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Variability of sediment diatom assemblages in an upland, wind-stressed lake (Loch Fleet, Galloway, S.W. Scotland)

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Abstract

The variability of diatom distribution in an acidified, upland wind-stressed lake (Loch Fleet, Galloway, S.W. Scotland) was assessed by analysis of 28 surface sediment samples and 11 cores. Correspondence analysis (CA) and cluster analysis were used to illustrate the variability of the surface sediment and core samples. There was reasonable uniformity of taxa in most of the surface sediment samples, although 7 samples, as indicated by both CA and cluster analyses were atypical. Most cores recorded clearly the acidification of the lake, although percentages of individual taxa varied up to 20% between cores. Two cores had old, preacidification diatom assemblages (of indeterminate age) close to the sediment surface. These old sediments were probably the source of the re-worked diatoms found in the atypical surface sediment assemblages. Diatom trends, as CA ordinations and pH profiles, were less variable than the surface sediment assemblages. It is argued that non-uniform sediment accumulation rates and diatom deposition cause variability in surface sediment diatom samples. This variability may be reduced in core profiles by homogenization during further resuspension/deposition cycles and burial. Cores, and the associated time component they offer, may be useful in assessing the variability of surface sediment assemblages.

Introduction

Most palaeoecological studies are based on a single core taken from the deepest part of a lake and assume that deposition in such areas is conformable and representative. However, the complexity of diatom deposition in lake basins is being increasingly recognised as a result of a number of multicore studies (Battarbee, 1978; Dixit & Evans, 1986; Anderson, 1986, 1990). Attempts to understand causal processes are hindered by the restricted range of lake types studied to date. Therefore, the analysis of diverse sets of lakes offers the opportunity to expand our understanding of diatom deposition. Because of the need for spatial coverage or proximity to monitored catchments, acidification studies have incorporated lakes that would not normally be considered for palaeoecological work (e.g. Battarbee *et al.*, 1988a).

Diatom-based palaeoecological studies generally use relative frequency data, and to a lesser extent, accumulation rates. Percentage data can be misleading due to closure problems, but varia-

bility of sediment deposition has greater influence on quantitative data (Battarbee, 1978; Anderson, 1990). Sediment assemblages consist of a mixture of extant communities living in the lake (Battarbee, 1986), reworked diatoms from the last few years (the importance of which will vary in relation to sediment accumulation rate and the thickness of the sediment sample being used), and to a lesser extent erosion and redeposition of old diatoms (Haworth, 1972), or inwash of diatoms from the catchment (Battarbee & Flower, 1985). Reworking of diatoms as part of sediment resuspension-deposition cycles in lakes has been highlighted, in part, by the occurrence of planktonic diatoms (e.g. *Cyclotella*), albeit at greatly reduced values, at the surface of sediment cores taken from acidified lakes (Charles, 1984; Renberg & Wallín, 1985; Flower *et al.*, 1987). Contamination is suggested because these planktonic diatoms have long since ceased to be part of the lake's diatom flora, as indicated by contemporary monitoring (e.g. Lydén & Grahn, 1985). This problem has severe implications for the calculation of diatom-based environmental indices, if re-worked diatoms are a major component of the sedimentary assemblage.

This paper presents percentages, concentrations, and accumulation rates for surface sediment samples and short cores from an upland wind-stressed lake with complex sediment distribution in Galloway (S.W. Scotland). It demonstrates how quantitative data can be used to complement qualitative data in assessing the variability of sedimentary diatom assemblages, and their reworking within the basin.

Study site

Loch Fleet was an acidic lake, situated at 340 m asl on the Cairnsmore of Fleet, a granitic intrusion (grid reference: NX 560695). In 1985 the lake had a mean pH of 4.5, which was subsequently raised to ca. 7, immediately after liming (Howells, 1986). Further details of the catchment and lake chemistry are given in Howells (1986). The lake has an area of 17.1 ha, maximum depth of 16.5 m (mean

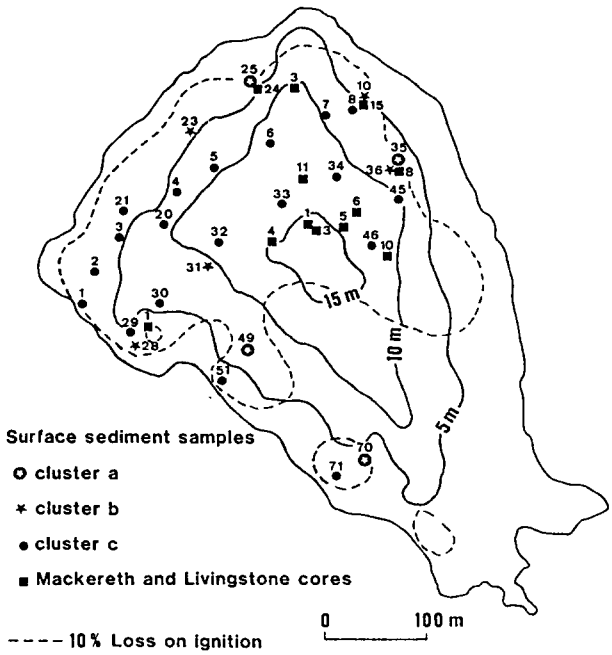

Fig. 1. Locations of Mackereth and Livingstone cores, together with the Kajak surface sediment samples. The different groups in the latter are based on a cluster analysis (see text & Fig. 10). Basin bathymetry and the limit of organic deposition as determined by loss-on-ignition are indicated (Anderson & Battarbee, 1985).

6 m) (Fig. 1), and retention time ca. 0.5 yr. The lake's catchment area is 110 ha, of which 10% is afforested with Sitka Spruce (*Picea sitchensis* (Bong.) Carriere). Sediment distribution is asymmetric, with organic sediments confined to the NW end of the lake (Anderson & Battarbee, 1985), and maximum sediment accumulation occurs at core L3, in ca. 8 m water depth, off the inflow stream (Fig. 1; cf. Anderson *et al.*, 1986). Sediment accumulation in the deepest part of the lake is minimal and complicated by a number of hiatuses (Anderson *et al.*, 1986). Many of the Galloway lakes have complex sediment distribution patterns as a result of their situation on exposed hillsides at high altitude, and the recent problem of catchment disturbance effects, notably ploughing for afforestation.

At Loch Fleet the composition of the recent sediments reflect the ploughing of the catchment in 1960–1 prior to afforestation, and consist of a

major increase in organic matter, mainly eroded peat from the ploughed SW part of the catchment. ^{210}Pb dating confirms that the lake's acidification, as recorded by the diatoms, occurred after this event, a rapid pH decline starting ca. 1972 (Anderson *et al.*, 1986).

Galloway (S.W. Scotland) lakes have been the subject of detailed biological and chemical monitoring (e.g. Harriman *et al.*, 1987), and palaeoecological research (Flower & Battarbee, 1985; Flower *et al.*, 1987; Jones *et al.*, 1989), because it was realised that the area was affected by atmospheric pollution. Loch Fleet has been the site of a project to assess catchment liming, as a means of ameliorating lake acidification (Howells, 1986). A preliminary core taken in May 1981 from 14 m water depth as part of a Central Electricity Generating Broad (CEGB) funded survey of lake acidification (Flower *et al.*, 1987), proved to have complex sediment stratigraphy inappropriate for ^{210}Pb dating, and so the project was temporarily abandoned. When the lake was chosen as the site of a CEGB liming programme (Howells, 1986), however, further sediment based work was initiated (Anderson & Battarbee, 1985). Attempts to reconstruct Loch Fleet's recent pH history, as a baseline for the current monitoring of the lake, involved assessing the sediment distribution and the variability of the diatom biostratigraphic record (Anderson & Battarbee, 1985; Howells, 1986).

