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Palaeolimnological investigation of English Lake SSSIs

Final Report to the Environment Agency and English Nature
Contract No. 13063

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ECRC Research Report No. 102

June 2005

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(Cover photo: Broomlee Lough, Roman Wall Loughs SSSI, Northumbria – H. Bennion)

Executive Summary

This is the final report to the Environment Agency and English Nature under an extension to project no.13063, '*Lake Monitoring to support Environment Agency Water Framework Directive intercalibration exercise and classification tool development, and CCW Site Condition Assessment - Phase 2*', funded by the Environment Agency and English Nature. This project forms part of the UK strategy for the implementation of the European Council Water Framework Directive (WFD) which requires reference conditions to be determined for all water body types including lakes. The project is also expected to produce data of relevance to the Habitats Directive. This study aims to use palaeoecological techniques, principally diatom analysis, to describe reference conditions and assess ecological change for a set of lakes in Sites of Special Scientific Interest (SSSIs) in England. The project builds on existing palaeoecological work in the UK, in particular the '*Identification of reference lakes and evaluation of palaeoecological approaches to define reference conditions for UK (England, Wales, Scotland & Northern Ireland) ecotypes, WFD08'* (Bennion, 2004), and aims to enhance the low resolution (core top and bottom) diatom analysis being carried out in the ongoing project '*Development of a phytobenthos classification tool for lakes and lochs, DALES'*. A further objective is to employ spheroidal carbonaceous particle analysis to estimate the time period represented by cores from selected key sites.

The study focuses largely on the analysis of diatom remains in sediment cores. Diatoms are sensitive to water quality changes and shifts in the diatom community often correspond closely to changes in other biological elements. Sediment cores were taken from ~50 sites in the UK during 2002-2003 as part of the WFD08 project (Bennion, 2004), and from a further ~100 lakes in England and Wales in 2004 as part of the Lake Monitoring Phase 2 programme. However, funding within those projects was insufficient to allow all of the material to be analysed. Therefore, 13 cores from lakes located in English SSSIs, where the waterbody is the reason for the designation, and which had not been previously analysed were selected for diatom analysis. Subfossil diatoms were analysed in five samples from each core, including the bottom sample which was taken to represent the reference condition, the surface sample which represents present-day conditions and three intermediate samples (typically 5, 10 and 20 cm).

Detrended correspondence analysis (DCA) was employed to assess the direction and nature of change in the diatom assemblages. Axis 1 of the DCA appeared to represent an alkalinity-productivity gradient with all cores, except Tatton Mere, displaying a general pattern from left to right of the plot as the samples move from the core bottom to the core top. This reflects the shift towards a more nutrient-rich diatom flora at the study sites. DCA Axis 2 appeared to represent a depth axis, differentiating the non-planktonic dominated, shallow lake floras from the planktonic dominated assemblages of the deeper, stratifying waters. The degree of floristic change between the reference and every other sample in each core was assessed using a squared chord distance dissimilarity coefficient which ranges from 0 (no difference) to 2 (completely different). A score of <0.475 (5th percentile) is used here to define low floristic change between samples. In six sites (Broomlee Lough, Cole Mere, Crag Lough, Dozmary Pool, Rostherne Mere and White Mere) the diatom changes were large enough to result in squared chord distance dissimilarity scores > 0.475. At the remaining seven sites, the floristic changes were subtle or relatively modest and scores were <0.475. In many cases this was because the same taxa were present throughout the sediment record but there were often important changes in their relative abundance indicative of ecological alterations and possible shifts in trophic status.

Diatom-total phosphorus (TP) transfer functions were applied to the data to assess the extent of chemical change at each site. Application of the diatom transfer functions to the fossil diatom assemblages in the 13 cores met with variable success. Comparison of the DI-TP for the surface sample of each core with the current annual mean TP concentration of that lake was used to assess the ability of the transfer function to produce good estimates of historical TP values for a site. In seven lakes, there was good agreement between the modelled and measured data but in four sites the model over-estimated current values and in two sites the model under-estimated current concentrations.

In summary, ten of the thirteen sites (Blelham Tarn, Broomlee Lough, Cole Mere, Crag Lough, Derwent Water, Dozmary Pool, Frensham Little Pond, Tabley Mere, The Loe and White Mere) appear to have experienced enrichment over the period represented by the cores, based on a combination of the species shifts and the results of the transfer functions. In four of these ten sites (Blelham Tarn, Broomlee Lough, Cole Mere and White Mere), there is evidence of ecological recovery towards the top of the cores, possibly arising from a recent reduction in nutrient concentrations. Tatton Mere is the only site to exhibit a consistent decrease in productivity over the sediment record but this may be because the core represents a very short time period. Two sites, Mere Mere and Rostherne Mere, exhibit floristic change but it is difficult to interpret the observed shifts in terms of trophic change.

The second main component of the project was to estimate the timescales represented by selected sediment cores using the spheroidal carbonaceous particle (SCP) dating technique. Nineteen cores from lakes in English SSSIs were chosen for study from the set of cores taken in 2002-2004 (see above). Between five and seven samples from each core, taken at roughly equidistant levels from the sediment surface to the core base, were analysed with the aim of providing a broad estimate of sediment chronology. Complete profiles were observed at seven sites (Burton Mill Pond, Buttermere, Crummock Water, Derwent Water, Dozmary Pool, Frensham Great Pond and Little Sea Mere), indicating that the cores date back to at least 1850 AD. Incomplete but interpretable profiles were identified at four sites (Bomere Pool, Broomlee Lough, Cotswold Park Lake No. 12 and Ullswater) which allowed a chronology to be approximated but the data suggest that these cores do not extend back as far as 1850 AD. Unfortunately, the profiles of eight lakes (Blelham Tarn, Chew Valley Lake, Crag Lough, Frensham Little Pond, Mere Mere, Tabley Mere, Tatton Mere and The Loe) were beyond interpretation and therefore a chronology could not be estimated for these cores.

In conclusion, simple methods such as ordination and dissimilarity measures applied to palaeoecological data, combined with transfer functions, offer powerful techniques for defining ecological and chemical reference conditions, and assessing environmental change. Spheroidal carbonaceous particle analysis is a valuable tool for establishing the time period represented by sediment records although the data produced in this study, on the basis of between 5-7 samples per core, indicates that a higher number of samples is generally required to establish a reliable chronology. Nonetheless, the project illustrates that relatively low resolution palaeolimnological studies can provide valuable information to aid implementation of the Water Framework Directive and Habitats Directive at the national level.

Key words: chronology, diatoms, ecological status, lakes, palaeolimnology, reference conditions, spheroidal carbonaceous particles, total phosphorus, Water Framework Directive.

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Acknowledgements

The authors would like to thank the following people for their contributions to this study:

Numerous colleagues in the Environment Agency, English Nature and the National Trust for assistance in arranging site access;

All landowners, estate managers and local wardens for their co-operation and for granting permission to carry out the work;

Gavin Simpson at UCL for assistance with the squared chord distance dissimilarity data analysis;

Ewan Shilland, James Shilland and Ben Goldsmith at UCL for technical support in the field;

and Ellie Liptrot, Sophie Theophile and Simon Turner at UCL for laboratory work.

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1. INTRODUCTION

1.1 Study rationale and objectives

There is a pressing need for simultaneous progress along several fronts in gaining understanding of lakes in the United Kingdom (UK). Specifically Annex II of the European Council Water Framework Directive (WFD) requires the identification of candidate reference lakes; and for Annex V, the development of tools for determining reference condition and classifying status (European Union, 2000). Furthermore, the European Council Habitats and Species Directive requires the setting of conservation objectives which may in turn lead to the need for restoration targets for lakes. The conservation agencies are currently engaged in setting conservation objectives for lakes of high conservation value, situated in Special Areas of Conservation (SAC) and Sites of Special Scientific Interest (SSSI), and input is needed on determining what should constitute favourable condition. For lakes, the use of palaeolimnological techniques has the potential to contribute to the delivery of these requirements. Consequently, a number of recently completed and ongoing projects employ palaeolimnological methods to identify reference lakes, describe reference conditions and assess ecological status of UK lakes.

The current project aims to build on these studies for selected key sites within English SSSIs by enhancing the low resolution diatom analysis undertaken so far, and by employing spheroidal carbonaceous particle analysis to estimate the time period represented by the sediment record. Sediment cores were taken from ~50 sites in the UK during 2002-2003 as part of the '*Identification of reference lakes and evaluation of palaeoecological approaches to define reference conditions for UK (England, Wales, Scotland & Northern Ireland) ecotypes, WFD08'* project (Bennion, 2004), and from a further ~100 lakes in England and Wales in 2004 as part of the '*Lake Monitoring to support Environment Agency Water Framework Directive intercalibration exercise and classification tool development, and CCW Site Condition Assessment - Phase 2*' programme. However, funding within those projects was insufficient to allow all of the material to be analysed. For instance, the WFD08 project (Bennion, 2004) involved diatom analysis of a number of sediment cores but many were not analysed to their full potential and the chronologies were not established. The ongoing project '*Development of a phytobenthos classification tool for lakes and lochs, DALES'* includes the analysis of only the surface sediment of a series of sediment cores, whilst an extension to DALES involves analysis of core bottoms from ~50 sites across England, Wales and Scotland. The '*Lake Monitoring to support Environment Agency Water Framework Directive intercalibration exercise and classification tool development, and CCW Site Condition Assessment - Phase 2*' programme involves the analysis of the tops and bottoms of cores from 19 lakes in Wales.

A total of 22 cores from lakes within English SSSIs, where the water body is the reason for the conservation designation, were short-listed for analysis. The site characteristics are given in Table 1 and details of the cores and analysis undertaken on each site are given in Table 2.

The objectives of the project were to:

1. Analyse subfossil diatoms in five samples from 13 cores, including the bottom sample taken to represent the reference condition, the surface sample which represents present-day conditions and three intermediate samples (typically 5, 10 and 20 cm).

2. Perform detrended correspondence analysis (DCA) and a dissimilarity measure to assess the nature and degree of change in the diatom assemblages.

3. Apply appropriate diatom-total phosphorus (TP) transfer functions to the diatom data to assess the extent of water quality change at each site.

4. Analyse between five and seven samples from 19 selected sediment cores, using the spheroidal carbonaceous particle (SCP) technique to provide a broad estimate of sediment chronology.

1.2 Background

The European Council Water Framework Directive (WFD) 2000/60/EC came into force in 2000 (European Union, 2000) and aims to achieve good ecological quality in all relevant waters within 15 years. It requires that biological, hydromorphological and chemical elements of water quality should be assessed by the degree to which present day conditions deviate from those expected in the absence of significant anthropogenic influence, termed reference conditions. The WFD specifically requires the determination of reference conditions for different waterbody types in order to identify sites of High status, i.e. where the various elements correspond totally or almost totally to undisturbed conditions. The four categories of Good, Moderate, Poor and Bad status are defined according to the degree of deviation from the reference state. In the absence of long-term data, the WFD states that reference conditions based on modelling may be derived using hindcasting methods, and palaeolimnology is given as one such technique (Pollard & Huxham, 1998; European Union, 2000).

The study of the sediment accumulated in a waterbody can provide a record of its past biology and chemistry, a science known as palaeoecology. Diatoms (*Bacillariophyceae*: single-celled, siliceous algae) are commonly used in such studies because they are sensitive to water quality changes and are, therefore, good indicators of past lake conditions such as lake pH (Battarbee *et al.,* 1999; 2001) and total phosphorus (TP) concentrations (Hall & Smol, 1999). In recent years, transfer functions have been developed to model the relationship between diatom assemblage composition and water chemistry in a training set of lakes. Once calibrated, such models are then applied to fossil diatom assemblages in sediment cores to infer past water chemistry. Weighted averaging (WA) regression and calibration (ter Braak & van Dam, 1989) and its extension WA partial least squares (WA-PLS) (ter Braak & Juggins, 1993) are the most widely used techniques for reconstructing past environmental variables in this way (Birks, 1998). Of the biological elements relevant to the WFD, diatoms represent components of both the phytoplankton and phytobenthos, but importantly shifts in the diatom community often correspond closely to changes in other biological groups (e.g. Kingston *et al*., 1992). The diatom record is a potentially useful tool, therefore, for assessing water quality and defining lake reference conditions, both chemical and ecological (e.g. Kauppila *et al*., 2002; Bennion *et al*., 2004).

In order to assess timescales of change, chronologies of the sediment cores need to be established. There are a number of techniques available to provide such chronologies, and spheroidal carbonaceous particle (SCP) analysis was selected for this particular study as it can provide a rapid and reliable means of sediment dating (Rose *et al*., 1995). SCPs are produced from the high temperature combustion of fossil-fuels and have no natural sources. Therefore, in lake sediments they provide an unambiguous record of industrially-derived, atmospherically deposited pollution. Apart from physical mixing, by bioturbation for example, little post-depositional alteration of the SCP record occurs and, once calibrated to an independent chronology, the resulting robust and replicable SCP concentration profile can be used to date sediment cores from across broad regions (Rose & Appleby, in press).

The use of palaeoecological techniques for determining reference conditions and assessing ecological change in lakes is well established with many examples of their application to aquatic management and conservation (e.g. Battarbee, 1999; Stoermer & Smol, 1999; Bennion *et al*., 1996, 2004).

1.3 Report structure

In addition to the introduction chapter, the report is comprised of two main chapters: Chapter 2 reports on the SCP analysis of the 19 selected cores and Chapter 3 details the results of the diatom analysis. A summary of the findings is given at the end of each chapter.

Table 1 Summary site characteristics of the 22 lakes short-listed for analysis

GB Lakes WBID	Name	Altitude (m)	Surface area (ha)	[1]Max depth (m)	[2]Mean depth (m)	[3]GB Lake type	pH	Cond (µS/cm)	Alk (mg/L)	TP (µg/L)	SRP (µg/L)	TN (mg/L)	Chla (µg/L)
28172	Broomlee Lough	257	27.94	1.9	<3	Marl, Sh	7.4	136	67	18	na	0.8	7
28220	Crag Lough	244	10.06	1.8	<3	Marl, Sh	7.6	164	83	20	na	1.0	7
28955	Ullswater (North Basin)	144	868.2	34	>3	MA, D	7.8	66	20	18	11	0.5	8
28965	Derwent Water	76	528.7	22	>3	LA, D	6.8	52	8	27	2	0.3	6
29000	Crummock Water	96	249.7	42	>3	LA, D	7.0	38	6	13	3	0.9	4
29052	Buttermere	103	90.9	27	>3	LA, D	6.5	32	6	16	1	0.3	2
29270	Blelham Tarn	47	10.57	14.5	>3	MA, D	7.1	97	34	28	7	0.7	14
32650	Rostherne Mere	27	48.42	25	>3	HA, D	8.0	383	117	145	106	1.8	59
32744	Mere Mere	52	16	7	>3	HA, D	7.8	368	83	53	13	2.4	27
32804	Tatton Mere	46	33.94	10	>3	HA, D	8.3	415	141	105	63	0.9	25
32960	Tabley Mere	32	24.7	4	<3	HA, Sh	7.8	556	142	327	150	3.1	15
35079	Cole Mere	88	27.07	10	>3	HA, D	7.9	274	124	119	91	1.1	17
35091	White Mere	96	23.53	10	>3	HA, D	8.1	269	97	477	309	1.1	16
36544	Bomere Pool	78	10	14.5	>3	HA, D	7.9	550	129	61	35	7.6	37
41559	Cotswold Park Lake No 12	86	15.57	5	<3	HA, Sh	8.4	234	72	24	7	0.8	5
43096	Chew Valley Lake	56	464.65	8	>3	HA, D	8.2	390	173	182	87	2.3	23
43943	Frensham Little Pond	54	14.66	1.5	<3	HA, Sh	8.3	321	111	65	61	2.0	36
44031	Frensham Great Pond	61	29.2	2	<3	HA, Sh	9.1	266	74	75	34	1.8	41
45108	Burton Mill Pond	16	21.9	2	<3	HA, Sh	8.0	436	197	43	18	3.5	11
46102	Little Sea Mere	5	31.4	1.5	<3	MA, Sh	7.5	194	19	26	10	1.0	7
46232	Dozmary Pool	268	14.92	1	<3	LA, Sh	6.9	53	11	37	7	1.1	12
46556	The Loe	4	53.81	8	>3	MA, D	8.1	232	30	93	37	4.8	22

[1] Maximum depths given are those measured at the coring location. Note that these may not always be the absolute deepest point.

[2] An estimate is given of whether mean depth is <3 or >3 m based on echo soundings during the lake surveys.

[3] GB Lake type follows the scheme of Phillips (2004); LA, MA, HA =low, medium & high alkalinity, respectively; Sh=shallow, D=deep.

Chemical data are given as annual means calculated from the Environment Agency WFD 2003-2004 dataset.

Table 2 Details of the cores and analysis undertaken at the 22 short-listed lakes

GB Lakes WBID	Name	EA REGION	SSSI name	Grid Reference	AMPHORA site code	Core code	Coring Date	Core length (cm)	Sample Intervals analysed for diatoms (cm)	Core analysed for SCPs
28172	Broomlee Lough	North East	Roman Wall Loughs	NY790697	BROL	BROL1	25/06/2003	24	0, 5, 10, 20, 24	Yes
28220	Crag Lough	North East	Roman Wall Loughs	NY766679	CRAZ	CRAZ1	21/07/2004	29	0, 5, 10, 20, 28	Yes
28955	Ullswater (N Basin)	North West	River Eden & Tributaries	NY425204	ULLS	ULLS1	01/07/2002	29	None*	Yes
28965	Derwent Water	North West	River Derwent & Tributaries	NY259209	DERW	DERW1	25/07/2004	27	0, 5, 10, 20, 26	Yes
29000	Crummock Water	North West	River Derwent & Tributaries	NY157188	CRUM	CRUM1	01/07/2002	37	None*	Yes
29052	Buttermere	North West	Buttermere	NY182157	BUTM	BUTM1	01/07/2002	25	None*	Yes
29270	Blelham Tarn	North West	Blelham Tarn & Bog	NY366004	BLEL	BLEL1	24/07/2004	31	0, 5, 10, 20, 30	Yes
32650	Rostherne Mere	North West	Rostherne Mere	SJ744842	SCM39	SCM39B	09/08/2004	30	0, 5, 10, 20, 30	No
32744	Mere Mere	North West	The Mere, Mere	SJ732818	SCM37	SCM37B	09/08/2004	25	0, 5, 10, 20, 25	Yes
32804	Tatton Mere	North West	Tatton Meres	SJ755801	SCM41	SCM41B	26/06/2003	26	0, 5, 10, 20, 25	Yes
32960	Tabley Mere	North West	Tabley Mere	SJ723769	SCM40	SCM40B	10/08/2004	25	0, 5, 10, 20, 25	Yes
35079	Cole Mere	Midlands	Cole Mere	SJ433332	SCM02	SCM02E	09/08/2004	30	0, 5, 10, 20, 30	No
35091	White Mere	Midlands	White Mere	SJ414329	SCM09	SCM09C	11/08/2004	35	0, 5, 10, 20, 35	No
36544	Bomere Pool	Midlands	Bomere, Shomere & Betton Pools	SJ498080	SCM28	SCM28B	05/07/2002	61	None*	Yes
41559	Cotswold Park Lake No 12	Thames	Cotswold Water Park	SU063968	COTS	COTS1	13/09/2004	13	None**	Yes
43096	Chew Valley Lake	South West	Chew Valley Lake	ST569597	CHEW	CHEW3	17/09/2004	7	None**	Yes
43943	Frensham Little Pond	Thames	Thursley, Hankley & Frensham Commons	SU859414	PFRE	PFRE1	06/09/2004	31	0, 5, 10, 20, 30	Yes
44031	Frensham Great Pond	Thames	Thursley, Hankley & Frensham Commons	SU845401	FREN	FREN1	25/09/2002	49	None*	Yes
45108	Burton Mill Pond	Southern	Burton Park	SU974175	BURT	BURT1	25/09/2002	78	None*	Yes
46102	Little Sea Mere	South West	Studland & Godlingston Heaths	SZ029846	LITT	LITT1	23/09/2002	56	None*	Yes
46232	Dozmary Pool	South West	Dozmary Pool	SX194745	EN17	EN17A	24/09/2004	21	0, 5, 10, 15, 20	Yes
46556	The Loe	South West	Dozmary Pool	SW648248	TLOE	TLOE1	27/09/2004	28	0, 5, 10, 20, 25	Yes

* Diatom analysis already undertaken as part of WFD08
** Diatom preservation too poor for analysis

2. AN ASSESSMENT OF SEDIMENT CHRONOLOGIES FOR 19 LAKES IN ENGLAND BASED ON SKELETON SPHEROIDAL CARBONACEOUS PARTICLE ANALYSIS

2.1 Objectives

The aim of the spheroidal carbonaceous particle (SCP) analysis was to provide approximate chronologies for selected cores from 19 English SSSI lakes.

2.2 Methods

With the exception of Bomere Pool, between five and seven samples from within a single sediment core, taken at roughly equidistant levels from the sediment surface to the core base, were analysed for SCPs with the aim of providing a broad estimate of sediment chronology for each core. For the Bomere Pool core, 11 samples were analysed as part of a student dissertation and therefore a more detailed chronology was produced. The names and locations of the study sites are shown in Table 3 and Figure 1. Ten of the cores were also analysed for diatoms in the current study (see Chapter 3), but unfortunately diatom analysis could not be carried out at two sites owing to poor preservation (Table 2). The remaining seven cores had already been analysed for diatoms as part of project WFD08 but had not previously been dated (Bennion, 2004).

SCPs are composed mainly of elemental carbon and although physically fragile are chemically robust. Unwanted fractions of the sediment can therefore be removed by the use of strong mineral acids without affecting the particles. The procedure for extraction and enumeration of SCPs from the sediment samples followed Rose (1994). Sequential attack using HNO_3, HF and HCl removed organic, siliceous and carbonate fractions, respectively, resulting in a suspension of mainly carbonaceous material in water. A known volume of this suspension was then evaporated onto a coverslip and the number of SCPs counted at 400 times magnification under a light microscope. Sediment concentrations are calculated in units of ‘number of SCP per gram dry mass of sediment’ or gDM^{-1}. For each set of sediment digestions, a SCP reference sediment was also included. This SCP standard is currently under development (Rose, unpublished data) and allows an indication of the comparability of the data resulting from the analysis. Reference SCP concentrations for the sample digestions had a mean of 6150 gDM^{-1} compared to the SCP reference standard mean of 6005 gDM^{-1} ($\sigma = 516$; $N = 210$) suggesting that the SCP concentration data for these sediment digestions are reliable.

