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A study of recent environmental change at

Llyn Tegid (Lake Bala), Wales

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A Report to the Environment Agency

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Environmental Change Research Centre

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Executive Summary

1. This is the final report to the Environment Agency: A study of recent environmental change at Llyn Tegid (Lake Bala), Wales.
2. The project employs palaeolimnological techniques to evaluate the ecological implications and extent of eutrophication at Llyn Tegid since c. 1925 AD.
3. This report describes the lithostratigraphy, carbonaceous particle profile, radiometric dating, and fossil diatom assemblages in eleven levels of a sediment core from the deep basin of the lake.
4. A diatom-based transfer function is applied to the core data to generate a quantitative reconstruction of total phosphorus (TP) concentrations for the lake, following taxonomic harmonization between the training set and core species data.. The TP reconstruction is calculated using a Northwest European calibration set of 152 lakes (Bennion *et al.*, 1996).
5. The study shows that Llyn Tegid is naturally an oligotrophic lake with diatom assemblages indicative of nutrient-poor waters and diatom-inferred TP (DI-TP) concentrations of c. 10 $\mu\text{g l}^{-1}$ from 1925 until the mid to late 1970s. The diatom community was remarkably stable with very little variation throughout this period. There was a clear shift in the diatom community, however, at c. 1975 marked by a significant decline in the small, oligotrophic *Cyclotella* taxa and an increase in *Asterionella formosa*, a taxon typically associated with mesotrophic conditions. There was more variability from year to year in the recent diatom assemblages than in those of the lower core section with blooms of *Tabellaria flocculosa* in c. 1992 and *Fragilaria crotonensis* in c.1994, indicating increased ecosystem instability in recent years. The DI-TP results indicate a recent phase of eutrophication with values increasing from c. 10 $\mu\text{g l}^{-1}$ to c. 30 $\mu\text{g l}^{-1}$ over the period 1975-1996.

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1. Objectives

Eutrophication is one of the major threats to the freshwater conservation resource in Wales. The objective of this study was to employ palaeolimnological techniques to assess the extent, rate and timing of eutrophication at Llyn Tegid (Lake Bala), the largest natural Welsh lake, situated in the Snowdonia National Park. The lake is an SSSI and a designated Ramsar site and is a popular recreational site for watersports. The occurrence of blue-green algal blooms on the lake since summer 1995 has given some cause for concern and in response, the Environment Agency has instigated a project to investigate the current trophic state of the lake. In addition to the contemporary research it is important to assess the degree of environmental change at the site in order to assist with future management. Historical water chemistry and biological data are few, therefore this project aims to reconstruct past nutrient concentrations using the diatom transfer function approach enabling realistic targets to be set for the possible amelioration of eutrophication-related problems.

2. Methods

2.1. Coring and Lithostratigraphic Analyses

A short (38 cm) sediment core was taken from Llyn Tegid on 12th July 1996 from the deep, central basin in 40 m of water, using a Glew corer. The core, coded BALA1, was extruded in the laboratory and sliced at 0.5 cm intervals to a depth of 5 cm and then at 1 cm intervals to the core base.

The percentage dry weight (%dw) for each sample was calculated by weighing approximately 1g of wet sediment in a pre-weighed crucible, from each pre-homogenised sediment layer, drying the sediment at 105°C for at least 16 hours, then reweighing the crucible. Approximate organic matter content was then determined (as a percentage loss on ignition - %loi) by placing the crucible containing the dried sediment in a muffle furnace at 550°C for two hours and then reweighing.

The wet density of the sediment is determined by its composition. Variations in density down a core indicate fluctuations in sediment composition suggesting more than one sediment source. Sediment density is also required for calculations of sediment accumulation rate if the core is to be dated. It is measured by weighing an empty 2cm³ capacity brass phial to 4 decimal places and then filling it with wet sediment. The phial is then re-weighed and the weight of the sediment divided by 2 to determine the density as grams per cm³.

2.2. Spheroidal Carbonaceous Particle (SCPs) Analysis

Analysis for Spheroidal Carbonaceous Particles (SCPs) followed the procedure described in Rose (1994) involving the removal of unwanted sediment fractions by selective chemical attack. HNO₃, HF and HCl were used to remove the organic matter, mineral and biogenic silicates and carbonate minerals respectively from 20 levels of the core. A sub-sample of the resulting concentrate was

evaporated onto a coverslip, mounted onto a microscope slide and counted at 400 x magnification using a light microscope.

Primarily SCP profiles in lake sediments in the United Kingdom show three main characteristics that enable approximate dates to be allocated to previously undated cores: the start of the record (linked to the start of high temperature fossil fuel combustion), the rapid increase in concentration (following increases in energy demand after the Second World War), and the peak in SCP concentration (changes in the trends in energy production). The approximate dates assignable to these characteristics are the 1850s, the 1950s and 1978 +/- 2 respectively. For a full account of the historical arguments and the techniques used for dating using SCP profiles refer to Rose *et al.* (1995).

2.3. Radiometric Dating

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

^{210}Pb dates for sediment cores can be calculated using both the constant rate of ^{210}Pb supply (CRS) model and the constant initial ^{210}Pb concentration (CIC) model (Appleby & Oldfield, 1978). The CRS model is most widely accepted; it assumes that the ^{210}Pb supply is dominated by direct atmospheric fallout, resulting in a constant rate of supply of ^{210}Pb from the lake waters to the sediments irrespective of net dry mass accumulation rate changes. If there are interruptions to the ^{210}Pb supply, for example sediment focusing, dates are calculated either by the CIC model or by using a composite of both models. The factors controlling the choice of model are described in full in Appleby & Oldfield (1983), and Oldfield & Appleby (1984).

^{137}Cs activity in sediments prior to the 1986 Chernobyl nuclear accident derives mainly from nuclear weapons testing fallout. Where this isotope is strongly adsorbed on to sediments, the activity versus depth profile is presumed to reflect varying fallout rate and useful chronological markers are provided by the onset of ^{137}Cs fallout in 1954, and peak fallout in 1963.

Sediment samples from core BALA1 were analysed for ^{210}Pb , ^{226}Ra , ^{137}Cs , ^{134}Cs and ^{241}Am by direct gamma assay in the Liverpool University Environmental Radioactivity Laboratory, using an Ortec HPGe GMX series coaxial low background intrinsic germanium detectors (Appleby *et al.* 1986). ^{210}Pb was determined via its gamma emissions at 46.5keV, and ^{226}Ra by the 295keV and 352keV γ -rays emitted by its daughter isotope ^{214}Pb following 3 weeks storage in sealed containers to allow radioactive equilibration. ^{137}Cs and ^{241}Am were measured by their emissions at 662keV and 59.5keV, and ^{134}Cs by its emissions at 605 keV and 795 keV. The absolute efficiencies of the detectors were determined using calibrated sources and sediment samples of known activity. Corrections were made for the effects of self absorption of low energy γ -rays within the sample (Appleby *et al.* 1992) and, in the case of ^{134}Cs , for the effects of cascade summing.

2.4. Diatom-based Transfer Functions

In the absence of long-term historical water chemistry data, the sediment accumulated in lakes can provide a record of past events and past chemical conditions (e.g. Smol, 1992). Diatoms (unicellular, siliceous algae) are particularly good indicators of past limnological conditions, for example lake pH, nutrient concentrations and salinity. In recent years, quantitative approaches have been developed, of which the techniques of weighted averaging (WA) regression and calibration, developed by ter Braak (e.g. ter Braak & van Dam, 1989), are currently the most statistically robust and ecologically appropriate. WA has become a standard technique in palaeolimnology for reconstructing past environmental variables. The methodology and the

advantages of WA over other methods of regression and calibration are well documented (e.g. ter Braak & van Dam, 1989; ter Braak & Juggins, 1993; Line *et al.*, 1994).

Using the technique of WA, a predictive equation known as a transfer function can be 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 in recent years to quantitatively infer lake pH (e.g. Birks *et al.*, 1990) and lake total phosphorus (TP) concentrations (e.g. Anderson *et al.*, 1993; Bennion, 1994; Bennion *et al.*, 1996), whereby modern diatom pH and TP optima are calculated for each taxon based on their distribution in the training set, and then past pH and TP concentrations are derived from the weighted average of the optima of all diatoms present in a given fossil sample. These models are able to provide estimates of baseline pH and TP concentrations in lakes, and coupled with dating of sediment cores (radiometric or spherical carbonaceous particles), enable the timing, rates and possible causes of acidification and enrichment to be assessed for a particular site. This information can be used to design lake classification systems and can be incorporated into lake management and conservation programmes.

In this study, eleven levels from the BALA1 core were prepared and analysed for diatoms using standard techniques (Battarbee, 1986). At least 300 valves were counted from each sample using a Leitz research quality microscope with a 100 x oil immersion objective and phase contrast. The data were expressed as percentage relative abundance.

A diatom-phosphorus transfer function was applied to the core data to generate quantitative reconstructions of TP for the lake, following taxonomic harmonization between the training set and core species data.. The TP reconstruction was calculated using a Northwest European calibration set of 152 lakes (Bennion *et al.*, 1996), based on simple WA with inverse deshinking on log-transformed annual mean TP data. The relationship between diatom-inferred (DI-TP) and measured TP is strong ($r^2 = 0.85$) and has low errors of prediction with an apparent root mean

square error (RMSE) of 0.19 and a cross-validated RMSE (RMSE-P) of 0.22 (log values), indicating that the model performs well. The reconstruction was implemented using CALIBRATE (Juggins & ter Braak, 1993).

Cluster analysis was performed on the diatom core data to identify the major zones in the diatom profile using CONISS (Grimm, 1987), implemented by TILIA and TILIAGRAPH (Grimm, 1991). CONISS is a program for stratigraphically constrained cluster analysis by the method of incremental sum of squares.

3. Results

3.1. Lithostratigraphy

Figure 1 and Figure 2 illustrate the results of the lithostratigraphic analyses. The sediment becomes gradually more organic from the core base to the surface; for example, %dw decreases from c. 30% in the lower core section to only c. 10% in the upper part, whilst %loi increases from c. 12% at the base to c. 20% at the top, clearly indicating an increase in organic content, particularly in recent years. The %dw and %loi values fluctuate slightly throughout the core but there are no marked peaks or troughs, indicating that there were no single events which impacted the sediment record. Likewise, the wet density values only vary slightly from c. 1.2 g cm⁻³ at the core base to c. 1.1 g cm⁻³ at the surface.

3.2. Carbonaceous Particle Profile

The SCP results for the core BALA1 are illustrated in Figure 3 and are expressed in terms of concentration and flux (accumulation rate). The actual values are shown in the Appendix. Both particle concentration and profile shape exhibit trends consistently seen in sediments throughout the United Kingdom (Rose *et al.* 1995). This demonstrates that the core is unlikely to have been disturbed and contains a complete, continuous sediment record.