Methods

To assess the variability of diatom assemblages, 28 surface sediment samples were taken in May 1984 with a modified Kajak corer (Brinkhurst *et al.*, 1969) (Fig. 1). The top ca. 1 cm section was extruded and stored in plastic bags. Twelve Mackereth cores (Mackereth, 1969) were also taken. The spatial coverage of both surface sediment samples and cores is limited because of the restricted organic sediment distribution within the lake. To obtain sufficient sediment for a variety of chemical and biological analyses a modified, wide diameter Livingstone core was taken in May 1984, at a site assumed to provide a full stratigraphic record of the lake's acidification. ^{210}Pb analyses indicated that this core (L1) was unsuitable for further analysis, due to complex ^{210}Pb distribution below ca. 50 cm, thus diatom stratigraphy of the surface to 40 cm depth only is presented here. In July 1985 another Livingstone core (L3) was taken and dated successfully using ^{210}Pb (Anderson *et al.*, 1986). All cores were accurately located using shore-based surveying equipment. Mackereth and Livingstone cores were extruded vertically in the laboratory. Dry weight, wet density and loss-on-ignition analyses were made on all levels using standard methods (Dean, 1974).

Diatom analysis followed standard methods (Battarbee, 1986), and concentrations determined using the microsphere method (Battarbee & Kneen, 1982). Repeatability of the technique is good, (coefficient of variation $< 15\%$, Anderson, 1990). Diatom inferred pH was estimated using multiple regression of preference categories (Flower, 1986). Nomenclature follows Hartley (1986) unless stated otherwise.

Multivariate methods were used to analyse the percentage data and objectively assess trends in the data. An agglomerative hierarchial cluster analysis was performed on the surface sediment assemblages using a chord distance coefficient. Correspondence analysis (CA) was done on the combined surface sediment and Mackereth core data. For both analyses only those taxa with $> 2\%$ occurrence in any one sample were used. Although it is usual to create joint plots (i.e. combined ordinations of species and samples) when using CA (Gordon, 1982), this was not done here for reasons of clarity. The rationale for the use of these techniques in palaeolimnology is well established (Birks, 1987).

For the purpose of comparing between core variability of diatom concentrations and accumulation rates only one biostratigraphic feature was identified, the decline of *Brachysira vitrea*, which dates to ca. 1976 in core L3 (Anderson *et al.*, 1986). Mean diatom concentrations within this zone were converted to an accumulation rate using the calculated mean dry mass accumulation

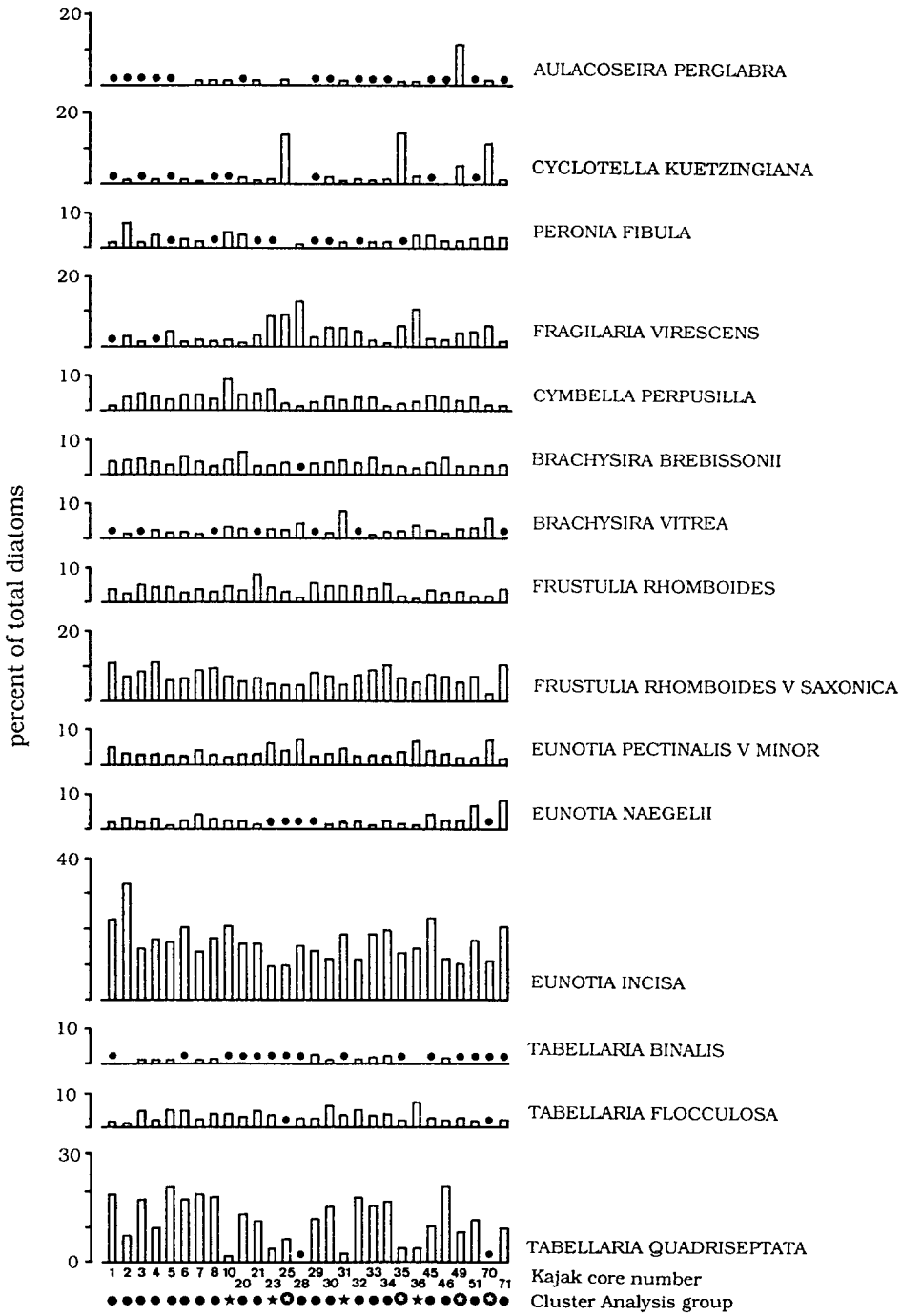

Fig. 2. Diatom summary diagram for the Kajak surface sediment samples (expressed as percentage of total diatoms). • represents $<0.5\%$. X-axis symbols relate to cluster analysis groups (see Fig. 10).

rate for individual cores and a mean for all cores calculated.

Results

Surface sediment samples

i. percentages (Fig. 2)

There is reasonable floristic similarity between samples, with repeatability of percentages for many taxa, values varying by $<10\%$ between samples (e.g. *Tabellaria flocculosa*, *Frustulia rhombodies* var. *saxonica* (mean 7.27%, range 2.3–11.3%). However, some taxa show greater variability, especially *Tabellaria quadriseptata* (4 samples $<2\%$, mean 11.6%), *Eunotia incisa* (mean 16.3%, range 9.5–32.5%), *Cyclotella kuetzingiana* (3 samples $>10\%$, maximum 14.8%, mean 2.6%) and a localised occurrence of *Aulacoseria perglabra* (9% in sample 49). Samples 51 and 71 have higher than average values of *Eunotia naegelii* (mean 2.2%, range 0.4–8.1%). There is no apparent spatial pattern in the distribution of the anomalous samples (Fig. 1).

