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A PALAEOLIMNOLOGICAL STUDY OF RECENT WATER QUALITY CHANGES IN LOCHS WITH BLACK-THROATED DIVER POPULATIONS: A REPORT TO THE ROYAL SOCIETY FOR THE PROTECTION OF BIRDS

T.E.H. ALLOTT & N.L. ROSE

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Environmental Change Research Centre
Department of Geography
University College London
26 Bedford Way
London WC1H 0AP
United Kingdom

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EXECUTIVE SUMMARY

1. This report presents an assessment of recent water quality change at seven lochs currently supporting Black-throated diver populations. The lochs selected were considered at risk of water quality change due to either acidification, nutrient enrichment or afforestation.

2. The stratigraphic and diatom records of these lochs were examined to evaluate changes in water chemistry.

3. There is clear evidence of recent (post 1860 AD) acidification at one loch, a site highly sensitive to acidification (alkalinity <30 μeq l^{-1}). This indicates that although lochs in the north-west of Scotland are remote from deposition sources, that the most sensitive sites may have acidified.

4. There is clear evidence of nutrient enrichment at one loch over the last decade. This site has a relatively high alkalinity (c.150 μeq l^{-1}), and fish cages are set on the loch. These data suggest that aquaculture can lead to nutrient enrichment of oligotrophic, highland lochs.

5. The study presents evidence from an afforested site suggesting rapid sediment accumulation rates, which may be a result of inwash of eroded soils following catchment ploughing. However, the data from the afforested sites studied, however, are difficult, and general conclusions on the effect of afforestation on the water quality of these lochs cannot be made with confidence.

Acknowledgements

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1. INTRODUCTION

This report presents an assessment of recent (post-1850 AD) water chemistry changes in seven lochs in north-west Scotland which currently support breeding populations of Black-throated Divers (*Garvia arctica*), a Schedule 1 species of considerable conservation importance. Many freshwater lochs in Scotland have experienced changes in water chemistry over the past 150 years. These changes are generally related to human activities, either through increasing levels of pollution (e.g. acid deposition) or through changes in land-use practice (e.g. afforestation).

It is now accepted that surface water acidification in Scotland has been caused by increasing deposition of sulphur and nitrogen compounds during the last 150 years (Harriman 1988). Palaeolimnological studies have demonstrated the pattern of acidification across Scotland (Battarbee 1989). Strongly acidified lochs and streams are found in Galloway, Arran, and the Trossachs. Acidified surface waters have also been identified on Rannoch Moor, in the Cairngorms and in Strontian (Battarbee *et al.* 1988).

The acidification status of sites in the north and north-west of Scotland have not been thoroughly investigated, as these areas are remote from deposition sources and experience relatively low acid deposition. Consequently these areas have often been assumed to be unaffected by acidification. Battarbee (1989) reports that palaeolimnological studies of Loch Coire nan Arr, a sensitive site on the Applecross peninsula, revealed no acidification. However surface sediments at the site were contaminated by carbonaceous particles, demonstrating that even this remote area receives atmospheric pollution. Harriman (1988) considers that although a few clearwater streams and lochs north of the Great Glen Fault may have acidified slightly, the waters are not sufficiently acid to cause biological problems.

Recent developments in acidification research, however, suggest that freshwater acidification may be more widespread in north and north-west Scotland than previously considered. Models based on the critical loads approach (Bull 1991) have been developed to predict the spatial extent of surface water acidification across the United Kingdom. Maps based on these critical loads models show significant areas of critical load exceedance, or predicted surface water acidification, in north and north-west Scotland (Battarbee *et al.* 1992).

Another major environmental problem affecting lochs throughout the British Isles is eutrophication through nutrient enrichment. Increased loadings of phosphorus and nitrogen into loch systems can result from the application and runoff of chemical fertilizers to agricultural land or by the discharge of urban or industrial effluent into freshwater bodies. Nutrient enrichment can lead to significant changes in aquatic ecosystems (Harper 1988). Productivity increases as a result of increased supplies of nutrients. This leads to increased growth of phytoplankton and other primary producers, but often also of aquatic macrophytes. As a result of increased phytoplankton growth, water turbidity can increase. Species diversity can decrease and the dominant biota change. The changes in nutrient status may therefore be deleterious to species adapted to oligotrophic waters.

In Scotland problems of eutrophication are generally associated with lowland water bodies such as Loch Leven (Bailey-Watts 1978), which are naturally relatively productive. Nutrient enrichment, however, could also affect oligotrophic upland lochs, such as those in the north-west of Scotland containing diver populations. These lochs are usually remote from sources of industrial and urban effluent, and fertilizer applications onto the catchment for agriculture are uncommon. However, over the last decade increasing numbers of fish cages have been set on oligotrophic lochs in the west of Scotland as part of aquaculture developments. In these developments waste from excess fish feed and fish excreta is usually released directly into the lochs, leading to enhanced phosphorus levels in both the water column and the sediment (e.g. Kelly 1992). The extent to which such fish cage developments may cause deleterious effects to oligotrophic lochs requires careful evaluation.

Afforestation provides a further major environmental impact on upland Scotland. Silviculture, and the practices prior to planting, can affect aquatic ecosystems in several ways. Land preparation for planting normally involves ploughing and the creating of drainage ditches. These changes can result in the increased erosion of peat and soils, and the subsequent inwash of eroded material into loch basins causing a substantial increase in the sediment accumulation rate. A further result of increased sediment inwash is a decrease in the turbidity of loch water. This change can adversely affect phytoplankton and aquatic macrophyte growth due to reductions in light availability. At Loch Fleet, Galloway, the palaeoecological record revealed that catchment ploughing in 1961 prior to afforestation resulted in an increase in sediment accumulation rates from c.0.2 cm $year^{-1}$ to 10 cm^{-1} year (Anderson *et al.* 1986). The inwash of peats to Loch Fleet caused a rapid decline in both the diatom phytoplankton and in the abundance of *Isoetes lacustris*, the dominant aquatic macrophyte.

Afforestation can also increase the level of acid deposition in a catchment. Forests are more efficient scavengers of acid deposition, particularly dry deposition, than grassland or rough grazing. Comparisons of afforested and non-afforested catchments in areas of high levels of acid deposition demonstrate that afforestation can exacerbate problems of surface water acidification (e.g. Harriman & Morrison 1982, Kreiser *et al.* 1990).

Silviculture practices often include the use of chemical fertilizers to promote tree growth. These practices are common in forests planted on peaty upland soils, which have low nutrient status. Nutrients from fertilizer applications can be released into drainage waters, and thereby into lochs. This can lead to enhanced nutrient levels in the loch water, resulting in the changes outlined above.

2. SITE SELECTION

Seven sites were chosen which reflected the range of contemporary water chemistry at sites supporting Black-throated Divers (cf. Harriman & Christie 1992). Sites were also chosen which were considered to have been at risk from the changes in water quality described above; acidification, nutrient enrichment and the effects of afforestation. A list of site names and grid references is presented in Appendix A.

Loch A was chosen as a site potentially at risk from acidification. The catchment geology consists of Torridonian sandstones and quartzite, and the loch has an extremely low base cation status (loch water calcium concentration 24 μeq l^{-1}, alkalinity 26 μeq l^{-1}). It is therefore extremely sensitive to acidification, and critical loads models predict that the site has acidified (see below).

Lochs B and C are located within 2 km of one another, and have contemporary water chemistry indicative of higher alkalinity sites located on the Lewisian gneiss. Loch-water calcium and alkalinity levels are relatively high (170-190 and 140-150 μeq l^{-1} respectively). These lochs are therefore well buffered from the effects of acid deposition. However, fish cages have been set on Loch B. This pair of sites were selected to assess the effect of the setting of these cages on Loch B, with Loch C acting as a control site.

Lochs D and E are also located within 2 km of one another, and are indicative of sites located on Lewisian gneiss with relatively low alkalinities. However, they are not as sensitive to acidification as Loch A, having calcium concentrations of 65-70 μeq l^{-1} and alkalinities in the range 40 50 μeq l^{-1}. Fish cages have been set on Loch D. This pair of sites were therefore principally selected to assess the effects of setting fish cages on relatively low alkalinity lochs.

Sections of the catchments of both Lochs F and G were afforested within the last decade. Contemporary water chemistry indicates that these sites are well buffered from the effects of acid deposition (alkalinities >100 μeq l^{-1}). The sites were chosen to assess the effects of afforestation on the water quality of Diver lochs.

3. METHODS

A brief introduction to the techniques used is given below. Further information may be found in Stevenson *et al.* (1987), Rose (1990) and Stevenson *et al.* (1991).

Sediment Coring

Cores were generally taken from the deepest part of the loch where the sediment record is usually the longest. In this study most cores were taken with a Glew gravity corer (Glew 1989). This provides short sediment cores between 20 and 40 cm in length. One of the lochs was cored using a mini-Mackereth corer, providing a core of c.80 cm length. Cores were sliced in the field at 0.5 cm intervals for the upper 5 cm of each core, and at 1 cm intervals below this depth. The core sub-samples were returned to the laboratory and stored wet at 4°C.

Routine Sediment Analysis

The wet density, percentage dry mass (weight loss at 105°C) and percentage loss on ignition (LOI) (at 550°C) of each sub-sample was determined using standard techniques (Stevenson *et al.* 1987). This gives an indication of the proportions of mineral and organic material in the sample. The sub-samples were then dried.

Carbonaceous particles

Spherical carbonaceous particles are produced as a result of high temperature fossil fuel combustion, and vary in size from 200 μm to less than 1 μm. When carbonaceous particles (CPs) are emitted into the atmosphere they are dispersed over a wide area before deposition. They are then incorporated into loch sediments. Carbonaceous particles are resistant to chemical attack and can therefore be isolated in loch sediments and quantified by using chemical digestion to remove the unwanted sediment fraction (Rose 1990). Carbonaceous particle analysis of loch sediment can therefore indicate the extent to which a loch has been exposed to atmospheric pollution from fossil-fuel sources.

The history of fossil-fuel combustion in the United Kingdom is well known (Munday 1990). The trends in carbonaceous particle concentration down a sediment cores can therefore be used to approximately date a core in the absence of ^{210}Pb data. Rose (1991) has carried out an extensive study of carbonaceous particle concentration profiles in radiometrically dated sediment cores from lochs in Scotland. He identifies three features of these profiles which can be used to provide approximate dating;

i) first continuously presence of CPs at approximately 1860 AD;

ii) a sharp rise in CP concentration at approximately 1950 AD corresponding to the post-war boom in power generation;

iii) a peak in CP concentration at approximately 1978 AD, followed by a decline in CP concentration corresponding to reductions in UK fossil fuel burning.

In this study CP concentrations were analysed from selected cores to provide dates. It must be stressed that these dates should be regarded as approximate, and are used to give a rough guide to sediment accumulation rates.

Diatom analysis and environmental reconstruction

Diatoms are siliceous, unicellular algae which grow in a wide range of aquatic habitats. After death they accumulate at the bottom of a loch, and their basic siliceous structure means that they are well preserved loch sediments. A sediment core will therefore contain a record of the diatoms growing in the loch through time. In order to identify diatoms under a light microscope, the sediment is treated with hydrogen peroxide (H_2O_2) to remove the organic, non-siliceous component. The diatoms are then concentrated and mounted in a medium of high refractive index on a glass slide. The diatom assemblage can then be enumerated by counting a minimum number of diatom valves and expressing each taxon as a proportion of the total number of diatoms counted. In this study a minimum of 300 diatom valves were counted on each slide.

Diatoms are sensitive to the chemistry of the environment in which they live, and in particular respond to changes in loch-water chemistry. They therefore provide reliable water chemistry indicators. The recent development of large diatom/water chemistry data-sets have extended our understanding of how individual species respond to loch-water acidity (e.g. Stevenson *et al.* 1991), trophic-status (e.g. Hall and Smol 1992) and salinity (e.g. Fritz *et al.* 1991). These data allow quantitative inferences of water quality to be made from diatom assemblages. Recent changes in loch-water chemistry can therefore be assessed from the diatom assemblages preserved in sediment cores.

In this study diatom analyses are used to examine the evidence for recent (post-1850 AD) changes in water chemistry at seven sites in north-west Scotland with breeding populations of Black-throated Divers. Quantitative reconstructions of loch-water pH are mode using the Surface Water Acidification Programme's modern diatom/loch-water chemistry data-set (Stevenson *et al.* 1991) and the computer programme WACALIB 2.1 (Line & Birks 1990). No suitable data-set is currently available for reconstructing nutrients in upland, oligotrophic lochs in Scotland from diatom assemblages. However, inferences of past changes in nutrient status can be made using known ecological preferences, and by comparing total phosphorus optima of taxa calculated from studies in other regions (e.g. Hall and Smol 1992).

Contemporary loch-water chemistry and critical loads models

Data on contemporary loch-water chemistry is taken from Harriman & Christie (1992). This data can be used to predict the acidification status of a loch using critical loads models. Battarbee (1989) presents a dose-response model of acidification based on palaeolimnological data. This diatom critical loads model uses loch-water calcium concentration (as an indicator of sensitivity) and sulphur (S) deposition at each site to define a critical Ca^{2+}:S ratio which differentiates between acidified and non-acidified sites. Lochs which have a Ca^{2+}:S ratio of less than 94:1, where Ca^{2+} is measured in $\mu eq\ l^{-1}$ and S deposition in keq ha^{-1} $year^{-1}$, are predicted to have acidified. Lochs which have a Ca^{2+}:S ratio of greater than 94:1 are predicted to be non-acidified.

In this study this critical ratio has been applied to contemporary loch-water chemistry, using the S deposition data of the Critical Loads Advisory Group (CLAG 1992), to predict the acidification status of the lochs investigated.

4. RESULTS AND DISCUSSION

4a. LOCH A

Site details

Table 4.1 Loch A: site characteristics

Lake altitude (m)	96
Catchment relief (m)	876
Catchment area (ha) (excluding lake)	4910
Lake area (ha)	62
Catchment:lake ratio	792
Maximum depth (m)	26

Table 4.2 Loch A: summary water chemistry (from Harriman & Christie 1992)

pH	5.95
Alkalinity ($\mu eq\ l^{-1}$)	26
Conductivity ($\mu S\ cm^{-1}$)	28
Na^+ ($\mu eq\ l^{-1}$)	139
K^+ ($\mu eq\ l^{-1}$)	8
Mg^{2+} ($\mu eq\ l^{-1}$)	20
Ca^{2+} ($\mu eq\ l^{-1}$)	24
Cl^- ($\mu eq\ l^{-1}$)	195
NO_3^- ($\mu eq\ l^{-1}$)	0
SO_4^{2-} ($\mu eq\ l^{-1}$)	25
TOC ($mg\ l^{-1}$)	2.6

Sulphur deposition at this site is currently 0.62 keq ha^{-1} $year^{-1}$ (CLAG 1992). The site therefore has a Ca^{2+}:S ratio of 38.7, and is therefore predicted to have acidified according to the diatom critical loads model.

A short sediment core was taken from the deepest point of the loch basin (26 m) in May 1992.

Carbonaceous particle analysis

The carbonaceous particle profile for this core is shown in Figure 4.1. The concentrations of CPs in the core are low when compared to those in cores from areas of high acid deposition. The concentration of CPs in a core from Loch Tinker in the Trossachs, for example, reached levels of >70,000 particles gDM^{-1}. The low levels of CPs at Loch A reflect the relatively low levels of acid deposition in the north-west of Scotland.

The first continuous appearance of CPs in the profile is found at a depth of 17.5 cm. This indicates a mean post-1860 AD accumulation rate of c.1.3 mm $year^{-1}$. This value is a fairly typical of upland, oligotrophic lochs (Battarbee *et al.* 1988). A peak in concentration occurs at 3.3 cm, indicating a mean post-1978 AD accumulation rate of c.2.4 mm $year^{-1}$. These data suggest an increase in the sediment accumulation rate in the upper part of the sediment core.

