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RESEARCH REPORT

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Diatom derived phosphorus targets-broadland

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Final Report to the Environment Agency

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Executive Summary

1. This is the final report to the Environment Agency under contract 5289: Diatom derived phosphorus targets - Broadland.

2. The report employs palaeolimnological techniques to determine dated profiles of diatom-inferred phosphorus concentrations for 3 lakes in the Norfolk Broads: Barton Broad, Rollesby Broad and Wroxham Broad.

3. The report describes the lithostratigraphies (% dry weight and loss on ignition), and presents results of radiometric dating and diatom analysis of ten levels from a sediment core from each site.

4. A diatom-based phosphorus transfer function is applied to the core data to generate quantitative reconstructions of total phosphorus (TP) for each site, following taxonomic harmonization between the training set and core species data. The TP reconstructions are calculated using a northwest European calibration set of 152 lakes (Bennion *et al.*, 1996a).

5. The report interprets the findings with reference to previously published work (Moss, 1980; Osborne & Moss, 1977).

6. The study shows that all three sites have experienced a recent shift in their diatom assemblages from one dominated by non-planktonic taxa indicative of clearwater, macrophyte-dominated communities to one dominated by planktonic taxa, commonly observed in highly nutrient-rich, shallow, alkaline freshwaters.

7. A number of problems were encountered, however, with the radiometric dating of the Barton Broad core, and with the application of the diatom-phosphorus transfer function to the fossil diatom assemblages in all cores. Therefore, the quantitative data must be interpreted with caution. The results for Wroxham Broad (the site with the clearest diatom-inferred TP {DI-TP} trend) indicate that the switch from the non-plankton dominated flora to the planktonic one occurred at an annual mean TP concentration of approximately 100 μg l^{-1}.

8. Information on the history of the lakes will be important in the development of Environment Agency management plans. The results will assist the selection of appropriate TP targets and the formation of informed action plans to improve the current water quality.

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Maps showing the core locations in Barton, Rollesby and Wroxham Broad

1 Objectives

The overall project objective was to determine dated profiles of total phosphorus (TP) concentrations using diatom transfer functions for 3 lakes in the Norfolk Broads: Barton Broad, Rollesby Broad and Wroxham Broad, to assist the EA in determining appropriate water quality targets.

The specific objectives were as follows:

1. To collect cores from Barton, Rollesby and Wroxham Broad.
2. To determine dates using ^{210}Pb from a minimum of 10 horizons covering the surface to the period c. 1800.
3. To determine the diatom composition for each horizon, giving particular attention to the period 1920-1970 and derive TP concentrations.
4. To produce a brief report detailing TP profiles for each site.

A considerable amount of research has been carried out by the EA (formerly NRA) into the most effective way of restoring the Norfolk Broads. Phosphorus removal from sewage effluents has been undertaken at several key sites progressively since 1980. This has not resulted in expected changes in the community structure of these shallow lakes and research has indicated two probable reasons. The first relates to the significant release of phosphorus from the lake sediment and the second is the apparent resilience of the ecosystem to change. It has now been demonstrated that the latter effect can be overcome by biomanipulation, although further work will be required to demonstrate how such induced changes to the community structure can be stabilised. A key element of this stability is the growth of macrophytes and earlier research suggests that stability will only be achieved if phosphorus concentrations can be reduced below a threshold value. This concentration would then form a long term (non-statutory) water quality target which the EA and other organisations could use for management purposes.

It is suspected that this threshold lies within the range of 30-100 µg TP l^{-1}, but an additional approach to determining an appropriate value is the reconstruction of phosphorus from fossil diatom assemblages in sediment cores. Anecdotal evidence suggests that these shallow lakes were still dominated by aquatic vegetation during the 1940s, although it is clear that enrichment probably started from 1920 onward (Osborne & Moss, 1977; Moss, 1980). This has led to the concept that 3 phases of enrichment occurred in these lakes:

Phase 1 (ending around 1900) was probably dominated by a diverse aquatic macrophyte flora.
Phase 2 (1900-1950) was dominated by an increasing biomass of less diverse macrophytes.
Phase 3 (1950-date) was dominated by phytoplankton.

Therefore, by using palaeolimnological techniques, information regarding lake history can be obtained and by reconstructing the phosphorus concentrations for these periods, appropriate phosphorus targets for these lakes can be set

2 Methods

2.1 Coring and Lithostratigraphic Analyses

Long cores were taken from the deepest and/or the least disturbed point in all three sites using a piston corer, operated from an inflatable boat. The cores were extruded in the laboratory and sliced at 0.5 cm vertical intervals to a depth of 20 cm and subsequently 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.

2.2 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.

Approximately ten selected sediment samples from each core were analysed at the Department of Applied Mathematics and Theoretical Physics, University of Liverpool. For full details see chapter 3.

2.3 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 set of lakes. This approach has been successfully employed in recent years to quantitatively infer lake pH (e.g. Battarbee *et al.*, 1988; Birks *et al.*, 1990; Stevenson *et al.*, 1991) and lake total phosphorus (TP) concentrations (e.g. Anderson *et al.*, 1993; Bennion, 1994; Bennion *et al.*, 1995; Bennion *et al.*, 1996a), 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 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 (e.g. Bennion *et al.*, 1996b).

In this study, ten levels from each 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 phosphorus transfer function was applied to the core data to generate quantitative reconstructions of TP for each site, following taxonomic harmonization between the training set and core species data. The TP reconstructions were calculated using a northwest European calibration set of 152 lakes (Bennion *et al.*, 1996a) and the results are based on simple WA with inverse deshrinking on log-transformed annual mean TP data. The European model performs well with a squared correlation (r^2) between observed and inferred values of 0.85, a root mean square of the error (RMSE) (observed - inferred) of 0.19 $\log_{10}$ TP units, and an RMSE of prediction (RMSEP) obtained by jackknifing of 0.22 $\log_{10}$ TP units. This training set can infer epilimnetic TP concentrations across a large range from ~10 to ~1000 μg TP l^{-1}. The reconstructions were implemented using CALIBRATE (Juggins & ter Braak, 1993).

3 Radiometric Dating Report

Methods

Sediment cores from Barton Broad, Rollesby Broad and Wroxham Broad were analysed for ^{210}Pb, ^{226}Ra and ^{137}Cs by direct gamma assay using Ortec HPGe GWL series well-type coaxial low background intrinsic germanium detectors (Appleby *et al.* 1986) in the Liverpool University Environmental Radioactivity Laboratory. ^{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 was measured by its emissions at 662keV. The absolute efficiencies of the detectors were determined using calibrated sources and sediment samples of known activity. Corrections were made for the effect of self absorption of low energy γ rays within the sample (Appleby *et al.* 1992).