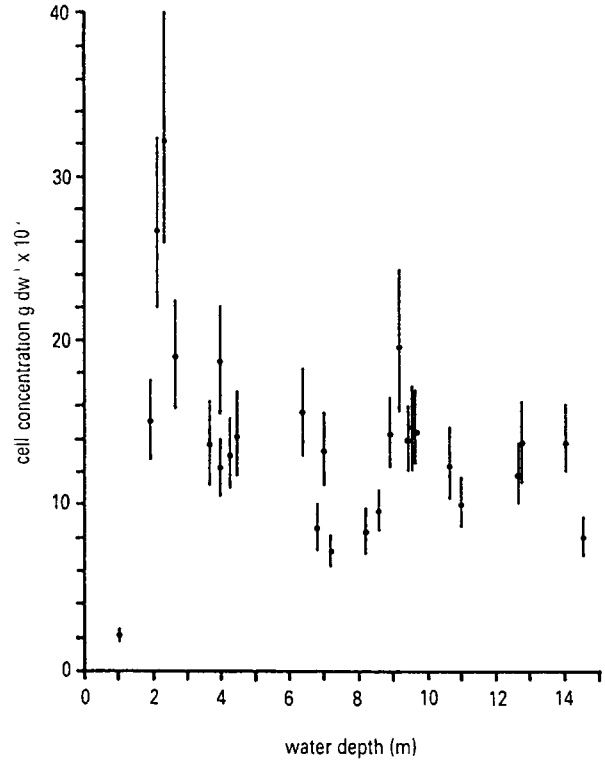

Fig. 3. Diatom concentrations for Kajak core surface sediment samples ($\times 10^7$ g DW^{-1}).

ii. concentrations (Fig. 3)

Cell concentrations are variable, ranging from maxima of 26 and 32 $\times 10^7$ cells g dry weight $(DW)^{-1}$ in samples 70 and 28 respectively to a minimum of 2 $\times 10^7$ cells g DW^{-1} in sample 1. Mean concentration is 13.76, and correcting these values for in bulk density increases the variation (Table 2). Cell concentrations show no relation-

Table 1. Summary diatom concentration data expressed as cells g dry weight $(DW)^{-1}$ and cm^{-3} for depths 0–1 cm and 1–2 cm.

a. $\times 10^7$ gDW^{-1}										
core cm	M1	M3	M4	M5	M6	M10	M11	M15	M24	L1
0–1	11.5	14.7	10.2	9.4	16.2	18.5	9.8	13.4	14.3	7.1
1–2	13.5	8.4	° #	8.8	19.2	11.9	12.2	22.8	19.6	12.8
b. $\times 10^6$ cm^{-3}										
core cm	M1	M3	M4	M5	M6	M10	M11	M15	M24	L1
0–1	3.2	6.2	6.0	6.4	6.8	9.3	9.1	7.0	5.6	6.2
1–2	9.0	6.0	° #	12.4	15.8	9.7	12.2	18.2	14.7	14.3

not included because of its atypical composition

Table 2. Comparative mean concentrations (both gDW^{-1} and cm^{-3}) of all cores ($n = 11$) and surface sediment samples ($n = 27$). Mackereth core means were calculated on a 0–1 cm and 0–2 cm basis because of the possible influence of variable water content in the surface layer, and to allow for possible variable recovery between the Mackereth and Kajak corers. Coefficient of variation (%) in parentheses.

Cores	$\times 10^7$ gDW^{-1}	$\times 10^6$ cm^{-3}
0–1 cm	12.5 ± 3.5 (28%)	6.6 ± 1.7 (26%)
0–2 cm	13.6 ± 4.4 (32%)	9.6 ± 4.2[=] (45%)
Kajak samples (0–1 cm)	13.8 ± 5.8 (42%)	13.2 ± 13.6 (103%)

[=] excludes M4 0–2 cm samples

ship to water depth, except that the three atypical samples (numbers 1, 28, 70) are situated in < 3 m water depth.

iii. pH reconstructions (Fig. 4)

The variability of diatom assemblages results in a comparable variability of reconstructed pH. Some samples have a reconstructed pH (multiple regression (MR) of preference groups) as high as 5.7, due to the low occurrence of acidobiontic taxa (e.g. *Tabellaria quadriseptata*). Sixteen samples have reconstructed pH 5.0 or below, but the median reconstructed value (5.0) is higher than the measured mean value (4.5).

Sediment cores

i. percentages (Figs 5 & 6)

Most cores (M3, M5, M6, M11, M24, and M1 above 25–26 cm) have repeatable species trends (Fig. 5 & 6), although dry mass accumulation rates differ (Table 3). Sequential declines of *Achnanthes minutissima*, *Fragilaria virescens*, and *Brachysira vitrea* are followed by a major increase in *Eunotia incisa*, with slight increases of *Frustulia rhomboides* and *F. rhomboides* var. *saxonica*. *Cymbella perpusilla* and *Peronia fibula* increase temporarily, and decline towards core surfaces as *Tabellaria quadriseptata*, *T. binalis*, *Eunotia naegelii*, *Fragilaria* cf. *oldenburgiana*, *Navicula cumbriensis* Haworth, and *N. cumbriensis* var. 1 increase. Despite repeatable trends, percentages vary between cores for different species. For example, maximum percentages of *T. quadriseptata* in the core tops vary from ca. 15–16% in M24 and M10, to > 35% in M11. Similarly, maxima of *Achnanthes minutissima* and *B. vitrea* vary prior to their decline (Fig. 5). *Eunotia incisa* maxima reach ca. 30% in most cores but only ca. 15% in M24. Between core profiles for this taxon show better repeatability than others. In general, cores M15, M10, and M24 are slightly different compared to others. M10 and M15 lack the characteristic stepwise increase in *Tabellaria quadriseptata*, values increasing to ca. 20% over

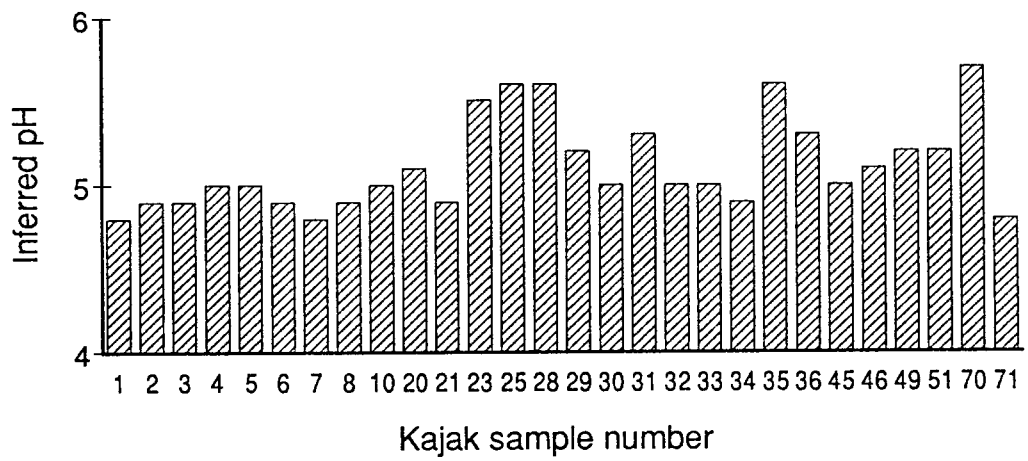

Fig. 4. Reconstructed pH for Kajak core surface sediment samples, using Index B (Galloway) and Multiple regression of pH groups (Flower, 1986).