Of the 3 main features characteristically found and interpreted in UK SCP profiles (see section 2.2) only two are discernible in the core. The onset of high temperature fossil fuel combustion, that heralds the beginning of the SCP sediment record, would appear to predate the bottom of the profile. Thus an approximate 1850 horizon is unidentifiable. The radiometric dating corroborates this, showing the core to begin circa 1925. Moving up the profile, SCP flux and concentration demonstrate a gradual increasing trend from 39.5cm to 24.5cm where the rate of contamination begins to rise more sharply, echoing the post war rise in electricity production. This trend then continues up to 12.5 cm which exhibits maximum SCP concentration and flux, and can be interpreted as the final of the three

characteristic SCP features - that of peak contamination occurring in 1978 ± 2 . This peak is followed by a marked decline towards the core top and the present day. All the main features of this profile correspond well with other lakes studied for SCPs in North Wales (Rose *et al.* 1995) and the results obtained can be viewed as typical for the region.

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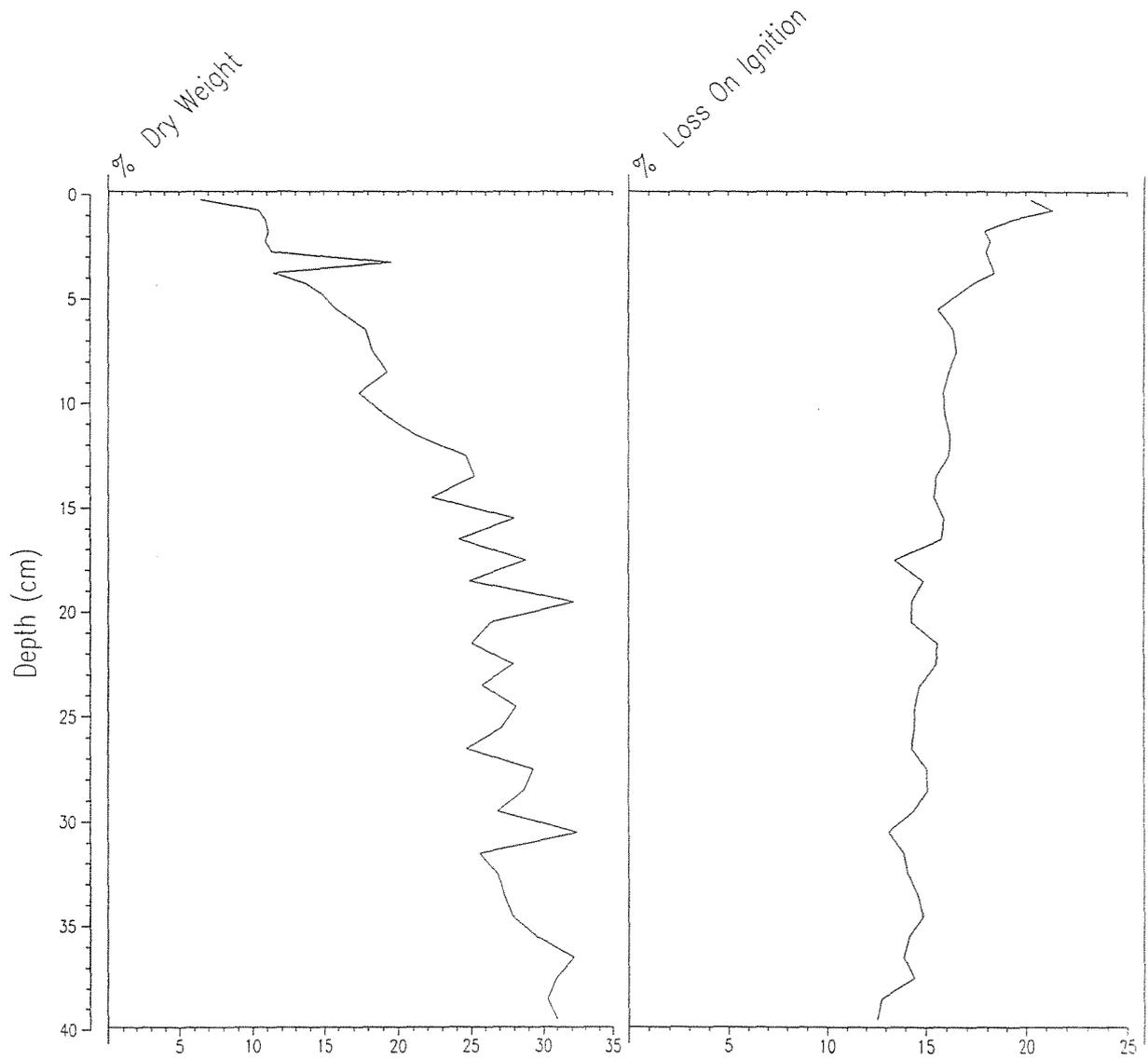
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Figure 1 Lithostratigraphic Data for Llyn Tegid - Core BALA1



3.3. Radiometric Dating

The results of the radiometric analyses are given in Table 1 and shown graphically in Figure 4 and Figure 5. Activities of the short-lived radionuclide ^{134}Cs , which derives solely from Chernobyl fallout, have been corrected for decay since May 1986.

Lead-210 Activity

The ^{210}Pb results indicate moderately high sediment accumulation rates at this site. Equilibrium with the supporting ^{226}Ra is not attained within the 40 cm depth spanned by the core (Figure 4). Unsupported ^{210}Pb activity (Figure 5) declines more or less exponentially with depth, suggesting relatively uniform sediment accumulation, though there is a significant non-monotonic feature at about 24.5 cm.

Artificial Fallout Radionuclides

The ^{137}Cs activity versus depth profile (Figure 6) has two sub-surface peaks, at depths 8.5 cm and 16.5 cm. Identification of the more recent peak as a record of fallout from the 1986 Chernobyl accident is confirmed by the presence of a similar peak in ^{134}Cs activity at the same level. The relatively high activities in the ^{137}Cs peak indicate that this area experienced high levels of Chernobyl fallout. Using the $^{134}\text{Cs}/^{137}\text{Cs}$ activity ratio of 0.61 in fresh Chernobyl fallout (Cambray *et al.* 1987) to partition the ^{137}Cs activity into its Chernobyl and weapons components, the total inventory of Chernobyl derived ^{137}Cs in the core is estimated to be 9550 Bq m^{-2} .

The weapons fallout origin of the second ^{137}Cs peak is confirmed by the presence of a similar peak in ^{241}Am activity at the same depth (Appleby *et al.* 1991). Although neither of the weapons fallout peaks is particularly well resolved, the record is sufficiently clear to date the 16-20 cm section of the core to the mid 1960s.

Core Chronologies

^{210}Pb chronologies were calculated using both the CRS and CIC dating models (Appleby *et al.* 1986) and the results are shown in Figure 7. Differences between the two models are relatively small, implying that net changes in accumulation rates during the past 90 years have been relatively moderate, except possibly during the episode recorded by the ^{210}Pb irregularities between 16-28 cm. Since there is no evidence of an major inwash event, as suggested by the CIC model, and the dilution in ^{210}Pb activity at 24.5 cm is consistent with the assumptions of the CRS model, dates given by the latter are considered to be more reliable and are given in detail in Table 2. These suggest that sedimentation was very stable from c.1900 up to about 1950, the mean accumulation rate during this time being $0.10\pm 0.02 \text{ g cm}^{-2} \text{ y}^{-1}$ ($0.28\pm 0.04 \text{ cm y}^{-1}$). An increase since the early 1950s to $0.14\pm 0.02 \text{ g cm}^{-2} \text{ y}^{-1}$ ($0.58\pm 0.08 \text{ cm y}^{-1}$) was accompanied by a qualitative change to less uniform accumulation.

Figure 7 shows that the ^{210}Pb dates are in good agreement with those determined by the Chernobyl fallout record, 1986 being placed at a depth of 8.5 cm. Agreement with the weapons fallout record is less good, 1963 being placed at 21 cm depth, though this may be due in part to the poor resolution of the ^{137}Cs and ^{241}Am profiles.

Table 1 **Fallout Radionuclide Concentrations in Llyn Tegid - Core BALA1**

Depth		²¹⁰ Pb						¹³⁷ Cs		¹³⁴ Cs		²⁴¹ Am	
		Total		Unsupported		Supported							
cm	g cm ⁻²	Bq kg ⁻¹	±	Bq kg ⁻¹	±	Bq kg ⁻¹	±	Bq kg ⁻¹	±	Bq kg ⁻¹	±	Bq kg ⁻¹	±
0.25	0.02	307.4	33.0	225.4	33.8	82.0	7.3	320.5	11.6	191.4	42.7	0.0	0.0
4.25	0.55	311.8	24.9	243.5	25.2	68.3	4.1	383.9	8.5	241.1	42.2	0.0	0.0
6.5	0.95	262.8	18.5	209.0	18.9	53.8	3.9	470.7	8.2	336.8	73.0	2.9	1.9
8.5	1.37	250.6	15.5	201.4	15.8	49.3	3.3	539.1	7.3	384.5	53.9	2.9	1.9
10.5	1.78	220.3	15.0	163.9	15.4	56.4	3.4	421.2	6.4	223.6	54.5	3.1	1.7
12.5	2.27	181.3	16.1	129.3	16.4	52.0	3.3	249.4	5.5	23.2	6.1	0.0	0.0
16.5	3.44	147.2	16.0	93.5	16.4	53.7	3.5	289.9	6.0	0.0	0.0	5.9	1.9
20.5	4.78	143.9	13.3	94.8	13.6	49.1	3.1	148.9	4.0	0.0	0.0	3.6	1.5
24.5	6.05	107.7	11.8	57.9	12.1	49.8	2.6	42.7	2.4	0.0	0.0	0.0	0.0
28.5	7.36	124.9	14.7	80.2	15.0	44.8	3.1	22.6	2.5	0.0	0.0	0.0	0.0
32.5	8.74	91.4	8.7	46.1	8.9	45.3	2.0	15.1	1.5	0.0	0.0	0.0	0.0
36.5	10.12	87.2	12.5	36.6	12.9	50.7	2.9	3.7	1.7	0.0	0.0	0.0	0.0
39.5	11.23	72.1	7.9	24.4	8.1	47.7	2.0	2.7	1.2	0.0	0.0	0.0	0.0

