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Environmental Change Research Centre

Research Report No.92

Sediment survey of the Suffolk Broads
Final Report to English Nature Contract No. NB/T/806/02-04

H. Bennion, A. Burgess, J. Boyle, P.G. Appleby, N. Rose,
C. Sayer and S. Theophile

December 2003

ISSN: 1366-7300

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Executive Summary

This is the final report to English Nature under contract number NB/T/806/02-04: Sediment survey of the Suffolk Broads. This project aims to assess environmental change in four Broads in the River Waveney Valley: Barnby Broad within the Barnby Broad and Marshes Site of Special Scientific Interest (SSSI) and Sprat's Water, Round Water and Woolner's Carr within the Sprat's Water and Marshes, Carlton Colville SSSI. The sites are of international importance for their wildlife but their conservation value is potentially under threat from silt deposition, nutrient enrichment, and successional changes. The results of the project will help to inform future management decisions.

Eleven wide diameter piston cores, approximately 1 m to 1.5 m in length, were taken in March 2003 as follows: four from Barnby Broad, three from Sprat's Water, two from Round Water and two from Woolner's Carr. One core from each lake was dated using a combination of radiometric and spheroidal carbonaceous particle (SCP) based methods. A range of palaeoecological techniques, principally magnetic susceptibility, geochemistry, particle size measurements, and analysis of diatom and macrofossil remains, were used to assess the physical, chemical and biological characteristics of the sediments.

The 1.4 m sediment core taken from **Barnby Broad** extends back to the creation of the broad. Sediment accumulation rates have increased from a relatively steady rate prior to ~1960 of ~0.037 g cm^{-2} yr^{-1} (or ~0.2 cm yr^{-1}) to present rates of ~0.07 g cm^{-2} yr^{-1} (or ~0.9 cm yr^{-1}). On this basis the sections of the lake with only 30 cm of water depth will be silted up in approximately 30 to 40 years. Sediment characterisation analyses showed that the upper ~40-50 cm of the sediment represents the industrial period of nutrient and atmospheric pollution. This amounts to a sediment volume of around 5000 to 7000 m^3. The increase in geochemical P concentrations towards the top of the cores may reflect the increased nutrient status of the site over the last 30 years. There was very little change in the diatoms of Barnby Broad over the last 150 years with the exception of a slight increase in *Stephanodicus parvus* in the upper 30 cm of the core (post 1950) which may signal a rise in nutrient concentrations in recent decades. Three zones were identified in the macrofossil record: 1) an early phase of colonisation (~1500 to ~1750) following peat extraction in the medieval period with abundant charophyte and molluscs remains, 2) an intermediate period (~1750 to ~1850) of semi-terrestrial peat bog with high numbers of bryophyte and sphagnum leaves, bryozoans and *Juncus* seeds, suggesting drainage, and 3) a recent period (post ~1850) representing an open water environment suitable for aquatic plants with remains of macrophytes such as *Chara* spp., *Zannichellia palustris* and *Ceratophylum demersum,* and ephippia of chydorid cladoceran. The biological data indicate that Barnby Broad has been a shallow, clear-water environment for at least the last 150 years. *Chara* spp. oospores were found throughout the core but remains of the more nutrient tolerant plants, *Z. palustris* and *C. demersum,* were found only in the more recent sediments, suggesting enrichment of the system since around the 1950s. High abundance of *Ledigia* spp. in the upper part of the core suggests shallowing and the presence of large numbers of *Daphnia magna* ephippia in the surface sediments indicates that there is less fish predation than in the past.

The 1.4 m sediment core taken from **Sprat's Water** extends back to the creation of the broad. Sediment accumulation rates increased from a relatively steady rate prior to ~1930 of ~0.04 g cm^{-2} y^{-1} (or 0.18 cm yr^{-1}) to very high values in the 1960s of 0.15 g cm^{-2} yr^{-1} (or ~0.6 cm yr^{-1}), followed by a return to those of the pre-1960 period (0.049 g cm^{-2} yr^{-1} or ~ 0.4 cm yr^{-1}). If current rates continue then the lake has a life span of approximately 350 years. Sediment characterisation analyses showed that the upper ~40-50 cm of the sediment represents the industrial period of nutrient and atmospheric pollution. This amounts to a sediment volume of between about 1000 and 1300 m^3. Four zones were identified in the biological records: 1) an early period (~1300 to ~1500) representing an estuarine, marine-influenced environment with remains of foraminifera, 2) the period from ~1500 to ~1700 indicating an open-water habitat able to support phytoplankton with diatoms typical of nutrient-rich, circumneutral to alkaline waters, and aquatic plant remains (particularly water lily), 3) the period from ~1700 to ~1900 with a benthic dominated diatom community and few plant macrofossil or zooplankton remains indicating a change in macrophyte species, habitat shifts and/or a shallowing of the site possibly due to major drainage of the Carlton

Marsh area in the 18th century, and 4) the recent period post ~1900 indicating a nutrient-rich, open water habitat with a diverse non-planktonic and planktonic diatom assemblage, high abundances of the submerged aquatic plant *Ceratophyllum demersum*, zooplankton ephippia and mollusc remains. Statoblasts of the UK BAP species *Lophopus crystallinus*, a freshwater bryozoan, were found in the recent sediments.

The sediment record of **Round Water** has been disturbed by mud pumping in the 1980s, hence it is not possible to assign a chronology to the core. We speculate that the sediment below approximately 30 cm represents material that was not removed during the pumping operation and if this is the case the sediment below this depth is likely to provide a record of the early lake history. The 1 m sediment cores do not quite penetrate the peat layer but the elevated organic matter in the basal layers suggests that the record almost extends back to the creation of the broad. There appears to be a hiatus in the record with the loss of several decades of material (presumably removed by pumping). It is likely that the upper 30 cm of the core is a combination of resettled old material and very recently deposited, unconsolidated new material accumulated over the last few decades. On the basis of recent accumulation rates at neighbouring Sprat's Water, the lake has a life span of around 300 years. The upper 35 cm of sediment had lower heavy metal concentrations than the older sediments suggesting that the recent contaminated sediment has already been removed, and there is no basis for any further removal at present. Three broad zones were identified in the biological records: 1) a lower zone (below ~65 cm) indicating a shallow water environment in the early part of the lake's history, with presence of diatom species and large numbers of bryophytes and bryozoan remains, 2) a middle zone (~30-65 cm) indicating an environment with (tycho)planktonic and a diverse range of epiphytic/epilithic diatoms, open water and plant-associated cladocera, and submerged and floating-leaved (*Nymphaeaceae*) aquatic plants, and 3) an upper zone (0 to ~30 cm) representing recently accumulated material with abundant remains of *Ceratophylum demersum,* but fewer macrofossils of *Nymphaeaceae*, bryozoans and *Ceriodaphnia* spp. and less benthic diatom taxa relative to epiphytic taxa than in the lower zones. *Ceratophylum demersum* appears to have increased in abundance in recent decades, perhaps at the expense of the floating-leaved flora and the benthic diatom community.

The 1 m sediment core from **Woolner's Carr** did not penetrate the peat layer and therefore does not appear to represent the full history of the lake. The data suggest a baseline sedimentation rate of ~0.065 g cm^{-2} yr^{-1} (~0.4 cm yr^{-1}) with brief episodes of rapid sedimentation in excess of 1 cm yr^{-1} at ~2000, ~1987 and ~1969. On the basis of the recent accumulation rates for WOOC1 (1 cm yr^{-1}) the life span of the lake is around 100-150 years. The average composition of the sediment was not well constrained by the two cores as WOOC1 appeared to have twice the accumulation rate of WOOC2. The upper 75 cm of WOOC1 and 40 cm of WOOC2 had maximum concentrations of heavy metals, representing the industrial period. This amounts to a sediment volume of between 500 and 900 m^3. Two major zones were identified in the biological record: 1) a lower zone (pre ~1985) indicating a shallow, open water environment with a diverse benthic and epiphytic diatom flora, high numbers of C*eratophyllum demersum*, and cladoceran remains, and 2) an upper zone (post ~1985) indicating a possible increase in plant density over approximately the last 20 years with higher abundances of planktonic and epiphytic diatom taxon relative to benthic taxa, and high *Ceratophyllum demersum* and algal remains. Statoblasts of *Lophopus crystallinus* were present throughout the core, including the surface sediments, indicating that Woolner's Carr provides a suitable habitat for this BAP species.

Recommendations

Based on the success of the previous mud pumping operation, the severe shallowing of the lake, the lack of macrophytes in the northern section and the existing control on external sources of sediment, removal of sediment in the northerly part of Barnby Broad is recommended. Sediment removal is not recommended, however, at Sprat's Water, Round Water and Woolner's Carr. All three lakes currently support a high volume of submerged plants and clear water conditions, and there is no evidence of major ecological change over approximately the last 150 years. Water depth is not currently a limiting factor at these sites. While there is some evidence of slight enrichment with an increase in plant biomass and the appearance of nutrient tolerant plants in recent years, the Sprat's Marshes sites have not switched from a plant-dominated state to a plankton-dominated, turbid state, and appear to be able to tolerate the current nutrient loads. The changes in the diatom and macrofossil records were relatively minor compared to those seen in other lowland water bodies subject to eutrophication. Risk of disturbance to the rich array of habitats by any sediment removal operation is a major concern. Statoblasts of the UK BAP species *Lophopus crystallinus* were found in both the Sprat's Water and Woolner's Carr cores and sediment removal may threaten this rare species. Any physical disturbance to bankside substrates such as reeds and woody debris on which the bryozoan grows should be avoided. Measures to reduce the sediment and nutrient load from local farmland to the broads, and particularly to the dyke which feeds the system, are advised. Management plans should include agri-environment schemes such as creation of buffer strips to reduce nutrient enrichment and sediment inputs from adjacent arable fields, and either land purchase or involvement of landowners in a stewardship scheme. We advocate protection and surveillance of the sites rather than restoration. Both chemical and biological monitoring are recommended to assess any change and to inform future management decisions. Bryozoan and fish surveys are advised.

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Acknowledgements

The authors would like to thank the following people for their assistance during this study: David Rowley at Barnby Broad, and Steve Aylward and Steve Milton at Carlton Marshes Reserve, Mike Hughes for drawing the maps, Jane Knott and Phil Henderson for help in the field, and James Shilland for technical support.

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1. INTRODUCTION AND PROJECT OBJECTIVES

1.1 Study rationale

The Suffolk Broads lie in the River Waveney Valley close to Lowestoft. There are four in total. Barnby Broad within the Barnby Broad and Marshes Site of Special Scientific Interest (SSSI) and Sprat's Water, Round Water and Woolner's Carr within the Sprat's Water and Marshes, Carlton Colville SSSI.

The sites are of international importance for their wildlife and are included within The Broads candidate Special Area of Conservation, and The Broadland Special Protection Area. There is evidence to indicate, however, that the conservation value of these broads is declining due to a variety of factors including silt deposition, nutrient enrichment, and successional changes.

The purpose of this study is to provide information on environmental change in all four broads which can then allow informed decisions to be made concerning remedial action.

1.2 Objectives

The objectives of the study were to:

1. Provide a chronology of the lake sediments
2. Infer past nutrient conditions from analysis of diatom assemblages and geochemical phosphorus (P) in sediment cores.
3. Assess changes in the aquatic vegetation from analysis of plant macrofossils in sediment cores.
4. Identify sediment distributions.
5. Characterise the sediments.

2. METHODS

2.1 Coring and lithostratigraphic analyses

Eleven wide diameter piston cores (7.4 cm), approximately 1 m to 1.5 m in length, were taken in March 2003 as follows: four from Barnby Broad, three from Sprat's Water, two from Round Water and two from Woolner's Carr. The cores were extruded in the laboratory at 1 cm intervals from 0-50 cm and thereafter at 2 cm intervals to the core base. The main characteristics of the sediment and any stratigraphic changes were noted. The percentage dry weight (%DW) which gives a measure of the water content of the sediment, and percentage loss on ignition (%LOI) which gives a measure of the organic matter content, were determined for each sample of the mastercores and alternate samples of the other cores by standard techniques (Dean, 1974).

2.2 Radiometric dating and spheroidal carbonaceous particle analyses (SCPs)

A reliable method of establishing a chronology for sediment cores is to use radiometric dating techniques. ^{210}Pb occurs naturally in lake sediments as one of the radioisotopes in the ^{238}U decay series. It has a half-life of 22.26 years, making it suitable for dating sediments laid down over the past 100-150 years. The total ^{210}Pb activity in sediments comprises supported and unsupported ^{210}Pb (Oldfield & Appleby, 1984). In most samples the supported ^{210}Pb can be assumed to be in radioactive equilibrium with ^{226}Ra and the unsupported activity at any level of a core is obtained by subtracting the ^{226}Ra activity from the total ^{210}Pb.

^{210}Pb dates for sediment cores can be calculated using both the constant rate of ^{210}Pb supply (CRS) model and the constant initial ^{210}Pb concentration (CIC) model (Appleby & Oldfield, 1978). The CRS model is most widely accepted; it assumes that the ^{210}Pb supply is dominated by direct atmospheric fallout, resulting in a constant rate of supply of ^{210}Pb from the lake waters to the sediments irrespective of net dry mass accumulation rate changes. If there are interruptions to the ^{210}Pb supply, for example sediment focusing, dates are calculated either by the CIC model or by using a composite of both models. The factors controlling the choice of model are described in full in Appleby & Oldfield (1983), and Oldfield & Appleby (1984). ^{137}Cs activity in sediments prior to the 1986 Chernobyl nuclear accident derives mainly from nuclear weapons testing fallout. Where this isotope is strongly adsorbed on to sediments, the activity versus depth profile is presumed to reflect varying fallout rate and useful chronological markers are provided by the onset of ^{137}Cs fallout in 1954, and peak fallout in 1963.

Sediment samples from four cores, Barnby Broad (BARB4), Sprat's Water (SPRA1), Round Water (ROUW2) and Woolner's Carr (WOOC1) were analysed for ^{210}Pb, ^{226}Ra, and ^{137}Cs by direct gamma assay in the Liverpool University Environmental Radioactivity Laboratory, using Ortec HPGe GWL series well-type coaxial low background intrinsic germanium detectors (Appleby *et al*. 1986). ^{210}Pb was determined via its gamma emissions at 46.5keV, and ^{226}Ra by the 295keV and 352keV γ-rays emitted by its daughter isotope ^{214}Pb following three weeks storage in sealed containers to allow radioactive equilibration. ^{137}Cs was measured by its emissions at 662keV. The absolute efficiencies of the detectors were determined using calibrated sources and sediment samples of known activity. Corrections were made for the effect of self absorption of low energy γ-rays within the sample (Appleby *et al.* 1992). Supported ^{210}Pb activity was assumed to be equal to the measured ^{226}Ra activity and unsupported ^{210}Pb activity was calculated by subtracting supported ^{210}Pb from the measured total ^{210}Pb activity. Radiometric dates were calculated using the CRS ^{210}Pb dating model (Appleby & Oldfield, 1978), and the 1963 depth determined from the ^{137}Cs stratigraphic record. Use of the CIC model was precluded either by the non-monotonic nature of the ^{210}Pb record or the large standard errors arising from the very low concentrations. Definitive chronologies based on an assessment of all the data were calculated using the methods described in Appleby (2001).

Sediment samples from the same four cores as those analysed using radiometric techniques, were analysed for spheroidal carbonaceous particles (SCPs) using the method described in Rose (1994). This technique removes unwanted sediment fractions by means of sequential mineral acid attack leaving a suspension of mainly carbonaceous material in water. A known fraction of this final suspension is then evaporated on a coverslip, mounted on a microscope slide, and the number of SCPs counted using a light microscope at 400x magnification. Concentrations of SCPs are expressed as number of SCPs per gram dry mass of sediment (or gDM^{-1}).

Dates are ascribed to the sediment profiles using the cumulative SCP percentage profile calibrated for this region of the UK from a number of previously radiometrically dated sediment cores (Rose & Appleby, in prep). Dates for each 10-percentile of the cumulative SCP profile, from the start of the record (0%) to the concentration peak (100%), can be allocated to the core. The Suffolk Broads sites fall in the region classified as 'south and central England' where the concentration peak is expected to occur at 1970 ± 5 years and, therefore, 11 dates can be placed on the sediment cores between 1850 and 1970. These dates, combined with the date of sampling (2003), provide the basis for the SCP derived chronologies for these cores.

There are errors associated with both radiometric dating and the chronologies based on SCP profiles and, therefore, the results of the two sets of analyses were combined to produce a corrected chronology for each core.

2.3 Magnetic susceptibility

Magnetic parameters were measured on all cores at the University of Liverpool. Low field AC magnetic susceptibility was measured using a dual frequency (470 Hz = χ_{LF} , 4700 Hz = χ_{HF}) Bartington Instruments MS2 sensor. Anhysteretic remnant magnetisation (ARM) was induced in a steady field of 0.1 mT with a parallel peak alternating field of 100 mT using a DTECH AF demagnetiser and measured on a Molspin spinner magnetometer. Acquisition of isothermal remanent magnetisation (IRM) in fields of 1 T (SIRM), -20 mT ($IRM_{-20\ mT}$), and –300 mT ($IRM_{-300\ mT}$) was carried out using a Molspin pulse magnetiser and measured on a Molspin spinner magnetometer. SOFT is calculated as (SIRM- $IRM_{-20\ mT}$)/2 and HIRM as (SIRM- $IRM_{-300\ mT}$)/2, both on a mass specific basis. HARD% is 100 × (HIRM/SIRM). FD% is 100 × $(\chi_{LF} - \chi_{HF})/\chi_{LF}$.

2.4 Sediment geochemistry and particle size analysis

All geochemical analyses were undertaken at the Geography Department, University of Liverpool. Total silicon (Si), calcium (Ca), iron (Fe), sulphur (S), rubidium (Rb) and strontium (Sr) were measured on all cores using energy dispersive isotope-source X-Ray fluorescence (XRF) following the techniques described in Boyle (2000).Total cadmium (Cd), copper (Cu), lead (Pb) and zinc (Zn) were measured on nitric acid extracts by flame atomic absorption with a Unicam 939 Atomic Absorption Spectrophotometer (AAS). A STATS tube was used for Cd and Pb to enhance sensitivity. Phosphorus (P) was measured on nitric acid extracts using spectrophotometry. For all elements quality control was achieved using international Certified Reference Materials.

Particle size distributions were measured using a Coulter LS130 Laser Granulometer.

2.5 Diatom analyses

In the absence of long-term historical water chemistry data, the sediment accumulated in lakes can provide a record of past events and past chemical conditions (e.g. Smol, 1992). Diatoms (*Bacillariophyceae*) are unicellular, siliceous algae and their silica valves are generally well preserved in most lake sediments. Diatoms are sensitive to water quality changes and are, therefore, good indicators of past lake conditions such as lake pH, nutrient concentrations and salinity.

Approximately ten sub-samples from each of the four mastercores, selected to cover the period of interest, were prepared and analysed for diatoms using standard techniques (Battarbee, 1986; Battarbee *et al*., 2001). Fewer samples were analysed in BARB4 due to severe dissolution of diatoms below ~50 cm. At least 300 valves were counted from each sample using a Leitz research microscope with a 100x oil immersion objective (magnification 1000x) and phase contrast. Principal floras used in identification were Krammer & Lange-Bertalot (1986, 1988, 1991a, b) although other taxonomic floras and references were employed as necessary. All slides are archived at the ECRC. Information on the life-form preference of each taxon was obtained from both the literature and personal observations in order to describe each of the common species as either predominantly benthic (associated with sediment substrates), epiphytic (associated with plant substrates), epilithic (associated with stony substrates) or planktonic (living in the open water). A simple measure of floristic diversity for each sample was calculated as the number of species divided by the total valve count.

All diatom data are expressed as percentage relative abundance (% relative abundance). Diatom concentrations were not determined. Cluster analysis was performed on the diatom core data to identify the major zones in the diatom profiles using CONISS (Grimm, 1987), implemented by TILIA and TILIAGRAPH (Grimm, 1991). CONISS is a program for stratigraphically constrained cluster analysis by the method of incremental sum of squares.

2.6 Diatom transfer functions

In recent years, the technique of weighted averaging (WA) regression and calibration, developed by ter Braak (e.g. ter Braak & van Dam, 1989), has become a standard technique in palaeolimnology for reconstructing past environmental variables. A predictive equation known as a transfer function is generated that enables the inference of a selected environmental variable from fossil diatom assemblages, based on the relationship between modern surface-sediment diatom assemblages and contemporary environmental data for a large training (or calibration) set of lakes. This approach has been successfully employed to quantitatively infer lake total phosphorus (TP) concentrations (Hall & Smol, 1999), whereby modern diatom TP optima and tolerances are calculated for each taxon based on their distribution in the training set, and then past TP concentrations are derived from the weighted average of the optima of all diatoms present in a given fossil sample. The methodology and the advantages of WA over other methods of regression and calibration are well documented (e.g. ter Braak & van Dam, 1989).

A diatom-TP transfer function has been generated from 152 relatively small, shallow (< 10 m maximum depth), productive lakes in six regions of Northwest Europe (south-east England, the Cheshire and Shropshire meres, Northern Ireland, Denmark, Sweden and Wales) which is able to reconstruct epilimnetic TP concentrations with reasonable accuracy (Bennion *et al*., 1996). Annual mean TP concentrations in the training set range from 5-1200 µg TP l^{-1}, with a median value for the dataset of 104 µg TP l^{-1}. The transfer function was developed using the method of WA partial least squares (WA-PLS) which is an extension of WA that uses the residual correlation in the diatom data to improve the predictive power of the WA regression coefficients (ter Braak & Juggins, 1993). This is done through the selection of a small number of components, the optimum number of components being estimated by jack-knifing cross-validation. The optimum number of components in the TP model used here was two (see Bennion *et al*., 1996 for further details). However the two component model (WA-PLS2) only slightly improves on the one component model (WA-PLS1) (which equates to simple WA) and, therefore, both are applied in this study.

The errors of the models are described by the root mean square error (RMSE) which essentially summarises the difference between the measured values for the training set of lakes and the diatom inferred values generated by the model. These are calculated based on the original training set (the apparent RMSE) and more realistically on a cross-validated test set (the RMSE of prediction or RMSEP). The lower the error, the better the model performs. Both models perform well and have relatively low errors of prediction with a RMSEP for WA-PLS1 and WA-PLS of 0.22 and 0.21 $\log_{10}$ µg TP l^{-1}, respectively.

The one and two component models were applied to the core data following taxonomic harmonisation between the training set and core species data. The TP data used in the models were $\log_{10}$-transformed annual mean concentrations. The reconstructions were implemented using CALIBRATE (Juggins & ter Braak, 1993).

2.7 Macrofossil analysis

Approximately ten sub-samples from each of the four mastercores, selected to cover the period of interest, were prepared and analysed for macrofossils. Sediment sample sizes were determined both by mass and volume, and samples were divided into two size fractions as follows. Samples were washed through 350 µm and 125 µm sieves. The entire retent of the 350 µm was examined using a stereo-microscope at 10-40x magnification and identifiable plant remains enumerated. This fraction contained the larger macrofossils including the majority of plant reproductive remains, *Ceratophyllum demersum* and *Stratiotes aloides* leaf spines, molluscs, fish scales and the larger bryozoan statoblasts and cladoceran ephippia. A sub-sample, approximately a fifth of the total sample, from the 125 µm sieve was analysed at a higher magnification for smaller vegetative fossils including *Juncus* spp. seeds, *Plumatella* spp. statoblasts and *Nymphaeaceae* leaf trichosclereids. Decisions concerning the proportion of sample to examine were dependent upon the concentration of fossil remains retained in each size fraction. Macrofossils were identified by comparison with herbarium documented reference material. Assistance with the identification of problematic remains was provided by Dr. Hilary Birks, University of Bergen, Norway (plant parts and seeds) and Tom Davidson, UCL (zooplankton). Many of the macrofossils have been retained for future reference and are stored under glycerol to prevent desiccation and fungal infestations. Macrofossil data are expressed as number of macrofossils per gram dry mass of sediment (or gDM^{-1}), which helps to account for variations in water content of the sediment and the effects of sediment compaction down core.

Aquatic macrophyte surveys were carried out by English Nature at all four broads in July 2003. The data were compared with the surface sediment macrofossil assemblages to assess how well the current flora was represented by the fossil record.

3. BARNBY BROAD

3.1 Site and core description

Barnby Broad (TM 480 906) is a relatively small, shallow, lowland lake (surface area 2.5 ha, altitude 1 m above sea level) surrounded by wet woodland with a floating fringe of vegetation (hover). The broad was formed by medieval peat cutting. The south-western half of Barnby Broad (south of the line in Figure 1) was mud pumped in 1990, deepening the area by approximately 1 m. This section has recovered well and now supports rigid hornwort *Ceratophyllum demersum*, species of stonewort *Chara* spp. and horned pondweed *Zannichellia palustris*. The area that has not been pumped has a water depth of ~30-80 cm and is too shallow for plants.

Four piston cores were taken in the northerly end of the lake in the section that has not been pumped on 12 March 2003 (Figure 1):
BARB1 (TM 48052 90675). Core length 145 cm. Water depth 30 cm.
BARB2 (TM 48030 90690). Core length 114 cm. Water depth 30 cm.
BARB3 (TM 48012 90655). Core length 110 cm. Water depth 80 cm.
BARB4 (TM 47999 90652). Core length 126 cm. Water depth 80 cm.

All cores exhibit broadly the same stratigraphy with a basal black peat layer at a depth of approximately 1 m, above which is a brownish-grey calcareous layer containing abundant mollusc remains. Above this is a slightly darker, more organic section and the uppermost layer (0- 40 cm) is a greenish-grey gyttja (lake mud). The dry weight and organic matter profiles (Figure 2) show that, whilst there are a number of minor differences between the four sequences, the cores are well correlated. BARB4 was selected as the mastercore.

Figure 1 Map of Barnby Broad showing the location of the sediment cores

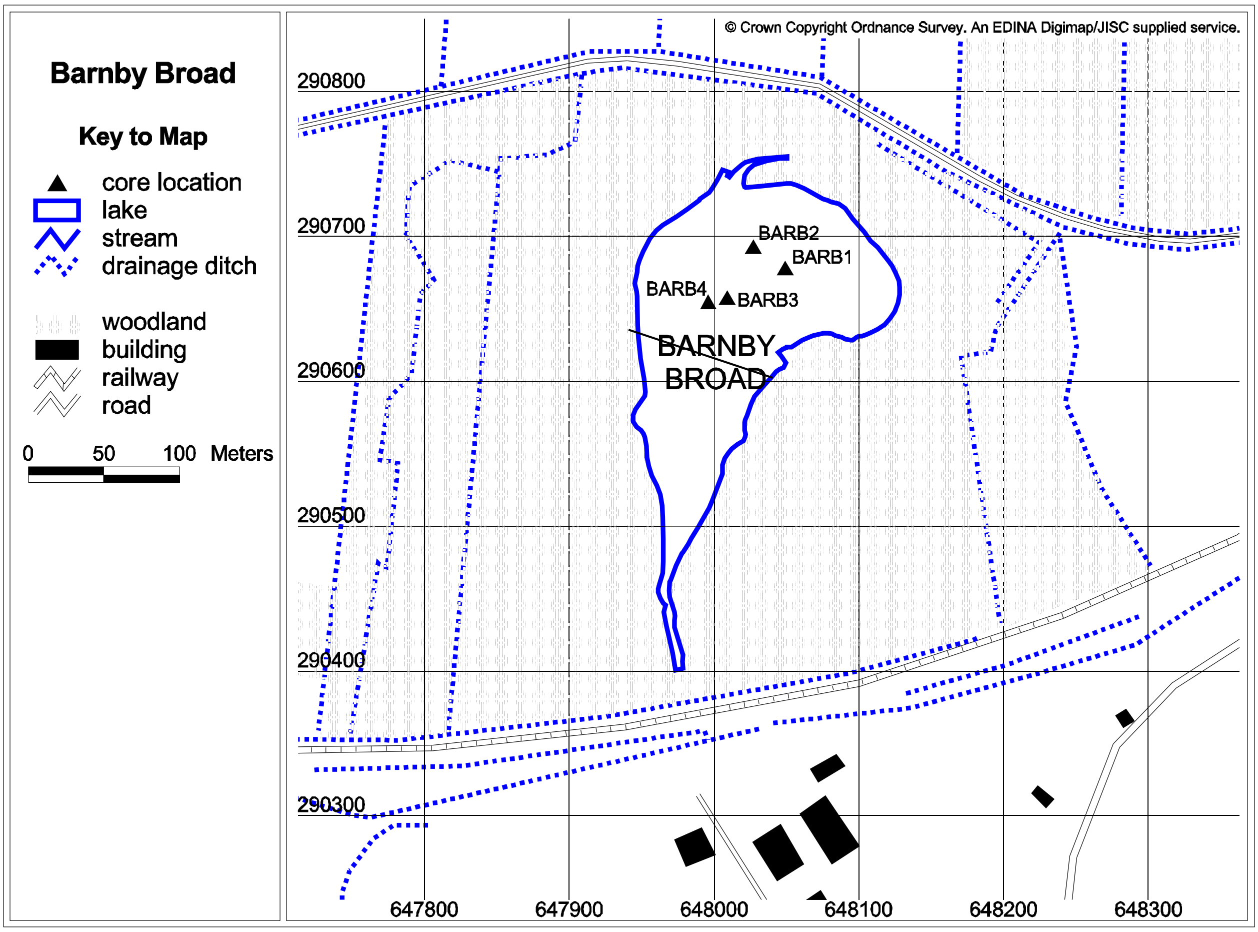
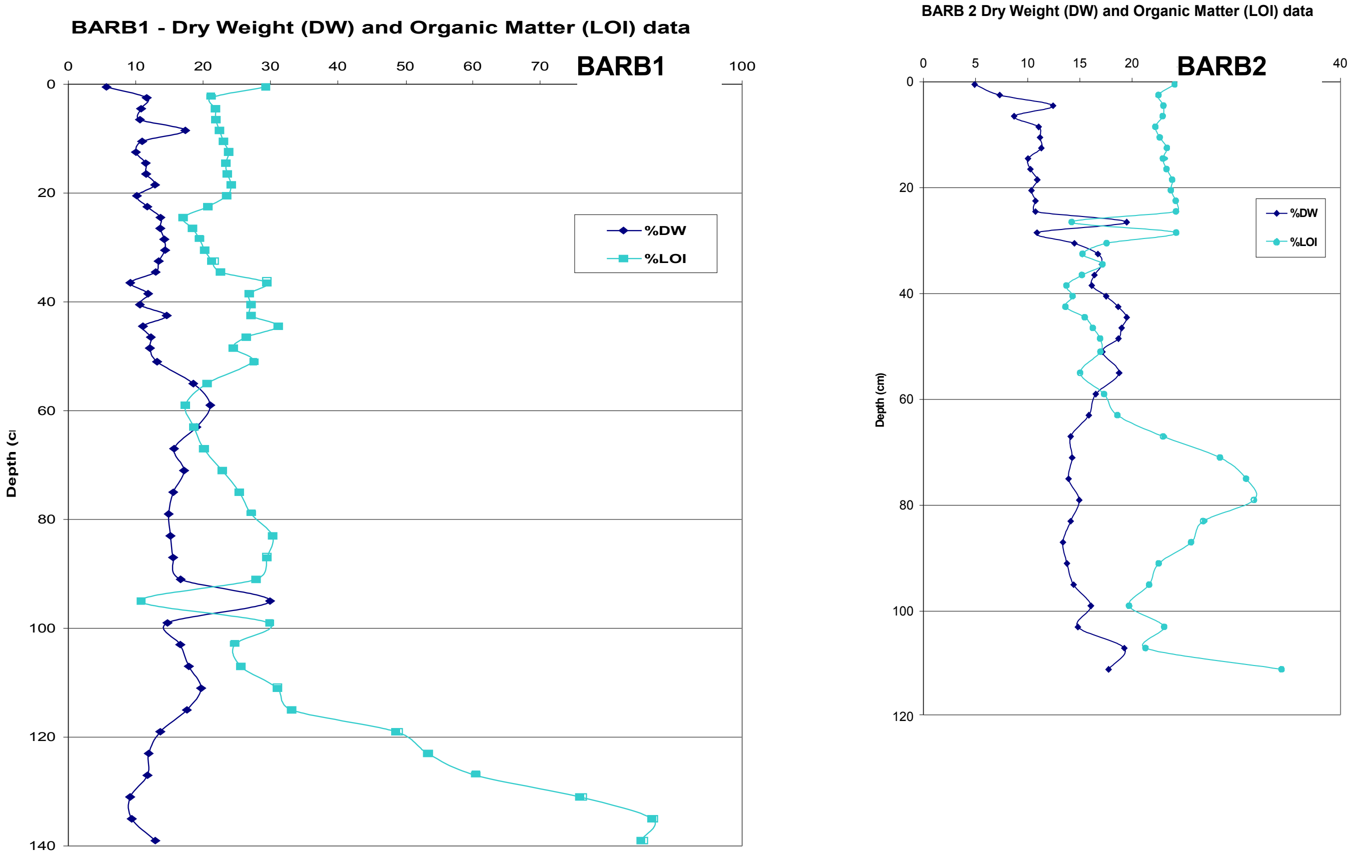
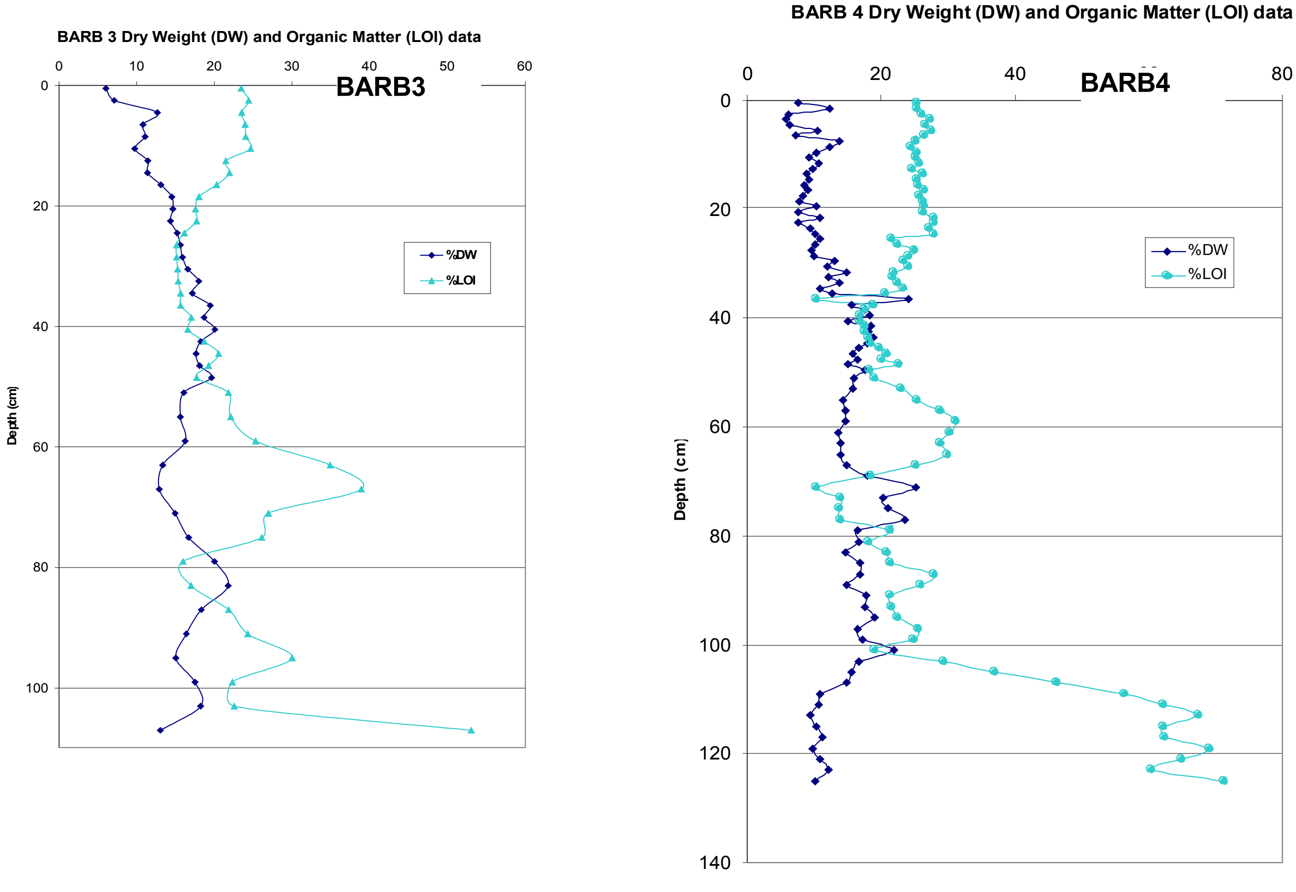


Figure 2 Dry weight and organic matter profiles for the Barnby Broad cores


BARB1 - Dry Weight (DW) and Organic Matter (LOI) data

BARB 2 Dry Weight (DW) and Organic Matter (LOI) data


BARB 3 Dry Weight (DW) and Organic Matter (LOI) data

BARB 4 Dry Weight (DW) and Organic Matter (LOI) data

3.2 Chronology

The fallout radionuclide concentrations in the Barnby Broad core BARB4 are shown in Table 1.