The identification of SCP dating horizons used in this study is mainly based on Rose *et al*. (1995) and Rose & Appleby (in press). The former paper applies dates based on three main SCP profile features: the start of the SCP record; the start of the rapid increase in SCP concentration; and the peak in SCP concentration. However, in this paper few cores were available from the southern UK and dates could only be tentative in this region. More recently, further work has been undertaken to define SCP-derived sediment chronologies for the whole of the UK based on 80 independently dated SCP concentration profiles. Eight regions of the UK were identified and for each a chronology has been defined in two ways. First, using the three features described above and second using dates based on percentage cumulative inventory data. This latter approach sets the SCP concentration peak at 100% and calculates dates for each 10-percentile of the cumulative SCP inventory from the start of the record (0%). This allows 11 dates to be ascribed to each profile rather than the original three. However, this cumulative inventory approach requires reasonably complete profiles to be accurate and hence the dates in this report are based on the former approach, but with more accurate dates determined from the later Rose & Appleby (in press) study. The cores of interest in this report fall into the two regions, “north-west England” and “south and central England” and for these areas, the features of the SCP profiles are ascribed the following dates:

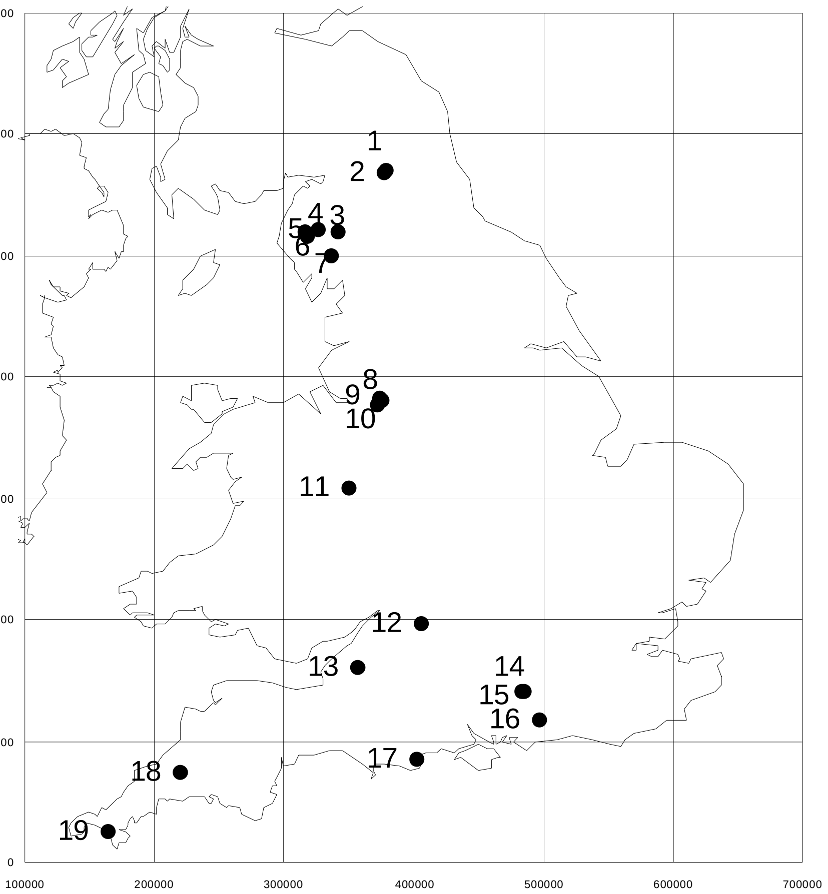
	North-west England	**South & Central England**
Start of the record	1850 ± 25	1850 ± 25
Rapid increase	1950s	1950s
Concentration peak	1978 ± 4	1970 ± 5

The exception is Bomere Pool, for two reasons. First, a more complete SCP profile was produced which allowed the cumulative inventory approach to be used. Second, it lies on the borders of the "Wales" and "South & Central England" regions. This is discussed in more detail below.

Table 3 List of sites analysed for spheroidal carbonaceous particles, along with summary of profile type (numbers relate to Figure 1)

1	Broomlee Lough; incomplete, interpretable	11	Bomere Pool; incomplete, interpretable
2	Crag Lough; incomplete, uninterpretable	12	Cotswold Park Lake No. 12; incomplete, interpretable
3	Ullswater; incomplete, interpretable	13	Chew Valley Lake; incomplete, uninterpretable
4	Derwent Water; complete	14	Frensham Little Pond; incomplete, uninterpretable
5	Crummock Water; complete	15	Frensham Great Pond; complete
6	Buttermere;; complete	16	Burton Mill Pond; complete
7	Blelham Tarn; incomplete, uninterpretable	17	Little Sea Mere; complete
8	Mere Mere; incomplete, uninterpretable	18	Dozmary Pool; complete
9	Tatton Mere; incomplete, uninterpretable	19	The Loe; incomplete, uninterpretable
10	Tabley Mere; incomplete, uninterpretable		

Figure 1 Locations of sites analysed for spheroidal carbonaceous particles (see Table 3 for lake names)



2.3 Results and discussion

Given the relatively small number of samples analysed per core and the coarse interval between samples, any estimated chronology contains a reasonable amount of uncertainty. Further, to produce any chronology at all requires a number of assumptions. The main one of these is that sediment accumulation rate has not varied greatly over the last 150 years. Without this assumption, no chronologies can be attributed to the profiles; however, the small number of samples analysed means that it is not possible to determine whether this is a reasonable assumption or not. A number of external driving factors can influence sediment accumulation rate and it is, therefore, possible that this assumption is not valid in many cases.

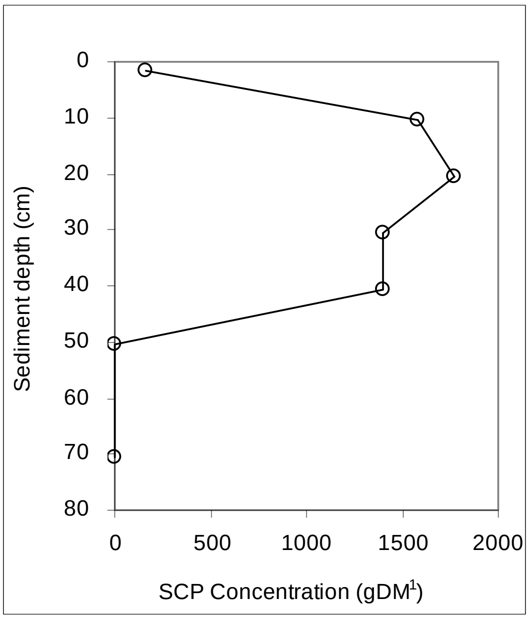
Three main profile types were identified amongst the 19 sediment cores:

1. Complete profiles. Those in which at least the bottom sample has a SCP concentration of 0 gDM^{-1}. This allows an estimate of 1850 to be made within the length of the sediment core, with the obvious caveats relating to the sampling interval for that core.
2. Incomplete profiles – interpretable. Those in which SCPs were found in all samples, including the basal sample but which otherwise may show a reasonable SCP profile. This suggests that the full core represents a post-1850 period, and any estimate of the 1850 date will be an extrapolation beyond the base of the core.
3. Incomplete profiles – uninterpretable. Profiles for which SCPs appear in all samples and which do not show any identifiable trend. In these cases, the only conclusion that can be drawn is that the core is either (a) of very rapid accumulation rate such that no trends can be identified or (b) the sediment record has been disturbed at the site such that the record is not reliable.

The results for each site are given below, sub-divided into these three profile categories. Seven cores exhibited complete profiles, four cores had incomplete but interpretable profiles and eight cores had incomplete and uninterpretable profiles (see Table 3). Summary figures are presented for each site whilst full data are provided in Appendix 1.

2.3.1 Complete profiles

Figure 2 SCP concentration profile for Burton Mill Pond (BURT1)

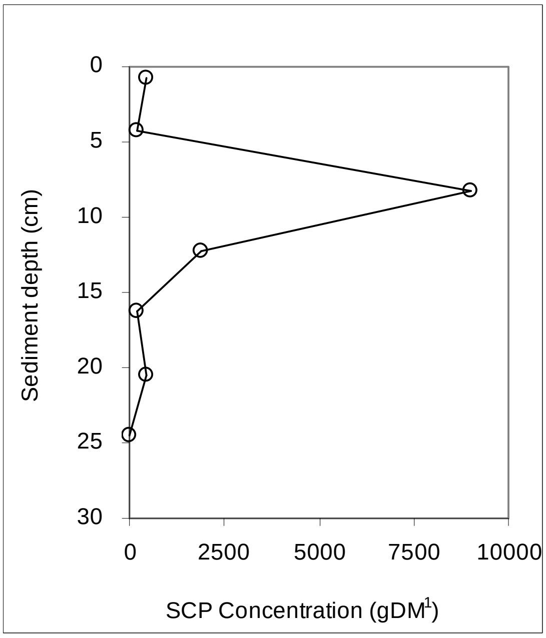


Although the SCP profile is complete in that concentrations fall to 0 gDM^{-1}, the shape of the profile is atypical and therefore not straightforward to interpret. No SCPs are recorded in the 50 – 51 cm sample suggesting that 1850 lies between the 40 - 41 and 50 – 51 cm samples. However, the major change in concentration between these two levels makes this assumption a little doubtful. If 1850 were toward the bottom of this range and assuming a reasonably constant rate of sediment accumulation then the SCP peak (1970 ± 5) would lie at c. 10 – 11 cm. The shape of the profile

would suggest that a 'best estimate' for the peak would be between 10 – 11 cm and 20 – 21cm but it is difficult to identify where the SCP 'rapid increase in concentration' might lie. Therefore, the best estimate of the chronology is:
1970 ± 5: c. 15 cm
1850 ± 25: > 50 cm

Alternatively, this unusual SCP profile shape may be produced if a rapid sediment accumulation rate has diluted the lower samples to below the limit of detection, such that the 1950 rapid increase feature appears here as the start of the record (i.e. a move from below to above the limit of detection). If this is the case then the rapid increase occurs at c.50 cm giving an accumulation of c. 1cm yr^{-1}. This would put 1970 +/- 5 years at c. 30 cm and 1850 +/- 25 years at c. 150 cm.

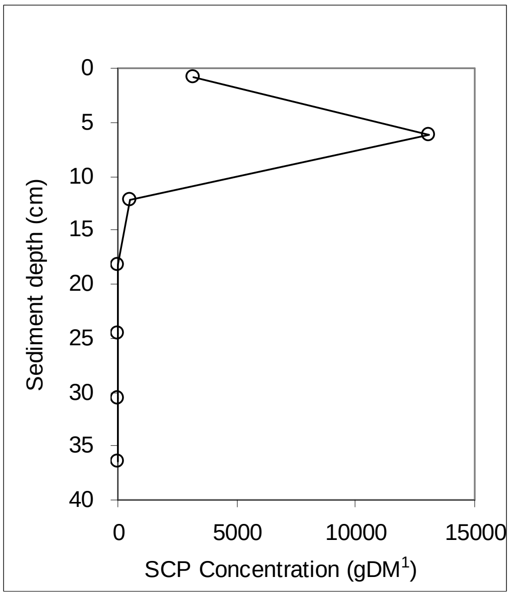
Figure 3 SCP concentration profile for Buttermere (BUTM1)



No SCPs are recorded in the 24 – 25 cm sample of Buttermere suggesting that 1850 lies between 21 and 24 cm. The shape of the profile suggests that it is probably towards the lower end of this range. Assuming a reasonably constant rate of accumulation, this depth range for 1850 would suggest 3.5 - 4 cm for 1978 (the SCP concentration peak), and 7 – 9 cm for 1950 (the start of the rapid increase in SCP concentration). However, the available data would suggest that the peak and the rapid increase are below this depth.

If the rapid increase feature is that observed in this profile, then it would seem to be reasonably simple to identify and hence 1950 would be at c. 13cm. This would place the SCP peak (1978) at 6.5cm which would also be reasonable. However, assuming a constant rate of accumulation places 1850 at c. 38 cm, well below the base of the core and the zero concentration observed at 24 – 25cm. Therefore, there has either been an increase in sedimentation rate at some point between 1850 and 1950 in this core, or the zero concentration at 24 – 25cm is an artefact of the analytical detection limit. Hence it is not possible to state with confidence that the base of this core is at 1850. The best estimate of the chronology is:
1978 ± 5: 6 - 8 cm
1950 ± 15: 12 - 15 cm

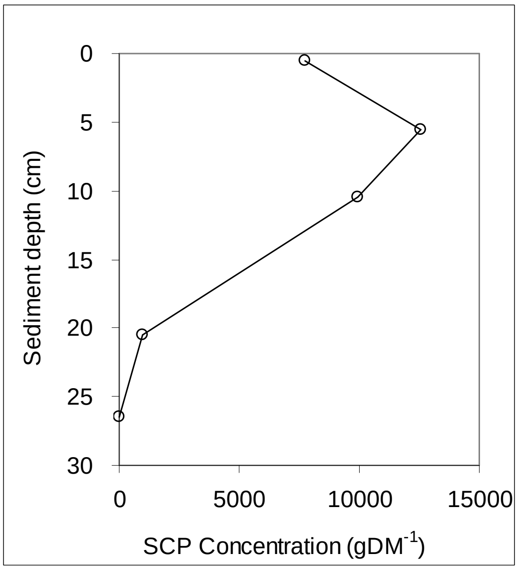
Figure 4 SCP concentration profile for Crummock Water (CRUM1)



No SCPs are recorded in the 18 – 19 cm sample of CRUM1 suggesting that 1850 lies between 13 and 18 cm. The shape of the profile suggests that it is probably towards the lower end of this range. Assuming a reasonably constant rate of accumulation, this depth range for 1850 would suggest a depth of between 2 – 3 cm for 1978 ± 5 (the SCP concentration peak), and 4.5 – 6.5 cm for 1950 (the start of the rapid increase in SCP concentration). However, from the available data the start of the rapid increase would seem to be below this and probably in the range 7 - 10 cm. This would then move the peak to a slightly lower depth or there have been changes in sediment accumulation rate. Therefore, the best estimate of the chronology is:

1978 ± 5:	3 – 4 cm
1950 ± 15:	7 - 10 cm
1850 ± 25:	≥ 18 cm

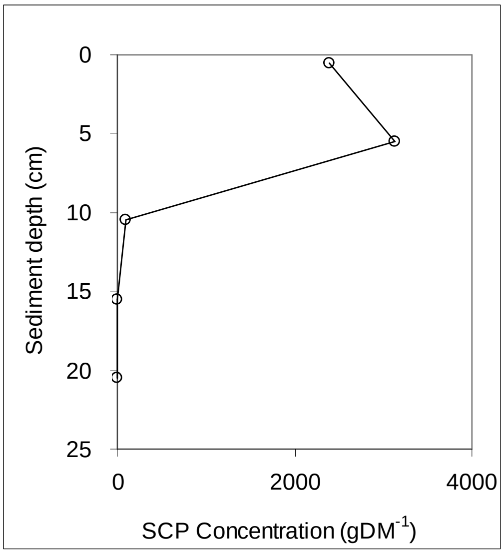
Figure 5 SCP concentration profile for Derwent Water (DERW1)



No SCPs are recorded in the 25 – 26 cm sample of DERW1 suggesting that 1850 lies between 21 and 26 cm. The shape of the profile suggests that it is probably towards the lower end of this range. Assuming a reasonably constant rate of accumulation, this depth range for 1850 would suggest a depth of between 3 – 5 cm for 1978 ± 5 (the SCP concentration peak), and 7 – 9.5 cm for 1950 (the start of the rapid increase in SCP concentration). However, from the available data the start of the rapid increase would seem to be below the 10 – 11 cm sample. These data therefore only agree if there has been an increase in sediment accumulation rate in recent times. The best estimate of the chronology is:

1978 ± 5: 3 – 5 cm
1950 ± 15: 11 - 15 cm
1850 ± 25: c. 25 cm

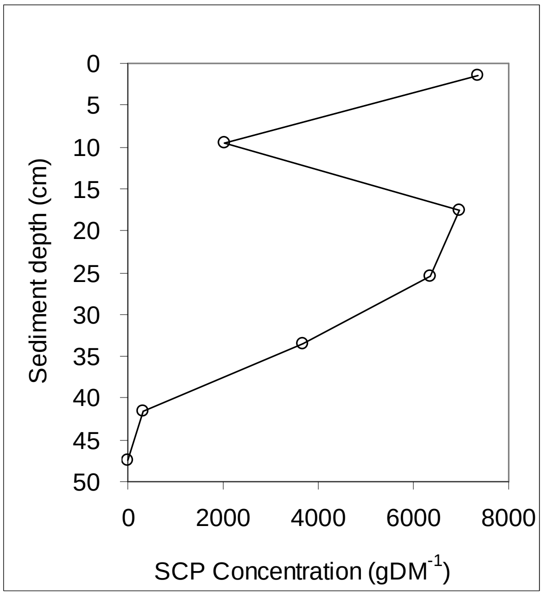
Figure 6 SCP concentration profile for Dozmary Pool (EN17A)



No SCPs are recorded in the 15 – 16 cm sample of EN17A suggesting that 1850 lies between 11 and 15 cm. The shape of the profile suggests that it is probably towards the lower end of this range. Assuming a reasonably constant rate of accumulation, this depth range for 1850 would suggest a depth of between 2 – 3.5 cm for 1970 ± 5 (the SCP concentration peak), and 3.5 – 5.5 cm for 1950 (the start of the rapid increase in SCP concentration). However, from the available data the start of the rapid increase would seem to be below this and probably in the range 7 - 9 cm. These data therefore only agree if there has been an increase in sediment accumulation rate in recent times. The best estimate of the chronology is:

1970 ± 5: 2 – 3.5 cm
1950 ± 15: 7 - 9 cm
1850 ± 25: c. 15 cm

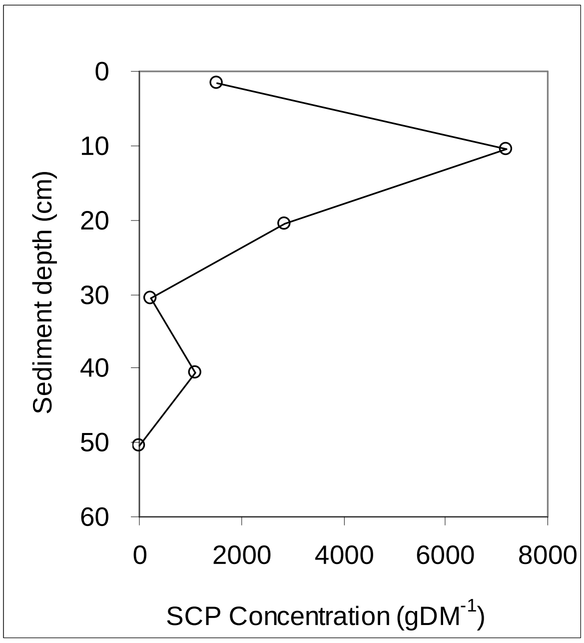
Figure 7 SCP concentration profile for Frensham Great Pond (FREN1)



No SCPs are recorded in the 47 – 48 cm sample of FREN1 suggesting that 1850 lies between 42 and 47 cm. Assuming a reasonably constant rate of accumulation, this depth range for 1850 would suggest a depth of between 9 – 11 cm for 1970 ± 5 (the SCP concentration peak), and 14 – 17 cm for 1950 (the start of the rapid increase in SCP concentration). However, the available data precludes the identification of these features and the dating must remain highly speculative. Further, the SCP maximum concentration is in the surface sample making it uncertain whether this profile is complete or not. Therefore, the best estimate of the chronology is:

1850 ± 25: 42 - 47 cm

Figure 8 SCP concentration profile for Little Sea Mere (LITT1)

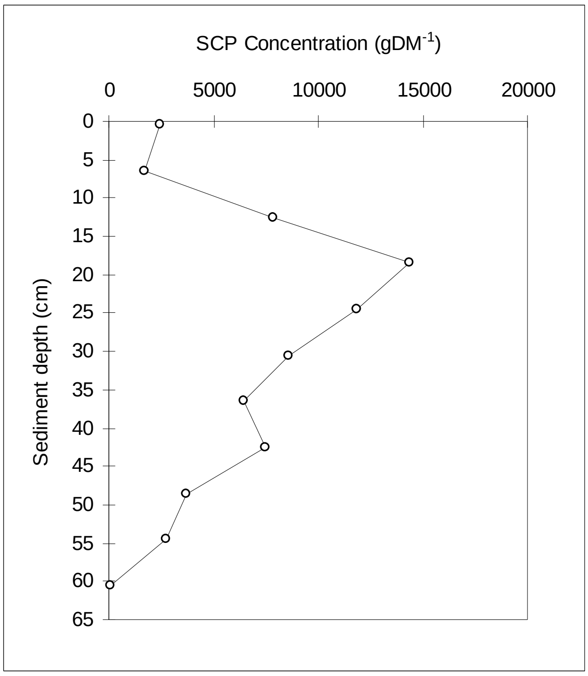


No SCPs are recorded in the 50 – 51 cm sample of LITT1 suggesting that 1850 lies between 41 and 50 cm. The shape of the profile suggests that it is probably towards the lower end of this range. Assuming a reasonably constant rate of accumulation, this depth range for 1850 would suggest a depth of between 9 – 11 cm for 1970 ± 5 (the SCP concentration peak), and 14 – 18 cm for 1950 (the start of the rapid increase in SCP concentration). However, from the available data the start of the rapid increase would seem to be below this and probably around 25 cm. These data therefore only agree if there have been changes in sediment accumulation rate over the period covered by the core. Therefore, the best estimate of the chronology is:

1970 ± 5:	5 - 15 cm
1950 ± 15:	20 - 25 cm
1850 ± 25:	45 - 50 cm

2.3.2 Incomplete profiles - interpretable

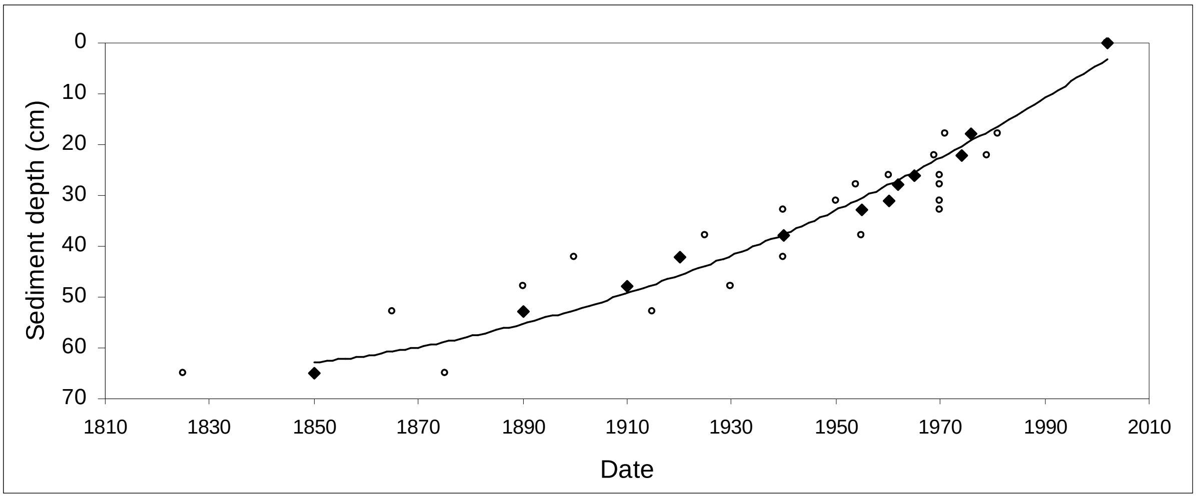
Figure 9 SCP concentration profile for Bomere Pool (SCM28B)



The profile for core SCM28B is more detailed than for the other cores as more sediment levels were analysed as part of a student dissertation (Bowers, 2004). The maximum SCP concentration occurs between 13 and 24 cm although the shape of the profile suggests that this is probably quite close to the 18 – 19 cm sample. In terms of SCP dating, Bomere Pool lies on the borders of the "Wales" and "South & Central England" regions. There is little difference in the dating in these regions over most of the period, except in the most recent levels when the SCP peak in the Wales region is dated to 1976 ± 5, and for the South & Central England region is 1970 ± 5. A presence of SCPs exists in the lowest level of the core (60 – 61 cm) but concentrations are very low suggesting that this is close to the start of the record. Therefore, assuming that the first presence of SCPs (1850 ± 25) is just below 60 – 61 cm level then the SCP inventory can be calculated. Setting 100% at either 1970 or 1976, depending on whether the site falls within the Wales or Southern & Central England dating region, therefore allows dates to be ascribed to the cumulative profile accordingly.

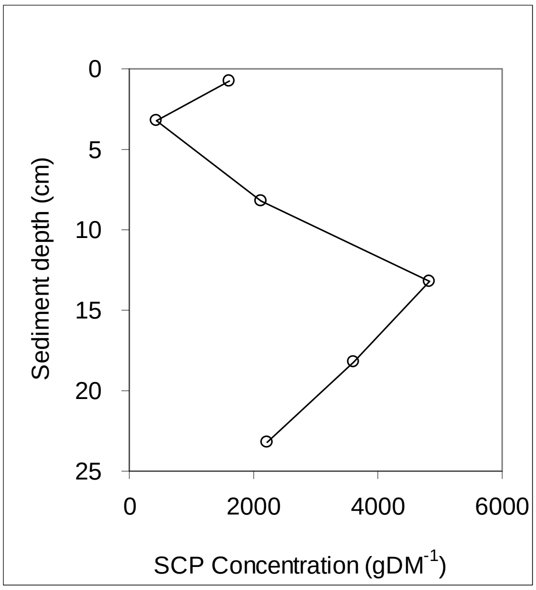
If the dates for the South & central England region are used then the data suggest that there has been a change to a faster sedimentation rate in the 1950s. Using the Wales regional data the acceleration is more gradual, although in reality the actual chronology (i.e. sediment depth against date) changes little. The chronology, based on the Wales regional data is shown in Figure 10.