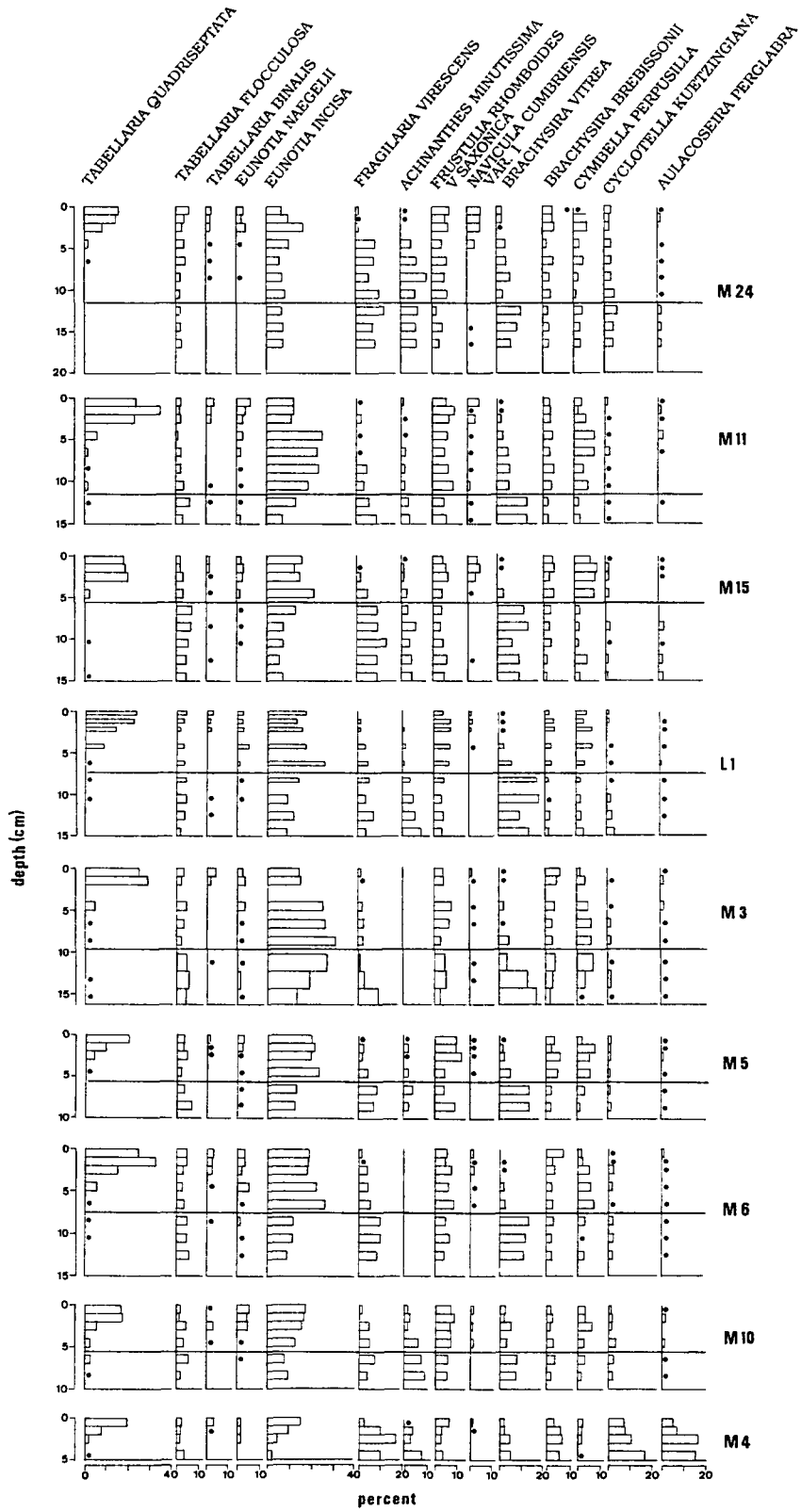

Fig. 5. Summary diatom biostratigraphy of selected Mackereth cores. Histogram thickness relates to sample thickness. • represents <0.5%. The line represents the *B. vitrea* decline, which dates to ca. 1976.

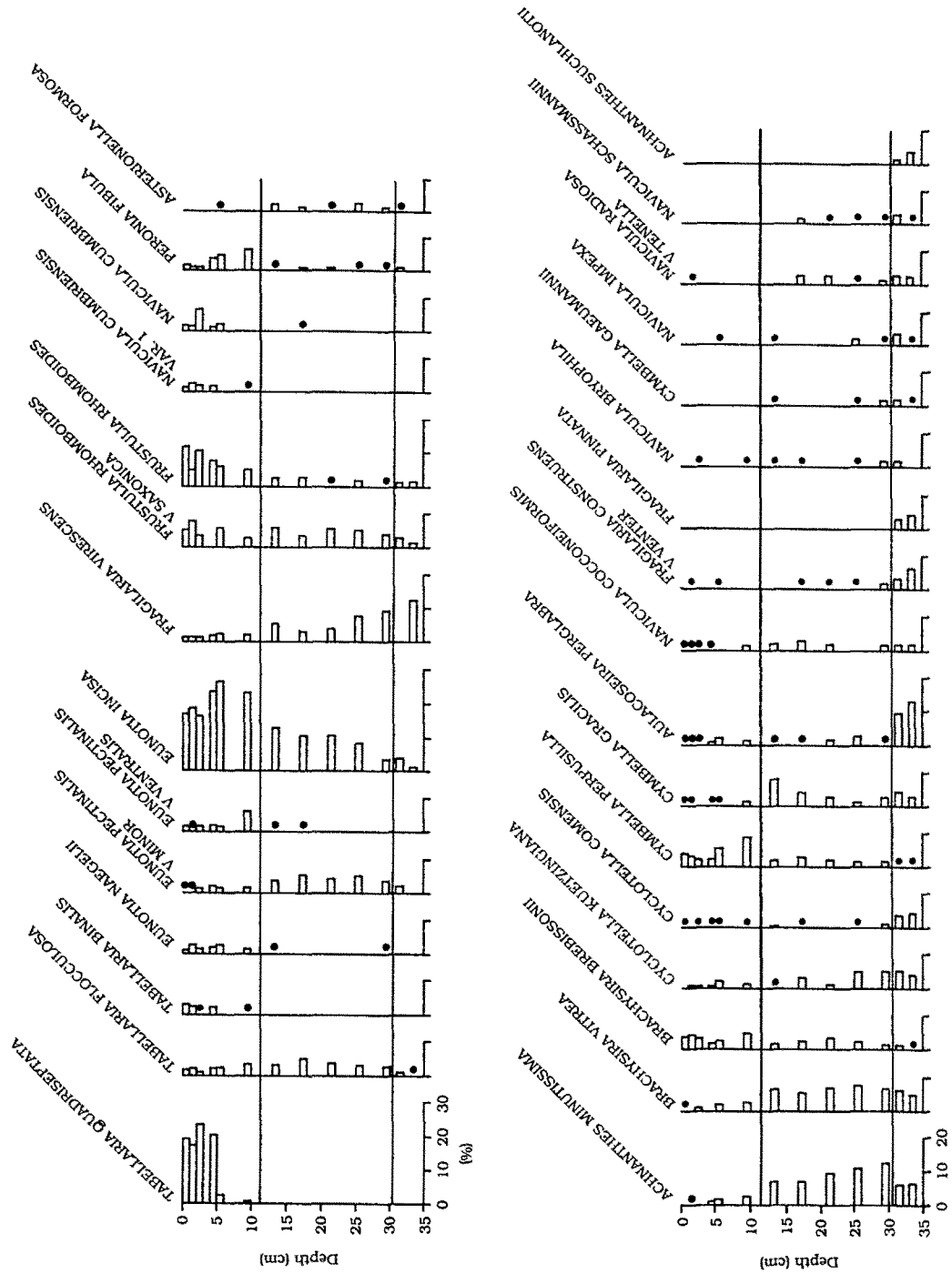

Fig. 6. Summary diatom biostratigraphy for Mackereth core M1. ● represents <0.5%. The upper line represents the *B. vitrea* decline, which dates to ca. 1976. The bottom line represents the probable hiatus between early Holocene and post-1960 assemblages.