Results

The results of the radiometric analyses are given in Table 1 and shown graphically in Figs.1-3. Table 2 compares inventories of fallout radionuclides in each core with estimates of the atmospheric fluxes.

Lead-210 Activity

Of the three cores analysed, only the Rollesby Broad core (Fig.2a) appears to have a reasonably complete record of fallout ^{210}Pb. Total ^{210}Pb activity in this core declines more or less steadily with depth from a maximum value in the topmost sample, and reaches equilibrium with the supporting ^{226}Ra at c.50 cm. Significantly lower ^{210}Pb activities were recorded in the Barton Broad core (Fig.1a), and although unsupported ^{210}Pb was detectable down to c.30 cm (Fig.1b), values were scarcely above the limits of detection. A feature of both cores was the significant increase in ^{226}Ra values in the top 20 cm, presumably indicating a shift in recent decades to a more minerogenic sediment. Although ^{210}Pb activities in the Wroxham Broad core are similar to those in the Barton Broad core, this is to some extent attributable to dilution resulting from higher dry mass accumulation rates. The unsupported ^{210}Pb inventory (Table 2) is comparable to that of Rollesby Broad.

Artificial Fallout Radionuclides

Although neither the Barton Broad or Rollesby Broad cores (Figs.1c & 2c) have a well resolved peak in ^{137}Cs activity, both record a steep increase in activity between 20-30 cm that would appear to distinguish pre-1950 sediments from those post-dating the period of maximum fallout in the early 1960s. Traces of ^{137}Cs below 40 cm depth (pre-dating the 1954 onset of weapons test fallout) can be attributed to post-depositional transport either by mixing or diffusion through the pore waters. As in the case of ^{210}Pb, ^{137}Cs activities in the Barton Broad core are substantially lower than in Rollesby Broad. In contrast to the other two sites, the Wroxham Broad core has a well resolved ^{137}Cs peak at a depth of 40.5 cm (Fig.3c) that clearly records the 1963 weapons test fallout maximum.

Core Chronologies

^{210}Pb chronologies were calculated where possible using the CRS and CIC dating models (Appleby & Oldfield 1978), and, in the case of Wroxham Broad, using the 1963 ^{137}Cs date as a reference level (Oldfield & Appleby, 1984). Figs.4-6 plot the results for all three sites, together with dated levels suggested by the artificial fallout records.

Barton Broad

Calculation of tentative ^{210}Pb dates using the CRS model (Fig.4) was possible in spite of the very low ^{210}Pb activities. Although the dates of specific levels have very high standard errors, the mean sedimentation rate calculated for the past 40 years of 0.15 ± 0.03 g cm^{-2}y^{-1} is in relatively good agreement with the post-1963 sedimentation rate of 0.19 ± 0.03 g cm^{-2}y^{-1} (0.78 cm y^{-1}) determined from the ^{137}Cs date. Table 3 gives a chronology for the core based on the average value from these two methods of 0.17 ± 0.03 g cm^{-2}y^{-1}, though in view of the very poor quality of the radionuclide records the dates must be viewed with a good deal of caution. Table 2 shows that this core has retained only 25% of the atmospheric ^{210}Pb flux, though somewhat unusually it has experienced relatively smaller losses of ^{137}Cs. From the relatively uniform radionuclide activities in the top 20 cm it is quite conceivable that the sediments are highly mixed and that real sedimentation rates are substantially lower than those given in Table 3.

Rollesby Broad

The radionuclide inventories given in Table 2 support the view suggested by the activity versus depth profile that the Rollesby Broad core has a good record of fallout ^{210}Pb. The lower ^{137}Cs inventory is quite typical of open water bodies with relatively high flushing rates. Although significant irregularities in the unsupported ^{210}Pb activity versus depth profile (Fig.2b) give rise to substantial discrepancies between CRS and CIC model ^{210}Pb dates (Fig.5), the two methods give similar values for the mean sedimentation rate. Fig.5 also shows that the ^{210}Pb dates are in quite good agreement with the 1963 ^{137}Cs date. Using all three methods the mean sedimentation rate is calculated to be 0.042±0.008 g $cm^{-2}y^{-1}$ (0.51 cm y^{-1}), and this value has been used to calculate the chronology given in Table 4.

Wroxham Broad

Because of the highly non-monotonic unsupported ^{210}Pb profile (Fig.3b) only the CRS ^{210}Pb dating model could be applied to this core. Even so, calculations using the ^{210}Pb data alone gave dates that were clearly too old when compared with the ^{137}Cs date, presumably due to the low activities and consequent difficulty in assessing the full core inventory. From the well defined 1963 ^{137}Cs date, the mean sediment accumulation rate for the past 30 years is calculated to be 0.37±0.05 g $cm^{-2}y^{-1}$ (1.3 cm y^{-1}). Since CRS model ^{210}Pb dates calculated using the ^{137}Cs date as a reference level (Fig.6) suggest a more or less uniform accumulation rate throughout this period, the above value has been used to calculate the core chronology given in Table 5.

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Table 1. Norfolk Broads Sediment Cores: Radiometric Data

Barton Broad

Depth	Dry Mass	^{210}Pb Concentration				^{226}Ra Conc		^{137}Cs Conc	
		Total		Unsupp					
cm	gcm^{-2}	Bq kg^{-1}	±	Bq kg^{-1}	±	Bq kg^{-1}	±	Bq kg^{-1}	±
0.25	0.02	48.7	10.1	7.9	10.3	40.8	1.8	24.6	2.2
10.25	1.75	43.8	8.5	8.5	8.8	35.3	2.0	24.0	2.0
20.50	3.99	42.7	7.8	3.8	8.1	38.8	2.1	20.6	2.8
30.50	6.11	32.9	7.4	16.4	7.4	16.5	1.2	3.4	1.2
40.50	8.71	15.4	4.9	-3.7	5.0	19.1	1.2	0.0	0.0
50.50	11.00	5.2	6.5	-9.5	6.6	14.7	1.1	0.0	0.0
60.50	13.23	7.2	3.9	-2.7	3.9	9.8	0.7	0.0	0.0