Lead-210 Activity

Equilibrium between total ^{210}Pb activity and the supporting ^{226}Ra (Figure 3a) is still not reached at the depth of the deepest sample analysed (33 cm). Unsupported ^{210}Pb activity declines more or less exponentially with depth (Figure 3b), though there are non-monotonic features at ~8-9 cm and ~20-21 cm suggesting episodes of accelerated sedimentation.

Artificial Fallout Radionuclides

The ^{137}Cs activity versus depth profile (Figure 3c) has a relatively well resolved subsurface peak between 20-25 cm that almost certainly records the 1963 fallout maximum from the atmospheric testing of nuclear weapons.

Core Chronology

Figure 4 shows that there is a large discrepancy between ^{210}Pb dates calculated using the CRS model and those indicated by the ^{137}Cs record. Figure 4 also shows corrected ^{210}Pb dates calculated using the 1963 ^{137}Cs date as a reference point. The results, given in Table 2, suggest much lower sedimentation rates in the past, accelerating from ~0.024 g cm^{-2} y^{-1} (0.19 cm y^{-1}) before 1960 to a contemporary value of ~0.074 g cm^{-2} y^{-1} (0.77 cm y^{-1}).

Table 1 Fallout Radionuclide Concentrations in Barnby Broad core BARB4

				^{210}Pb					
Depth		Total		Unsupported		Supported		^{137}Cs	
cm	g cm^{-2}	Bq kg^{-1}	±	Bq kg^{-1}	±	Bq kg^{-1}	±	Bq kg^{-1}	±
0.5	0.04	51.3	9.7	35.4	10.0	15.9	2.6	11.2	1.7
4.5	0.37	53.6	7.9	35.5	8.1	18.1	1.9	14.0	1.5
8.5	0.81	39.8	9.3	28.1	9.4	11.7	1.6	10.9	1.4
12.5	1.25	47.3	7.2	31.7	7.4	15.6	1.8	15.9	1.4
16.5	1.63	43.6	8.6	27.9	8.9	15.7	2.4	12.9	2.5
20.5	2.00	32.7	7.5	18.9	7.7	13.7	1.8	19.6	1.6
24.5	2.39	47.2	9.4	23.6	9.6	23.6	2.2	19.6	2.5
28.5	2.82	37.3	6.5	22.7	6.7	14.5	1.6	12.9	1.2
32.5	3.38	32.7	5.7	22.1	5.9	10.6	1.3	13.0	1.1

Table 2 ^{210}Pb chronology of Barnby Broad core BARB4

Depth		Chronology			Sedimentation Rate		
		Date	Age				
cm	g cm^{-2}	AD	y	±	g cm^{-2} y^{-1}	cm y^{-1}	± (%)
0.0	0.00	2003	0	0			
0.5	0.04	2002	1	1	0.078	0.90	29.8
4.5	0.37	1998	5	2	0.067	0.80	24.8
8.5	0.81	1992	11	2	0.070	0.57	34.9
12.5	1.25	1984	19	3	0.049	0.50	25.9
16.5	1.63	1976	27	4	0.043	0.50	34.0
20.5	2.00	1968	35	4	0.049	0.42	42.3
24.5	2.39	1957	46	6	0.029	0.28	44.0
28.5	2.82	1940	63	14	0.022	0.19	28.5
32.5	3.38	1915	88	20	0.022	0.16	28.5

Figure 3 Fallout radionuclides in Barnby Broad core BARB4, showing (a) total and supported ^{210}Pb, (b) unsupported ^{210}Pb, (c) ^{137}Cs concentrations versus depth.

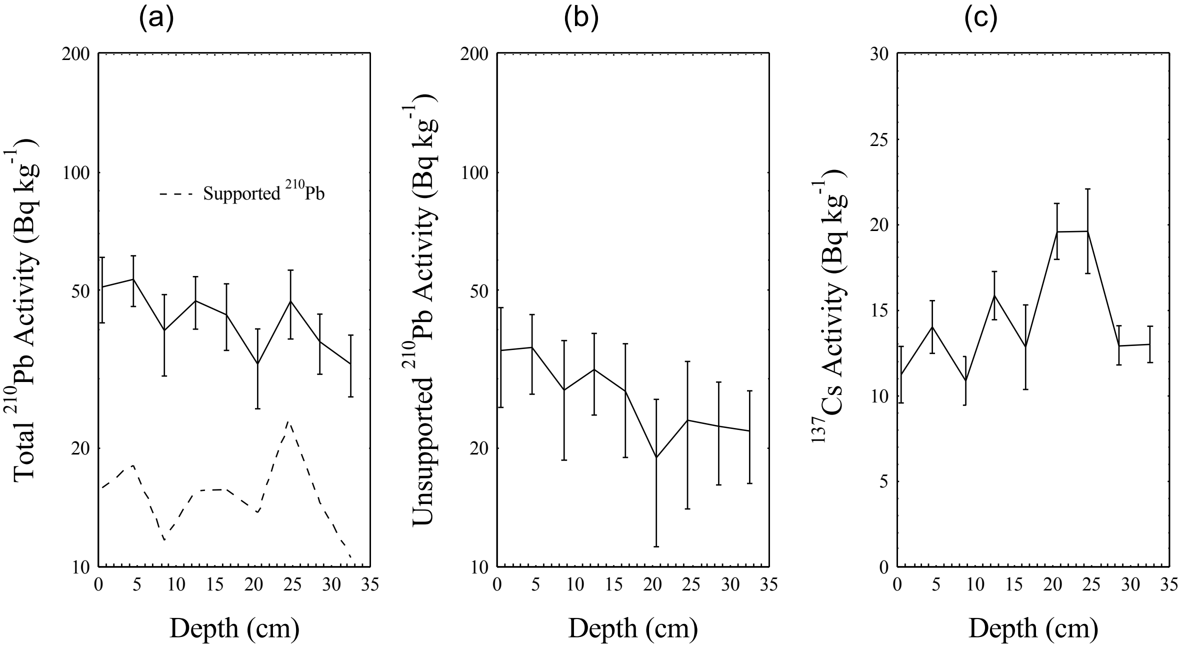
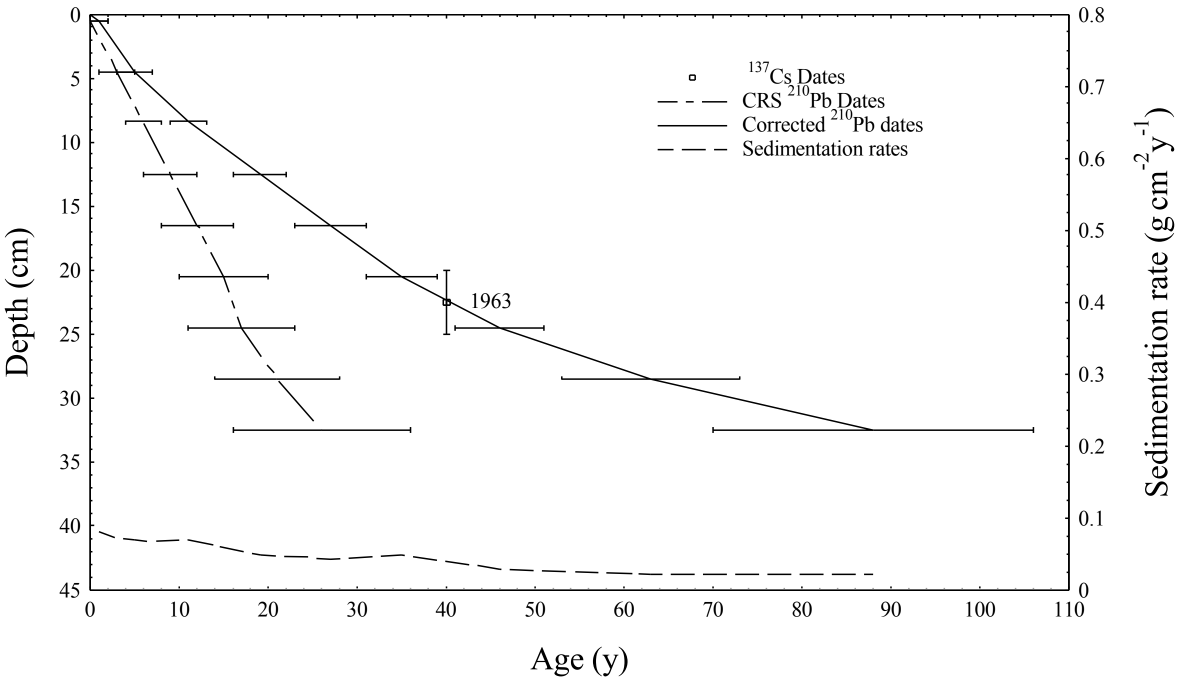


Figure 4 Radiometric chronology of Barnby Broad core BARB4, showing CRS model ^{210}Pb dates together with the 1963 depth determined from the ^{137}Cs stratigraphy. Also shown are the corrected ^{210}Pb dates and sedimentation rates.



Spheroidal carbonaceous particles (SCPS)

The SCP concentration profile for BARB4 is shown in Figure 5. First presence of SCPs is at 50 – 52 cm and above this the concentration increases irregularly to a peak of almost 3000 gDM^{-1} at 15 – 16 cm. This is followed by a decline to the sediment surface. Although irregular, the profile is not atypical and dates can be ascribed using the cumulative percentage profile. Dates for each 10-percentile of BARB4 are shown in Table 3, together with the confidence limits for each date, and graphically in Figure 6. The dates would appear to show a reasonably steady accumulation rate with possibly a slight acceleration over the last two decades. The depth for the 1963 ^{137}Cs peak for this core is also shown on Figure 6 (black square) and is in good agreement with the SCP dates, thus providing supporting evidence for this depth-age profile.

Figure 5 SCP concentration profile of Barnby Broad (BARB4)

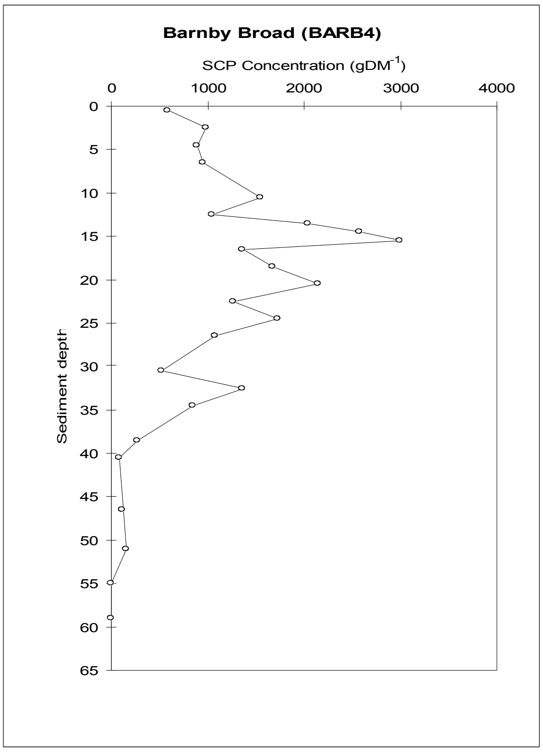
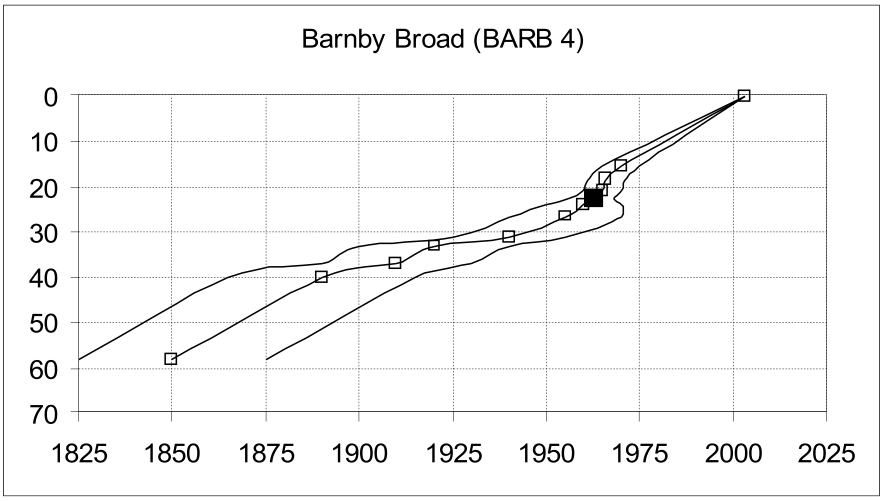


Table 3 Sediment depths and dates for each 10-percentile of the cumulative SCP profiles for Barnby Broad (BARB4) calibrated to the 'south and central England' regional SCP profiles from Rose & Appleby (in prep).

10-percentile	Date	Confidence interval	BARB4 (cm)
0	1850	1875 – 1825	58
10	1890	1915 – 1865	40
20	1910	1930 – 1890	37
30	1920	1940 – 1900	33
40	1940	1955 – 1925	31
50	1955	1970 – 1940	26.5
60	1960	1970 – 1950	24
70	1962	1968 – 1956	22.5
80	1965	1970 – 1960	21
90	1966	1971 – 1961	18.5
100	1970	1975 – 1965	15.5
	2003		0

Figure 6 SCP dating profile for Barnby Broad. Open squares show SCP dates and depths for each 10-percentile. Black square shows the ^{137}Cs 1963 peak.



Corrected chronology using combined radiometric dating and SCP data

Figure 7 compares the final radiometric dates with those determined from the SCP record. Where they overlap, these two independent chronologies are in relatively good agreement The SCP dates suggest a mean sedimentation rate for the pre-1960 period of 0.037 g cm^{-2} y^{-1} (0.29 cm y^{-1}), significantly less than the mean post-1960 value of 0.054 g cm^{-2} y^{-1} (0.56 cm y^{-1}), and contemporary value of ~0.074 g cm^{-2} y^{-1} (0.77 cm y^{-1}) determined from the radiometric record. A corrected chronology (Figure 7, Table 4) has been constructed using the radiometric dates for the post-1960 period, and the SCP determined mean sedimentation rate for the earlier period.

Figure 7 Chronology of Barnby Broad core BARB4, showing the radiometric dates, SCP dates, and corrected dates based on both methods.

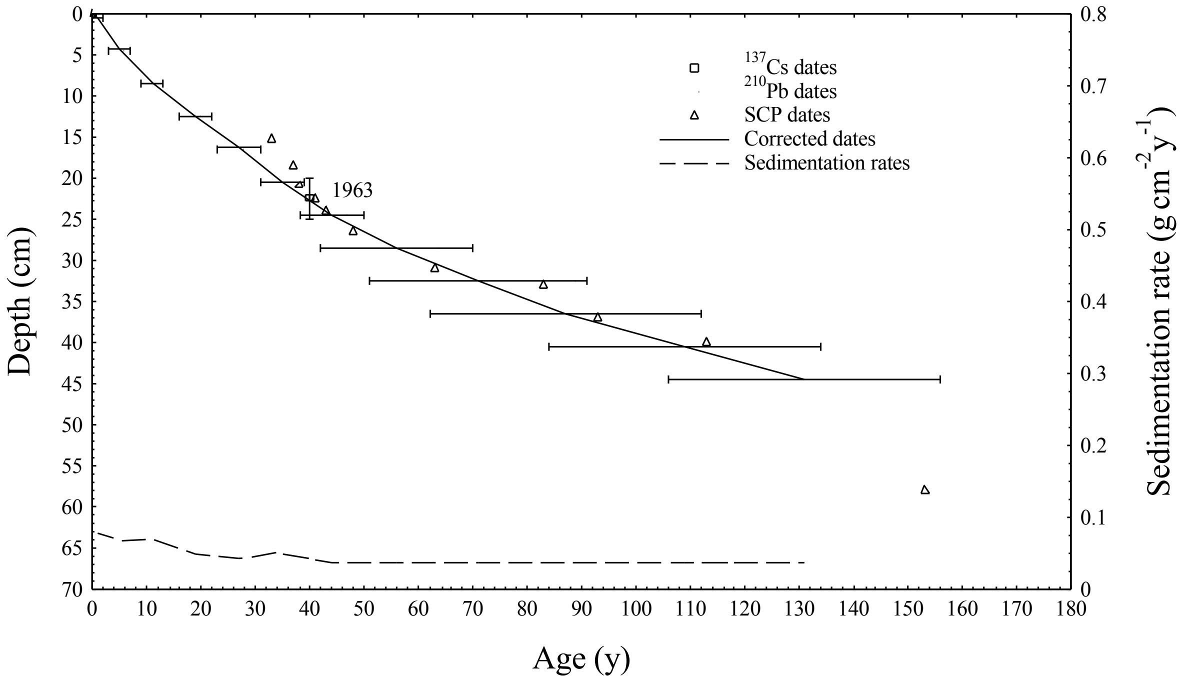


Table 4 Corrected chronology of Barnby Broad core BARB4

Depth		Chronology			Sedimentation Rate		
		Date	Age				
cm	$g\ cm^{-2}$	AD	y	±	$g\ cm^{-2}\ y^{-1}$	$cm\ y^{-1}$	± (%)
0.0	0.00	2003	0	0			0.0
0.5	0.04	2002	1	1	0.078	0.90	29.8
4.5	0.37	1998	5	2	0.067	0.80	24.8
8.5	0.81	1992	11	2	0.070	0.57	34.9
12.5	1.25	1984	19	3	0.049	0.50	25.9
16.5	1.63	1976	27	4	0.043	0.50	34.0
20.5	2.00	1968	35	4	0.049	0.47	42.3
24.5	2.39	1959	44	6	0.037	0.38	
28.5	2.82	1947	56	14	0.037	0.30	
32.5	3.38	1932	71	20	0.037	0.25	
36.5	3.99	1916	87	25	0.037	0.21	
40.5	4.79	1894	109	25	0.037	0.18	
44.5	5.60	1872	131	25	0.037	0.19	

3.3 Geochemistry and sediment characterisation

The mineral magnetics, geochemistry and particle size data for the Barnby Broad cores are presented in Figure 8. The Ca data show that the sediment in Barnby Broad is highly calcareous, comprising 60-80% calcium carbonate in the top 1 m and about 20% in the lowermost section (Figure 8b). The basal sediment is highly organic, comprising ~70% of highly sulphur-enriched organic matter.

The mineral matter content of the sediment is generally low, and its magnetic properties suggest that little soil is getting into the lake (Figure 8a). The increase in Si in the top 30 - 40 cm (Figure 8b) is unlikely to reflect enhanced soil supply because the Rb and Fe do not mirror the Si increase. This suggests that the Si source is principally sand or biogenic silica. The high values of several magnetic parameters at depth in BARB1 and BARB4 are probably due to magnetic sulphides of diagenetic origin (Figure 8a). The mineral magnetic parameters mainly reflect two types of material. Increases in χarm and SIRM above ~40 cm, closely matching the Zn concentration profiles, reflect atmospheric pollution. The high values for many parameters in the deeper sediment reflect secondary sulphide formation, and therefore have little palaeoenvironmental significance.

Phosphorus (P) content is low in the bottom of the cores (Figure 8b). The P increase at around 100–115 cm accompanies the switch to highly calcareous sediment. Further increases in P occur at around 40-60 cm and furthermore toward the top of the cores from ~20 cm to the surface which represents the post-1970 period. This recent rise in P content may reflect the increased nutrient status of the site over the last 30 years. The maximum total sediment P concentration (2.0-3.3 mg g^{-1}) is typical for UK lowland lake sediments and river suspended sediment, reflecting a high nutrient loading. The calculated sediment P loading (1.5-2.4 g m^{-2} yr^{-1}) places the site an order of magnitude above the mesotrophic/eutrophic boundary of Vollenweider (1976).

The heavy metals show a range of different patterns (Figure 8c). Pb increases steadily from the base of the core to around the 30 cm level and subsequently declines towards the surface. The other elements are broadly constant (barring Cu dilution in the organic sediment) in the deeper sediment, but increase sharply above 40-60 cm. All the metals show a broad peak at 20-30 cm before declining to the sediment surface.

The particle size data show a tendency towards finer material in the upper part of the cores (Figure 8d). The deeper sediment has a higher proportion of medium and coarse sand, and less clay and silt than the upper sediment. The particle size data do not reveal any significant changes, however, and this may be expected given the small catchment size (limiting potential source materials) and the shallow depth of the site (minimising spatial sorting by particle size).

There is excellent agreement between the four cores indicating that we can confidently describe the average state of the sediment. Zones of similar character have been identified based on the above data. The compositional zonation is shown in Figure 9, with quantitative characteristics summarised in Table 5. The table includes the metal concentrations in the different sediment zones and the area normalised heavy metal inventory (gm^{-2}). Only Pb and Zn show inventories above background. There are essentially three zones: Zone 1 (>105 cm) characterised by low Ca and high organic matter which represents the peat layer, Zone 2 (~40-105 cm; pre 1850) characterised by high Ca, low Si and slight Pb enrichment which appears to represent the pre-industrial period of sediment accumulation, and Zone 3 (0 to ~40 cm; post 1850) characterised by higher levels of Si, P, Pb and Zn, representing the industrial period of nutrient and atmospheric pollution.

At Barnby Broad the thickness of the uppermost contaminated zone varies between 40 and 53 cm, corresponding to a dry mass quantity between 50 and 70 kg per square metre of lake bed. Given a total lake area of 2.5 ha, this amounts to a sediment volume of between 10 000 and 13 000 m^3, with a dry mass of 500 -1000 tonnes. However, approximately half of the lake (south-westerly part) has already been mud pumped and therefore the volume of remaining sediment in the broad is likely to be around 5000 to 7000 m^3.

Table 5 Compositional zones in Barnby Broad

							BARB 4			**BARB 1**			**BARB 2**			**BARB 3**		
Zone	***Description and interpretation***						Conc		Mass	Conc		Mass	Conc		Mass	Conc		Mass
	CORE	**4**	**1**	**2**	**3**		Mean	sd	g m^{-2}	Mean	sd	g m^{-2}	Mean	sd	g m^{-2}	Mean	sd	g m^{-2}
Zone 3	Sediment enriched in Si, P, Pb and Zn, with relatively low Ca Industrial period sediment with marked nutrient and atmospheric pollution	0 – 40 cm	0 – 53 cm	0 – 45 cm	0 – 41 cm	Si mg/g	38.9	24.2	1393	34.8	24.4	2044	46.1	10.1	2578	45.1	14.5	1948
						Ca mg/g	279	28	11250	310	11	19862	305	9	17038	315	19	15060
						Fe mg/g	3.7	0.6	142	3.2	0.6	203	2.9	0.3	155	3.0	0.4	135
						S mg/g	1.4	0.7	50.9	0.6	0.3	31.9	0.2	0.3	9.4	0.2	0.3	6.7
						P mg/g	1.1	0.5	41.0	1.3	0.7	72.3	1.8	1.0	79.6	1.8	0.9	83
						Cd µg/g	0.29	0.07	0.012	0.39	0.08	0.025	0.36	0.05	0.021	0.41	0.08	0.019
						Cu µg/g	11.6	2.9	0.44	9.1	2.0	0.58	8.5	2.8	0.43	8.5	1.5	0.41
						Pb µg/g	48.5	12.1	2.0	45.6	12.9	3.0	46.8	14.0	2.6	44.4	5.2	2.1
						Zn µg/g	81.7	28.4	3.3	60.3	15.5	3.9	73.6	30.4	4.0	73.3	18.9	3.4
Zone 2	Maximum Ca and minimum Si. Minor Pb enrichment Pre-industrial sediment infill	40 – 105 cm	53 – 105 cm	45 - >105 cm	41 - >105 cm	Si mg/g	3.0	2.5	374	0.8	2.1	77	59.1	47	>5926	4.0	4.0	>537
						Ca mg/g	321	28	39626	331	21	35549	291	39	>32026	303	21	>41082
						Fe mg/g	10.8	3.1	1343	11.5	6.1	1190	9.6	3.7	>1003	12.1	4.8	>1597
						S mg/g	3.5	1.4	434	1.9	1.7	188	2.5	1.7	>258	2.1	1.7	>269
						P mg/g	0.5	0.3	57	0.5	0.3	54	0.7	0.2	>73	0.6	0.3	>76
						Cd µg/g	0.05	0.05	0.007	0.20	0.09	0.021	0.23	0.04	>0.025	0.21	0.03	>0.029
						Cu µg/g	7.4	1.5	0.89	7.4	1.3	0.78	6.3	1.5	>0.67	6.1	1.1	>0.82
						Pb µg/g	16.5	5.0	2.0	22.1	8.2	2.3	24.4	7.7	>2.7	19.4	11.2	>2.6
						Zn µg/g	12.3	2.2	1.5	17.5	3.4	1.8	12.6	3.7	>1.4	13.7	2.2	>1.9
Zone 1	Minimum Ca, maximum organic matter. Pre-cutting peat?	105 - >125 cm	105 - >135 cm			Si mg/g	2.1	4.1		0.0	0.0							
						Ca mg/g	141	58		126	50							
						Fe mg/g	14.8	2.3		36.2	5.1							
						S mg/g	8.7	2.4		11.3	2.6							
						P mg/g	0.1	0.0		0.2	0.1							
						Cd µg/g	0.12	0.08		0.24	0.02							
						Cu µg/g	5.1	0.4		3.2	0.3							
						Pb µg/g	8.1	3.9		7.8	8.0							
						Zn µg/g	10.8	1.1		7.4	2.8							