Table 2 ^{210}Pb chronology of Llyn Tegid - Core BALA1

Depth		Chronology			Sedimentation Rate		
cm	g cm^{-2}	Date AD	Age y	\pm	$\text{g cm}^{-2} \text{y}^{-1}$	cm y^{-1}	\pm (%)
0.0	0.0	1996	0				
2.0	0.3	1994	2	2	0.14	1.06	14
4.0	0.5	1992	4	2	0.13	0.89	12
6.0	0.9	1990	6	2	0.13	0.74	11
8.0	1.3	1987	9	2	0.13	0.64	11
10.0	1.7	1984	12	2	0.14	0.63	12
12.0	2.2	1980	16	2	0.16	0.61	14
14.0	2.7	1977	19	2	0.17	0.59	17
16.0	3.3	1974	22	2	0.18	0.59	19
18.0	3.9	1970	26	2	0.17	0.53	19
20.0	4.6	1966	30	3	0.15	0.45	18
22.0	5.3	1962	34	3	0.16	0.48	21
24.0	5.9	1958	38	4	0.17	0.54	24
26.0	6.5	1953	43	4	0.15	0.45	25
28.0	7.2	1948	48	5	0.11	0.32	25
30.0	7.9	1941	55	6	0.10	0.29	27
32.0	8.6	1935	61	7	0.11	0.31	30
34.0	9.3	1928	68	9	0.10	0.29	38
36.0	10.0	1920	76	10	0.09	0.25	47
38.0	10.7	1912	84	13	0.09	0.24	52