Rollesby Broad

Depth	Dry Mass	^{210}Pb Concentration				^{226}Ra Conc		^{137}Cs Conc	
		Total		Unsupp					
cm	gcm^{-2}	Bq kg^{-1}	±	Bq kg^{-1}	±	Bq kg^{-1}	±	Bq kg^{-1}	±
0.25	0.01	223.4	30.5	139.8	31.2	83.6	6.6	51.4	10.1
5.25	0.34	136.0	23.2	80.8	23.7	55.2	4.8	47.2	4.3
10.25	0.69	155.4	22.5	106.1	22.8	49.2	3.9	53.2	4.9
15.25	1.08	142.9	20.0	96.7	20.4	46.2	4.3	51.3	4.7
20.50	1.55	96.7	10.2	69.4	10.4	27.3	1.8	48.9	2.3
30.50	2.46	49.9	9.8	18.5	10.2	31.5	2.6	6.1	3.1
40.50	3.39	46.1	8.0	23.1	8.1	23.0	1.5	5.8	1.3
50.50	4.30	22.5	12.9	-11.2	13.2	33.7	2.8	1.0	2.6
60.50	5.22	15.2	7.6	-12.9	7.7	28.1	1.4	1.6	1.2
70.50	6.39	25.1	3.7	-3.3	3.8	28.4	1.0	0.1	0.9

Wroxham Broad

Depth	Dry Mass	^{210}Pb Concentration				^{226}Ra Conc		^{137}Cs Conc	
		Total		Unsupp					
cm	gcm^{-2}	Bq kg^{-1}	±	Bq kg^{-1}	±	Bq kg^{-1}	±	Bq kg^{-1}	±
0.25	0.03	38.1	8.5	6.9	8.7	31.2	2.0	10.7	1.8
10.25	2.53	37.4	4.1	13.2	4.2	24.2	1.0	15.2	1.2
20.50	5.91	31.0	4.2	9.9	4.3	21.1	0.8	15.6	0.7
30.50	9.17	44.4	5.4	17.0	5.5	27.4	1.2	31.7	1.6
40.50	11.80	36.8	5.6	8.6	5.7	28.2	1.1	48.4	1.4
50.50	14.55	25.7	4.3	0.4	4.4	25.3	1.0	3.6	0.8
60.50	17.43	26.0	4.3	5.4	4.3	20.6	0.8	3.1	0.6
70.50	20.31	17.9	3.9	-1.2	4.0	19.1	1.0	0.0	0.0
80.50	23.20	15.4	4.2	-1.8	4.3	17.2	0.9	0.3	0.7
90.50	26.08	16.4	4.2	-2.2	4.3	18.6	0.9	0.0	0.0
100.50	28.97	20.3	4.0	0.5	4.1	19.8	0.8	1.0	0.6

Table 2 Radionuclide inventories of Norfolk Broads Cores

	Unsupported ^{210}Pb				^{137}Cs		^{137}Cs/^{210}Pb
	Inventory		Flux		Inventory		Ratio
	Bq m^{-2}	±	Bq $m^{-2}y^{-1}$	±	Bq m^{-2}	±	
Barton	626	324	20	10	1224	88	2.0
Rollesby	2075	222	65	8	1140	61	0.5
Wroxham	2193	637	68	20	3547	117	1.6
Direct Fallout (per m rain)	2470		77		2570		1.0

Table 3. Barton Broad ^{210}Pb chronology

Depth	Dry Mass	Date	Age		Sedimentation Rate		
cm	g cm^{-2}	AD	yr	±	g cm^{-2}y^{-1}	cm y^{-1}	±
0.00	0.00	1995	0		0.17	0.78	~18%
5.00	0.84	1990	5	1			
10.00	1.71	1985	10	2			
15.00	2.79	1979	16	3			
20.00	3.88	1972	23	4			
25.00	4.94	1966	29	5			
30.00	6.00	1960	35	6			
35.00	7.25	1952	43	8			
40.00	8.57	1944	51	9			

Table 4. Rollesby Broad ^{210}Pb chronology

Depth	Dry Mass	Date	Age		Sedimentation Rate		
cm	g cm^{-2}	AD	yr	±	g $cm^{-2}y^{-1}$	cm y^{-1}	±
0.00	0.00	1995	0		0.042	0.51	~18%
5.00	0.32	1987	8	1			
10.00	0.67	1979	16	3			
15.00	1.06	1970	25	5			
20.00	1.50	1960	35	6			
25.00	1.96	1949	46	8			
30.00	2.41	1938	57	10			
35.00	2.88	1927	68	12			
40.00	3.34	1916	79	14			

Table 5. Wroxham Broad ^{210}Pb chronology

Depth	Dry Mass	Date	Age		Sedimentation Rate		
cm	g cm^{-2}	AD	yr	±	g $cm^{-2} y^{-1}$	cm y^{-1}	±
0.00	0.00	1995	0				
5.00	1.22	1992	3	1	0.37	1.3	13%
10.00	2.47	1988	7	2			
15.00	4.10	1984	11	2			
20.00	5.75	1979	16	3			
25.00	7.38	1975	20	3			
30.00	9.01	1971	24	4			
35.00	10.35	1967	28	4			
40.00	11.67	1963	32	5			
45.00	13.03	1960	35	5			
50.00	14.41	1956	39	6			
55.00	15.84	1952	43	6			
60.00	17.29	1948	47	7			