Figure 8a Barnby Broad organic matter and mineral magnetic parameters

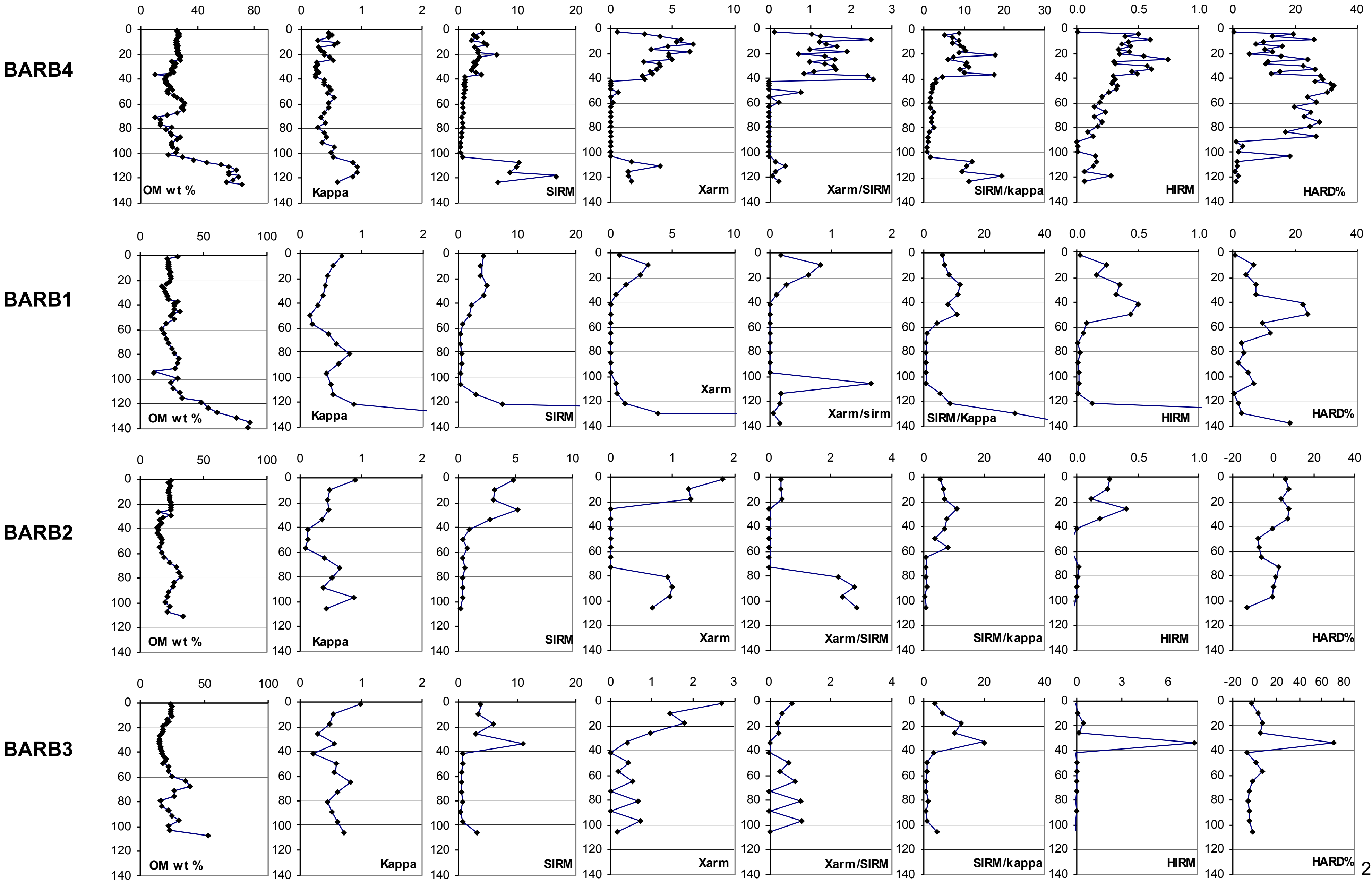


Figure 8b Barnby Broad major element concentrations

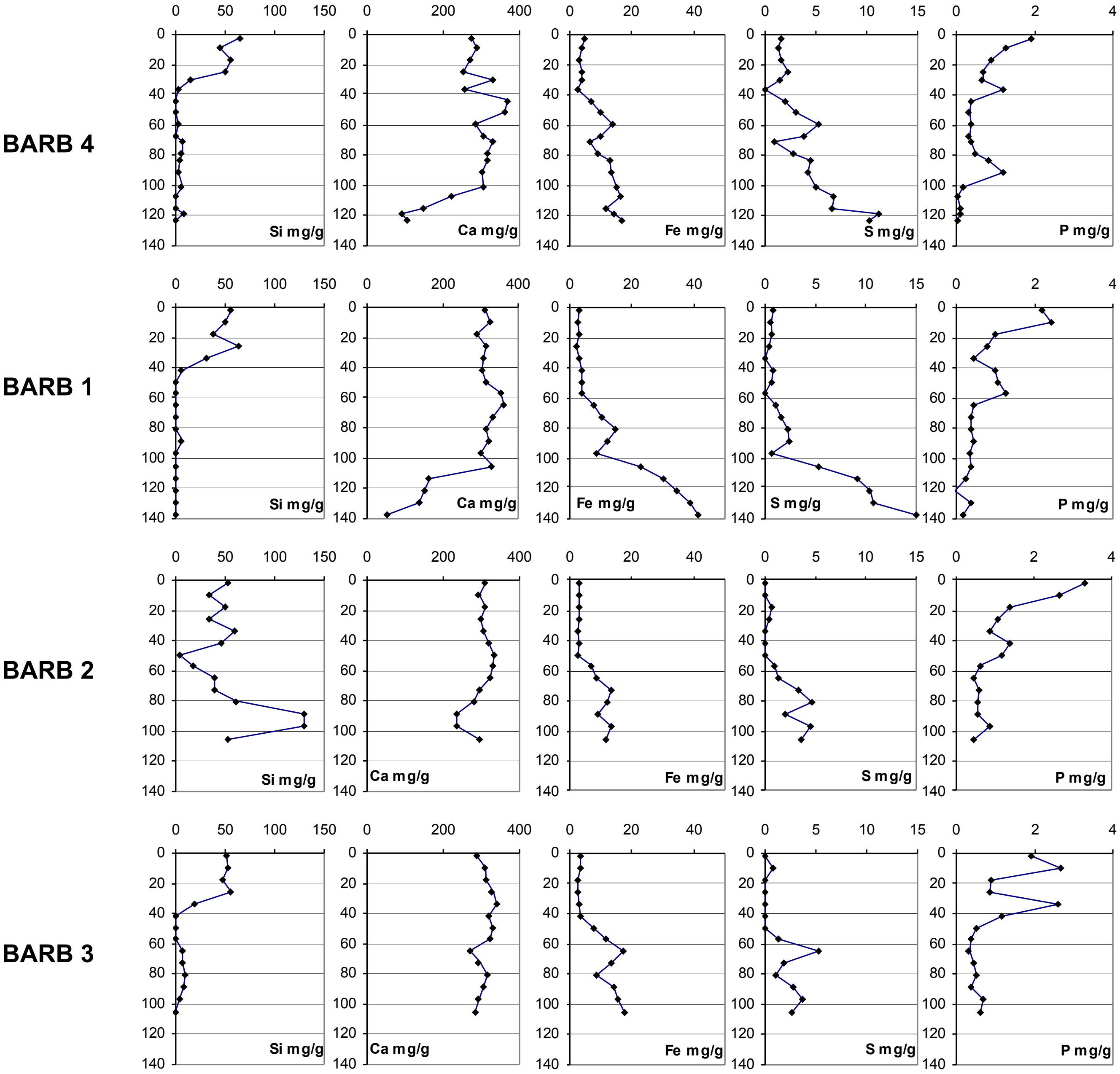


Figure 8c Barnby Broad trace element concentrations

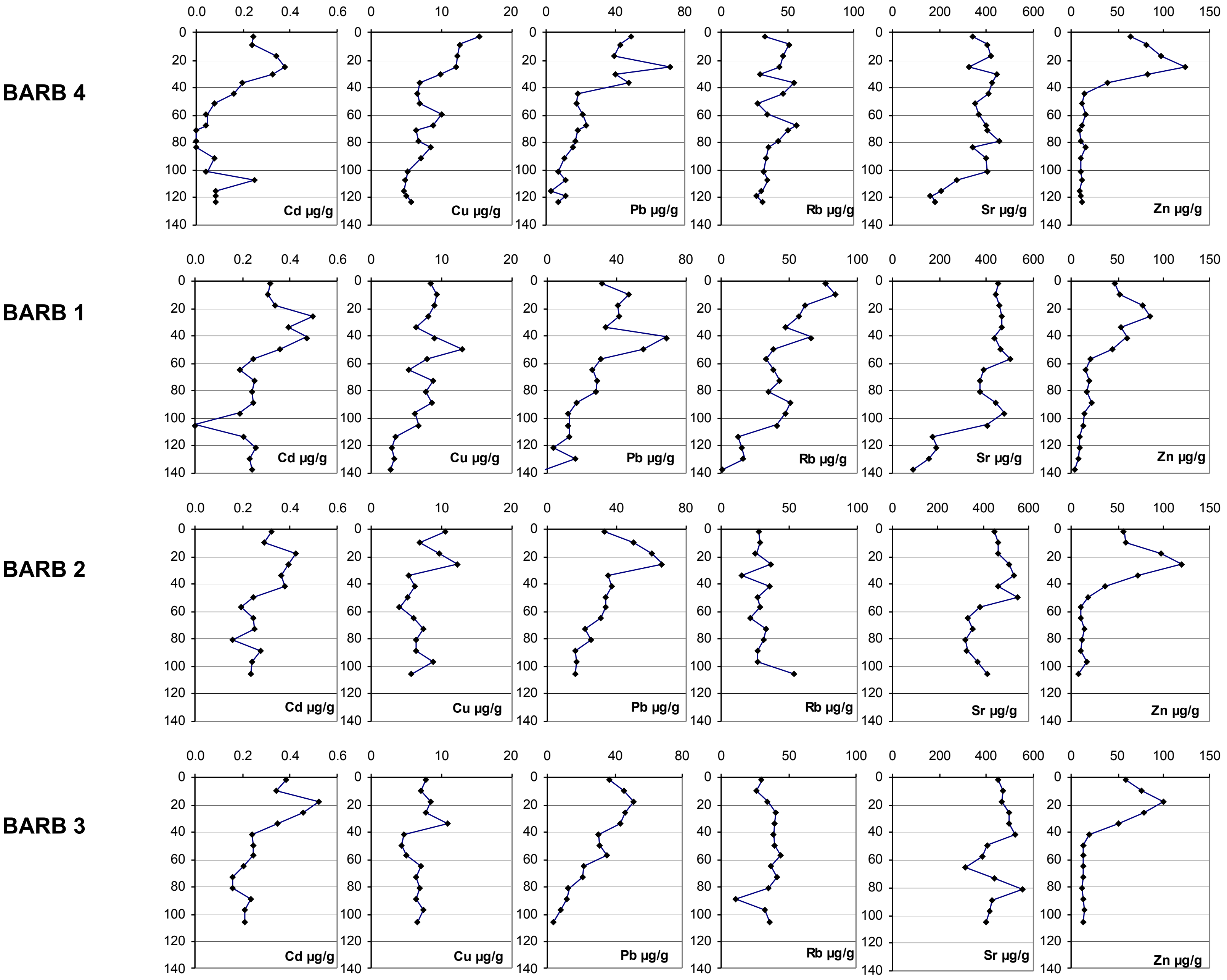


Figure 8d Barnby Broad particle size data

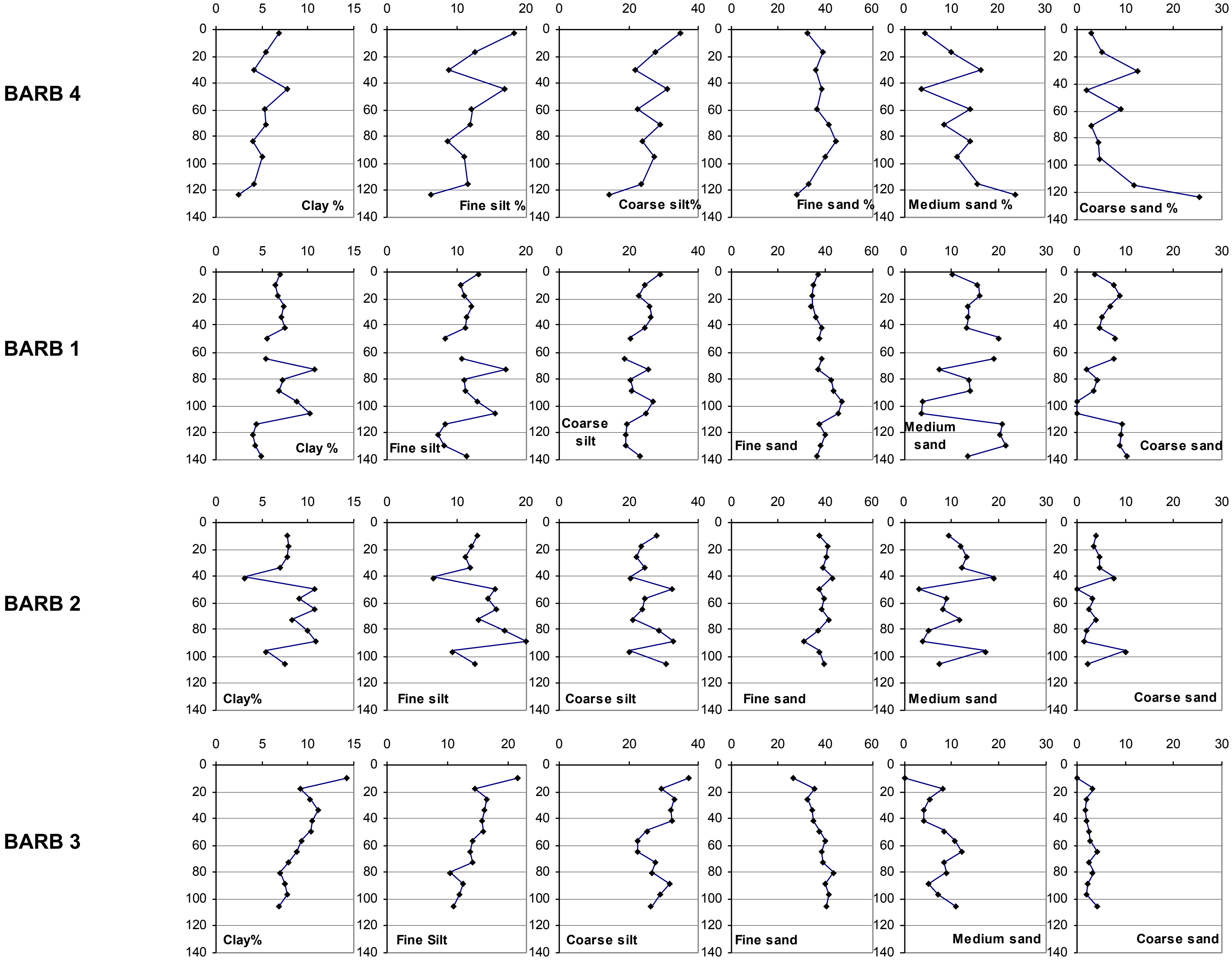
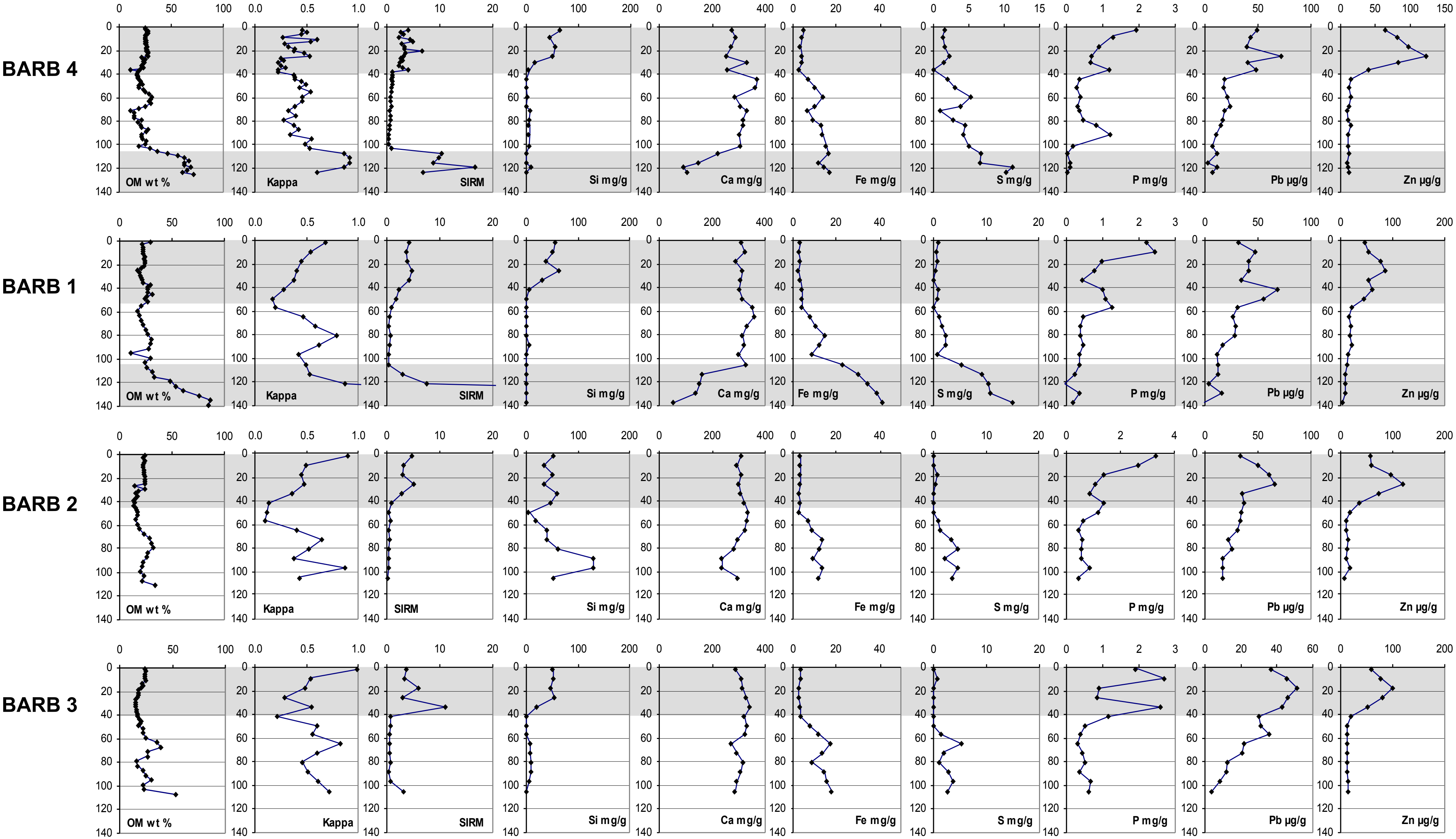


Figure 9 Barnby Broad summary chemical and mineral magnetic data showing compositional zones



3.4 Diatoms

Six samples were analysed for diatoms in Barnby Broad core BARB4 (Table 6) and the summary diatom diagram is shown in Figure 10. Samples below 50 cm sediment depth could not be counted owing to very poor diatom preservation. The diatom species diversity in the upper 50 cm of the core was low compared with the other three broads with a total of 31 species observed throughout the core, compared with 70-80 species in cores from the other sites

Table 6 Summary of samples analysed for diatoms in Barnby Broad core BARB4

Depth (cm)	Total count	No. species	Floristic diversity
3.5	364	21	0.06
11.5	361	14	0.04
19.5	521.5	19	0.04
29.5	373	13	0.03
39.5	336	15	0.04
49.5	308	17	0.06

Cluster analysis showed that the assemblages were similar throughout the core and therefore zones were not assigned to the diatom record. BARB4 was dominated throughout by small *Fragilaria* species. *Fragilaria brevistriata* was the dominant taxon consistently occurring at relative abundances of between 50 and 70%, with *Fragilaria construens*, *Fragilaria elliptica* and *Fragilaria pinnata* occurring as subdominants. These diatom species are periphytic and are generally found living in the littoral amongst the roots and stems of emergent plants as well as on the sediment surface throughout shallow water bodies. They indicate shallow and/or clear water environments where light availability is such to enable diatom growth on the lake bottom. Other species present in this core, occurring throughout the sequence but in low relative abundances, include benthic *Navicula* species, the epiphytic taxon *Cocconeis placentula*, and the planktonic diatom *Stephanodiscus parvus*. The (tycho)planktonic species *Aulacoseira italica* was present in small amounts in the surface sample. The presence of *Aulacoseira italica* and the slight increase in *Stephanodicus parvus* in the upper 30 cm of the core (post 1950) may signal a rise in nutrient concentrations in recent decades as these taxa are commonly associated with enriched waters.

There is evidence of dissolution and low diatom concentrations below approximately 50 cm (~1850 AD). This is indicated by the presence of only the central areas of many species (e.g. large *Navicula* spp.) and the continued predominance of those species which are highly silicified, and as such more resistant to dissolution (e.g. small *Fragilaria* species). Towards the core base sponge spicules predominate, with very few diatom remains. Caution should be exercised in the interpretation of the diatom profile of this core due to the evidence of dissolution and low diatom concentrations. Nevertheless there appears to have been very little change in the diatoms in the last 150 years. It is noted that the lack of diatom remains below 50 cm is supported by the very low Si concentrations below this depth recorded in the geochemistry data. The low Si concentrations are associated with high concentrations of Fe and S, perhaps indicating the presence of a reducing environment with lack of oxygen in the sediments.

Diatom-inferred total phosphorus concentrations (DI-TP) show little change in the upper 50 cm of the core (Figure 11) with concentrations of ~150 µg l^{-1} throughout. This reflects the stability of the diatom record during this period (~1850 to present). The key taxa in the sediment core were well represented in the training set but in the absence of measured TP data the reliability of the DI-TP values cannot be assessed. The application of diatom-P transfer functions to non-plankton diatom sequences, such as those of Barnby Broad, can be problematic and do not always yield reliable nutrient reconstructions. Particular problems have been encountered when applying the models to diatom assemblages dominated by non-planktonic *Fragilaria* spp. which are typically found in shallow, nutrient-rich, alkaline waters, such as the Norfolk Broads. The influence of factors such as light and substrate in addition to water chemistry on the distribution of these taxa and their wide tolerance to nutrient concentrations, makes them poor indicators of lake trophic status (e.g. Bennion *et al*. 2001, Sayer 2001). Their distribution along the whole length of the TP gradient in the northwest European training set illustrates that these species have wide ecological tolerances and that their TP optima essentially lie in the centre of the sampled environmental gradient. Our training set spans a long TP gradient of ~5 to ~1000 μg TP l^{-1} with a dataset median of 104 μg TP l^{-1}, and thus the TP optima for these taxa tend to be approximately at, or greater than, 100 μg TP l^{-1}, often leading to over-estimation of DI-TP in samples where they dominate. It is highly likely, therefore, that TP concentrations in Barnby Broad were lower than those inferred by the model and the results should not be used to derive P reference conditions for this site.

3.5 Macrofossils

Ten samples were analysed for macrofossils in the upper 105 cm of core BARB4 (Figure 12). The macrofossil record indicates more dynamic shifts in higher plant species assemblages than those seen in the diatom record and suggests that there have been changes in the ecosystem of Barnby Broad. The macrofossil record was divided into three major zones. Dates prior to 1850 AD have been extrapolated based on the sediment accumulation rate of 0.19 cm y^{-1} calculated in Table 4. There are large uncertainties associated with any extrapolated data and therefore these dates serve only as a guide to the approximate time period represented by the earlier part of the core.

Zone 1 (67-102cm; ~1500 to ~1750) representing the earliest period of the broad contains few macrofossil remains. However, the 102 cm sample contained plentiful charophyte oospores, large quantities of charophyte stem heavily encrusted with lime, and very large numbers of molluscs. This sample probably represents the early colonisation of Barnby Broad following peat extraction in the medieval period. Charophytes are known to be rapid colonisers of recently disturbed freshwater environments. The high numbers of molluscs found in association with the *Chara* spp. oospores suggests that the chara beds provided numerous colonisation opportunities for epiphytic algae, which in turn provided plentiful food sources for grazing molluscs (predominantly *Lymnaea* spp. and *Pisidium* spp.). The lack of macrofossil remains at the boundary with Zone 2 may indicate a period of extensive reed bed development whose density and shading effects limited open-water habitat and hence prevented the growth of submerged and floating-leaved aquatic plants. Whilst the development of reed bed during this period is not corroborated by similarly high numbers of *Typha* spp. and *Phragmites* spp. remains, it should be noted that these macrophyte species reproduce vegetatively using their extensive underground network of rhizomes. As such, it is unsurprising that few reproductive remains (seeds) of these taxa are found in the sediment record. Furthermore, any reproductive remains which are produced are susceptible to decomposition. Stems and leaves of the emergent taxa can be preserved in the sediments but identification is very difficult from such remains.

Zone 2 (55-67cm; ~1750 to ~1850) indicates a period of semi-terrestrial peat bog or wetland rather than an open water environment, and illustrates the dynamics of the littoral vegetation. Particularly high numbers of bryophyte and sphagnum leaves and associated *Plumatella* spp. bryozoans, along with moderate quantities of *Juncus* spp. seeds are found in this section of the core. This peat bog habitat could have been created by draining of the Broadland environment for agricultural purposes in the 18th century. The period of most severe draining appears to have been short-lived and insufficient for the development of substantial peat deposits, as indicated by the LOI profile for this section of the core (Figure 2).

Zone 3 (0-55cm; post ~1850) is equivalent to the entire undissolved diatom profile, representing approximately the last 150 years. The plant macrofossils in this upper zone include the submerged macrophytes *Chara* spp. and *Zannichellia palustris,* indicating an open water environment suitable for aquatic plants. There were also high numbers of *Ceratophyllum demersum* leaf spines in the surface sediments. It was noted by the gamekeeper, David Rowley, (personal communication) that following mud pumping of the southerly basin in 1990, *C. demersum* grew in profusion. Furthermore, Sayer (1998, unpublished) found this plant to be dominant. In the aquatic macrophyte survey undertaken in July 2003, *C. demersum* was recorded as dominant and *Z. palustris* as frequent. No other submerged plants were observed. The macrofossils in the surface sediments, therefore, provide a reliable record of the major components of the current macrophyte flora. The high numbers of *C. demersum* leaf spines in the surface sediments of the unpumped north basin are likely to have been transported from the south basin by wind and water currents. As such, this probably reflects the period of recovery in the south basin rather than current conditions in the very shallow north basin where plant abundance remains low. *C. demersum* appears to be associated with algae in BARB4, since both *C. demersum* and algal fragments increase simultaneously. The suitability of *C. demersum* as a habitat for the colonisation of algae has been noted elsewhere. The presence of *Zannichellia palustris* in Zone 3 is indicative of high nutrient levels since it is a nutrient-tolerant plant (Palmer *et al*., 1992; Heegard *et al*., 2001) and has been found in other water bodies where deterioration in water quality is evident (e.g. Bennion, 2001). This species also grows well in very shallow water. In common with charophytes, *Z. palustris* readily colonises available habitats when conditions are suitable and produces numerous seeds to enable its successful domination. *Chara* spp. and *Z. palustris* may be over-represented in the sediment record due to the high production of reproductive bodies.

The other macrofossil evidence in Zone 3 indicates the presence of large numbers of ephippia of the chydorid cladoceran *Ledigia* spp. This cladoceran is associated with the mud and its high abundance in the upper part of the core is indicative of shallowing and a gradual shift in habitat availability with reduction in depth leading to a decline in plant biomass. The presence of large numbers of *Daphnia magna* ephippia in the surface sediments of this core indicates that there is less fish predation at Barnby Broad than in the past. This may be due to the severe shallowing of the site in recent years leading to reduced habitat availability for fish and more intense predation on fish due to insufficient water depth.

Figure 10 Summary diatom diagram for Barnby Broad core BARB4

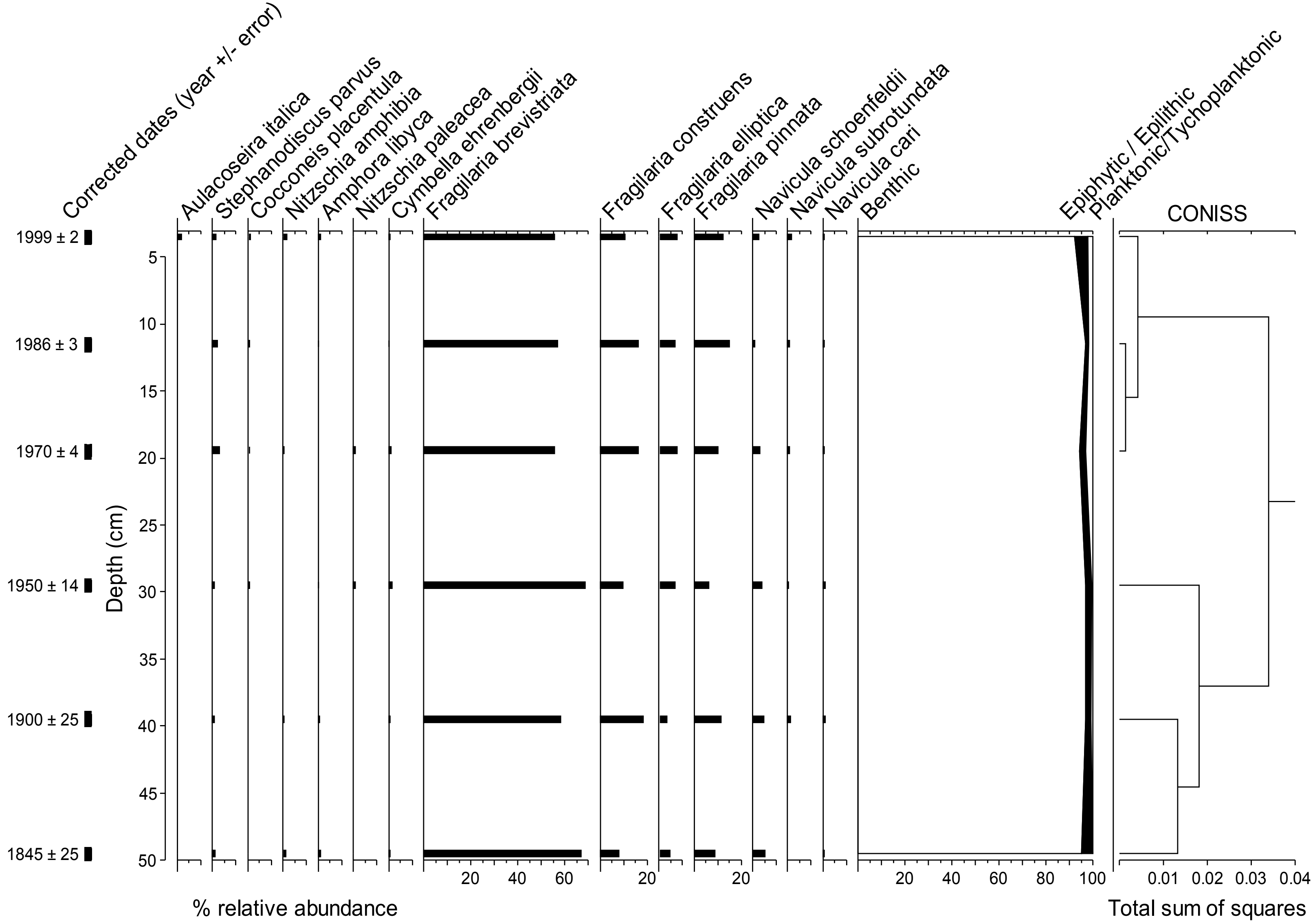


Figure 11 Diatom-inferred total phosphorus (DI-TP µg l^{-1}) reconstruction for Barnby Broad core BARB4

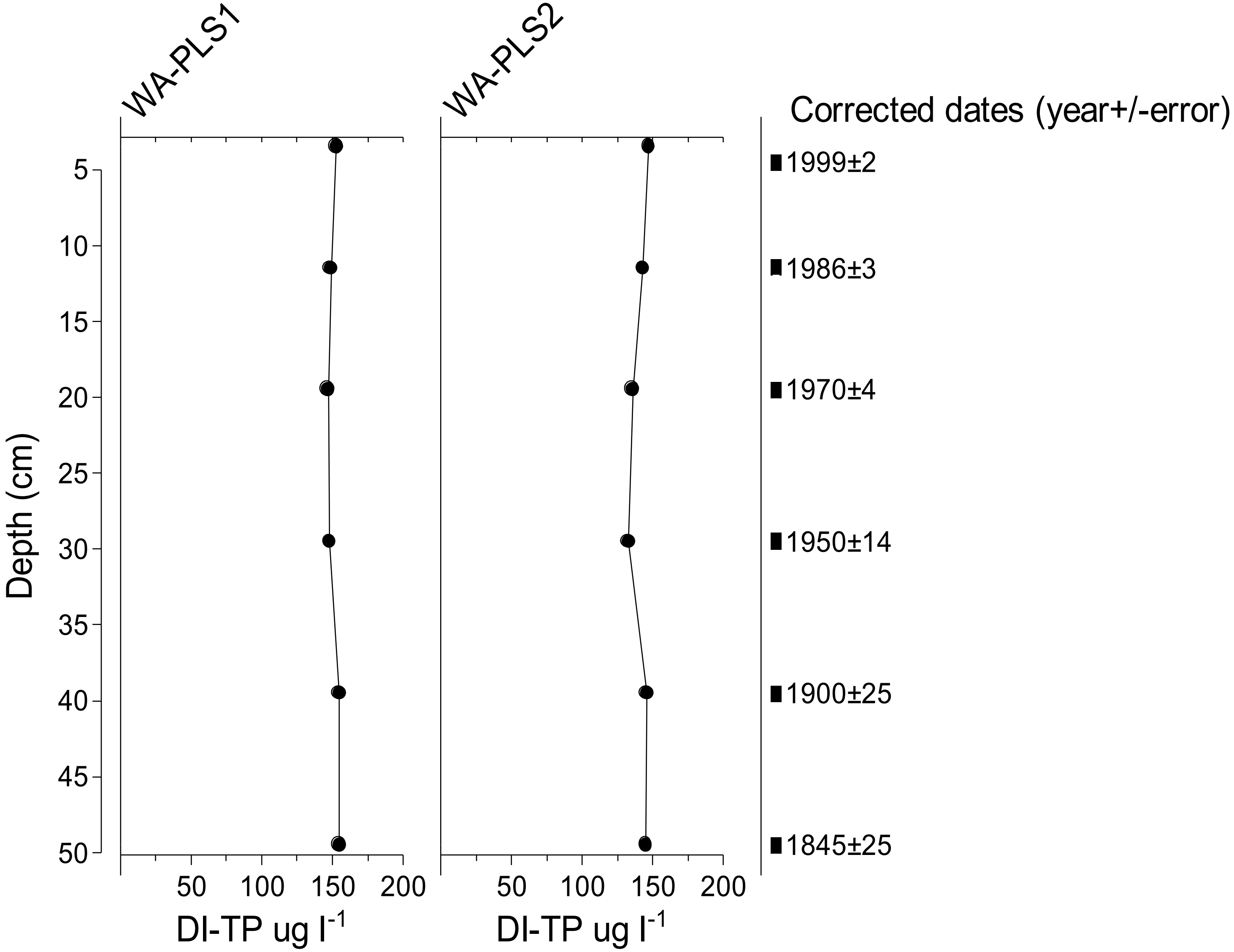
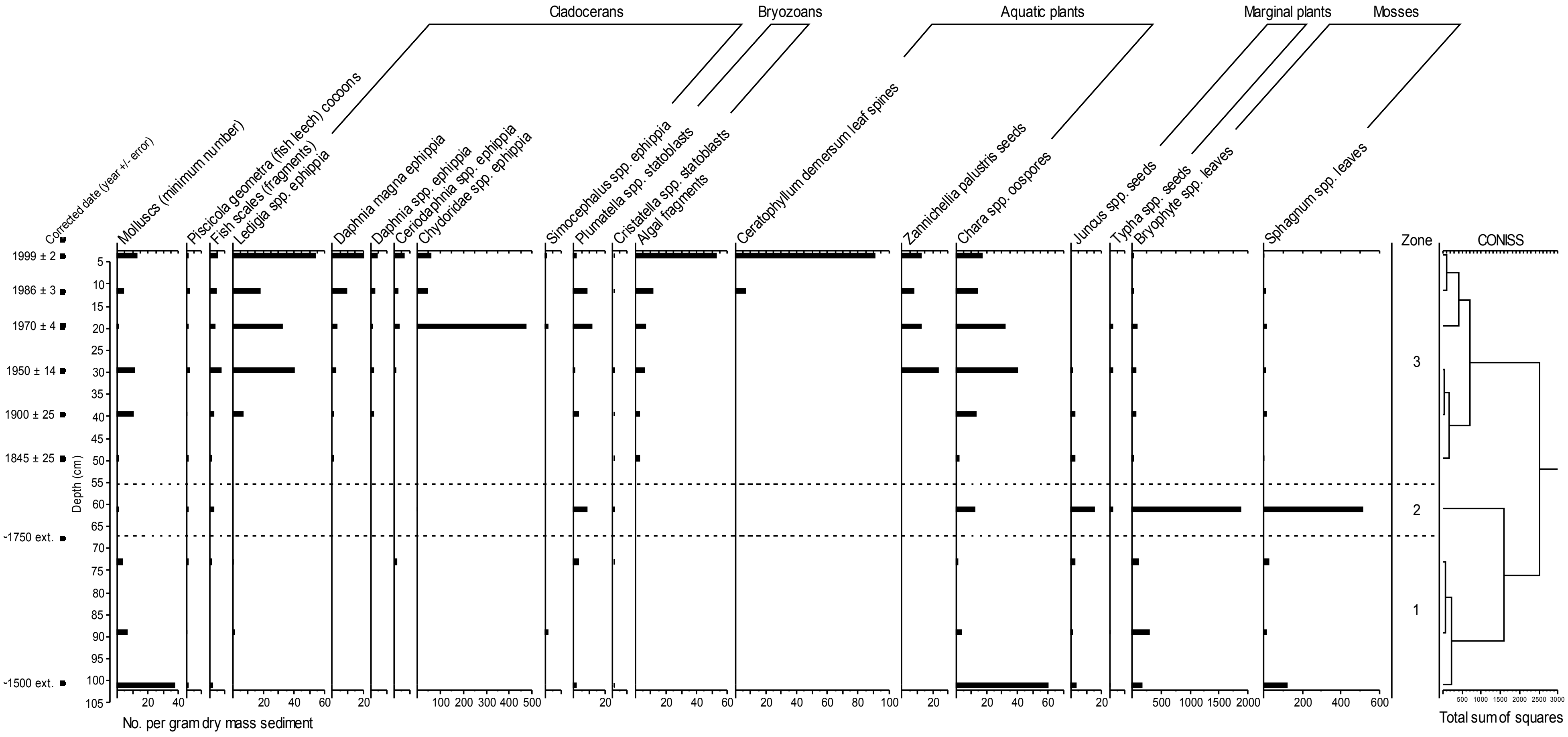


Figure 12 Summary macrofossil diagram for Barnby Broad core BARB4



4. SPRAT'S WATER

4.1 Site and core description

Sprat's Water (TM 504 917) is a very small, shallow, lowland lake (surface area 0.27 ha, altitude 1 m above sea level), situated just to the north-east of Round Water and Woolner's Carr within the Sprat's Water and Marshes SSSI at Carlton Colville. The SSSI comprises areas of spring-fed mixed fen, open water, alder carr and wet grazing marsh on deep peat. The broads themselves are flooded medieval peat workings and are reported to contain abundant bladderwort and hornwort. Sprat's Water is the largest of the three water bodies within the SSSI. It is fringed by alder carr and reedbed. There is a field of arable crops adjacent to the site on the south-east side.

Three piston cores were taken from the lake (Figure 13):
SPRA1 (TM 50575 91782). Core length 142 cm. Taken on 11 March 2003. Water depth 1.35 m.
SPRA2 (TM 50562 91763). Core length 104 cm. Taken on 11 March 2003. Water depth 1.55 m.
SPRA3 (TM 50545 91748). Core length 80 cm. Taken on 13 March 2003. Water depth 1.4 m.

All cores had the same stratigraphy and are thus well correlated (Figure 14). SPRA1 is considerably longer than the other two cores and is the only one that penetrates into a very dark brown, organic layer, rich in molluscs (> 120 cm). All cores have a lower section of dark, greyish-brown, relatively organic material (> 80 cm). Above this is a less organic, greyish-brown section ~40-80 cm) with fewer plant remains although there are a number of marked fluctuations within this, consistent across all three cores, reflecting numerous minor layers. There is a marked increase in organic matter from 40 cm to the top of all three cores. The section from ~ 40-30 is a transitional layer between the uppermost mid-brown organic material and the greyer-brown layer below. The upper 30 cm of sediment contain abundant *Ceratophyllum demersum* remains. SPRA1 was selected as the mastercore.

Figure 13 Map of Sprat's Water showing the location of the sediment cores

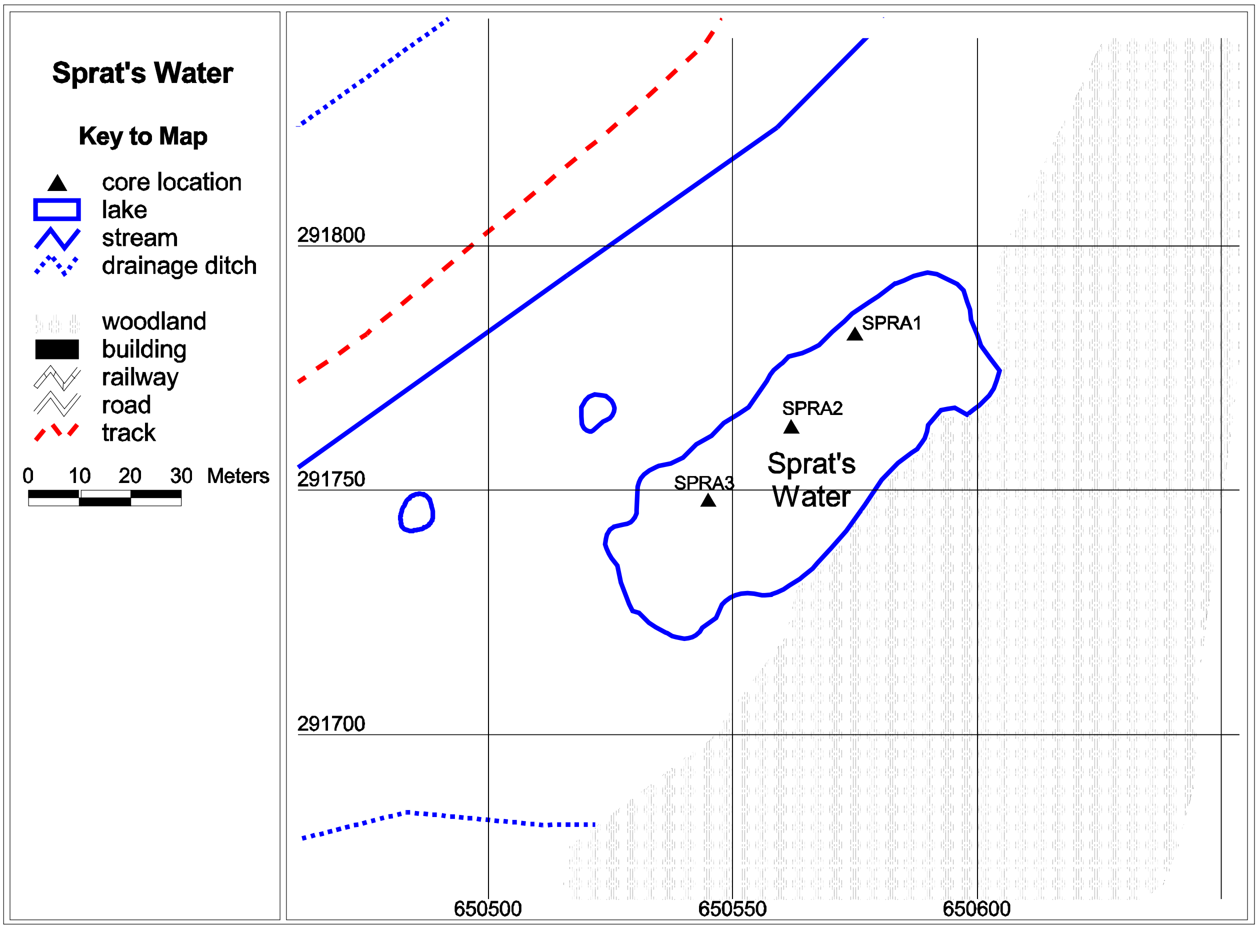
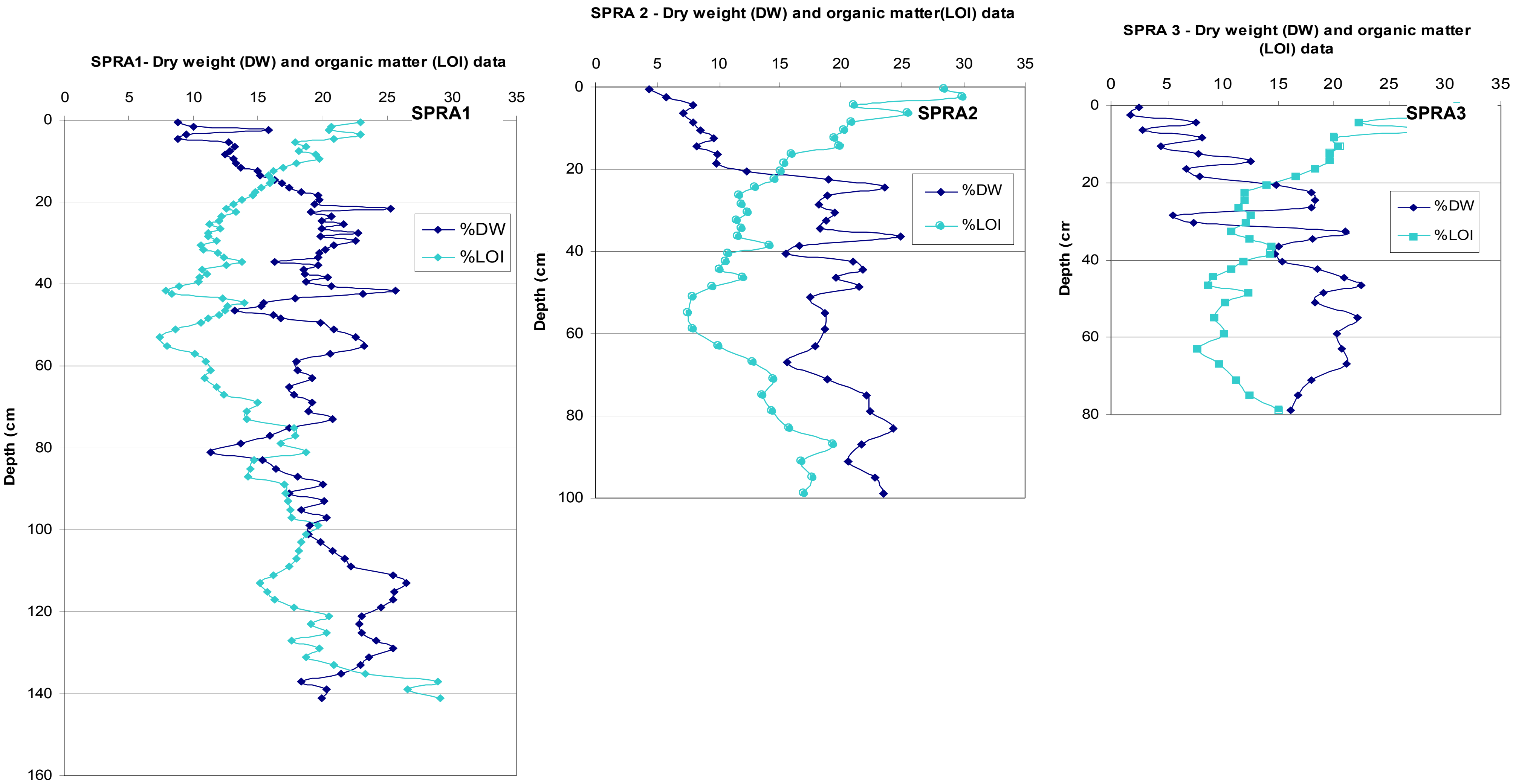


Figure 14 Dry weight and organic matter profiles for the Sprat's Water cores



4.2 Chronology

The fallout radionuclide concentrations in the Sprat's Water core SPRA1 are shown in Table 7.