Table 3. Dry mass and diatom accumulation rates for selected cores.

core	M1	M3	M5	M6	M10	M11	M15	M24	L1
a. dry mass#; g cm^{-2} yr^{-1}									
	°*	0.16	0.07	0.08	0.04	0.15	0.07	0.12	0.1
b. diatoms=; cells × 10^6 cm^{-2} yr^{-1}									
	°*	23.3	7.2	12.2	4.8	20.5	12.6	13.4	14.6

mean 0.098 ± 0.38 g cm^{-2} yr^{-1}
= mean 13.36 ± 5.76 cells × 10^6 cm^{-2} yr^{-1}
* Not determined

one sample. Percentages in M24 tend to be lower than other cores analysed.

M1 (Fig. 6) was analysed to below the loss-on-ignition increase (associated with the post-ploughing peat inwash) (Anderson *et al.*, 1986). The species succession from 10–15 cm depth to the surface – the acidification period – is directly comparable to other cores. Below the *B. vitrea* decline horizon (13–14 cm) to ca. 30 cm depth, *Fragilaria virescens* and *A. minutissima* show steady increases with increasing sediment depth; and there is a reciprocal decline in *E. incisa*. There are also increases in *E. pectinalis* var. *minor* and *Tabellaria flocculosa*. However, the samples below 30 cm are quite different from those above (cf. CA analysis below; Fig. 11); They are characterised by higher values of *C. kuetzingiana*, *C. comensis*, *A. perglabra*, *Fragilaria construens* var. *venter* and *F. pinnata*. Only the basal samples (> 30 cm depth) contain *Achnanthes suchlandtii*.

For M4 only the top 5 cm was analysed because of its atypical stratigraphy (Fig. 5). Although the surface sample has a typical assemblage (high *T. quadriseptata*, *T. binalis*, *E. incisa*), there are also high percentages (5–10%) of *C. kuetzingiana* and *A. perglabra*. The values of these latter taxa increase substantially immediately sub-surface.

ii. concentrations (Figs 7 & 8; Table 1)

Cell concentration (g DW^{-1}) profiles show reasonable similarity between cores (values ranging from ca. 10 to 25 × 10^7 g DW^{-1}). Surface samples (0–1 cm) have concentrations between

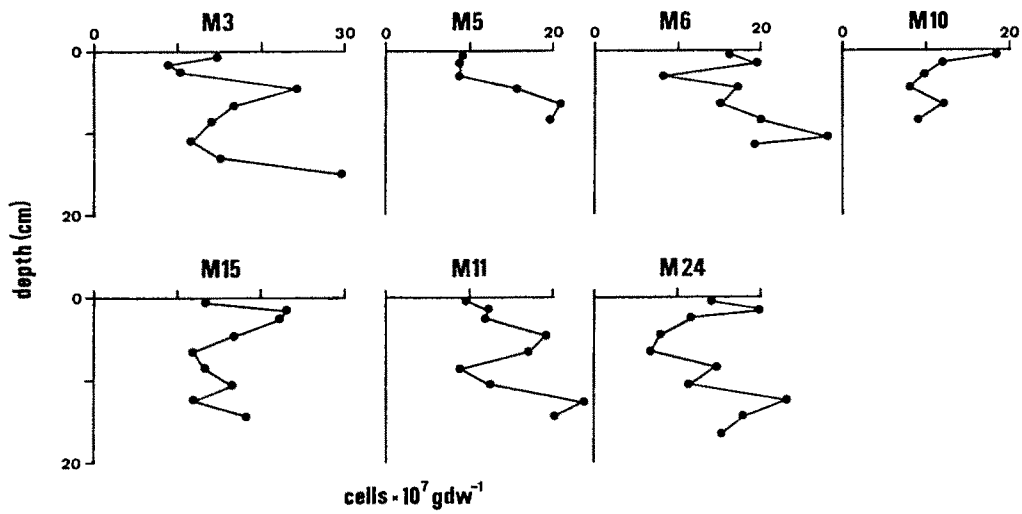

Fig. 7. Summary diatom concentrations for selected Mackereth cores (× 10^7 g DW^{-1}).

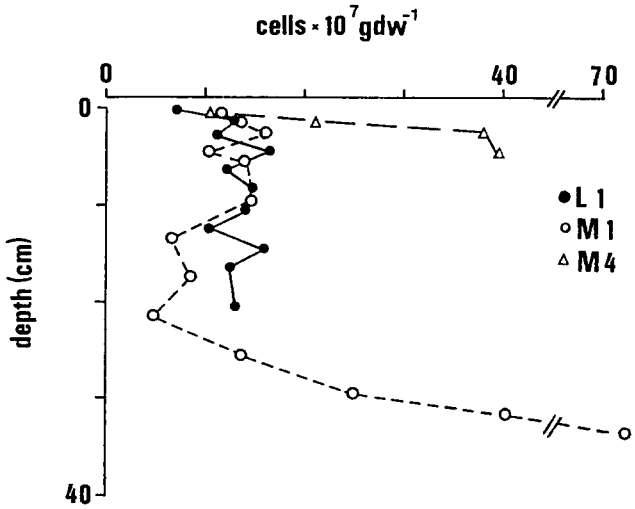

Fig. 8. Summary of diatom concentrations for Mackereth cores M1 and M4 and Livingstone core L1 ($\times 10^7$ g DW^{-1}).

7.1 and 22.8 $\times$ 10^7 g DW^{-1}, mean 12.5 ($\pm$ 3.5) $\times$ 10^7 g DW^{-1} (Table 1). Maxima for different cores range from $<20 \times 10^7$ in M10 to ca. 30×10^7 g DW^{-1} in M3 (Fig. 7). The longer profile of M1 (Fig. 8) has a decrease in concentrations below 12 cm. The M4 concentrations at 3–5 cm (>30 cells $\times$ 10^7 g DW^{-1}) are higher than the mean for the surface zone in other cores (Fig. 8; cf. Table 1). Similarly, M1 values at 30–34 cm (40–70 $\times$ 10^7 g DW^{-1}) are much higher than other cores (Fig. 8).

iii. pH reconstructions (Fig. 9)

All cores show a decline in pH upcore, and reflect the acidification of the lake. However, no core approaches the measured pH of 4.5. With the exception of M15 and M24 (inferred pH 5.2) inferred pH of core surface samples ranged between 4.8 and 5.0. As individual cores have different sediment accumulation rates (below) it is not possible to compare directly between cores. pH was not estimated for M4 because of its atypical diatom assemblages.

Ordination and variability

With large and relatively complex data sets, it has become common in palaeoecology to synthesize