Fig.1a

Barton Broad
Total ^{210}Pb Activity versus Depth

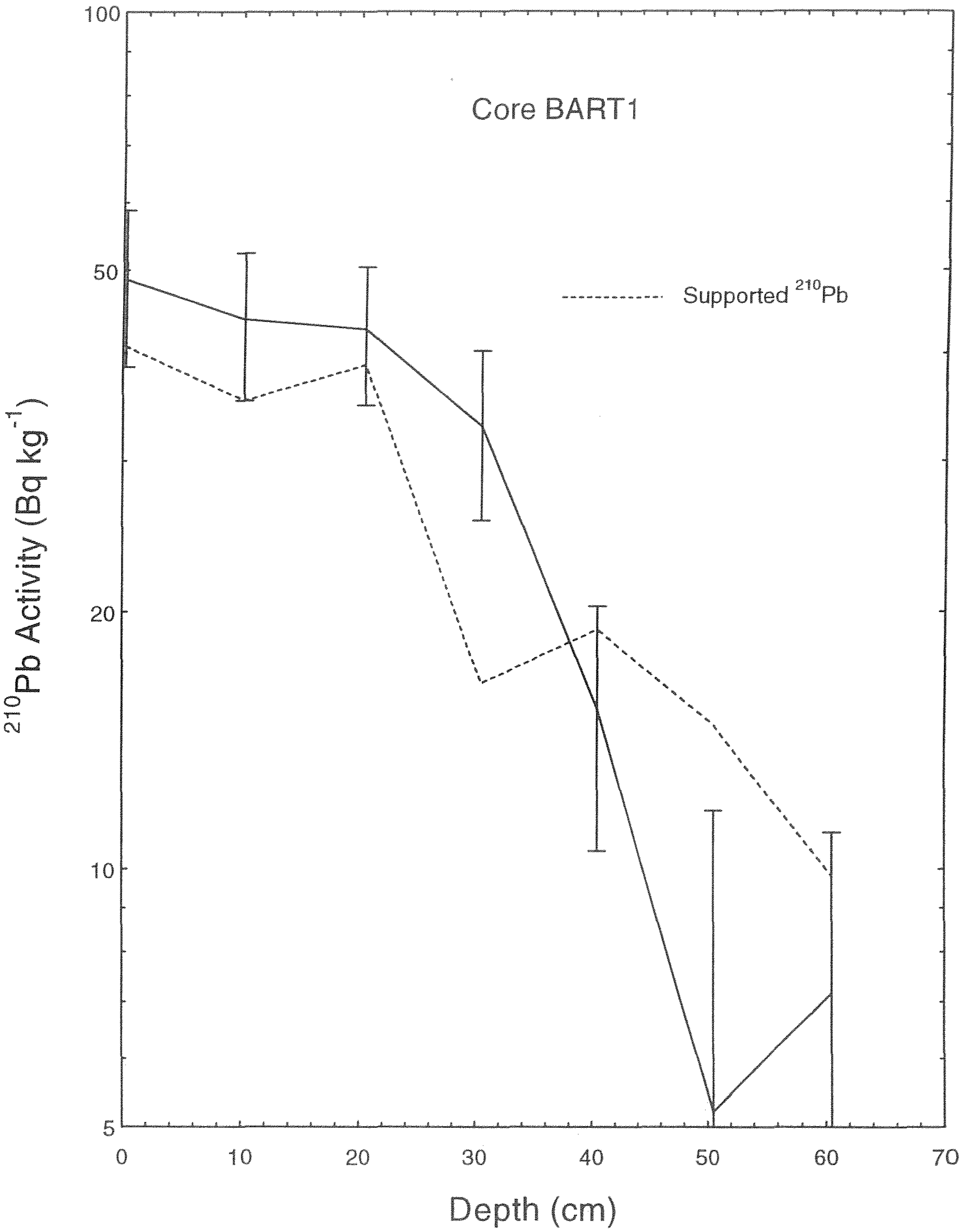
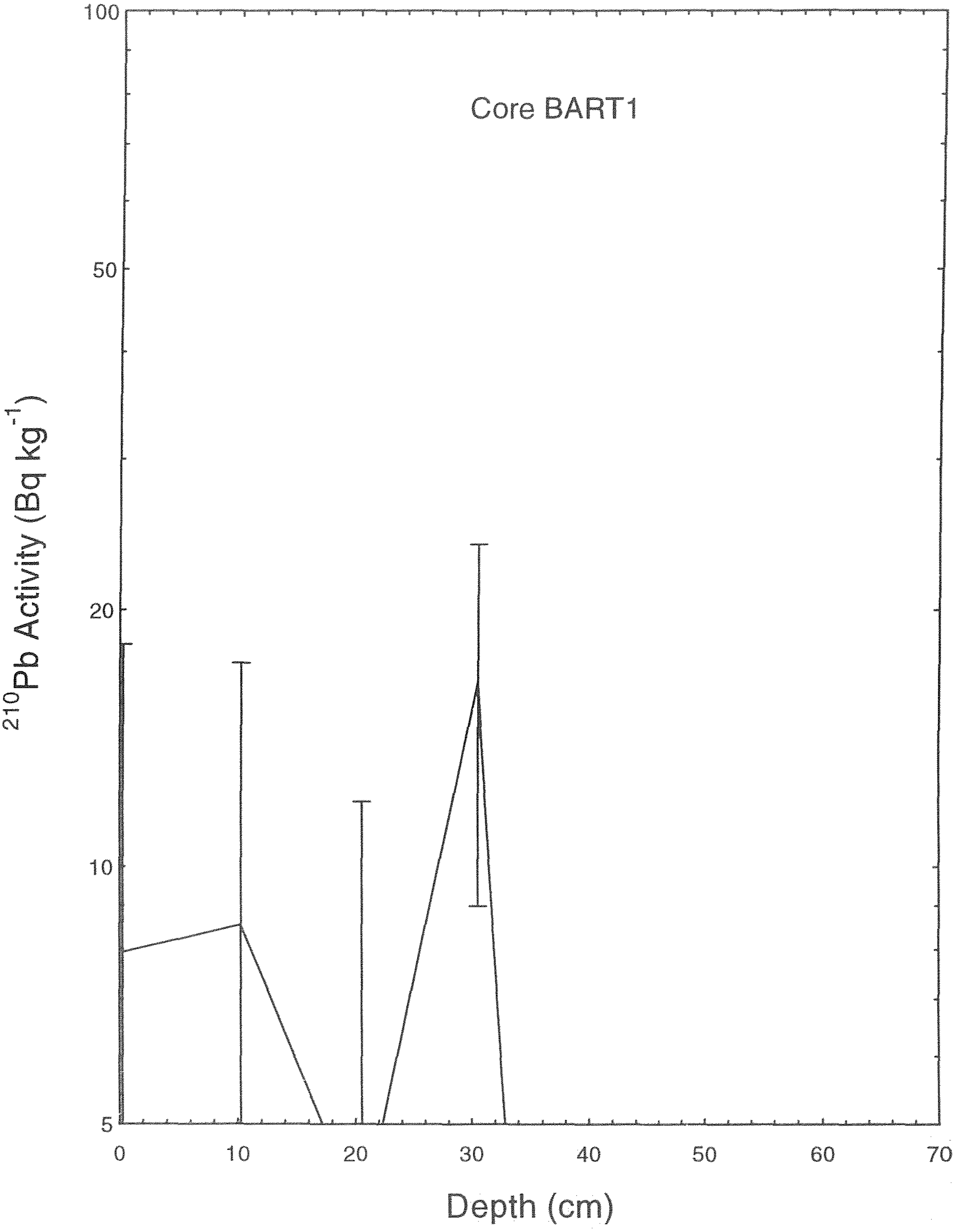