Figure 10 Chronology for Bomere Pool (SCM28B)



Chronology for Bomere Pool: ◆ symbols show the best available chronology, whilst ○ show the dating errors for each point. The fitted trend-line is for guidance only.

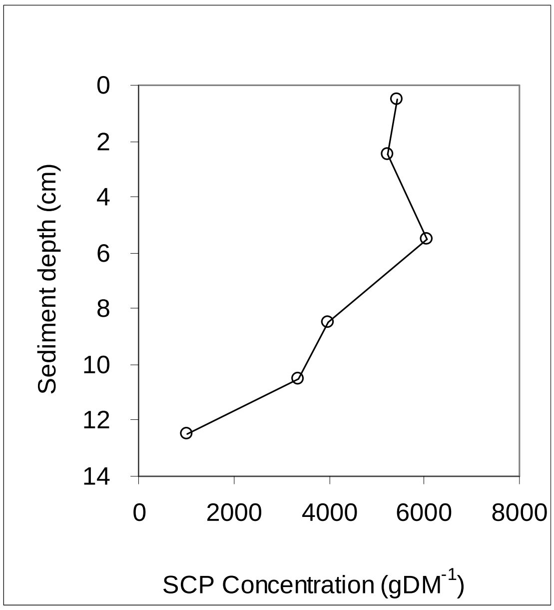
Figure 11 SCP concentration profile for Broomlee Lough (BROL1)



SCPs are present in all samples from BROL1 suggesting that the entire core represents a post-1850 period. The maximum observed SCP concentration of almost 5000 gDM^{-1} is in the 13 – 14 cm sample and the peak concentration therefore probably lies somewhere between 9 and 18 cm. Assuming a reasonably constant accumulation rate, if the peak concentration lies in this range, then 1950 would occur between 18 and 38cm and 1850 would occur between 53 and 110cm. However, from the shape of the profile, the start of the rapid increase would seem more likely to occur at 30 – 35 cm (if the core were this long) suggesting the following best estimate of the chronology:

1978 ± 5:	14 - 17 cm
1950 ± 15:	30 - 35 cm
1850 ± 25:	85 - 100 cm

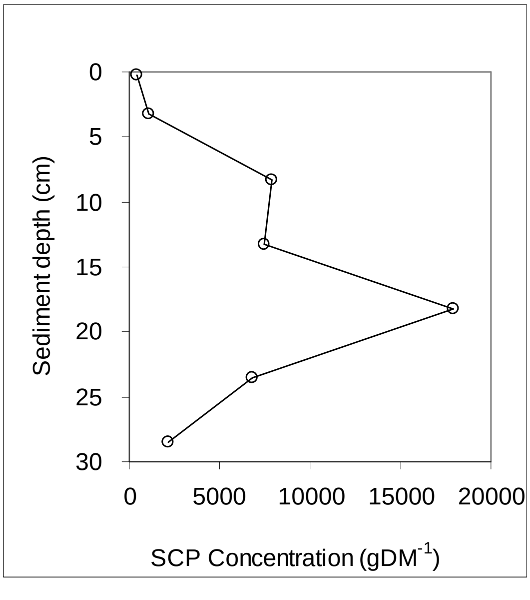
Figure 12 SCP concentration profile for Cotswold Park Lake No. 12 (COTS1)



SCPs are present in all samples from COTS1 suggesting that the entire core represents a post-1850 period. It should be noted that Cotswold Park Lake No. 12 is an artificial waterbody. The date of creation is uncertain but given that it is a restored gravel pit it is unlikely to date back to as early as 1850. Whilst the SCP concentration peak (c. 6000 gDM^{-1} in the 5 - 6 cm) is not very well defined, if we assume that the profile is reliable, then the maximum concentration probably lies somewhere between 3 and 8 cm. Assuming a reasonably constant accumulation rate, if the peak concentration lies in this range, then 1950 would occur between 4.5 and 12.5cm. However, the shape of the profile indicates that the start of the rapid increase most likely occurs at the lower end of this range suggesting the following best estimate of the chronology:

1978 ± 5:	7 - 8 cm
1950 ± 15:	11 - 13 cm

Figure 13 SCP concentration profile for Ullswater (ULLS1)

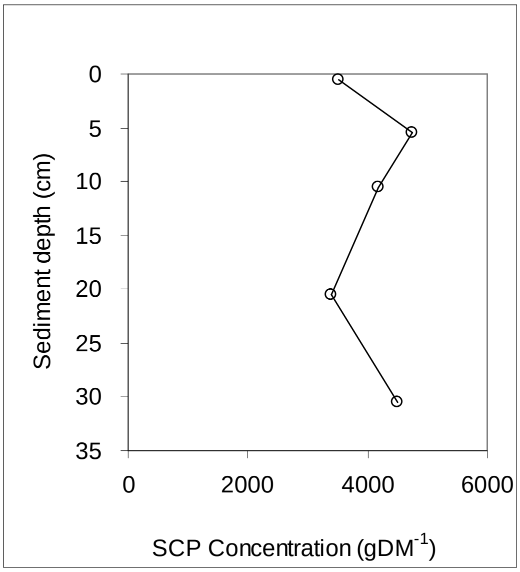


SCPs are present in all samples from ULLS1 suggesting that the entire core represents a post-1850 period. The maximum observed SCP concentration of almost 18000 gDM^{-1} is in the 18 – 19 cm sample and the peak concentration therefore probably lies somewhere between 14 and 23 cm. Assuming a reasonably constant accumulation rate, if the peak concentration lies in this range, then 1950 would occur between 29 and 47cm and 1850 would occur between 82 and 135 cm. However, from the shape of the profile, the start of the rapid increase seems more likely to occur at or just below the base of the core (i.e. 28 – 32 cm) suggesting the following best estimate of the chronology:

1978 ± 5:	13 – 16 cm
1950 ± 15:	28 - 32 cm
1850 ± 25:	80 - 95 cm

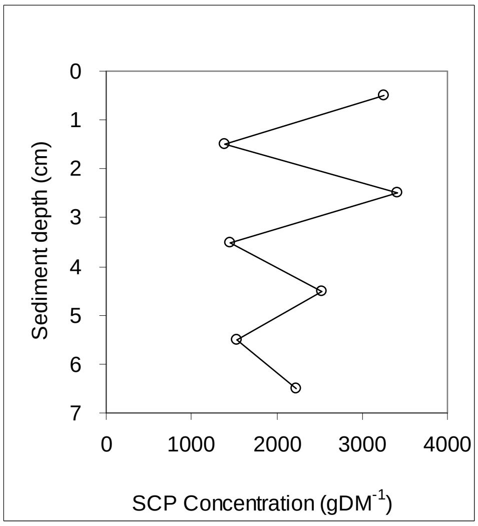
2.3. 3. Incomplete profiles - uninterpretable

Figure 14 SCP concentration profile for Blelham Tarn (BLEL1)



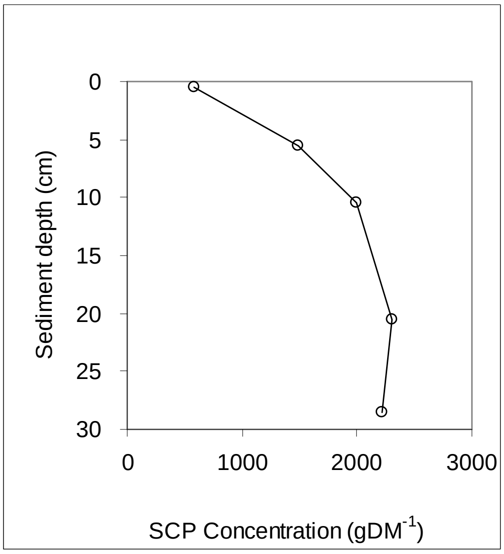
The SCP concentration profile for BLEL1 shows no real trend and no identifiable features. The presence of SCPs at every sampled depth suggests that the whole core represents a period post-1850. However, the similar concentrations throughout the core imply either a very rapid sediment accumulation rate or a disturbed sediment record.

Figure 15 SCP concentration profile for Chew Valley Lake (CHEW3)



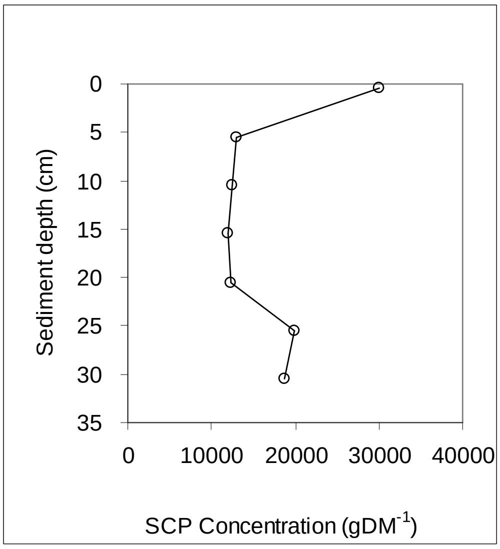
The SCP concentration profile for CHEW3 shows no real trend and no identifiable features. The presence of SCPs at every sampled depth suggests that the whole core represents a period post-1850. However, the lack of trend and the highly erratic concentrations imply either a changing sediment accumulation rate or a disturbed sediment record. It should be noted that Chew Valley Lake is a reservoir and not a natural lake and, therefore, water level fluctuation may impact upon sedimentation rates.

Figure 16 SCP concentration profile for Crag Lough (CRAZ1)



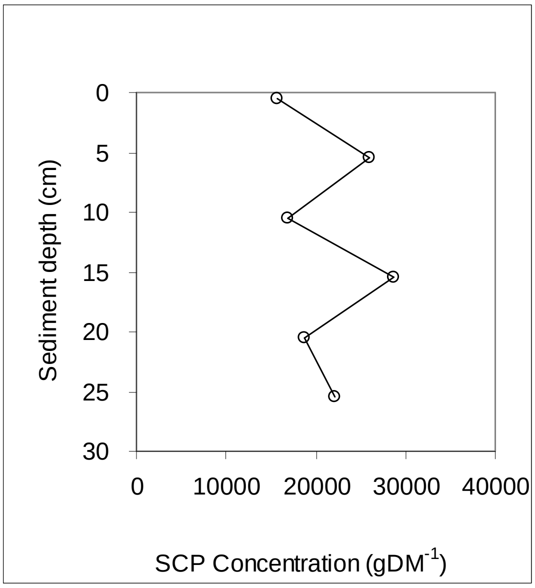
The SCP concentration profile for CRAZ1 shows no identifiable features. The presence of SCPs at every sampled depth suggests that the whole core represents a period post-1850. If the profile is reliable then the peak SCP concentration probably lies between 11 and 28 cm which would suggest that the whole core covers a period of c. 40 – 50 years, but this is highly speculative.

Figure 17 SCP concentration profile for Frensham Little Pond (PFRE1)



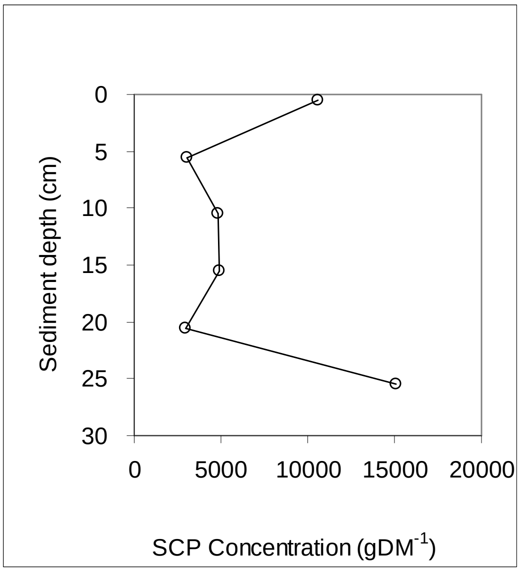
The SCP concentration profile for PFRE1 shows no real trend and no identifiable features. The presence of SCPs at every sampled depth suggests that the whole core represents a period post-1850. No further chronological interpretation is possible.

Figure 18 SCP concentration profile for Mere Mere (SCM37B)



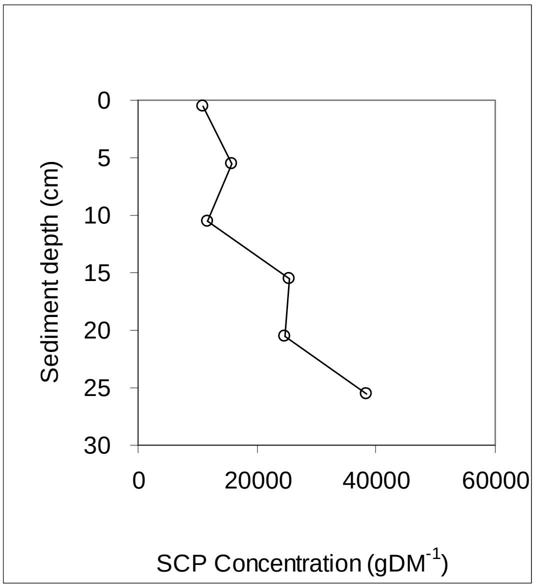
The SCP concentration profile for SCM37B shows no real trend and no identifiable features. The presence of SCPs at every sampled depth suggests that the whole core represents a period post-1850. However, the lack of trend and the erratic concentrations imply either a changing sediment accumulation rate or a disturbed sediment record.

Figure 19 SCP concentration profile for Tabley Mere (SCM40B)



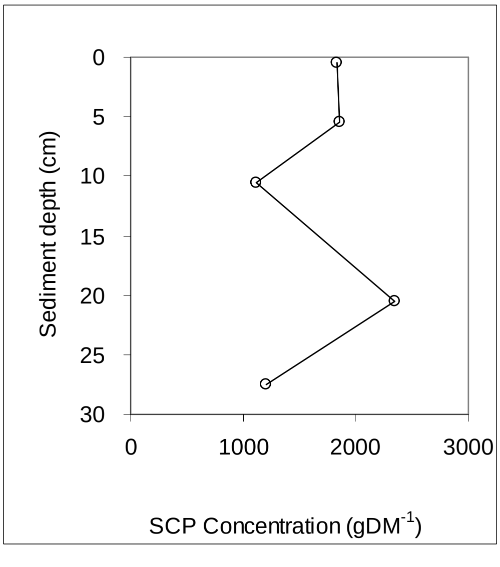
The SCP concentration profile for SCM40B shows no real trend and no identifiable features. The presence of SCPs at every sampled depth suggests that the whole core represents a period post-1850. No further chronological interpretation is possible.

Figure 20 SCP concentration profile for Tatton Mere (SCM41B)



The SCP concentration profile for SCM41B shows no identifiable features. The presence of SCPs at every sampled depth suggests that the whole core represents a period post-1850. If the profile is reliable then the peak SCP concentration has not been attained at the bottom of the core, suggesting that the entire profile is post-1970, but this is highly speculative.

Figure 21 SCP concentration for The Loe (TLOE1)



The SCP concentration profile for TLOE1 shows no real trend and no identifiable features. The presence of SCPs at every sampled depth suggests that the whole core represents a period post-1850. However, the similar concentrations throughout the core imply either a very rapid sediment accumulation rate or a disturbed sediment record.

2.4 Summary of findings

Nineteen cores from lakes in English SSSIs were chosen for SCP analysis. Between five and seven samples from each core, taken at roughly equidistant levels from the sediment surface to the core base, were analysed with the aim of providing a broad estimate of sediment chronology.

1. Complete profiles were observed at seven sites (Burton Mill Pond, Buttermere, Crummock Water, Derwent Water, Dozmary Pool, Frensham Great Pond and Little Sea Mere), indicating that the cores date back to at least 1850 AD.

2. Incomplete but interpretable profiles were identified at four sites (Bomere Pool, Broomlee Lough, Cotswold Park Lake No. 12 and Ullswater) which allowed a chronology to be approximated but the data suggest that these cores do not extend back as far as 1850 AD.

3. A detailed analysis of 11 samples was carried out at Bomere Pool, allowing a more complete chronology to be constructed for this core. The core displayed the typical features of UK profiles and therefore the SCP inventory method was applied to calculate the chronology. The results indicate that the core dates back to just after 1850.

4. Unfortunately, the profiles of eight lakes (Blelham Tarn, Chew Valley Lake, Crag Lough, Frensham Little Pond, Mere Mere, Tabley Mere, Tatton Mere and The Loe) were beyond interpretation and thus a chronology could not be estimated for these cores. The data suggest either a very rapid sediment accumulation rate or a disturbed sediment record. It should be noted that all of these lakes are productive systems and therefore rapid sedimentation rates might be expected. Higher resolution analysis would be required to attempt further interpretation of these profiles although it is likely that longer cores would be necessary to provide a sediment record that extends back as far as ~1850.

3. AN ASSESSMENT OF ECOLOGICAL CHANGE AT 13 LAKES IN ENGLAND BASED ON DIATOM ANALYSIS

3.1 Objectives

The aim of the diatom analysis was to build on existing work being carried out on the tops and bottoms of sediment cores within other projects, namely *WFD08* (Bennion, 2004), *DALES* and *Lake Monitoring to support Environment Agency Water Framework Directive intercalibration exercise and classification tool development, and CCW Site Condition Assessment - Phase 2*. The top and bottom approach involves the analysis of only two samples per site from a sediment core (Cumming *et al*., 1992) and has been successfully applied by the US Environmental Protection Agency's (USEPA) Environmental Monitoring and Assessment Program for Surface Waters (EMAP-SW) (Dixit *et al*., 1999) and in Canada to infer changes in southeastern Ontario lakes (Reavie *et al*., 2002). The approach makes the assumption that the top and bottom samples represent the present day and reference conditions, respectively. For the UK, it is generally agreed that approximately 1850 AD is a suitable date against which to assess impacts for lakes as this represents a period prior to major industrialisation and agricultural intensification (Battarbee, 1999; Fozzard *et al*., 1999). The analysis of reference samples in this way removes the problem inherent in spatial-state schemes in which the lakes have been subject to different pressures and varying degrees of impact. The diatom data from the surface (uppermost 0.5 or 1 cm) sample of each core is used to provide information on the current diatom assemblages of the lakes. The surface sediment sample represents the last few years' accumulation of diatoms deposited from a variety of habitats within the lake.

Where available, core chronologies based on the SCP analysis detailed in Chapter 2, were used to establish the time period represented by the cores. At Derwent Water and Dozmary Pool, the sample approximating to ~1850 AD was selected to represent the reference condition but in one case (Broomlee Lough), the core did not extend back as far as 1850 and in seven cases (Blelham Tarn, Crag Lough, Frensham Little Pond, Mere Mere, Tabley Mere, Tatton Mere and The Loe) the SCP profiles could not be interpreted with any confidence. In these latter situations or in the absence of dates (Cole Mere, Rostherne Mere, White Mere), the bottom sample of the core was taken to represent the reference sample. It is accepted that aquatic systems have been subjected to anthropogenic impacts over much longer time-scales than simply the last 100-150 years and, therefore, our reference conditions are unlikely to equate to the natural or pristine state.

Whilst the top and bottom approach is useful for broadly assessing degree of change at large numbers of sites, it is a very low resolution technique and does not allow the timing and rate of change to be established. This study aimed to enhance the existing top and bottom data by analysing three additional samples per core to give a total of five samples per site. Bennion (2004) showed that this resolution was sufficient to detect broad shifts in water quality. A further objective was to employ simple measures of change, ordination methods and transfer functions to assess the degree and nature of the floristic change and to infer shifts in nutrient status.

3.2 Methods

Site selection

A total of 15 lakes in English SSSIs were selected for diatom analysis (see Table 2). The sites represent a range of lake types in the GB Lake Typology (Phillips, 2004) including low alkalinity, medium alkalinity, high alkalinity and marl systems, and with examples of both shallow and deep waters, although the dataset is slightly bias towards high alkalinity lakes (Table 1). Most of the lakes are circumneutral to alkaline and are not sensitive to acidification. Even the low alkalinity waters are only mildly acid. With the exception of Broomlee Lough, Crag Lough and Dozmary Pool which are at altitudes >200 m, the study lakes lie in relatively productive, lowland catchments and hence eutrophication is likely to be the key pressure. Further details of the sites and their chemistry are given in Table 1.

Field and laboratory methods

A sediment core was taken in the summer of 2002, 2003 or 2004 from the deepest part of each lake using either a piston corer or a gravity corer. The core sampling undertaken in 2004, as part of *Lake Monitoring to support Environment Agency Water Framework Directive intercalibration exercise and classification tool development, and CCW Site Condition Assessment - Phase 2,* involved only a Glew gravity corer which collects short cores of typically 20-40 cm in length. It might be expected, therefore, that at very productive sites, the short cores would not extend back as far as 100 years. All cores were extruded in the field at either 0.5 cm or 1.0 cm intervals (depending on expected sediment accumulation rate).

Slides for diatom analysis were prepared from selected levels of each core (approximately 5-6 per core) covering the whole core length (see Table 2), using standard methods (Battarbee *et al*., 2001). Screening of the slides revealed that two sites, Cotswold Park Lake No. 12 and Chew Valley Lake, have extremely poor diatom preservation. Therefore, analysis was subsequently carried out at 13 lakes. At least 300 valves (siliceous component of the cell wall bearing the taxonomic features) were counted from each sample using a Leitz research microscope with a 100x oil immersion objective and phase contrast. Principal floras used in identification were Krammer & Lange-Bertalot (1986-1991). Five samples per core were analysed to allow the reference condition and general trend in water quality to be determined. All slides are archived at the ECRC and the data are stored in the Amphora database.

Data analysis

All diatom data were expressed as percentage relative abundance, and were screened and harmonised prior to data analysis. The full dataset of 65 samples (13 cores x 5 samples) was comprised of 287 diatom taxa. The most common 134 taxa (occurring at >1% in >2 samples) are listed in Appendix 2. Summary diagrams of the diatom changes (showing only those taxa present with a relative abundance of >2% in at least one sample) were produced for each site using C^2 (Juggins, 2003) – see Figures 22 to 34.

The degree of floristic change between the bottom sample and each of the other four samples analysed in each core was assessed using the squared chord distance dissimilarity coefficient (Overpeck *et al*., 1985) implemented in the statistical software R (R Development Core Team, 2004). This is preferred to other dissimilarity measures as it maximises the signal to noise ratio, it performs well with percentage data and has sound mathematical properties (Overpeck *et al*., 1985). The scores range from 0 to 2 whereby 0 indicates that two samples are exactly the same and 2 that they are completely different. Scores less than 0.29, 0.39, 0.48 and 0.58 indicate insignificant floristic change at the 1st, 2.5th, 5th and 10th percentile, respectively (Simpson, 2003). The 5th percentile (score <0.475) is used here to define sites with low floristic change between the bottom (reference) sample and each of the upper samples. The scores are plotted for each lake (Figures 22 to 34) to show how dissimilar the four upper samples are from the reference sample, and the values are shown in Appendix 3. The vertical line in Figures 22-34 is drawn at a squared chord distance dissimilarity score of 0.475 to illustrate which samples fall above and below this critical value.

Detrended correspondence analysis (DCA) (Hill & Gauch, 1980) was performed using CANOCO version 4.5 (ter Braak & Smilauer, 2002) to assess the direction and magnitude of floristic change at each site. Only those 134 taxa present with a maximum relative abundance of > 1% in > 2 samples were included in the ordination analyses. The results are presented as biplots of axis 1 and 2 sample scores and species scores in Figure 35. In Figure 35a, samples with similar scores on the two axes lie in close proximity, reflecting similar diatom composition. For each core, lines connect the samples in a series from core bottom to core top (see Appendix 3 for sample codes). The direction of the line indicates the direction of floristic change and its length is a measure of species turnover in Hill's standards deviation units (Hill & Gauch, 1980).

Weighted averaging (WA) regression and calibration (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 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).