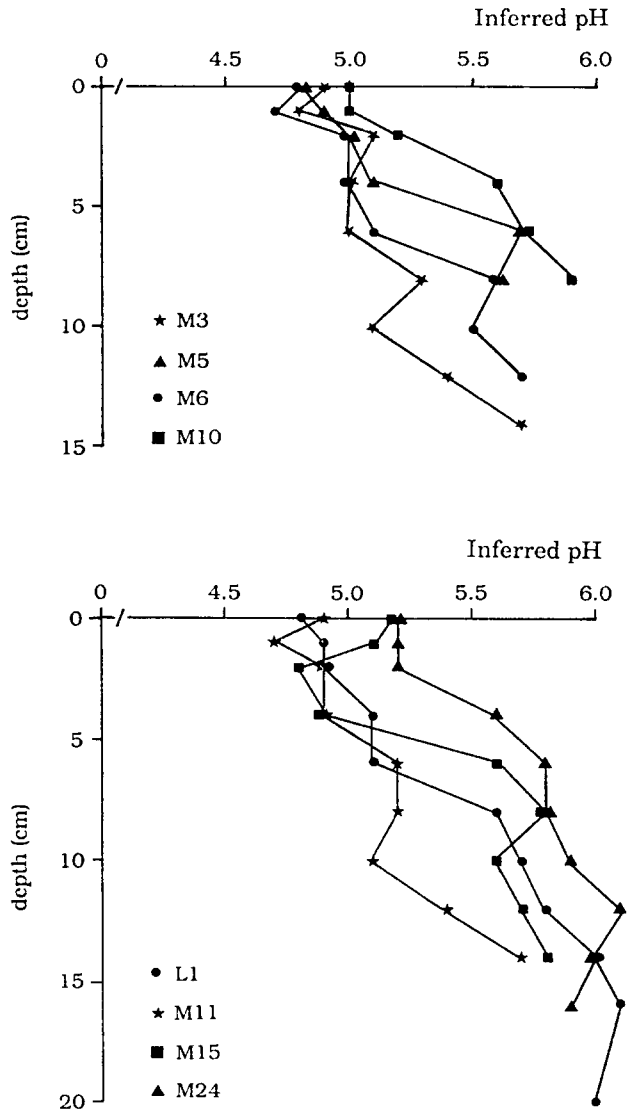

Fig. 9. Reconstructed pH (Multiple Regression of pH categories; Flower, 1986) for selected cores.

and analyse the data using ordination techniques. These methods reduce multivariate data to fewer geometric dimensions and permit different core samples to be compared directly.

The cluster analysis (Fig. 10) for the surface sediment samples shows 3 clear groups. Cluster *a* characterised by high *Cyclotella kuetzingiana* and *Aulacoseira* spp., and cluster *b* (low *Tabellaria quadriseptata*) (Fig. 2) show no spatial pattern in their distribution (Fig. 1). These groups are also

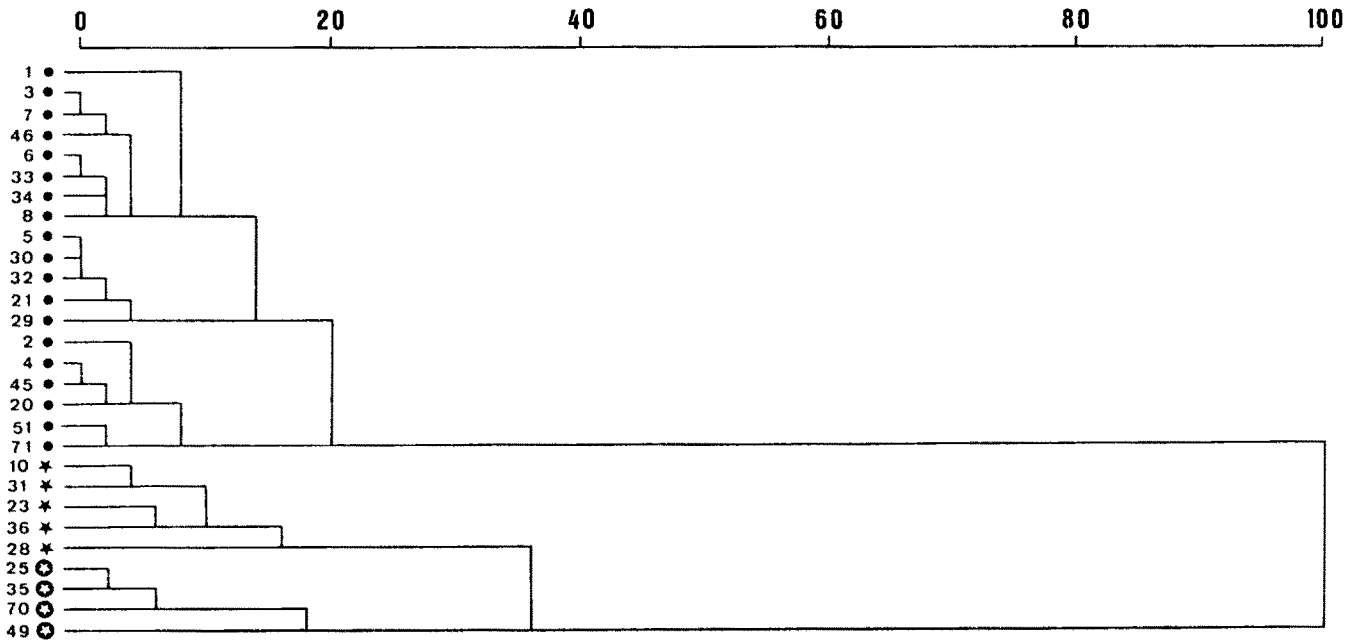

Fig. 10. Dendrogram results for the Cluster Analysis of the Kajak core surface sediment diatom assemblages.

clearly identified by the CA ordination (Fig. 11); cluster *a* has high positive scores on axis 2, while cluster *b* has low axis 1 and axis 2 scores. The other Kajak samples (cluster *c*), which were not clearly differentiated by the cluster analysis (Fig. 10), have low positive to negative scores on axis 2, and high negative scores on axis 1. However, the sample scores of cluster *c* surface sediments are not the same as the surface 0–2 cm of the Mackereth cores (Fig. 11).

The CA axis 1 eigenvalue (0.299) suggests the suitability of the technique for the data. Plotted as time-trends the Mackereth core samples show a strong alignment with axis 1, with comparatively minimal spread on axis 2 (Fig. 11). The acid tolerant taxa in the Galloway lakes (e.g. *Tabellaria quadriseptata*, *T. binalis*, *Eunotia incisa*, *Fragilaria* cf. *oldenburgiana*; Flower, 1986) have high negative axis 1 loadings whereas the less-acid tolerant species (*Cymbella lunata*, *F. virescens*, *Achnanthes minutissima*) have positive scores, indicating that axis 1 largely reflects the acidification of the lake. All cores, apart from M10 (Fig. 11), show slightly more negative scores on axis 2 at the mid-point of their plots, associated with the negative loadings of *Eunotia* spp. (e.g. *E. incisa*, *E. pectinalis* var. *minor*, *E. pectinalis* var. *ventralis*), *Peronia fibula*, *Achnanthes alteica*, and *A. marginulata* on axis 2. All these taxa are associated with the early phases of acidification.

The CA analyses indicate the slight dissimilarity of M10 and M24 when compared to other cores (Figs. 11); the surface of M10 has lower axis 1 scores (i.e. less negative) and both cores have axis 2 scores ca. zero. The time-trend of M1 begins with high positive scores on axis 2 (associated with high species loadings for *Achnanthes suchlandtii* and *Fragilaria pinnata*, *Cyclotella kuetzingiana* and *Aulacoseira perglabra*) but align with other cores as the younger samples' axis 1 scores become negative. Similarly, the four samples of M4 are clearly separated from the other cores, and do not coincide with any of the other core trends, but plot close to Kajak cluster *a* (Fig. 11). M4 core samples, together with cluster *a*, appear to be intermediate between the basal samples of M1 and the more typical assemblages and trends of the other cores.