Figure 4 Total ^{210}Pb activity versus depth for Llyn Tegid

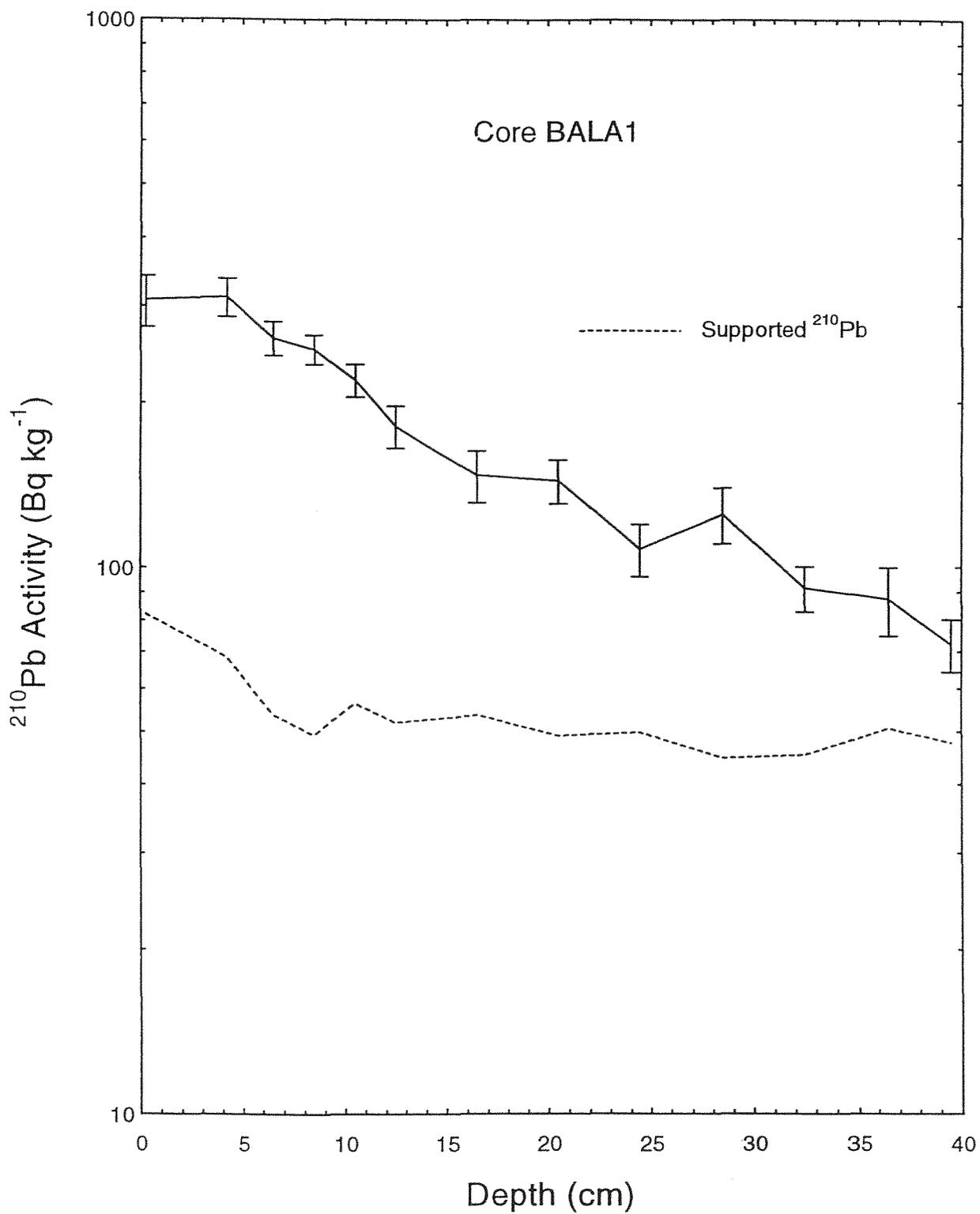


Figure 5 Unsupported ^{210}Pb activity versus depth for Llyn Tegid

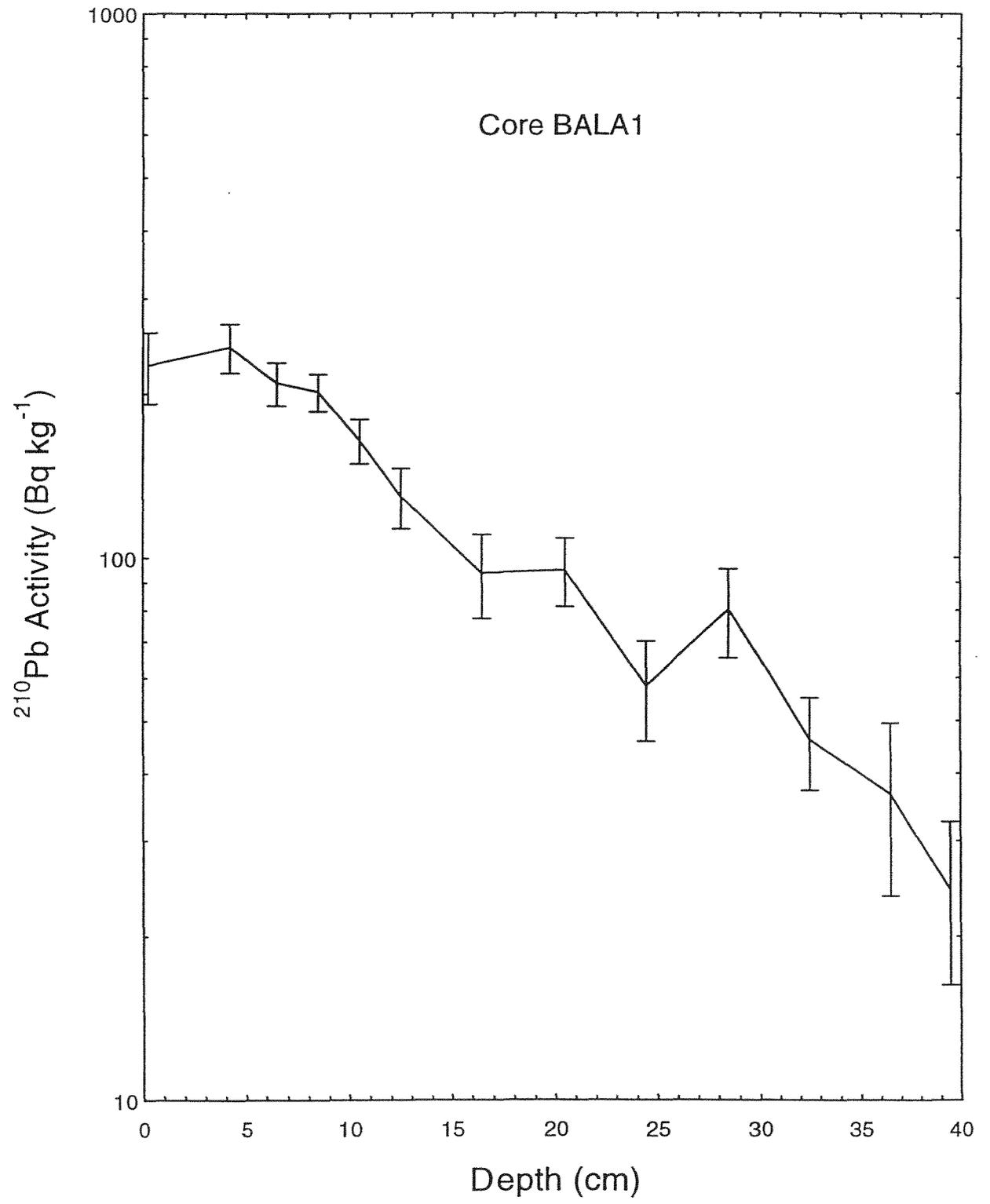


Figure 6 ^{137}Cs , ^{134}Cs and ^{241}Am activity versus depth for Llyn Tegid

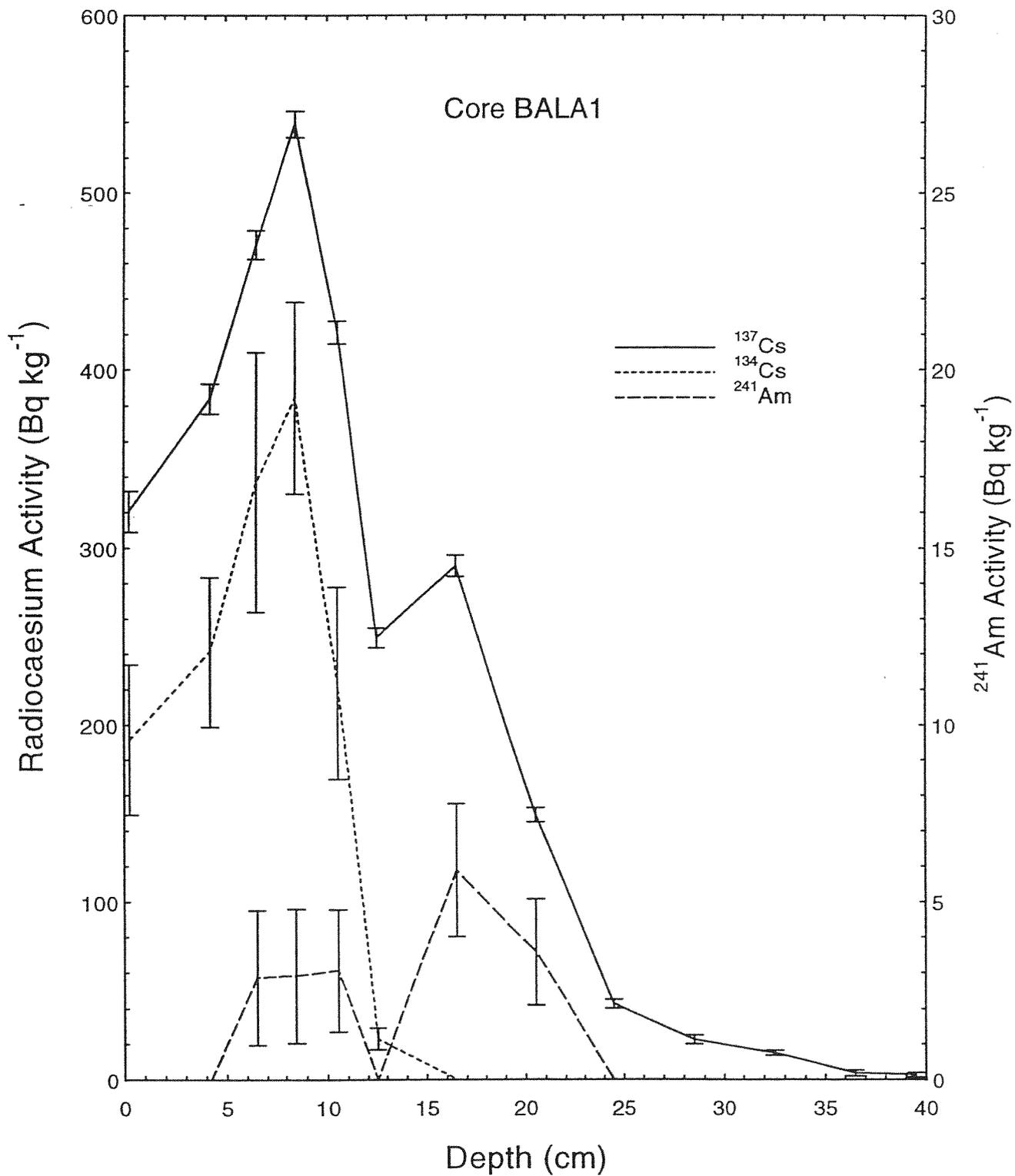
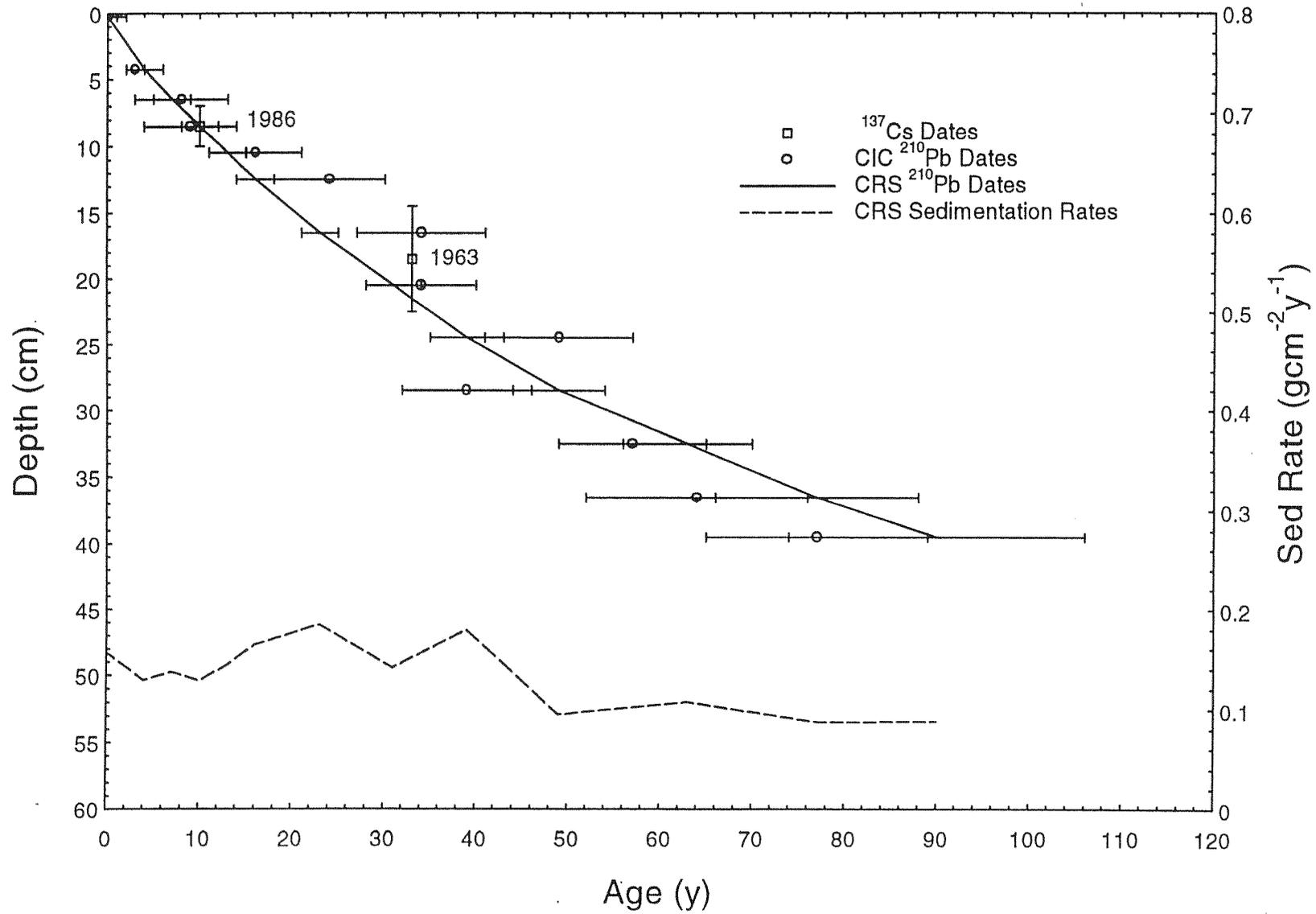


Figure 7 Depth versus age for Lynn Tegid



3.4. Diatom Stratigraphy

The percentage relative frequencies of diatom species in eleven levels of the sediment core BALA1 were calculated and Figure 8 illustrates the results for the major taxa. A list of the complete diatom names and codes for each sample are given in the Appendix. Diatom preservation was generally good throughout the core. A total of 104 taxa was observed, 75 of which were present in the TP calibration set. Species analogues were good with greater than 90% of the fossil assemblage being used in the TP reconstructions, except for the bottom sample where only 83% was used owing to the presence (10%) of an unidentified, small *Cyclotella* taxon, here named *Cyclotella* [cf. *atomus*]. This species was similar to *C. atomus* in terms of size and marginal features but the large, central process, characteristic of *C. atomus*, was not visible in light microscope in these samples. The other unknown taxon in the BALA1 core was named *Cyclotella* [cf. *planctonica*]. This diatom was present in all levels of the core but in small percentages. It had features of both *C. rossii* and *C. planctonica* but its exact identity remains unresolved. Further work on a scanning electron microscope will be necessary to aid identification.

Figure 8 illustrates that there has been a marked change in the diatom species composition over the period represented by the core, estimated as 1925 to 1996, although the fossil assemblages have always been dominated by planktonic taxa. The diatom diagram has been divided into two major zones, according to the results of cluster analysis, to facilitate description.

Zone 1 (35-15 cm; c. 1925-1975)

This zone was dominated by a number of *Cyclotella* taxa, many of which are typically found in oligotrophic, circumneutral to alkaline waters, for example, *C. glomerata* and *C. comensis*, as well as the two unidentified taxa, *C.* [cf. *atomus*] and *C.* [cf. *planctonica*]. Other important taxa were *Achnanthes minutissima*, commonly found attached to plants in a wide range of conditions, and *Aulacoseira subarctica*, a planktonic diatom frequently observed in oligo- to meso-trophic waters. The diatom species composition was remarkably stable throughout this period.

Zone 2 (15-0 cm; c. 1975-1996)

The marked change in the core occurred at around the 15 cm level (c.1975). Here, the relative importance of the *Cyclotella* taxa which were abundant in Zone 1 declined and there was a large expansion of *Asterionella formosa*, a species commonly found in the plankton of mesotrophic waters. This taxon became dominant, increasing from only a few percent pre-1975 to 40% of the assemblage by 1996. *A. subarctica* remained important and *Tabellaria flocculosa*, which had constituted less than 5% of the assemblages in Zone 1, increased to 15% in the early 1990s. This taxon is associated with mesotrophic waters. A further major feature of Zone 2 was the sudden appearance of *Fragilaria crotonensis*, another species found in the plankton of mesotrophic lakes, at the 2 cm level (c. 1994) and its subsequent decline in the surface sample.