Fig.1b



Barton Broad
Unsupported ^{210}Pb Activity versus Depth

Fig.1c

Barton Broad
^{137}Cs Activity versus Depth

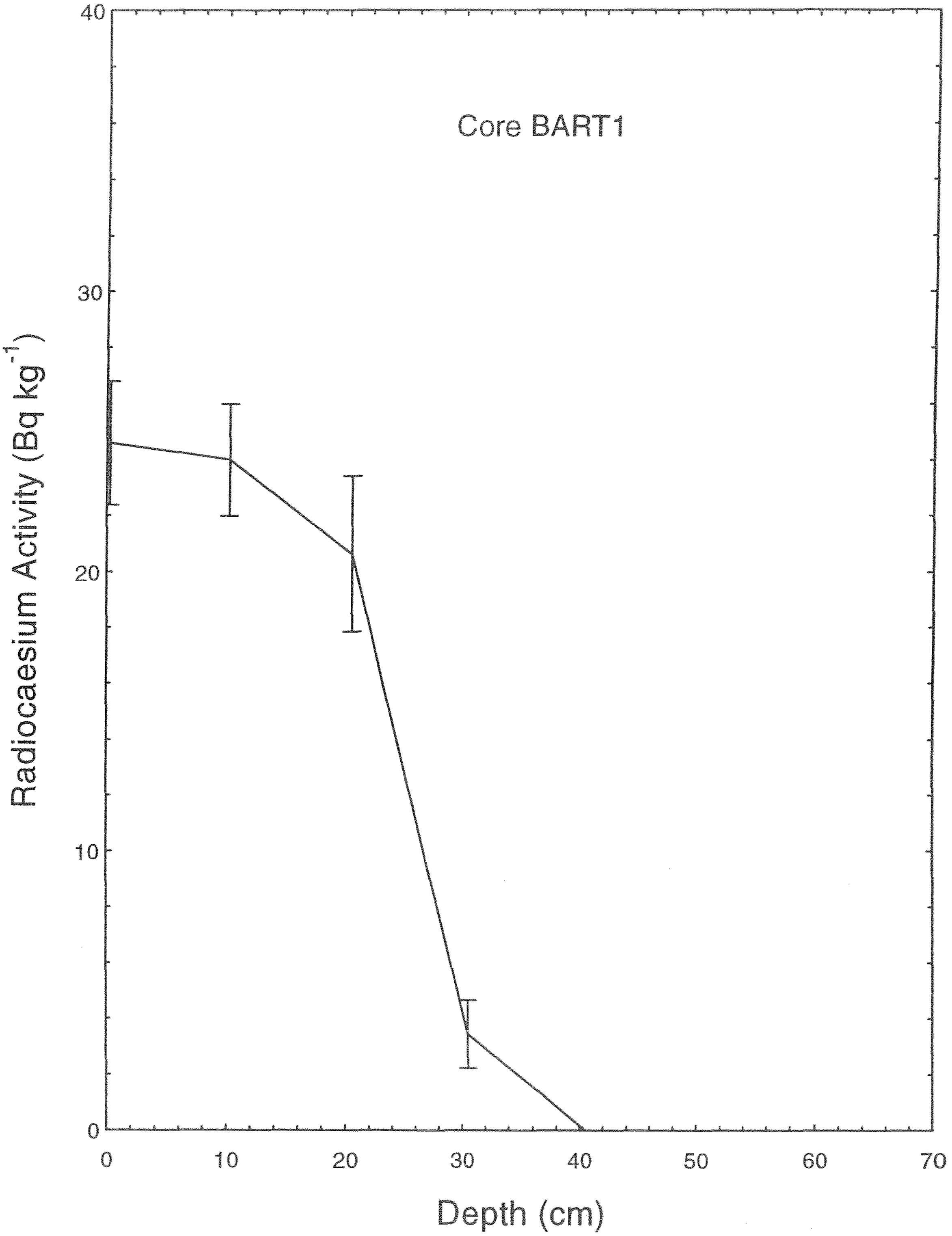
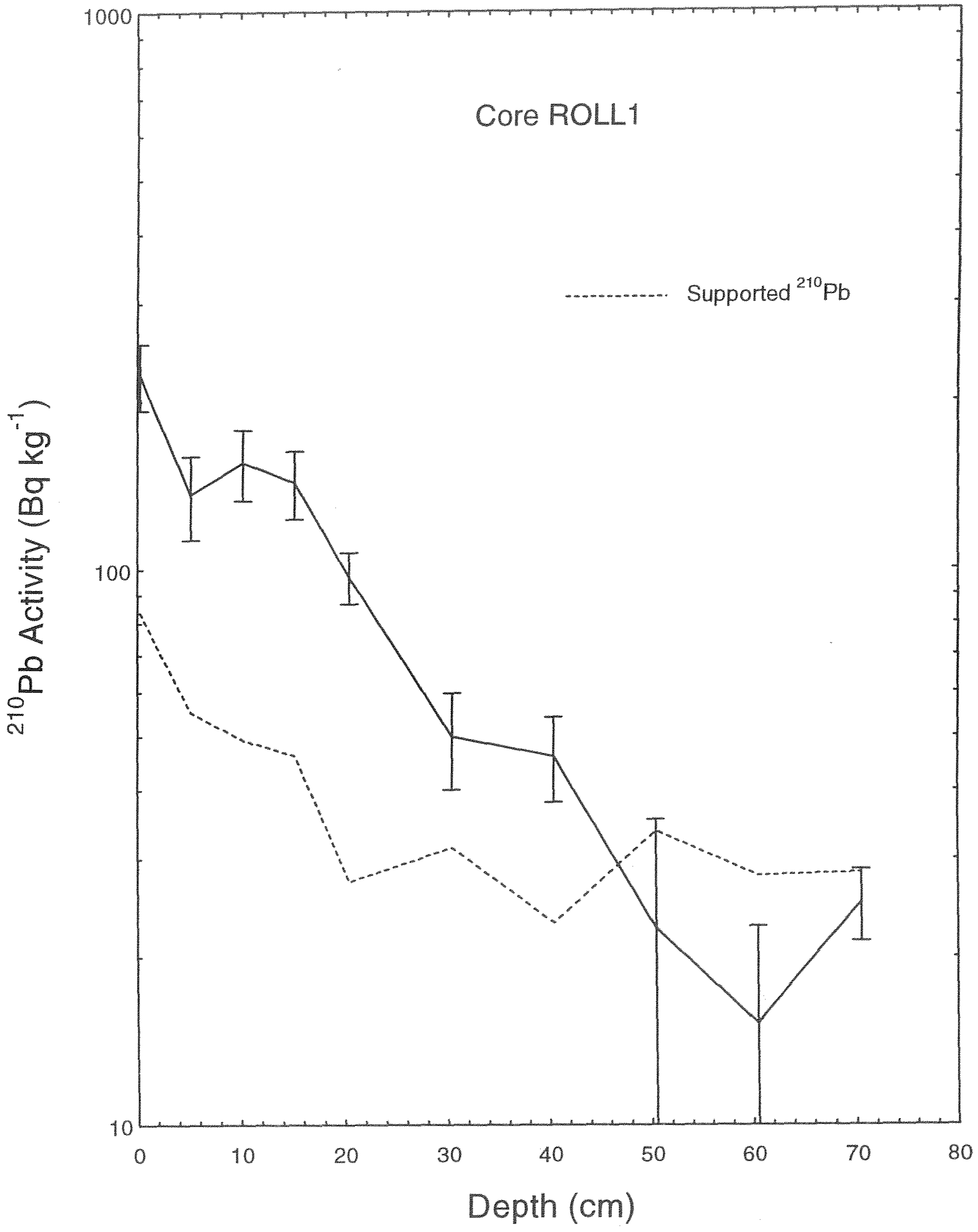