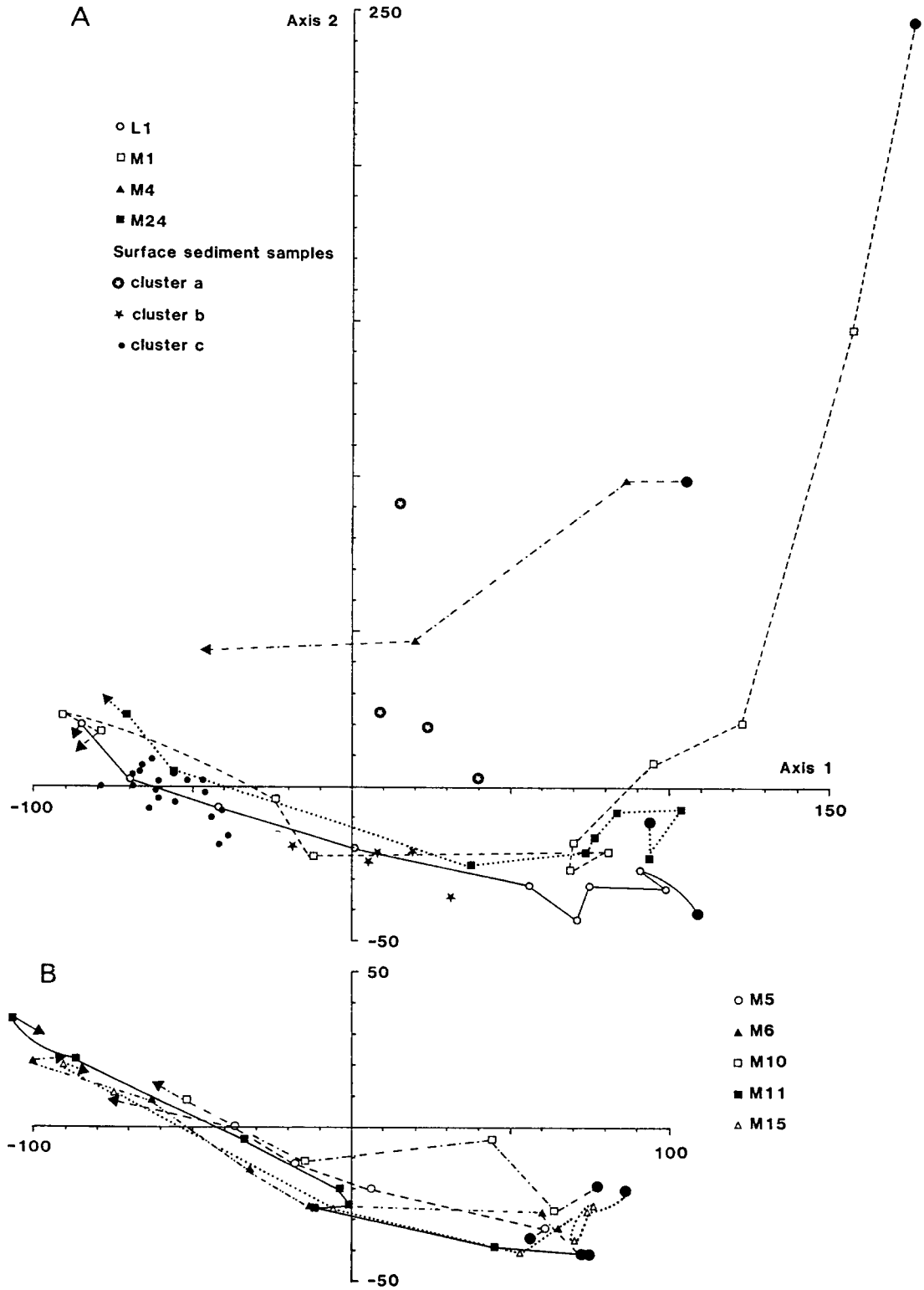

Fig. 11. CA ordination of selected cores, as time-trends, and Kajak surface sediment samples. The basal sample analysed for each core is represented by ● and the surface sample by ◂. To assist clarity the ordination has been split into two parts: A.) Cores L1, M4, M1 and M24, and Kajak surface sediment samples; B.) M5, M6, M15, M11 and M10 are plotted separately at the same scale. The repeatability of the trends is clear; the 4 cores plotted in part A would overly those of M24 and L1, together with the samples of M1 < 30 cm depth.

Core correlation and accumulation rates (Table 3)

Although some earlier biostratigraphic features (decline of *Fragilaria virescens* and *Achnanthes minutissima*) could have been used to correlate between a number of cores (e.g. M3, M24), the ambiguity of these features in some cores, and absence in others, meant that only the decline of *Brachysira vitrea* (Figs. 5 & 6) was used to compare cores. Mean total diatom accumulation rates for the surface zone (post-*B. vitrea* decline) for individual cores range from 4.87 (M10) to 21.6 (M3) $\times 10^6$ cells $cm^{-2}\,yr^{-1}$; mean of all cores 13.36×10^6 cells $cm^{-2}\,yr^{-1}$. The average dry mass accumulation rate for the same period is 0.098 g $cm^{-2}\,yr^{-1}$ (range 0.044 [M10] – 0.149 [M11]).

Discussion

Despite the variability of the Kajak surface sediment samples (Figs. 2 & 10), their species content largely reflects the composition of the extant diatom flora prior to liming, apart that is from the occurrence of *Cyclotella kuetzingiana* and *Aulacoseira* spp. Neither of these taxa were found in modern epiphytic and epilithic samples taken at the time of core sampling from a range of water depths and locations within the basin (N.J. Anderson unpublished data). As a planktonic species one would not expect to find *C. kuetzingiana* in littoral habitats, however, it was not recorded in plankton samples (Flower, 1985a). *Aulacoseira*, a tychoplanktonic-benthic genus, may be difficult to locate. Finding modern analogues in the surface sediment samples (Flower, 1986) for the acid tolerant *Aulacoseira* spp. assemblages in Holocene Galloway profiles has been difficult (cf. Jones *et al.*, 1989). It appears that in this area *Aulacoseira* spp. are no longer a significant part of modern communities, and their occurrence in the surface sediments of the Kajak samples is difficult to explain. However, their common occurrence near the surface of some cores suggests that they are probably a significant source of the re-worked diatoms found at this, and other lakes. The occurrence of > 5% *Melosira* (*Aulacoseira*) *perglabra* in the surface sediment of the Round Loch of Glenhead (Flower *et al.*, 1987), and its absence in littoral samples (Jones & Flower, 1986) suggests a similar problem. In these Scottish (Galloway) sites sediment erosion and re-working have significantly contaminated the surface assemblages and modern diatom productivity has been unable to mask or reduce the effect of old diatom input.

There is old sediment close to the surface of the current sediment surface in many places within the lake, not only those identified by the Mackereth cores (Fig. 11), and is probably the source of the *Aulacoseira* and *Cyclotella* taxa contaminating the surface assemblages. The CA ordination of cores and surface samples clearly shows the similarity of the atypical Kajak samples (cluster *a*) and the 'old' samples of cores M4 and M1, as the latter cores track through cluster *a* samples towards the surface assemblages dominated by *Tabellaria quadriseptata* (Fig. 11). The absence of the *Aulacoseira* spp.-*Fragilaria* spp.-*Navicula schassmanii-Achnanthes suchlandtii* assemblage from modern samples (Flower, 1986) and its occurrence at depth in M1 and L3, suggests that it is undoubtedly a mid-Holocene assemblage (Fig. 11; Anderson *et al.*, 1986; A.C. Stevenson pers. comm. & unpublished ^{14}C dates). That the atypical samples of M4 and the base of M1 were a possible contamination source for the recent sediments, was also indicated by concentrations > 2 times than those of the mean concentrations of the Kajak samples and the other Mackereth cores (Figs. 7 and 8).

The variability of the surface sediment assemblages is also a result of the complex and focussed nature and variable sediment accumulation in the lake (Table 3), causing Kajak surface samples to cover different time periods. Variable sediment accumulation rates mean that samples taken in areas of relatively low sediment accumulation may include quantities of earlier material. Similarily, the samples from areas of rapid accumulation may contain material deposited in < 1 year or may have been contaminated by the erosion and redistribution of older sediment within the system.