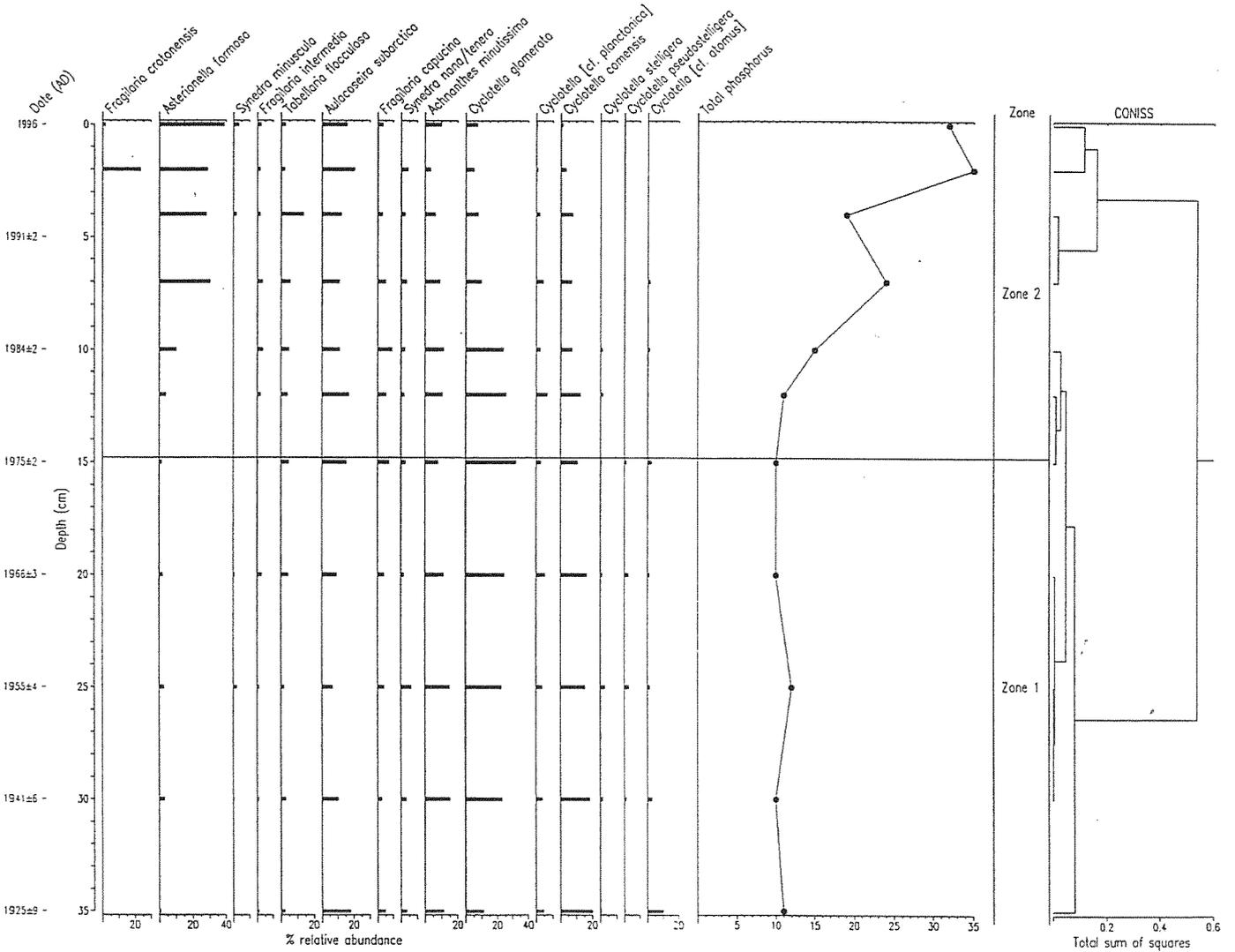
3.5. TP Reconstruction

The TP reconstruction (Table 3 and Figure 8) suggests that Llyn Tegid is naturally an oligotrophic lake with relatively stable concentrations of around $10 \mu\text{g TP l}^{-1}$ until the late 1970s/early 1980s. The diatom-inferred TP (DI-TP) concentrations increase markedly from this time, indicating a recent eutrophication phase, with a doubling in concentrations over the last 10 years and a current DI-TP value of c. $30 \mu\text{g TP l}^{-1}$. The decrease in DI-TP at the 4 cm sample is due to the relatively high abundance of *T. flocculosa* which has a low TP optimum relative to *A. formosa*. This taxon appears to have bloomed in this particular year.

Table 3 **Diatom-inferred TP results for Llyn Tegid -Core BALA1**

Depth	Date AD	TP
cm	approx.	$\mu\text{g l}^{-1}$
0	1996	32
2	1994	35
4	1992	19
7	1989	24
10	1984	15
12	1980	11
15	1975	10
20	1966	10
25	1955	12
30	1941	10
35	1925	11

Figure 8 Summary diatom diagram and TP reconstruction for Llyn Tegid



4. Discussion

The diatom flora and the DI-TP results indicate that Llyn Tegid is naturally an oligotrophic lake (i.e. c. $10 \mu\text{g TP l}^{-1}$). The lake has, however, experienced recent changes in the diatom communities, indicating a period of nutrient enrichment, and this is reflected in the increase in DI-TP concentrations to values of c. $30 \mu\text{g l}^{-1}$ by the mid 1990s. The lake would be classed as mesotrophic today based on its current DI-TP levels (OECD, 1982).

The results of this study appear to be consistent with descriptions of Llyn Tegid in the literature. The finding that the lake is a naturally oligotrophic one fits with the origin and nature of the site, as it is a large, deep, glacial lake on predominantly acidic bedrock with mostly upland farming in the catchment and therefore one would expect the lake to be naturally nutrient-poor. When the site was last designated as an SSSI in 1982, it was reported to have an oligotrophic aquatic macrophyte flora, invertebrate fauna typical of exposed oligo-to meso-trophic lakes and a fish community typical of a relatively nutrient-poor system, including Perch, Pike, Rudd, Roach, Ruff, Grayling and the unique Gwyniad (*Corogonus lavaretus*). The *Cyclotella* taxa in Zone 1 of the core are typical of oligotrophic waters and have been observed in many lakes with low TP concentrations, e.g. in Northern Ireland (Anderson, 1997) and Alpine and pre-alpine lakes of central Europe (Wunsam & Schmidt, 1995).

The stability of the diatom community and hence the DI-TP values in Zone 1 of the core suggests that there was very little natural variability in the Llyn Tegid system prior to the recent human impact. Unfortunately, the BALA1 core only extends back as far as c. 1925 and a longer core would be required to explore the full post-1850 history of the lake, but the lack of change over the 50 year period 1925-1975 is so marked that it is unlikely that the diatom assemblages would be very different if one went further back in time. According to the sediment work of Dancer (1990), there is evidence of human settlement in the Tegid region at c. 3000 BP and therefore, one would have to go beyond this date, or possibly even beyond the Neolithic period (c. 6000-5000 BP), to establish true, pre-anthropogenic, baselines for the lake.

The physical disturbance that occurred during the development of the Bala Lake Scheme as part of the River Dee Regulation system in the mid 1950s does not appear to have impacted the diatom community, and by implication the fluctuating lake water level has apparently had no significant impact on the water chemistry, at least not in terms of epilimnetic nutrient concentrations.

The diatom data indicate that the first major change in the lake did not occur until the mid to late 1970s. The replacement of a small number of *Cyclotella* species by *Asterionella formosa* and *Fragilaria crotonensis* is clearly indicative of enrichment. Similar species changes have been observed at other sites throughout Europe and North America (Bradbury, 1975; Battarbee, 1986; Anderson, 1997). The exact cause of this enrichment is not clear and there is very little documentary data on land use changes and historical events in the catchment to aid interpretation of the findings. Plans are currently underway, however, for an investigation of land use changes by analysis of historical satellite images by the Institute of Terrestrial Ecology (ITE) (Millband, 1996) and once these data become available, they may help to elucidate the causes of eutrophication. An earlier study by ITE identified an increase in the use of fertilisers during the late 1980s and this may be one of the important sources of nutrients. Given that there are only three small sewage treatment works in the catchment, which are estimated to contribute only 13% of the total phosphate entering the lake (Millband, 1996), it is unlikely that these are the main cause of increased TP levels in the lake, and diffuse, agricultural sources are likely to be more important. Another possible source of P is the effluent from the number of caravan parks that have developed around the lake, and this is currently being investigated by the Environment Agency.

Owing to the lack of historical TP data it is not possible to compare the DI-TP concentrations with measured water chemistry. The only available P data are from a survey carried out in June 1977 by Mills (data collated by Dancer, 1990) where orthophosphate ranged from 7 to 13 $\mu\text{g P l}^{-1}$, and from a Welsh Water report in which orthophosphate data was averaged for the period 1979-1983 (based on 9 data points) and ranged from less than 10 to 50 $\mu\text{g P l}^{-1}$ with a mean of 30 $\mu\text{g P l}^{-1}$ (Heller, 1985). Total phosphorus was not measured in either of these studies so direct comparisons with the DI-TP values cannot be made, although clearly the modelled values are in a similar range.

Current water chemistry data are available, however, against which the DI-TP concentrations for the surface sample can be compared. The Environment Agency have reported data from three Llyn Tegid sampling stations collected during summer 1996. Surface water TP ranged from 5 to 47 $\mu\text{g P l}^{-1}$ with a data set mean of 13 $\mu\text{g P l}^{-1}$, placing the lake in the oligo-mesotrophic category (Millband, 1996). The current DI-TP value of c. 30 $\mu\text{g P l}^{-1}$, therefore compares favourably with the measured data, although the model does seem to slightly over-estimate the measured concentrations. This may partly be due to the fact that the measured data is biased towards the summer (March to September) and it is possible that TP concentrations are higher during the winter when nutrients are not being taken up by the algae, thus increasing the annual mean values. The model over-estimation may also partly be due to the TP range of the training set from which the model was generated. The training set includes lakes with TP concentrations ranging from 5 to over 1000 $\mu\text{g P l}^{-1}$ (Bennion *et al.*, 1996). However, only a few of these have TP concentrations as low as Llyn Tegid and the diatom model still needs expanding to include more lakes that are analogous to Llyn Tegid both in terms of TP levels and diatom assemblages. This work is currently in progress, whereby approximately 30 currently oligo- to meso-trophic lakes from Wales and Scotland will be added to the training set to enable more accurate reconstructions for such sites.

The presence of the two unknown *Cyclotella* taxa also introduces error into the TP reconstruction because these taxa are not present in the training set and their abundances cannot be used in the calculations. The addition of more lakes similar to Llyn Tegid will allow the ecology of the oligo- to meso-trophic diatom taxa to be better described and will help to reduce these no analogue situations. Indeed, preliminary diatom analysis of the Scottish lochs surface sediments has already identified similar unknown *Cyclotella* taxa to those recorded in the Llyn Tegid fossil assemblages.

The recent phase of nutrient enrichment at Llyn Tegid as indicated by the diatom data is supported by the occurrence of blue-green algal blooms on the lake during summer 1995 and 1996. Such blooms had not been observed on the lake prior to these years, and their sudden appearance indicates that changes are taking place in the algal communities of the lake and causes some concern with regard to changes that might be occurring to the lake ecosystem as a whole. There is considerable variability in the diatom assemblages of Zone 2 (Figure 8), particularly when compared with the stability of the community in Zone 1. Given the lack of natural variability in

Zone 1, it is clear that the variability in Zone 2 is anthropogenically induced. One notable feature was the sudden appearance of *Fragilaria crotonensis* in the fossil assemblage for 1994. This represents a bloom of this species in the lake during that year. It was not observed in such high percentages in the 1996 sample, most probably because conditions were not as favourable in that year and possibly due to competition for nutrients and/or light from the blue-green algae.

After at least 50 years of stability in the diatom assemblages, nutrient enrichment appears to have caused changes in the algal communities. Continued monitoring of the site is recommended to assess the impacts of eutrophication on other aspects of the lake's biota and on overall lake ecosystem stability. It might be that in oligo- to mesotrophic sites such as Llyn Tegid, the diatom record can provide an early warning to raise the alarm that ecological changes are occurring in the lake before enrichment can be detected by nutrient chemistry data. This has been recently illustrated in a study of a sediment core from Loch Ness where there are significant changes in the recent diatom assemblages but where the water chemistry methods are not sensitive enough to detect such small changes in nutrient concentrations (Jones *et al.*, in press).

Further recommendations

- Continued chemical and biological monitoring of the site is recommended in order to observe whether there is any further deterioration in water quality. The effects of the inferred chemical changes upon the stability of the lake's flora and fauna should be monitored.
- Nutrient reductions from external sources are clearly desirable but any improvement in water quality may not be observed for some years given that there is likely to be an internal P load already locked up in the lake sediments. The calculation of nutrient budgets would help to more clearly define the major sources of nutrients to the lake.
- Collation of any historical data (land-use, STW data, water chemistry, algal records) would allow a more complete assessment of environmental change to be made and would enable a fuller interpretation of the palaeolimnological record.

