca.* 4000 BP, there has been no recent increase in these taxa.

TABLE 2. THE pH-RELATED DIATOM SPECTRUM FROM THREE LEVELS OF POST-GLACIAL LAKE SEDIMENT, SHOWING THE DECLINE IN ALKALIPHILOUS TAXA SINCE THE END OF THE LATE-GLACIAL PERIOD AND THE HIGH PERCENTAGE OF ACIDOPHILOUS TAXA AT THE SURFACE OF DEVOKE WATER

(Depth, below sediment surface; alkb., alkalibiontic; alkf., alkaliphilous; ind., indifferent (= circumneutral); acf., acidophilous; acb., acidobiontic.)

		pH categories/(%)					
	depth/cm	alkb	alkf	ind	acf	acb	date
Devoke Water	0	0	10.6	52.0	26.6	0	1985 A.D.
	85	0	27.6	54.4	5.2	0	*ca.* 1000 BP
	540	2.7	71.5	14.8	4.1	0	*ca.* 10000 BP
Loch Sionascaig	0	0	2.6	78.3	6.6	0.3	1986 A.D.
	80	0.2	5.4	80.4	10.4	0	*ca.* 1000 BP
	540	1.3	61.3	25.7	3.0	0	*ca.* 10000 BP

The diatom profile of the upper 1 m of sediment, collected in 1986, is dominated by *Cyclotella* spp. (figure 2), together with *Achnanthes* and *Brachysira* spp. There is little evidence of change in the upper part; since 1900, *Achnanthes minutissima* and *Aulacoseira distans* var. *tenella* declined and *C. glomerata* and *Stephanodiscus minutulus* (not shown) occurred more consistently and *A. subarctica* increased very recently. There is certainly no equivalent of the increase in acidic taxa found in other, upland sites (Battarbee *et al.* 1988) as the pH spectrum illustrates the

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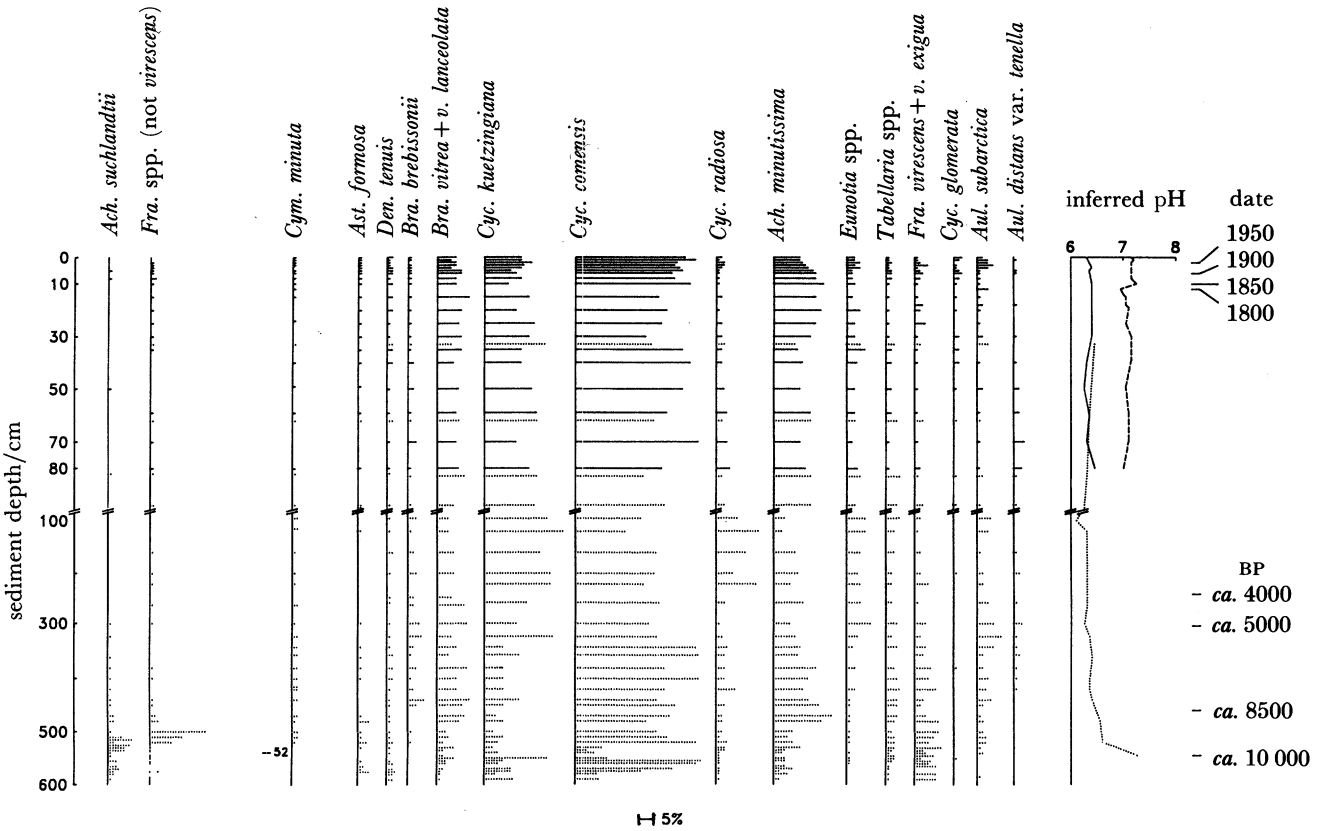