A further problem is the variable water content (and hence bulk density) of the core tops and Kajak samples. There is reasonable agreement of concentrations between the core tops (0–1 cm) and Kajak samples when expressed as cells $\times 10^7$ g DW^{-1}, and the coefficient of variation is low, (Table 2). However, when expressed as cells $\times 10^6$ cm^{-3}, which takes into account water content, there is a 2 × difference in mean concentration of the 0–1 cm layer of the two core types, and the CV is higher (Table 2). The Kajak surface samples may have contained variable amounts of water due to inconsistent sub-sampling in the field (i.e. different depths 0.5–1 cm), or the differences may reflect variability between the coring techniques. It is possible that the two corers used may have differential 'bow-waves' associated with core entry.

Prior to afforestation and catchment ploughing, sedimentation within the lake was complex. However, the peat inwash appears to have partially stabilized deposition across the basin (Anderson *et al.*, 1986). If sediment input and/or production is sufficient to maintain the current pattern of accumulation, the influence of old sediments may decrease. However, outlying pockets such as that containing site 71 may remain a source of old diatoms for sometime (Fig. 1). These outlying areas of organic sediment may represent only temporary deposition from where sporadic erosion (by high energy winter storms) may erode and resuspend sediment, causing further contamination. These processes may be operating at other exposed sites with restricted contemporary sediment distribution (Pennington *et al.*, 1972; R.W. Battarbee, pers. comm.)

Although some variability in the Kajak samples may be caused by the sampling of *in situ* live communities, this was not confirmed by checking for chloroplast content. However, live communities occur at depth in many acidic oligotrophic lakes (Björck-Ramberg, 1984; Stevenson *et al.*, 1985), and may even expand with the increased light climate as the lakes acidify. Limited or low diversity in benthic communities (Stevenson *et al.*, 1985) may have caused some of the observed higher percentages of certain taxa in the surface sediment samples and the variation in concentrations (Fig. 3).

All cores, except M4, have a species succession typical of acidified lakes in the Galloway region (Flower *et al.*, 1987), but at Loch Fleet the rate of change is faster (< 20 years Anderson *et al.*, 1986) than at other lakes within Galloway (40–100 years; Flower *et al.*, 1987). Although most cores show recent acidification (Figs. 5, 9, 11), there is some between core variation in the reconstructed surface value, which is higher than the measured pH for this period (4.5). The extraction of a clear acidification trend by the CA axis 1 is not unexpected given the strong ecological response of diatom taxa to acidification, and the suitability of CA for strong environmental gradients (Ter Braak & Prentice, 1988). The similarity of the scores and trends indicates that all cores would give approximately the same recent history of ecological change in the lake. Variability of the reconstructed pH (Fig. 9) for individual cores comes in part from the reworking of older diatoms, the variable distribution (and therefore percentages) of taxa currently extant in the lake (e.g. *Tabellaria quadriseptata*; Fig. 2), together with error associated with variable diatom deposition, sampling, and counting.

The mean total diatom accumulation rate (ca. 13×10^6 cm^{-2} yr^{-1}) compares well with the recent accumulation rate at Loch Grannoch (another forested site), based on one core, ($10–15 \times 10^6$ cm^{-2} yr^{-1} Battarbee & Flower, 1985b), but is higher than the unafforested sites (R.J. Flower, unpublished data). Whether the variability of accumulation rates relates to differences in land-use practices, or reflects subtle differences in catchment geology is unclear. Further speculation is unwarranted because of the problems in comparing accumulation rates between lakes unless whole-basin estimates are used. Similarly, the effects of acidification on diatom productivity are not fully understood.

There are some other studies with which the present study can be compared. Earle *et al.* (1988) found considerable variability between diatom assemblages. They probably overestimated the variability of the lake's diatom assemblages

because they did not consider differential sediment accumulation rates (which influence diatom concentrations) and the effect of diatom source communities. Surface samples cover different time periods and given the morphometry of their study lakes it is unlikely that sediment accumulation rates would be uniform across the basin (cf. Evans & Rigler, 1980). The Loch Fleet results suggest that surface sediment samples are more variable than core trends. Anderson (1990) found similar results in a eutrophic, monomictic lake. Because of variable accumulation rates, diatom inputs and the spatial-temporal variability of deposition and resuspension processes, the integration and (partial) homogenization of diatom assemblages occurs primarily after burial to depths >2 cm. This depth will vary in relation to sediment accumulation rate, sample interval, and lake type. Short cores are useful to assess surface sediment diatom assemblage variability. Taylor *et al.* (1987) did not consider the possibility that reworked diatoms may contribute to the presence of *Cyclotella* species in the surficial sediments of acidic lakes (pH < 5.5).

Dixit & Evans (1986) in a detailed comparison of a polymictic lake and a dimictic lake, found greater variation of surface sediment diatom assemblages in the latter, both in terms of diatom relative frequency and inferred pH. Unfortunately, core analyses were made only for the polymictic lake, and biostratigraphies were not compared using multivariate methods. Presentation of pH profiles can not identify possible variability of taxon profiles – different taxa may have similar pH categories but variable representation across the basin. While this is not important for pH reconstruction studies it restricts attempts to understand the causal processes influencing space-time variability in biostratigraphy. The use of CA axis scores, as a summary of core biostratigraphy (Fig. 11) (Birks, 1987), overcomes this problem, since individual taxa contribute differentially to the sample scores, as opposed to a pH profile based on multiple regression of pH categories, or Index B. However, comparison of multiple pH profiles derived using a weighted averaging (WA) approach invalidates this argument.

Despite the reasonable repeatability of taxa trends within cores, there is 5–20% variability of percentages (Fig. 5) and time trends, as indicated by the range of axis 1 and 2 sample scores (Fig. 11). This variability has implications for the degree of finescale spatial and temporal inference possible from this type of depositional system. Recently, Battarbee *et al.* (1988b) argued for reversibility of lake acidification on the basis of changes in water chemistry and changes in the time-trend of diatom biostratigraphy in CA and canonical correspondence analysis ordinations. While broad scale temporal acidification trends are indisputable, whether one can infer accurate short-term changes (i.e. changes of ca. 0.2 pH units) from the sediment record is unlikely (cf. Fig. 9; Dixit & Evans, 1986). If all cores do not reach the same end point (Fig. 11), it is reasonable to expect that they will not respond equally or uniformly to any later changes in diatom source communities brought about by increases in pH. The variable position of the end-points in the Loch Fleet CA ordination (Fig. 11), suggests that the results of Battarbee *et al.* (1988b) may represent variability rather than community structural responses to increasing pH. The variability of species percentages indicate that relative changes in community structure will also be influenced by depositional variability. The results presented here suggest that the variability of individual lakes should be assessed prior to use of their diatom biostratigraphy for finescale inferences.

While sediment diatom records provide clear trends of acidification, without laminated sediments or freezer core techniques, finescale changes may be within the error limits of the technique. The link between lake-water pH, diatom communities and the sedimentary diatom assemblage will vary with ecological (i.e. community response times) and physical (resuspension and transport) lag effects, that distort the sediment signal. It is probable that the inherent variability of sediment (and diatom) deposition in lakes contributes to the error in reconstructed pH in sediment core studies. The error in calibration data sets (e.g. Charles, 1985; Flower, 1986) will in part be due to the variability of diatom deposi-

tion, which influences the composition of the diatoms in the surface sediment sample used for the calibration relationship, as well as variable chemical measurements, and the complex ecological-physiological relationship between diatoms and pH (Battarbee, 1984). Identifiably re-worked diatoms should be removed, perhaps, from the sample prior to use in a calibration relationship.

Not all lakes will be as extreme as Loch Fleet. As a result of the higher sediment accumulation rates at Loch Fleet, variability may have been enhanced and the problems caused by reworking of old diatoms may not be typical of all lakes. However, similar problems can occur elsewhere, especially as applied studies force palaeolimnologists to investigate more extreme lakes (in terms of their depositional environment). More research is required to fully understand the processes controlling sediment and diatom deposition in such lakes.

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