Sediment stratigraphy

The sediment consisted of a dark brown organic detritus. The percentage dry mass, percentage loss on ignition and wet density are shown in Figure 4.2. There is a peak in the mineral content of the core at 13.5 cm. Above this level there is a trend of decreasing mineral material up the core.

Diatom analysis

A summary diatom diagram is shown in Figure 4.3. The species are ordered from left to right in order of decreasing tolerance to low pH. The diatom assemblages are dominated by *Eunotia incisa*, *Peronia fibula*, *Tabellaria flocculosa* var. *flocculosa*, *Brachysira vitrea* and *Achnanthes minutissima*, indicative of low alkalinity, oligotrophic conditions. There is a marked shift in the relative importance of these taxa through the length of the core. At the base of the core *Achnanthes minutissima* is the dominant taxon. Also present are the circumneutral diatoms *Cymbella microcephela* and *Tabellaria flocculosa* var. III. Above 15 cm, however, these diatoms start to decline in abundance, and more acidophilous species such as *Tabellaria flocculosa* var. *flocculosa*, *Peronia fibula* and *Eunotia incisa* increase in abundance.

The pH reconstruction for this core is shown in Figure 4.4. The reconstruction reflects the floristic changes apparent in Figure 4.3. The reconstructed pH at 17.5 cm (c.1860 AD) is 6.0. Above 17 cm there is a marked trend of steadily declining pH. At 3.3 cm (c.1978 AD) the reconstructed pH value is 5.6. The reconstructed pH of the uppermost sediment sample is 5.5. These data suggest an overall decrease of 0.4-0.5 pH units over the past 130 years

Discussion

The carbonaceous particle profile suggests that the core contains a good record of sediment accumulation for at least the last 150 years. The diatom record indicates that the loch has acidified over the last 130 years. The acidification occurs after the loch has been contaminated by low concentrations of carbonaceous particles, so it seems probable that the acidification is related to increasing acid deposition in the area. The loch has an extremely low base cation status, indicating a high degree of sensitivity. These data therefore suggest that although levels of acid deposition are low in the north-west of Scotland, very sensitive sites are still at risk from acidification.

The diatom-inferred pH value of 5.5 from the uppermost sediment sample falls well below the recorded value of 5.95. This discrepancy could be the result of taking a single water sample as representative of mean pH conditions.

Figure 4.1 **Loch A: carbonaceous particle concentrations plotted against sediment depth**

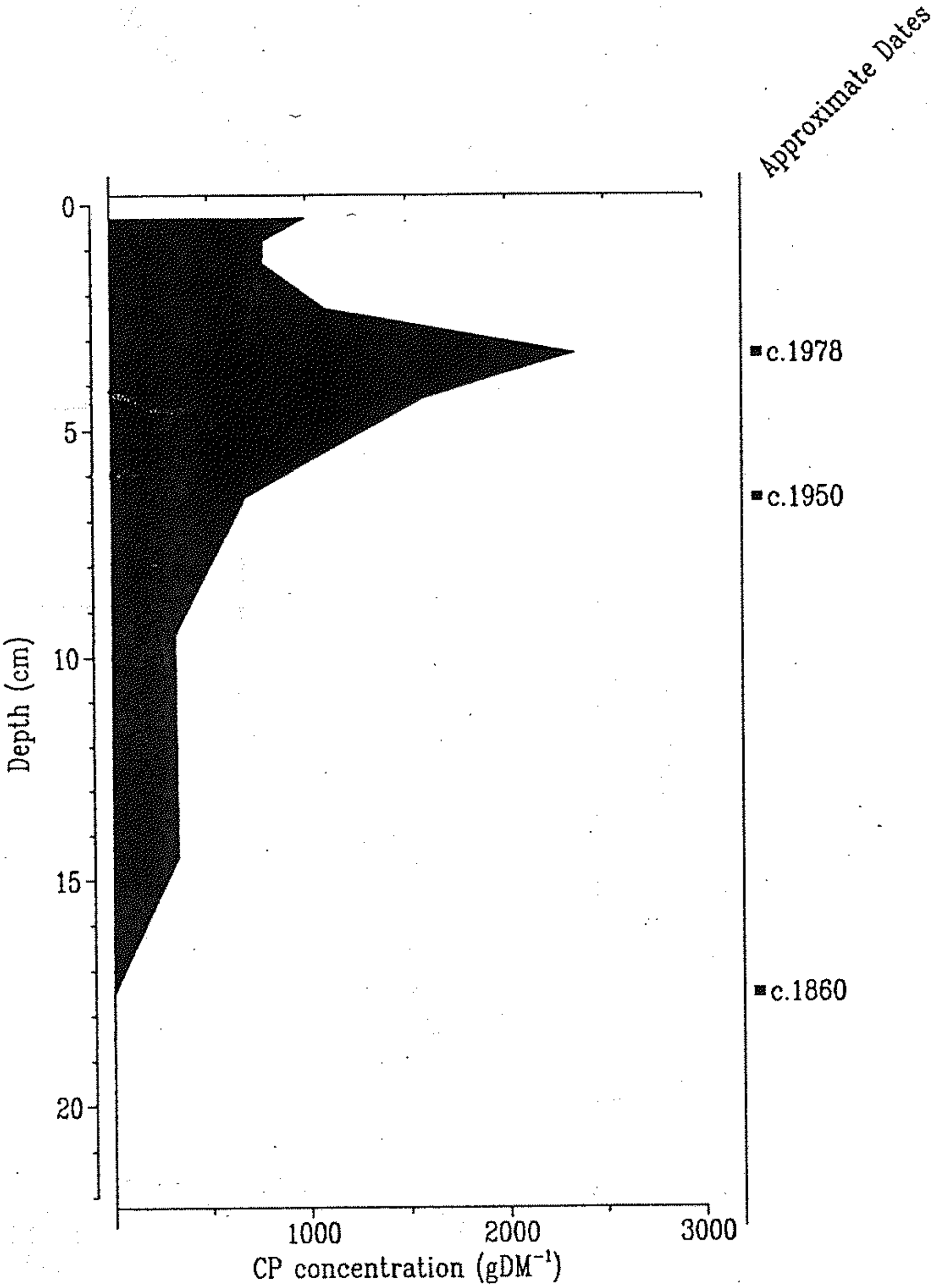
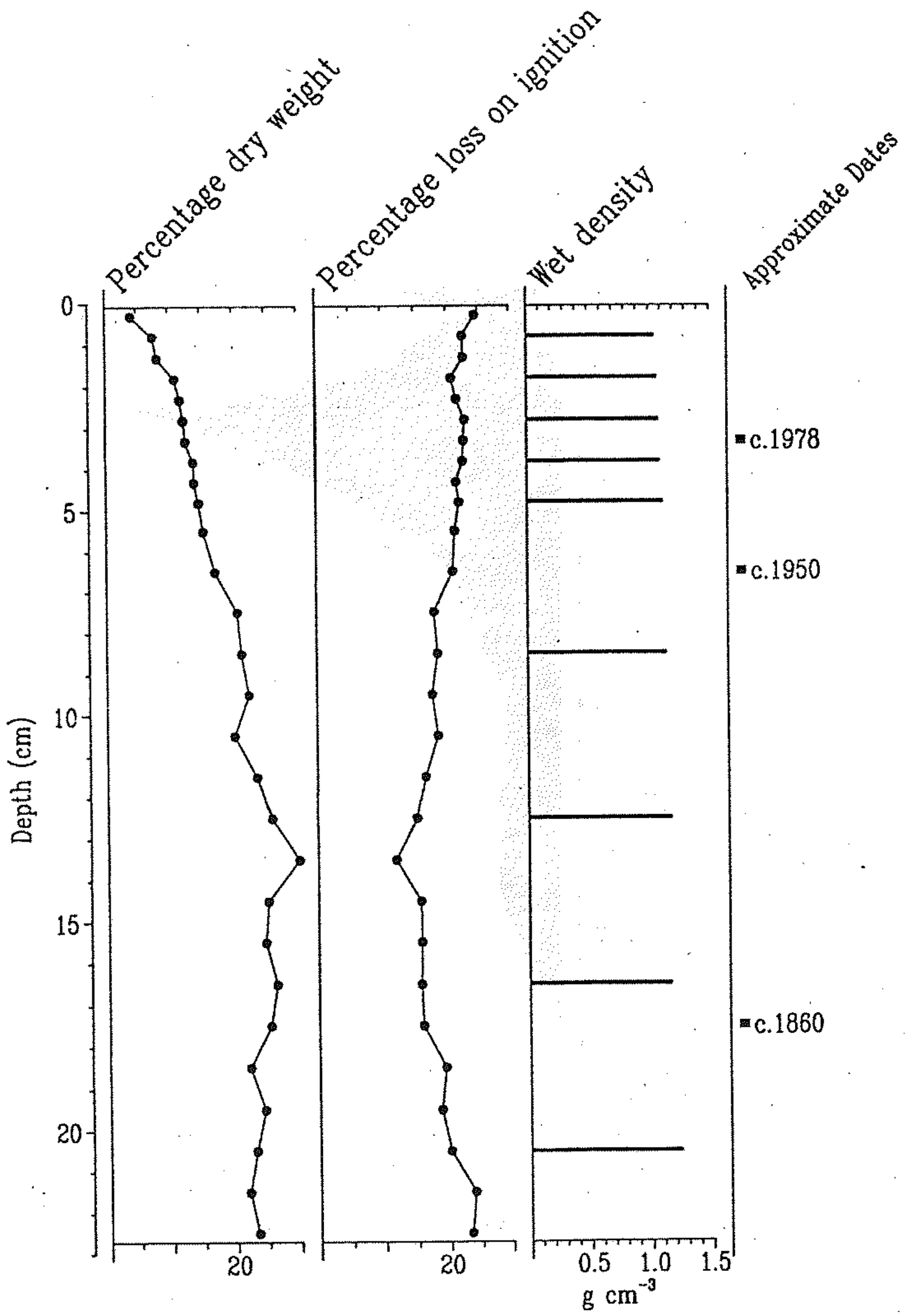


Figure 4.2 **Loch A: sediment characteristics**



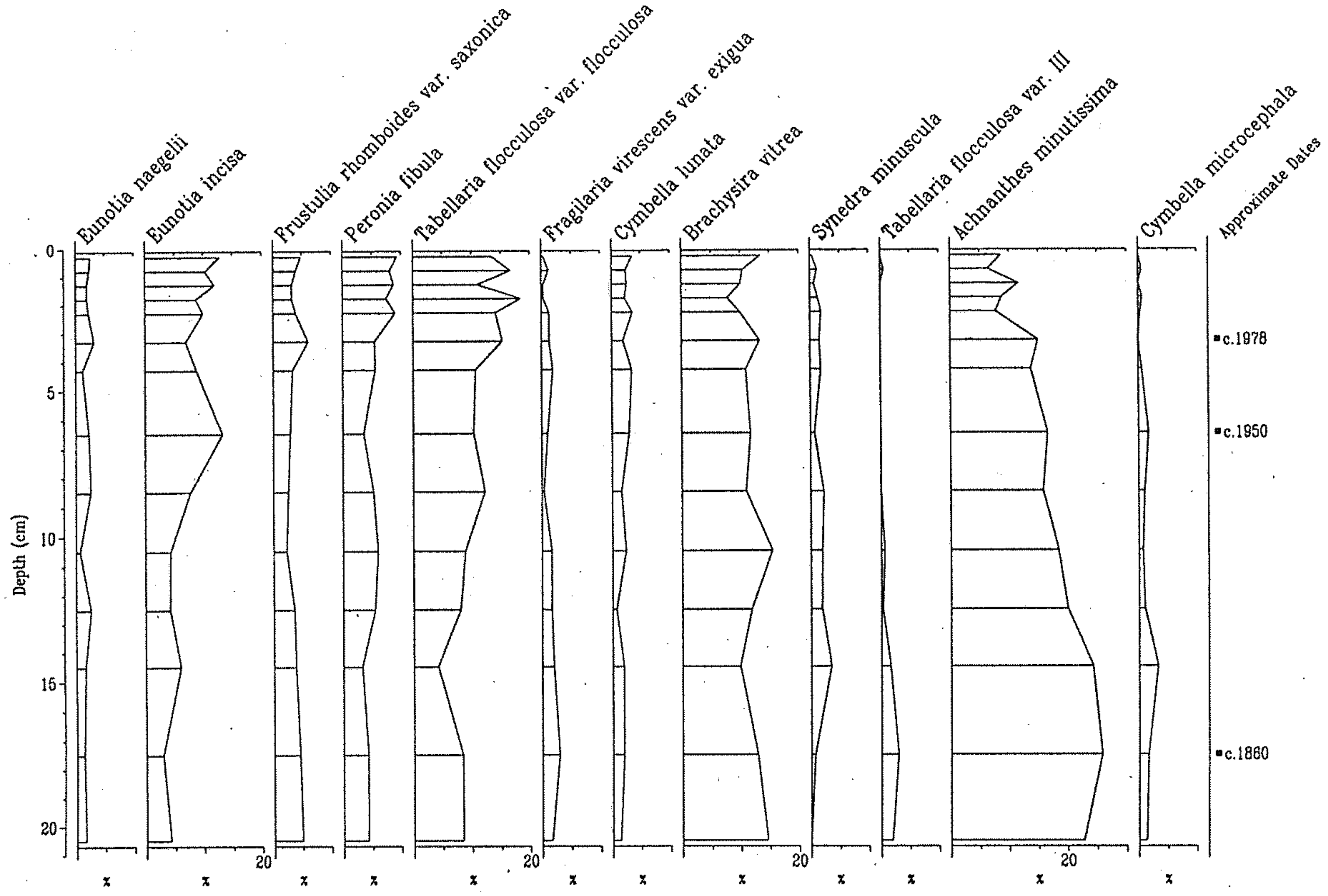
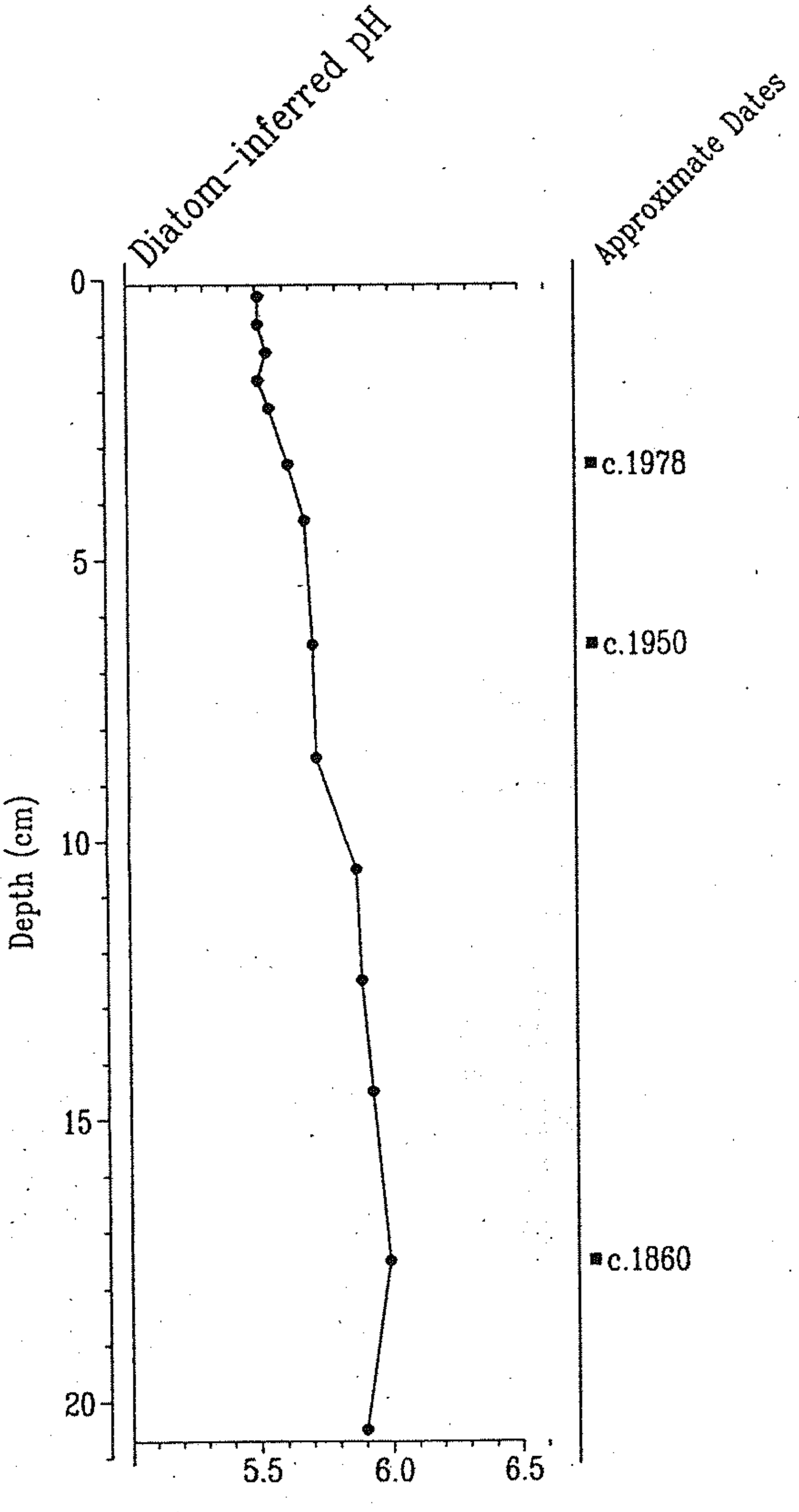