- A TP reconstruction for Llyn Tegid could be re-calculated using the improved diatom-P transfer function for oligo- to meso-trophic lakes once it has been developed later this year. ENSIS would forward this to the Environment Agency at no extra cost.

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APPENDIX

List of full diatom names and codes for each sample of BALA1.

The information given on the top line for each sample is as follows, eg:

- BALA = site code
- BALA00 = sample code
- BALA1 = core code
- CORE = sample type
- 13246 = slide number
- 12/07/96 = sampling date
- 347 = no. of diatom valves counted
- BALA00 = sample code
- 0 0.5 = top and bottom depth of the sample in cm.

Followed by a list of the diatoms present in the sample, ordered alphabetically by code.

BALA	BALA00	BALA1	CORE	13246	12/07/96	347
	BALA00	0	.5			
AC002A				Achnanthes linearis (W. Sm.) Grun. in Cleve & Grun. 1880		
AC013A				Achnanthes minutissima minutissima Kutz. 1833		
AC116A				Achnanthes rossii Hust. 1954		
AC136A				Achnanthes subatomoides (Hust.) Lange-Bertalot & Archibald in Krammer & Lange-Bertalot 1985		
AC9999				Achnanthes sp.		
AS001A				Asterionella formosa formosa Hassall 1850		
AU020A				Aulacoseira subarctica (O.Mull.) Haworth		
CM015A				Cymbella cesatii cesatii (Rabenh.) Grun. in A. Schmidt 1881		
CM103A				Cymbella silesiaca Bleisch ex Rabenh. 1864		
CM9999				Cymbella sp.		
CY007A				Cyclotella glomerata Bachm. 1911		
CY010A				Cyclotella comensis Grun. in Van Heurck 1882		
DT003A				Diatoma vulgare vulgare Bory 1824		
EU049A				Eunotia curvata curvata (Kutz.) Lagerst. 1884		
EU9999				Eunotia sp.		
FR008A				Fragilaria crotonensis Kitton 1869		
FR009A				Fragilaria capucina capucina Desm. 1825		
FR009B				Fragilaria capucina mesolepta (Rabenh.) Rabenh. 1864		
FR019A				Fragilaria intermedia Grun. in Van Heurck 1881		
FR045A				Fragilaria parasitica (W. Sm.) Grun. in Van Heurck 1881		
FR9999				Fragilaria sp.		
FU002A				Frustulia rhomboides rhomboides (Ehrenb.) De Toni 1891		
GO013A				Gomphonema parvulum parvulum (Kutz.) Kutz. 1849		
GO9999				Gomphonema sp.		
HN001A				Hannaea arcus arcus (Ehrenb.) Patr. in Patr. & Reimer 1966		
NA005A				Navicula seminulum Grun. 1860		
NA084A				Navicula atomus (Kutz.) Grun. 1860		
NA9845				Navicula [cryptotenella [var. 1]] Ballestera (JR) 1994		
NI008A				Nitzschia frustulum (Kutz.) Grun. in Cleve & Grun. 1880		
NI009A				Nitzschia palea palea (Kutz.) W. Sm. 1856		
NI024A				Nitzschia sublinearis Hust. 1930		
NI9999				Nitzschia sp.		
SY003A				Synedra acus acus Kutz. 1844		
SY010A				Synedra minuscula Grun. in Van Heurck 1881		
TA001A				Tabellaria flocculosa flocculosa (Roth) Kutz. 1844		
TE9999				Tetracyclus sp.		
ZZZ990				Temporary sp. 10		

BALA	BALA02	BALA1	CORE	13248	12/07/96	320
	BALA02	2	2.5			
AC013A				Achnanthes minutissima minutissima Kutz. 1833		
AC022A				Achnanthes marginulata Grun. in Cleve & Grun. 1880		
AC136A				Achnanthes subatomoides (Hust.) Lange-Bertalot & Archibald in Krammer & Lange-Bertalot 1985		
AM012A				Amphora pediculus (Kutz.) Grun.		
AS001A				Asterionella formosa formosa Hassall 1850		
AU020A				Aulacoseira subarctica (O.Mull.) Haworth		
CM103A				Cymbella silesiaca Bleisch ex Rabenh. 1864		
CY007A				Cyclotella glomerata Bachm. 1911		
CY010A				Cyclotella comensis Grun. in Van Heurck 1882		
DT002A				Diatoma hyemale hyemale (Roth) Heib. 1863		
EU009A				Eunotia exigua exigua (Breb. ex Kutz.) Rabenh. 1864		
EU049A				Eunotia curvata curvata (Kutz.) Lagerst. 1884		
FR008A				Fragilaria crotonensis Kitton 1869		
FR019A				Fragilaria intermedia Grun. in Van Heurck 1881		
FR9999				Fragilaria sp.		
FU002A				Frustulia rhomboides rhomboides (Ehrenb.) De Toni 1891		
GO013A				Gomphonema parvulum parvulum (Kutz.) Kutz. 1849		
NA008A				Navicula rhyncocephala rhyncocephala Kutz. 1844		
NA084A				Navicula atomus (Kutz.) Grun. 1860		
NA9845				Navicula [cryptotenella [var. 1]] Ballestera (JR) 1994		

NA9999 Navicula sp.
 NI017A Nitzschia gracilis Hantzsch 1860
 PI004A Pinnularia interrupta W. Smith
 SY001A Synedra ulna ulna (Nitzsch) Ehrenb. 1836
 SY009A Synedra nana Meister 1912
 TA001A Tabellaria flocculosa flocculosa (Roth) Kutz. 1844
 ZZZ990 Temporary sp. 10

BALA BALA04 BALA1 CORE 13250 12/07/96 320
 BALA04 4 4.5
 AC013A Achnanthes minutissima minutissima Kutz. 1833
 AC035A Achnanthes pusilla pusilla Grun. in Cleve & Grun. 1880
 AC136A Achnanthes subatomoides (Hust.) Lange-Bertalot & Archibald in
 Krammer & Lange-Bertalot 1985
 AS001A Asterionella formosa formosa Hassall 1850
 AU020A Aulacoseira subarctica (O.Mull.) Haworth
 BR001A Brachysira vitrea (Grun.) R. Ross in Hartley 1986
 CM018A Cymbella gracilis (Rabenh.) Cleve 1894
 CM031A Cymbella minuta minuta Hilse ex Rabenh. 1862
 CM103A Cymbella silesiaca Bleisch ex Rabenh. 1864
 CY007A Cyclotella glomerata Bachm. 1911
 CY010A Cyclotella comensis Grun. in Van Heurck 1882
 CY9999 Cyclotella sp.
 DT002A Diatoma hyemale hyemale (Roth) Heib. 1863
 DT003A Diatoma vulgare vulgare Bory 1824
 EU047A Eunotia incisa W. Sm. ex Greg. 1854
 EU108A Eunotia intermedia (Hust) Norpel, Lange-Bertalot & Alles 1991
 EU9999 Eunotia sp.
 FR009A Fragilaria capucina capucina Desm. 1825
 FR019A Fragilaria intermedia Grun. in Van Heurck 1881
 FR9999 Fragilaria sp.
 FU002A Frustulia rhomboides rhomboides (Ehrenb.) De Toni 1891
 GO013A Gomphonema parvulum parvulum (Kutz.) Kutz. 1849
 GO050A Gomphonema minutum (Ag.) Ag. 1831
 HN001A Hannaea arcus arcus (Ehrenb.) Patr. in Patr. & Reimer 1966
 MR001A Meridion circulare circulare (Grev.) Ag. 1831
 NA008A Navicula rhyncocephala rhyncocephala Kutz. 1844
 NA042A Navicula minima minima Grun. in Van Heurck 1880
 NA084A Navicula atomus (Kutz.) Grun. 1860
 NA9845 Navicula [cryptotenella [var. 1]] Ballestera (JR) 1994
 NI009A Nitzschia palea palea (Kutz.) W. Sm. 1856
 SY001A Synedra ulna ulna (Nitzsch) Ehrenb. 1836
 SY009A Synedra nana Meister 1912
 SY010A Synedra minuscula Grun. in Van Heurck 1881
 TA001A Tabellaria flocculosa flocculosa (Roth) Kutz. 1844
 TE9999 Tetracyclus sp.
 ZZZ990 Temporary sp. 10

BALA BALA07 BALA1 CORE 13252 12/07/96 371
 BALA07 7 8
 AC013A Achnanthes minutissima minutissima Kutz. 1833
 AC023A Achnanthes conspicua conspicua A. Mayer 1919
 AS001A Asterionella formosa formosa Hassall 1850
 AU020A Aulacoseira subarctica (O.Mull.) Haworth
 CM031A Cymbella minuta minuta Hilse ex Rabenh. 1862
 CM103A Cymbella silesiaca Bleisch ex Rabenh. 1864
 CY007A Cyclotella glomerata Bachm. 1911
 CY010A Cyclotella comensis Grun. in Van Heurck 1882
 CY9999 Cyclotella sp.
 DT002A Diatoma hyemale hyemale (Roth) Heib. 1863
 EU009A Eunotia exigua exigua (Breb. ex Kutz.) Rabenh. 1864
 EU9999 Eunotia sp.
 FR002C Fragilaria construens venter (Ehrenb.) Grun. in Van Heurck 188
 1
 FR006A Fragilaria brevistriata brevistriata Grun. in Van Heurck 1885

FR009A Fragilaria capucina capucina Desm. 1825
 FR019A Fragilaria intermedia Grun. in Van Heurck 1881
 FR9999 Fragilaria sp.
 GO013A Gomphonema parvulum parvulum (Kutz.) Kutz. 1849
 GO050A Gomphonema minutum (Ag.) Ag. 1831
 HN001A Hannaea arcus arcus (Ehrenb.) Patr. in Patr. & Reimer 1966
 NA084A Navicula atomus (Kutz.) Grun. 1860
 NA9999 Navicula sp.
 NI009A Nitzschia palea palea (Kutz.) W. Sm. 1856
 NI017A Nitzschia gracilis Hantzsch 1860
 NI198A Nitzschia lacuum Lange-Bertalot 1980
 NI9999 Nitzschia sp.
 SA9999 Stauroneis sp.
 SU005A Surirella linearis linearis W. Sm. 1853
 SY001A Synedra ulna ulna (Nitzsch) Ehrenb. 1836
 SY003A Synedra acus acus Kutz. 1844
 SY009A Synedra nana Meister 1912
 TA001A Tabellaria flocculosa flocculosa (Roth) Kutz. 1844
 ZZZ990 Temporary sp. 10
 ZZZ991 Temporary sp. 9