Given that eutrophication was thought to be the key pressure at the study lakes, diatom-TP transfer functions were applied to the diatom data for each core, following taxonomic harmonisation between the training sets and the fossil data. All taxa were included in the analysis. Reconstructions of diatom-inferred TP (DI-TP) were produced using either a Northwest European training set of 152 relatively shallow lakes (< 10 m maximum depth) with a median value for the dataset of 104 µg TP l^{-1} and a root mean squared error of prediction (RMSEP) of 0.21 $\log_{10}$ µg TP l^{-1} for the weighted averaging partial least squares two-component (WA-PLS2) model (Bennion *et al*., 1996), or a model based on a training set of 56 relatively large, deep lakes (> 10 m maximum depth) from Scotland, Northern Ireland, Cumbria, southern Norway and central Europe, with a median value for the dataset of 22 µg TP l^{-1} (Bennion *et al*., 2004). For this dataset, the best model was generated with simple WA and inverse deshrinking (RMSEP of 0.25 $\log_{10}$ µg TP l^{-1})$^{.}$ The RMSEP values were calculated using the jack-knife, or 'leave-one-out', cross validation method which better estimates the true predictive ability of the model (ter Braak & Juggins, 1993). For each core, the training set containing the greatest percentage of the taxa present in the fossil samples was selected. For all lakes, except Derwent Water where the large, deep lakes model was best suited to the data, the Northwest European model was used. For all core samples, there was good representation of the common taxa in the training sets. All reconstructions were implemented using C^2 (Juggins, 2003) and are shown for each site in Figures 22 to 34. The DI-TP values and the percentage of the taxa in each fossil sample that are present in the training set are given in Appendix 3.

The results are detailed below on a site by site basis. For each site, the major species shifts are described, the degree of floristic change is presented and the changes in nutrients as inferred by the diatom-TP transfer functions are discussed.

3.3 Results and discussion

Blelham Tarn

The five samples from the Blelham Tarn core, BLEL1, contained a total of 80 taxa. A summary diagram of the common taxa, many of which are planktonic forms, is shown in Figure 22. Blelham Tarn has experienced floristic change over the period represented by the core. Unfortunately the SCP profile could not be interpreted and the presence of SCPs at every sampled depth suggests that the whole core represents the post-1850 period. The lowermost sample (30 cm) is composed of taxa typical of mesotrophic conditions (e.g. *Aulacoseira subarctica*, *Asterionella formosa*, *Synedra tenera/nana, Tabellaria flocculosa*) but the appearance of *Stephanodiscus hantzschii*, a diatom associated with nutrient-rich waters and the rise in *Asterionella formosa* in the 20 cm sample signals enrichment of the lake. *Asterionella formosa* continues to occur in relatively high abundances in the upper part of the core but the upper two samples are characterised by an increase in *Fragilaria crotonensis* and *Diatoma elongatum*, indicating further ecological change. The relative abundance of *Stephanodiscus hantzschii* declines slightly towards the surface and conversely *Aulacoseira subarctica,* which had been abundant in the bottom sample, increases. Indeed, with the exception of relatively high amounts of *Diatoma elongatum*, the composition of the surface-sediment diatom assemblage exhibits some recovery to that seen in the lower section of the core. However, notably *Tabellaria flocculosa* and *Synedra tenera/nana* have not returned to the assemblage.

The species shifts are reflected in the squared chord distance dissimilarity scores (Figure 22). None of the scores exceed the critical value of 0.475 because the three common taxa, namely

Aulacoseira subarctica, *Achnanthes minutissima* and *Asterionella formosa* remain dominant components of the assemblage throughout the core. The highest dissimilarity score occurs between the bottom sample and the 5 cm sample (0.41) owing largely to the expansion of *Fragilaria crotonensis* and the arrival of *Diatoma elongatum*. The data-point for the bottom sample is located at a distance from the other samples in the core in the DCA biplot (Figure 35a) highlighting its dissimilarity. However, the close proximity of the surface sample to the 20 cm sample indicates the reversal of the diatom assemblage to a community similar to that observed in the lower part of the core. The general enrichment trend is reflected in the DI-TP reconstruction where values increase from ~30 µg l^{-1} in the bottom sample to ~60 µg l^{-1} in the middle part of the record. The DI-TP subsequently declines to 50 µg l^{-1} in the surface sample, indicating a slight recovery. The latter is somewhat higher than the current annual mean TP of the lake (28 µg l^{-1}) suggesting that the model over-estimates TP values for this site.

Broomlee Lough

The five samples from the Broomlee Lough core, BROL1, were diverse, containing a total of 139 taxa. A summary diagram of the common taxa, over 90% of which are non-planktonic, is shown in Figure 23. Broomlee Lough has experienced floristic change over the period represented by the core which is estimated to date back to only ~1960 on the basis of the SCP profile. The two lowermost samples (1960 & 1970 AD) are comprised of a diverse, non-planktonic diatom community typical of relatively nutrient-rich, alkaline waters, including *Achnanthes minutissima*, *Fragilaria pinnata*, *Amphora pediculus*, *Navicula jaernefeltii* and *Gomphonema angustum*. Many of these are epiphytic taxa, commonly found attached to plant surfaces especially in shallow, clearwater lakes. The 10 cm and 5 cm samples, dated to 1985 and 1995, respectively, see an expansion in the relative abundance of the benthic *Fragilaria* spp. (e.g. *F. construens* var. *venter*, *F. pinnata* and *F. brevistriata*), which are frequently observed growing *in situ* on sediment surfaces, at the expense of *Achnanthes minutissima* and a number of other typical epiphytic taxa that were observed in the 20 cm and 25 cm samples. *Navicula hungarica* and *Rhoicosphenia curvata*, taxa associated with nutrient-rich, alkaline conditions appear for the first time in the 10 cm sample. These shifts may signal a degree of nutrient enrichment and potential habitat loss as the benthic *Fragilaria* taxa replace those diatoms more frequently associated with plant substrates. Further changes are seen in the surface sample, most notably an increase in *Navicula minuscula* var. *muralis*, *Nitzschia palea* and *Cyclotella pseudostelligera*. The benthic *Fragilaria* spp. remain an important part of the assemblage but *Achnanthes minutissima* recovers to a relative abundance similar to that observed in the lowermost samples.

The species shifts are reflected in the squared chord distance dissimilarity scores (Figure 23). The dissimilarity scores between the bottom sample and the 10 cm and 5 cm samples both exceed the critical value of 0.475 (0.67) indicating significant compositional change. The slightly lower score for the surface sample can be explained by the recent increase in *Achnanthes minutissima*. The higher abundance of this taxon at the top of the core is also reflected in the DCA biplot (Figure 35) by the close proximity of the surface sample to the 20 cm sample. However, the data-point for the bottom sample is located at a distance from the other samples in the core highlighting that floristic change has occurred since 1960. The observed species shifts result in a gradual increase in DI-TP values from ~60 µg l^{-1} in the bottom sample to ~160 µg l^{-1} in the middle part of the record (1985 AD). The DI-TP subsequently declines to 77 µg l^{-1} in the surface sample, indicating a reduction in TP concentrations over the last two decades. The latter value is considerably higher than the current annual mean TP of the lake (18 µg l^{-1}) suggesting that the model over-estimates TP values for this site.

Cole Mere

The five samples from the Cole Mere core, SCM02E, contained a total of 73 taxa. A summary diagram of the common taxa is shown in Figure 24. Cole Mere has experienced floristic change over the period represented by the core; the main species shifts being seen in the planktonic forms. SCP analysis was not undertaken on this core and therefore a chronology has not been established. The lowermost sample was comprised of both non-planktonic, alkaline taxa (e.g. *Navicula submuralis*, *Navicula scutelloides*, *Amphora pediculus*, *Achnanthes lanceolata*) and planktonic forms typical of alkaline, relatively productive waters (e.g. *Stephanodiscus neoastraea*, *Cyclotella radiosa*, *Stephanodiscus parvus*). The 20 cm saw a marked decline in *Stephanodiscus neoastraea,* and the disappearance of *Cyclotella radiosa* along with a number of non-planktonic taxa. Conversely, planktonic species typically associated with early phases of enrichment expanded (e.g. *Aulacoseira granulata* and its variety a*ngustissima*, *Stephanodiscus parvus*). These floristic changes indicate a loss of habitats for the non-planktonic species, and the replacement of planktonic diatoms typically associated with intermediate nutrient concentrations with those more commonly observed in highly nutrient-rich lakes. However, the presence of *Stephanodiscus parvus* in the bottom-most sample suggests that the lake has been relatively nutrient-rich for the whole period represented by the core. The planktonic taxa continued to dominate the assemblages in the 10 cm and 5 cm samples with a further rise in *Stephanodiscus parvus* and an increase in *Fragilaria crotonensis* and *Asterionella formosa*. The surface sample was comprised of the same main taxa as the previous two samples but was characterised by higher abundance of *Cyclostephanos tholiformis* and *Aulacoseira islandica*, taxa commonly found in the plankton of nutrient-rich, alkaline waters.

The species shifts are reflected in the squared chord distance dissimilarity scores (Figure 24). The dissimilarity scores between the bottom sample and the mid-core samples are just below the critical value of 0.475. The higher score for the surface sample (0.635) can be explained by the recent increase in *Cyclostephanos tholiformis* and *Aulacoseira islandica*, taxa which were not observed in the bottom sample. The sample scores in the DCA biplot (Figure 35a) move from lower left to upper right reflecting the gradual compositional change in the sediment record. The early species shifts in the lower part of the core result in a slight increase in DI-TP values from ~110 µg l^{-1} in the bottom sample to ~130-140 µg l^{-1} in the middle part of the record. The DI-TP for the surface sample is 107 µg l^{-1}, indicating a small reduction in TP concentrations in recent times. The latter value is in good agreement with the current annual mean TP of the lake (118 µg l^{-1}) suggesting that the model provides reasonable estimates of TP for this site.

Crag Lough

The five samples from the Crag Lough core, CRAZ1, were diverse containing a total of 126 taxa. A summary diagram of the common taxa is shown in Figure 25. There have been moderate floristic changes over the period represented by the core which, according to the SCP profile, most likely represents a period of approximately 40 – 50 years. The assemblages were dominated by non-planktonic taxa typical of alkaline, shallow lakes throughout the sediment record. The most abundant taxa in the bottom sample are *Achnanthes minutissima*, *Fragilaria pinnata* and *Cocconeis placentula.* The bottom sample also contains a number of taxa that are not seen in such high relative abundances in the four upper samples, namely *Fragilaria capucina* var. *gracilis*, *Tabellaria flocculosa, Synedra acus, Fragilaria virescens* var. *exigua, Gomphonema pumilum* and *Fragilaria intermedia*. The three main species, *Achnanthes minutissima*, *Fragilaria pinnata* and *Cocconeis placentula,* continue to be important components of the assemblages in the central part of the core (20 and 10 cm samples) and a number of other non-planktonic taxa increase in relative abundance including *Amphora pediculus, Fragilaria elliptica, Achnanthes lanceolata, Navicula cryptocephala,* and *Fragilaria construens* var. *venter*. Based on the ecological preferences of the taxa, these species shifts appear to signal a slight rise in productivity. Further subtle changes are seen in the two upper samples as the planktonic taxon, *Stephanodiscus parvus*, expands slightly and small increases are observed in a number of the *Navicula* taxa (e.g. *N. menisculus, N. crytocephala, N. reichardtiana*). These changes most likely indicate further enrichment.

The modest floristic changes are reflected in the squared chord distance dissimilarity scores (Figure 25). The dissimilarity scores between the bottom sample and the three mid-core samples are all below the critical value of 0.475 and the score of 0.484 for the surface sample just exceeds the critical value. Similarly, the samples in the DCA biplot (Figure 35a) are all in relatively close proximity although the data point for the bottom sample is positioned to the left of the other core samples reflecting it's slightly different composition. The species shifts in the lower part of the core result in a slight increase in DI-TP values from ~70 µg l^{-1} in the bottom sample to ~80 µg l^{-1} in the 20 cm sample and a further increase to ~130 µg l^{-1} in the 10 cm sample, largely due to the expansion of the *Fragilaria* taxa at the expense of *Achnanthes minutissima*. The DI-TP values for the two upper samples remain high at ~100 µg l^{-1}. The latter value is considerably higher than the current annual mean TP of the lake (20 µg l^{-1}) suggesting that the model over-estimates TP values for this site.

The diatom assemblages of Crag Lough are similar to those of the neighbouring Broomlee Lough with the same common taxa in the sediment records of both sites (*Achnanthes minutissima, Fragilari pinnata, Fragilaria construens* var. *venter, Amphora pediculus*). The floristic similarity is shown by the close positioning of the sample scores for the two cores in the DCA biplot (Figure 35). The diatom assemblages of both lakes experience an increase in *Fragilaria* taxa and the arrival of a number of taxa indicative of more productive waters in the uppermost samples. Therefore, whilst both sites continue to be dominated by non-planktonic diatom taxa typical of moderate nutrient concentrations, reflecting clearwater and availability of plant substrates, there have been a number of notable ecological shifts that appear to indicate slight nutrient enrichment over the last three or four decades.

Derwent Water

The five samples from the Derwent Water core, DERW1, contained a total of 101 taxa. A summary diagram of the common taxa is shown in Figure 26. There was little floristic change in the period represented by the core, which is estimated by the SCP analysis to cover the period from ~1850 AD, with the exception of the surface sample which was markedly different from the assemblages in the four lower samples. The latter were relatively diverse and were co-dominated by *Achnanthes minutissima* and the planktonic diatom *Cyclotella comensis,* with *Brachysira vitrea* also relatively abundant. These taxa are typical of deep, oligotrophic, slightly acid to circumneutral waters and have been observed as the dominant diatoms in the reference samples of many lakes of this type in the UK (e.g. Bennion, 2004; Bennion *et al*., 2004). The 10 cm and 5 cm samples, dated to 1950 and 1978 respectively, contained slightly higher relative abundances of a few of the more “mesotrophic” taxa which may signal the start of enrichment. The surface sample, however, was notably different with higher percentages of *Asterionella formosa* and *Tabellaria flocculosa* than seen in the lower samples and the arrival of three taxa not previously recorded in the core, *Cocconeis placentula, Fragilaria brevistriata* and *Aulacoseira subarctica*. Consequently the relative abundances of *Achnanthes minutissima*, *Cyclotella comensis* and *Brachysira vitrea* declined. These shifts indicate a slight increase in the productivity of the lake as the expanding and new taxa are commonly associated with higher trophic status than those taxa in decline.

The relative stability of the diatom assemblages in the Derwent Water core is reflected in the low squared chord distance dissimilarity scores (Figure 26). The dissimilarity scores between the bottom sample and the three mid-core samples are well below the critical value of 0.475 and even that for the surface sample is only 0.426 owing to the continued presence of the same two co-dominant taxa throughout the core. Similarly, the samples in the DCA biplot (Figure 35a) are all in close proximity although the data points tend to move from left (bottom sample) to right (surface sample) reflecting some degree of compositional change, albeit it relatively low. The very subtle species shifts in the middle part of the core result in a slight increase in DI-TP values from ~7 µg l^{-1} in the bottom two samples to ~9 µg l^{-1} in the 10 cm and 5 cm samples. There is a further increase to 11 µg l^{-1} in the surface sample, due to the expansion of the taxa commonly associated with more productive waters. The latter value is lower than the current annual mean TP of the lake (27 µg l^{-1}) suggesting that the large lakes model under-estimates TP values for this site.

Dozmary Pool

The five samples from the Dozmary Pool core, EN17A, contained a total of 66 taxa. A summary diagram of the common taxa is shown in Figure 27. Dozmary Pool has experienced major floristic change over the period represented by the core, which is estimated by the SCP data to extend back to before 1850 AD. The two lower samples (dated to pre-1850 and ~1850) were comprised of three predominant taxa, *Aulacoseira perglabra, Eunotia incisa* and *Frustulia rhomboides*, diatoms which are associated with oligotrophic, relatively acid conditions. The first change occurred at the 10 cm sample, dated to ~1940, when *Frustulia rhomboides* increased at the expense of *Eunotia* *incisa*. However, a more notable change was observed at the 5 cm sample, dated to ~1960, when the abundance of *Frustulia rhomboides* decreased from ~40% to less than 5% and a number of new taxa arrived, namely *Fragilaria virescens* var. *exigua*, *Fragilaria elliptica, Cymbella hebridica, Fragilaria constricta, Tabellaria flocculosa, Eunotia intermedia* and *Gomphonema parvulum*. These shifts most likely indicate an increase in lake productivity and possibly alkalinity as many of the new arrivals favour less acid conditions with moderate nutrient concentrations. A further floristic change was seen in the surface sample with the decline of *Aulacoseira perglabra* and the arrival of more new taxa including *Navicula atomus, Navicula cocconeiformis, Achnanthes minutissima, Nitzschia gracilis*, and *Amphora libyca*. Thus, the surface sample has a very different diatom assemblage from that of the two lowermost core samples being comprised of taxa typically associated with relatively nutrient-rich, shallow lakes rather than the acid, nutrient-poor flora of the bottom assemblages.

The species shifts are reflected in the squared chord distance dissimilarity scores (Figure 27). The dissimilarity scores between the bottom sample and the 15 cm and 10 cm samples are very low but those for the two upper samples are well in excess of the critical value with a very high value of 1.26 for the surface sample. The sample scores in the DCA biplot (Figure 35a) move from left to right reflecting the compositional change in the sediment record and the large distances between data points reflect the large degree of change. The early species shifts in the core do not result in any change in DI-TP with values of 1-2 µg l^{-1} for the lower four samples (pre-1960). The DI-TP for the surface sample, however, is markedly higher with a value of 27 µg l^{-1} and this is in good agreement with the current annual mean TP of the lake (37 µg l^{-1}) suggesting that the model provides reasonable estimates of TP for this site. The data indicate that Dozmary Pool has experienced considerable enrichment over the last 40 years although higher analytical resolution is required to estimate the rate of change and to explore the timing and nature of the species shifts over this period in more detail.

Frensham Little Pond

The five samples from the Frensham Little Pond core, PFRE1, contained a total of 92 taxa. A summary diagram of the common taxa is shown in Figure 28. The diatom assemblages are dominated by the same three non-planktonic *Fragilaria* taxa (*F. brevistriata, F. pinnata* and *F. construens*) throughout the period represented by the sediment core. Unfortunately the SCP profile could not be interpreted and the presence of SCPs at every sampled depth suggests that the whole core represents the post-1850 period. These *Fragilaria* taxa are frequently observed in high abundances in shallow, alkaline lakes and can grow attached to plants, stones or typically sediment surfaces where light penetration is sufficient (Bennion *et al*., 2001). A number of floristic changes were evident, however, towards the top of the core (from 5 cm upwards) when *Aulacoseira ambigua* increased and two other planktonic taxa, *Fragilaria crotonensis* and *Aulacoseira granulata*, appeared for the first time. The increase in the planktonic component of the diatom community suggests that there have been habitat shifts with a move away from clearwater conditions which favour the attached forms. This may have been brought about by higher nutrient concentrations.

The relative stability of the diatom assemblages in the Frensham Little Pond core is reflected in the low squared chord distance dissimilarity scores (Figure 28). The dissimilarity scores between the bottom sample and the three mid-core samples are well below the critical value of 0.475 and even that for the surface sample is only 0.414 owing to the continued presence of the same three *Fragilaria* taxa throughout the core. The samples in the DCA biplot (Figure 35a) are in relatively close proximity although the data points for the two uppermost samples are at some distance from the three lower core samples, reflecting the recent compositional change. There is no clear trend in the DI-TP reconstruction with high values of ~140-180 µg l^{-1} throughout the core. The modelled values are considerably higher than the current annual mean TP of the lake (65 µg l^{-1}) suggesting that the model over-estimates TP values for this site.

Mere Mere

The five samples from the Mere Mere core, SCM37B, contained a total of 97 taxa. A summary diagram of the common taxa is shown in Figure 29. There has been only modest floristic change over the period of the core. The SCP profile could not be interpreted and the presence of SCPs at every sampled depth suggests that the whole core represents the post-1850 period. Indeed the lack of trend and the erratic SCP concentrations imply either a changing sediment accumulation rate or a disturbed sediment record. The two co-dominant taxa, occurring in approximately equal relative abundances, throughout the core were *Aulacoseira ambigua* and *Asterionella formosa*. These are planktonic forms, commonly associated with relatively deep, circumneutral to alkaline lakes of moderate nutrient concentrations. In the two lowermost samples the remainder of the assemblage was comprised of a diverse mix of planktonic (e.g. *Cyclotella radiosa, Aulacoseira granulata*) and non-planktonic (e.g. *Cocconeis placentula, Fragilaria construens* var. *venter*, *Achnanthes minutissima*) taxa generally found in alkaline, mesotrophic waters. The most notable change occurred at the 10 cm sample when *Aulacoseira subarctica* markedly increased in relative abundance from ~2% below this level in the core to ~15% and furthermore to ~20% in the 5 cm sample. Subsequently, the abundance of this taxon declined to 10% at the sediment surface. Other changes include the higher relative abundance of *Aulacoseira granulata* in the three uppermost samples, and the appearance of *Stephanodiscus parvus* albeit in small amounts.

The relatively small floristic changes are reflected in the low squared chord distance dissimilarity scores (Figure 29). The dissimilarity scores between the bottom sample and all four upper samples are below the critical value of 0.475. Similarly, the samples in the DCA biplot (Figure 35a) are all in relatively close proximity although the data points for the 10 cm and 5 cm samples are the most distant from the bottom sample reflecting the higher amounts of *Aulacoseira subarctica* in this mid-core section. There is no clear trend in the DI-TP reconstruction with intermediate TP values of ~50-60 µg l^{-1} throughout the core. The very slight decrease in DI-TP for the 10 cm and 5 cm samples arises largely because of the high abundance of *Aulacoseira subarctica* which has a lower TP optimum in the training set than *Asterionella formosa* and *Aulacoseira ambigua.* The DI-TP for the surface sample is 58 µg l^{-1} and is in good agreement with the current annual mean TP of the lake (53 µg l^{-1}). It is difficult to interpret the diatom changes in Mere Mere in terms of water quality shifts but the data do suggest that the lake has been relatively nutrient-rich for the whole period represented by the sediment core.

Rostherne Mere

The five samples from the Rostherne Mere core, SCM39B, contained a total of 85 taxa. A summary diagram of the common taxa is shown in Figure 30. There were major floristic changes over the time period represented by the core but SCP analysis was not undertaken and therefore a chronology was not established. The assemblages were dominated by planktonic forms, typical of nutrient-rich, alkaline lakes that are deep enough to stratify and support a diverse planktonic community, including *Asterionella formosa, Fragilaria crotonensis, Stephanodiscus parvus, Stephanodiscus neoastraea, Stephanodiscus hantzschii, Aulacoseira granulata* var. *angustissima, Aulacoseira subarctica*, and *Cyclostephanos dubius*. The relative abundances of these taxa fluctuated markedly from one sample to another: the bottom sample was comprised of roughly equal percentages of *Asterionella formosa, Fragilaria crotonensis, Stephanodiscus parvus, Stephanodiscus neoastraea,* and *Aulacoseira granulata* var. *angustissima;* the 20 cm sample was dominated by *Asterionella formosa* with high amounts of *Stephanodiscus parvus* and *Stephanodiscus hantzschii*; the 10 cm sample was dominated by *Aulacoseira granulata* var. *angustissima* with high amounts of *Aulacoseira subarctica;* the 5 cm sample was composed of roughly equal percentages of *Stephanodiscus neoastraea, Aulacoseira granulata* var. *angustissima, Asterionella formosa* and *Cycostephanos dubius;* and the surface sample was dominated by *Asterionella formosa* with a reasonably high amount of *Stephanodiscus hantzschii.*

The shifts in the planktonic taxa are reflected in the squared chord distance dissimilarity scores (Figure 30). The dissimilarity scores between the bottom sample and all of the four upper core samples are high with all but the 5 cm sample exceeding the critical value of 0.475. Similarly, the relatively large distances between data points in the DCA biplot (Figure 35a) reflect the large amount of compositional change in the sediment record. There is no clear trend in the DI-TP reconstruction with high TP values of ~100-140 µg l^{-1} throughout the core. The DI-TP for the surface sample is 136 µg l^{-1} and is in good agreement with the current annual mean TP of the lake (144 µg l^{-1}). It is difficult to interpret the floristic changes in Rostherne Mere in terms of water quality shifts but the data do suggest that the lake has been relatively nutrient-rich for the whole period represented by the sediment core. A higher analytical resolution is required to explore the timing and nature of the species shifts in more detail.