Figure 4.3 Loch A: summary diatom diagram

Figure 4.4 **Loch A: pH reconstruction**



4b. LOCH B

Site details

Table 4.3 Loch B: site characteristics

Lake altitude (m)	67
Catchment relief (m)	55
Catchment area (ha) (excluding lake)	211
Lake area (ha)	56
Catchment:lake ratio	3.8
Maximum depth (m)	23

Table 4.4 Loch B: summary water chemistry (from Harriman & Christie 1992)

pH	7.05
Alkalinity (μeq l^{-1})	149
Conductivity (μS cm^{-1})	165
Na^+ (μeq l^{-1})	906
K^+ (μeq l^{-1})	23
Mg^{2+} (μeq l^{-1})	179
Ca^{2+} (μeq l^{-1})	187
Cl^- (μeq l^{-1})	1284
NO_3^- (μeq l^{-1})	3
SO_4^{2-} (μeq l^{-1})	124
TOC (mg l^{-1})	3.6

Sulphur deposition at this site is currently 0.3 keq ha^{-1} $year^{-1}$ (CLAG 1992). The site therefore has a Ca^{2+}:S ratio of 623, and therefore on the basis of the diatom critical loads model is not predicted to have acidified. The loch has a high alkalinity (>100μ eq l^{-1}) and is not susceptible to current levels of acid deposition in north-west Scotland.

Fish cages are currently set on this loch for aquaculture.

A short sediment core was taken from the deepest point of the loch (23 m) in May 1992.

Carbonaceous particle analysis

The carbonaceous particle profile for this core is shown in Figure 4.5. Again, the concentrations of CPs in the core are relatively low, indicating low levels of acid deposition. The first continuous appearance of CPs is found at a depth of 9.5 cm, indicating a mean post-1860 AD accumulation rate of c.0.7 mm year^{-1}. There is a pronounced peak in CP concentration at 2.3 cm, indicating a mean post-1978 accumulation rate of c.1.6 mm year^{-1}. These data suggest an increase in the sediment accumulation rate towards the top of the core.

Sediment stratigraphy

The percentage dry mass, percentage loss on ignition and wet density data are shown in Figure 4.6. The sediment consists of a dark brown organic detritus. However, the sediment at the very base of the core consists has a higher mineral content. At 32 cm there is a relatively sharp increase in the LOI curve. Similar increases in LOI have been observed in loch sediment from western Scotland and Ireland at approximately 1500-1700 AD (Stevenson *et al.* 1990). Stevenson *et al.* consider that this event represents peat erosion from the loch catchments. A date of 1500-1700 AD for 32 cm in the core is consistent with the accumulation rates calculated from the CP data.

Diatom analysis

A summary diatom diagram is presented in Figure 4.7. In the lower part of the core (2-20 cm) the diatom assemblages are dominated by the planktonic taxon *Cyclotella kuetzingiana* var. *minor*. *Fragilaria virescens* var. *exigua*, *Denticula tenuis*, *Cymbella microcephela*, *Brachysira vitrea* and *Cyclotella rossii* are also common. This assemblage is indicative of a relatively high alkalinity oligotrophic loch. There are major changes in the diatom assemblages in the uppermost 2.5 cm of the core. Abundances of *Cyclotella kuetzingiana* var. *minor* decline steeply, and the planktonic taxa *Asterionella formosa*, *Tabellaria flocculosa* var. IIIp, and *Cyclotella glomerata* increase. These latter taxa are present in the earlier diatom assemblages, but in very low abundances (Figure 4.7).

Asterionella formosa and *Tabellaria flocculosa* var. IIIp are indicators of mesotrophic conditions. In a study of Canadian lakes by Hall and Smol (1992) these taxa had total phosphorus (TP) optima of 12-15 μg l^{-1}, whereas *Brachysira vitrea*, *Fragilaria virescens* var. *exigua* and *Achnanthes minutissima* were indicative of low TP conditions (optima 7-9 μg l^{-1}). Such values cannot be applied directly to upland Scottish lochs, but these ecological preferences suggest that the floristic changes in the top of the core represent slight nutrient enrichment. The extent of this enrichment cannot be fully evaluated due to the lack of a suitable diatom/nutrient data-set from upland Scottish lochs.

The pH reconstruction for the core is shown in Figure 4.8. This indicates a stable pH at approximately 6.8-6.9 for much of the length of the core. However, in the top 2 cm of the core the reconstructed pH increases slightly, reflecting the floristic changes described above. The reconstructed pH of the uppermost sample is 7.04, corresponding closely to the measured pH of 7.05.

Discussion

The CP profile suggests that the core contains a good, continuous record of sediment accumulation for at least the last 150 years. The diatom record suggests that slight nutrient enrichment has occurred in Loch B within the last decade. Within this relatively short time period the beginning of the enrichment cannot be determined precisely because of the approximate nature of CP dating. Prior to this recent enrichment the chemistry of the loch was stable for at least 150 years.

Figure 4.5 **Loch B: carbonaceous particle concentrations plotted against sediment depth**

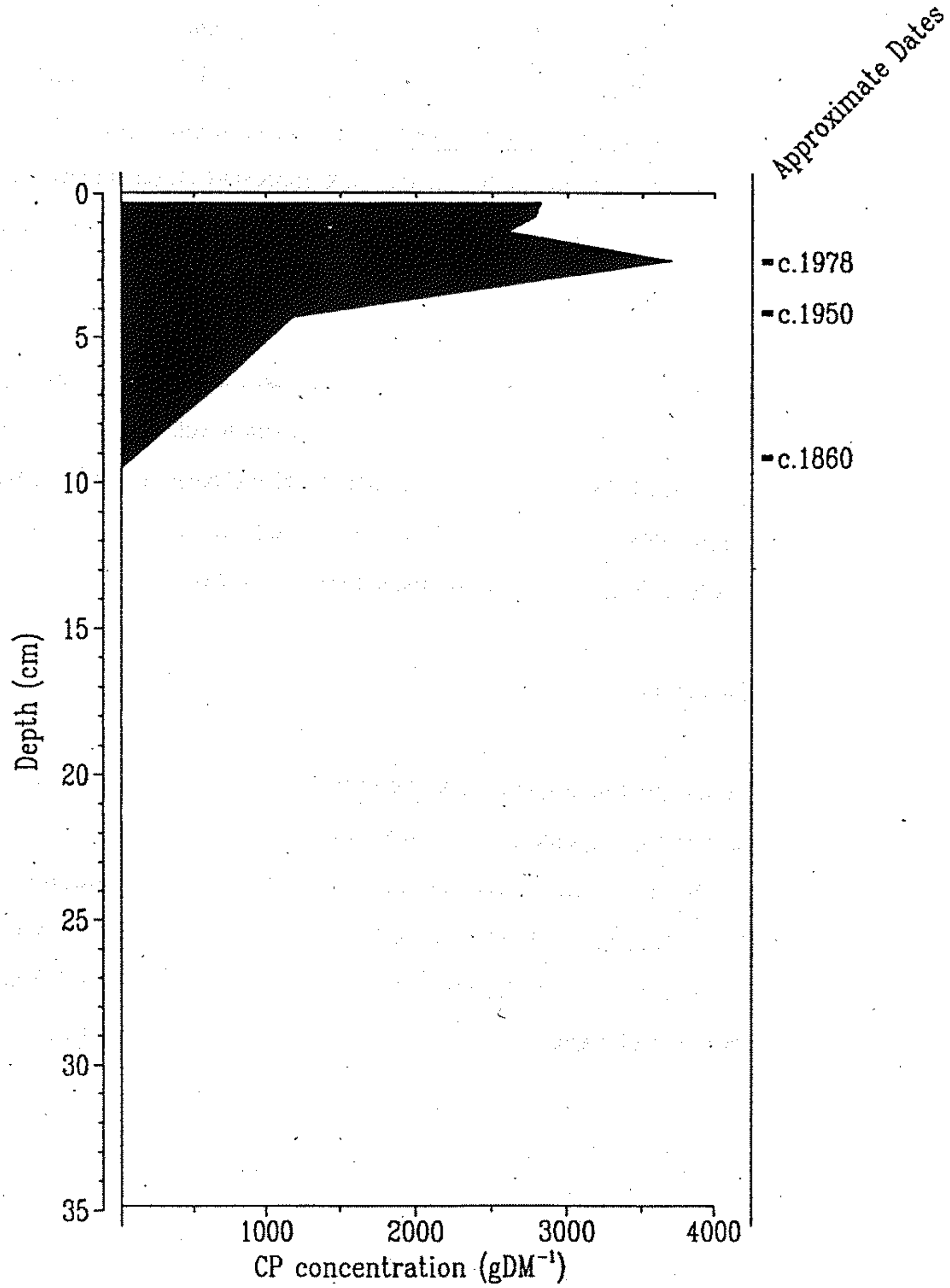
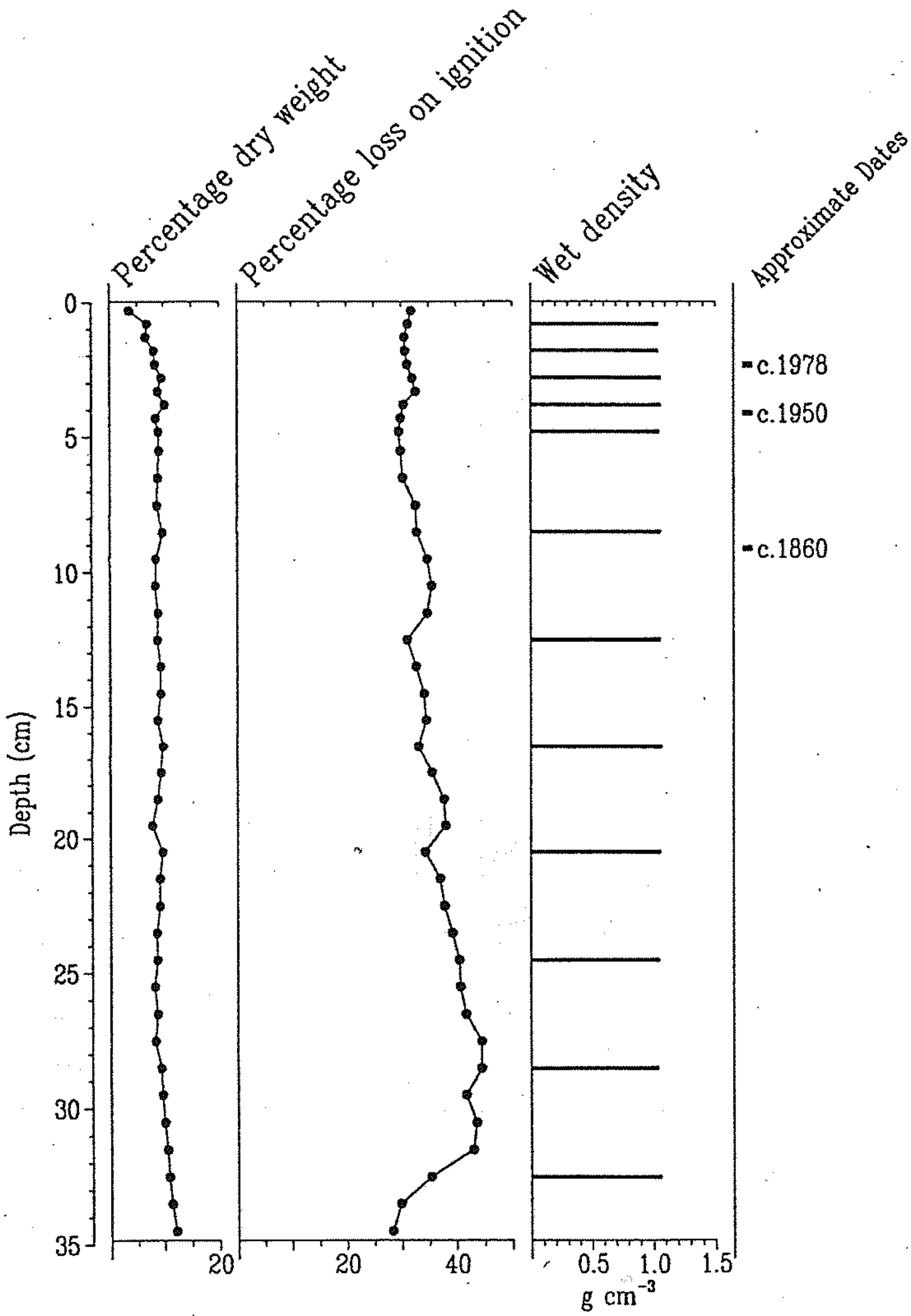
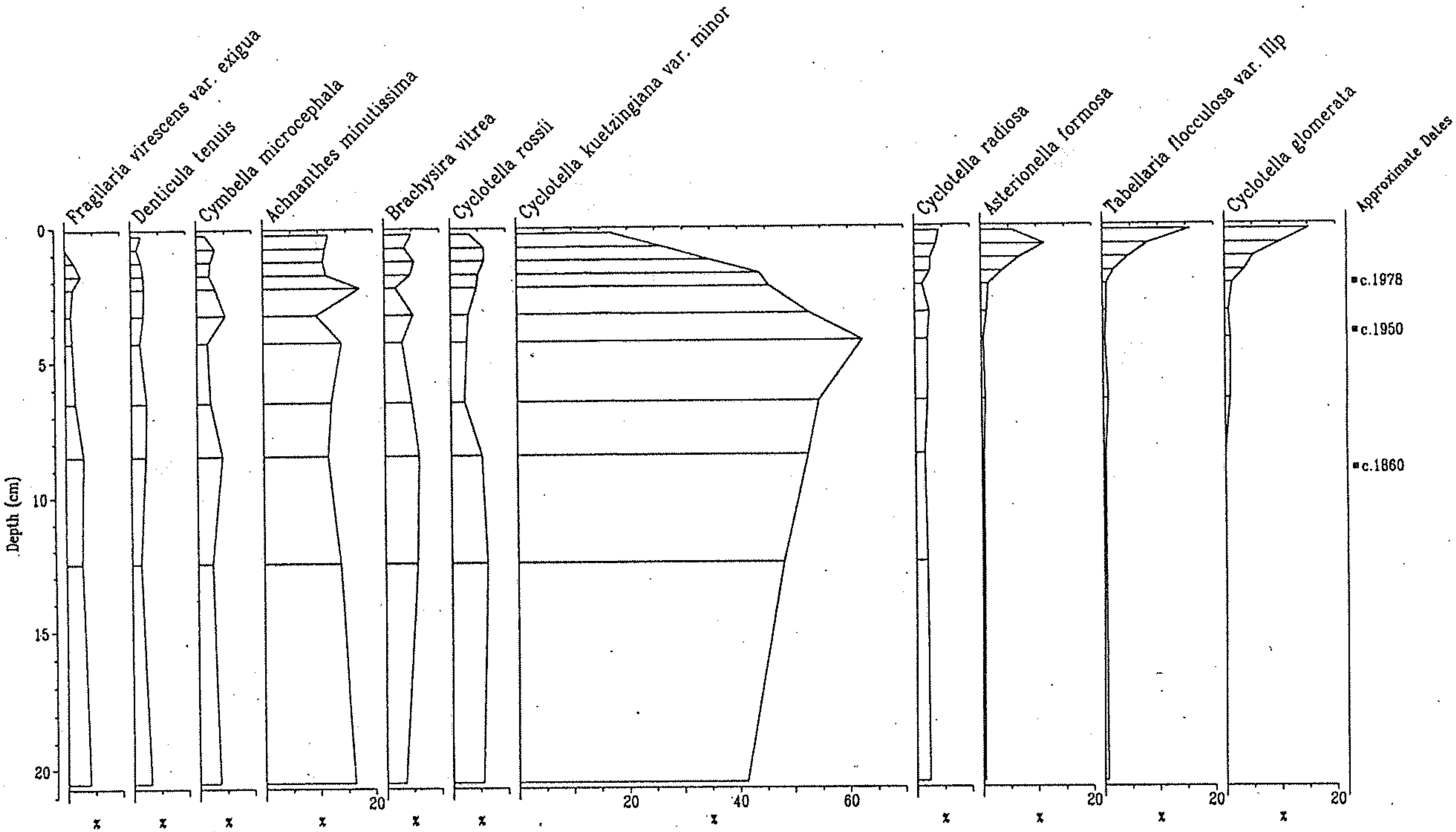