Lead-210 Activity

Total ^{210}Pb activity apparently reaches equilibrium with the supporting ^{226}Ra at a depth of about 25 cm (Figure 15a), though since the maximum unsupported ^{210}Pb concentration is just 42 Bq kg^{-1} this is unlikely to span significantly more than around 60 years. Unsupported ^{210}Pb activity (Figure 15b) declines irregularly with depth, with a significant non-monotonic feature at around 12-13 cm.

Artificial Fallout Radionuclides

^{137}Cs concentrations in the core are very low, though there is a relatively well defined peak at 16-17 cm (Figure 15c) that probably dates from the mid 1960s, the period of fallout maximum from the atmospheric testing of nuclear weapons. Since the events diluting the ^{210}Pb activity at 12-13 cm may well have also diluted the ^{137}Cs activity, the maximum value of the ^{137}Cs/^{210}Pb ratio may be a better guide to the 1963 depth. Since this occurs in the 12-13 cm sample, the best estimate of the 1963 depth is that it occurs between 12-17 cm.

Core Chronology

Figure 16 plots ^{210}Pb dates calculated using the CRS model, together with the 1963 depth indicated by the ^{137}Cs record. The ^{210}Pb dates place 1963 at a depth of around 18 cm, a little deeper than the depth determined from the ^{137}Cs record. Using both the ^{210}Pb and ^{137}Cs data the mean accumulation rate is estimated to be 0.049 ± 0.009 g cm^{-2}y^{-1} following the dilution event at 12-13 cm, and 0.033 ± 0.006 g cm^{-2}y^{-1} prior to this event (Table 8).

Table 7 Fallout Radionuclide Concentrations in Sprat's Water core SPRA1

Depth		^{210}Pb Total		^{210}Pb Unsupported		^{210}Pb Supported		^{137}Cs	
cm	g cm^{-2}	Bq kg^{-1}	±	Bq kg^{-1}	±	Bq kg^{-1}	±	Bq kg^{-1}	±
0.5	0.05	65.0	8.9	42.1	9.2	23.0	2.3	5.3	1.5
4.5	0.52	44.4	7.6	28.5	7.8	15.9	1.8	4.6	1.2
8.5	1.06	41.0	11.1	25.0	11.3	16.0	1.9	6.1	1.5
12.5	1.64	25.7	8.8	7.6	9.4	18.1	3.1	6.8	1.4
16.5	2.36	42.4	7.7	25.2	7.8	17.2	1.8	7.6	1.7
20.5	3.22	37.6	5.9	18.1	6.2	19.5	1.7	1.8	1.4
24.5	4.20	17.7	6.4	1.2	6.8	16.5	2.2	0.0	0.0
28.5	5.16	24.6	10.2	5.1	10.5	19.5	2.2	0.0	0.0

Table 8 ^{210}Pb chronology of Sprat's Water core SPRA1

Depth		Chronology			Sedimentation Rate		
cm	g cm^{-2}	Date AD	Age y	±	g cm^{-2} y^{-1}	cm y^{-1}	± (%)
0.0	0.00	2003	0	0			
0.5	0.05	2002	1	1	0.049	0.42	17.9
4.5	0.52	1992	11	3	0.049	0.39	17.9
8.5	1.06	1981	22	5	0.049	0.37	17.9
12.5	1.64	1971	32	7	0.062	0.31	17.9
16.5	2.36	1956	47	10	0.033	0.19	19.2
20.5	3.22	1930	73	14	0.033	0.14	17.9

Figure 15 Fallout radionuclides in Sprat's Water core SPRA1, showing (a) total and supported ^{210}Pb, (b) unsupported ^{210}Pb, (c) ^{137}Cs concentrations versus depth.

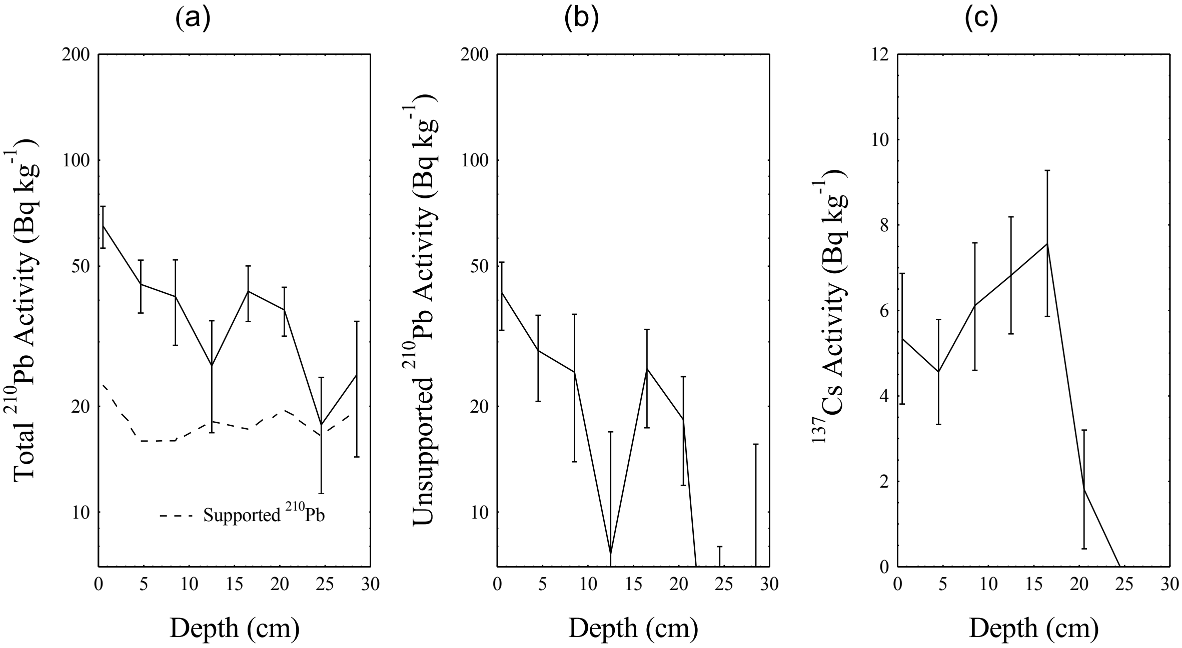
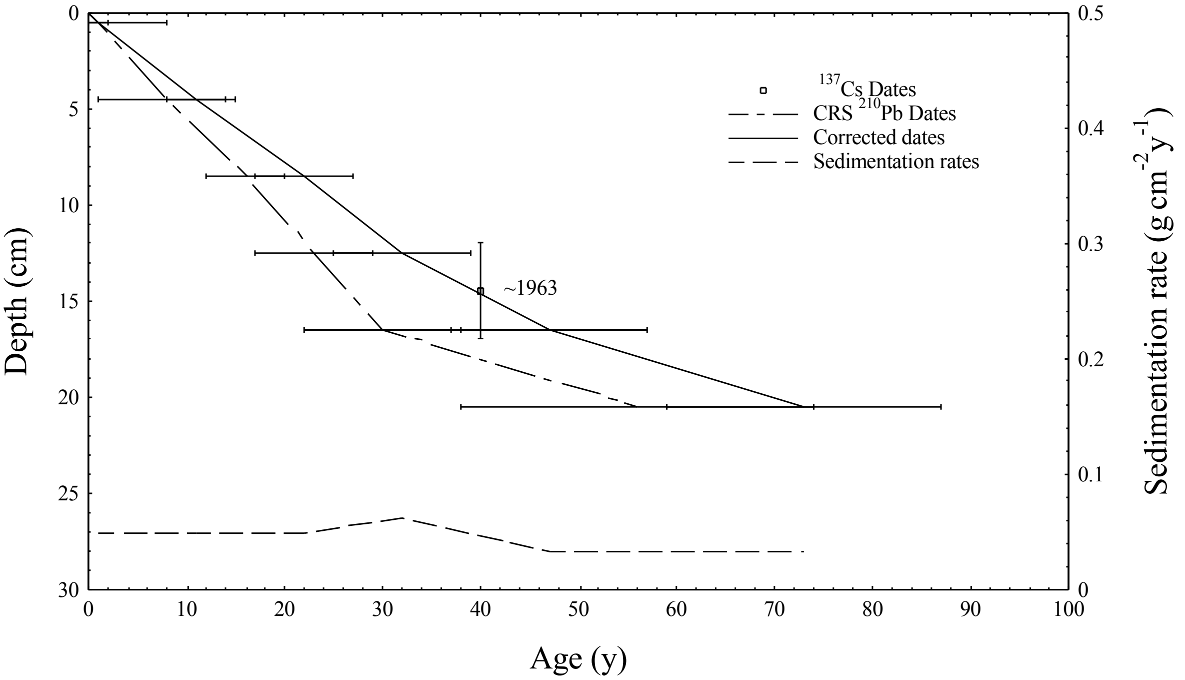


Figure 16 Radiometric chronology of Sprat's Water core SPRA1, showing CRS model ^{210}Pb dates and sedimentation rates together the 1963 depth determined from the ^{137}Cs stratigraphy. Also shown are the corrected ^{210}Pb dates and sedimentation rates.



Spheroidal carbonaceous particles (SCPs)

The SCP concentration profile for SPRA1 is shown in Figure 17. First presence of SCPs is at 42 – 43 cm and above this, apart from a sharp peak at 22-23 cm, the concentration increases steadily to a peak of almost 4500 gDM^{-1} at 12 –13cm. This is followed by a significant decline to the sediment surface. The slightly shorter profile and higher concentrations of SPRA1, with respect to BARB4, are consistent with a slower sediment accumulation rate at the Sprat's Water site. The SCP concentration profile is typical of that found across the UK. The SCP concentration peak is radiometrically dated to 1971 ± 7 and is in good agreement with the 1970 date used for the SCP dating for this ‘south and central England’ region. Dates for each 10-percentile of SPRA1 are shown in Table 9, together with the confidence limits for each date, and graphically in Figure 18. The dates show a reasonably steady accumulation rate between 1850 and 1950 with an increase in accumulation rate from the 1950s until the 1970s since when the accumulation rate may have reverted to the pre-1950 rate. The depth for the 1963 ^{137}Cs peak for this core is also shown on Figure 18 (black square) and, coinciding with the period of more rapid accumulation, provides good supporting evidence for this depth-age profile.

Figure 17 SCP concentration profile of Sprat’s Water (SPRA1)

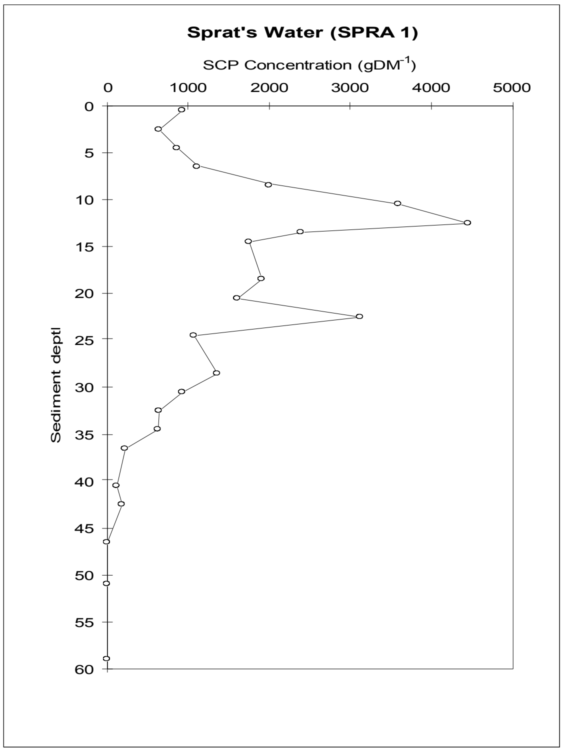
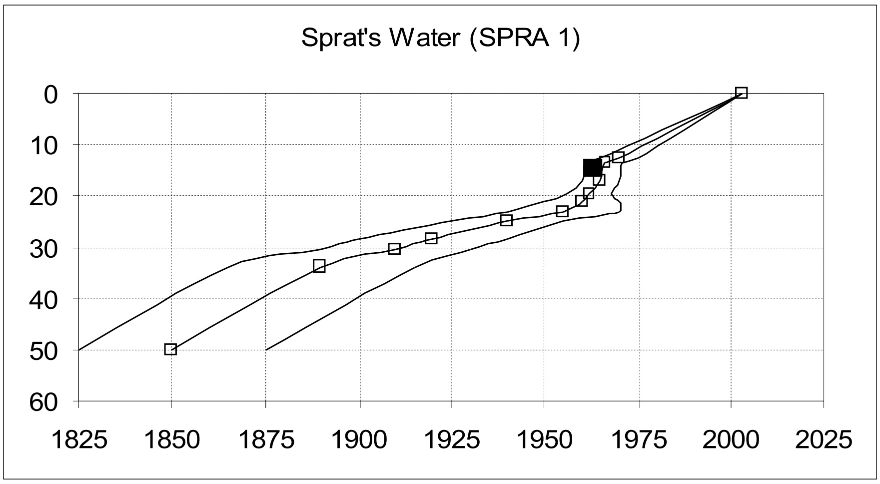


Table 9 Sediment depths and dates for each 10-percentile of the cumulative SCP profiles for Sprat’s Water (SPRA1) calibrated to the ‘south and central England’ regional SCP profiles from Rose & Appleby (in prep).

10-percentile	Date	Confidence interval	SPRA1 (cm)
0	1850	1875 – 1825	50
10	1890	1915 – 1865	34
20	1910	1930 – 1890	30.5
30	1920	1940 – 1900	28.5
40	1940	1955 – 1925	25
50	1955	1970 – 1940	23
60	1960	1970 – 1950	21
70	1962	1968 – 1956	19.5
80	1965	1970 – 1960	17
90	1966	1971 – 1961	13.5
100	1970	1975 – 1965	12.5
	2003		0

Figure 18 SCP dating profile for Sprat's Water. Open squares show SCP dates and depths for each 10-percentile. Black square shows the ^{137}Cs 1963 peak.



Corrected chronology using combined radiometric dating and SCP data
Figure 19 compares the final radiometric dates with those determined from the SCP record. SCP dates around 1963 are in quite good agreement with the radiometric dates for this period. The SCP dates do however suggest a much stronger episode of accelerated sedimentation in the early 1960s. Prior to this event they suggest a mean sedimentation rate of 0.040 g cm^{-2} y^{-1} (0.17 cm y^{-1}), significantly higher than that suggested by the ^{210}Pb results. The corrected chronology (Figure 19, Table 10) has been constructed using the radiometric dates for the post-1970 period, and the SCP results for the earlier period.

Figure 19 Chronology of Sprat's Water core SPRA1, showing the radiometric dates, SCP dates, and corrected dates based on both methods.

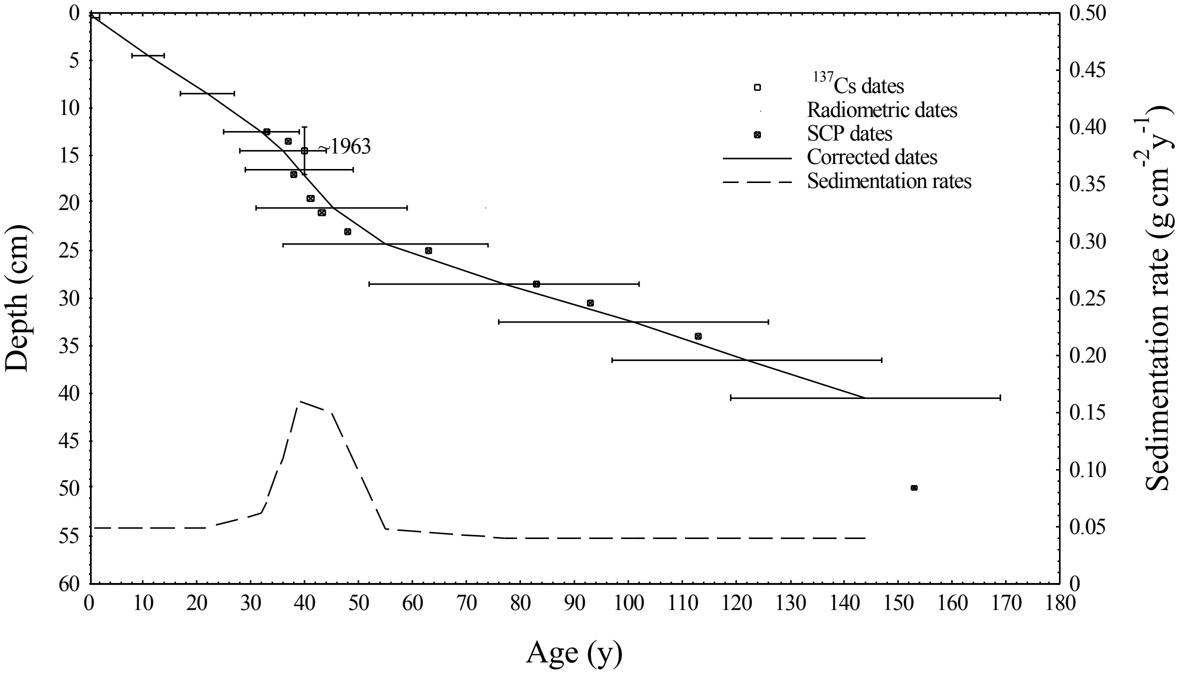


Table 10 Corrected chronology of Sprat's Water core SPRA1

Depth		Chronology			Sedimentation Rate		
cm	g cm^{-2}	Date AD	Age y	±	g cm^{-2} y^{-1}	cm y^{-1}	± (%)
0.0	0.00	2003	0	0			
0.5	0.05	2002	1	1	0.049	0.42	17.9
4.5	0.52	1992	11	3	0.049	0.39	17.9
8.5	1.06	1981	22	5	0.049	0.37	17.9
12.5	1.64	1971	32	7	0.062	0.41	17.9
14.5	1.98	1967	36	8	0.11	0.59	19.2
16.5	2.36	1964	39	10	0.16	0.71	19.2
20.5	3.22	1958	45	14	0.15	0.51	
24.5	4.20	1948	55	19	0.048	0.25	
28.5	5.16	1926	77	25	0.040	0.17	
32.5	6.12	1902	101	25	0.040	0.18	
36.5	6.96	1881	122	25	0.040	0.19	
40.5	7.84	1859	144	25	0.040	0.18	

4.3 Geochemistry and sediment characterisation

The mineral magnetics, geochemistry and particle size data for the Sprat's Water cores are presented in Figure 20. The mineral magnetic profiles were dominated by high values of many parameters in the deepest sediment, reflecting secondary sulphide formation of little palaeoenvironmental significance (Figure 20a). There was a weak χarm and SIRM signal above 25-50 cm, broadly matching the Zn concentration profiles, and reflecting atmospheric pollution. The Ca data show that the sediment in Sprat's Water is highly calcareous, with calcium carbonate ranging from 50 to 90% (Figure 20b). There were no notable changes in particle size throughout the profiles (Figure 20d). As for Barnby Broad, the small catchment and the shallow depth of the site most likely explains this situation.

The sediment in two of the cores (SPRA1 and SPRA2) can be divided into three major zones with distinctly different sediment composition (Table 11 and Figure 21). Zone 1 (> 70-100 cm) representing the lowermost sediment (not seen in SPRA3 due to the shorter core length) is Si-poor, and enriched in S, Rb, Fe and high susceptibility minerals. This suggests soil derived mineral matter, with added diagenetic sulphides and appears to represent pre-industrial material. Above this zone, the sediment is enriched in Si. The Si is very high for the concentration of mineral matter present, suggesting that it is either biogenic silica or sand/silt associated. The silica enriched sediment can be subdivided into two zones. Zone 2 (~40-100 cm; pre-1850) also appears to represent the pre-industrial period as it has low concentrations of P, Pb and Zn. Zone 3 (upper 40 cm; post 1850) is distinctly enriched in P, Pb, and Zn representing the industrial period of nutrient and atmospheric pollution. The maximum total sediment P concentration (1.0-1.8 mg g^{-1}) is typical for UK lowland lake sediments and river suspended sediment, reflecting a high nutrient loading. The calculated sediment P loading (0.5-0.9 g m^{-2} yr^{-1}) places the site significantly above the mesotrophic/eutrophic boundary of Vollenweider (1976).

The high level of agreement between the three sediment cores suggests that we have a reasonable sample of the lake sediment. At Sprat's Water the thickness of the most recent contaminated sediment ranges between 39 and 47 cm depth, corresponding to a dry mass quantity of between 46 and 90 kg per square metre of lake bed. Given a total area of 0.27 ha, this amounts to a sediment volume of ~1000 and 1300 m^3, with a dry mass of around 50 to 120 tonnes.

Table 11 Compositional zones in Sprat's Water

						SPRA 1			SPRA 2			SPRA 3		
Zone	***Description and interpretation***					Conc		Mass	Conc		Mass	Conc		Mass
	CORE	**1**	**2**	**3**										
						Mean	sd	g m^{-2}	Mean	sd	g m^{-2}	Mean	sd	g m^{-2}
Zone 3	Sediment enriched in Si, P, Pb and Zn Industrial period sediment with marked nutrient and atmospheric pollution	0 – 47 cm	0 – 39 cm	0 – 39 cm	Si mg/g	112	31	9785	96	26	7674	88	29	6904
					Ca mg/g	309	24	27696	273	30	22919	279	11	19158
					Fe mg/g	5.2	1.4	444	6.6	1.6	469	7.0	1.8	469
					S mg/g	2.2	1.0	161	3.7	1.1	252	2.9	0.8	178
					P mg/g	0.6	0.3	45.2	0.9	0.5	51.5	1.0	0.6	57.8
					Cd µg/g	0.31	0.08	0.027	0.25	0.02	0.02	0.26	0.06	0.16
					Cu µg/g	7.4	2.1	0.58	6.4	0.8	0.50	7.3	2.6	0.43
					Pb µg/g	24.9	10.7	2.0	24.7	8.1	1.8	25.5	11.9	1.6
					Zn µg/g	48.2	25.3	3.8	43.4	13.4	3.2	45.7	15.1	2.6
Zone 2	Sediment enriched in Si but depleted in P, Pb and Zn Pre-industrial sediment infill	47 – 100 cm	40 – 70 cm	40 - >73 cm	Si mg/g	119	48	13300	71			88	17	
					Ca mg/g	289	48	28301	338			291	20	
					Fe mg/g	14.1	5.2	1354	6.2			8.5	6.0	
					S mg/g	6.3	3.5	660	2.3			3.0	2.0	
					P mg/g	0.3	0.1	28.7	0.3			0.6	0.2	
					Cd µg/g	0.22	0.05	0.023	0.23			0.18	0.04	
					Cu µg/g	6.7	0.8	0.66	6.4			5.6	3.2	
					Pb µg/g	19.9	8.5	1.9	28.5			20.1	4.4	
					Zn µg/g	14.1	2.8	1.4	13.2			16.5	2.9	
Zone 1	Minimum Si, Pre-industrial sediment infill	100 - >140 cm	70 – > 97 cm		Si mg/g	33	14		8.2	3.0				
					Ca mg/g	274	43		297	19				
					Fe mg/g	22.3	8.0		19.1	2.4				
					S mg/g	7.0	2.2		6.1	0.8				
					P mg/g	0.4	0.1		0.8	0.2				
					Cd µg/g	0.21	0.03		0.21	0.07				
					Cu µg/g	7.1	1.0		4.6	1.0				
					Pb µg/g	21.5	12.8		12.3	7				
					Zn µg/g	17.3	4.9		15.6	3.5				

Figure 20a Sprat’s Water organic matter and mineral magnetic parameters

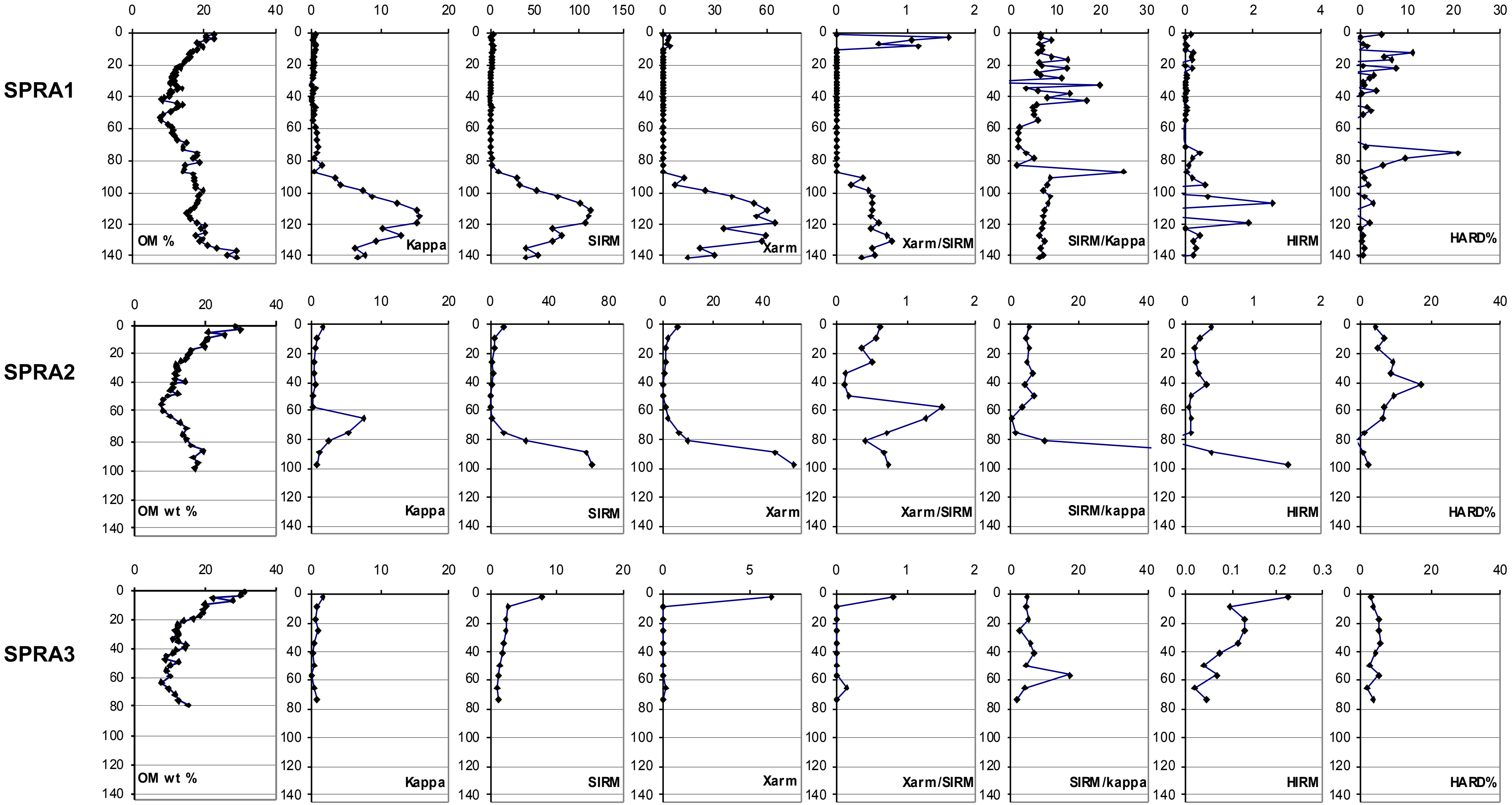
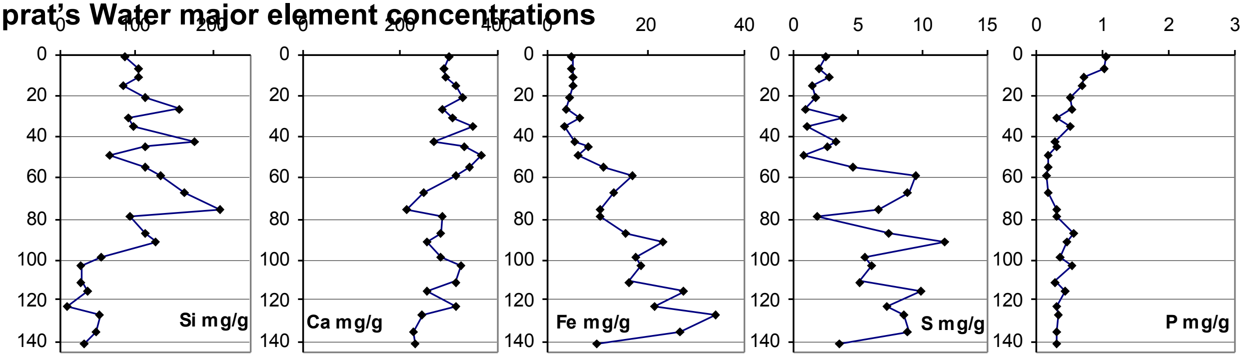
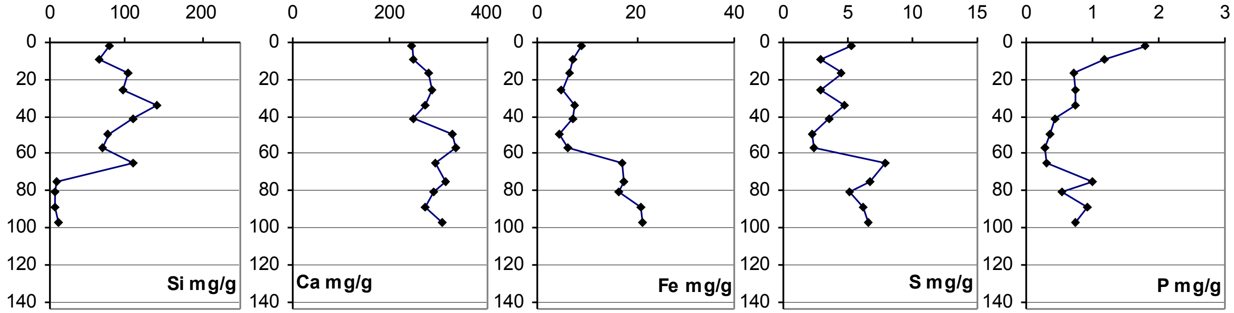