Fig.2a

Rollesby Broad
Total ^{210}Pb Activity versus Depth



Artificial Fallout Radionuclides

Although neither the Barton Broad or Rollesby Broad cores (Figs.1c & 2c) have a well resolved peak in ^{137}Cs activity, both record a steep increase in activity between 20-30 cm that would appear to distinguish pre-1950 sediments from those post-dating the period of maximum fallout in the early 1960s. Traces of ^{137}Cs below 40 cm depth (pre-dating the 1954 onset of weapons test fallout) can be attributed to post-depositional transport either by mixing or diffusion through the pore waters. As in the case of ^{210}Pb, ^{137}Cs activities in the Barton Broad core are substantially lower than in Rollesby Broad. In contrast to the other two sites, the Wroxham Broad core has a well resolved ^{137}Cs peak at a depth of 40.5 cm (Fig.3c) that clearly records the 1963 weapons test fallout maximum.

Core Chronologies

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Table 1. Norfolk Broads Sediment Cores: Radiometric Data

Barton Broad

Depth	Dry Mass	^{210}Pb Concentration				^{226}Ra Conc		^{137}Cs Conc	
		Total		Unsupp					
cm	gcm^{-2}	Bq kg^{-1}	±	Bq kg^{-1}	±	Bq kg^{-1}	±	Bq kg^{-1}	±
0.25	0.02	48.7	10.1	7.9	10.3	40.8	1.8	24.6	2.2
10.25	1.75	43.8	8.5	8.5	8.8	35.3	2.0	24.0	2.0
20.50	3.99	42.7	7.8	3.8	8.1	38.8	2.1	20.6	2.8
30.50	6.11	32.9	7.4	16.4	7.4	16.5	1.2	3.4	1.2
40.50	8.71	15.4	4.9	-3.7	5.0	19.1	1.2	0.0	0.0
50.50	11.00	5.2	6.5	-9.5	6.6	14.7	1.1	0.0	0.0
60.50	13.23	7.2	3.9	-2.7	3.9	9.8	0.7	0.0	0.0

Rollesby Broad

Depth	Dry Mass	^{210}Pb Concentration				^{226}Ra Conc		^{137}Cs Conc	
		Total		Unsupp					
cm	gcm^{-2}	Bq kg^{-1}	±	Bq kg^{-1}	±	Bq kg^{-1}	±	Bq kg^{-1}	±
0.25	0.01	223.4	30.5	139.8	31.2	83.6	6.6	51.4	10.1
5.25	0.34	136.0	23.2	80.8	23.7	55.2	4.8	47.2	4.3
10.25	0.69	155.4	22.5	106.1	22.8	49.2	3.9	53.2	4.9
15.25	1.08	142.9	20.0	96.7	20.4	46.2	4.3	51.3	4.7
20.50	1.55	96.7	10.2	69.4	10.4	27.3	1.8	48.9	2.3
30.50	2.46	49.9	9.8	18.5	10.2	31.5	2.6	6.1	3.1
40.50	3.39	46.1	8.0	23.1	8.1	23.0	1.5	5.8	1.3
50.50	4.30	22.5	12.9	-11.2	13.2	33.7	2.8	1.0	2.6
60.50	5.22	15.2	7.6	-12.9	7.7	28.1	1.4	1.6	1.2
70.50	6.39	25.1	3.7	-3.3	3.8	28.4	1.0	0.1	0.9

Wroxham Broad

Depth	Dry Mass	^{210}Pb Concentration				^{226}Ra Conc		^{137}Cs Conc	
		Total		Unsupp					
cm	gcm^{-2}	Bq kg^{-1}	±	Bq kg^{-1}	±	Bq kg^{-1}	±	Bq kg^{-1}	±
0.25	0.03	38.1	8.5	6.9	8.7	31.2	2.0	10.7	1.8
10.25	2.53	37.4	4.1	13.2	4.2	24.2	1.0	15.2	1.2
20.50	5.91	31.0	4.2	9.9	4.3	21.1	0.8	15.6	0.7
30.50	9.17	44.4	5.4	17.0	5.5	27.4	1.2	31.7	1.6
40.50	11.80	36.8	5.6	8.6	5.7	28.2	1.1	48.4	1.4
50.50	14.55	25.7	4.3	0.4	4.4	25.3	1.0	3.6	0.8
60.50	17.43	26.0	4.3	5.4	4.3	20.6	0.8	3.1	0.6
70.50	20.31	17.9	3.9	-1.2	4.0	19.1	1.0	0.0	0.0
80.50	23.20	15.4	4.2	-1.8	4.3	17.2	0.9	0.3	0.7
90.50	26.08	16.4	4.2	-2.2	4.3	18.6	0.9	0.0	0.0
100.50	28.97	20.3	4.0	0.5	4.1	19.8	0.8	1.0	0.6

Table 2 Radionuclide inventories of Norfolk Broads Cores

	Unsupported ^{210}Pb				^{137}Cs		$^{137}Cs/^{210}Pb$
	Inventory		Flux		Inventory		Ratio
	Bq m^{-2}	±	Bq $m^{-2}y^{-1}$	±	Bq m^{-2}	±	
Barton	626	324	20	10	1224	88	2.0
Rollesby	2075	222	65	8	1140	61	0.5
Wroxham	2193	637	68	20	3547	117	1.6
Direct Fallout (per m rain)	2470		77		2570		1.0

Table 3. Barton Broad ^{210}Pb chronology

Depth	Dry Mass	Date	Age		Sedimentation Rate		
cm	g cm^{-2}	AD	yr	±	g cm^{-2}y^{-1}	cm y^{-1}	±
0.00	0.00	1995	0		0.17	0.78	~18%
5.00	0.84	1990	5	1			
10.00	1.71	1985	10	2			
15.00	2.79	1979	16	3			
20.00	3.88	1972	23	4			
25.00	4.94	1966	29	5			
30.00	6.00	1960	35	6			
35.00	7.25	1952	43	8			
40.00	8.57	1944	51	9			