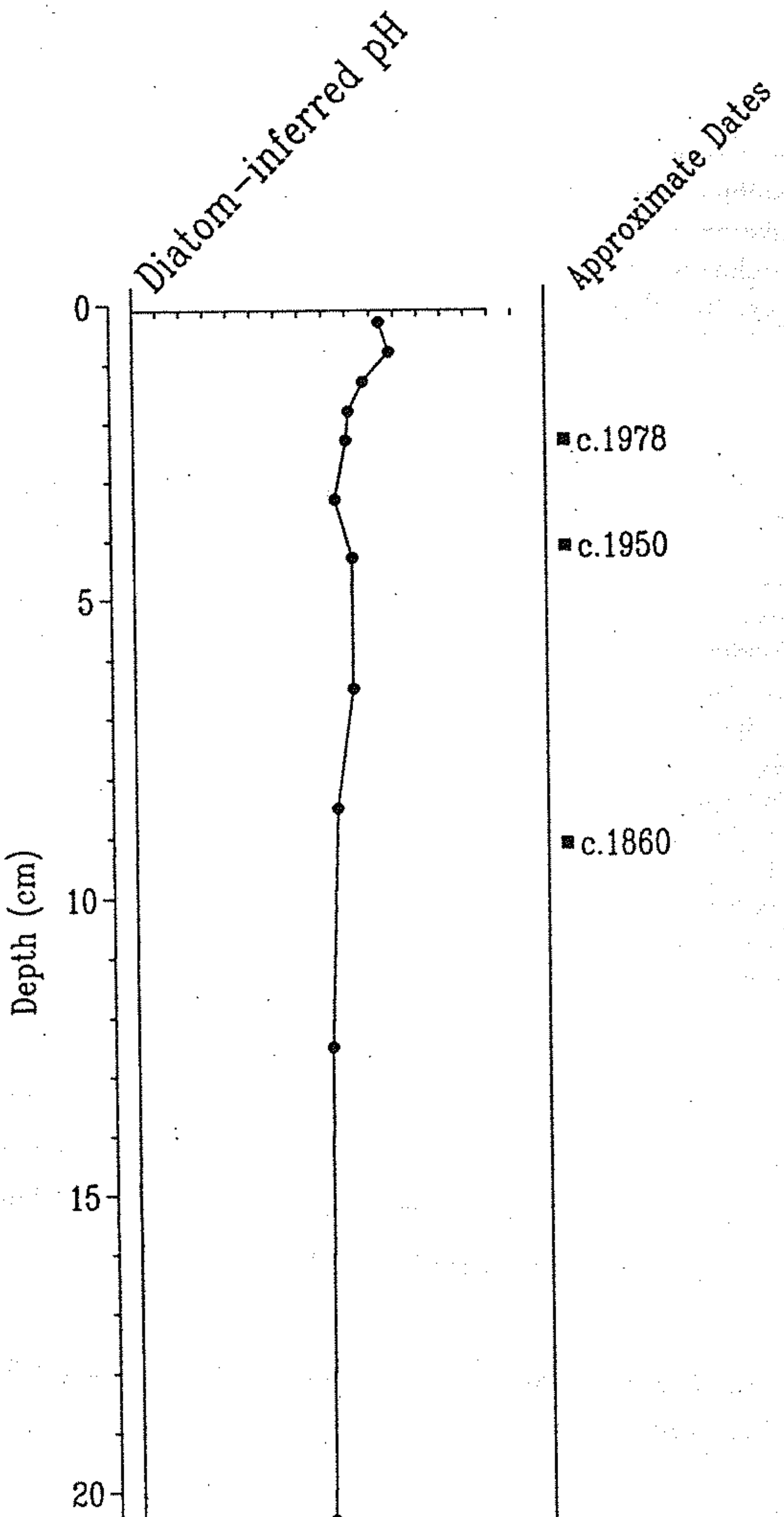
Figure 4.6 **Loch B: sediment characteristics**





F ure 4.7 Loch B: summary diatom di ram

Figure 4.8 **Loch B: pH reconstruction**



4c. LOCH C

Site details

Table 4.5 Loch C: site characteristics

Lake altitude (m)	46
Catchment relief (m)	109
Catchment area (ha) (excluding lake)	596
Lake area (ha)	13
Catchment:lake ratio	45.8
Maximum depth (m)	10.5

Table 4.6 Loch C: summary water chemistry (from Harriman & Christie 1992)

pH	6.99
Alkalinity ($\mu eq\ l^{-1}$)	140
Conductivity ($\mu S\ cm^{-1}$)	134
Na^+ ($\mu eq\ l^{-1}$)	728
K^+ ($\mu eq\ l^{-1}$)	20
Mg^{2+} ($\mu eq\ l^{-1}$)	123
Ca^{2+} ($\mu eq\ l^{-1}$)	168
Cl^- ($\mu eq\ l^{-1}$)	962
NO_3^- ($\mu eq\ l^{-1}$)	1
SO_4^{2-} ($\mu eq\ l^{-1}$)	88
TOC ($mg\ l^{-1}$)	4.2

Sulphur deposition at this site is currently 0.71 keq ha^{-1} $year^{-1}$ (CLAG 1992). The site has a Ca^{2+}:S ratio of 237, and is not predicted to have acidified according to the diatom critical loads model. The loch has a high alkalinity (>100 $\mu eq\ l^{-1}$) and is not susceptible to current levels of acid deposition.

A short sediment core was taken from the deepest part of the loch basin (10.5 m) in May 1992.

Carbonaceous particle analysis

The carbonaceous particle profile for this core is shown in Figure 4.9. CP concentrations are relatively low, reflecting low levels of acid deposition in north-west Scotland. The CP data suggest that 17.5 cm dates to c.1860 AD, 13 cm dates to c.1950 AD, and 2.3 cm dates to c.1978 AD. These data indicate a mean post-1860 AD sediment accumulation rate of c.1.3 mm $year^{-1}$, a value typical for upland oligotrophic lochs in Scotland (Battarbee *et al.* 1988). However, the data also suggest considerable variation in the accumulation rate through the length of the core. The mean accumulation rate is approximately 0.5 mm $year^{-1}$ between c.1860 AD and c.1950 AD, 3.8 mm $year^{-1}$ between c.1950 AD and c.1978 AD, and 1.6 mm $year^{-1}$ between c.1978 AD and 1992 AD.

Sediment stratigraphy

The sediment consists of a blackish organic detritus. Percentage dry mass, percentage loss on ignition and wet density data are shown in Figure 4.10. These curves vary little, indicating uniformity of sediment type.

Diatom analysis

A summary diatom diagram for Loch C is shown in Figure 4.11. The assemblages are dominated by the periphytic species *Achnanthes minutissima* and *Brachysira vitrea*. Also common are the planktonic taxon *Cyclotella kuetzingiana* var. *minor* and the periphytic species *Cymbella microcephela*, *Eunotia pectinalis* var. *minor*, *Fragilaria virescens* var. *exigua* and *Gomphonema intricatum*. *Diatoma elongatum* var. *tenue* is common between 5 and 10 cm. These assemblages are indicative of a relatively high alkalinity, oligotrophic loch.

Although the diatom assemblages in the core are relatively stable, the one major floristic change in the core is the increase in the abundance of *Achnanthes abundans* above 10 cm. This taxon occurs in low abundances at the base of the core, but reaches an abundance of >10% in the uppermost sample. The ecology of this species is not well known, but it also seems to be most abundant in relatively high alkalinity oligotrophic lochs. The floristic changes in the core do not therefore suggest a significant environmental change.

The pH reconstruction for Loch C is shown in Figure 4.12. This indicates a stable pH at 6.5-6.6. The reconstructed pH of the uppermost sample is 6.53, whereas the measured pH value is 6.99 (Table 4.6). This discrepancy may be due to the limitation of using a single water chemical sample as representative of mean conditions.

Discussion

The CP profile indicates that the core contains a continuous record of sediment accumulation for the last 150 years. The sediment accumulation rate in the core has varied substantially, with the highest rates of over 3 mm $year^{-1}$ between c.1950 and c.1978. The diatom assemblages do not suggest that there has been a change in water quality over the time-span of the core.

4d. LOCH D

Site details

Table 4.7 Loch D: site characteristics

Lake altitude (m)	118
Catchment relief (m)	251
Catchment area (ha) (excluding lake)	341
Lake area (ha)	63
Catchment:lake ratio	5.4
Maximum depth (m)	26.5

Table 4.8 Loch D: summary water chemistry (from Harriman & Christie 1992)

pH	6.51
Alkalinity (μeq l^{-1})	48
Conductivity (μS cm^{-1})	72
Na^+ (μeq l^{-1})	374
K^+ (μeq l^{-1})	24
Mg^{2+} (μeq l^{-1})	67
Ca^{2+} (μeq l^{-1})	71
Cl^- (μeq l^{-1})	560
NO_3^- (μeq l^{-1})	1
SO_4^{2-} (μeq l^{-1})	56
TOC (mg l^{-1})	2.8

Sulphur deposition at this site is currently 0.55 keq ha^{-1} $year^{-1}$ (CLAG 1992). The loch has a Ca^{2+}:S ratio of 129, and is not predicted to have acidified on the basis of the diatom critical loads model. The loch has a relatively low alkalinity (<50 μeq l^{-1}), so can be considered susceptible to acid deposition.

Fish cages are currently set on this loch for aquaculture.

A short sediment core was obtained from the deepest point of the loch basin (26.5 m) in May 1992.

Figure 4.9 **Loch C: carbonaceous particle concentrations plotted against sediment depth**