Figure 20b Sprat's Water major element concentrations

SPRA 1



SPRA 2



SPRA 3

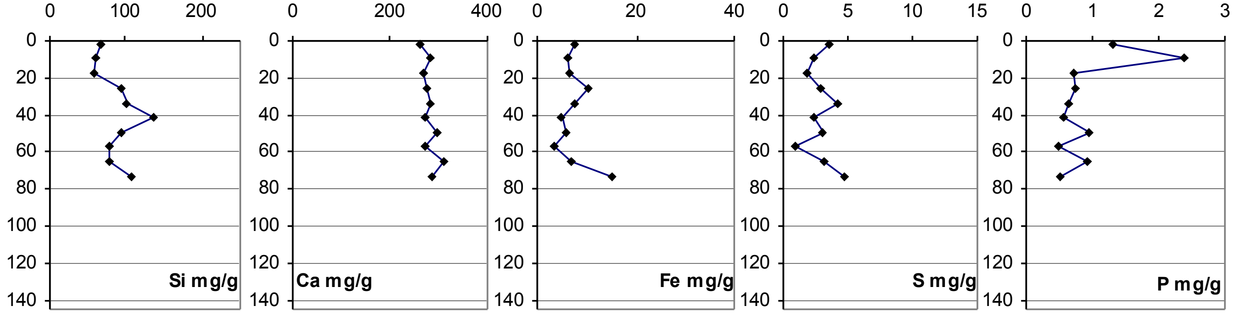


Figure 20c Sprat's Water trace element concentrations

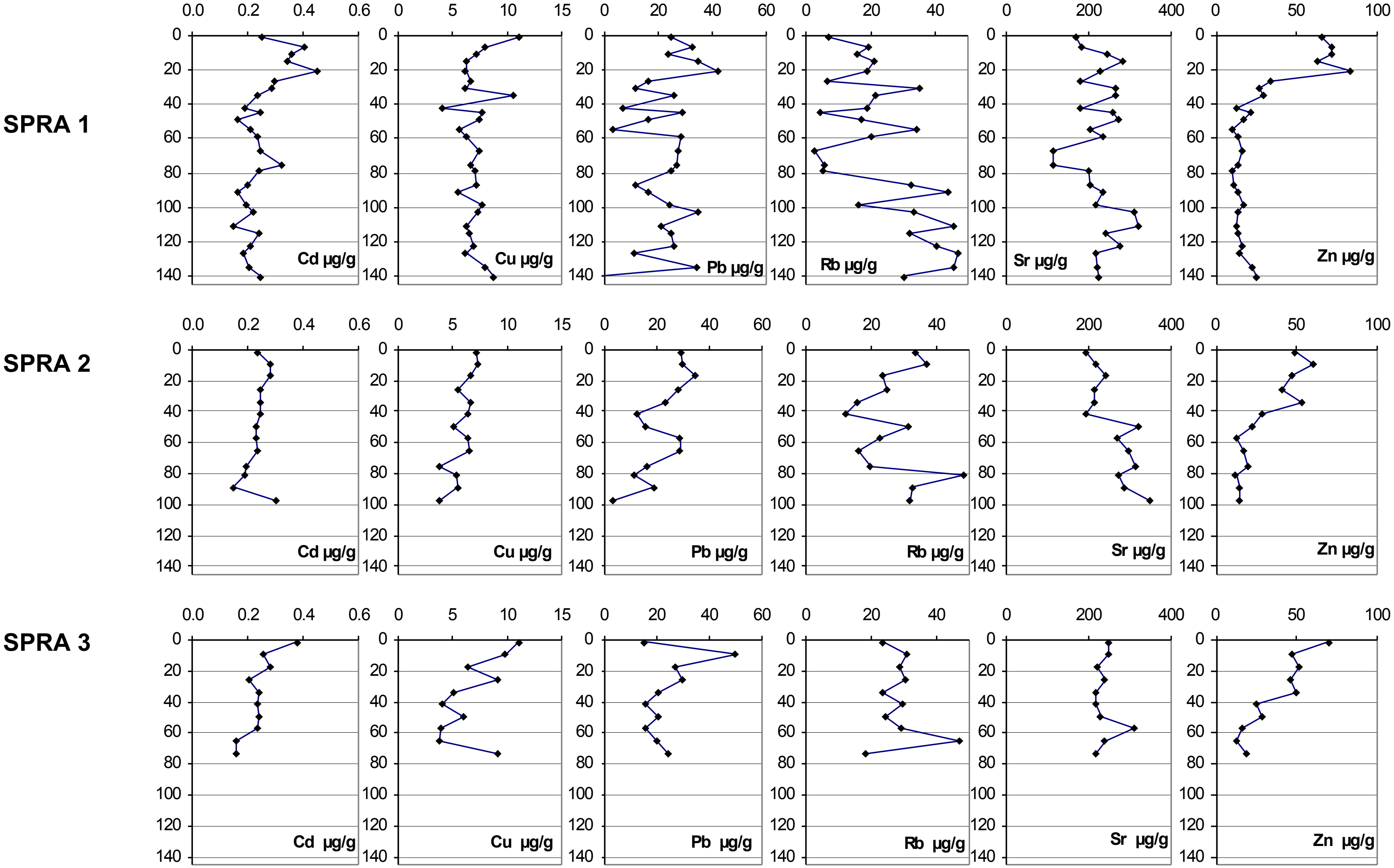


Figure 20d Sprat’s Water particle size data

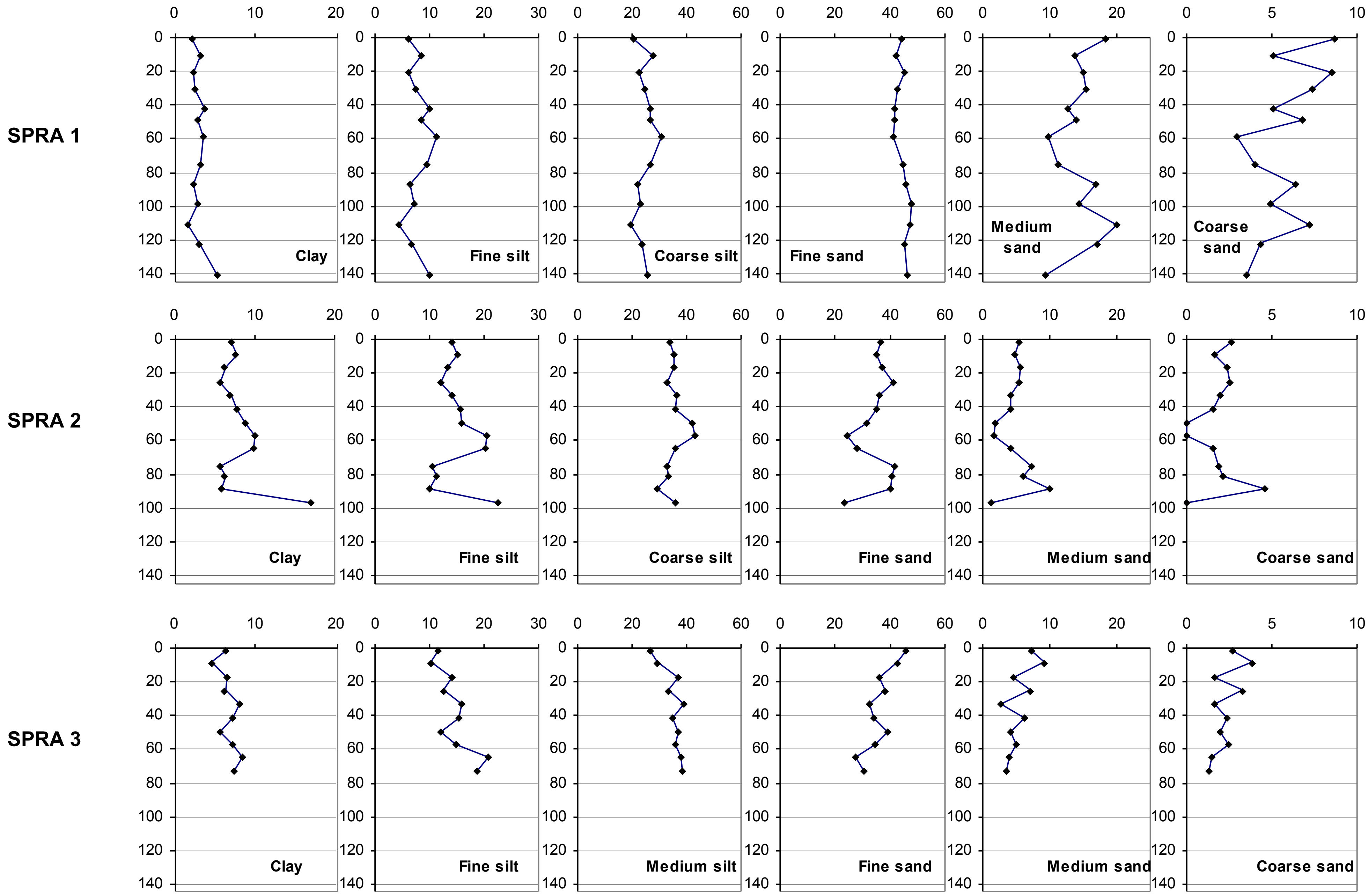
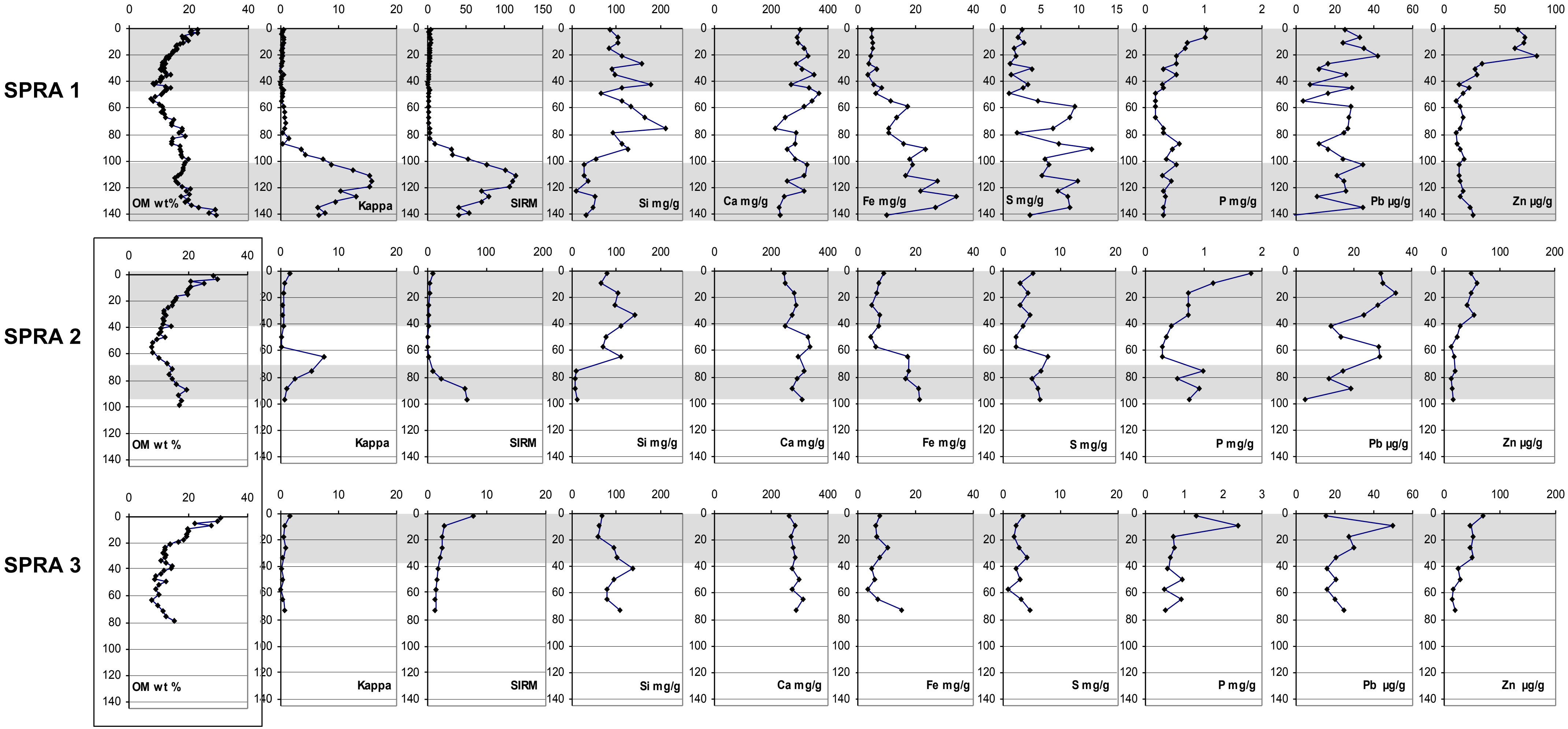


Figure 21 Sprat's Water summary chemical and mineral magnetic data showing compositional zones



4.4 Diatoms and macrofossils

Thirteen samples were analysed for diatoms in the Sprat's Water core SPRA1 (Table 12) and the summary diatom diagram is shown in Figure 22. Samples below 113 cm sediment depth could not be counted owing to very poor diatom preservation. The diatom species diversity was variable ranging from 0.04 to 0.15 with a total of 80 taxa observed throughout the core.

Table 12 Summary of samples analysed for diatoms in Sprat's Water core SPRA1

Depth (cm)	Total count	No. of species	Floristic diversity
1.5	393.5	25	0.06
7.5	413	32	0.08
13.5	394.5	28	0.07
19.5	395	43	0.11
28.5	333.5	44	0.13
39.5	427.5	32	0.07
53	492.5	19	0.04
63	668	24	0.04
71	536.5	37	0.07
79	429	43	0.10
91	370	54	0.15
99	387.5	50	0.13
113	478	48	0.10

Eleven samples were analysed for macrofossils representing the full length of the 140 cm core and the summary diagram is shown in Figure 24. Cluster analysis identified three major zones at approximately the same depths in both the diatom record and the upper 110 cm of the macrofossil record. A fourth zone was identified for the lowermost part of the macrofossil profile (100-140 cm). Dates prior to 1850 AD have been extrapolated based on the sediment accumulation rate of 0.18 cm y^{-1} calculated in Table 10. As for Barnby Broad, these dates serve only as a guide to the approximate time period represented by the earlier part of the core.

Zone 1 of the macrofossil profile (110-140 cm; ~1300 to ~1500) contains remains of foraminifera (Figure 24). These organisms are only found in brackish and marine environments, suggesting that Sprat's Water was originally a component of a wider estuarine environment experiencing periodic salt-water inundation. Identification of the foraminifera to species level may provide clues as to the extent of marine influence. Identification of the *Juncus* spp. seeds found in similarly high concentrations in the same sample may further aid ecological interpretations. Diatom dissolution was evident below ~100 cm with the extent of dissolution increasing with depth down-core. The onset of diatom dissolution coincides with depletion of Si in the sediments recorded by geochemical analyses. Consequently, diatoms were not enumerated below 113 cm and therefore there are no corresponding diatom data for this zone in the macrofossil record.

Zone 1 of the diatom profile/Zone 2 of the macrofossil profile (75-110 cm; ~1500 to ~1700) was relatively diverse in terms of diatoms with both littoral/periphytic taxa (e.g. *Fragilaria* spp., the epiphytic *Epithemia* spp.) and planktonic taxa such as *Cyclostephanos dubius*, *Cyclostephanos invisitatus, Stephanodiscus parvus* and *Stephanodiscus hantzschii*. The macrofossil record contained relatively high numbers of water lily remains in the form of trichosclereids derived from *Nymphaeaceae* species, and statoblasts of the bryozoan *Plumatella* spp. These taxa indicate that at this time Sprat's Water was an open-water habitat able to support phytoplankton. The diatoms are indicative of nutrient-rich, circumneutral to alkaline waters.

Zone 2 of the diatom profile/Zone 3 of the macrofossil profile (35-75 cm; ~1700 to ~1900) had low diatom diversity with a flora dominated by small benthic *Fragilaria* spp., most notably *Fragilaria brevistriata*. There was an almost complete absence of the planktonic species and epiphytic taxa seen in Zone 1. This may indicate a change in macrophyte species, habitat shifts and/or a shallowing of the site during this period. The inferred shallowing of Sprat's Water appears to coincide with major drainage of the Carlton Marsh area in the 18th century (Waveney District Council leaflet, undated). The macrofossil record supports this theory since there were very few plant remains or zooplankton ephippia in this part of the core but there were high concentrations of gelatinous algal remains.

Zone 3 of the diatom profile/Zone 4 of the macrofossil profile (0-35 cm; post-~1900) could perhaps be divided into two diatom sub-zones, 0-17 cm (~1960-present) and 17–35 cm (~1900- ~1960). The lower zone is diverse and is comprised of (tycho)planktonic species (e.g. *Aulacoseira italica*, *Fragilaria capucina* var. *mesolepta*), epiphytic/epilithic taxa (e.g. *Nitzschia amphibia*, *Fragilaria capucina* var. *vaucheriae* / var. *distans* and *Cocconeis placentula*) and the benthic *Fragilaria* taxa. Whilst most of the taxa observed in the lower zone continue to be present in the upper zone, the latter has stronger dominance of benthic diatoms, namely *Fragilaria lapponica* and *Navicula minima* perhaps suggesting a habitat shift. Examination of modern samples of epipelon (surface sediment) and floating algal benthos (FLAB) from this site suggests that these two species are currently growing on the sediment surface of the broad. The predominance of *F. lapponica* in Sprat's Water over the last 40 years (0-15cm) is of interest because this species is described by K.B. Clarke (pers. comm.), in Kelly (2000), as "common in the Norfolk Broads before the onset of eutrophication, but there are no modern records". This suggests that Sprat's Water may currently have relatively low nutrient concentrations.

Zone 4 of the macrofossil record contains higher abundances of the submerged aquatic plant *C. demersum* and mollusc remains than the previous zones. The high abundance of *C. demersum* would provide colonisation space for epiphytic algae, which in turn would provide a food source for molluscan grazers and, therefore, a simultaneous increase in remains of these biota is not unexpected. Zooplankton ephippa were also present in relatively high numbers in this upper zone. Statoblasts of the freshwater bryozoan *Lophopus crystallinus* were found in the surface sediments (to a depth of 11 cm, ~mid-1970s), albeit in low absolute numbers (note scaling on Figure 24). The low numbers are not surprising given that *Lophopus* colonies are usually small (Clegg, 1965) Their presence in the upper sediments indicates that this site currently provides a suitable habitat for this species. *Lophopus crystallinus* is classed as rare in the UK Biodiversity Action Plans (BAP) for invertebrates (HMSO, 1999) and since 1970 has been found at only four sites in the UK, none of which are in Suffolk, although older records exist from the Norfolk and Suffolk Broads and dykes. The species is generally found attached to water plants, rocks, shells, wood and leaf litter but is threatened by a range of factors including eutrophication, water abstraction and removal of substrates such as woody debris. In light of the high conservation status of *Lophopus crystallinus*, the discovery of statoblasts in the recent sediments of Sprat's Water is an important one.

Comparison of the aquatic macrophyte survey data from July 2003 with the macrofossil remains in the surface sediments showed good agreement between the two datasets. *C. demersum* and *Lemna minor* were recorded as co-dominants in the recent survey and remains of both these taxa were observed in the core. *Stratiotes aloides* (water soldier) leaf spines were found in the surface sediments (and lower down the core) but were not recorded in the 2003 plant survey, suggesting that this was missed or that this plant has disappeared from the lake very recently.

There were problems with the application of the diatom transfer function to Sprat's Water because *Fragilaria lapponica*, the dominant taxon in the upper core, was poorly represented in the training set (only four occurrences). Consequently the optimum of this taxon is not well defined and is unrealistically high (264 µg l^{-1}), and is particularly unstable using the WA-PLS2 component model. The WA-PLS1 component model results only are presented in Figure 23 and show that DI-TP in the upper 113 cm of the core was stable at ~150 µg l^{-1}, except for a short period of very high concentrations of ~400 µg l^{-1} during the 1970s and early 1980s coincident with the peak in *Fragilaria lapponica*. This reconstruction is not robust and should not be interpreted as an increase in TP concentrations in the lake. The switch from *Fragilaria brevistriata* to *Fragilaria lapponica* dominance is more likely to be associated with habitat shifts than changes in epilimnetic nutrient concentrations. As for Barnby Broad, the inferred values are likely to be over-estimates and should not be used to set P reference concentrations.

Figure 22 Summary diatom diagram of Sprat's Water core SPRA1

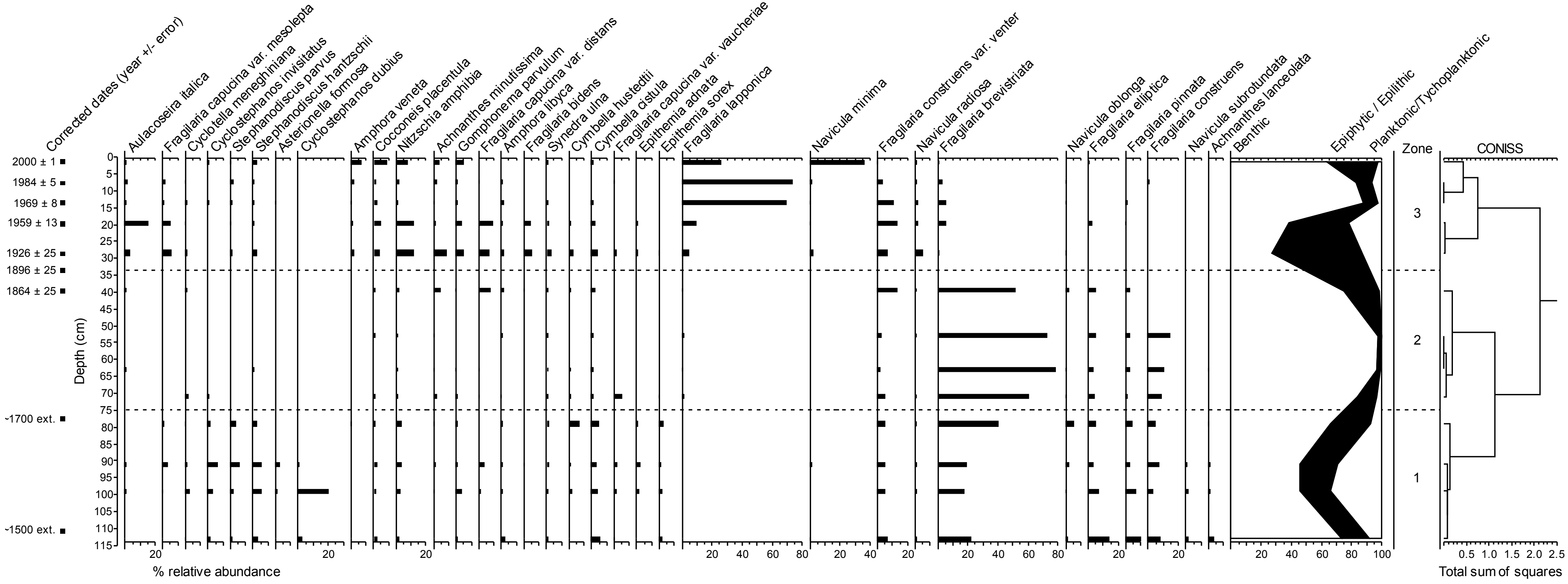


Figure 23 Diatom-inferred total phosphorus (DI-TP μg l^{-1}) reconstruction for Sprat's Water core SPRA1

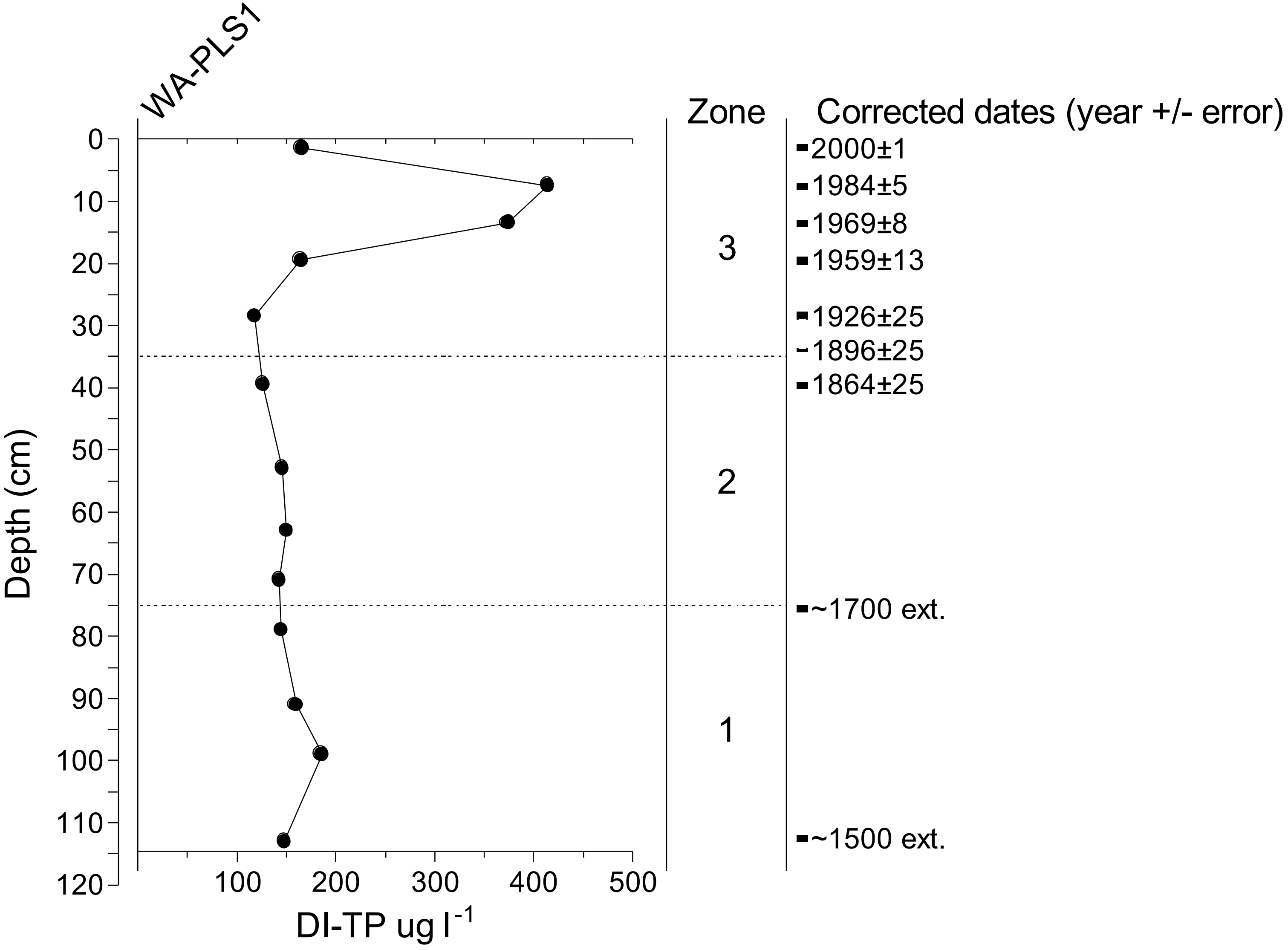
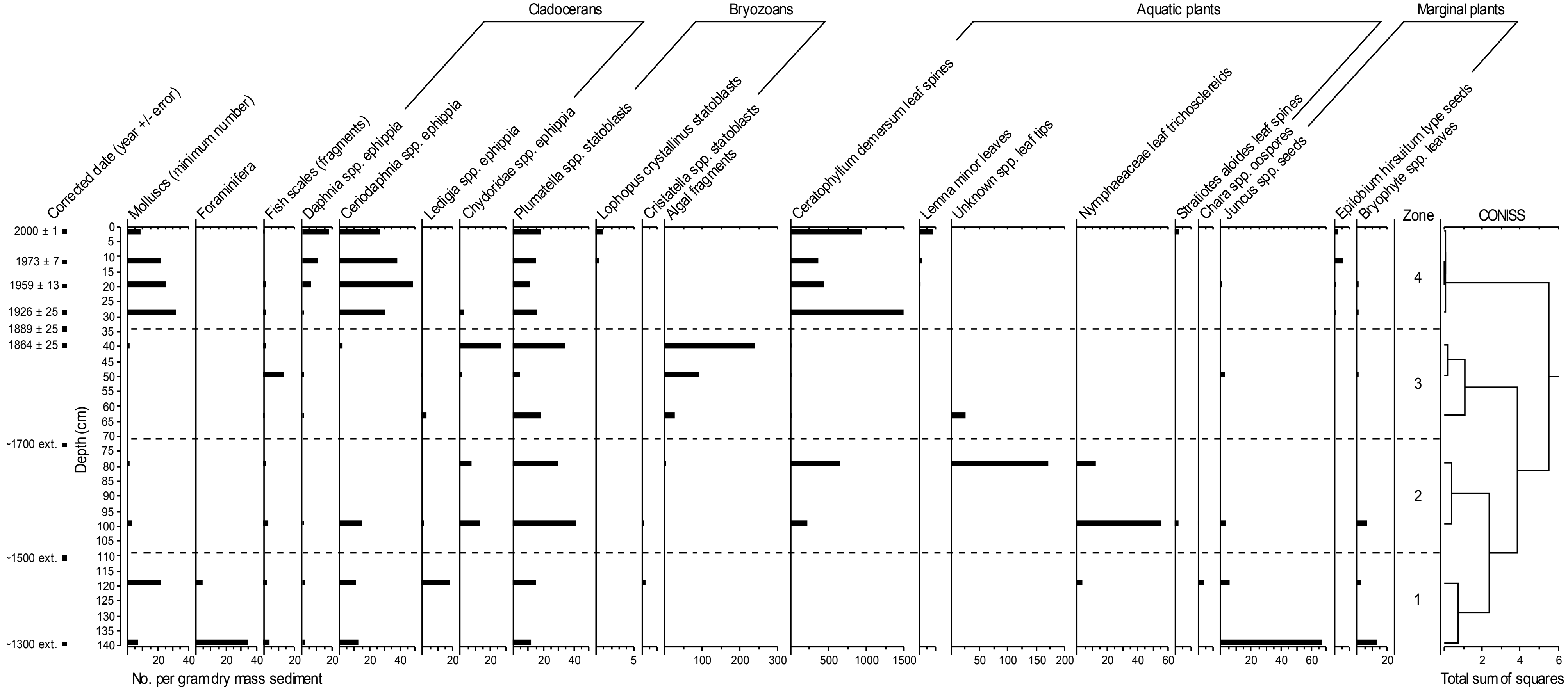


Figure 24 Summary macrofossil diagram of Sprat's Water core SPRA1
(Note different scale used for *Lophopus crystallinus* to aid visualisation of data)



5. ROUND WATER

5.1 Site and core description

Round Water (TM 504 916) is a very small, shallow, lowland lake (surface area 0.14 ha, altitude 1 m above sea level) and lies between Sprat's Water to the north-east and Woolner's Carr to the south-west within the Sprat's Water and Marshes SSSI at Carlton Colville. Like the two neighbouring water bodies, Round Water is a flooded medieval peat working. It is fringed by alder carr and reedbed with an arable field adjacent to the site on the east side. There is a small jetty on the western side of the lake. Suffolk Wildlife Trust reported that the site had been mud pumped during the 1980s although the depth and areal extent of the disturbance is not known.

Two piston cores were taken from the lake on 13 March 2003 (Figure 25):
ROUW1 (TM 50402 91686). Core length 104 cm. Water depth 1.14 m.
ROUW2 (TM 50402 91688). Core length 94 cm. Water depth 1.10 m.

The two cores had broadly similar stratigraphies with a dark brown organic basal layer containing plant remains (~ 80-100 cm), above which was a lighter brown, less organic section with fewer plant remains. The upper section was black-brown in colour and the uppermost 10 cm was extremely unconsolidated with abundant plant material (dominated by *Ceratophyllum* spp.). The dry weight and organic matter profiles (Figure 26) show good agreement between the two cores in the lower section below 30 cm but there are a number of discrepancies between the two profiles in the upper section. ROUW2 has a lower organic content than ROUW1 between 10-20 cm with values of 5-10% and 15-20%, respectively. Organic content in the two cores is similar again in the uppermost 10 cm. These differences may arise as a result of the mud pumping in the early 1980s which will have caused disturbance to the record and most likely led to redistribution of material across the lake. ROUW2 was selected as the mastercore.

Figure 25 Map of Round Water showing the location of the sediment cores

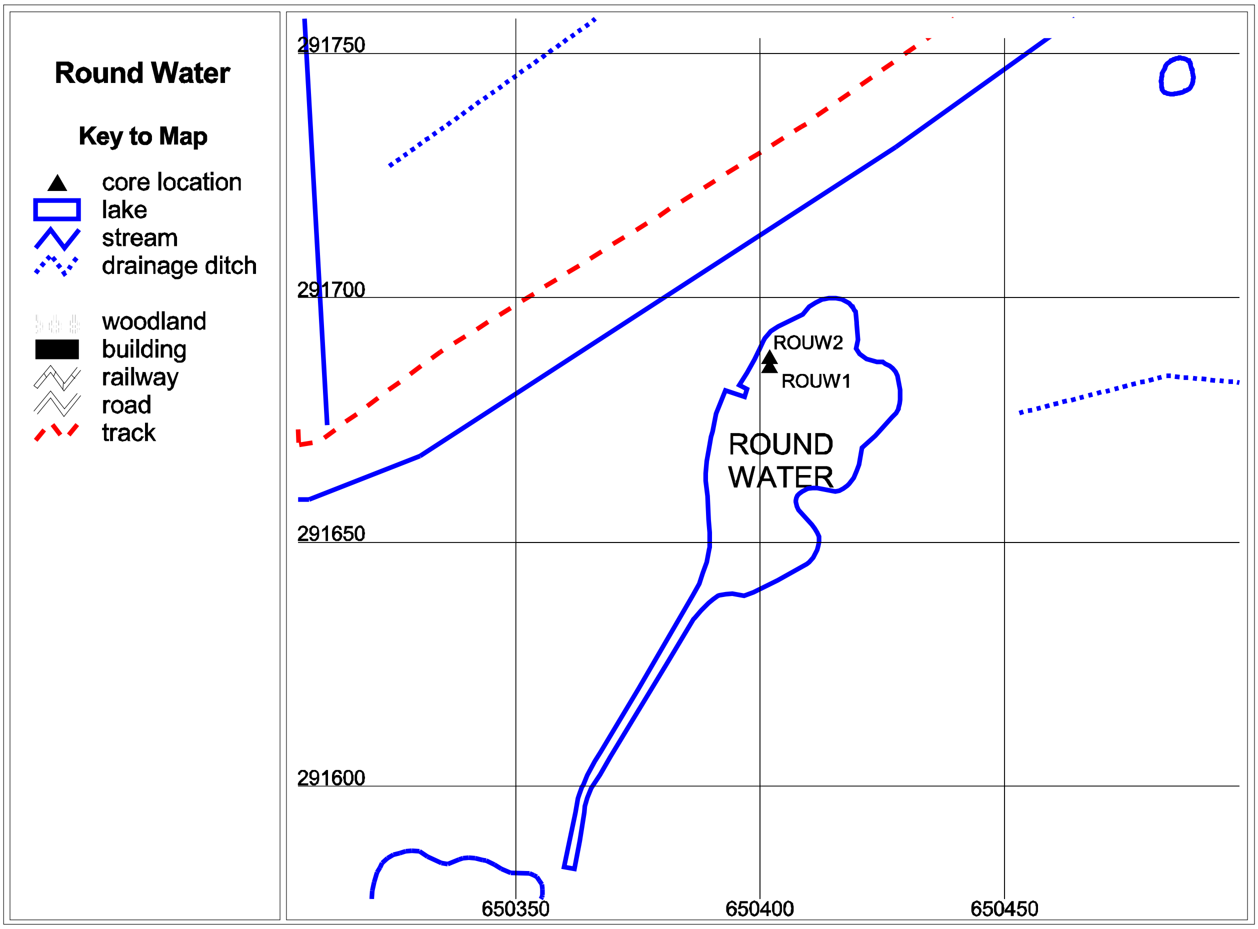
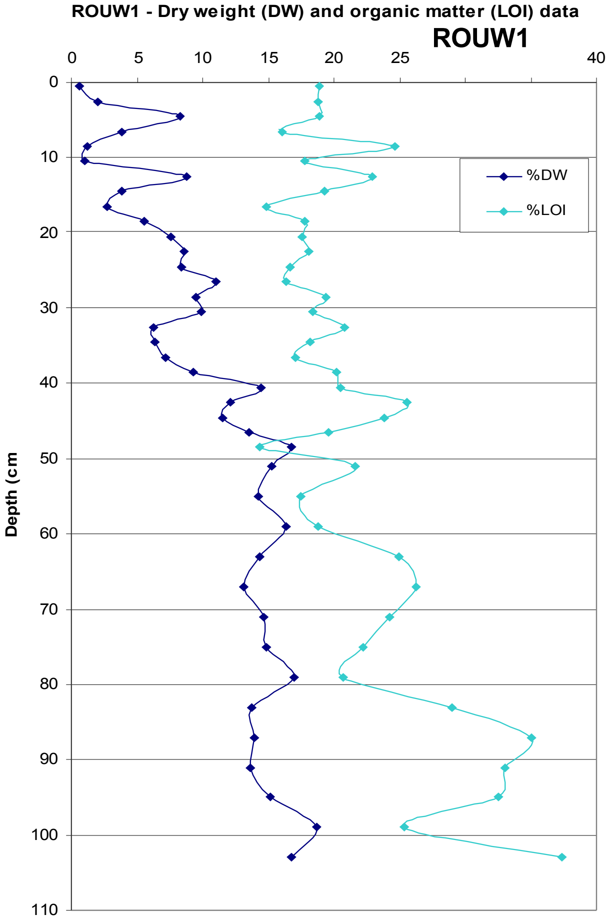
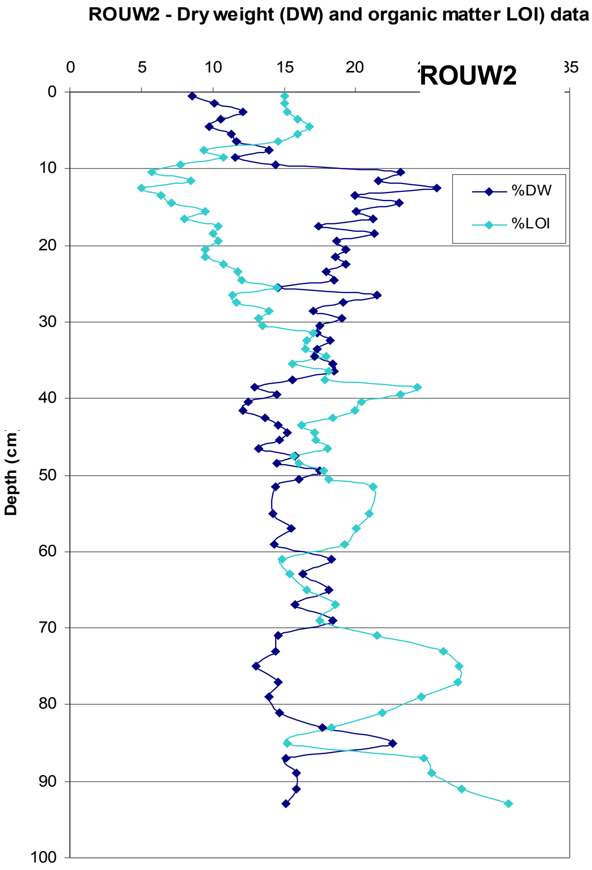


Figure 26 Dry weight and organic matter profiles for the Round Water cores





5.2 Chronology

The fallout radionuclide concentrations in the Round Water core ROUW2 are shown in Table 13.

Lead-210 Activity

Total ^{210}Pb activity significantly exceeded that of the supporting ^{226}Ra only in the uppermost sample analysed (Figure 27a). Unsupported ^{210}Pb activities (Figure 27b) were extremely low, and the ^{210}Pb inventory of the core was just 3% of the value supported by the normal atmospheric flux.

Artificial Fallout Radionuclides

^{137}Cs concentrations were extremely low (Figure 27c), and above limits of detection only in the top 5 cm. The fact that concentrations were highest in the 4-5cm sample is of little significance.

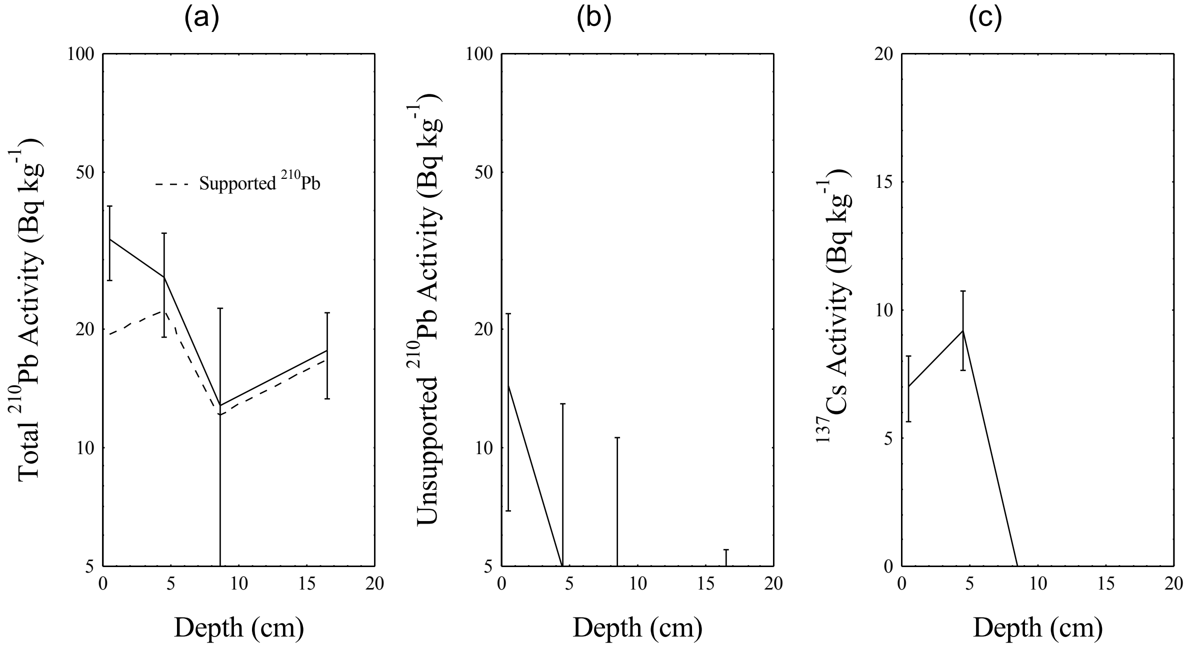
Core Chronology

Because of the very poor quality of the record of fallout radionuclides in this core it was not possible to date the core either by ^{210}Pb or ^{137}Cs. Assuming an atmospheric flux of ~70 Bq m^{-2} y^{-1}, the surficial ^{210}Pb concentration suggests a contemporary sedimentation rate of ~0.5 g cm^{-2} y^{-1}, or ~3 cm y^{-1}, though this value only has some credibility if there is evidence that the core has an undisturbed record. The mud pumping event in the 1980s, however, is likely to have disturbed the sediment record.