Table 4. Rollesby Broad ^{210}Pb chronology

Depth	Dry Mass	Date	Age		Sedimentation Rate		
cm	$g\ cm^{-2}$	AD	yr	±	$g\ cm^{-2}y^{-1}$	$cm\ y^{-1}$	±
0.00	0.00	1995	0		0.042	0.51	~18%
5.00	0.32	1987	8	1			
10.00	0.67	1979	16	3			
15.00	1.06	1970	25	5			
20.00	1.50	1960	35	6			
25.00	1.96	1949	46	8			
30.00	2.41	1938	57	10			
35.00	2.88	1927	68	12			
40.00	3.34	1916	79	14			

Table 5. Wroxham Broad ^{210}Pb chronology

Depth	Dry Mass	Date	Age		Sedimentation Rate		
cm	g cm^{-2}	AD	yr	±	g $cm^{-2} y^{-1}$	cm y^{-1}	±
0.00	0.00	1995	0				
5.00	1.22	1992	3	1	↑	↑	↑
10.00	2.47	1988	7	2			
15.00	4.10	1984	11	2			
20.00	5.75	1979	16	3			
25.00	7.38	1975	20	3			
30.00	9.01	1971	24	4	0.37	1.3	13%
35.00	10.35	1967	28	4			
40.00	11.67	1963	32	5			
45.00	13.03	1960	35	5			
50.00	14.41	1956	39	6			
55.00	15.84	1952	43	6	↓	↓	↓
60.00	17.29	1948	47	7			