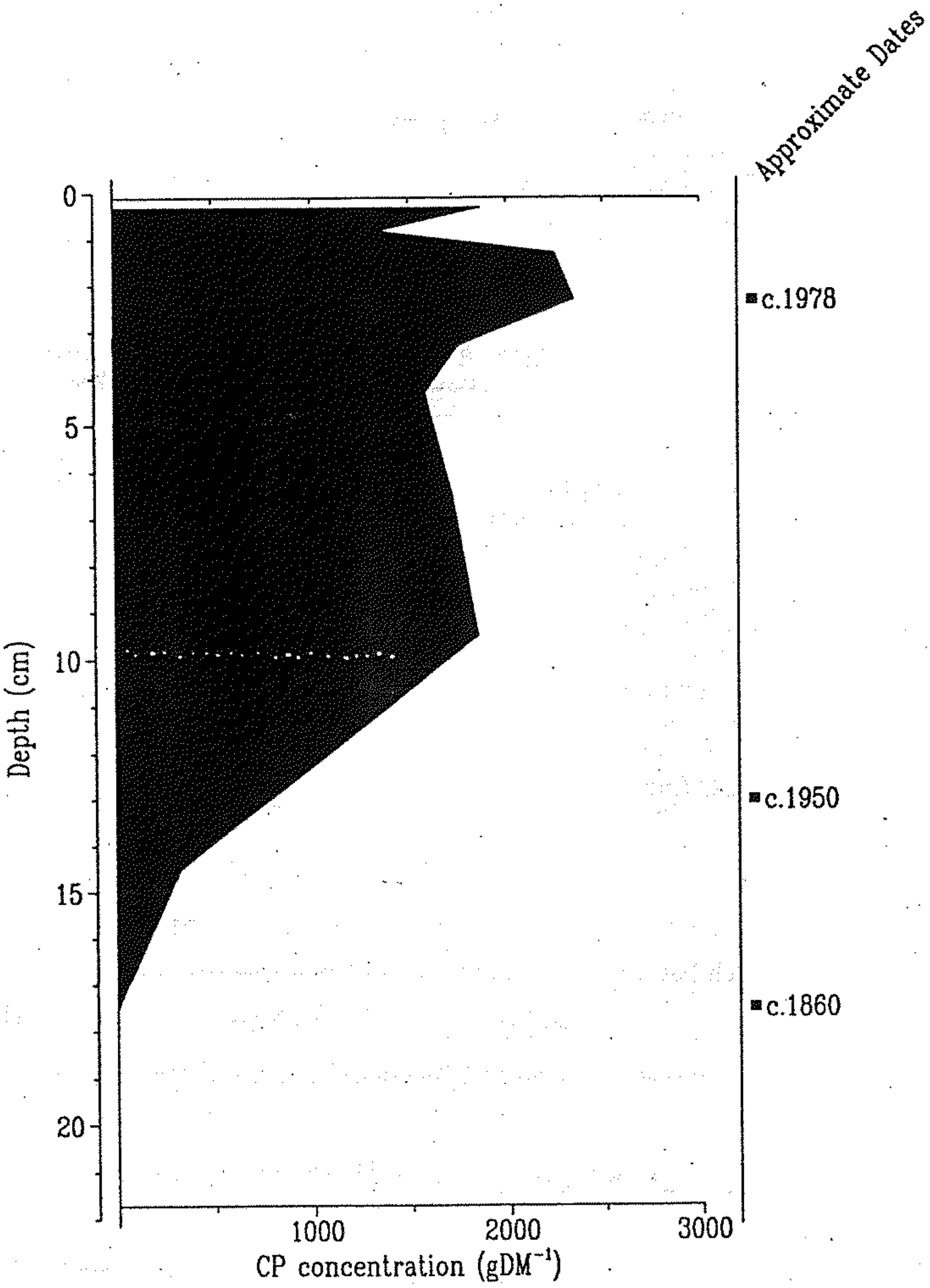
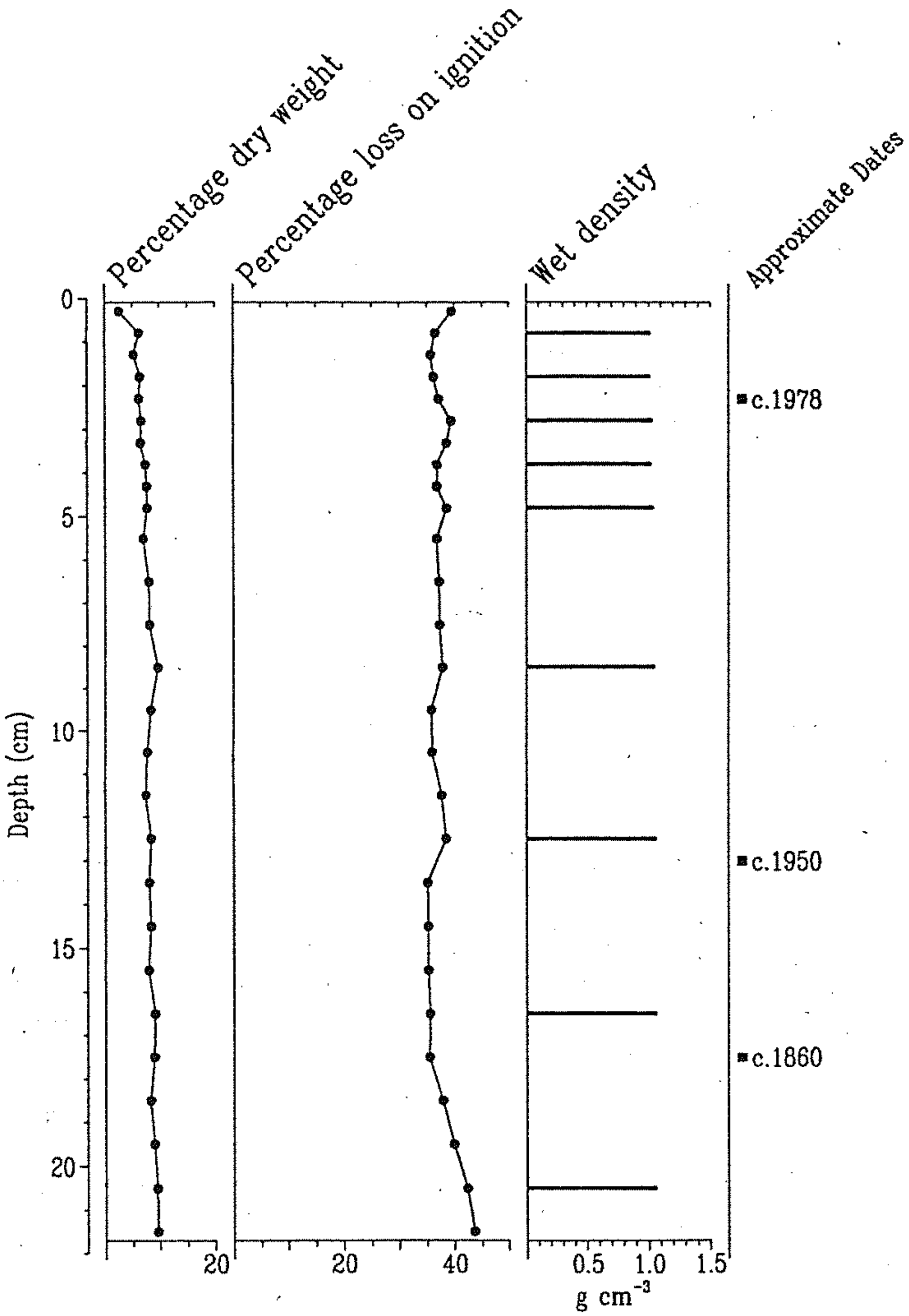


Figure 4.10 Loch C: sediment characteristics



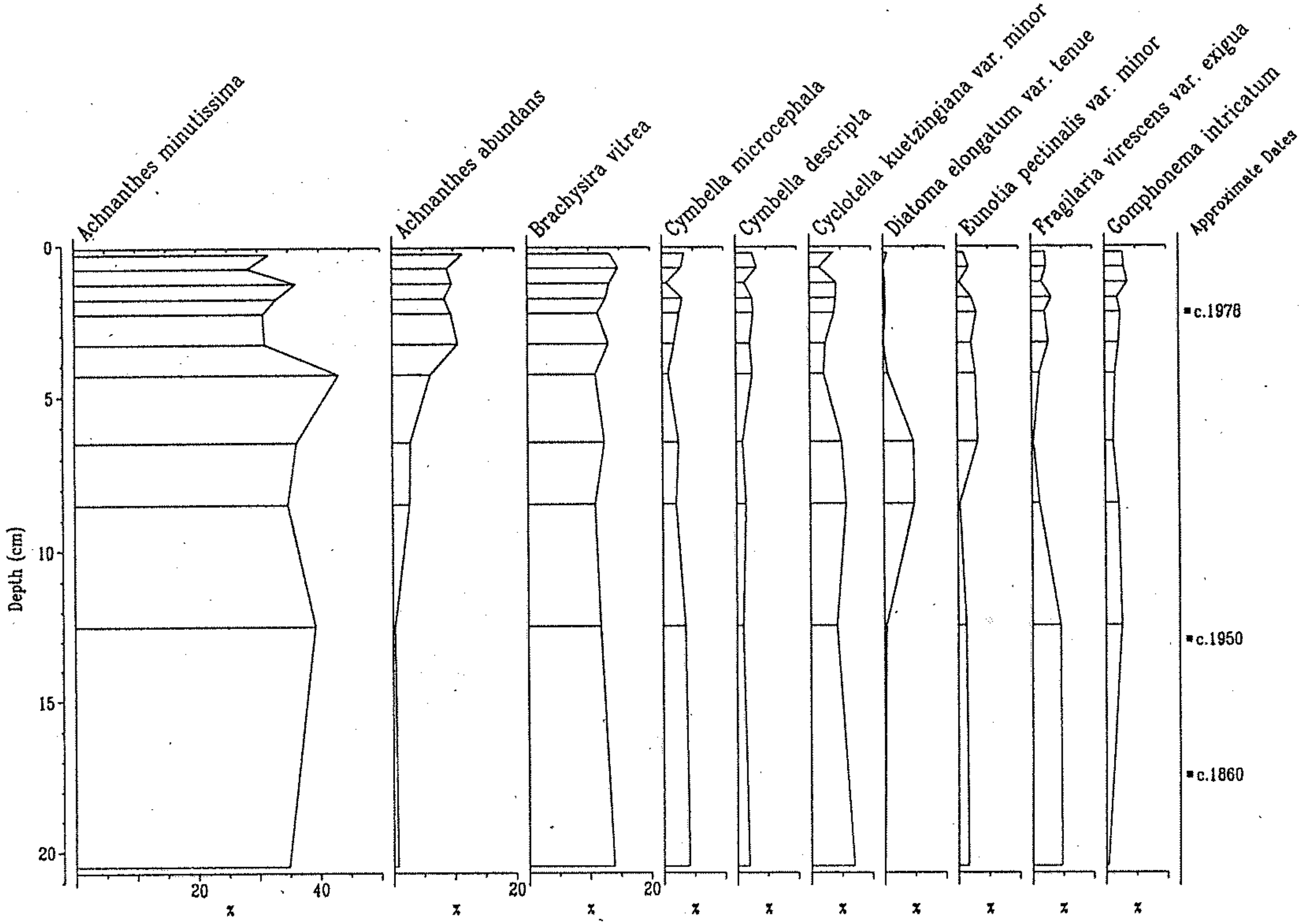


Figure 4.11 **Loch C: summary diatom diagram**

Figure 4.12 **Loch C: pH reconstruction**

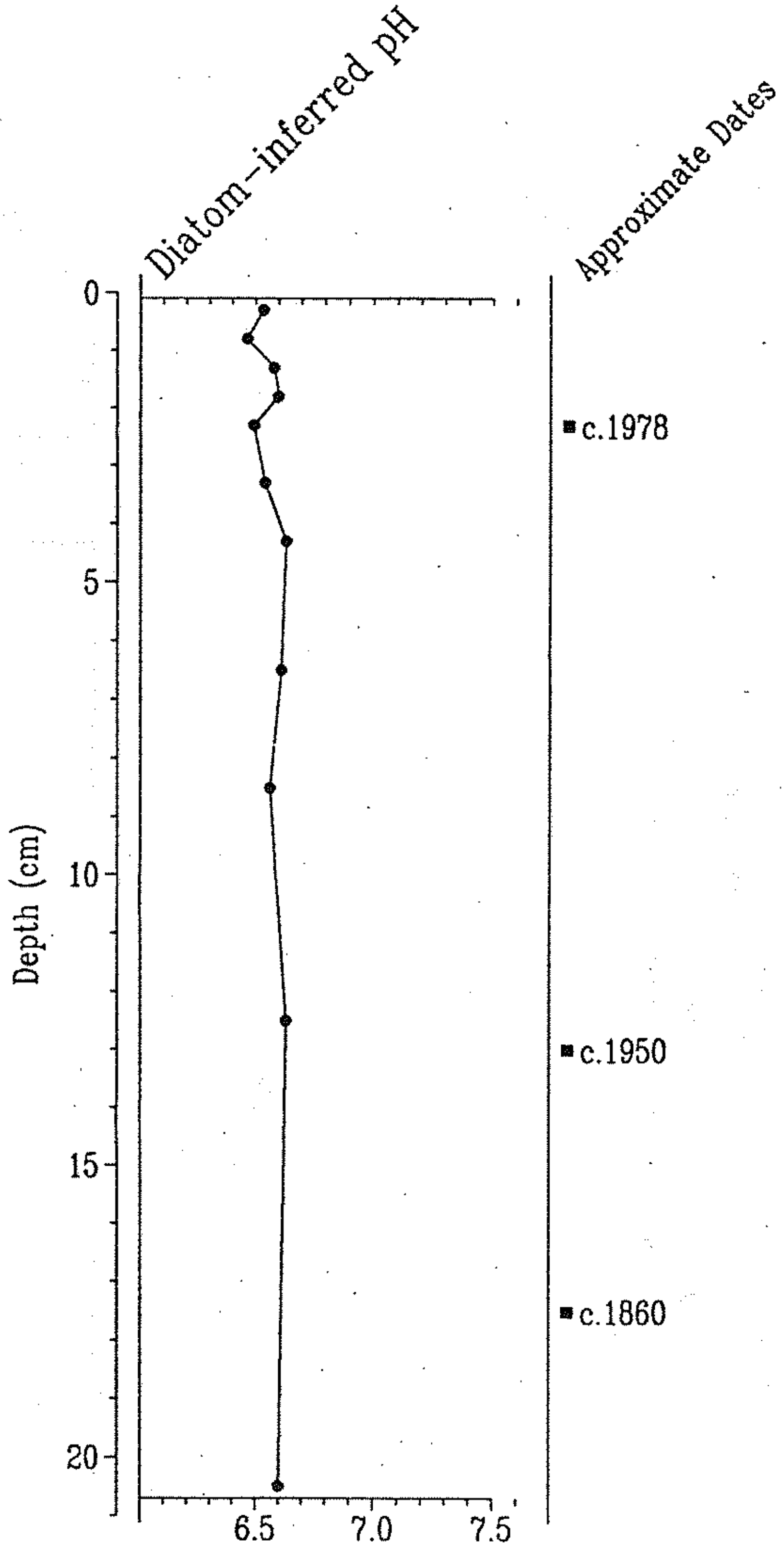
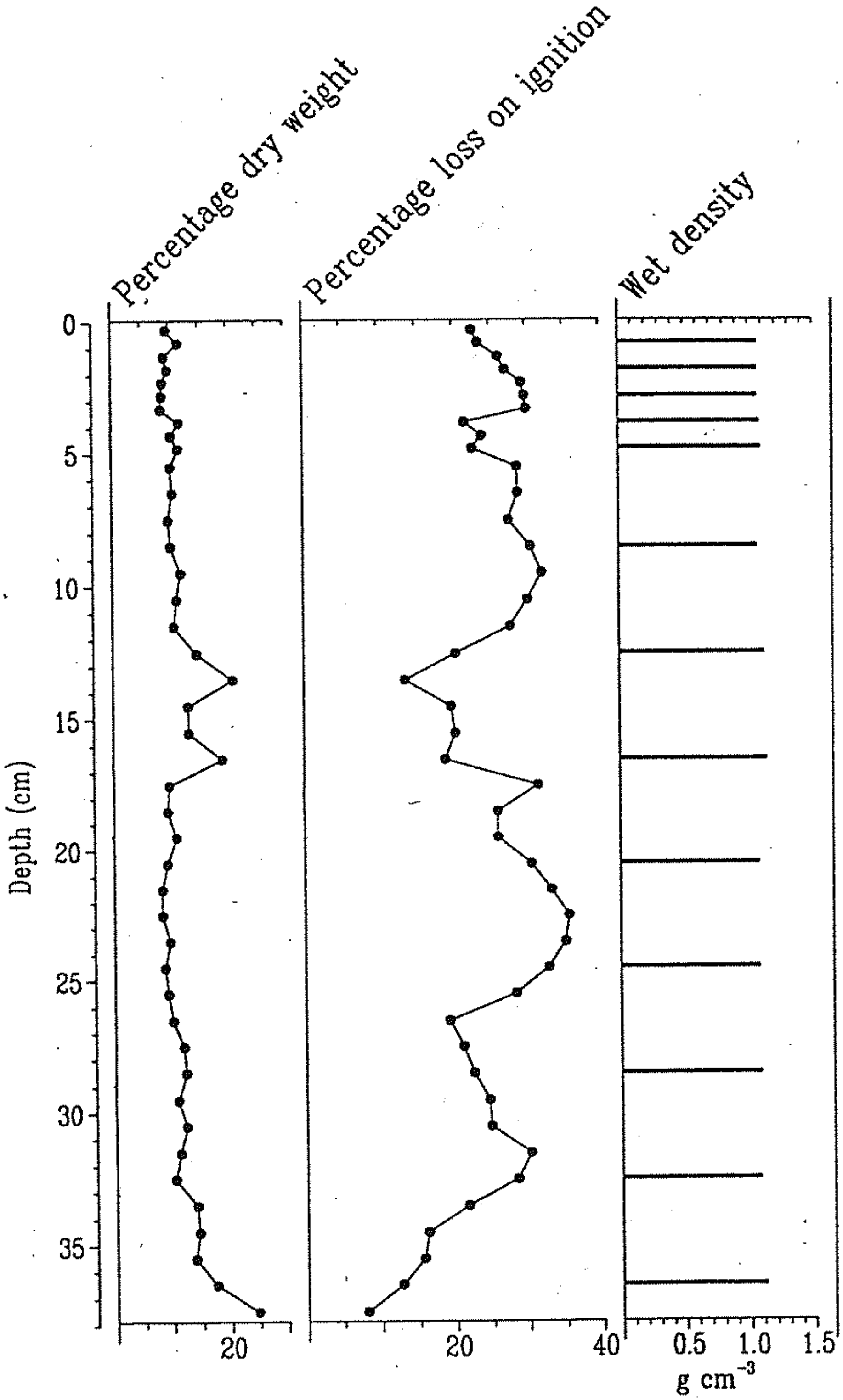


Figure 4.13 **Loch D: sediment characteristics**



Sediment stratigraphy

Percentage dry mass, percentage loss on ignition, and wet density data are shown in Figure 4.13. The sediment consists of dark brown organic detritus, with paler bands of mineral rich material at 4-5 cm and 13-17 cm. These bands are clearly identifiable in the dry weight and LOI curves, and suggest inwashing of mineral material from the catchment. They could result from catchment disturbance and soil erosion, and the sediment accumulation rate in the core could fluctuate accordingly. Carbonaceous particle data is not available for this core, consequently the timing of these inwash events cannot be determined.