Table 13 Fallout Radionuclide Concentrations in Round Water core ROUW2

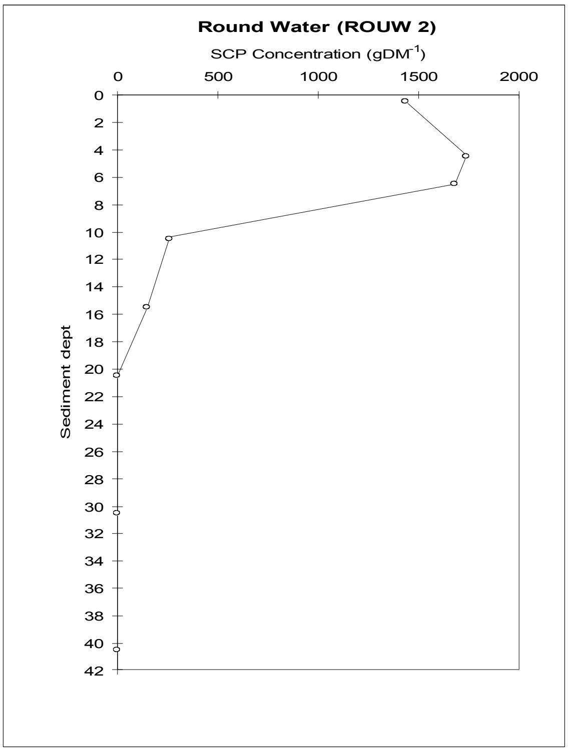
Depth		^{210}Pb Total		^{210}Pb Unsupported		^{210}Pb Supported		^{137}Cs	
cm	g cm^{-2}	Bq kg^{-1}	±	Bq kg^{-1}	±	Bq kg^{-1}	±	Bq kg^{-1}	±
0.50	0.05	33.8	7.2	14.4	7.5	19.4	2.0	6.9	1.3
4.50	0.49	27.0	8.0	4.7	8.2	22.4	2.0	9.2	1.6
8.50	1.01	12.8	9.8	0.7	9.9	12.1	1.6	0.0	0.0
16.50	2.90	17.6	4.3	0.9	4.6	16.8	1.5	0.0	0.0

Figure 27 Fallout radionuclides in Round Water core ROUW2, showing (a) total and supported ^{210}Pb, (b) unsupported ^{210}Pb, (c) ^{137}Cs concentrations versus depth.



Spheroidal carbonaceous particles (SCPs)
The SCP concentration profile for ROUW2 is shown in Figure 28. No SCPs were found below 15 – 16 cm and hence the profile is very short in comparison with the other sites. However, the concentrations are not elevated with respect to the other sites suggesting that this short profile is not due to a slow sediment accumulation rate. Therefore, the profile appears to be curtailed and could be caused by physical disturbance of the sediment, possibly as a result of sediment removal with perhaps a few years of recent accumulation at the surface. Dating of the profile by SCP means is therefore not possible, although if this assessment of the profile is correct, and the lower sediment is not disturbed, then a date of 1850 ± 25 years could be ascribed to ~20 cm.

Figure 28 SCP concentration profile of Round Water (ROUW2)



Combined radiometric dating and SCP data
Both the radiometric dating and the SCP data indicate that the sediment record of Round Water has been disturbed by the mud pumping in the 1980s and therefore it is not possible to assign a chronology to the core. We speculate that the sediment below approximately 30 cm represents the material that was not removed during the pumping operation and if this is the case the sediment below this depth is likely to provide a record of the early lake history. However, there appears to be a hiatus in the record with the loss of several decades of material (presumably removed by pumping). It is likely that the upper 30 cm of the core is a combination of resettled old material and very recently deposited, unconsolidated new material accumulated over the last few decades.

5.3 Geochemistry and sediment characterisation

The mineral magnetics, geochemistry and particle size data for the Round Water cores are presented in Figure 29. As for Barnby Broad and Sprat's Water, the sediment in Round Water is highly calcareous, with calcium carbonate ranging from 50 to 75% (Figure 29b). There is a general increase in organic matter with depth down-core but the cores lack the distinct organic-rich bottom layer indicating that the cores do not extend down to the basal peat.

There was good agreement between the two cores, with particularly striking mineral magnetic peaks at 40 – 50 cm (Figure 29a). The sediment in both cores can be divided into two zones (Table 14, Figure 30). The lower zone (35 to ~100 cm) has low Ca concentrations. The upper zone (0–35 cm) is characterised by higher Ca concentrations and lower levels of Si and heavy metals, and most strikingly Cu, than the lower zone. The upper zone also has a higher sand content. While this shows that post-pumping sediment infill differs slightly from the previously deposited sediment, it is not possible to determine whether this is due to differing source material or differing sediment transport pathways.

The general similarity between the cores breaks down in the upper sediment. ROUW2 uniquely shows strongly depressed P in the upper sediment, in addition to a distinct minimum in organic matter. A decrease in P content was not observed in the upper part of ROUW1. The spatial variation may be due to disturbance caused by mud pumping. The maximum total sediment P concentration (0.8-1.0 mg g^{-1}) is on the low side for lowland lake sediments and river suspended sediment for the UK, and probably reflects the removal of the internal P source via dredging. The absence of a reliable chronology for this site prevents a more complete interpretation of the P profiles. Neither the mineral magnetic profiles nor the heavy metal concentration data provide any evidence of an atmospheric contamination signal. The peaks in Kappa, SIRM and χarm mid-way down the profiles conceivably reflect the diagenetic sulphide enrichment seen deeper in the Sprat's Water and Barton Broad profiles. At Round Water it appears that recent contaminated sediment has already been removed, and there is no basis for any further removal.

Table 14 Compositional zones in Round Water

					ROUW2			**ROUW1**		
Zone	***Description and interpretation***				Conc		Mass	Conc		Mass
	CORE	**2**	**1**		Mean	sd	g m^{-2}	Mean	sd	g m^{-2}
Zone 2	Maximum Ca, depleted Cu, Pb and Zn In washed pre-industrial sediment	0 – 35 cm	0 – 35 cm	Si mg/g	106	32	7619	28.6	32.4	922
				Ca mg/g	307	19	18973	289	20	5796
				Fe mg/g	15.1	4.8	1043	8.8	6.4	251
				S mg/g	6.9	3.4	504	1.5	2.4	53
				P mg/g	0.3	0.1	14.6	0.7	0.2	13.7
				Cd µg/g	0.15	0.08	0.01	0.28	0.08	0.006
				Cu µg/g	4.9	1.0	0.30	4.5	1.8	0.11
				Pb µg/g	12.7	7.7	0.90	10.8	11.7	0.3
				Zn µg/g	14.1	6.9	0.7	22.5	11.1	0.6
Zone 1	Minimum Ca, high Pb Pre-industrial sediment infill	35 – 95 cm	35 – 98 cm	Si mg/g	105	56	>9468	75.6	62.7	>6719
				Ca mg/g	249	29	>23743	239	12	>20040
				Fe mg/g	22.3	7.1	>2258	35.2	10.7	>2863
				S mg/g	9.6	2.5	>932	11.5	2.6	>953
				P mg/g	0.5	0.2	>46.8	0.5	0.1	>39.4
				Cd µg/g	0.12	0.08	>0.009	0.17	0.07	>0.013
				Cu µg/g	9.1	1.0	>0.84	9.2	2.2	>0.75
				Pb µg/g	21.0	3.8	>2.0	16.3	8.0	>1.5
				Zn µg/g	17.5	4.7	>1.5	18.8	7.2	>1.5

Figure 29a Round Water organic matter and mineral magnetic parameters

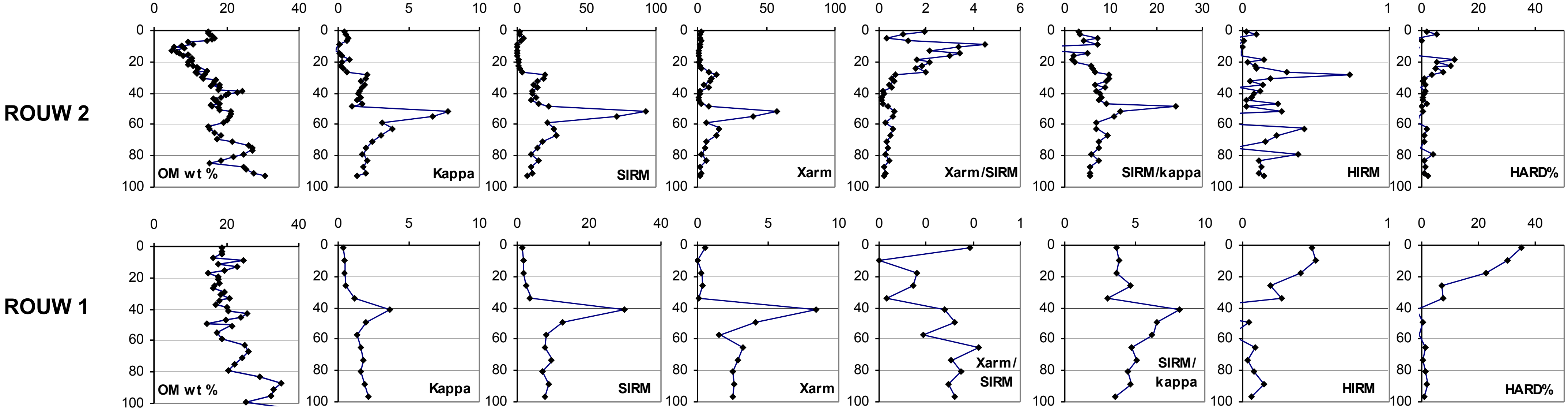


Figure 29b Round Water major and trace elements

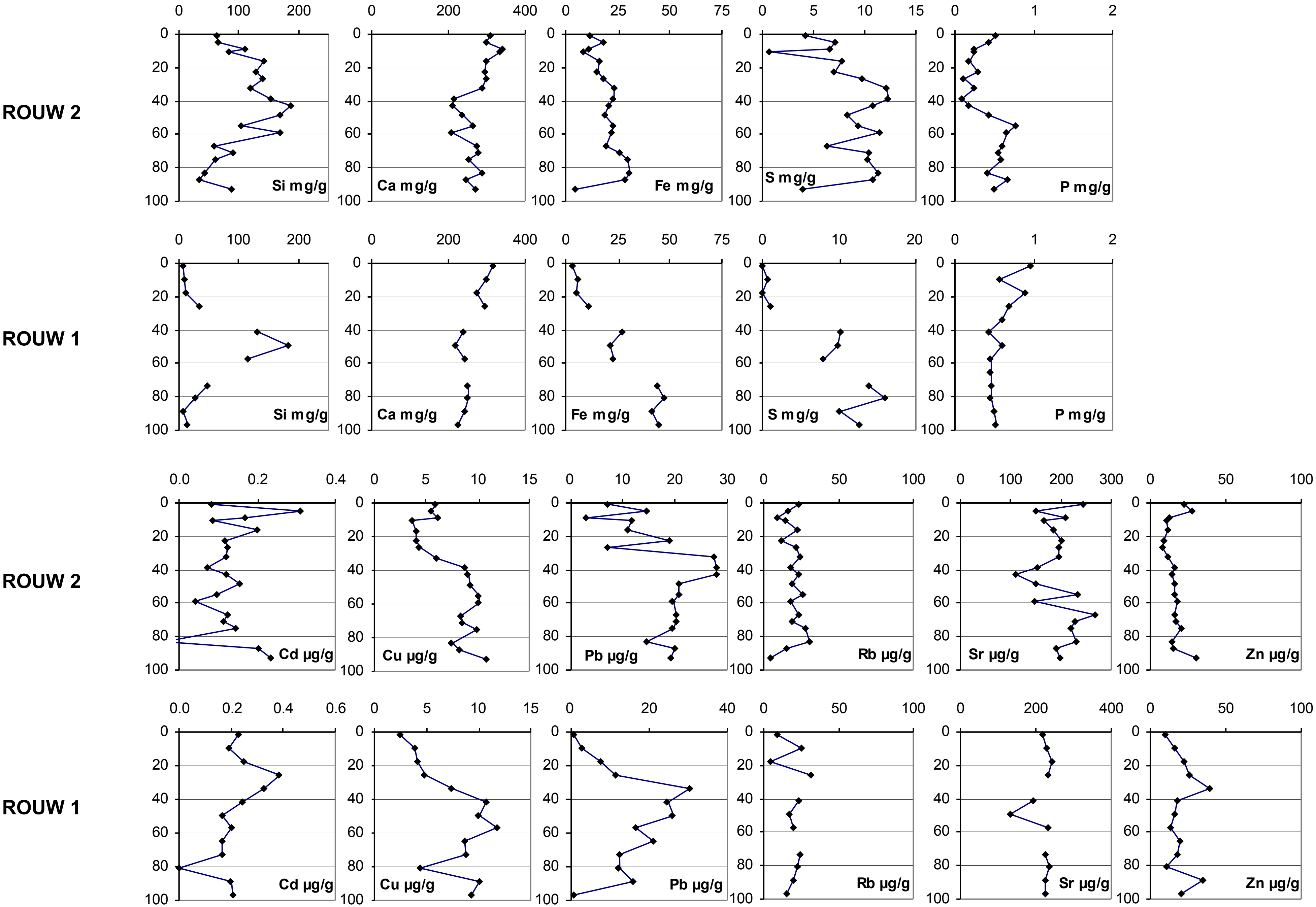


Figure 29c Round Water particle size data

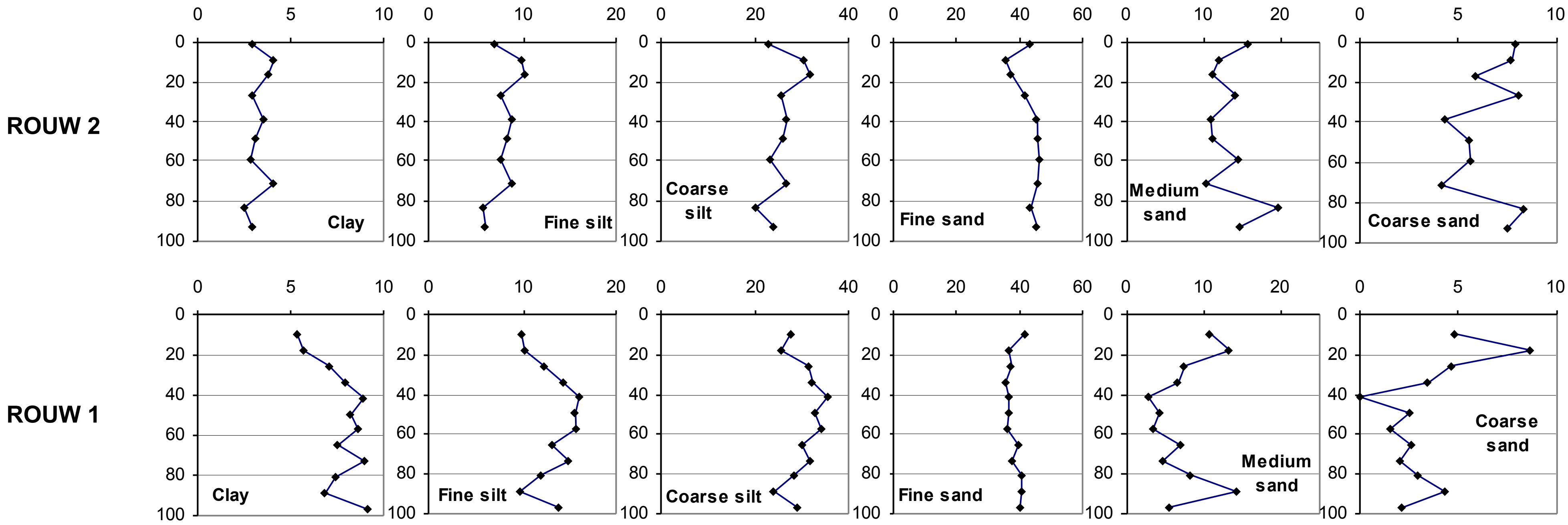
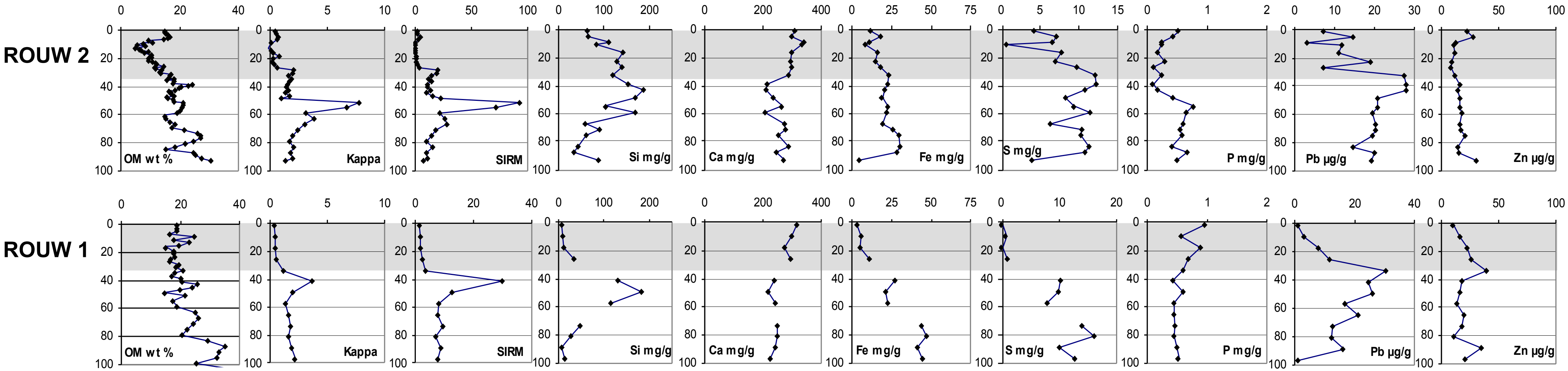


Figure 30 Round Water summary chemical and mineral magnetic data showing compositional zones



5.4 Diatoms and macrofossils

Eleven samples were analysed for diatoms in Round Water core ROUW2 (Table 15) and the summary diatom diagram is shown in Figure 31. The diatom species diversity was variable ranging from 0.08 to 0.15 with a total of 83 taxa observed throughout the core.

Table 15 Summary of samples analysed for diatoms in Round Water core ROUW2

Depth (cm)	Total count	No. species	Floristic diversity
1.5	315.5	43	0.14
11.5	395	52	0.13
19.5	343.5	53	0.15
29.5	365.5	50	0.14
39.5	350.5	47	0.13
49.5	337	49	0.15
55	354.5	51	0.14
63	381	49	0.13
77	351.5	28	0.08
85	374	37	0.10
91	324.5	36	0.11

Ten samples were analysed for macrofossils representing the full length of the core and the summary diagram is shown in Figure 33. Given that the integrity of the sediment record has been affected by sediment removal, the majority of samples were selected from the section below 30 cm which is likely to provide a record of the early lake history prior to mud pumping.

Cluster analysis identified four major zones in both the diatom and macrofossil record although the levels at which these occur are different. Owing to the disturbed record, a combined interpretation of the diatom and macrofossil remains from ROUW2 has been made.

The remains in Zones 1 and 2 of both the macrofossil and diatom profiles (below ~65 cm) indicate a shallow water environment in the early part of the lake's history. This is suggested by the presence of small benthic *Fragilaria* diatom species and large numbers of moss leaves (bryophytes) and *Plumatella* spp. statoblasts in the sediment.

The middle section of the core (Zone 3 in the macrofossil record and the lower section of Zone 3 in the diatom record, ~30-65 cm) indicates an environment where planktonic and a diverse range of epiphytic/epilithic diatoms were able to thrive alongside the free-living and plant-associated cladoceran *Ceriodaphnia* spp., and submerged (*Ceratophyllum demersum*, *Stratiotes aloides*) and floating-leaved (*Nymphaeaceae*) aquatic plants. Bryozoans ('moss' animals) such as *Plumatella* spp. and *Cristatella* spp. are commonly found on mosses and the underside of floating-leaved vegetation (Olsen *et al*., 2001), and in this core they appear to be related to the presence of both *Nymphaeaceae* leaves and mosses. This section appears to represent the sediment accumulated prior to mud pumping.

The upper section of the core (Zone 4 in the macrofossil record and the upper part of Zone 3 and Zone 4 in the diatom record, 0- ~30 cm) most likely represents recently accumulated material. *Ceratophylum demersum* remains were abundant but *Nymphaeaceae* leaf trichosclereids, bryozoan statoblasts and *Ceriodaphnia* spp. remains were markedly less numerous than in the lower zones of the core. Whilst *Ceratophylum demersum* occurs throughout ROUW2 it appears to have increased in abundance in recent decades, perhaps at the expense of the floating-leaved flora. The increase in *C. demersum* may have been stimulated by mud-pumping activities in the 1980s, as seen in Barnby Broad. A small patch of *Nymphaea alba* was seen on Round Water during the March 2003 sampling and was recorded in the July 2003 survey, but the core was not taken adjacent to this patch and this may explain the absence of trichosclereids in the surface sediment sample. The macrophyte survey carried out in July 2003 recorded *C. demersum* as dominant and was the only submerged species seen. Floating leaved species recorded were *Lemna trisulca*, *Lemna minor*, *Nymphaea alba* and *Hydrocharis morsus-ranae*. Remains of the floating taxa were not found in the surface sediments but the macrofossils faithfully recorded *C. demersum* as the dominant submerged plant species. *Stratiotes aloides* leaf spines were present throughout the core, including the surface sediment, indicating that this plant has been present throughout the lake's history, albeit perhaps in small numbers. This species was observed in the lake during the 1990s (M. Perrow, pers. comm.) but was not recorded, however, during the July 2003 plant survey. As for Sprat's Water, this may suggest that the plant has been lost from Round Water very recently.

Diatom-inferred total phosphorus concentrations (DI-TP) were relatively stable at ~140 µg l^{-1} in the lower core but decreased in the upper 30 cm to ~ 90 µg l^{-1} at the surface (Figure 32). This supports the view that the upper 30 cm is recently deposited material which has accumulated since mud pumping in the 1980s. The lake is likely to be less productive since sediment removal as the internal P load will have been reduced. Owing to the dominance of the benthic *Fragilaria* taxa in the lower core, DI-TP values are likely to be over-estimates of past TP concentrations of the lake and, as for the other sites in this study, should not be used to set nutrient reference conditions.

Figure 31 Summary diatom diagram of Round Water core ROUW2

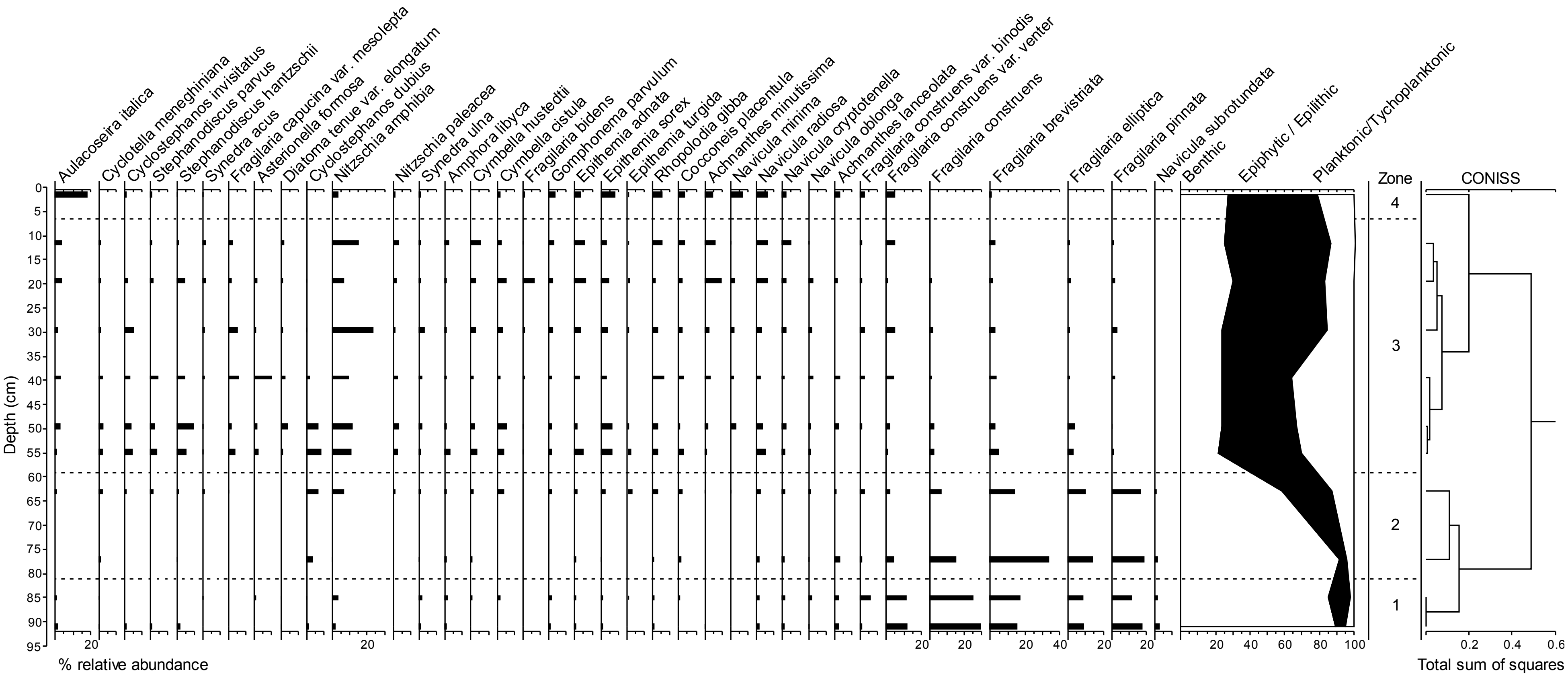


Figure 32 Diatom-inferred total phosphorus (DI-TP µg l^{-1}) reconstruction for Round Water core ROUW2

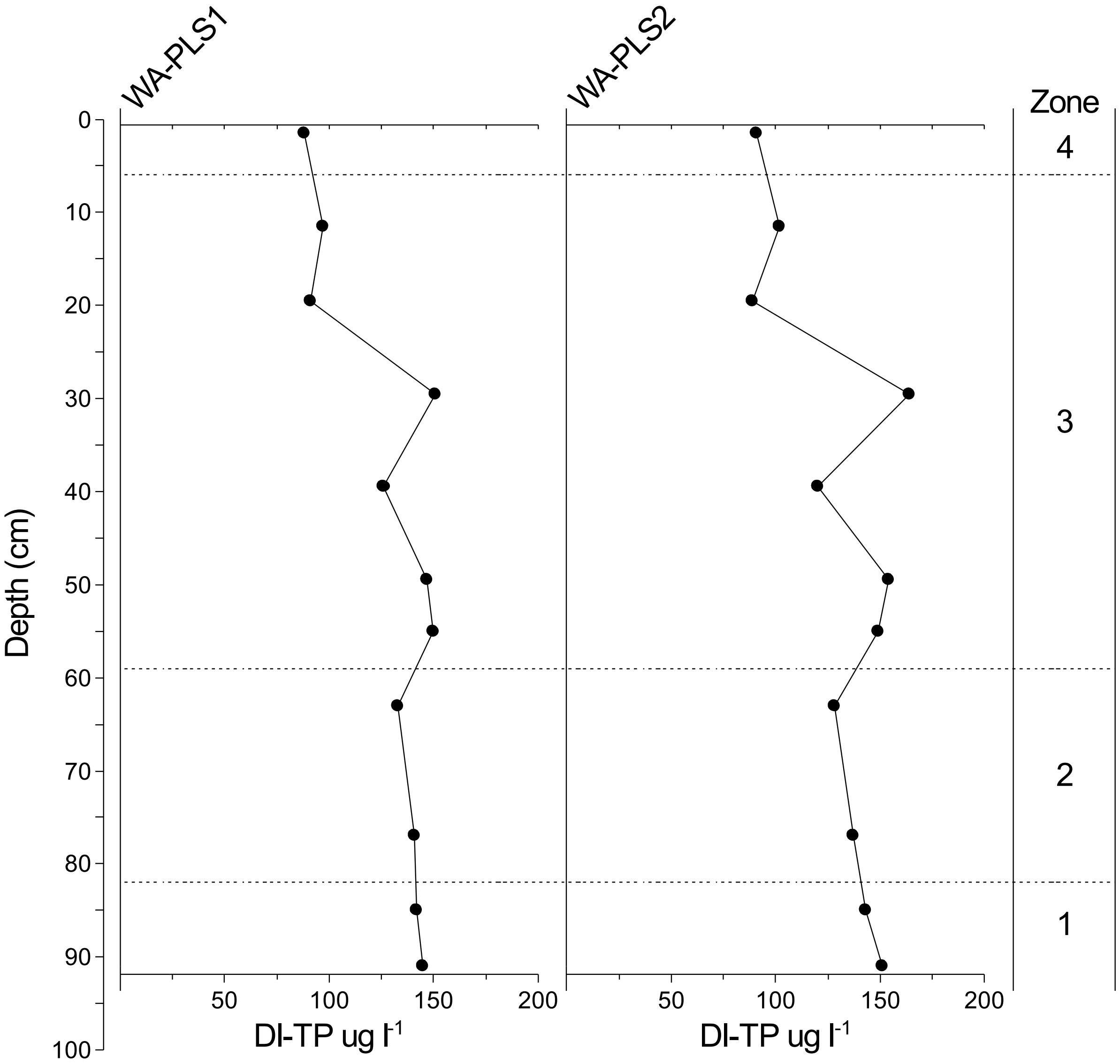
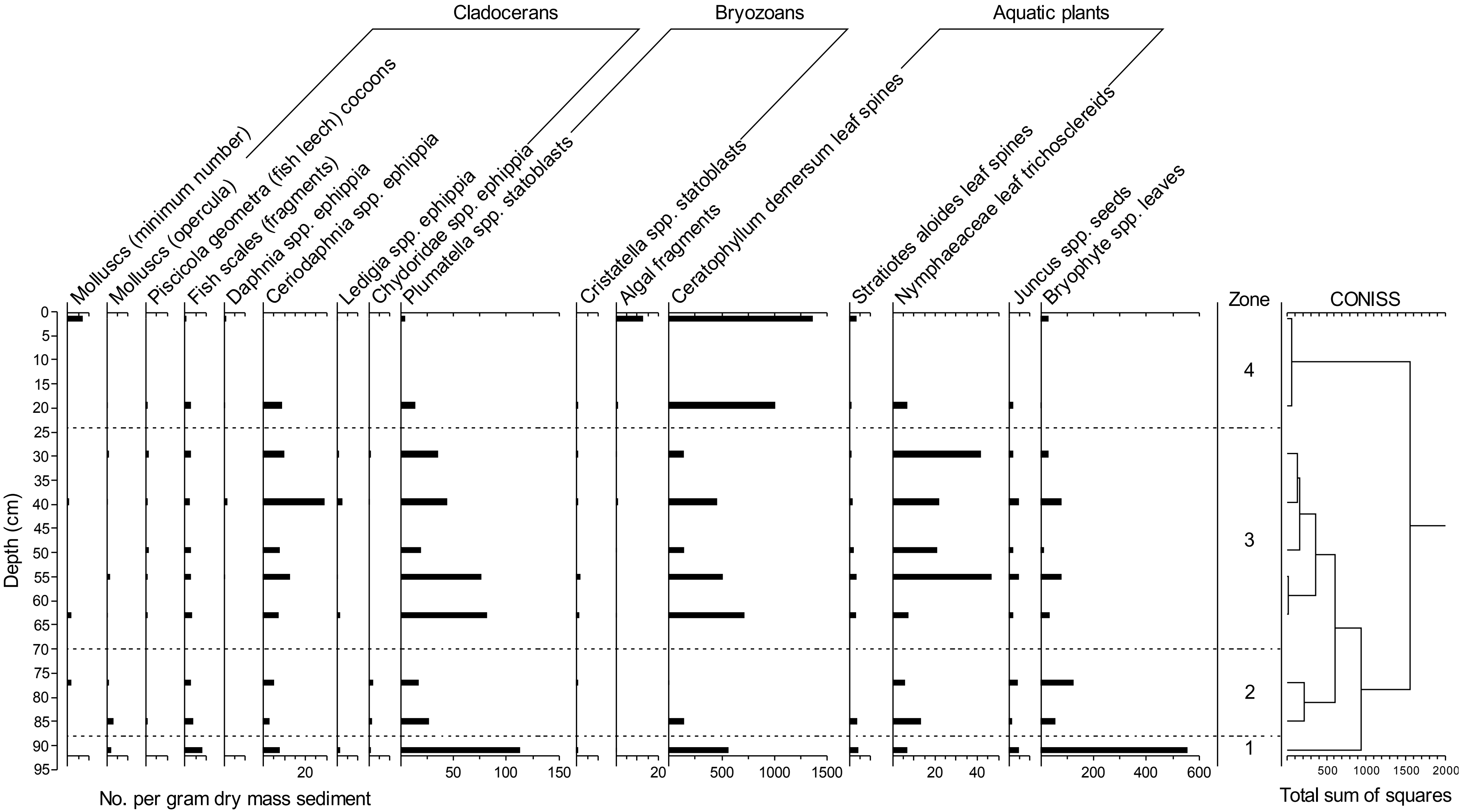


Figure 33 Summary macrofossil diagram of Round Water core ROUW2



6. WOOLNER'S CARR

6.1 Site and core description

Woolner's Carr (TM 504 915) is a very small, shallow, lowland lake (surface area 0.12 ha, altitude 1 m above sea level), situated just to the south-west of Round Water within the Sprat's Water and Marshes SSSI at Carlton Colville. Like the two neighbouring water bodies, Woolner's Carr is a flooded medieval peat working. It has only a very small area of open water today and is surrounded by emergent vegetation and carr woodland.

Two piston cores were taken on 13 March 2003 (Figure 34):
WOOC1 (TM 50330 91566). Core length 96 cm. Water depth 1.0 m.
WOOC2 (TM 50335 91562). Core length 62 cm. Water depth 1.06 m.

The two cores have similar stratigraphies with the same three major zones but there is clearly a difference in the sediment accumulation rates of the two cores with WOOC1 having approximately twice the accumulation rate of WOOC2 (Figure 35). Both cores have a basal, mid-brown colour organic layer at >90 cm and >55 cm in WOOC1 and WOOC2, respectively. The middle section is a dark brown-black material with sub-layers of lighter brown, less organic material and contains *Phragmites* debris and mollusc remains (40-90 cm and 20-55 cm in WOOC1 and WOOC2, respectively). The uppermost layer (0-40 cm and 0-20 cm in WOOC1 and WOOC2, respectively) is a mid-brown, relatively organic material containing abundant *Ceratophyllum* and mollusc remains. The organic matter rises steadily towards the surface in both cores to values of ~30%. WOOC1 was selected as the mastercore.