Tabley Mere

The five samples from the Tabley Mere core, SCM40B, contained a total of 79 taxa. A summary diagram of the common taxa is shown in Figure 31. There was only very subtle floristic change over the period represented by the core. Unfortunately the SCP profile could not be interpreted and the presence of SCPs at every sampled depth suggests that the whole core represents the post-1850 period. The assemblages were comprised of the same main taxa throughout the sediment record, namely three non-planktonic *Fragilaria* taxa (*F. brevistriata, F. pinnata* and *F. construens* var. *venter*), *Cocconeis placentula* (typically found attached to plant surfaces) and two small centric, planktonic taxa, *Stephanodiscus parvus* and *Stephanodiscus hantzschii*. The three *Fragilaria* taxa were present in roughly equal percentages in all five samples analysed, constituting ~40% of the total assemblage. However, above the 10 cm sample *Stephanodiscus hantzschii* increased slightly at the expense of *Stephanodiscus parvus* and two other planktonic taxa, *Cyclotella atomus* and *Cyclostephanos invistitatus,* both commonly associated with highly nutrient-rich waters, increased in importance. *Cocconeis placentula* concomitantly declined. These changes suggest slight enrichment of the lake in recent times.

The relatively small floristic changes are reflected in the low squared chord distance dissimilarity scores (Figure 31). The dissimilarity scores between the bottom sample and all four upper samples are well below the critical value of 0.475. Similarly, the samples in the DCA biplot (Figure 35a) are all in relatively close proximity reflecting the dominance of the same major taxa throughout the sediment record. There is no clear trend in the DI-TP reconstruction with very high TP values of ~210-250 µg l^{-1} throughout the core. The DI-TP for the surface sample is 228 µg l^{-1} and is in reasonable agreement with the current annual mean TP of the lake (327 µg l^{-1}) although it does under-estimate. It is difficult to interpret the diatom changes in Tabley Mere in terms of water quality shifts. Nevertheless the data suggest that the lake has been highly nutrient-rich for the whole period represented by the sediment core and has experienced slight ecological change in recent times possibly in response to nutrient enrichment.

Tatton Mere

The five samples from the Tatton Mere core, SCM41B, contained a total of 88 taxa. A summary diagram of the common taxa is shown in Figure 32. There was only very subtle floristic change over the period represented by the core with the assemblages being comprised of the same major taxa throughout the sediment record. Unfortunately the SCP profile could not be interpreted and the presence of SCPs at every sampled depth suggests that the whole core represents the post-1850 period. Indeed the peak SCP concentration has not been attained at the bottom of the core, suggesting that the entire profile represents the post-1970 period, but this is highly speculative. *Stephanodiscus parvus* was the dominant taxon throughout the core and other important planktonic taxa included *Stephanodiscus hantzschii*, *Aulacoseira ambigua* and *Asterionella formosa*. The benthic *Fragilaria* taxa were also present throughout, constituting approximately 15-20% of the whole assemblage. The most noteworthy shifts were the decrease in *Stephanodiscus hantzschii,* a diatom typically associated with highly nutrient-rich waters, above the 20 cm sample, and concomitant increases in *Asterionella formosa,* a planktonic diatom commonly found in lakes with intermediate nutrient concentrations, and the benthic *Fragilaria* spp. These changes suggest a decrease in lake productivity in recent times.

The relatively small floristic changes are reflected in the low squared chord distance dissimilarity scores (Figure 32). The dissimilarity scores between the bottom sample and all four upper samples are below the critical value of 0.475. In contrast to the other sites in this study, the samples in the

DCA biplot (Figure 35a) generally track from upper right to lower left of the plot as they move from core bottom towards the core top. This reflects the decline in taxa associated with strongly nutrient conditions. There is a general downward trend in the DI-TP reconstruction with high TP values of ~140 µg l^{-1} at the bottom of the core, decreasing gradually to 98 µg l^{-1} at the surface sample. The latter is in good agreement with the current annual mean TP of the lake (105 µg l^{-1}). The data, therefore, suggest that the lake has experienced slight ecological change in recent times, most likely in response to a decline in nutrient concentrations.

The Loe

The five samples from The Loe core, TLOE1, contained a total of 83 taxa. A summary diagram of the common taxa is shown in Figure 33. The Loe has experienced moderate floristic change over the period represented by the core. Unfortunately the SCP profile could not be interpreted and the presence of SCPs at every sampled depth suggests that the whole core represents the post-1850 period. Two planktonic taxa, *Aulacoseira granulata* var. *angustissima* and *Asterionella formosa,* were present in relatively constant abundances throughout the core. However, shifts were seen in some of the other major taxa. The two lowermost samples were comprised of a diverse range of non-planktonic, circumneutral to alkaline taxa including *Achnanthes minutissima*, *Amphora veneta*, *Navicula gregaria* and *Cocconeis placentula*, as well as planktonic forms typical of alkaline, relatively productive waters, namely *Aulacoseira granulata* var. *angustissima*, *Asterionella formosa*, *Fragilaria crotonensis, Stephanodiscus parvus* and *Cyclotella meneghiniana*.. From the 10 cm sample upwards, there was a marked decline in the non-planktonic taxa with a notable decrease in *Achnanthes minutissima*. Conversely, the planktonic species typically associated with enrichment expanded, particularly *Fragilaria crotonensis, Stephanodiscus parvus* and *Cyclotella meneghiniana*. These floristic changes indicate a loss of habitats for the non-planktonic species and their replacement by a plankton dominated diatom community typical of nutrient-rich lakes.

The species shifts are reflected in the squared chord distance dissimilarity scores (Figure 33) whereby the score between the bottom sample and the 20 cm sample is lower than that between the bottom sample and the three upper samples. Nevertheless the continued presence of the same set of taxa throughout the sediment record resulted in dissimilarity scores below the critical value of 0.475. The sample score for the bottom sample is positioned at a distance from the other core samples in the DCA biplot (Figure 35a) and samples move in the general direction from left to right reflecting the gradual compositional change towards taxa associated with nutrient-rich waters. The diatom shifts result in an increase in DI-TP values from ~90 µg l^{-1} in the bottom sample to ~126 µg l^{-1} in the surface sample, suggesting that The Loe has experienced enrichment in recent times. The latter value is in reasonably good agreement with the current annual mean TP of the lake (93 µg l^{-1}) although the model does appear to slightly overestimate the measured TP concentration.

White Mere

The five samples from the White Mere core, SCM09C, contained a total of 88 taxa. A summary diagram of the common taxa is shown in Figure 34. There were major floristic changes over the time period represented by the core but SCP analysis was not undertaken and therefore a chronology was not established. The lowermost sample is relatively diverse and is comprised of both non-planktonic (e.g. *Fragilaria pinnata, Achnanthes minutissima, Navicula vitabunda, Amphora pediculus* and *Cocconeis placentula*) and planktonic taxa (e.g. *Stephanodiscus parvus, Aulacoseira granulata* and *Aulacoseira granulata* var. *angustissima*) typical of alkaline, relatively nutrient-rich lakes. The subsequent sample (20 cm) sees a marked decline in the abundance of the non-planktonic diatoms and a considerable increase in *Stephanodiscus parvus* from 15 to 40%. A number of other planktonic taxa appear in the 20 cm sample including *Stephanodiscus hantzschii*, *Aulacoseira ambigua* and *Asterionella formosa*. The increase in planktonic forms at the expense of the non-planktonic ones indicates a shift in habitat availability with loss of substrates for the epiphytic and epipelic taxa, possibly associated with deterioration in the light climate. The diatom changes suggest that conditions became more favourable for the growth of the plankton. Many of the non-planktonic taxa that declined between the bottom and the 20 cm sample do not appear in the upper core at all. However, further changes in the plankton occur above the 20 cm sample with a decrease in *Stephanodiscus parvus* back to ~20%, expansion of *Aulacoseira granulata* and *Asterionella formosa* and the appearance of three other species, *Cyclostephanos invisitatus* and *Cyclostephanos tholiformis* in relatively small amounts, and *Aulacoseira islandica* with relative abundances of ~10%. The expansion of *Asterionella formosa* and the arrival of *Aulacoseira islandica* suggests that lake productivity may have declined in recent times as these are taxa commonly associated with waters of intermediate rather than high nutrient levels. However, the simultaneous appearance of *Cyclostephanos invisitatus* and *Cyclostephanos tholiformis,* both taxa typically found in strongly nutrient-rich lakes, seems to contradict this suggestion.

The diatom shifts are reflected in the squared chord distance dissimilarity scores (Figure 34). The dissimilarity scores between the bottom sample and the three upper core samples are high with all exceeding the critical value of 0.475. Similarly, the relatively large distances between data points in the DCA biplot (Figure 35a) reflect the large amount of compositional change in the sediment record. As for many of the study sites, the direction of change is from the lower left to the upper right of the plot as the assemblages become comprised of higher percentages of planktonic taxa typical of nutrient-rich waters. The DI-TP reconstruction infers a decline in TP concentrations with a high TP value of ~180 µg l^{-1} at the bottom of the core, decreasing gradually to ~122 µg l^{-1} at the surface. The latter considerably under-estimates the extremely high current annual mean TP of the lake (477 µg l^{-1}) and suggests that the model may under-estimate values throughout the White Mere core. The lower TP values in the upper core are due to the higher relative amounts of *Asterionella formosa* and *Aulacoseira islandica* which have lower TP optima in the training set than *Stephanodiscus parvus*. That said, it is surprising that the DI-TP results do not indicate an increase in TP between the bottom and 20 cm sample as *Stephanodiscus parvus* expands*.* The high DI-TP at the base of the core is most likely due largely to the high abundance of *Fragilaria pinnata* as this taxon has a very high TP optimum in the training set. The non-planktonic *Fragilaria* taxa are not especially useful indicators of trophic status and they have been reported to create problems with diatom-P transfer functions in a number of studies (e.g. Bennion *et al*., 2001; Sayer, 2001). In summary, it is difficult to interpret the floristic changes in White Mere in terms of water quality shifts as an interpretation based on ecological preferences of the taxa appears to be at odds with that inferred by the transfer function. Nonetheless, the data suggest that the lake has been relatively nutrient-rich for the whole period represented by the sediment core but it has undergone ecological change within that time. The most likely explanation for the observed changes is a period of enrichment between the 35 and 20 cm sample followed by a more recent phase of slightly reduced nutrient concentrations.

Figure 22 Summary diagram of diatom changes (% relative abundance), squared chord distance dissimilarity scores and diatom-inferred total phosphorus (DI-TP µg l^{-1}) in the Blelham Tarn core, BLEL1

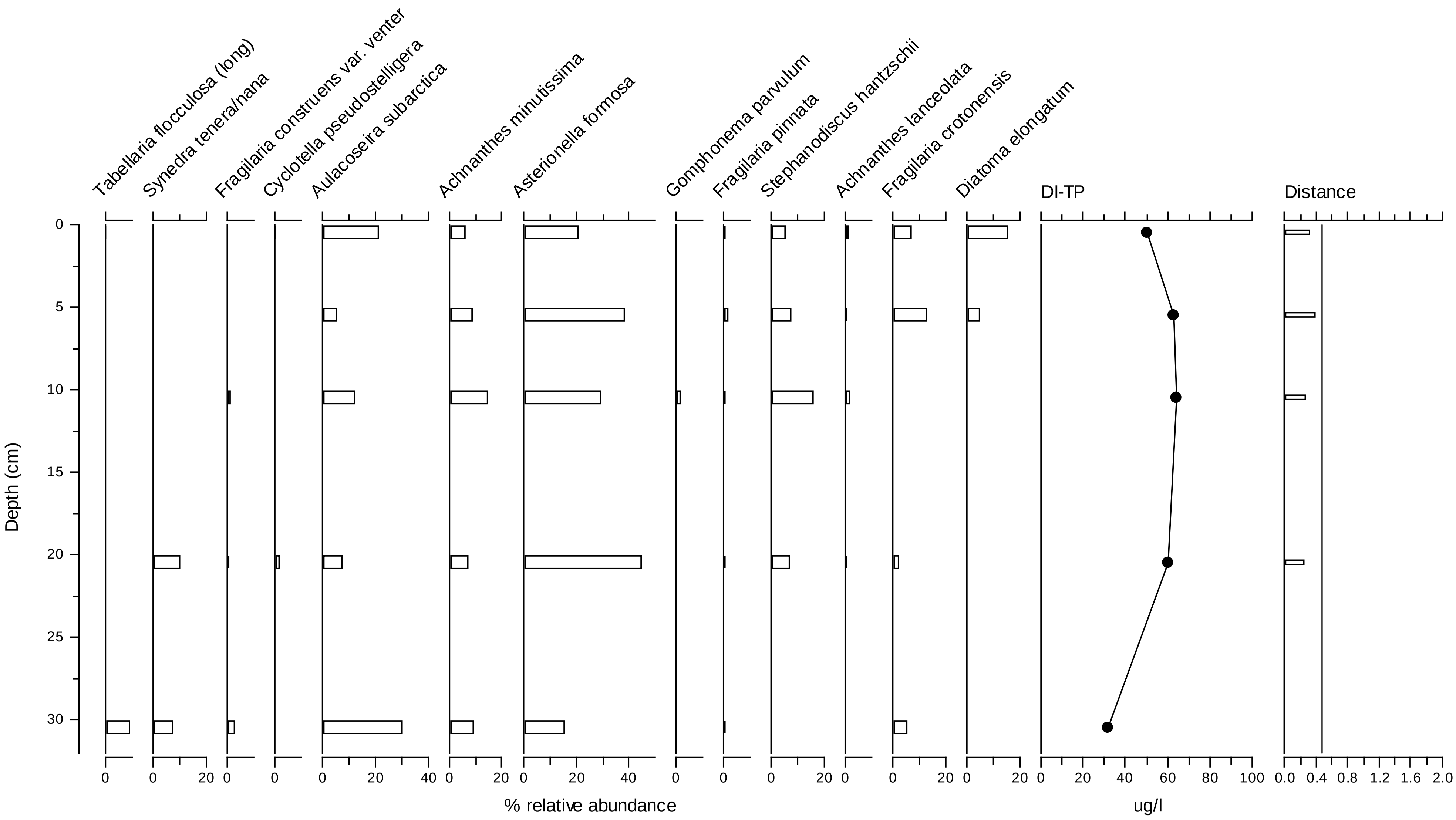


Figure 23 Summary diagram of diatom changes (% relative abundance), squared chord distance dissimilarity scores and diatom-inferred total phosphorus (DI-TP µg l^{-1}) in the Broomlee Lough core, BROL1

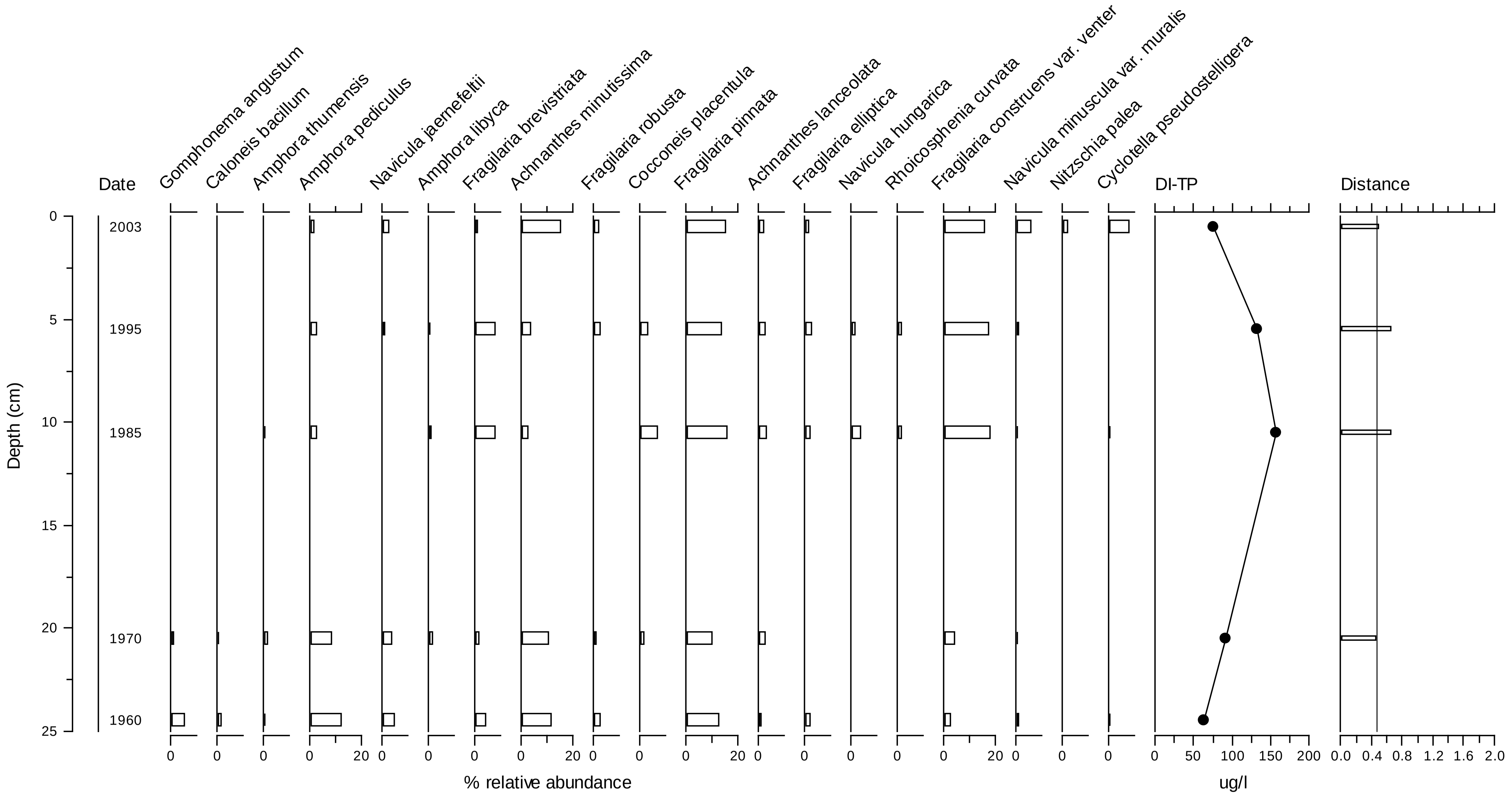


Figure 24 Summary diagram of diatom changes (% relative abundance), squared chord distance dissimilarity scores and diatom-inferred total phosphorus (DI-TP μg l^{-1}) in the Cole Mere core, SCM02E

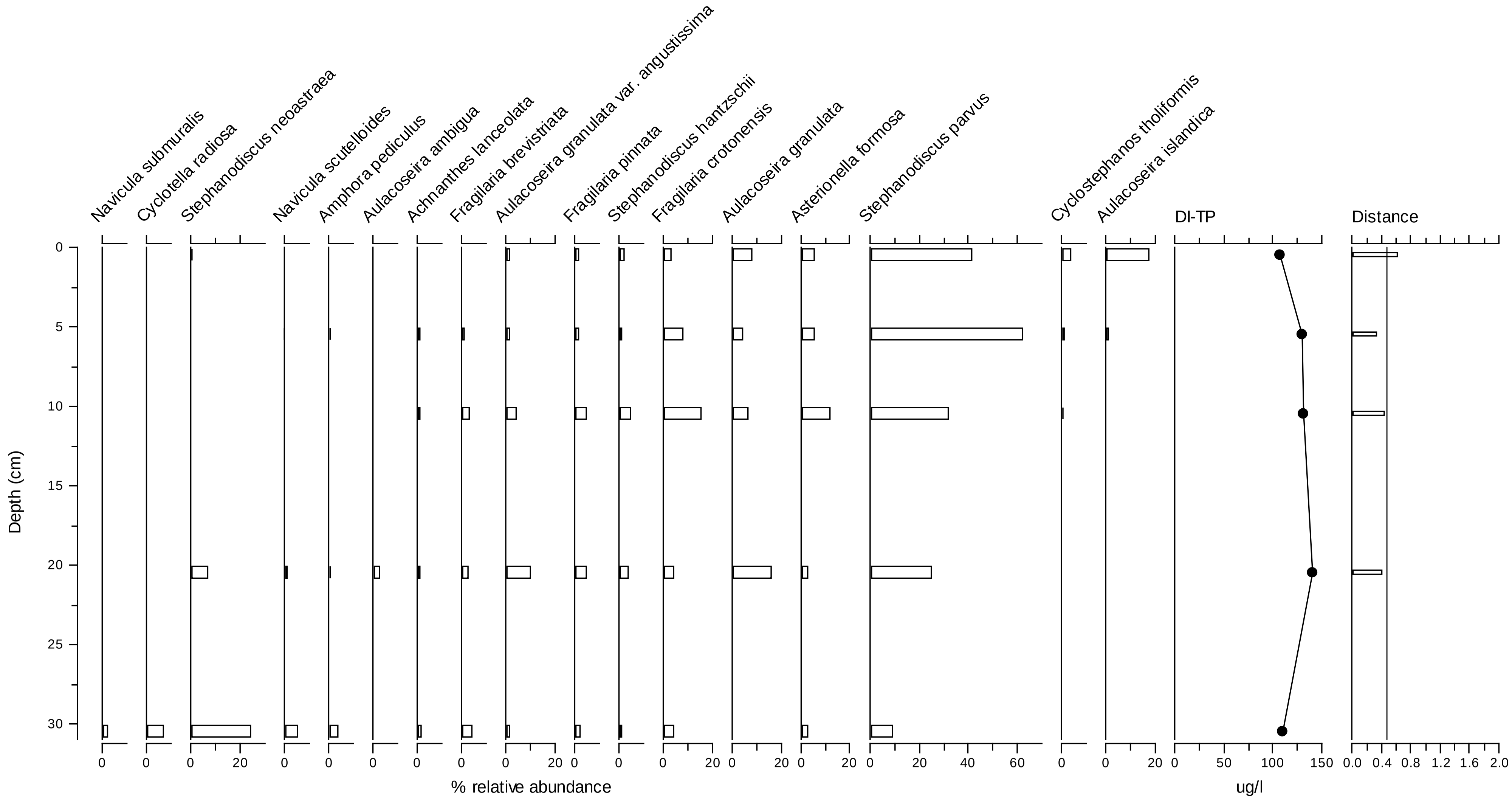


Figure 25 Summary diagram of diatom changes (% relative abundance), squared chord distance dissimilarity scores and diatom-inferred total phosphorus (DI-TP µg l^{-1}) in the Crag Lough core, CRAZ1

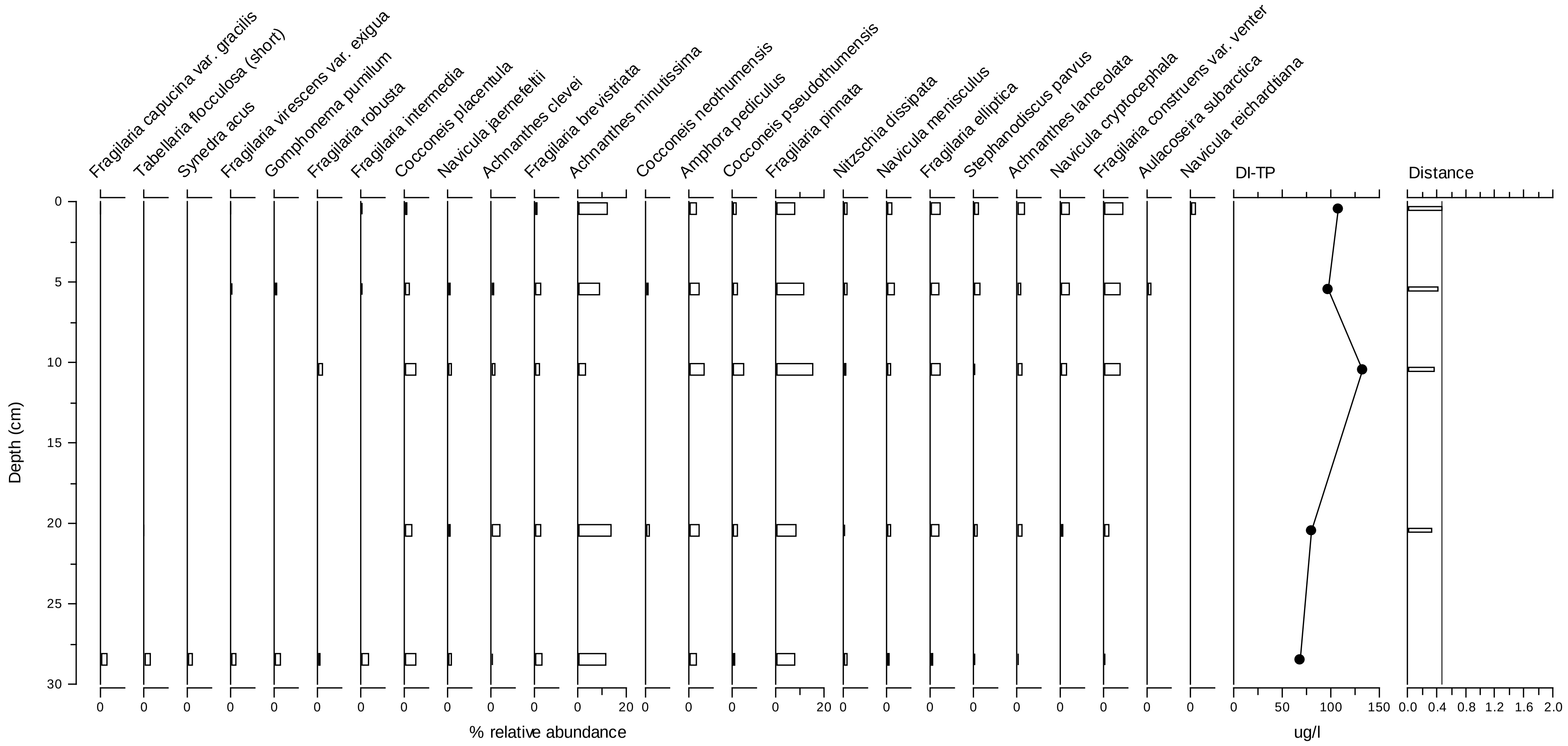


Figure 26 Summary diagram of diatom changes (% relative abundance), squared chord distance dissimilarity scores and diatom-inferred total phosphorus (DI-TP µg l^{-1}) in the Derwent Water core, DERW1