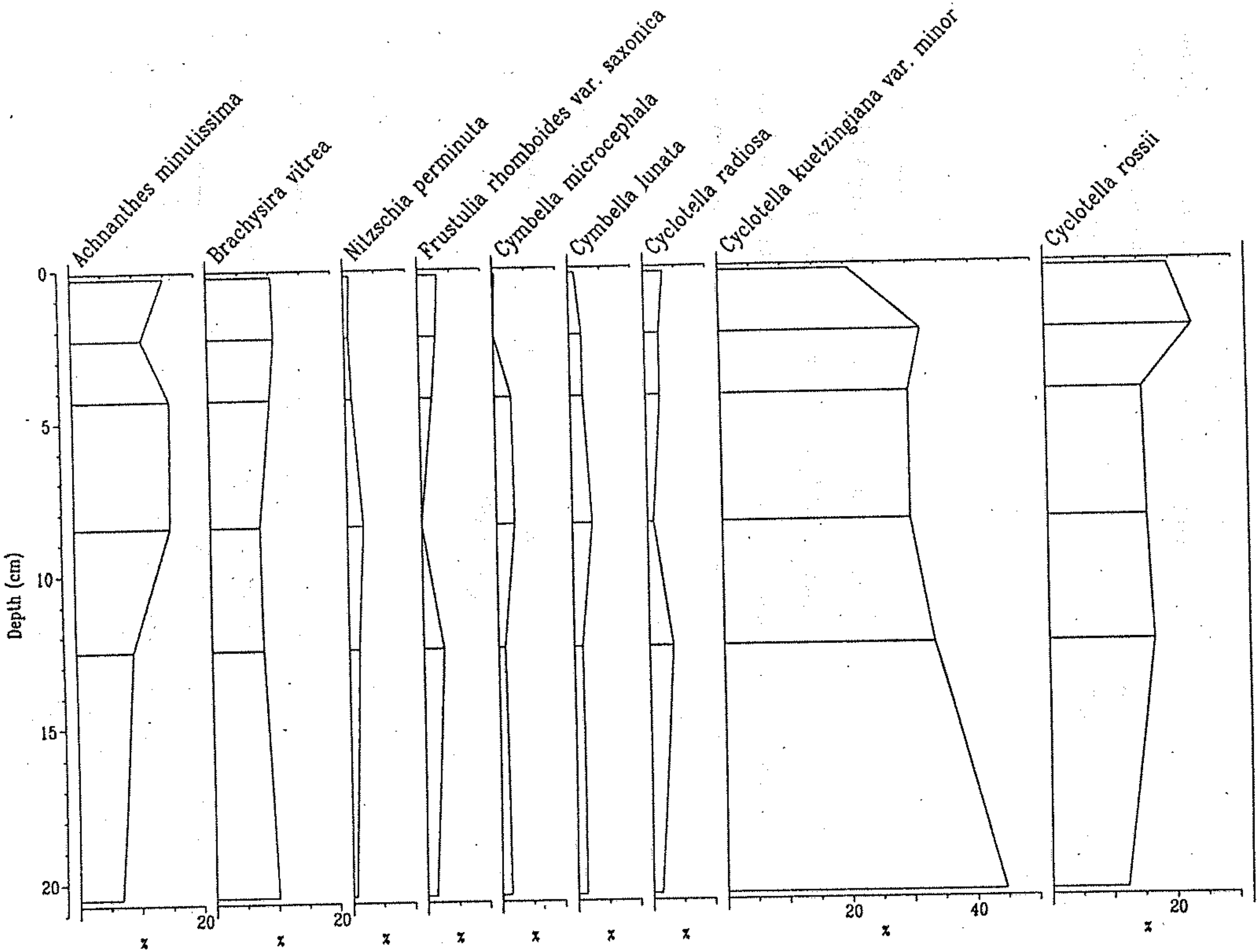
Diatom analysis

A summary diatom diagram for Loch D is shown in Figure 4.14. This indicates relatively stable diatom assemblages throughout the length of the core. The assemblages are dominated by the planktonic taxa *Cyclotella kuetzingiana* var. *minor* and *Cyclotella rossii.* The periphytic species *Achnanthes minutissima* and *Brachysira vitrea* are also common. The flora is indicative of an oligotrophic loch of relatively high alkalinity.

The stability of the diatom assemblages is reflected in the pH reconstruction (Figure 4.15). The reconstructed pH of the uppermost sample is 6.52, whereas the measured contemporary pH is 6.51 (Table 4.8).

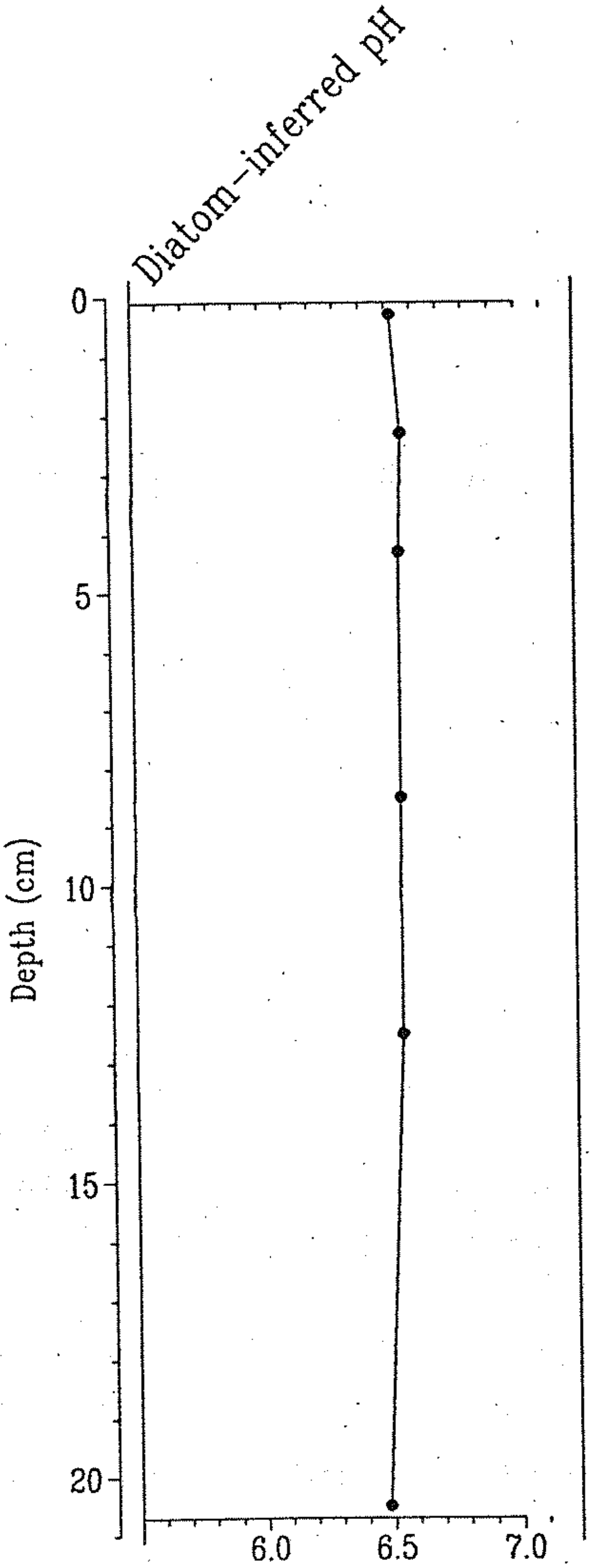
Discussion

The stratigraphic data indicates episodes of inwash of mineral material into Loch D. However, the diatom assemblages are stable throughout the length of the core, indicating stable chemical conditions. The site has not acidified and there is no evidence of nutrient enrichment.



ıgure 4.14 Loch D: summary diaton ˈiagram

Figure 4.15 **Loch D: pH reconstruction**



4e. LOCH E

Site details

Table 4.9 Loch E: site characteristics

Lake altitude (m)	159
Catchment relief (m)	93
Catchment area (ha) (excluding lake)	75
Lake area (ha)	24
Catchment:lake ratio	3.1
Maximum depth (m)	18

Table 4.10 Loch E: summary water chemistry (from Harriman & Christie 1992)

pH	6.46
Alkalinity (μeq l^{-1})	44
Conductivity (μS cm^{-1})	77
Na^{+} (μeq l^{-1})	391
K^{+} (μeq l^{-1})	12
Mg^{2+} (μeq l^{-1})	79
Ca^{2+} (μeq l^{-1})	66
Cl^{-} (μeq l^{-1})	588
NO_3^{-} (μeq l^{-1})	2
SO_4^{2-} (μeq l^{-1})	62
TOC (mg l^{-1})	2.6

Sulphur deposition at this site is currently 0.38 keq ha^{-1} $year^{-1}$ (CLAG 1992). The loch has a Ca^{2+}:S ratio of 174, and is not predicted to have acidified on the basis of the critical loads model. The relatively low alkalinity of the site (<50 μeq l^{-1}) suggests that the site is susceptible to acidification.

The loch was sampled in August 1992. No sediment could be located at the deepest point in the loch basin (18 m), and a short sediment core was obtained from a sub-basin of the loch in a depth of 6.5 m.

Sediment stratigraphy

The percentage dry mass, percentage loss on ignition and wet density data are shown in Figure 4.16. Below 19 cm the sediment is a dark brown mineral mud with LOI c.20%. At 19 cm there is a sharp increase in LOI, and a change in the sediment composition to a more organic, blackish detritus. LOI values between 17 and 9 cm are c.40%. In the top 9 cm of the core the data shows a decrease in the organic matter content.

The increase in LOI at 19 cm may represent the widespread peat erosion event described by Stevenson *et al.* (1990) which occurred in western Britain at approximately 1500-1700 AD. This would suggest a mean accumulation rate in the upper part of the core of 0.38-0.65 mm $year^{-1}$. These values are relatively low for upland lochs Scotland (Battarbee *et al.* 1988).

Diatom analysis

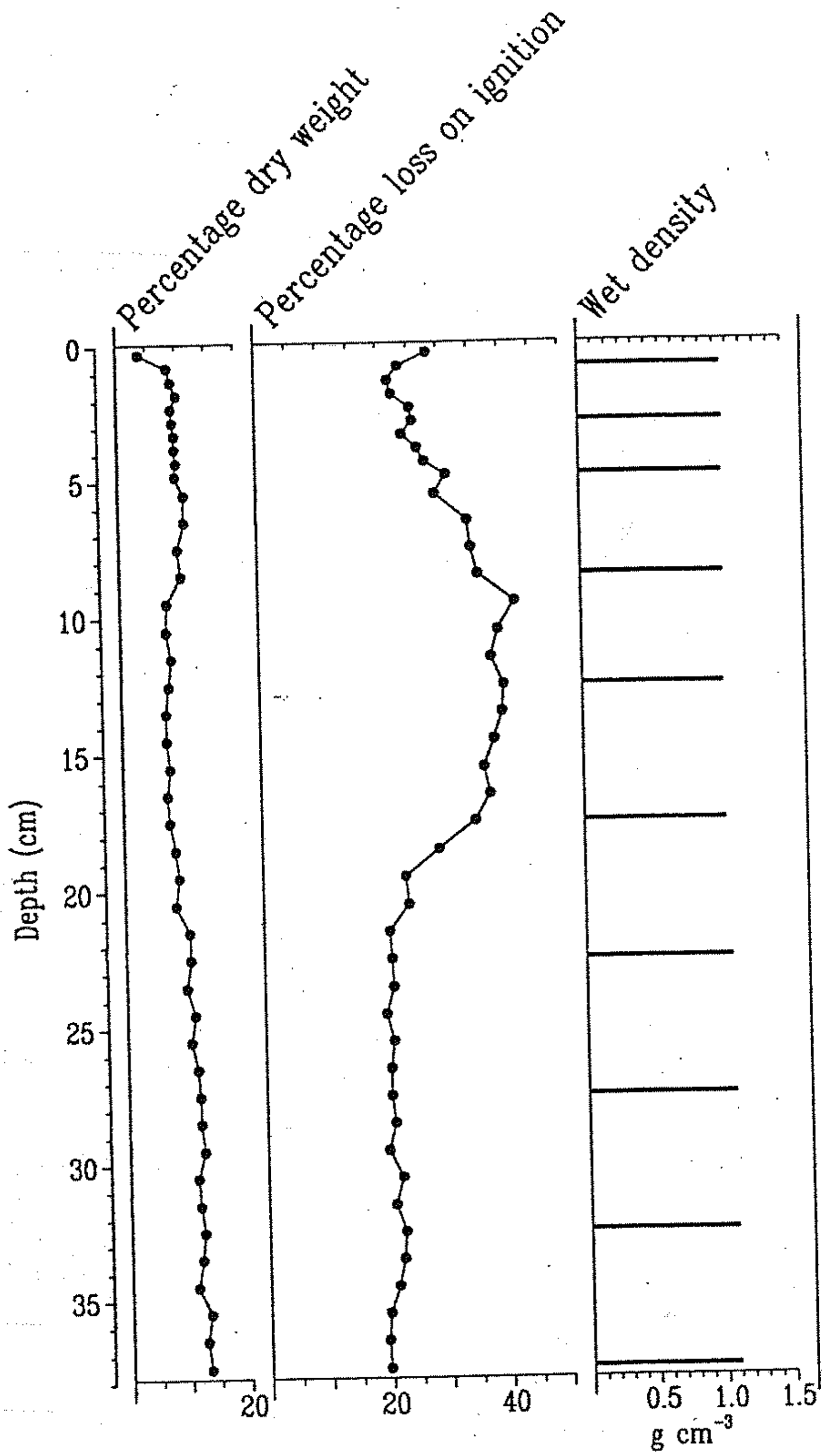
A summary diatom diagram is presented in Figure 4.17. The assemblages are relatively diverse. The planktonic taxa *Cyclotella kuetzingiana* var. *minor* and *Cyclotella rossii* and the periphytic species *Brachysira vitrea* and *Achnanthes minutissima* are dominant. Also common are *Fragilaria virescens* var. *exigua*, *Nitzchia perminuta*, *Cymbella lunata*, *Achnanthes pseudoswazi* and *Cyclotella rossii*. This flora is indicative of an oligotrophic loch of intermediate alkalinity. The diatom assemblages are stable throughout the length of the core.