Figure 34 Map of Woolner's Carr showing the location of the sediment cores

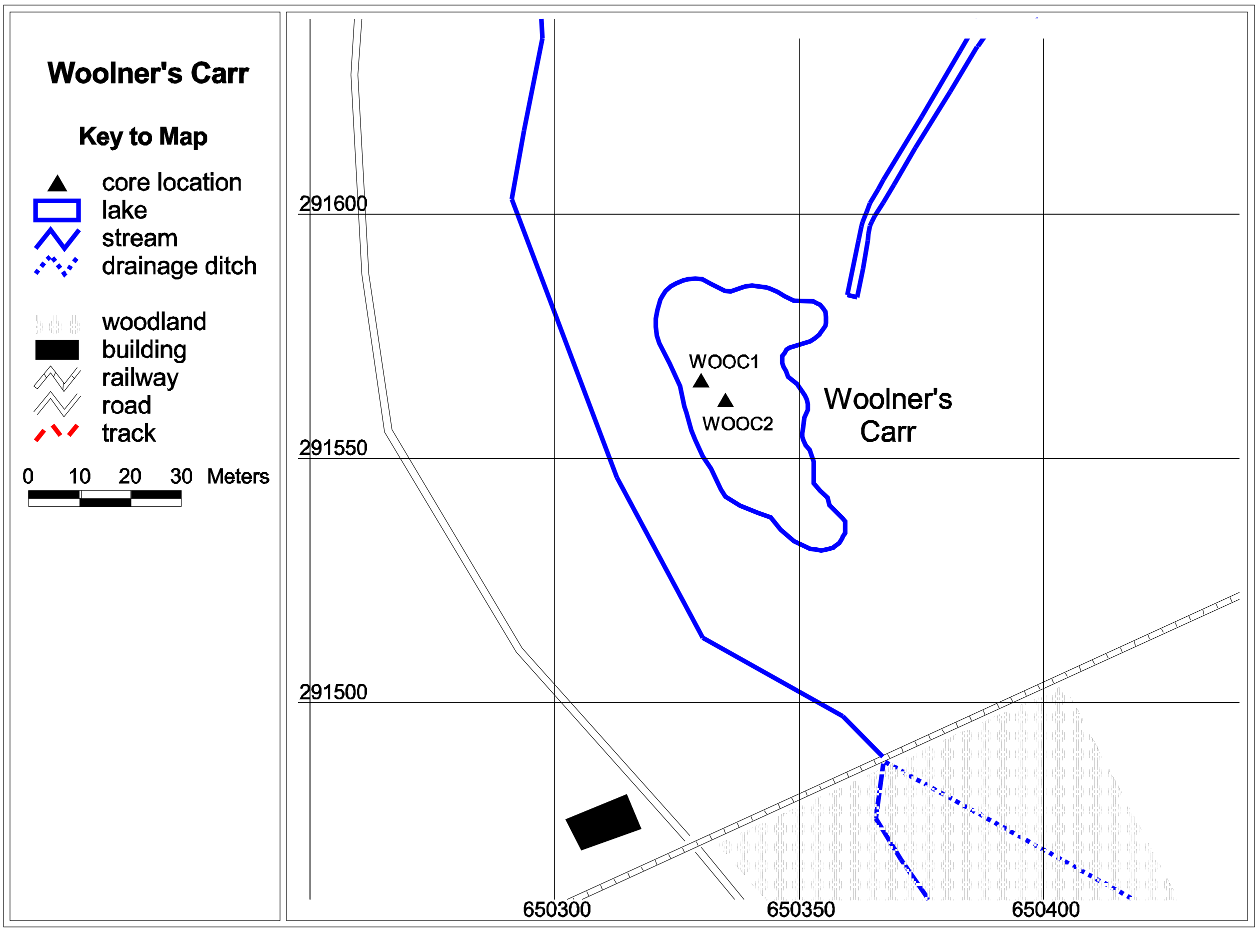
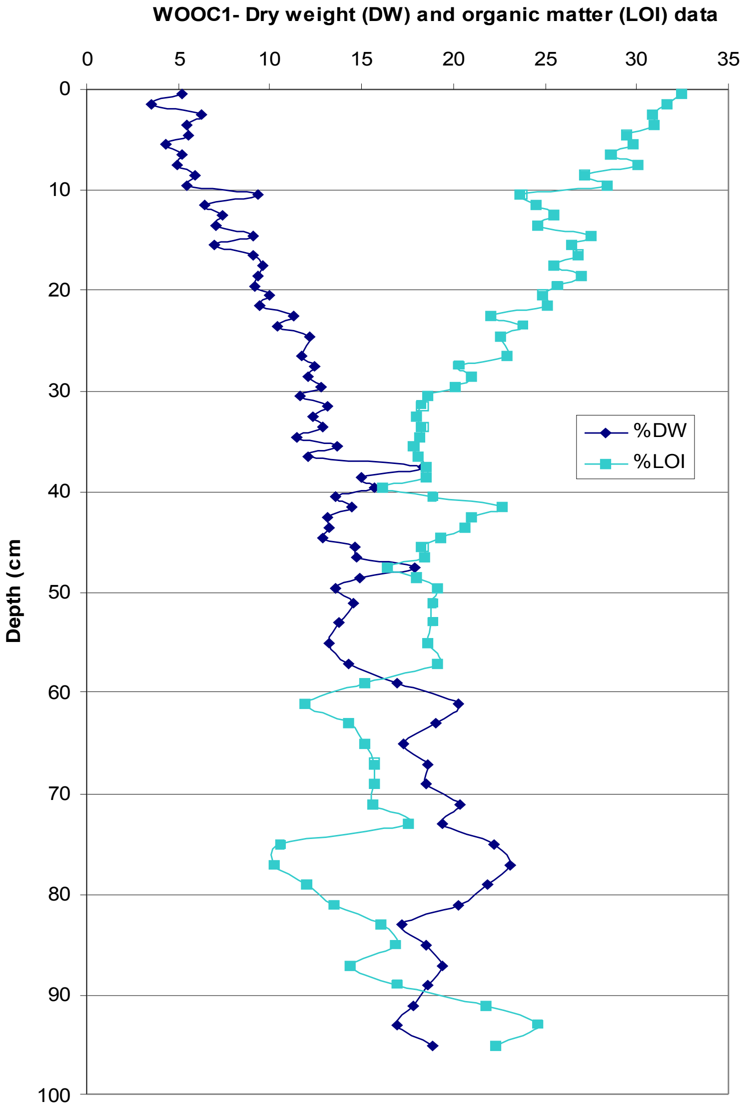
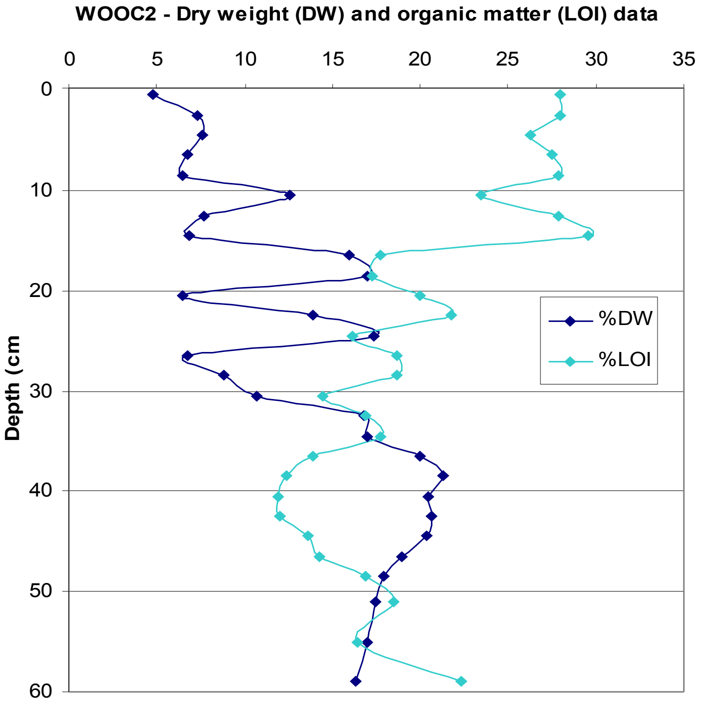


Figure 35 Dry weight and organic matter profiles for the Woolner's Carr cores





6.2 Chronology

The fallout radionuclide concentrations in the Woolner's Carr core WOOC1 are shown in Table 16.

Lead-210 Activity

Equilibrium between total ^{210}Pb activity and the supporting ^{226}Ra (Figure 36a) is still not reached at the depth of the deepest sample analysed (45 cm). Unsupported ^{210}Pb activity declines irregularly with depth (Figure 36b), with significant non-monotonic features at ~8-9 cm and ~20-21 cm.

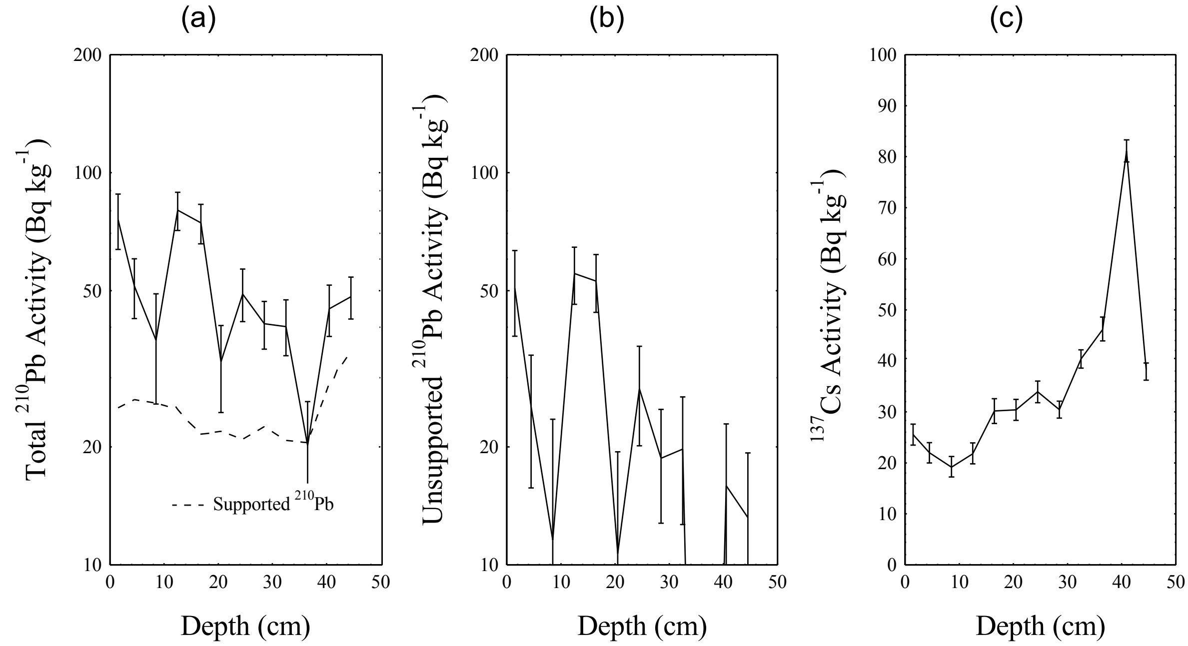
Artificial Fallout Radionuclides

The ^{137}Cs activity versus depth profile (Figure 36c) has a well-resolved peak at 40-41 cm that almost certainly records the 1963 fallout maximum from the atmospheric testing of nuclear weapons.

Table 16 Fallout Radionuclide Concentrations in Woolner's Carr core WOOC1

Depth		^{210}Pb						^{137}Cs	
		Total		Unsupported		Supported			
cm	g cm^{-2}	Bq kg^{-1}	±	Bq kg^{-1}	±	Bq kg^{-1}	±	Bq kg^{-1}	±
1.5	0.07	75.9	12.2	50.8	12.5	25.1	2.8	25.5	2.0
4.5	0.24	51.4	8.9	25.0	9.3	26.4	2.5	22.0	2.0
8.5	0.45	37.4	11.7	11.6	12.0	25.9	2.5	19.2	2.1
12.5	0.74	80.2	8.9	55.3	9.3	24.9	2.5	21.8	2.0
16.5	1.07	74.4	8.6	52.9	8.9	21.5	2.1	30.2	2.4
20.5	1.47	32.6	8.2	10.7	8.5	21.9	2.3	30.4	2.1
24.5	1.92	49.0	7.8	28.1	8.0	20.9	1.8	33.9	2.1
28.5	2.45	41.2	5.8	18.7	5.9	22.5	1.5	30.4	1.7
32.5	2.99	40.5	6.9	19.7	7.1	20.8	1.7	40.4	1.8
36.5	3.53	20.1	5.9	-0.4	6.2	20.5	1.7	46.1	2.2
40.5	4.21	45.0	6.7	15.9	7.0	29.1	1.8	81.1	2.2
44.5	4.80	48.3	5.9	13.2	6.1	35.1	1.5	37.9	1.7

Figure 36 Fallout radionuclides in Woolner's Carr core WOOC1, showing (a) total and supported ^{210}Pb, (b) unsupported ^{210}Pb and (c) ^{137}Cs concentrations versus depth.



Spheroidal carbonaceous particles (SCPs)

The SCP concentration profile for WOOC 1 is shown in Figure 37. First presence of SCPs is at 90 – 92 cm. Above this, SCP concentrations increase slowly to ~50 cm and then rapidly to a peak of over 6500 gDM^{-1} at 40 – 41 cm. This is followed by a general decline to the sediment surface although another, smaller, peak occurs at ~20 cm. Dates for each 10-percentile of WOOC1 are shown in Table 17, together with the confidence limits for each date, and graphically in Figure 38. Traditional use of SCPs for sediment dating (Rose *et al.*, 1995) allocates 1950 to the start of the rapid increase in concentration and this is in agreement with the cumulative percentile dates. These data suggest three phases of sediment accumulation, a period of steady sedimentation between 1850 and the 1920s, a slower period from the 1920s to the 1950s and a recent period of rapid accumulation from ~1960 to the present. The depth for the 1963 ^{137}Cs peak for this core (~41 cm) is also shown on Figure 38 (black square) and shows good agreement with the SCP profile.

Figure 37 SCP concentration profile of Woolner's Carr (WOOC1)

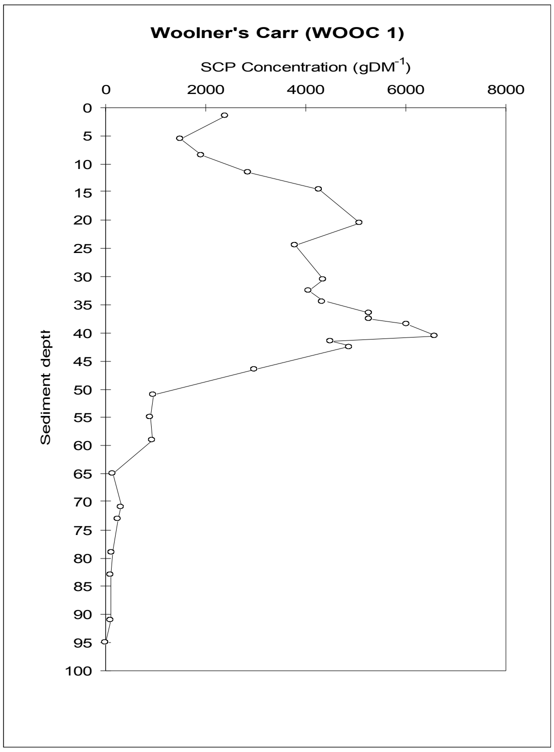
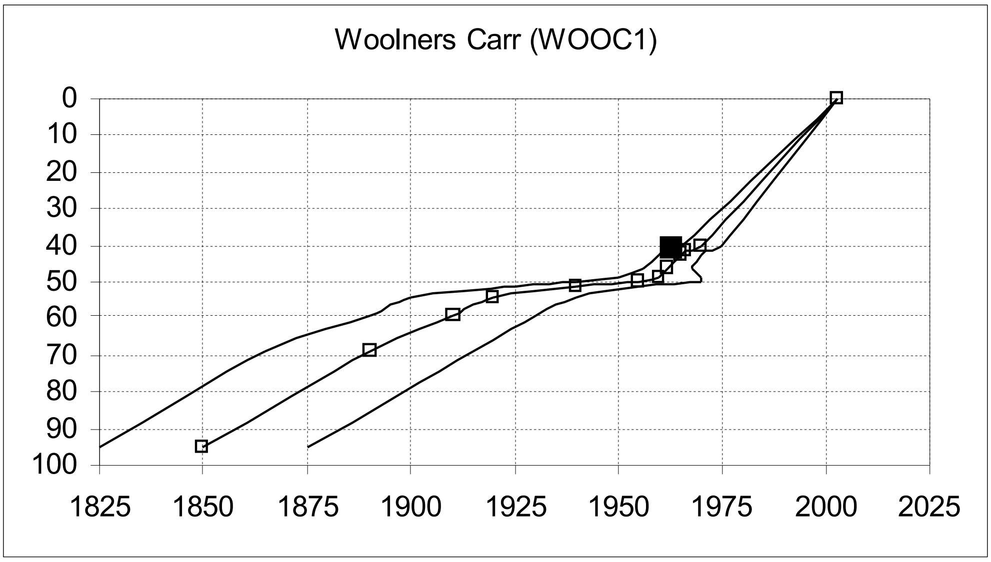


Table 17 Sediment depths and dates for each 10-percentile of the cumulative SCP profiles for Woolner's Carr (WOOC1) calibrated to the 'south and central England' regional SCP profiles from Rose & Appleby (in prep).

10-percentile	Date	Confidence interval	WOOC1 (cm)
0	1850	1875 – 1825	95
10	1890	1915 – 1865	69
20	1910	1930 – 1890	59
30	1920	1940 – 1900	54
40	1940	1955 – 1925	51.5
50	1955	1970 – 1940	50
60	1960	1970 – 1950	48.5
70	1962	1968 – 1956	46.5
80	1965	1970 – 1960	42.5
90	1966	1971 – 1961	41.5
100	1970	1975 – 1965	40.5
	2003		0

Figure 38 SCP dating profile for Woolner's Carr. Open squares show SCP dates and depths for each 10-percentile. Black square shows the ^{137}Cs 1963 peak.



Corrected chronology using combined radiometric dating and SCP data

Due to the incomplete determination of the ^{210}Pb record, dates calculated using the CRS model alone are unlikely to be reliable, and corrected ^{210}Pb dates were calculated using the 1963 ^{137}Cs date as a reference point. The results are plotted in Figure 39, together with dates determined from the SCP record. Where they overlap, these two independent chronologies are in relatively good agreement. A corrected chronology (Figure 39, Table 18) has been constructed using mainly the radiometric dates for the post-1960 period, and the SCP dates for the earlier period. The results suggest a baseline sedimentation rate of ~0.065 g cm^{-2} y^{-1}, with brief episodes of rapid sedimentation ~2000, ~1987 and ~1969. The SCP results also suggest higher sedimentation rates in the late 19th and early 20th century, possibly episodic in nature.

Figure 39 Chronology of Woolner's Carr core WOOC1, showing the radiometric dates, SCP dates, and corrected dates based on both methods

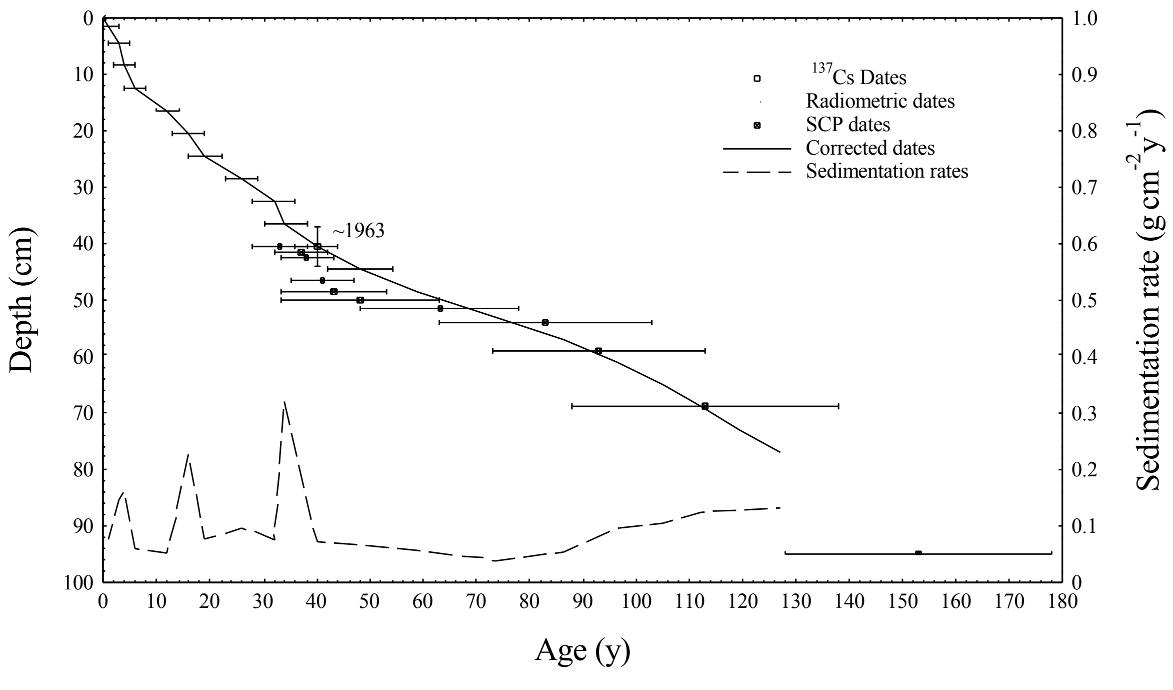


Table 18 Corrected chronology of Woolner's Carr core WOOC1

Depth		Chronology			Sedimentation Rate		
		Date	Age				
cm	g cm^{-2}	AD	y	±	g cm^{-2} y^{-1}	cm y^{-1}	± (%)
0.0	0.00	2003	0	0			
1.5	0.07	2002	1	2	0.076	1.50	26.1
4.5	0.24	2000	3	2	0.15	2.33	38.1
8.5	0.45	1999	4	2	0.16	2.67	53.0
12.5	0.74	1997	6	2	0.060	1.00	19.1
16.5	1.07	1991	12	2	0.052	0.80	19.7
20.5	1.47	1987	16	3	0.23	1.14	79.9
24.5	1.92	1984	19	3	0.077	0.80	30.3
28.5	2.45	1977	26	3	0.096	0.62	33.7
32.5	2.99	1971	32	4	0.075	1.00	37.6
36.5	3.53	1969	34	4	0.32	1.00	24.9
40.5	4.21	1963	40	4	0.072	0.57	44.2
44.5	4.80	1955	48	6	0.067	0.42	46.4
48.5	5.48	1944	59	10	0.057	0.33	
53.0	6.18	1930	73	17	0.038	0.31	
57.0	6.77	1917	86	20	0.054	0.35	
61.0	7.54	1906	97	20	0.096	0.43	
65.0	8.40	1898	105	22	0.11	0.51	
69.0	9.22	1891	112	25	0.12	0.56	
73.0	10.11	1884	119		0.13	0.54	
77.0	11.12	1876	127		0.13	0.53	
81.0	12.12	1869	134		0.14		

6.3 Geochemistry and sediment characterisation

The mineral magnetics, geochemistry and particle size data for the Woolner's Carr cores are presented in Figure 40. As for Barnby Broad, Sprat's Water and Round Water, the sediment in Woolner's Carr is highly calcareous, comprising 40 – 70 % calcium carbonate (Figure 40b). The sediment is different from the other sites, however. Si is highest at the base and declines upwards (Figure 40b). Soil-like mineral matter (indicated by Rb) is abundant throughout. Most other elements co-vary, with a strong peak in both heavy metals and soil-indicators (Figures 40a and b) midway down the cores (28 – 45 cm).

The upper sediments of both cores have a higher sand content than the lower sediments (Figure 40c), broadly corresponding with the Ca enriched material. Both cores show peaks in P at depth, rather deeper than the heavy metal enrichment peaks. Near-surface P enrichment is less marked than at the other sites. The onset and peaks of heavy metal enrichment are shallower in WOOC2 (40 and 30 cm) than in WOOC1 (75 and 35 cm) reflecting the different sediment accumulation rate of the two cores. In both cores, however, the heavy metal enrichment declines strongly towards the surface.

The two cores show similar overall patterns, though with a difference in the depths of the various sedimentary features. This is consistent with the data shown in Figure 35 which suggest that the sediment accumulation rate of WOOC1 is approximately double that of WOOC2. There are also differences in the heavy metal concentrations, most strikingly for Zn, plausibly due to sediment focussing. A consequence of this difference is that, even though the sedimentary history is similar, the average composition of the sediment is not well constrained by the two cores. Three broad zones have been identified (Table 19, Figure 41) with Zone 1 representing the pre-industrial period and Zones 2 and 3 representing the industrial period with maximum concentrations of heavy metals. The mineral magnetic profiles show strong correlation with the heavy metal concentration data, and are therefore dominantly influenced by atmospheric pollution. The particle size profiles show a clear pulse of medium and coarse sand following the peak in atmospheric contamination. This implies recent disturbance of the catchment resulting in enhanced supply of coarse material. It is not, however, possible to determine whether this is due to differing source material or differing sediment transport pathways. The maximum total sediment P concentration (2.5-3.2 mg g^{-1}) is typical for UK lowland lake sediments and river suspended sediment, reflecting a high nutrient loading. The calculated sediment P loading (0.9-1.2 g m^{-2} yr^{-1}) places the site an order of magnitude above the mesotrophic/eutrophic boundary of Vollenweider (1976).

At Woolner's Carr the thickness of recent contaminated sediment is uncertain, owing to the large discrepancy between the accumulation rates of the two cores. The two values are 40 and 75 cm (Table 19), and correspond with dry mass amounts of 53 and 103 kg m^2. Given a total area of 0.12 ha, this amounts to between 500 and 900 m^3 of sediment, with a dry mass in the range 25 – 93 tonnes.

Table 19 Compositional zones in Woolner's Carr

					WOOC1			**WOOC2**		
Zone	***Description and interpretation***				Conc		Mass	Conc		Mass
	CORE	**1**	**2**							
					Mean	sd	g m^{-2}	Mean	sd	g m^{-2}
	Maximum heavy metals			Si mg/g	72.8	30.8	8584	47.9	26.2	2564
				Ca mg/g	257	34	25823	253	30	8671
	Industrial period sediment	0 – 75 cm	0 – 40 cm	Fe mg/g	17.3	8.4	1842	15.7	9.2	806
				S mg/g	6.0	3.2	650	5.2	2.7	255
Zone 2/3				P mg/g	1.0	0.5	88.5	1.0	0.3	27.4
				Cd µg/g	0.45	0.12	0.046	0.42	0.09	0.017
				Cu µg/g	16.8	5.5	1.7	14.0	4.0	0.61
				Pb µg/g	39.5	11.6	4.0	38.6	10.1	1.7
				Zn µg/g	101	46.8	9.9	76.6	20.9	3.1
				Si mg/g	117.4	28.7		100.3	27	
	Minimum heavy metals			Ca mg/g	279	26		250	33	
		75 – 95 cm	40 – 57 cm	Fe mg/g	15.9	4.5		14.4	3.2	
Zone 1	Pre-industrial sediment infill			S mg/g	7.7	3.2		6.1	2.9	
				P mg/g	1.2	0.9		1.6	1.4	
				Cd µg/g	0.29	0.02		0.28	0.01	
				Cu µg/g	11.9	0.8		10.0	0.9	
				Pb µg/g	28.7	9.0		21.7	5.2	
				Zn µg/g	30.6	4.3		31.1	2.8	

Figure 40a Woolner’s Carr organic matter and mineral magnetic parameters

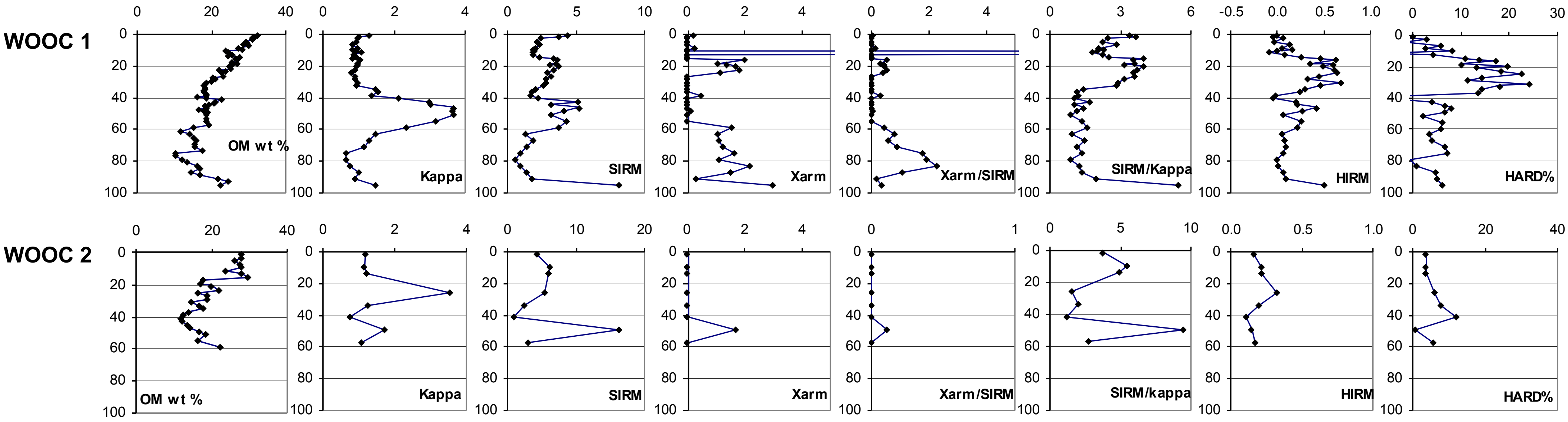


Figure 40b Woolner's Carr major and trace element concentrations

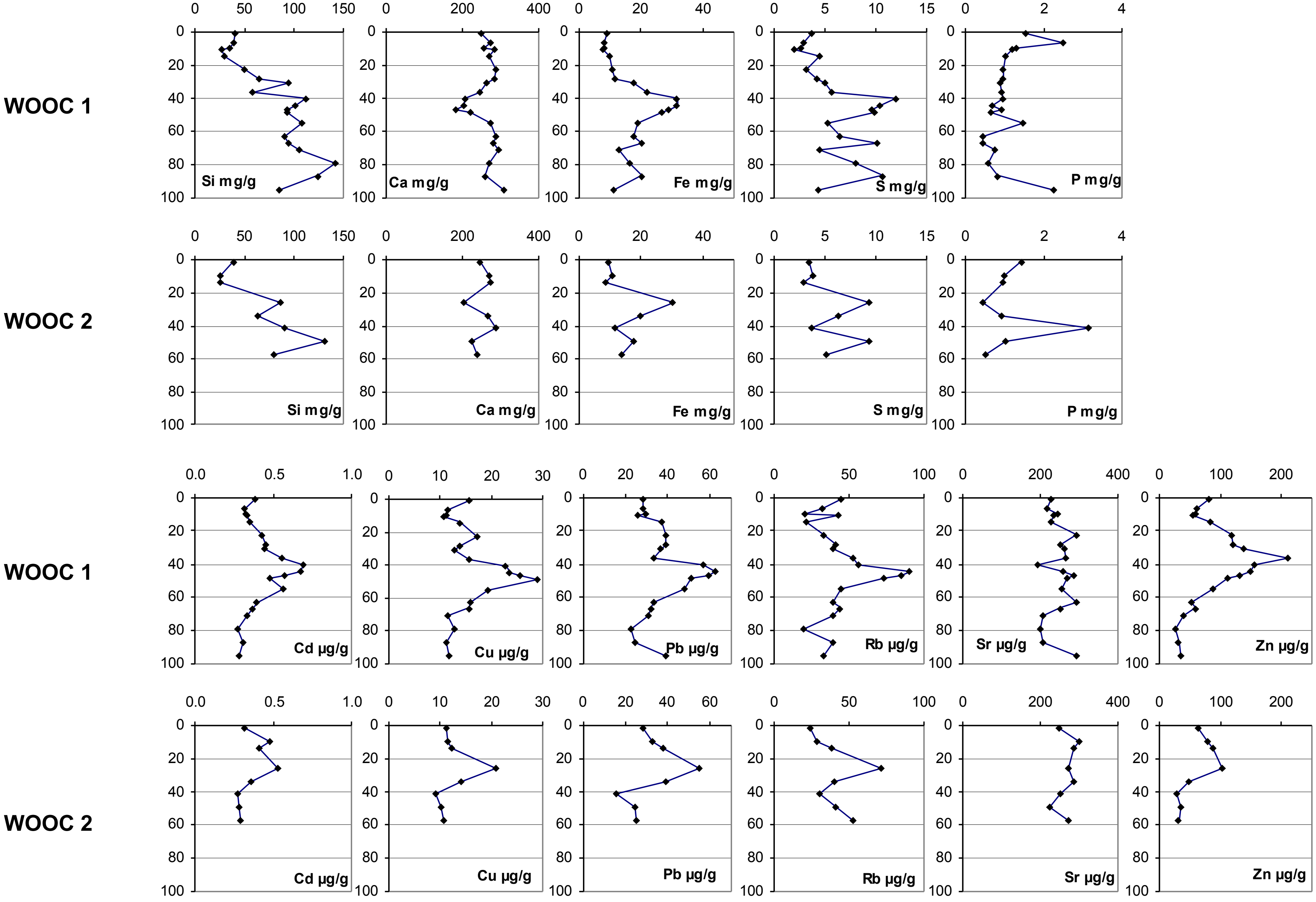


Figure 40c Woolner's Carr particle size data

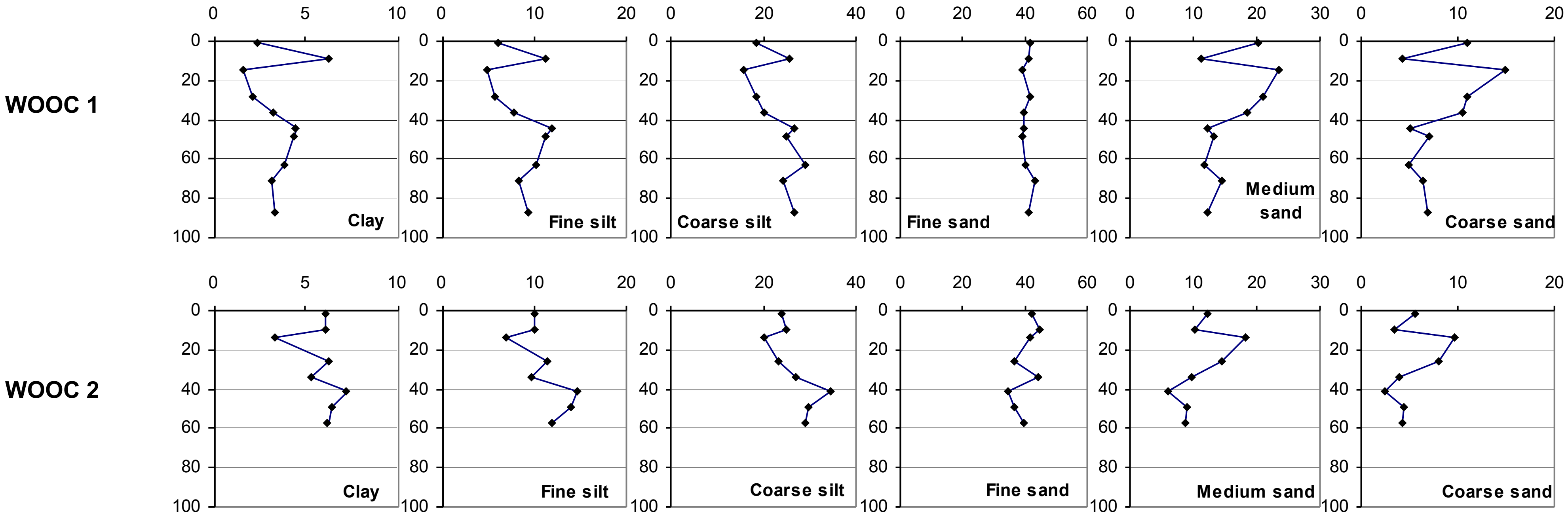
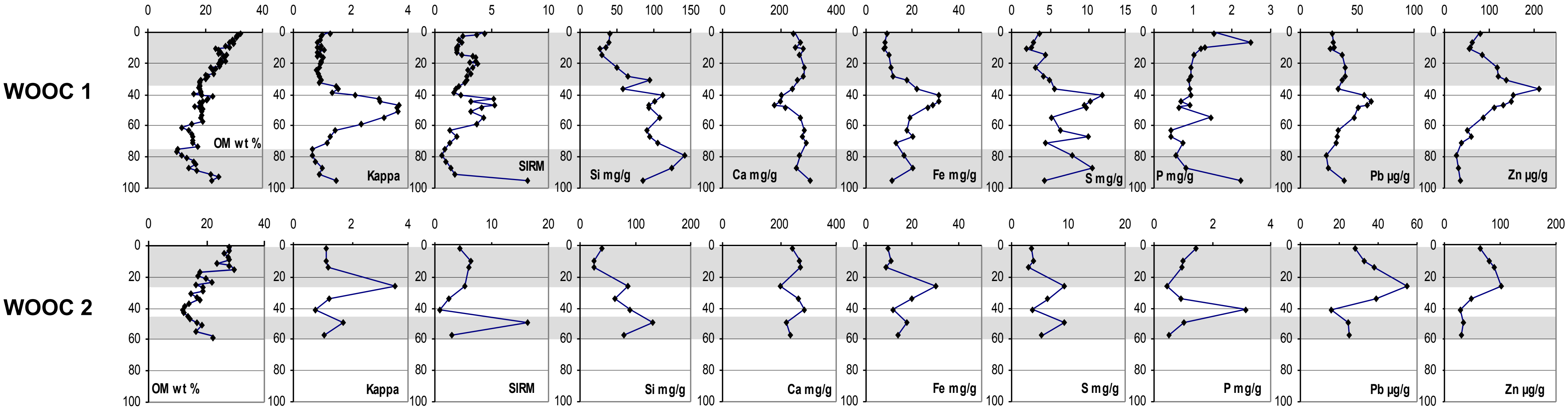


Figure 41 Woolner’s Carr summary chemical and mineral magnetic data showing compositional zones



6.4 Diatoms and macrofossils

Eleven samples were analysed for diatoms in Woolner's Carr core WOOC1 (Table 20) and the summary diatom diagram is shown in Figure 42. The diatom species diversity was similar throughout the core (~0.12) and a total of 78 taxa were observed.