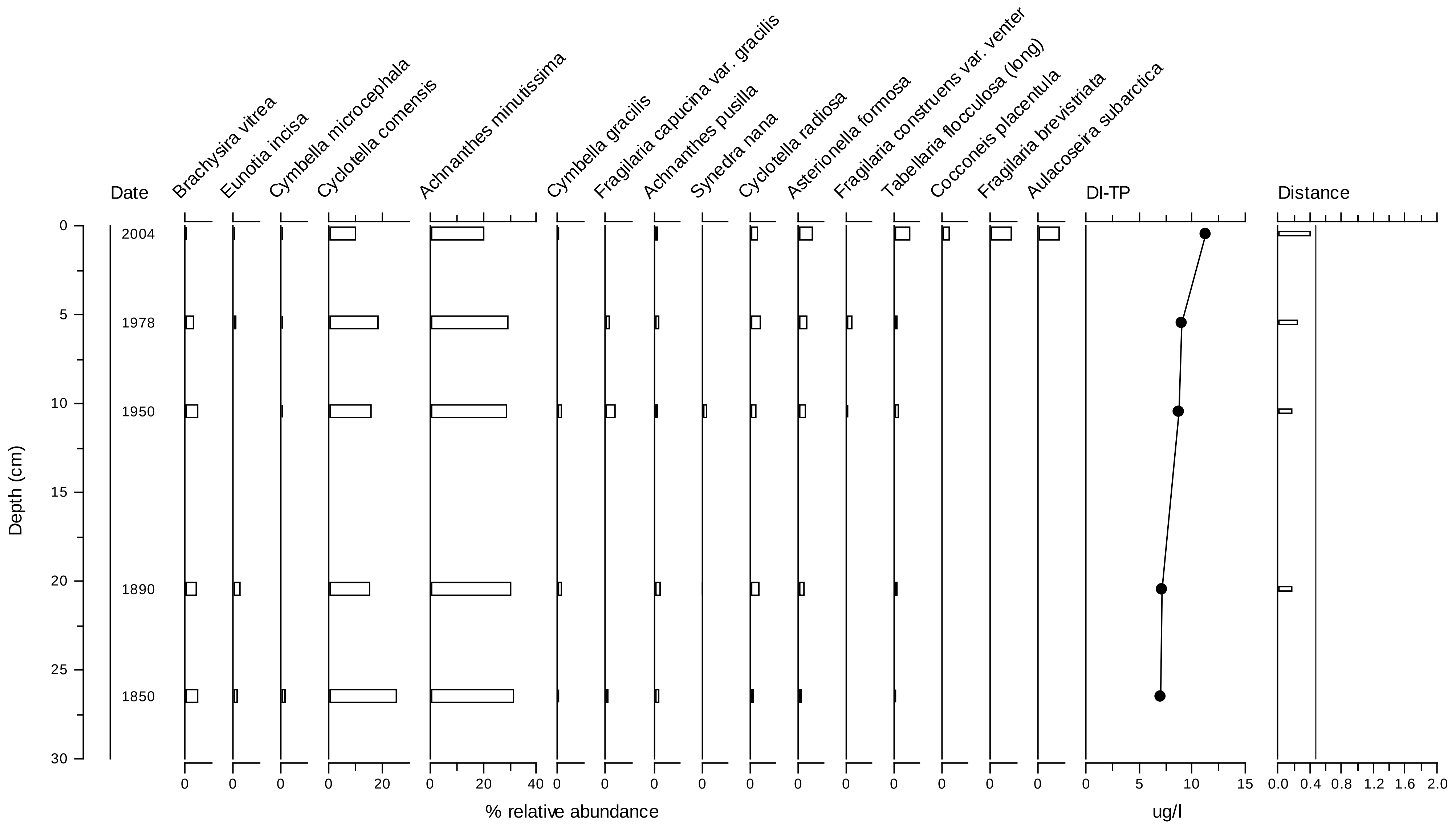


Figure 27 Summary diagram of diatom changes (% relative abundance), squared chord distance dissimilarity scores and diatom-inferred total phosphorus (DI-TP µg l^{-1}) in the Dozmary Pool core, EN17A

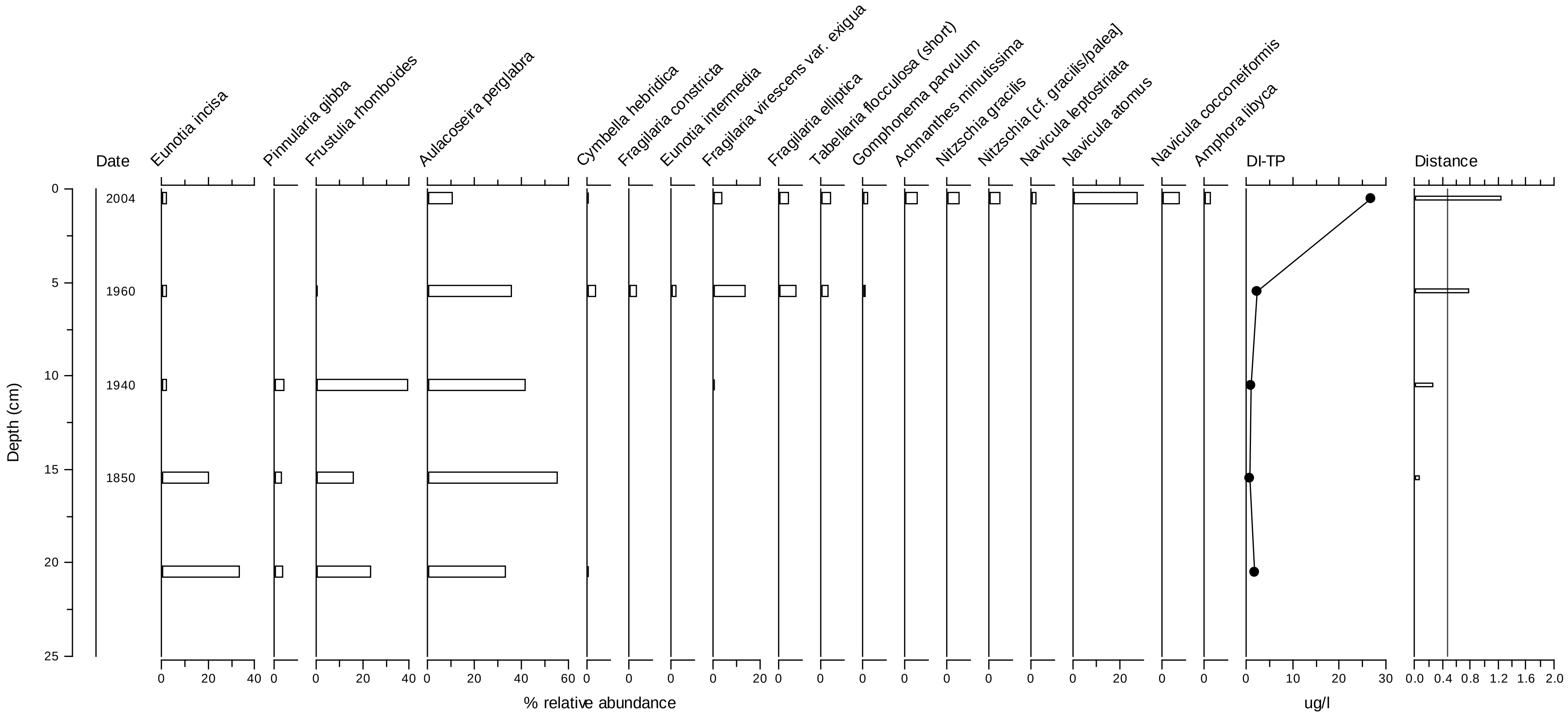


Figure 28 Summary diagram of diatom changes (% relative abundance), squared chord distance dissimilarity scores and diatom-inferred total phosphorus (DI-TP µg l^{-1}) in the Frensham Little Pond core, PFRE1

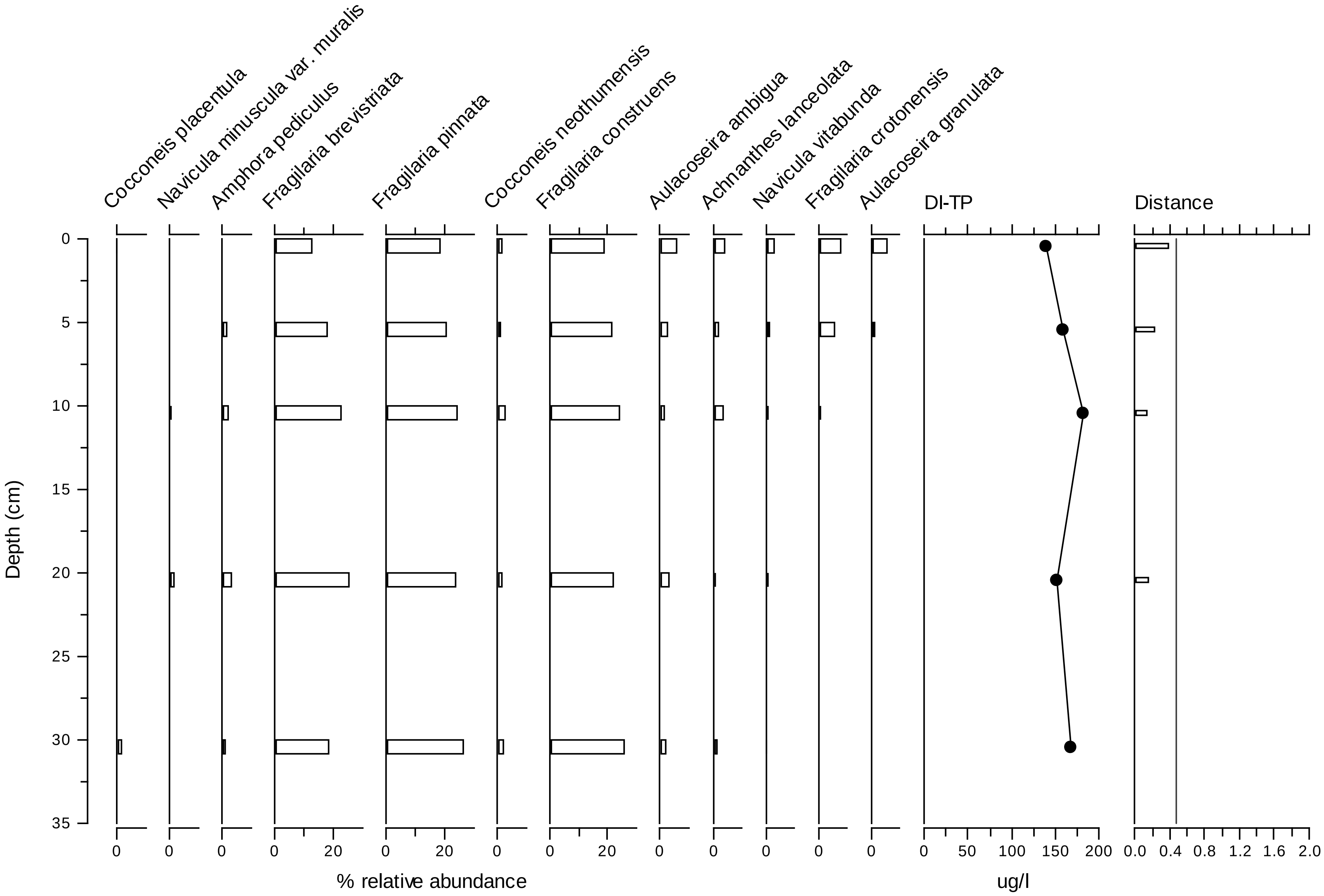


Figure 29 Summary diagram of diatom changes (% relative abundance), squared chord distance dissimilarity scores and diatom-inferred total phosphorus (DI-TP µg l^{-1}) in the Mere Mere core, SCM37B

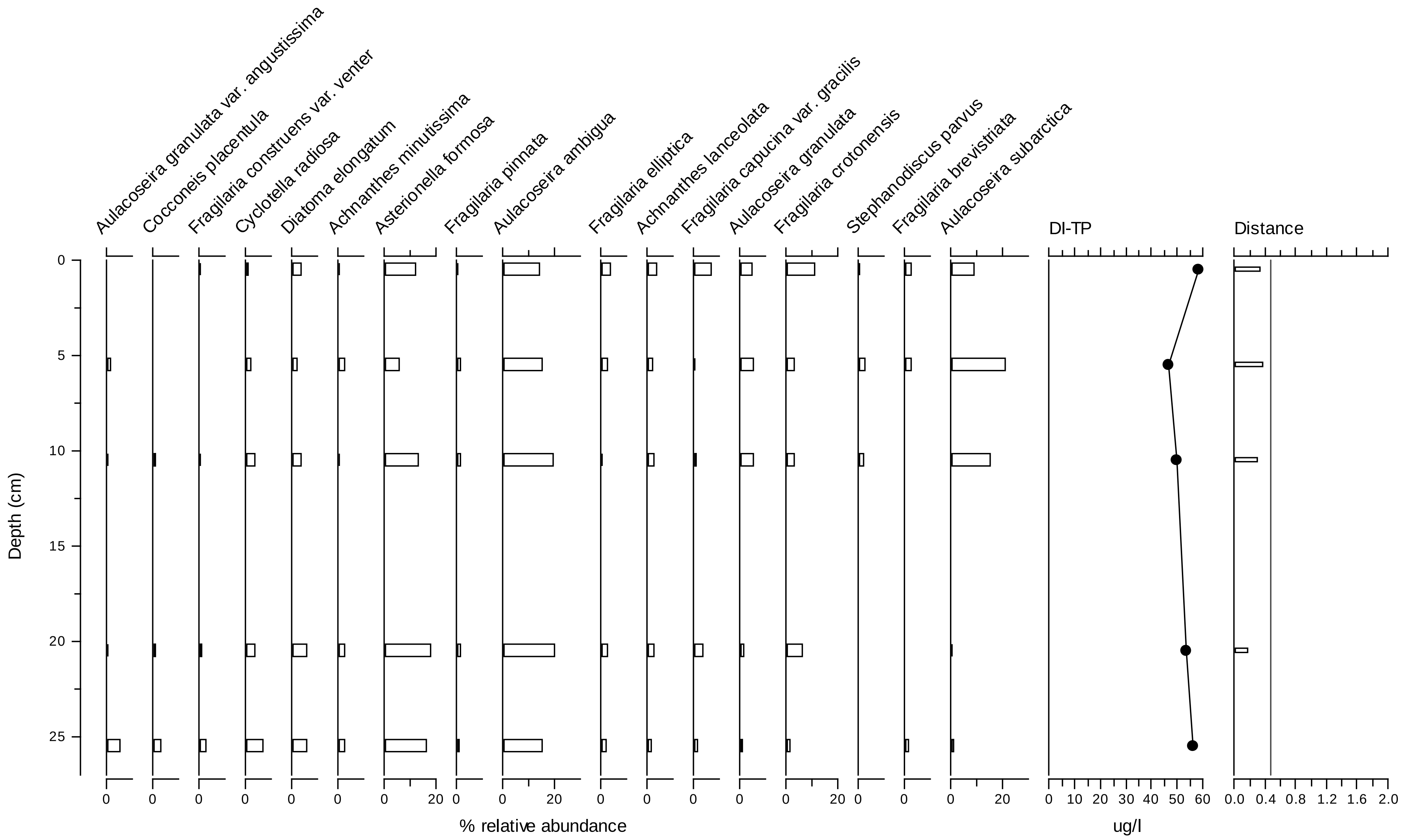


Figure 30 Summary diagram of diatom changes (% relative abundance), squared chord distance dissimilarity scores and diatom-inferred total phosphorus (DI-TP µg l^{-1}) in the Rostherne Mere core, SCM39B

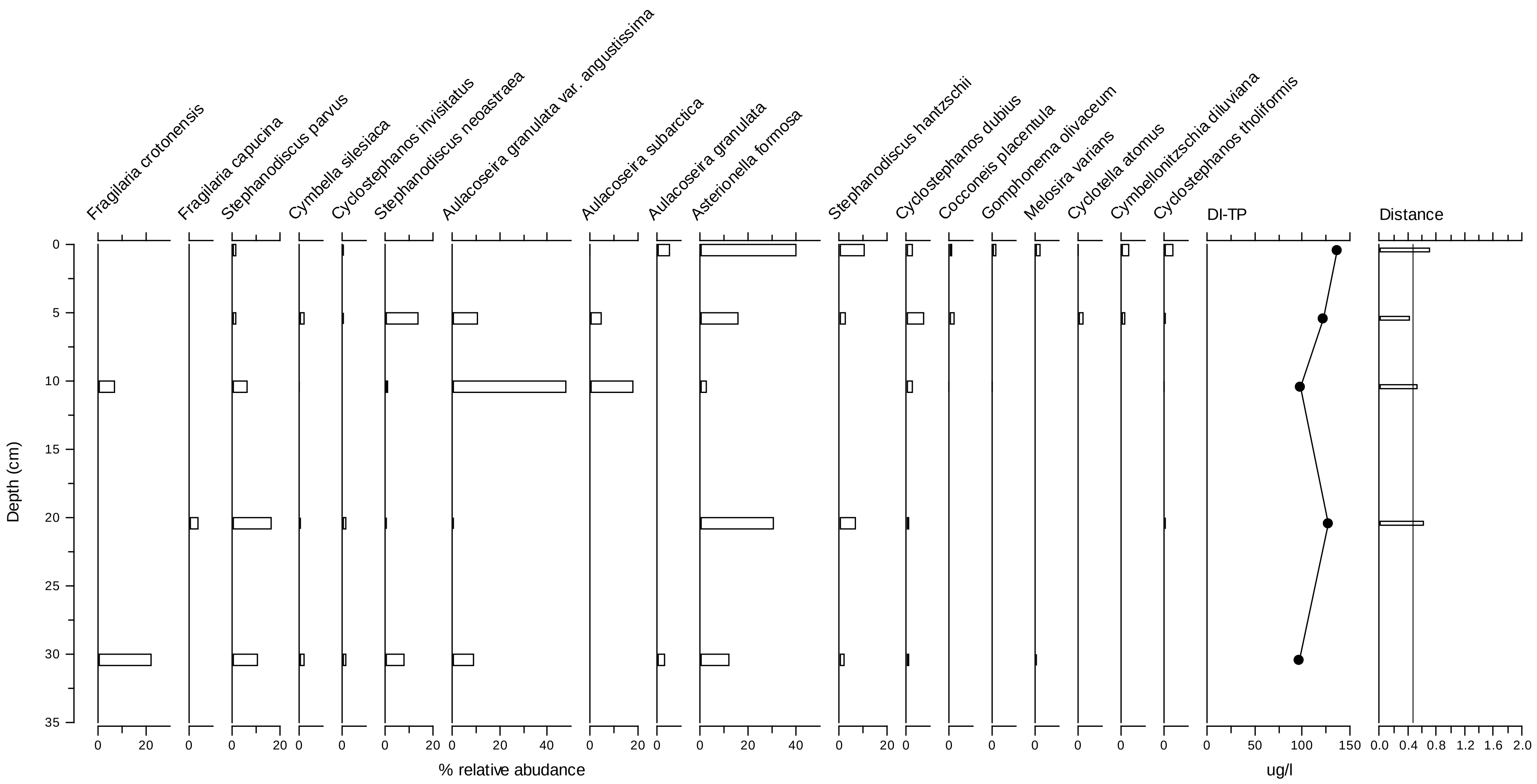


Figure 31 Summary diagram of diatom changes (% relative abundance), squared chord distance dissimilarity scores and diatom-inferred total phosphorus (DI-TP µg l^{-1}) in the Tabley Mere core, SCM40B

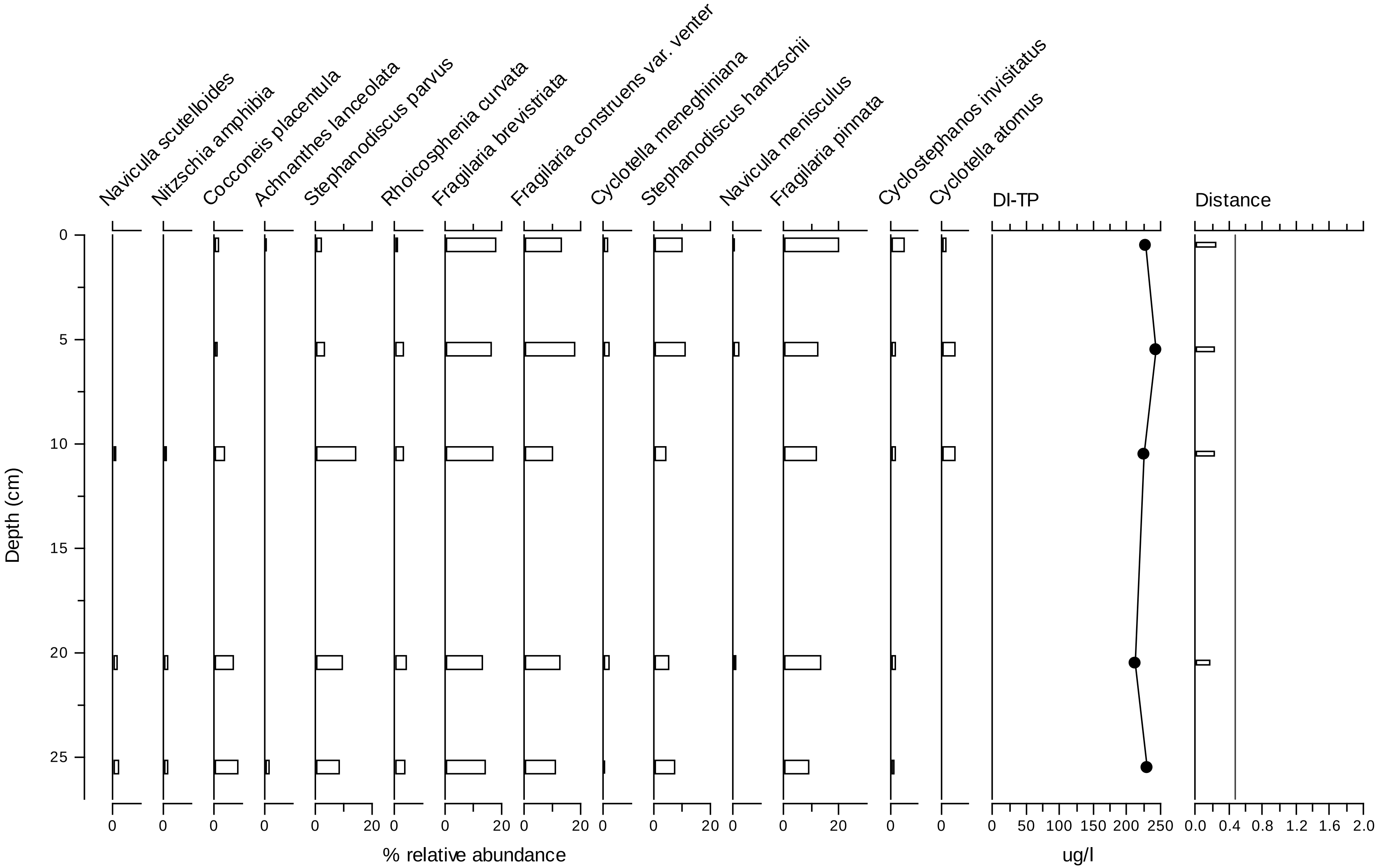


Figure 32 Summary diagram of diatom changes (% relative abundance), squared chord distance dissimilarity scores and diatom-inferred total phosphorus (DI-TP µg l^{-1}) in the Tatton Mere core, SCM41B