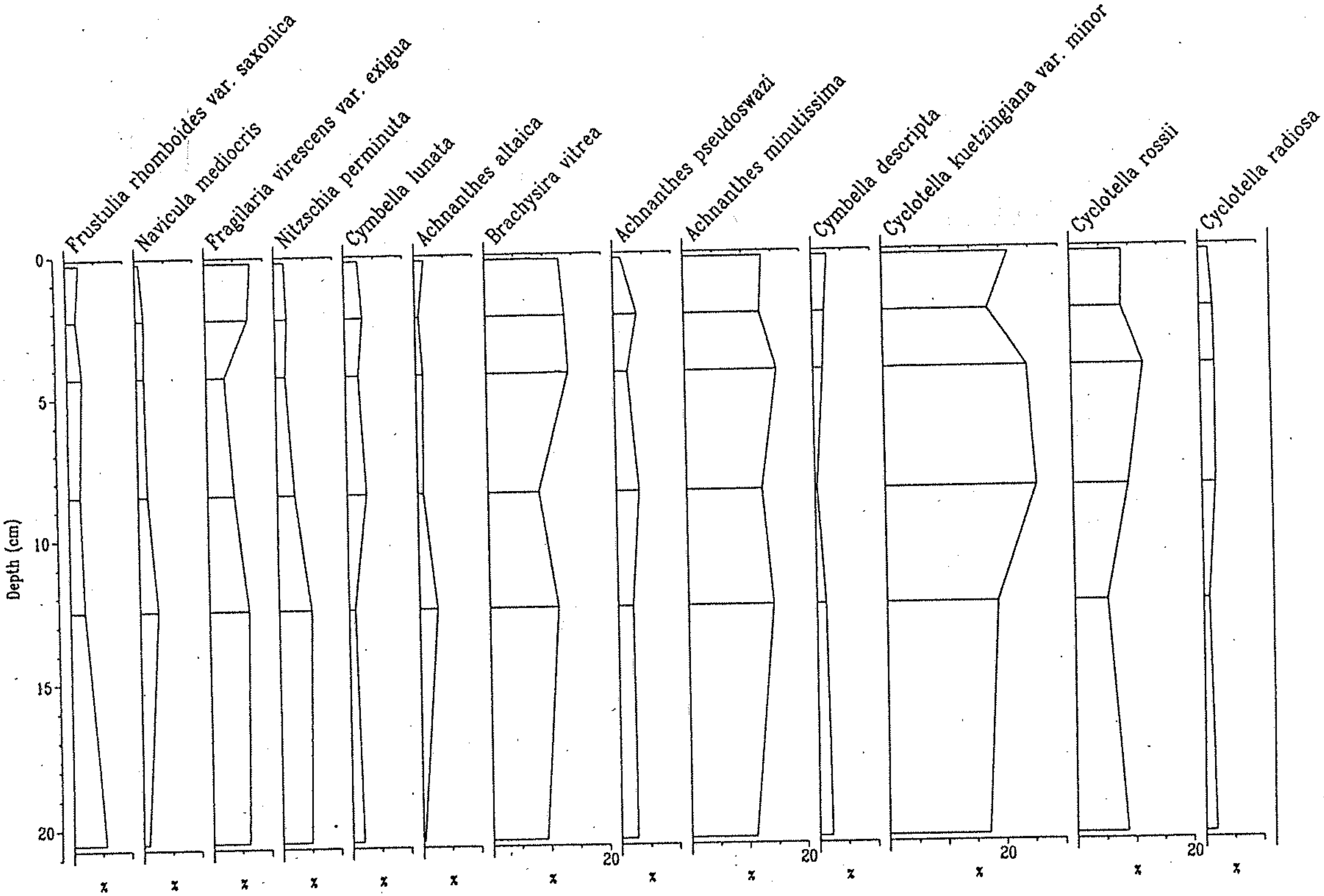
Figure 4.18 shows the pH reconstruction for the core. This indicates a stable pH at approximately 6.4 throughout the length of the core. The reconstructed pH of the uppermost sample is 6.47, whereas the measured pH value is 6.46.

Discussion

The diatom record shows that the chemistry of the loch has been stable throughout the length of the core. The loch has not acidified, and there is no evidence of changes in trophic status.

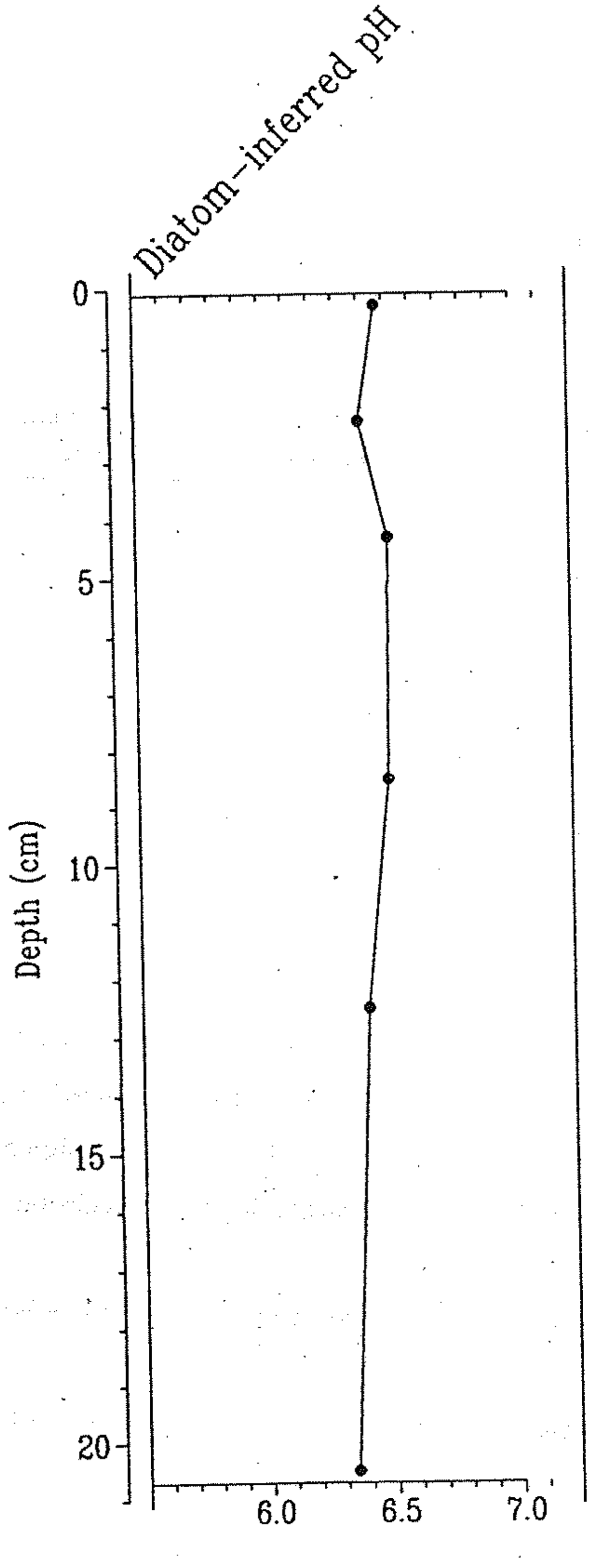
Figure 4.16 **Loch E: sediment characteristics**





gure 4.17 Loch E: summary diatom "agram

Figure 4.18 **Loch E: pH reconstruction**



4f. LOCH F

Site details

Table 4.11 Loch F: site characteristics

Lake altitude (m)	167
Catchment relief (m)	156
Lake area (ha)	52
Catchment area (ha) (excluding lake)	209
Catchment:lake ratio	4.0
Maximum depth (m)	4

Table 4.12 Loch F: summary water chemistry (from Harriman & Christie 1992)

pH	6.9
Alkalinity (μeq l^{-1})	160
Conductivity (μS cm^{-1})	84
Na^+ (μeq l^{-1})	395
K^+ (μeq l^{-1})	28
Mg^{2+} (μeq l^{-1})	120
Ca^{2+} (μeq l^{-1})	193
Cl^- (μeq l^{-1})	572
NO_3^- (μeq l^{-1})	0
SO_4^{2-} (μeq l^{-1})	89
TOC (mg l^{-1})	4.0

Sulphur deposition at this site is currently 0.40 keq ha^{-1} $year^{-1}$ (CLAG 1992). The site therefore ha a Ca^{2+}:S ratio of 482, and is not predicted to have acidified on the basis of the diatom critical loads model. The loch has a high alkalinity (>150 μeq l^{-1}) suggesting that the site is not susceptible to acid deposition.

Part of the catchment of this site was afforested within the last 10 years.

A short sediment core was obtained from the deepest point of the loch (4 m) in August 1992.

Sediment stratigraphy

The sediment consists of a brown organic detritus. Percentage dry mass, percentage loss on ignition and wet density data are shown in Figure 4.19. These data show evidence of a layer of mineral rich material at 15-16 cm. This could represent an inwash event from the catchment. Above 8 cm in the core there is a trend in increasing organic matter content.

Diatom analysis

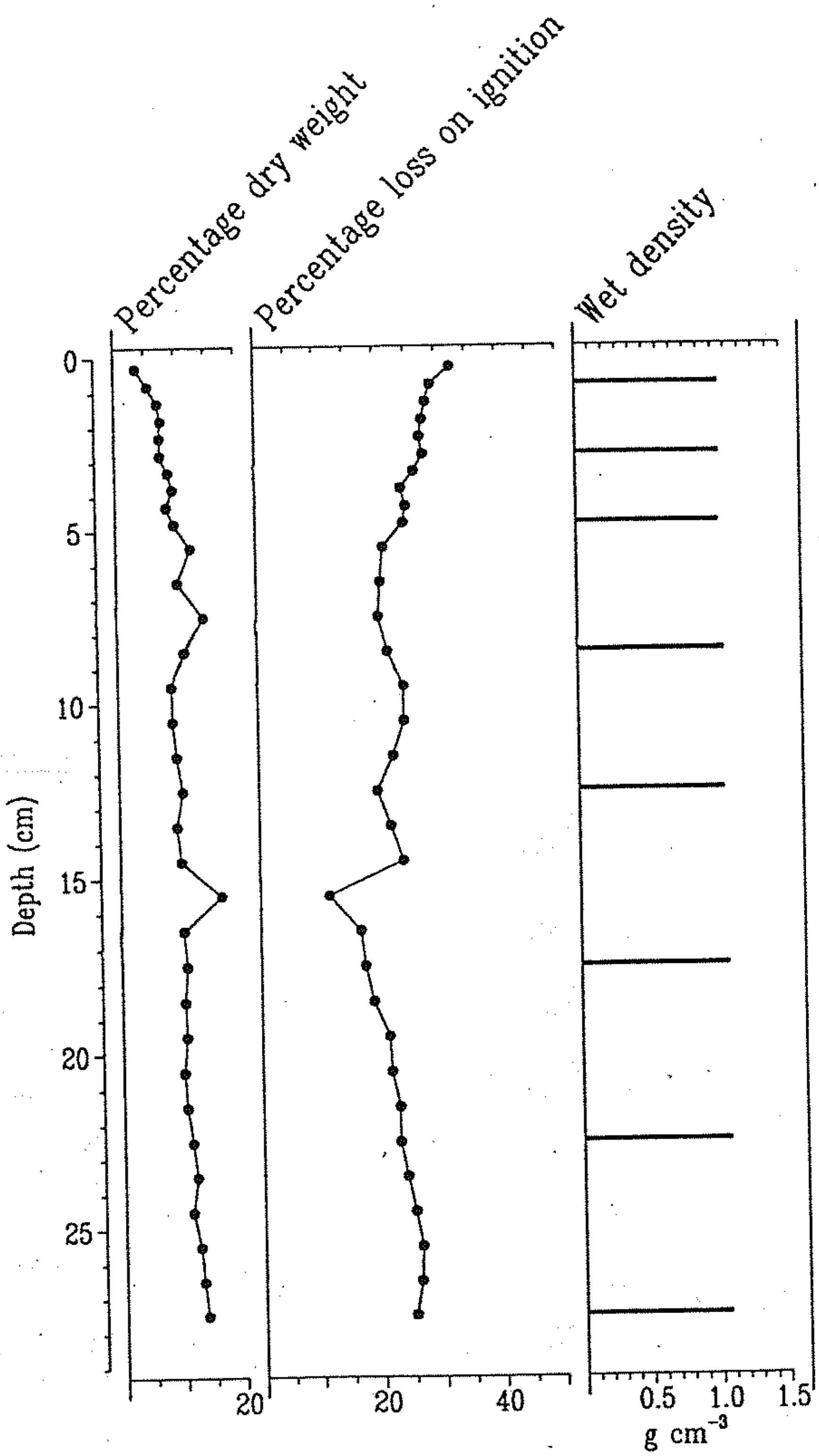
Figure 4.20 shows a summary diatom diagram for the loch. The assemblages are dominated by the *Fragilaria* species *Fragilaria pinnata*, *Fragilaria virescens* var. *exigua*. *Navicula* [cf. *viticosa*], *Achnanthes minutissima*, *Fragilaria construens* var. *construens* and *Fragilaria construens* var. *venter*. Most of these taxa are indicative of oligotrophic waters, but *Fragilaria pinnata*, *Fragilaria construens* var *construens* and *Fragilaria construens* var. *venter* are indicative of more productive, mesotrophic waters. The diatom assemblages are therefore indicative of a high alkalinity, oligo-mesotrophic loch.

There are no major changes in the diatom assemblages through the length of the core, indicating stable chemical conditions. This is reflected in the pH reconstruction which shows a relatively stable pH of approximately 6.7. The reconstructed pH of the uppermost sample is 6.77, whereas the measured pH value is 6.9.

Discussion

The diatom record shows a stable water chemistry, indicative of oligo-mesotrophic conditions, throughout the time-span represented by the core. However, there is no dating control for this core. In a typical non-afforested upland, oligotrophic loch, a 25 cm sediment core should represent the last 150-400 years of sediment accumulation (cf. Lochs A and B). Lochs with afforested catchments sometimes have very high accumulation rates (e.g. Anderson *et al.* 1986), but these normally result in either very high LOI values (>40%) or fluctuations in sediment dry weight and LOI. There is little evidence in the core from Loch F to suggest such rapid accumulation rates.