BALA	BALA10	BALA1	CORE	13253	12/07/96	362
	BALA10	10	11			
	AC013A	Achnanthes minutissima	minutissima	Kutz. 1833		
	AC044A	Achnanthes levanderi	Hust. 1933			
	AC049A	Achnanthes plonensis	Hust. 1930			
	AC116A	Achnanthes rossii	Hust. 1954			
	AC9999	Achnanthes sp.				
	AS001A	Asterionella formosa	formosa	Hassall 1850		
	AU020A	Aulacoseira subarctica	(O.Mull.)	Haworth		
	CM015A	Cymbella cesatii	cesatii (Rabenh.)	Grun. in A. Schmidt 1881		
	CM031A	Cymbella minuta	minuta	Hilse ex Rabenh. 1862		
	CM103A	Cymbella silesiaca	Bleisch ex Rabenh.	1864		
	CM9999	Cymbella sp.				
	CO001A	Cocconeis placentula	placentula	Ehrenb. 1838		
	CY004A	Cyclotella stelligera	(Cleve & Grun. in Cleve)	Van Heurck 188		
2	CY007A	Cyclotella glomerata	Bachm.	1911		
	CY010A	Cyclotella comensis	Grun. in Van Heurck	1882		
	DT002A	Diatoma hyemale	hyemale (Roth)	Heib. 1863		
	EU009A	Eunotia exigua	exigua (Breb. ex Kutz.)	Rabenh. 1864		
	EU010A	Eunotia faba	(Ehrenb.)	Grun. in Van Heurck 1881		
	EU047A	Eunotia incisa	W. Sm. ex Greg.	1854		
	EU9999	Eunotia sp.				
	FR009A	Fragilaria capucina	capucina	Desm. 1825		
	FR019A	Fragilaria intermedia	Grun. in Van Heurck	1881		
	FR9999	Fragilaria sp.				
	FU002A	Frustulia rhomboides	rhomboides (Ehrenb.)	De Toni 1891		
	GO001A	Gomphonema olivaceum	(Hornemann)	Breb. 1838		
	GO003A	Gomphonema angustatum	angustatum (Kutz.)	Rabenh. 1864		
	GO013A	Gomphonema parvulum	parvulum (Kutz.)	Kutz. 1849		
	GO050A	Gomphonema minutum	(Ag.)	Ag. 1831		
	MR001A	Meridion circulare	circulare (Grev.)	Ag. 1831		
	NA005A	Navicula seminulum	Grun. 1860			
	NA007A	Navicula cryptocephala	cryptocephala	Kutz. 1844		
	NA068A	Navicula impexa	Hust. 1961			
	NA133A	Navicula schassmannii	Hust. 1937			
	NA168A	Navicula vitabunda	Hust. 1930			
	NA9845	Navicula [cryptotenella [var. 1]]	Ballestera (JR)	1994		
	NI002A	Nitzschia fonticola	Grun. in Van Heurck	1881		
	NI015A	Nitzschia dissipata	(Kutz.)	Grun. 1862		
	NI9999	Nitzschia sp.				
	SY009A	Synedra nana	Meister	1912		
	TA001A	Tabellaria flocculosa	flocculosa (Roth)	Kutz. 1844		
	ZZZ990	Temporary sp.	10			

ZZZ991 Temporary sp. 9

BALA	BALA12	BALA1	CORE	13254	12/07/96	314
	BALA12	12	13			
	AC013A	Achnanthes minutissima	minutissima	Kutz. 1833		
	AC023A	Achnanthes conspicua	conspicua	A. Mayer 1919		
	AC044A	Achnanthes levanderi	Hust.	1933		
	AC049A	Achnanthes plonensis	Hust.	1930		
	AC136A	Achnanthes subatomoides	(Hust.) Lange-Bertalot & Archibald	in		
	Krammer & Lange-Bertalot 1985					
	AS001A	Asterionella formosa	formosa	Hassall 1850		
	AU020A	Aulacoseira subarctica	(O.Mull.)	Haworth		
	AU9999	Aulacoseira	sp.			
	BR001A	Brachysira vitrea	(Grun.)	R. Ross in Hartley 1986		
	CM103A	Cymbella silesiaca	Bleisch ex Rabenh.	1864		
2	CY004A	Cyclotella stelligera	(Cleve & Grun. in Cleve)	Van Heurck 188		
	CY007A	Cyclotella glomerata	Bachm.	1911		
	CY010A	Cyclotella comensis	Grun. in Van Heurck	1882		
7	DP007A	Diploneis oblongella	oblongella (Naegeli ex Kutz.)	R. Ross 194		
	DT002A	Diatoma hyemale	hyemale (Roth)	Heib. 1863		
	EU009A	Eunotia exigua	exigua (Breb. ex Kutz.)	Rabenh. 1864		
	EU047A	Eunotia incisa	W. Sm. ex Greg.	1854		
	FR009A	Fragilaria capucina	capucina	Desm. 1825		
	FR019A	Fragilaria intermedia	Grun. in Van Heurck	1881		
	FR9999	Fragilaria	sp.			
	GO013A	Gomphonema parvulum	parvulum (Kutz.)	Kutz. 1849		
	MR001A	Meridion circulare	circulare (Grev.)	Ag. 1831		
	NA005A	Navicula seminulum	Grun.	1860		
	NA084A	Navicula atomus	(Kutz.) Grun.	1860		
	NI002A	Nitzschia fonticola	Grun. in Van Heurck	1881		
	PI014A	Pinnularia appendiculata	(Ag.)	Cleve 1896		
	PI9999	Pinnularia	sp.			
	SY001A	Synedra ulna	ulna (Nitzsch)	Ehrenb. 1836		
	SY009A	Synedra nana	Meister	1912		
	TA001A	Tabellaria flocculosa	flocculosa (Roth)	Kutz. 1844		
	ZZZ990	Temporary sp. 10				
	ZZZ991	Temporary sp. 9				

BALA	BALA15	BALA1	CORE	13255	12/07/96	343
	BALA15	15	16			
	AC013A	Achnanthes minutissima	minutissima	Kutz. 1833		
	AC023A	Achnanthes conspicua	conspicua	A. Mayer 1919		
	AC136A	Achnanthes subatomoides	(Hust.) Lange-Bertalot & Archibald	in		
	Krammer & Lange-Bertalot 1985					
	AC141A	Achnanthes bioretii	Germain	1957		
	AC9999	Achnanthes	sp.			
	AS001A	Asterionella formosa	formosa	Hassall 1850		
	AU020A	Aulacoseira subarctica	(O.Mull.)	Haworth		
	BR001A	Brachysira vitrea	(Grun.)	R. Ross in Hartley 1986		
	CM031A	Cymbella minuta	minuta Hilse ex Rabenh.	1862		
	CM103A	Cymbella silesiaca	Bleisch ex Rabenh.	1864		
	CO001A	Cocconeis placentula	placentula	Ehrenb. 1838		
	CY002A	Cyclotella pseudostelligera	Hust.	1939		
	CY004A	Cyclotella stelligera	(Cleve & Grun. in Cleve)	Van Heurck 188		
2	CY007A	Cyclotella glomerata	Bachm.	1911		
	CY010A	Cyclotella comensis	Grun. in Van Heurck	1882		
	DT002A	Diatoma hyemale	hyemale (Roth)	Heib. 1863		
	EU009A	Eunotia exigua	exigua (Breb. ex Kutz.)	Rabenh. 1864		
	EU047A	Eunotia incisa	W. Sm. ex Greg.	1854		
	FR009A	Fragilaria capucina	capucina	Desm. 1825		
	FR019A	Fragilaria intermedia	Grun. in Van Heurck	1881		
	GO001A	Gomphonema olivaceum	(Hornemann)	Breb. 1838		

GO013A Gomphonema parvulum parvulum (Kutz.) Kutz. 1849
 HN001A Hannaea arcus arcus (Ehrenb.) Patr. in Patr. & Reimer 1966
 NA007A Navicula cryptocephala cryptocephala Kutz. 1844
 NA168A Navicula vitabunda Hust. 1930
 NA9999 Navicula sp.
 NI009A Nitzschia palea palea (Kutz.) W. Sm. 1856
 NI015A Nitzschia dissipata (Kutz.) Grun. 1862
 NI025A Nitzschia recta Hantzsch ex Rabenh. 1861
 SU005A Surirella linearis linearis W. Sm. 1853
 SY001A Synedra ulna ulna (Nitzsch) Ehrenb. 1836
 SY003A Synedra acus acus Kutz. 1844
 SY009A Synedra nana Meister 1912
 TA001A Tabellaria flocculosa flocculosa (Roth) Kutz. 1844
 ZZZ990 Temporary sp. 10
 ZZZ991 Temporary sp. 9

BALA BALA20 BALA1 CORE 13256 12/07/96 329
 BALA20 20 21

AC013A Achnanthes minutissima minutissima Kutz. 1833
 AC134A Achnanthes helvetica alpina Flower and Jones 1989
 AC136A Achnanthes subatomoides (Hust.) Lange-Bertalot & Archibald in
 Krammer & Lange-Bertalot 1985
 AC9999 Achnanthes sp.
 AS001A Asterionella formosa formosa Hassall 1850
 AU020A Aulacoseira subarctica (O.Mull.) Haworth
 BR001A Brachysira vitrea (Grun.) R. Ross in Hartley 1986
 CM031A Cymbella minuta minuta Hilse ex Rabenh. 1862
 CM103A Cymbella silesiaca Bleisch ex Rabenh. 1864
 CO001A Cocconeis placentula placentula Ehrenb. 1838
 CY002A Cyclotella pseudostelligera Hust. 1939
 CY004A Cyclotella stelligera (Cleve & Grun. in Cleve) Van Heurck 188

2

CY007A Cyclotella glomerata Bachm. 1911
 CY010A Cyclotella comensis Grun. in Van Heurck 1882
 DT002A Diatoma hyemale hyemale (Roth) Heib. 1863
 EU002A Eunotia pectinalis pectinalis (O.F. Mull.) Rabenh. 1864
 EU009A Eunotia exigua exigua (Breb. ex Kutz.) Rabenh. 1864
 EU047A Eunotia incisa W. Sm. ex Greg. 1854
 EU9999 Eunotia sp.
 FR009A Fragilaria capucina capucina Desm. 1825
 FR019A Fragilaria intermedia Grun. in Van Heurck 1881
 GO001A Gomphonema olivaceum (Hornemann) Breb. 1838
 GO013A Gomphonema parvulum parvulum (Kutz.) Kutz. 1849
 GO029A Gomphonema clavatum Ehr.
 GO050A Gomphonema minutum (Ag.) Ag. 1831
 HN001A Hannaea arcus arcus (Ehrenb.) Patr. in Patr. & Reimer 1966
 MR001A Meridion circulare circulare (Grev.) Ag. 1831
 NA005A Navicula seminulum Grun. 1860
 NA068A Navicula impexa Hust. 1961
 NA190A Navicula agrestis Hust. 1937
 NI009A Nitzschia palea palea (Kutz.) W. Sm. 1856
 NI015A Nitzschia dissipata (Kutz.) Grun. 1862
 NI198A Nitzschia lacuum Lange-Bertalot 1980
 PI007A Pinnularia viridis viridis (Nitzsch) Ehrenb. 1843
 SY001A Synedra ulna ulna (Nitzsch) Ehrenb. 1836
 SY009A Synedra nana Meister 1912
 SY010A Synedra minuscula Grun. in Van Heurck 1881
 TA001A Tabellaria flocculosa flocculosa (Roth) Kutz. 1844
 ZZZ990 Temporary sp. 10
 ZZZ991 Temporary sp. 9
 ZZZ991 Temporary sp. 9