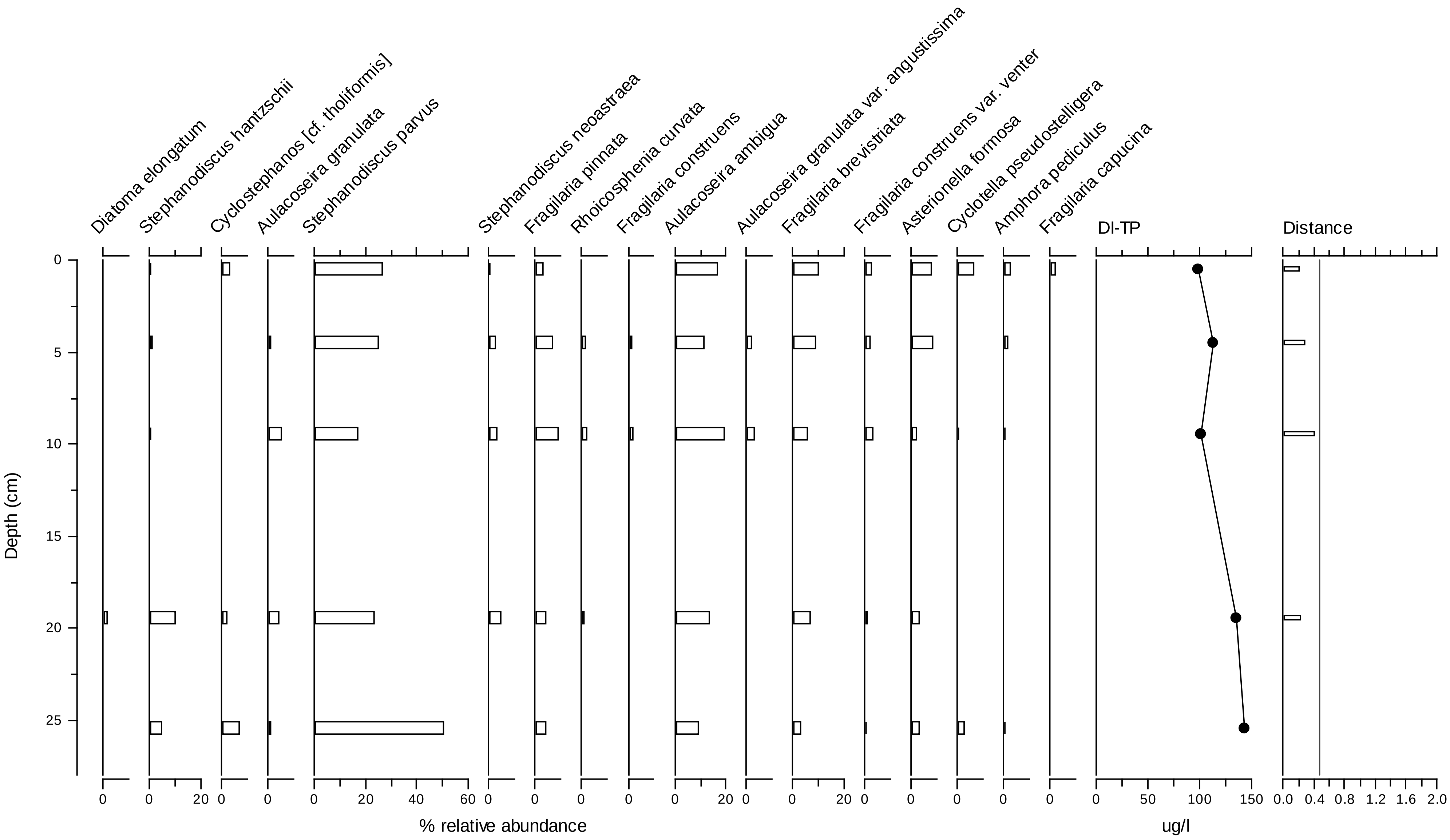


Figure 33 Summary diagram of diatom changes (% relative abundance), squared chord distance dissimilarity scores and diatom-inferred total phosphorus (DI-TP µg l^{-1}) in The Loe core, TLOE1

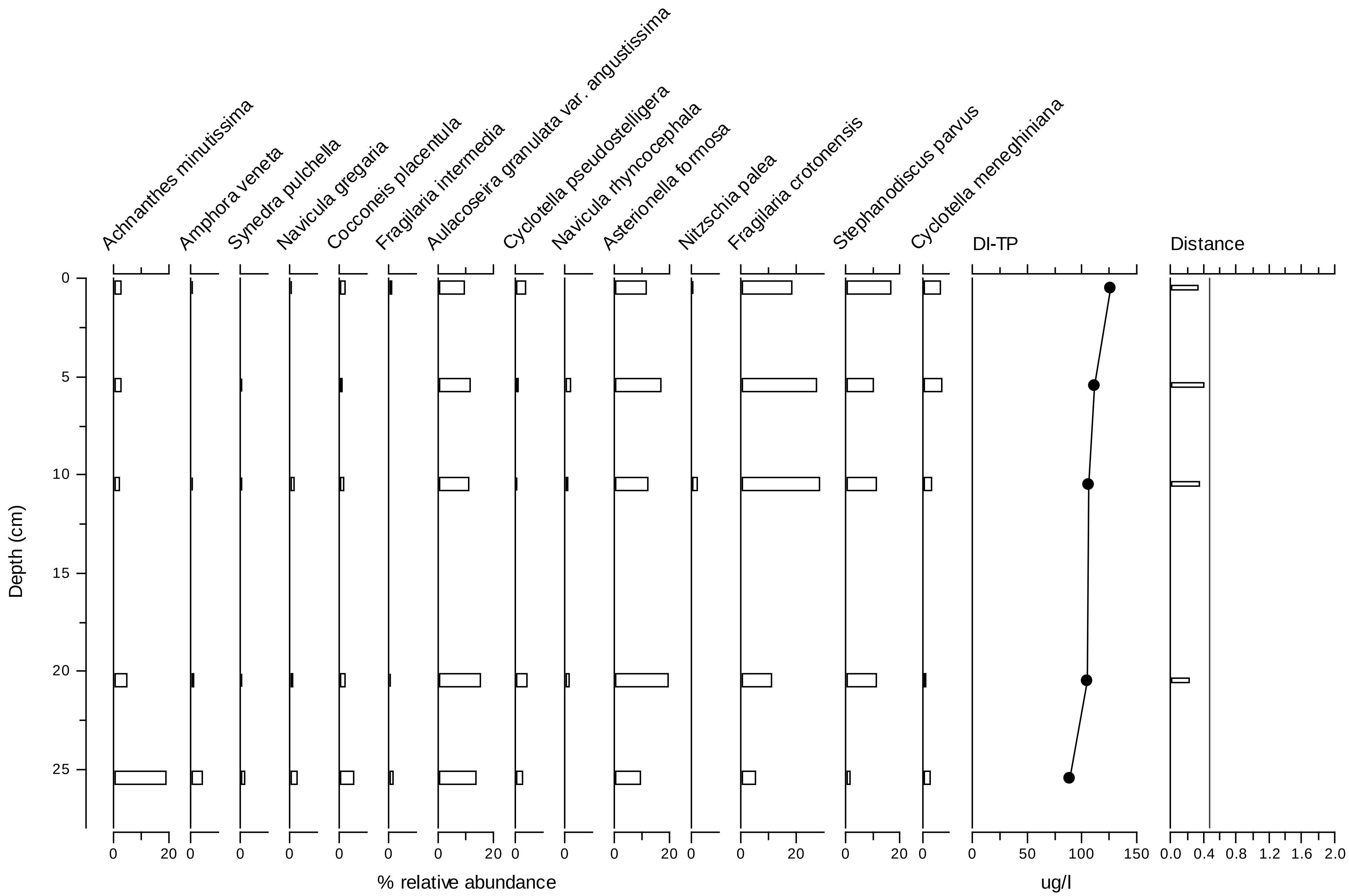


Figure 34 Summary diagram of diatom changes (% relative abundance), squared chord distance dissimilarity scores and diatom-inferred total phosphorus (DI-TP µg l^{-1}) in the White Mere core, SCM09C

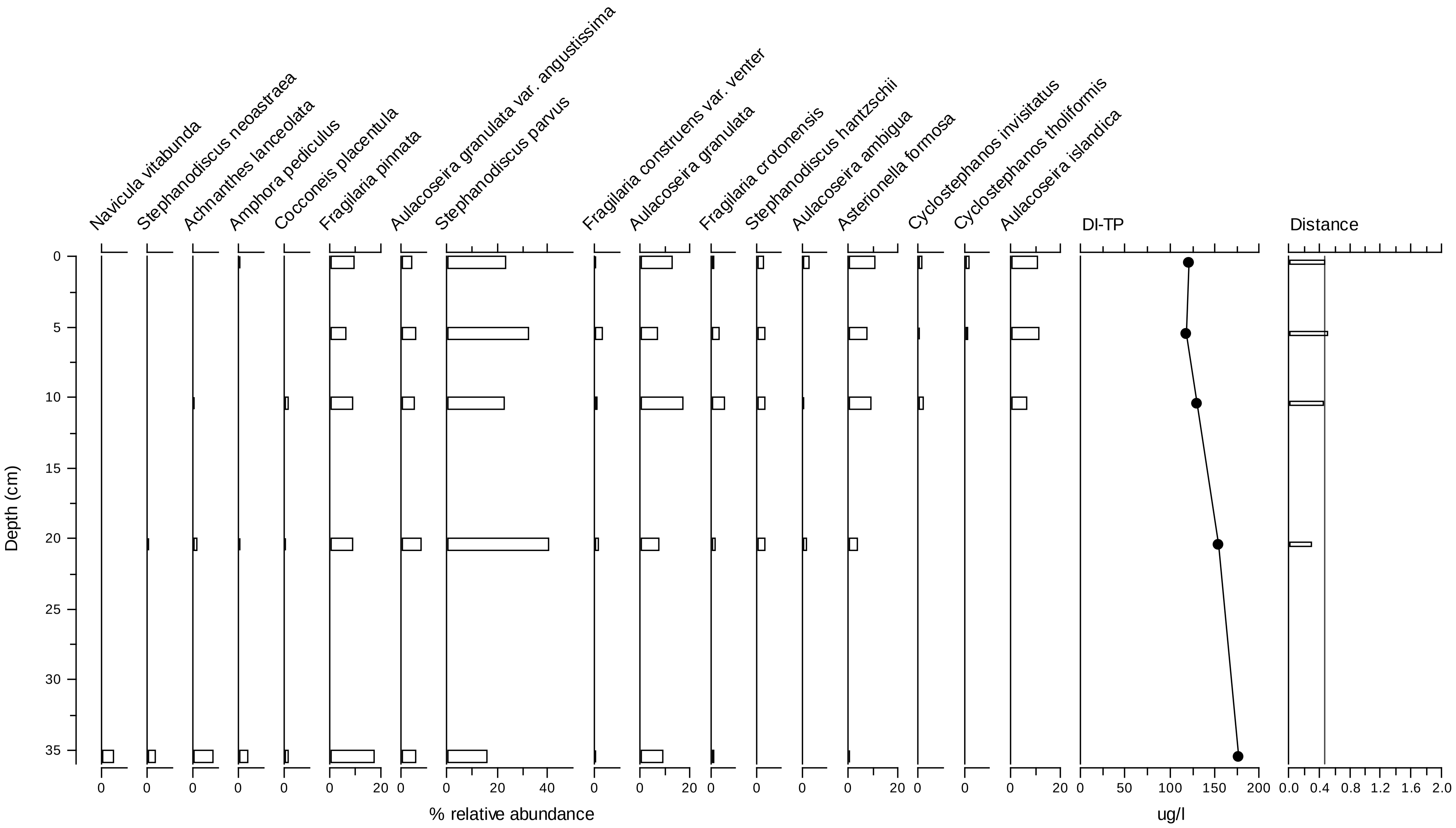


Figure 35 a) DCA biplot (axis 1 and 2) of the sample scores for the 13 cores (see Appendix 3 for sample codes)

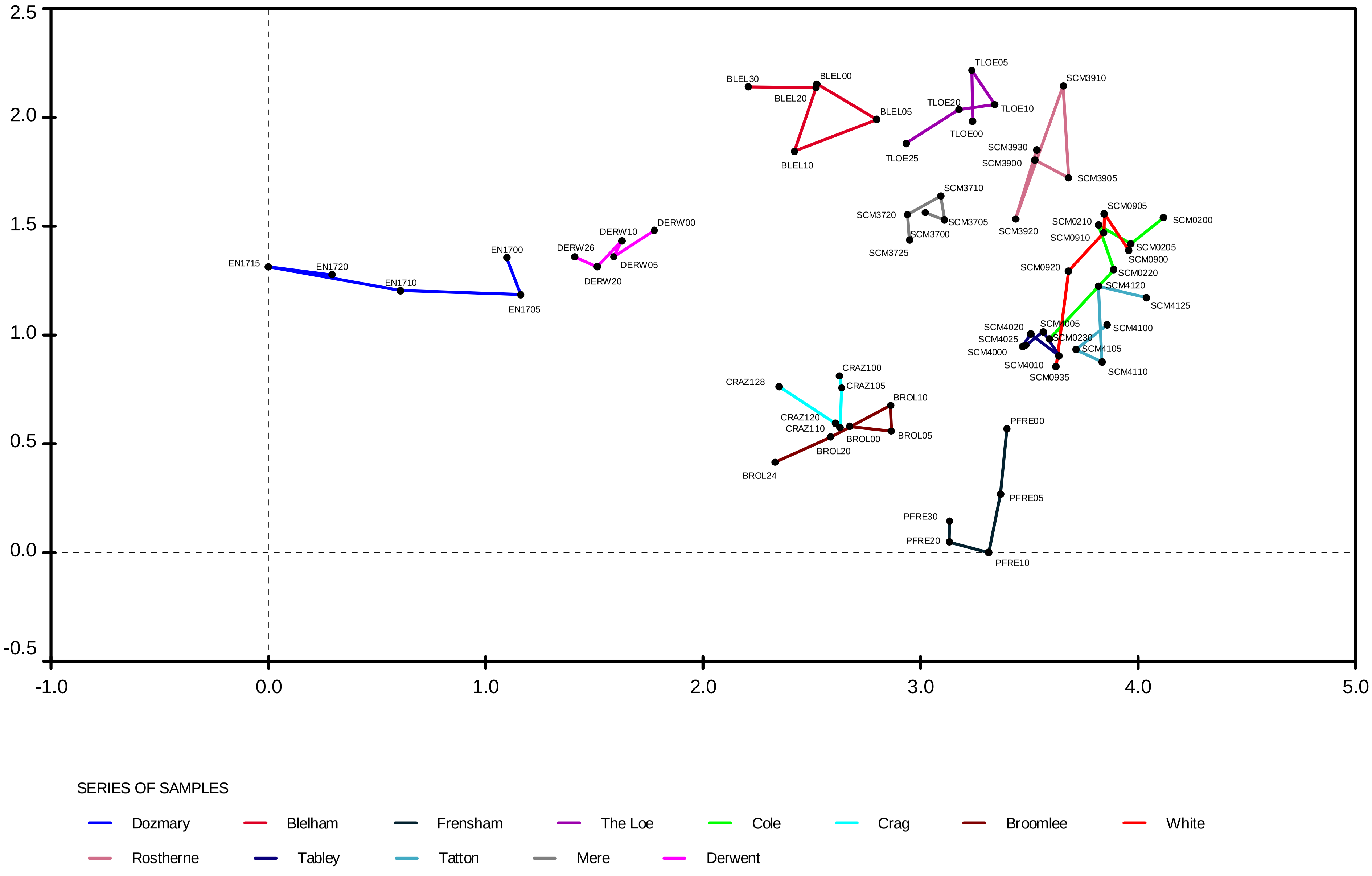
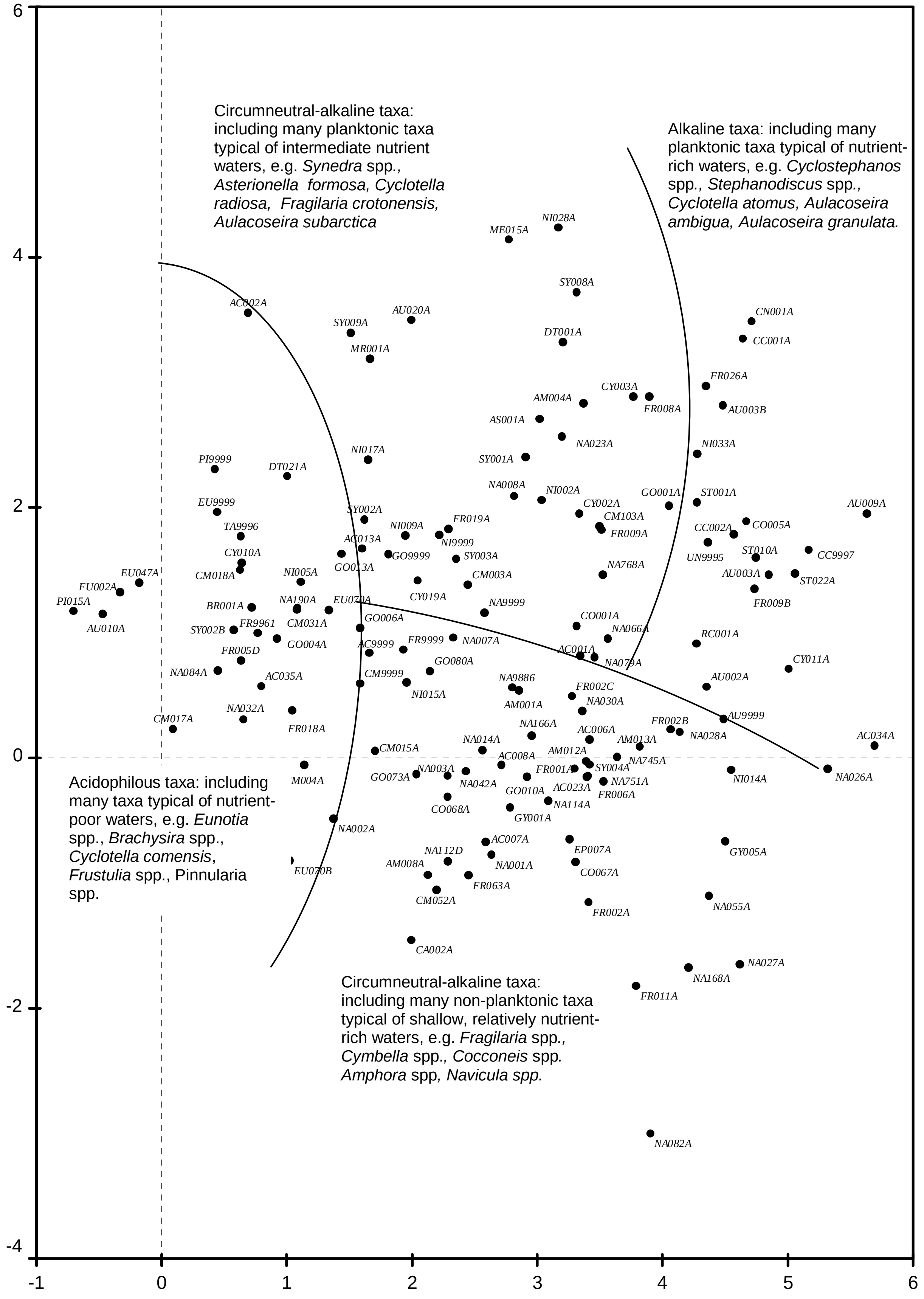


Figure 35 b) DCA biplot (axis 1 and 2) of the species scores for the 13 cores


Circumneutral-alkaline taxa: including many planktonic taxa typical of intermediate nutrient waters, e.g. *Synedra* spp., *Asterionella formosa, Cyclotella radiosa, Fragilaria crotonensis, Aulacoseira subarctica*

Alkaline taxa: including many planktonic taxa typical of nutrient-rich waters, e.g. *Cyclostephanos* spp., *Stephanodiscus* spp., *Cyclotella atomus, Aulacoseira ambigua, Aulacoseira granulata.*

Acidophilous taxa: including many taxa typical of nutrient-poor waters, e.g. *Eunotia* spp., *Brachysira* spp., *Cyclotella comensis*, *Frustulia* spp., Pinnularia spp.

Circumneutral-alkaline taxa: including many non-planktonic taxa typical of shallow, relatively nutrient-rich waters, e.g. *Fragilaria* spp., *Cymbella* spp., *Cocconeis* spp. *Amphora* spp, *Navicula spp.*

3.4 Summary of findings

Diatom analysis was carried out on thirteen cores. Five samples per core were analysed to allow the reference condition and general trend in water quality to be determined. The degree of floristic change between the bottom sample and each of the other four samples analysed in each core was estimated using the squared chord distance dissimilarity coefficient, and detrended correspondence analysis (DCA) was performed to assess the direction and magnitude of floristic change at each site. Given that eutrophication was thought to be the key pressure at the study lakes, weighted averaging-based, diatom-TP transfer functions were applied to the diatom data for each core. The results are summarised in Table 4 and an overview of the findings is discussed below.

Table 4 Summary results from the diatom analysis of 13 cores

Lake name	**[1]Trophic change?**	**[2]Significant floristic change?**	**[3]Transfer function performance**
Blelham Tarn	↑ then ↓	No	Over-estimates
Broomlee Lough	↑ then ↓	Yes	Over-estimates
Cole Mere	↑ then ↓	Yes	OK
Crag Lough	↑	Yes	Over-estimates
Derwent Water	↑	No	Under-estimates
Dozmary Pool	↑	Yes	OK
Frensham Little Pond	↑	No	Over-estimates
Mere Mere	?	No	OK
Rostherne Mere	?	Yes	OK
Tabley Mere	↑?	No	OK
Tatton Mere	↓	No	OK
The Loe	↑	No	OK
White Mere	↑ then ↓?	Yes	Under-estimates

[1] ↑ increase in trophic status; ↓ decrease in trophic status;? uncertain. Assessment of trophic change is based on a combination of species shifts and transfer function results.

[2] Change was deemed significant where the squared chord distance dissimilarity scores between the core bottom and any of the upper samples exceeded the critical value of 0.475.

[3] Based on comparison of DI-TP for the surface sample with current measured annual mean TP.

In summary, ten of the thirteen sites appear to have experienced enrichment over the period represented by the cores, based on a combination of the species shifts and the results of the transfer functions (Table 4). In four of these ten sites (Blelham Tarn, Broomlee Lough, Cole Mere and White Mere), there is evidence of ecological recovery towards the top of the cores, possibly arising from a reduction in nutrient concentrations. Tatton Mere is the only site to exhibit a consistent decrease in productivity over the sediment record but this may be because the core represents a very short period of time. The SCP data suggest that the entire profile may represent the post-1970 period. Two sites, Mere Mere and Rostherne Mere, exhibit floristic change but it is difficult to interpret the observed shifts in terms of trophic change.