Figure 4.19 **Loch F: sediment characteristics**



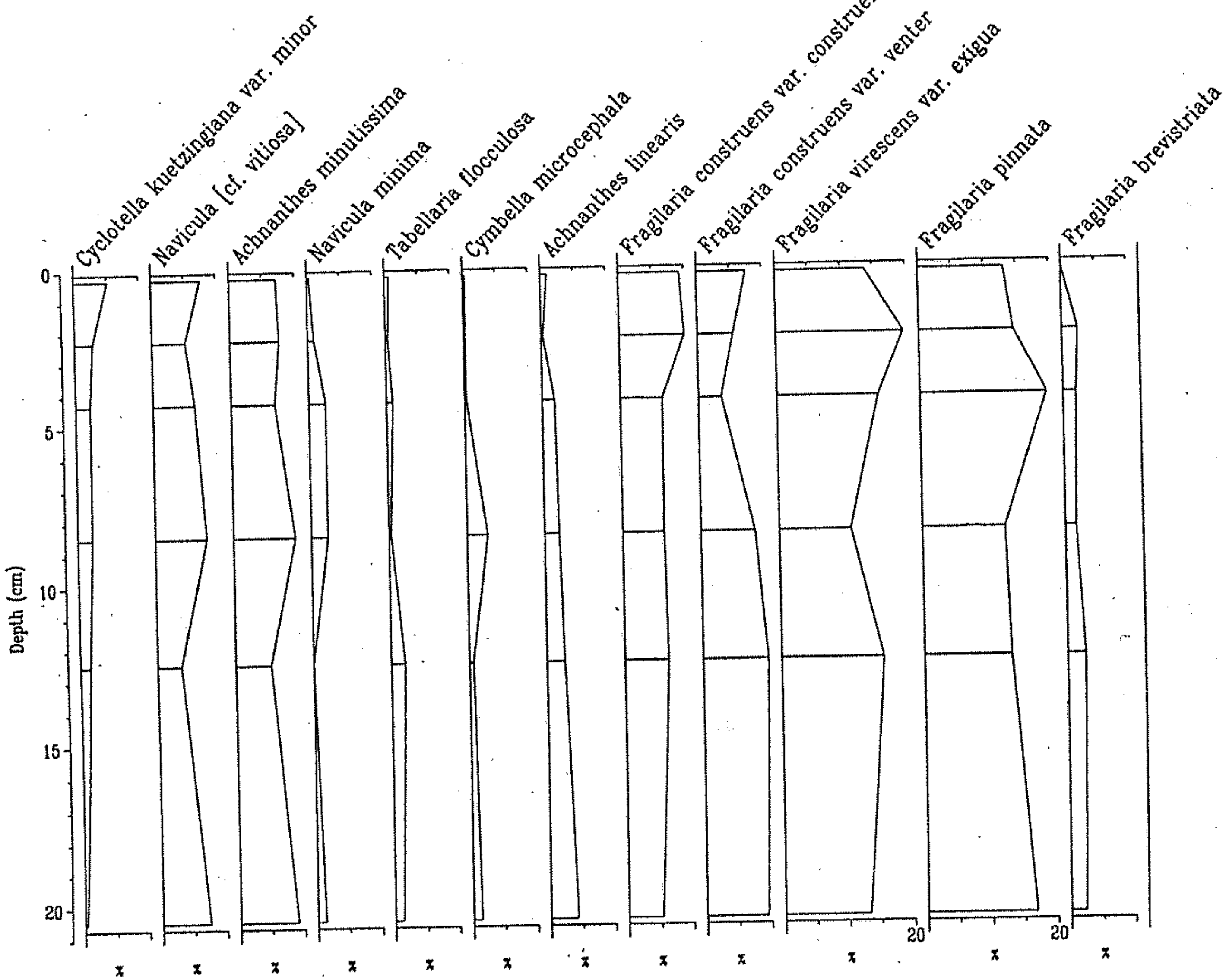
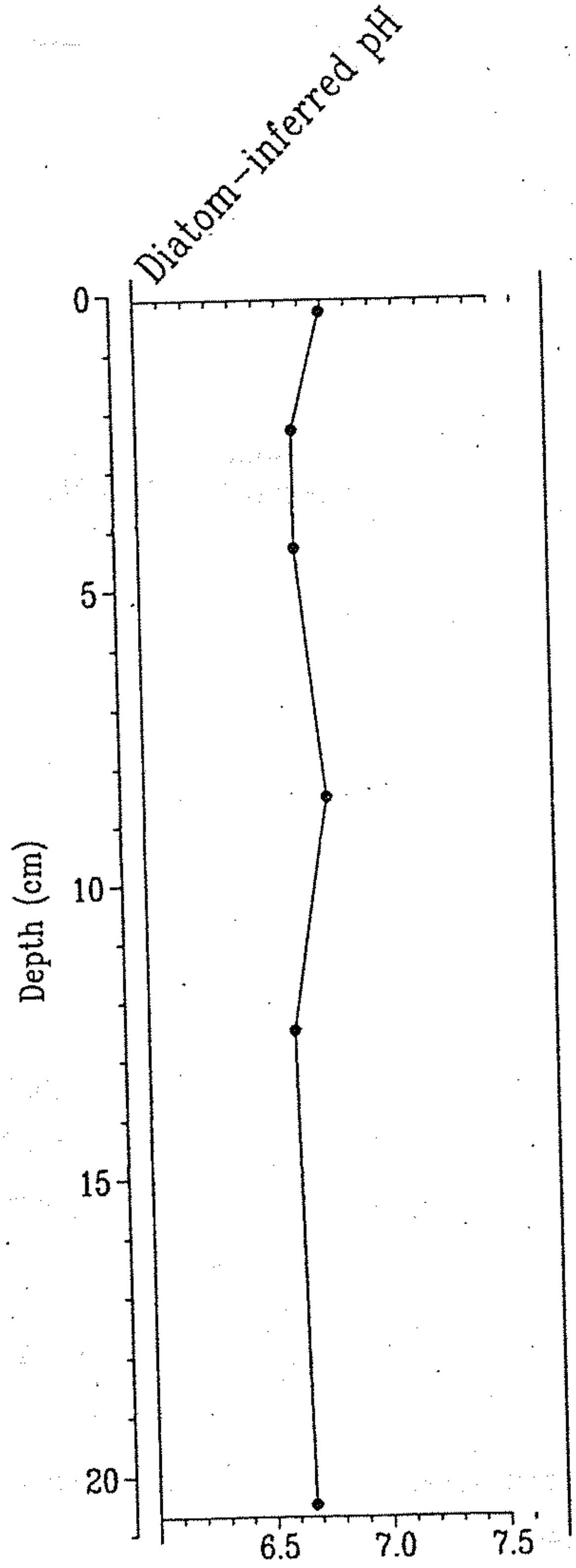


Figure 4.20 Loch F: summary diatom diagram

Figure 4.21 Loch F: pH reconstruction



4g. LOCH G

Site details

Table 4.13 Loch G: site characteristics

Lake altitude (m)	176
Catchment relief (m)	27
Catchment area (ha) (excluding lake)	117
Lake area (ha)	26
Catchment:lake ratio	4.5
Maximum depth (m)	2.5

Table 4.14 Loch G: summary water chemistry (from Harriman & Christie 1992)

pH	6.81
Alkalinity (μeq l^{-1})	119
Conductivity (μS cm^{-1})	88
Na^+ (μeq l^{-1})	443
K^+ (μeq l^{-1})	19
Mg^{2+} (μeq l^{-1})	121
Ca^{2+} (μeq l^{-1})	115
Cl^- (μeq l^{-1})	573
NO_3^- (μeq l^{-1})	0
SO_4^{2-} (μeq l^{-1})	73
TOC (mg l^{-1})	5.0

Sulphur deposition at this site is currently 0.51 keq ha^{-1} $year^{-1}$ (CLAG 1992). The site has a Ca^{2+}:S ratio of 230, and is not predicted to have acidified on the basis of the diatom critical loads model. The loch has a relatively high alkalinity (>100 μeq l^{-1}) so is not susceptible to acid deposition.

Part of the catchment of this site was afforested within the last 10 years.

A mini-Mackereth sediment core was taken from the deepest point of the loch basin in October 1991.

Carbonaceous particle analysis

Carbonaceous particle analysis revealed the presence of very low concentrations of CPs (<500 particles gDM^{-1}) only in the top 2 cm of the sediment core. No carbonaceous particles were identified below a depth of 2 cm. These data suggest that the sediment accumulation rate in the core is extremely high, diluting the CP concentrations. Dates cannot therefore be assigned to the sediment core.

Sediment stratigraphy

The percentage dry mass and percentage loss on ignition data are shown in Figure 4.22. Wet density data are not available for this site. Figure 4.22 indicates marked fluctuations in stratigraphy throughout the length of the core. There are bands of mineral rich material at 73-77 cm, 24-28 cm and 7-14 cm, indicating inwash of mineral material from the catchment. These bands alternate with layers of organic rich material (LOI >30%). The stratigraphy is particularly variable at the top of the core (0-30 cm). The variability in stratigraphy throughout the core is indicative of major inwash of eroded material for the catchment, by inference resulting in high sediment accumulation rates.

Diatom analysis

Diatom concentration rates in the sediment core were extremely low, making it difficult to locate 300 valves per sample. A diatom diagram is therefore not presented in this report, instead a description of the dominant diatoms occurring at different samples in the core is given.

The diatom assemblages at 0-1 cm are dominated by *Fragilaria pinnata*, with *Aulacoseira subarctica*, *Fragilaria construens* var. *venter* and *Achnanthes minutissima* also common. This assemblage is characteristic of oligo-mesotrophic surface waters with pH in the range 6.4-7.0. At 2-3 cm and 4-5 cm the assemblage is less diverse and is dominated by *Fragilaria pinnata*. Between 10 cm and 50 cm diatom concentrations were extremely low with only one or two valves occurring per slide. It was therefore impossible to obtain a reliable indication of the assemblages in this section of the core. At 60-61 cm the assemblage is dominated by *Fragilaria pinnata* with *Fragilaria brevistriata* also common.

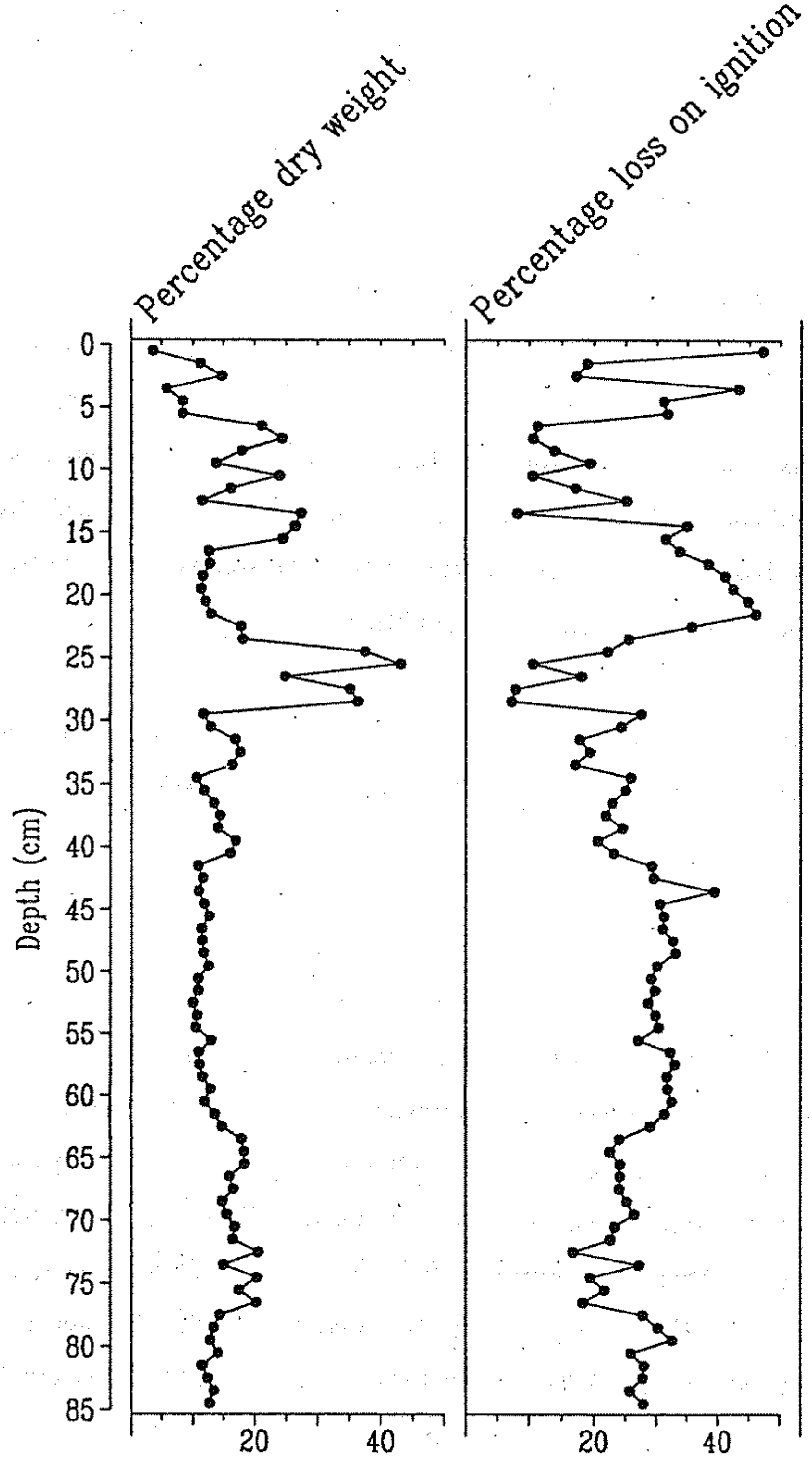
Fragilaria pinnata is therefore the dominant taxon throughout the length of the core. This taxon is indicative of relatively mesotrophic conditions. Without a full count of 300 valves from each level, however, it is impossible to say whether water quality has changed through the time-span represented by the core.

Discussion

The stratigraphic data and the very low concentrations of both carbonaceous particles and diatoms in the sediment core suggest that the sediment accumulation rate at the site is extremely rapid. The site was afforested within the last 10 years, and if the sediment core represents post-ploughing inwash from the catchment the sediment accumulation rate could be as high as 10 cm year^{-1}. Anderson *et al.* (1986) give an example of the significant perturbation of a loch system that can occur when such a large inwash of catchment material occurs. Abundances of planktonic taxa and aquatic macrophytes can occur.

The palaeolimnological record contained within the core is difficult to interpret. The sparse diatom record in Loch G makes it difficult to assess whether water chemistry has varied over the length of the core. The lack of dating control also makes the time-span represented by the core uncertain. Although the data suggest that the site may have suffered severe perturbation from sediment inwash, further studies would be required to clarify the nature, extent, timing and cause of changes at the site.

Figure 4.22 **Loch G: sediment characteristics**



5. CONCLUSIONS

The sites studied were selected to provide information on the extent to which Diver sites may be influenced by water quality changes caused by acidification, nutrient enrichment and afforestation. Evidence for the impact of these factors on the seven lochs will be described in turn.

1) Acidification

Loch A was studied as representative of a site of high sensitivity located in an area of low acid deposition. The palaeolimnological data show that the loch has acidified. Over the past 130 years the pH of the loch has decreased by 0.4-0.5 units. This result is highly significant, as it represents evidence of recent acidification in an area previously considered to be unpolluted (Battarbee 1989). The data show that even in areas of Scotland remote from emissions sources the most sensitive sites may have acidified.

Lochs D and E have relatively low alkalinities (>50 μeq l^{-1}), so are sensitive to acidification. However, neither of these sites have acidified.

2) Nutrient enrichment

The diatom record of Loch B shows evidence of nutrient enrichment over the last decade. Over this period the flora changed from one indicative of oligotrophic waters to one indicative of mesotrophic conditions. Fish cages are currently set on the loch, suggesting a possible source of nutrients. Loch C is located close to Loch B and has a very similar contemporary water chemistry, but has no fish cages set on it. There is no evidence for recent nutrient enrichment in Loch C. These data suggest that the setting of fish cages may have caused a change in the trophic status of Loch B. More detailed study would be required to confirm the timing and extent of the enrichment, and to confirm the cause with certainty.

Fish cages have also been set on Loch D. In this loch, however, the diatom record shows no indication of a change in the nutrient status of this loch.

3) Afforestation

Two sites were investigated where catchment afforestation had taken place, Lochs F and G. Both lochs have contemporary diatom floras indicative of oligo-mesotrophic conditions. Unfortunately, dating control is not available for either site, so it is impossible to say whether the cores taken represent both pre and post-afforestation conditions. Although contemporary water floras indicate mesotrophic conditions, it is difficult to say whether afforestation resulted in changes in water chemistry in these lochs.

At Loch G there is evidence of a very rapid recent sediment accumulation rate that may be the result of inwash following catchment ploughing. Such inwash may have caused perturbation of the loch system, and changes in loch water quality. Future work could build on the results obtained here by obtaining longer sediment cores, and by providing dating control to link the stratigraphic record with the afforestation history.

Recommendations for Future Research

i) Further studies of lochs which are highly sensitive to acidification (Ca^{2+} <40 μeq l^{-1}) to determine the spatial extent of acidification in north-west Scotland.

ii) Collation of a modern diatom/loch-water nutrient data-set to allow quantitative reconstruction of historical nutrient levels (TP and NO_3) from stratigraphic diatom records.

iii) Further studies of lochs on which fish cages have been set to more completely evaluate the role of aquaculture in increasing nutrient levels.

iv) Studies of long sediment cores from afforested sites to more accurately determine the link between catchment ploughing and sediment accumulation rates and to evaluate pre- and post-afforestation water quality conditions.

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7. APPENDIX A: SITE NAMES AND GRID REFERENCES

Site	Site name	Grid reference
Loch A	Loch Clair	NG 999 574
Loch B	Loch nam Brac	NC 179 480
Loch C	Loch na Claise Fearna	NC 201 468
Loch D	Loch Tollaidh	NG 841 785
Loch E	Loch na Curra	NG 823 800
Loch F	Loch Craggie	NC 625 072
Loch G	Loch Sletill	NC 965 470