BALA BALA25 BALA1 CORE 13257 12/07/96 347
 BALA25 25 26
 AC013A Achnanthes minutissima minutissima Kutz. 1833

AC023A Achnanthes conspicua conspicua A. Mayer 1919
AC034A Achnanthes suchlandtii Hust. 1933
AC044A Achnanthes levanderi Hust. 1933
AC083A Achnanthes laevis Ostr. 1910
AC136A Achnanthes subatomoides (Hust.) Lange-Bertalot & Archibald in
Krammer & Lange-Bertalot 1985
AS001A Asterionella formosa formosa Hassall 1850
AU020A Aulacoseira subarctica (O.Mull.) Haworth
BR001A Brachysira vitrea (Grun.) R. Ross in Hartley 1986
CA9999 Caloneis sp.
CM018A Cymbella gracilis (Rabenh.) Cleve 1894
CY002A Cyclotella pseudostelligera Hust. 1939
CY004A Cyclotella stelligera (Cleve & Grun. in Cleve) Van Heurck 188
2
CY007A Cyclotella glomerata Bachm. 1911
CY010A Cyclotella comensis Grun. in Van Heurck 1882
EU009A Eunotia exigua exigua (Breb. ex Kutz.) Rabenh. 1864
EU047A Eunotia incisa W. Sm. ex Greg. 1854
EU049A Eunotia curvata curvata (Kutz.) Lagerst. 1884
EU108A Eunotia intermedia (Hust) Norpel, Lange-Bertalot & Alles 1991
FR002C Fragilaria construens venter (Ehrenb.) Grun. in Van Heurck 188
1
FR009A Fragilaria capucina capucina Desm. 1825
FR019A Fragilaria intermedia Grun. in Van Heurck 1881
FR9999 Fragilaria sp.
FU002A Frustulia rhomboides rhomboides (Ehrenb.) De Toni 1891
GO004A Gomphonema gracile Ehrenb. 1838
GO013A Gomphonema parvulum parvulum (Kutz.) Kutz. 1849
GO029A Gomphonema clavatum Ehr.
GO9999 Gomphonema sp.
HN001A Hannaea arcus arcus (Ehrenb.) Patr. in Patr. & Reimer 1966
MR001A Meridion circulare circulare (Grev.) Ag. 1831
NA003A Navicula radiosa radiosa Kutz. 1844
NA007A Navicula cryptocephala cryptocephala Kutz. 1844
NA063A Navicula trivialis Lange-Bertalot 1980
NA133A Navicula schassmannii Hust. 1937
NA9845 Navicula [cryptotenella [var. 1]] Ballestera (JR) 1994
NA9999 Navicula sp.
NI015A Nitzschia dissipata (Kutz.) Grun. 1862
NI063A Nitzschia agnita Hust. 1957
SY001A Synedra ulna ulna (Nitzsch) Ehrenb. 1836
SY009A Synedra nana Meister 1912
SY010A Synedra minuscula Grun. in Van Heurck 1881
TA001A Tabellaria flocculosa flocculosa (Roth) Kutz. 1844
ZZZ990 Temporary sp. 10
ZZZ991 Temporary sp. 9

BALA BALA30 BALA1 CORE 13258 12/07/96 367
BALA30 30 31
AC013A Achnanthes minutissima minutissima Kutz. 1833
AC032A Achnanthes hungarica (Grun.) Grun. in Cleve & Grun. 1880
AC136A Achnanthes subatomoides (Hust.) Lange-Bertalot & Archibald in
Krammer & Lange-Bertalot 1985
AC9999 Achnanthes sp.
AS001A Asterionella formosa formosa Hassall 1850
AU020A Aulacoseira subarctica (O.Mull.) Haworth
BR001A Brachysira vitrea (Grun.) R. Ross in Hartley 1986
CM004A Cymbella microcephala microcephala Grun. in Van Heurck 1880
CM031A Cymbella minuta minuta Hilse ex Rabenh. 1862
CM103A Cymbella silesiaca Bleisch ex Rabenh. 1864
CO001A Cocconeis placentula placentula Ehrenb. 1838
CY002A Cyclotella pseudostelligera Hust. 1939
CY004A Cyclotella stelligera (Cleve & Grun. in Cleve) Van Heurck 188
2
CY007A Cyclotella glomerata Bachm. 1911

CY010A Cyclotella comensis Grun. in Van Heurck 1882
 DT002A Diatoma hyemale hyemale (Roth) Heib. 1863
 EU002A Eunotia pectinalis pectinalis (O.F. Mull.) Rabenh. 1864
 EU009A Eunotia exigua exigua (Breb. ex Kutz.) Rabenh. 1864
 EU047A Eunotia incisa W. Sm. ex Greg. 1854
 FR009A Fragilaria capucina capucina Desm. 1825
 FR019A Fragilaria intermedia Grun. in Van Heurck 1881
 FR9999 Fragilaria sp.
 GO013A Gomphonema parvulum parvulum (Kutz.) Kutz. 1849
 GO029A Gomphonema clavatum Ehr.
 GO050A Gomphonema minutum (Ag.) Ag. 1831
 HN001A Hannaea arcus arcus (Ehrenb.) Patr. in Patr. & Reimer 1966
 NA008A Navicula rhyncocephala rhyncocephala Kutz. 1844
 NA038A Navicula arvensis Hust.
 NA050A Navicula clementis clementis Grun. 1882
 NI005A Nitzschia perminuta (Grun. in Van Heurck) M. Perag. 1903
 NI009A Nitzschia palea palea (Kutz.) W. Sm. 1856
 NI017A Nitzschia gracilis Hantzsch 1860
 SY003A Synedra acus acus Kutz. 1844
 SY009A Synedra nana Meister 1912
 SY010A Synedra minuscula Grun. in Van Heurck 1881
 TA001A Tabellaria flocculosa flocculosa (Roth) Kutz. 1844
 ZZZ990 Temporary sp. 10
 ZZZ991 Temporary sp. 9

BALA	BALA35	BALA1	CORE	13259	12/07/96	333
	BALA35	36	37			
1880	AC001A	Achnanthes lanceolata	(Breb. ex Kutz.) Grun. in Cleve & Grun.			
	AC013A	Achnanthes minutissima	minutissima Kutz. 1833			
	AC049A	Achnanthes plonensis	Hust. 1930			
	AS001A	Asterionella formosa	formosa Hassall 1850			
	AU020A	Aulacoseira subarctica	(O.Mull.) Haworth			
	AU9999	Aulacoseira sp.				
	CM031A	Cymbella minuta	minuta Hilse ex Rabenh. 1862			
	CM103A	Cymbella silesiaca	Bleisch ex Rabenh. 1864			
	CM9999	Cymbella sp.				
	CO001A	Cocconeis placentula	placentula Ehrenb. 1838			
	CY002A	Cyclotella pseudostelligera	Hust. 1939			
2	CY004A	Cyclotella stelligera	(Cleve & Grun. in Cleve) Van Heurck 188			
	CY006A	Cyclotella kuetzingiana	kuetzingiana Thwaites 1848			
	CY007A	Cyclotella glomerata	Bachm. 1911			
	CY010A	Cyclotella comensis	Grun. in Van Heurck 1882			
	EU009A	Eunotia exigua	exigua (Breb. ex Kutz.) Rabenh. 1864			
	EU047A	Eunotia incisa	W. Sm. ex Greg. 1854			
	EU108A	Eunotia intermedia	(Hust) Norpel, Lange-Bertalot & Alles 1991			
	FR009A	Fragilaria capucina	capucina Desm. 1825			
	FR019A	Fragilaria intermedia	Grun. in Van Heurck 1881			
	FR9999	Fragilaria sp.				
	GO001A	Gomphonema olivaceum	(Hornemann) Breb. 1838			
	GO013A	Gomphonema parvulum	parvulum (Kutz.) Kutz. 1849			
	GO050A	Gomphonema minutum	(Ag.) Ag. 1831			
	MR001A	Meridion circulare	circulare (Grev.) Ag. 1831			
	NA045A	Navicula bryophila	bryophila J.B. Petersen 1928			
	NA084A	Navicula atomus	(Kutz.) Grun. 1860			
	NA133A	Navicula schassmannii	Hust. 1937			
	NA9845	Navicula [cryptotenella [var. 1]]	Ballester (JR) 1994			
	NI005A	Nitzschia perminuta	(Grun. in Van Heurck) M. Perag. 1903			
	NI031A	Nitzschia linearis	linearis W. Sm. 1853			
	NI9999	Nitzschia sp.				
	PI9999	Pinnularia sp.				
	SY003A	Synedra acus	acus Kutz. 1844			
	SY009A	Synedra nana	Meister 1912			
	TA001A	Tabellaria flocculosa	flocculosa (Roth) Kutz. 1844			

ZZZ990 Temporary sp. 10
ZZZ991 Temporary sp. 9

Carbonaceous Particle Data for Llyn Tegid - core BALA1.

Depth (cm)	Particles (gDM⁻¹)	Flux (cm⁻² yr⁻¹)
0.0 - 0.5	1348	188.7
0.5 - 1.0	3330	466.2
1.0 - 1.5	2817	394.4
1.5 - 2.0	4332	606.5
2.0 - 2.5	2627	364.5
3.0 - 3.5	4146	554.6
4.0 - 4.5	3939	512.0
5.0 - 6.0	3985	518.0
7.0 - 8.0	3297	428.6
9.0 - 10.0	4324	594.5
12.0 - 13.0	6899	1121.0
14.0 - 15.0	5447	966.9
16.0 - 17.0	6122	1086.6
18.0 - 19.0	3879	640.1
20.0 - 21.0	4474	682.2
24.0 - 25.0	2274	375.3
28.0 - 29.0	2042	219.5
32.0 - 33.0	904	92.7
36.0 - 37.0	1433	129.0
39.0 - 40.0	361	32.4