In six sites (Broomlee Lough, Cole Mere, Crag Lough, Dozmary Pool, Rostherne Mere and White Mere) the diatom changes were large enough to result in squared chord distance dissimilarity scores that were significant at the 5th percentile (i.e. > 0.475). At the remaining seven sites, the floristic changes were subtle or relatively modest and were not sufficient to produce scores >0.475. In many cases this was because the same main taxa were present throughout the sediment record but there were often important changes in their relative abundance indicative of ecological alterations and possible shifts in trophic status.

Axis 1 of the DCA biplot (Figure 35) appears to represent an alkalinity or productivity gradient with the unproductive samples and their associated taxa to the left of the figure and the more alkaline, nutrient-rich samples and taxa to the right. For example, Dozmary Pool and Derwent Water, positioned on the left of the diagram, are both classified as low alkalinity waters in the GB typology; Blelham Tarn and The Loe, positioned in the centre of axis 1, are classified as medium alkalinity waters; and the Meres and Frensham Little Pond, located to the right of the plot, are classified as high alkalinity waters. It is interesting to note that the two lakes classified as marl systems, Broomlee and Crag Lough, are positioned towards the centre of axis 1 suggesting that their floras are more akin to medium alkalinity systems than high alkalinity ones. The shift towards a more nutrient-rich diatom flora in the studied cores is reflected in the trajectories of the sample scores on the DCA biplot (Figure 35). In almost every case, with the exception of Tatton Mere, there is a general pattern from left to right as the samples move from the core bottom to the core top. The switch-back evident at some sites mirrors the return of the assemblage (at least to some degree) to that seen in the lower part of the core (e.g. Blelham Tarn and Broomlee Lough) and suggests that the lake is experiencing some degree of recovery.

Axis 2 of the DCA biplot appears to represent a depth gradient and hence the plot differentiates between the floras of the deep and shallow lakes. The deep sites are positioned to the upper part of the plot (Figure 35), e.g. Derwent Water, Blelham Tarn, The Loe, Mere Mere, Rostherne Mere, Cole Mere, White Mere and Tatton Mere, whilst the shallow lakes are located in the lower part of the diagram, e.g. Crag Lough, Broomlee Lough, Frensham Little Pond and Tabley Mere. This reflects the higher abundance of non-planktonic, attached forms in the shallow systems where littoral production is likely to dominate, in contrast to the deep Cumbrian lakes and kettle-hole basins of the Meres which stratify and support a relatively diverse planktonic community. Dozmary Pool, albeit a shallow waterbody, is positioned to the far left of the plot owing to the very different assemblage of this lake compared with the other study sites. The assemblages of Dozmary Pool are dominated by taxa typical of acid waters whereas all of the other lakes have circumneutral to alkaline floras.

The study highlights a number of biogeographical similarities in the diatom assemblages of the sites. For instance, all of the Cheshire-Shropshire Meres are located to the far right of Figure 35 reflecting a degree of similarity in their diatom assemblages. Their diatom floras are typical of eutrophic conditions even in the core bottom samples, indicating that the sites have been relatively nutrient rich for the whole of the period represented by the sediment cores. It is thought that the phosphorus-rich apatite geology gives rise to naturally high levels of TP in this region (Reynolds, 1979). Unfortunately, for these sites, the SCP profiles either could not be interpreted or SCP analysis was not carried out and, therefore, the time period represented by the sediment records could not be established. Where SCP analysis was undertaken, namely at Mere Mere, Tabley Mere and Tatton Mere, the data suggest either a very rapid sediment accumulation rate or a disturbed sediment record. Given that the meres are lowland systems in productive catchments, rapid sedimentation rates might be expected. Hence, it is likely that longer cores would be necessary to provide sediment records that extend back as far as ~1850 thereby enabling a more reliable assessment of change in ecological status from reference condition.

The diatom assemblages of Crag Lough are similar to those of the neighbouring Broomlee Lough with the same common taxa in the sediment records of both sites (*Achnanthes minutissima, Fragilaria pinnata, Fragilaria construens* var. *venter, Amphora pediculus*). The floristic similarity is shown by the close positioning of the sample scores for the two cores in the DCA biplot (Figure 35). The diatom assemblages of both lakes experience an increase in *Fragilaria* taxa and the arrival of a number of taxa indicative of more productive waters in the uppermost samples. Therefore, whilst both sites continue to be dominated by non-planktonic diatom taxa typical of moderate nutrient concentrations, reflecting clearwater and availability of plant substrates, there have been a number of notable ecological shifts that appear to indicate slight nutrient enrichment over the last three or four decades. These very shallow, marl sites currently support a diverse macrophyte flora with clearwater conditions (Ben Goldsmith, pers. comm.). Macrophytes are likely to play a role in maintaining good water quality through uptake of nutrients and provision of refuges for phytoplankton grazers. The relatively low percentage of planktonic diatoms in the recent assemblages of these two lakes suggests that they have not switched to algal-dominated, turbid conditions (cf. the alternative stable states theory of Scheffer *et al.,* 1993). Nevertheless, it is worth noting that the planktonic diatom, *Cyclotella pseudostelligera*, appears in small amounts in the surface sample of Broomlee Lough, having not been observed in similar percentages in the lower core sections, and the planktonic species, *Stephanodiscus parvus*, increases slightly in Crag Lough, perhaps providing an early warning that an ecologically important threshold has been crossed. In contrast, Frensham Little Pond, does not currently support any submerged macrophytes and notable increases in the planktonic diatoms *Aulacoseira ambigua, Fragilaria crotonensis* and *Aulacoseira granulata* were observed in the core. The increase in the planktonic component of the diatom community suggests that there have been habitat shifts with a move away from clearwater conditions which would have favoured the attached forms. This may have been brought about by higher nutrient concentrations.

Application of the diatom transfer functions to the fossil diatom assemblages in the 13 cores met with variable success. Comparison of the DI-TP for the surface sample of each core with the current annual mean TP concentration of that lake was used to assess the ability of the transfer function to produce good estimates of historical TP values for a site. In seven lakes, there was good agreement between the modelled and measured data but in four sites the model over-estimated current values and in two sites the model under-estimated current concentrations (see Table 4). When making this comparison, however, one has to bear in mind the shortcomings of the measured nutrient chemistry which has its own potential errors in terms of unrepresentative sampling locations, contamination, analytical error and so on (Bennion & Smith, 2000). Three of the lakes where DI-TP over-estimates current TP values are shallow systems where *Fragilaria* taxa are abundant. The non-planktonic *Fragilaria* spp. typically dominate the diatom assemblages of shallow, alkaline waters, such as those observed here, and are cosmopolitan taxa with relatively low sensitivity to changes in water chemistry. Their distributions are not related directly to epilimnetic chemistry but rather to habitat availability. Consequently they cause problems with diatom reconstructions and these have been reported in a number of shallow lake studies (e.g. Bennion *et al*., 2001; Sayer, 2001). The other lake where the transfer function appeared to over-estimate measured TP was Blelham Tarn. This was largely due to the relatively high abundance of *Stephanodiscus hantzschii* which has a very high TP optimum in the Northwest European training set. In contrast, DI-TP under-estimated current TP concentrations for Derwent Water. This is most likely because the large lakes model was applied to this core and the training set contains many oligotrophic lakes with TP concentrations considerably lower than those currently measured in Derwent Water (27 µg l^{-1}). Similarly, the Northwest European model under-estimated TP values of White Mere. This is a hypertrophic lake with currently very high TP concentrations (477 µg l^{-1}) and therefore is more likely to be nitrogen or light limited.

One limitation of the present study is that not all of the cores could be dated and even some of the cores where the SCP profile could be interpreted did not extend back more than around 50 years. Sediment accumulation rates are site specific and it is unlikely that our cores cover comparable time periods. The lack of a chronology is of less concern where the diatom assemblages remain stable throughout the core but it becomes a greater limitation when interpreting the data from sites that exhibit floristic change as we have no estimate of the time at which the changes occurred. Longer cores would need to be collected and a higher resolution of SCP or radiometric dating carried out to provide a more detailed assessment of the nature and timing of ecological changes at these sites over longer timescales. Analysis of remains of other biological elements preserved in lake sediment cores, such as cladocera, chironomids and macrofossils, would allow ecological reference conditions to be defined in a more holistic way than can be achieved using the diatom record alone, and would provide valuable information on changes in ecological structure and function (e.g. Sayer *et al*., 1999; Bennion, 2001).

Nevertheless, the study illustrates that even relatively low resolution analysis of sediment cores can produce valuable information on reference conditions and extent of ecological change in lakes. Simple techniques such as dissimilarity scores, ordination analyses and transfer functions applied to palaeoecological data can act as powerful tools for characterising lake types, defining both ecological and chemical reference conditions and assessing deviation from the reference state.

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APPENDICES

Appendix 1: Spheroidal carbonaceous particle (SCP) data

Site	Core	Mean depth (cm)	SCP concentration (gDM^{-1})	90% confidence limits (gDM^{-1})	
Crummock Water	CRUM1	0.75	3160	4094	2226
Crummock Water	CRUM1	6.25	13115	14915	11316
Crummock Water	CRUM1	12.25	488	826	150
Crummock Water	CRUM1	18.25	0	0	0
Crummock Water	CRUM1	24.5	0	0	0
Crummock Water	CRUM1	30.5	0	0	0
Crummock Water	CRUM1	36.5	0	0	0
Frensham Great Pond	FREN1	1.5	7369	8607	6130
Frensham Great Pond	FREN1	9.5	2031	2372	1689
Frensham Great Pond	FREN1	17.5	6956	8293	5619
Frensham Great Pond	FREN1	25.5	6371	8102	4639
Frensham Great Pond	FREN1	33.5	3668	4629	2707
Frensham Great Pond	FREN1	41.5	322	546	99
Frensham Great Pond	FREN1	47.5	0	0	0
Burton Mill Pond	BURT1	1.5	164	325	3
Burton Mill Pond	BURT1	10.5	1582	2050	1115
Burton Mill Pond	BURT1	20.5	1769	2270	1269
Burton Mill Pond	BURT1	30.5	1398	1831	965
Burton Mill Pond	BURT1	40.5	1395	1879	912
Burton Mill Pond	BURT1	50.5	0	0	0
Burton Mill Pond	BURT1	70.5	0	0	0
Little Sea	LITT1	1.5	1529	2058	999
Little Sea	LITT1	10.5	7192	8438	5946
Little Sea	LITT1	20.5	2855	3631	2079
Little Sea	LITT1	30.5	234	464	5
Little Sea	LITT1	40.5	1096	1576	616
Little Sea	LITT1	50.5	0	0	0
Buttermere	BUTM1	0.75	468	793	144
Buttermere	BUTM1	4.25	214	424	4
Buttermere	BUTM1	8.25	8998	10285	7712
Buttermere	BUTM1	12.25	1882	2579	1185
Buttermere	BUTM1	16.25	198	391	4
Buttermere	BUTM1	20.5	440	745	135
Buttermere	BUTM1	24.5	0	0	0
Ullswater	ULLS1	0.25	438	742	134
Ullswater	ULLS1	3.25	1100	1722	478
Ullswater	ULLS1	8.25	7920	9251	6589
Ullswater	ULLS1	13.25	7455	8789	6121
Ullswater	ULLS1	18.25	17947	20019	15874
Ullswater	ULLS1	23.5	6797	8217	5377
Ullswater	ULLS1	28.5	2142	2806	1478
Broomlee Lough	BROL1	0.75	1606	2201	1011
Broomlee Lough	BROL1	3.25	434	735	133
Broomlee Lough	BROL1	8.25	2124	2751	1496
Broomlee Lough	BROL1	13.25	4835	5823	3847
Broomlee Lough	BROL1	18.25	3603	4515	2692
Broomlee Lough	BROL1	23.25	2226	2883	1568
Derwent Water	DERW1	0.5	7769	9881	5657
Derwent Water	DERW1	5.5	12538	14781	10295
Derwent Water	DERW1	10.5	9960	11995	7925
Derwent Water	DERW1	20.5	953	1613	293
Derwent Water	DERW1	26.5	0	0	0

Site	Core	Mean depth	SCP concentration	90% confidence limits	
		(cm)	(gDM^{-1})	(gDM^{-1})	
Tabley Mere	SCM40B	0.5	10573	12376	8769
Tabley Mere	SCM40B	5.5	3021	4008	2034
Tabley Mere	SCM40B	10.5	4851	6532	3170
Tabley Mere	SCM40B	15.5	4918	6309	3526
Tabley Mere	SCM40B	20.5	2957	3874	2041
Tabley Mere	SCM40B	25.5	15048	17615	12481
Mere Mere	SCM37B	0.5	15719	18863	12574
Mere Mere	SCM37B	5.5	26011	30589	21432
Mere Mere	SCM37B	10.5	16898	19131	14665
Mere Mere	SCM37B	15.5	28640	31971	25309
Mere Mere	SCM37B	20.5	18667	21280	16053
Mere Mere	SCM37B	25.5	22067	25776	18359
Tatton Mere	SCM41B	0.5	11020	13180	8860
Tatton Mere	SCM41B	5.5	15800	18161	13439
Tatton Mere	SCM41B	10.5	11727	14073	9381
Tatton Mere	SCM41B	15.5	25413	28348	22478
Tatton Mere	SCM41B	20.5	24622	27337	21907
Tatton Mere	SCM41B	25.5	38495	41766	35224
Cotswold Park Lake No. 12	COTS1	0.5	5416	6949	3884
Cotswold Park Lake No. 12	COTS1	2.5	5235	6444	4026
Cotswold Park Lake No. 12	COTS1	5.5	6061	7127	4994
Cotswold Park Lake No. 12	COTS1	8.5	3999	4950	3049
Cotswold Park Lake No. 12	COTS1	10.5	3347	4143	2552
Cotswold Park Lake No. 12	COTS1	12.5	1005	1407	603
Chew Valley Lake	CHEW1	0.5	3263	4063	2464
Chew Valley Lake	CHEW1	1.5	1387	1900	873
Chew Valley Lake	CHEW1	2.5	3416	4532	2300
Chew Valley Lake	CHEW1	3.5	1452	1927	978
Chew Valley Lake	CHEW1	4.5	2526	3145	1907
Chew Valley Lake	CHEW1	5.5	1534	2102	966
Chew Valley Lake	CHEW1	6.5	2236	3065	1408
Frensham Little Pond	PFRE1	0.5	30032	34420	25645
Frensham Little Pond	PFRE1	5.5	13036	14919	11152
Frensham Little Pond	PFRE1	10.5	12509	15011	10006
Frensham Little Pond	PFRE1	15.5	11994	14445	9543
Frensham Little Pond	PFRE1	20.5	12289	14324	10253
Frensham Little Pond	PFRE1	25.5	19961	22910	17012
Frensham Little Pond	PFRE1	30.5	18768	21606	15930
Blelham Tarn	BLEL1	0.5	3524	4745	2303
Blelham Tarn	BLEL1	5.5	4741	5902	3579
Blelham Tarn	BLEL1	10.5	4172	5228	3116
Blelham Tarn	BLEL1	20.5	3395	4447	2343
Blelham Tarn	BLEL1	30.5	4502	5641	3363
Dozmary Pool	EN17A	0.5	2393	2845	1942
Dozmary Pool	EN17A	5.5	3130	3922	2338
Dozmary Pool	EN17A	10.5	100	198	2
Dozmary Pool	EN17A	15.5	0	0	0
Dozmary Pool	EN17A	20.5	0	0	0
Crag Lough	CRAZ1	0.5	587	779	395
Crag Lough	CRAZ1	5.5	1486	1862	1110
Crag Lough	CRAZ1	10.5	2002	2291	1713
Crag Lough	CRAZ1	20.5	2301	2605	1997
Crag Lough	CRAZ1	28.5	2214	2586	1842
The Loe	TLOE1	0.5	1829	2146	1512
The Loe	TLOE1	5.5	1858	2174	1541
The Loe	TLOE1	10.5	1120	1360	881
The Loe	TLOE1	20.5	2346	2789	1904
The Loe	TLOE1	27.5	1211	1517	905

Appendix 2: List of the common diatom taxa (>1% in >2 samples) in the 13 cores with diatcode and full name

Diatcode	Name	Diatcode	Name
AC001A	Achnanthes lanceolata	FR063A	Fragilaria robusta
AC002A	Achnanthes linearis	FR9961	Fragilaria intermedia [fine]
AC006A	Achnanthes clevei	FR9999	Fragilaria sp.
AC007A	Achnanthes oestrupii	FU002A	Frustulia rhomboides
AC008A	Achnanthes exigua	GO001A	Gomphonema olivaceum
AC013A	Achnanthes minutissima	GO004A	Gomphonema gracile
AC023A	Achnanthes conspicua	GO006A	Gomphonema acuminatum
AC034A	Achnanthes suchlandtii	GO010A	Gomphonema constrictum
AC035A	Achnanthes pusilla	GO013A	Gomphonema parvulum
AC9999	Achnanthes sp.	GO073A	Gomphonema angustum
AM001A	Amphora ovalis	GO080A	Gomphonema pumilum
AM004A	Amphora veneta	GO9999	Gomphonema sp.
AM008A	Amphora thumensis	GY001A	Gyrosigma attenuatum
AM012A	Amphora pediculus	GY005A	Gyrosigma acuminatum
AM013A	Amphora inariensis	ME015A	Melosira varians
AS001A	Asterionella formosa	MR001A	Meridion circulare
AU002A	Aulacoseira ambigua	NA001A	Navicula tuscula
AU003A	Aulacoseira granulata	NA002A	Navicula jaernefeltii
AU003B	Aulacoseira granulata var. angustissima	NA003A	Navicula radiosa
AU009A	Aulacoseira islandica	NA007A	Navicula cryptocephala
AU010A	Aulacoseira perglabra	NA008A	Navicula rhyncocephala
AU020A	Aulacoseira subarctica	NA014A	Navicula pupula
AU9999	Aulacoseira sp.	NA023A	Navicula gregaria
BR001A	Brachysira vitrea	NA026A	Navicula reinhardtii
CA002A	Caloneis bacillum	NA027A	Navicula viridula
CC001A	Cyclostephanos dubius	NA028A	Navicula scutelloides
CC002A	Cyclostephanos invisitatus	NA030A	Navicula menisculus
CC9997	Cyclostephanos [cf. tholiformis]	NA032A	Navicula cocconeiformis
CM003A	Cymbella sinuata	NA042A	Navicula minima
CM004A	Cymbella microcephala	NA055A	Navicula graciloides
CM015A	Cymbella cesatii	NA066A	Navicula capitata
CM017A	Cymbella hebridica	NA079A	Navicula pseudolanceolata
CM018A	Cymbella gracilis	NA084A	Navicula atomus
CM031A	Cymbella minuta	NA112D	Navicula minuscula var. muralis
CM052A	Cymbella descripta	NA114A	Navicula subrotundata
CM103A	Cymbella silesiaca	NA166A	Navicula submuralis
CM9999	Cymbella sp.	NA168A	Navicula vitabunda
CN001A	Cymbellonitzschia diluviana	NA190A	Navicula agrestis
CO001A	Cocconeis placentula	NA745A	Navicula capitoradiata
CO005A	Cocconeis pediculus	NA751A	Navicula cryptotenella
CO067A	Cocconeis neothumensis	NA768A	Navicula reichardtiana
CO068A	Cocconeis pseudothumensis	NA9886	Navicula [cf. seminulum]
CY002A	Cyclotella pseudostelligera	NA9999	Navicula sp.
CY003A	Cyclotella meneghiniana	NI002A	Nitzschia fonticola
CY010A	Cyclotella comensis	NI005A	Nitzschia perminuta
CY011A	Cyclotella atomus	NI009A	Nitzschia palea
CY019A	Cyclotella radiosa	NI014A	Nitzschia amphibia
DT001A	Diatoma elongatum	NI015A	Nitzschia dissipata
DT021A	Diatoma mesodon	NI017A	Nitzschia gracilis
EP007A	Epithemia adnata	NI028A	Nitzschia capitellata
EU047A	Eunotia incisa	NI033A	Nitzschia paleacea
EU070A	Eunotia bilunaris	NI9999	Nitzschia sp.
EU070B	Eunotia bilunaris var. mucophila	PI001A	Pinnularia gibba
EU9999	Eunotia sp.	PI9999	Pinnularia sp.
FR001A	Fragilaria pinnata	RC001A	Rhoicosphenia curvata
FR002A	Fragilaria construens	ST001A	Stephanodiscus hantzschii
FR002B	Fragilaria construens var. binodis	ST010A	Stephanodiscus parvus
FR002C	Fragilaria construens var. venter	ST022A	Stephanodiscus neoastraea
FR005D	Fragilaria virescens var. exigua	SY001A	Synedra ulna
FR006A	Fragilaria brevistriata	SY002A	Synedra rumpens
FR008A	Fragilaria crotonensis	SY002B	Synedra rumpens var. familiaris
FR009A	Fragilaria capucina	SY003A	Synedra acus
FR009B	Fragilaria capucina var. mesolepta	SY004A	Synedra parasitica
FR011A	Fragilaria lapponica	SY008A	Synedra pulchella
FR018A	Fragilaria elliptica	SY009A	Synedra nana
FR019A	Fragilaria intermedia	TA9996	Tabellaria flocculosa agg.
FR026A	Fragilaria bidens	UN9995	Centric undifferentiated

Appendix 3: Diatom-inferred total phosphorus (TP µg l^{-1}) values and squared chord distance dissimilarity scores for the 13 cores

Lake name	[1]Sample code	[2]Diatom-inferred TP (ug/l)	% of taxa in fossil sample that are present in the training set	Current TP (µg l^{-1})	[3]Squared chord distance dissimilarity score
Blelham Tarn	BLEL00	50	97	28	0.332
	BLEL05	63	96		0.409
	BLEL10	64	95		0.286
	BLEL20	60	97		0.269
	BLEL30	32	87		
Broomlee Lough	BROL00	77	93	18	0.508
	BROL05	133	86		0.667
	BROL10	158	90		0.673
	BROL20	92	78		0.471
	BROL24	64	84		
Cole Mere	SCM0200	107	97	118	0.635
	SCM0205	130	100		0.355
	SCM0210	131	99		0.453
	SCM0220	141	98		0.429
	SCM0230	110	95		
Crag Lough	CRAZ100	107	85	20	0.484
	CRAZ105	97	88		0.438
	CRAZ110	132	89		0.388
	CRAZ120	81	91		0.356
	CRAZ128	68	86		
Derwent Water	DERW00	11	92	27	0.426
	DERW05	9	93		0.261
	DERW10	9	91		0.194
	DERW20	7	90		0.197
	DERW26	7	92		
Dozmary Pool	EN1700	27	87	37	1.261
	EN1705	2	87		0.796
	EN1710	1	94		0.288
	EN1715	1	98		0.082
	EN1720	2	99		
Frensham Little Pond	PFRE00	139	97	65	0.414
	PFRE05	160	94		0.256
	PFRE10	182	95		0.155
	PFRE20	153	94		0.176
	PFRE30	169	97		
Mere Mere	SCM3700	58	95	53	0.358
	SCM3705	47	93		0.392
	SCM3710	50	95		0.319
	SCM3720	54	95		0.203
	SCM3725	56	95		
Rostherne Mere	SCM3900	136	97	144	0.720
	SCM3905	123	93		0.451
	SCM3910	98	98		0.554
	SCM3920	128	93		0.629
	SCM3930	97	95		
Tabley Mere	SCM4000	228	93	327	0.269
	SCM4005	244	95		0.248
	SCM4010	225	95		0.242

	SCM4020	212	93		0.203
	SCM4025	229	96		
Tatton Mere	SCM4100	98	98	105	0.222
	SCM4105	113	95		0.307
	SCM4110	101	93		0.417
	SCM4120	136	95		0.244
	SCM4125	144	98		
The Loe	TLOE00	126	96	93	0.363
	TLOE05	111	97		0.424
	TLOE10	106	97		0.378
	TLOE20	105	95		0.247
	TLOE25	89	93		
White Mere	SCM0900	122	95	477	0.493
	SCM0905	119	98		0.525
	SCM0910	131	98		0.478
	SCM0920	154	96		0.311
	SCM0935	177	91		

[1] Last 2 digits of sample code indicate sample depth (cm)

[2] DI-TP values for Derwent Water are calculated using the large lakes model; DI-TP for all other sites are calculated using the NW European model (see text)

[3] Squared chord distance dissimilarity score between the core bottom sample and each other sample in that core