FIGURE 2. Loch Sionascaig. Percentages of major diatom taxa and the inferred pH with the recent minicore (0–80 cm) superimposed on the 1967 Post-glacial profile. Depths below 90 cm relate to the long-core stratigraphy, whereas those above relate to the minicore and the long-core samples have been adjusted accordingly. Diatoms: (.....), 1967 long-core and (—), 1986 minicore. Inferred pH: (.....), Index B calculation of 1967 profile; (—), Index B calculation of 1986 profile; (------), weighted averaging of 1986 profile. Dates according to ^{210}Pb and ^{14}C. (*Cym.*, *Cymbella*; *Ast.*, *Asterionella*; *Den.*, *Denticula*; *Aul.*, *Aulacoseira*; *Cyc.*, *Cyclotella*; *Ach.*, *Achnanthes*; *Fra.*, *Fragilaria*.)

dominance of circumneutral taxa and the low percentage of acidic taxa. The Index B inferred pH varies between 6.2 and 6.4 throughout (figure 2). Alternatively, inferred pH values by using weighted averaging suggest a higher pH of about 7.1. This difference is currently difficult to explain as the measured pH is about 6.6; there may be a bias as the site is at the upper pH limit of lakes studied or there may be a greater degree of variation in pH at higher levels (W. Davison, personal communication).

CONCLUSIONS

Diatom changes indicate that alkaliphilous taxa declined during the immediate Postglacial period, the pH of the lakes becoming stable around 6.5 before 8500 BP in Loch Sionascaig and by 5000 BP in Devoke Water, there being better forest soils on the catchment of the latter.

Diatoms indicate that pH levels of both lakes (figures 1 and 2) have remained circumneutral even to the present day, with floras changing very little. Only in Devoke is there any recent change in floristic composition, with a significant 20% increase in acidic taxa; in Sionascaig, the changes are much less obvious. The inferred pH profile of recent sediments indicates that there has been no change in the acidity of Sionascaig as this has retained a pH of 6.2–6.4. In

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Devoke, however, there has been a distinct decrease in pH from 6.6 to 6.1 (according to Index B) since 1900 and there is a present measured mean of 6.3 (table 1).

Weighted Averaging (WA) (Birks *et al.*, this symposium) suggests a rather larger decline in Devoke, from 7.2 to 6.1. It also suggests that Sionascaig has always remained at about pH 7.1. The greatest difference between the two methods of pH calculation coincides with the dominance of *Cyclotella* in the profiles and, in Sionascaig, WA would appear to overestimate pH as all measured values are pH 6.6. As there is no good analogue in the dataset and Index B appears a closer estimate, WA has been set aside until the relevant taxa in the calibration data can be reviewed.

Devoke has clearly been more affected by acidity. It lies in an area where sulphur deposition is nearly ten times that at Loch Sionascaig (Battarbee & Renberg, this symposium); alkalinity is currently just below 50 μeq l^{-1} and any further decrease would accelerate the pH decline, as has been suggested by Sutcliffe & Carrick (1988). The present water quality is similar to that inferred for Scoat Tarn, in nearby Wasdale, before the industrial period (Haworth *et al.* 1987) when the diatom flora of the latter was also dominated by *Cyclotella* plankton. In Scoat Tarn, acid deposition has reduced the pH to less than 5.0 with considerable changes in taxa, whereas the decline from 6.6 to 6.1 in Devoke Water has proved less of a threshold. Even though acid deposition is similar at these two Cumbrian sites, there are differences in catchment sizes and soils and the Ca^{2+} level (table 1) shows Devoke Water to be a less sensitive site. In waters of this more neutral pH, there is also greater variability in the pH as it is less systematically related to alkalinity because of the fluctuations in CO_2; an annual variation of 1.0 unit is common. This variability applies also to Loch Sionascaig and so could explain the gap between the two pH calculations.

Post-glacial profiles show that Devoke Water has always been less sensitive to acidity than the more upland lakes (Haworth *et al.* 1987), as have other lowland Cumbrian lakes (Haworth 1985); Loch Sionascaig too started with better alkalinity and, although this was quickly lost, the lake is less sensitive than many other Scottish sites (Battarbee *et al.* 1988; Battarbee & Renberg, this symposium).

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