Table 20 Summary of samples analysed for diatoms in Woolner's Carr core WOOC1

Depth (cm)	Count	No. of species	Floristic diversity
1.5	387.5	41	0.11
3.5	353	29	0.08
9.5	399.5	40	0.10
19.5	407	48	0.12
29.5	360.5	45	0.12
39.5	410	49	0.12
49.5	410	50	0.12
59	316	50	0.16
69	395.5	55	0.14
79	375.5	47	0.13
89	371.5	46	0.12

Ten samples were analysed for macrofossils representing the full length of the core and the summary diagram is shown in Figure 44. Cluster analysis identified three major zones in the diatom record and two major zones in the macrofossil record with 15 cm marking a zone boundary in both records.

Zones 1 and 2 of the diatom profile and Zone 1 of the macrofossil profile (below ~15 cm, pre ~1985) is comprised of a diverse benthic and epiphytic diatom flora with abundant small *Fragilaria* spp. The macrofossil record contains high numbers of C*eratophyllum demersum* indicating the presence of this submerged macrophyte. The cladoceran ephippia in the macrofossil record indicate the presence of both macrophytes and open-water throughout the history of Woolner's Carr. *Simocephalus* spp. are macrophyte-associated cladocerans, possibly associated with the dominant submerged aquatic *C. demersum* at this site. The relative lack of change within these lower zones indicates that the ecosystem of Woolner's Carr was relatively stable.

Zone 3 of the diatom profile and Zone 2 of the macrofossil record (0 to ~15 cm, post ~1985) are slightly different from the lower core sections. There is a higher percentage relative abundance of the (tycho)planktonic diatom taxon *Fragilaria capucina* var. *mesolepta* towards the core top. This species is associated with the spring / early summer plankton of alkaline, meso-eutrophic sites (Burgess, unpublished). The occurrence of this species and other associated (tycho)planktonic and epiphytic taxa (e.g. *Nitzschia amphibia*, *Nitzschia paleacea*, *Amphora veneta* and *Achnanthes minutissima*) could perhaps indicate enrichment and an increase in plant biomass over approximately the last few decades. This is further supported by the macrofossil record where increasing abundance of *Ceratophyllum demersum* leaf spines and algal colony fragments in the upper sediments were seen and leaf remains of *Lemna minor* and *Lemna trisulca* were present. *C. demersum* and *Lemna trisulca* are often seen in association in contemporary plant communities.

The macrophyte survey carried out during July 2003 recorded *C. demersum* as dominant, *Lemna trisulca* as abundant, *Lemna minor* as frequent and *Hydrocharis morsus-ranae* as rare. Remains of all but the latter species were found in the surface sediments, indicating that the macrofossils faithfully record the main components of the present day macrophyte community. *Stratiotes aloides* leaf spines were present throughout the core, including the surface sediment, indicating that this plant has been present since the 1900s, albeit perhaps in small numbers. This species was not recorded during the July 2003 plant survey. As for neighbouring Sprat's Water and Round Water, this may suggest that the plant has disappeared from the lake very recently.

An interesting find in the macrofossil record of this site was statoblasts of the freshwater bryozoan, *Lophopus crystallinus*, which were also recorded in the Sprat's Water core (see Sprat's Water chapter for details of this species). Although absolute numbers were low (note scaling on Figure 44), this species was present throughout the lake's history, including the surface sediments, indicating that Woolner's Carr provides a suitable habitat for this BAP species.

Diatom-inferred total phosphorus concentrations (DI-TP) exhibited relatively little change in the 90 cm core (Figure 43), despite the marked shifts in species composition. There was a slight increase from ~100 µg l^{-1} at the base of the core to ~130 µg l^{-1} at 60 cm depth (dated to early 1900s) which then remained relatively stable to the present day. As for the other cores, the dominance of non-planktonic taxa causes difficulty in applying the diatom models and the species shifts are likely to be associated more strongly with habitat alteration rather than with changes in nutrient concentrations per se. Diatom-inferred TP values are likely to be over-estimates of past P concentrations.

Figure 42 Summary diatom diagram for Woolner's Carr core WOOC1

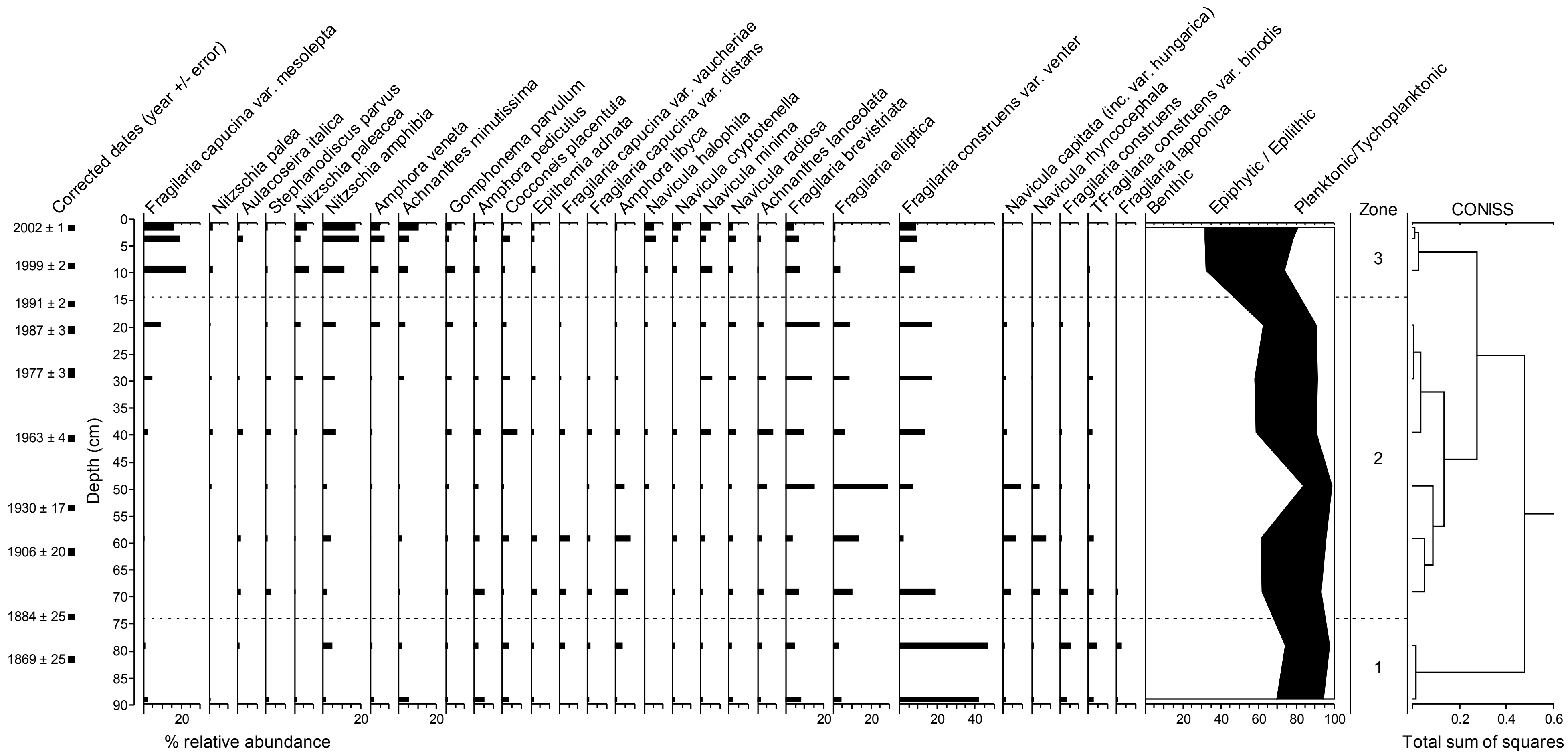


Figure 43 Diatom-inferred total phosphorus (DI-TP µg l^{-1}) reconstruction for Woolner's Carr core WOOC1

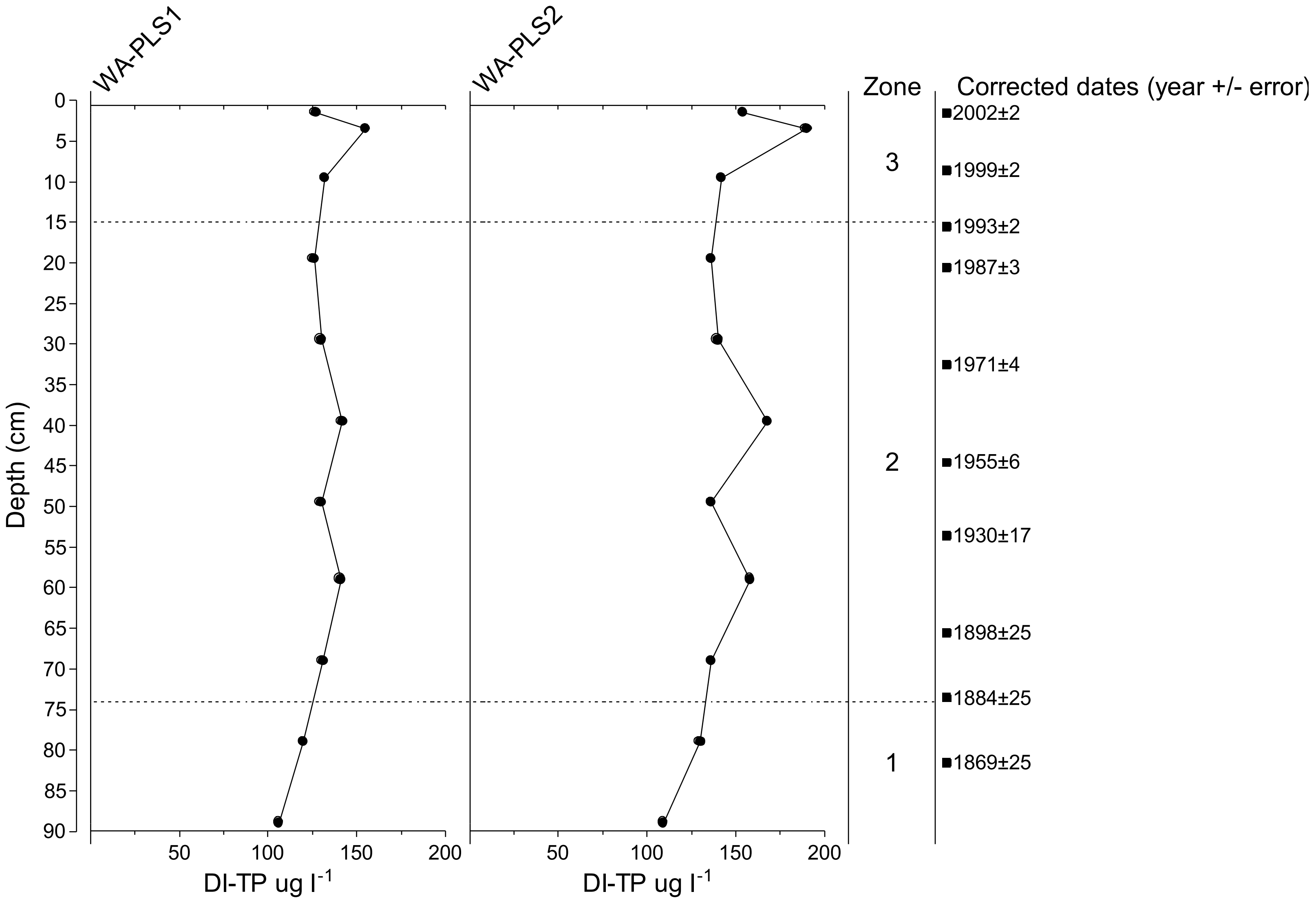
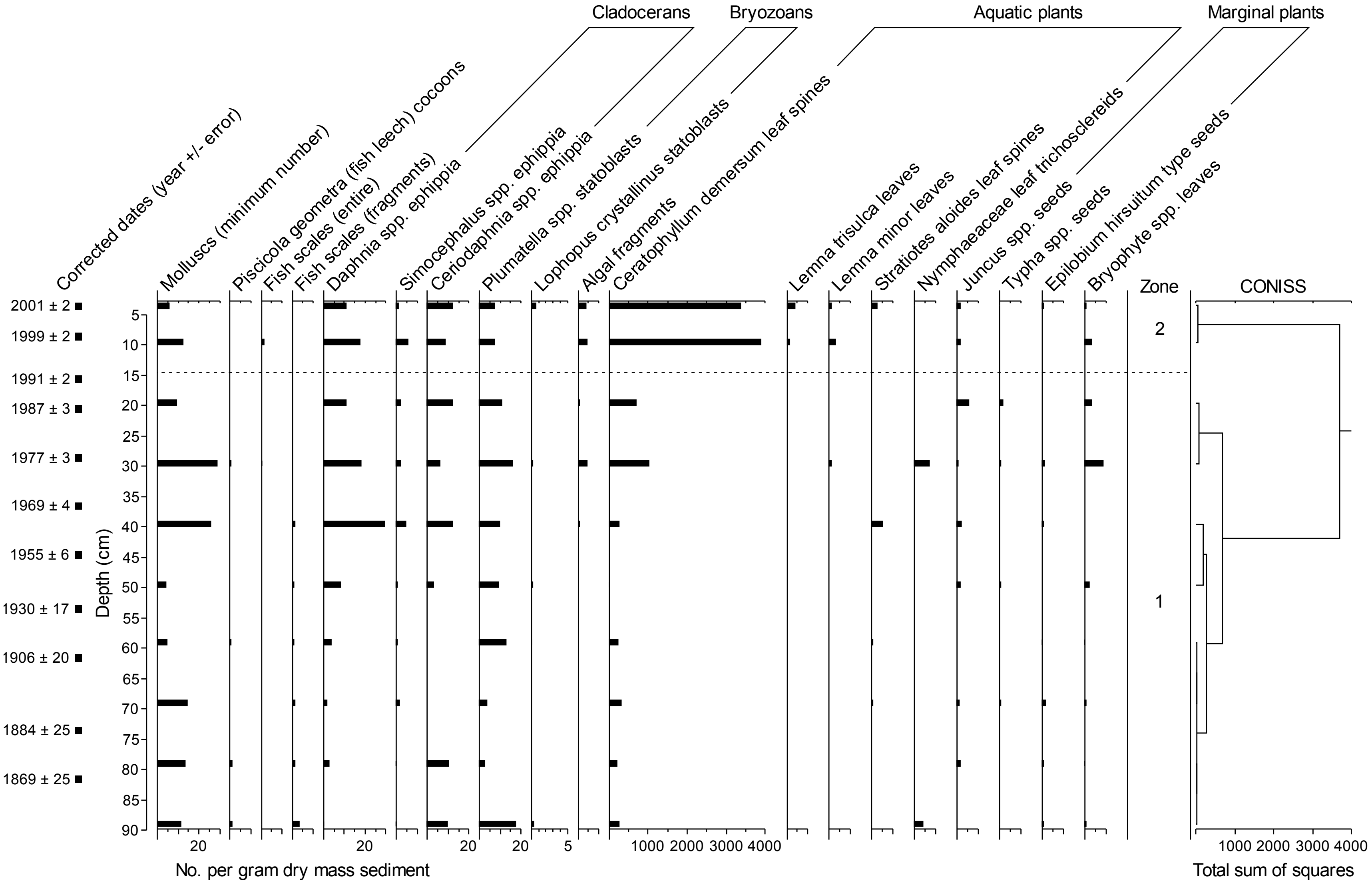


Figure 44 Summary macrofossil diagram for Woolner's Carr core WOOC1
(Note different scale used for *Lophopus crystallinus* to aid visualisation of data)



7. SUMMARY AND RECOMMENDATIONS

7.1 Barnby Broad summary

A combination of radiometric and SCP derived dates were employed to derive a reliable chronology for the Barnby Broad sediments. The 1.4 m sediment record penetrates the peat layer and therefore extends back to the creation of the broad. The data indicate that sediment accumulation rates have increased from a relatively steady rate of ~0.037 g cm^{-2} y^{-1} prior to ~1960 to ~0.045 g cm^{-2} y^{-1} in the 1970s and 1980s, and still further to ~0.070 g cm^{-2} y^{-1} over the last ten years. If the present rates of accumulation continue (~0.9 cm y^{-1}) then the sections of the lake with only 30 cm of water depth will be silted up in approximately 30 to 40 years.

There was excellent agreement between the four cores in terms of their compositional zones indicating that the data can be used to describe the average state of the sediment in the lake. Three zones were identified:

> Zone 1 (>105 cm) characterised by low Ca and high organic matter which represents the peat layer,
>
> Zone 2 (~40 to 105 cm; pre 1850) characterised by high Ca, low Si and slight Pb enrichment which appears to represent the pre-industrial period, and
>
> Zone 3 (0 to ~40 cm; post 1850) characterised by higher levels of Si, P, Pb and Zn, representing the industrial period of nutrient and atmospheric pollution. The increase in geochemical P concentrations may reflect the increased nutrient status of the site over the last 30 years.

At Barnby Broad the thickness of the uppermost contaminated zone varies between 40 and 53 cm, corresponding to a dry mass quantity between 50 and 70 kg per square metre of lake bed. Given a total lake area of 2.5 ha, this amounts to a sediment volume of between 10 000 and 13 000 m^3, with a dry mass of 500 -1000 tonnes. However, approximately half of the lake (south-westerly part) has already been mud pumped and therefore the volume of remaining sediment in the broad is likely to be around 5000 to 7000 m^3.

The BARB4 diatom record was dominated throughout by small *Fragilaria* species. These taxa indicate shallow and/or clear water environments where light availability is such to enable diatom growth on the lake bottom. Whilst caution should be exercised in the interpretation of the diatom profile of this core due to dissolution and low diatom concentrations, there appears to have been very little change in the diatoms over the last 150 years. However, the slight increase in *Stephanodicus parvus* in the upper 30 cm of the core (post 1950) may signal a rise in nutrient concentrations in recent decades as these taxa are commonly associated with enriched waters (e.g. Bennion, 1995). The diatom-inferred TP reconstructions were unreliable owing to the dominance of benthic *Fragilaria* taxa throughout the record.

The macrofossil record indicates more dynamic shifts in higher plant species assemblages than those seen in the diatom record and suggests that there have been changes in the ecosystem of Barnby Broad. There were three major zones:

> Zone 1 (67-102cm; ~1500 to ~1750) representing the early colonisation of Barnby Broad following peat extraction in the medieval period, with abundant charophyte and molluscs remains. The boundary of Zone 2 and 3 was scarce in macrofossils indicating a period of extensive reed bed development.
>
> Zone 2 (55-67cm; ~1750 to ~1850) indicating a period of semi-terrestrial peat bog with high numbers of bryophyte and sphagnum leaves, bryozoans, and moderate quantities of *Juncus* spp. seeds. This suggests draining of the Broadland environment for agricultural purposes in the 18th century.

Zone 3 (0-55cm; post ~1850) representing an open water environment suitable for aquatic plants with remains of macrophytes such as *Chara* spp., *Zannichellia palustris,* and *Ceratophylum demersum.* Large numbers of ephippia of the chydorid cladoceran *Ledigia* spp. provides further evidence (in association with the diatom data) that Barnby Broad has been a clear-water lake for at least the last 150 years. Whilst *Chara* spp. oospores were found throughout the core, remains of the more nutrient tolerant plants, *Z. palustris* and *C. demersum,* were found only in the more recent sediments from ~1950 and the mid-1980s, respectively. This suggests enrichment of the system since around the 1950s. High abundance of *Ledigia* spp. in the upper part of the core is indicative of shallowing and a gradual shift in habitat availability with reduction in depth leading to a decline in plant biomass The presence of large numbers of *Daphnia magna* ephippia in the surface sediments of this core indicates that there is less fish predation at Barnby Broad than in the past. This may be due to the severe shallowing of the site in recent years.

7.2 Sprat's Water summary

A combination of radiometric and SCP derived dates were employed to derive a reliable chronology for Sprat's Water sediments. The 1.4 m sediment record penetrates the peat layer and therefore extends back to the creation of the broad. The data indicate that sediment accumulation rates increased from a relatively steady rate of ~0.040 g cm^{-2} y^{-1} prior to ~1930 to very high values of ~0.15 g cm^{-2} y^{-1} in the 1960s. Accumulation rates have since returned to those of the pre-1960 period (~0.049 g cm^{-2} y^{-1} or 0.4 cm yr^{-1}). If these rates continue then the lake has a life span of approximately 350 years.

There was good agreement between the three cores in terms of their compositional zones indicating that the data can be used to describe the average state of the sediment in the lake. Three zones were identified:

Zone 1 (> 70 to 100 cm) characterised by low Si, high S, Rb, Fe and high susceptibility minerals, representing pre-industrial material,

Zone 2 (~40 to 100 cm; pre-1850) with low concentrations of P, Pb and Zn, also representing the pre-industrial period, and

Zone 3 (upper 40 cm; post 1850) enriched in P, Pb and Zn representing the industrial period of nutrient and atmospheric pollution.

At Sprat's Water the thickness of the most recent contaminated sediment ranges between 39 and 47 cm depth, corresponding to a dry mass quantity of between 46 and 90 kg per square metre of lake bed. Given a total area of 0.27 ha, this amounts to a sediment volume of between about 1000 and 1300 m^3, with a dry mass of around 50 to 120 tonnes.

Four zones were identified in the biological records:

Zone 1 (110-140 cm; ~1300 to ~1500) representing an estuarine, marine-influenced environment with remains of foraminifera,

Zone 2 (75-110 cm; ~1500 to ~1700) indicating an open-water habitat able to support phytoplankton with diatoms typical of nutrient-rich, circumneutral to alkaline waters, and aquatic plant remains (particularly water lily),

Zone 3 (35-75 cm; ~1700 to ~1900) indicating a change in macrophyte species, habitat shifts and/or a shallowing of the site with a benthic dominated diatom community and few plant macrofossil or zooplankton remains. This appears to coincide with major drainage of the Carlton Marsh area in the 18th century,

Zone 4 (0-35 cm; post-~1900) indicating a nutrient-rich, open water habitat with a diverse non-planktonic and planktonic diatom assemblage, high abundances of the submerged aquatic plant *Ceratophyllum demersum*, zooplankton ephippia and mollusc remains. A general increase in plant biomass can be inferred from the data, suggesting that nutrient enrichment may have started approximately 100 years ago. Statoblasts of the freshwater bryozoan *Lophopus crystallinus* were found in the upper sediments (from ~mid-1970s).

The diatom-inferred TP reconstruction was not reliable for this site. The switch from *Fragilaria brevistriata* to *Fragilaria lapponica* dominance is more likely to be associated with habitat shifts than changes in epilimnetic nutrient concentrations. As for Barnby Broad, the inferred TP values are likely to be over-estimates and should not be used to set nutrient reference concentrations.

7.3 Round Water summary

Both the radiometric dating and the SCP data indicate that the sediment record of Round Water has been disturbed by the mud pumping in the 1980s and therefore it is not possible to assign a chronology to the core. We speculate that the sediment below approximately 30 cm represents the material that was not removed during the pumping operation and if this is the case the sediment below this depth is likely to provide a record of the early lake history. The 1 m sediment cores do not quite penetrate the peat layer but the elevated organic matter in the basal layers suggests that the record almost extends back to the creation of the broad. There appears to be a hiatus in the record with the loss of several decades of material (presumably removed by pumping). It is likely that the upper 30 cm of the core is a combination of resettled old material and very recently deposited, unconsolidated new material accumulated over the last few decades. On the basis of recent accumulation rates at neighbouring Sprat's Water, the lake has a life span of around 300 years.

There was good agreement in the stratigraphic features between the two cores in the section below 30 cm but there were a number of discrepancies between the two profiles in the upper section. These differences are likely due to the redistribution of material across the lake caused by mud pumping. Two zones were identified:

> Zone 1 (~35 to ~100 cm) characterised by low Ca and high Pb concentrations,
>
> Zone 2 (0–35 cm) characterised by higher Ca concentrations and lower levels of Si and heavy metals than the lower zone. ROUW2 has lower P content in this zone but a decline in P was not observed in the upper part of ROUW1.

At Round Water it appears that recent contaminated sediment has already been removed, and there is no basis for any further removal at present.

Owing to the disturbed record, a combined interpretation of the diatom and macrofossil remains from ROUW2 was made and three broad zones were identified:

> Lower zone (below ~65 cm) indicating a shallow water environment in the early part of the lake's history, with presence of small benthic *Fragilaria* diatom species and large numbers of bryophytes and bryozoan remains,
>
> Middle zone (~30-65 cm) indicating an environment where (tycho)planktonic and a diverse range of epiphytic/epilithic diatoms were able to thrive alongside the open water and plant-associated cladoceran *Ceriodaphnia* spp., and submerged (*Ceratophyllum demersum*, *Stratiotes aloides*) and floating-leaved (*Nymphaeaceae*) aquatic plants. This section appears to represent the sediment accumulated prior to mud pumping,
>
> Upper zone (0 to ~30 cm) representing recently accumulated material with abundant remains of *Ceratophylum demersum* but fewer macrofossils of *Nymphaeaceae*, bryozoan and *Ceriodaphnia* spp than in the lower zones. *Ceratophylum demersum* appears to have increased in abundance in recent decades, perhaps at the expense of the floating-leaved flora. The decline in abundance of benthic diatom taxa relative to epiphytic taxa supports this theory as greater plant biomass would shade out the benthic habitat.

The diatom-inferred TP reconstruction suggested that TP concentrations were lower in the upper 30 cm than in the deeper sediments, supporting the view that the upper 30 cm is recently deposited material which has accumulated since mud pumping in the 1980s. The lake is likely to be less productive since sediment removal as the internal P load will have been reduced. Owing to the dominance of the benthic *Fragilaria* taxa in the lower core, DI-TP values are likely to be over-estimates of past TP concentrations of the lake and, as for the other sites in this study, should not be used to set nutrient reference conditions.

7.4 Woolner's Carr summary

A combination of radiometric dates and SCP derived dates were employed to generate a chronology, using mainly the radiometric dates for the post-1960 period, and the SCP dates for the earlier period. The data suggest a baseline sedimentation rate of ~0.065 g cm^{-2} y^{-1} (~0.4 cm y^{-1}) with brief episodes of rapid sedimentation in excess of 1 cm y^{-1} at ~2000, ~1987 and ~1969. The SCP results also suggest higher sedimentation rates in the late 19th and early 20th century, possibly episodic in nature. The 1 m sediment core does not penetrate the peat layer and therefore does not appear to represent the full history of the lake. On the basis of the recent accumulation rates for WOOC1 of ~1 cm yr^{-1}, the life span of the lake is around 100-150 years.

The two cores show similar overall patterns in compositional change but there was a difference in the depths of the various sedimentary features owing to the fact that the sediment accumulation rate of WOOC1 appears to be approximately double that of WOOC2. There are also differences in the heavy metal concentrations, most strikingly for Zn, plausibly due to sediment focussing. A consequence of this difference is that, even though the sedimentary history is similar, the average composition of the sediment is not well constrained by the two cores. Three broad zones were identified:

> Zone 1 (> 75 cm in WOOC1 and > 40 cm in WOOC2) characterised by low heavy metals, representing the pre-industrial period,
>
> Zones 2 and 3 (0-75 cm in WOOC1 and 0-40 cm in WOOC2) with maximum concentrations of heavy metals, representing the industrial period.

At Woolner's Carr the thickness of recent contaminated sediment is uncertain, owing to the large discrepancy between the accumulation rates of the two cores. The two values are 40 and 75 cm and correspond with dry mass amounts of 53 and 103 kg m^2. Given a total area of 0.12 ha, this amounts to a sediment volume of between 500 and 900 m^3 , with a dry mass in the range 25 to 93 tonnes.

Two major zones were identified in the biological record:

> Lower zone (below ~15 cm, pre ~1985) indicating a shallow, open water environment with a diverse benthic and epiphytic diatom flora, high numbers of C*eratophyllum demersum*, and cladoceran remains. The relative lack of change within the lower zone indicates that the ecosystem of Woolner's Carr was relatively stable.
>
> Upper zone (0 to ~15 cm, post ~1985) indicating a possible increase in the trophic status of this site over approximately the last 20 years with higher abundances of planktonic diatom taxa, *Ceratophyllum demersum* and algal remains. The decline in benthic diatom taxa relative to the epiphytic taxa supports the increase in plant biomass inferred from the macrofossil record, as the benthic habitat would be shaded out. Statoblasts of the freshwater bryozoan, *Lophopus crystallinus*, were present throughout the core, including the surface sediments, indicating that Woolner's Carr provides a suitable habitat for this BAP species.

As for the other cores, the dominance of non-planktonic taxa caused difficulty in applying the diatom models and the species shifts are likely to be associated more strongly with habitat alteration rather than with changes in nutrient concentrations. Diatom-inferred TP values are likely to be over-estimates of past P concentrations.

7.5 Management recommendations

Barnby Broad
The southerly part of the lake was mud pumped in 1990. The results are encouraging in terms of plant recolonisation as the mud pumped section of the lake now supports *Chara* spp., *Ceratophyllum demersum* and *Zannichellia palustris*, and water depths have been increased to > 1 m. The northerly part of the lake has not been mud pumped and measured water depths at the time of the sediment survey were as little as 30 cm. This section of the lake does not currently support submerged macrophytes and it appears that the current depth is too shallow for plants to grow. This is likely to be caused by a number of factors including frequent sediment resuspension, poor rooting conditions (i.e. flocculant, unconsolidated material – Schutten & Davy, 2000) and increased grazing pressure by herbivorous birds. Furthermore, if the present rates of sediment accumulation continue then the 30 cm areas will be silted up in approximately 30 to 40 years. It should be noted, however, that measures have been taken in recent years to reduce the external loading of sediment to the broad from the surrounding land. This has been achieved by the construction of a channel around the lake which takes material from the catchment directly out to sea at Lowestoft, bypassing the lake itself. The broad is thus isolated from any agricultural run off with a consequent reduction in both sediment and nutrient loading.

Based on the success of the previous mud pumping operation, the severe shallowing of the lake, the lack of macrophytes in the northern section and the existing control on external sources of sediment, removal of sediment in the northerly part of the lake is recommended. The sediment survey showed that the upper ~40 to 50 cm represents the industrial period with characteristic enrichment in atmospherically derived pollutants, chiefly SCPs, Pb and Zn, and also P. Thus, removal of the sediment exhibiting major atmospheric pollution also removes the bulk of the nutrient pollution. Whilst the upper sediments are clearly enriched in these elements relative to the pre-industrial material, the concentrations are not especially high and should not create problems for spoil disposal. Given an unpumped area of approximately 1.2 ha, we estimate that around 5000 to 7000 m^3 will need to be removed. The diatom and macrofossil records indicate that the lake has always been a shallow, relatively clear water environment and formerly supported *Chara* spp. This suggests that reduction of the internal nutrient load and increased water depth in the northerly part of the lake, following sediment removal, should enable plants to re-establish.

Sprat's Water, Round Water and Woolner's Carr
In contrast to Barnby Broad, the three broads in the Sprat's Water and Marshes SSSI still support a submerged macrophyte community (dominated by *Ceratophyllum demersum*) and currently have a reasonable depth (~1-1.5 m) and area of open water. Based on recent sediment accumulation rates, the lakes have a reasonable life-span with Sprat's Water and Round Water estimated to infill in ~300-350 years and Woolner's Carr to infill in ~100-150 years. Clearly the latter site is at a more advanced stage of succession than the former two lakes but in contrast to Barnby Broad, water depth does not appear to be a limiting factor to plant growth. The diatom and macrofossil records provide no evidence of major ecological change in the lakes in the last 150 years. There does appear to have been a recent increase in plant density as shown by the increasing abundance of epiphytic diatom taxa relative to benthic taxa, and the high numbers of *C. demersum* remains in the upper sediments. Furthermore, an increase in a number of diatom taxa typically associated with nutrient rich waters (e.g. *Nitzschia amphibia*, *Aulacoseira italica*) was observed at all three sites, suggesting a degree of enrichment. The macrofossil data suggest that the aquatic macrophyte flora of the lakes may have been more diverse in the past with a greater floating component and less dominance by *C. demersum*. There is also evidence that *Stratiotes aloides* has been present in all three water bodies although it was not recorded in the 2003 plant surveys. The sites may also have supported *Potamogeton* spp. in the past but unfortunately the pondweeds leave few identifiable remains in sediments and were not found in the studied cores. Nevertheless, the changes in the diatom and macrofossil records were relatively minor compared to those seen in other lowland water bodies subject to eutrophication (e.g. Bennion *et al*., 2001; Davidson *et al*., in press).

Whilst the present day macrophyte community is not particularly diverse, the submerged plant volume is high and the plants play an important role in oxygenating the water and taking up nutrients. Algal blooms were not seen on the broads in summer 2003. The sites have not experienced alternative stable state change (Scheffer *et al*., 1993) and from an ecological viewpoint there seems little reason to reset the systems by removal of sediment.

As for Barnby Broad, the upper sediment in all cores (except those of Round Water, where loss of the most recent sediment was indicated) shows characteristic enrichment in atmospherically derived pollutants. While it is evident that some Pb contamination of the sediment occurred prior to significant atmospheric pollution, this early contamination is relatively minor. The onset of atmospheric contamination coincides with P enrichment. Nevertheless, the concentrations of these elements are not particularly high and are typical of those seen in sediments laid down in the post-1850 period. If mud pumping were to go ahead, our survey estimates that a sediment volume of ~1000-1300 m^3 and ~500-900 m^3 would need to be removed from Sprat's Water and Woolner's Carr, respectively. At Round Water it appears that recent contaminated sediment has already been removed, and there is no basis for any further removal at present.

The first objective of any lake restoration programme, however, is to remove the major external nutrient sources (Moss *et al.* 1996) and this condition has not been met. There is currently an external source of both sediment and nutrients from the adjacent arable fields on the easterly side of the reserve which will continue to bring nutrients (particularly nitrate) into the lake. We encourage the introduction of agri-environment schemes and recommend that the code of good agricultural practice is promoted with respect to field run-off (MAFF, 1998; DEFRA, 2002). Ideally the first step would be to attempt to reduce the problem at source by liaising with the local farmer and ensuring best practice is followed in the use of chemical and slurry applications and cultivation. The introduction of buffer zones between the farmland and receiving waters has proved effective in the control of nitrogen and sediments (including particulate P) elsewhere (Moss *et al.* 1986). Riparian buffer zones are vegetated strips of land (ideally permanent pasture or wet woodland) alongside a watercourse which reduce direct pollution by creating a physical distance between the agriculture and the water body, and they function as a natural sink for sediments and nutrients derived from farmland (Environment Agency, undated; Haycock & Burt, 1993; Muscutt *et al*., 1993). Guidelines on implementing buffer strips to reduce pollution are given in Environment Agency (undated) and Ward *et al.* (1995). In this case any reduction in either sediment or nutrient load would be an advantage. If sediment removal is carried out, it is advised that this only be done in conjunction with efforts to reduce the catchment sediment sources.

A further concern with respect to possible sediment removal at these sites is that mud pumping is a high disturbance operation and it will undoubtedly result in temporary loss of habitat and species at the sites. Natural re-colonisation of plants is not guaranteed and there is even a risk that enrichment may be enhanced by release of nutrients following sediment disturbance (Hearn *et al*., 2002). Given the small size of the sites, damage could be caused to a range of habitats both within and around the lakes. The reedbed and carr woodland at the Sprat's Water and Marshes SSSI are important habitats in themselves, not least because they provide a degree of buffering from the surrounding arable land, and damage to these areas must be avoided. Importantly, sediment removal may pose a threat to *Lophopus crystallinus* which is a protected species (HMSO, 1999). Statoblasts of this rare freshwater bryozoan were found in both the Sprat's Water and Woolner's Carr cores. Potential loss of substrates for this species, such as woody debris, during sediment removal operations may occur and it is essential that this is avoided.

Moss *et al.* (1996) and Hearn *et al.* (2002) stress that sediment removal from lakes should only be considered as a last resort. In light of the above and the apparently healthy macrophyte assemblages, sediment removal from the three broads is not recommended. Aside from cost, risk of disturbance to the rich array of habitats is a major factor. Furthermore, due to the conservation importance of the immediate area around the broads, the local disposal of spoil is considered inappropriate. The process of infill itself is of value and the reedbed and carr habitats are equally as important as the open water.

We advocate protection and surveillance of the sites rather than restoration. We recommend that the sites are monitored both chemically and biologically to assess any change and to further inform future management decisions. Water quality monitoring should be carried out at a minimum interval of every three months and plant surveys at three to five year intervals, dependent on signs of any water quality change. The reintroduction of *Nymphaeaceae* may be desirable at Sprats' Water and Woolner's Carr and the presence or absence of *Stratiotes aloides* should be confirmed by more detailed survey. In light of the presence of *Lophopus crystallinus* statoblasts, a bryozoan survey is recommended. Fish survey data would also be valuable for establishing the present fish community structure. Species such as tench, rudd, pike and perch should be encouraged and the amounts of roach and bream kept to a minimum. As with any long term monitoring programme it is essential to have a contingency should any deterioration be observed.

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