Fig.1a

Barton Broad
Total ^{210}Pb Activity versus Depth

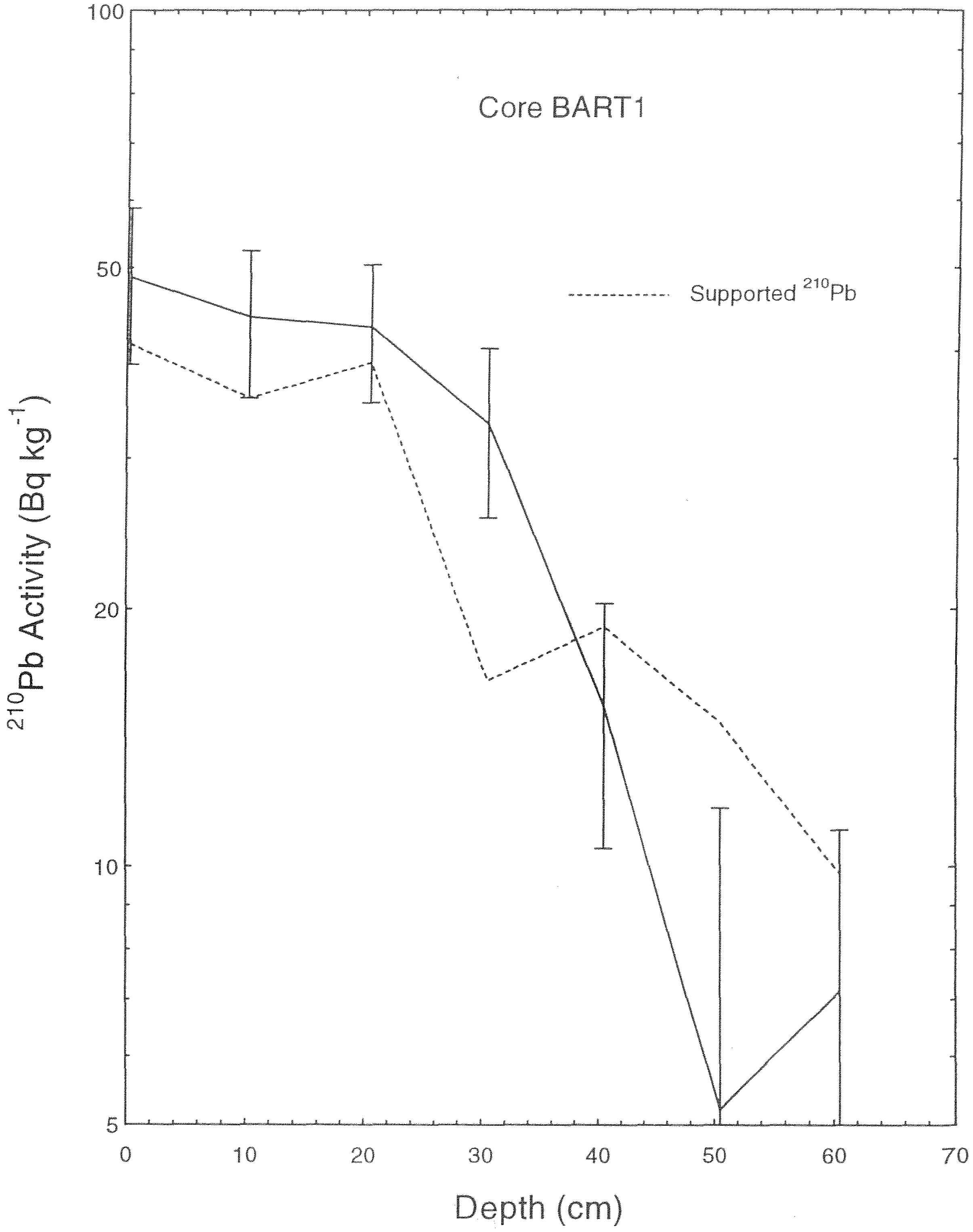


Fig.1b

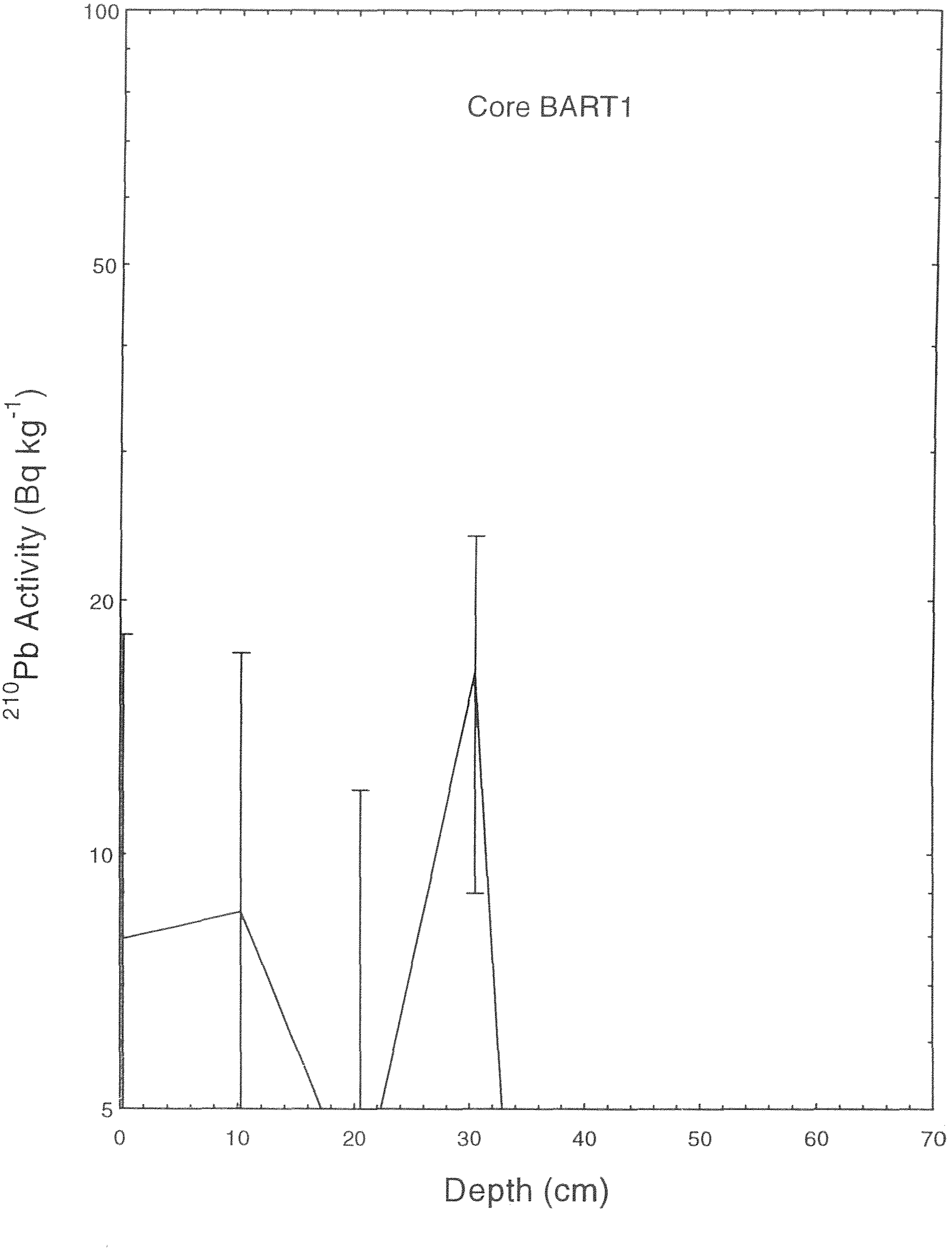

Barton Broad
Unsupported ^{210}Pb Activity versus Depth
Core BART1
^{210}Pb Activity (Bq kg^{-1})
100
50
20
10
5
0
10
20
30
40
50
60
70
Depth (cm)

Fig.1c

Barton Broad

^{137}Cs Activity versus Depth

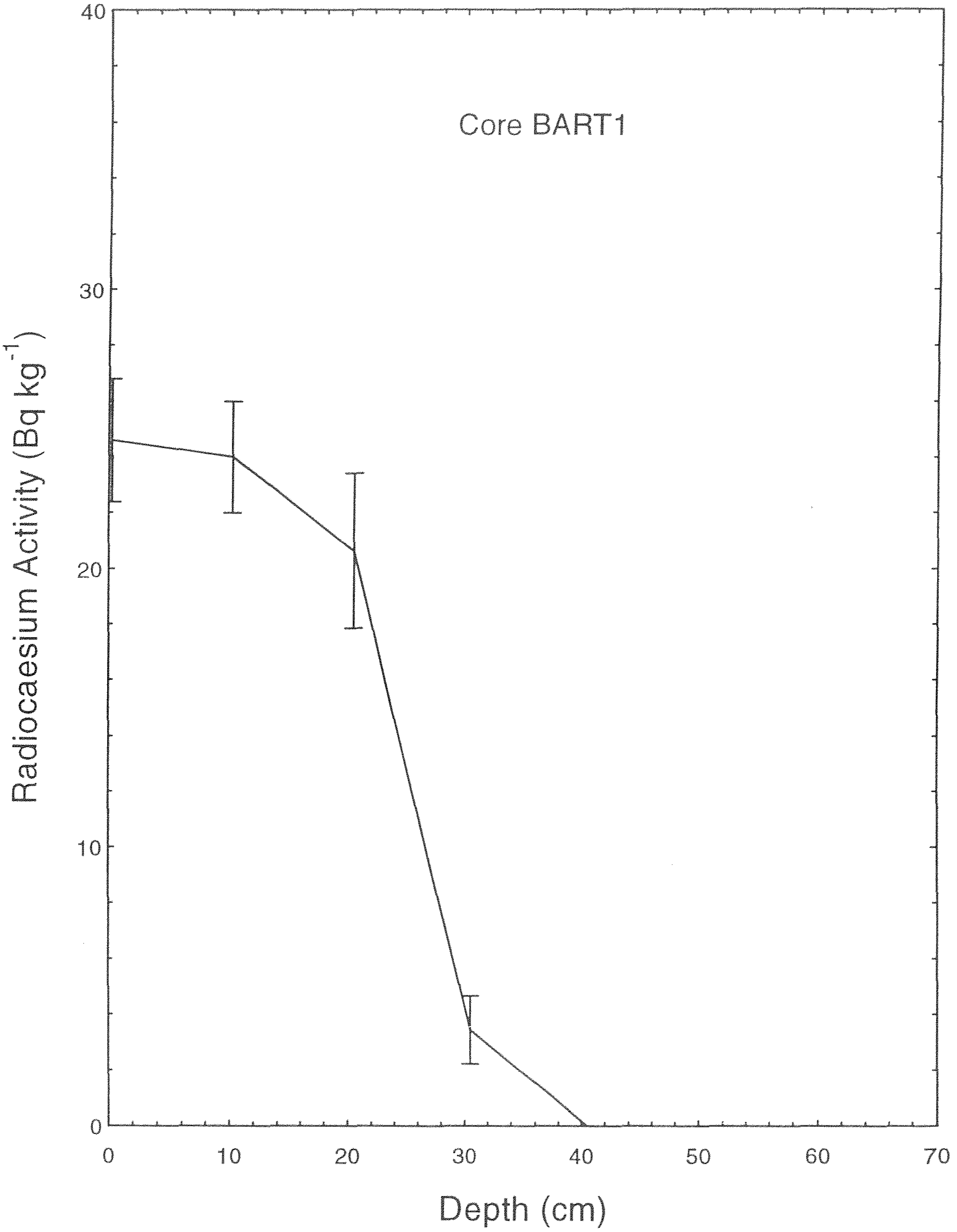


Fig.2a

Rollesby Broad
Total ^{210}Pb Activity versus Depth

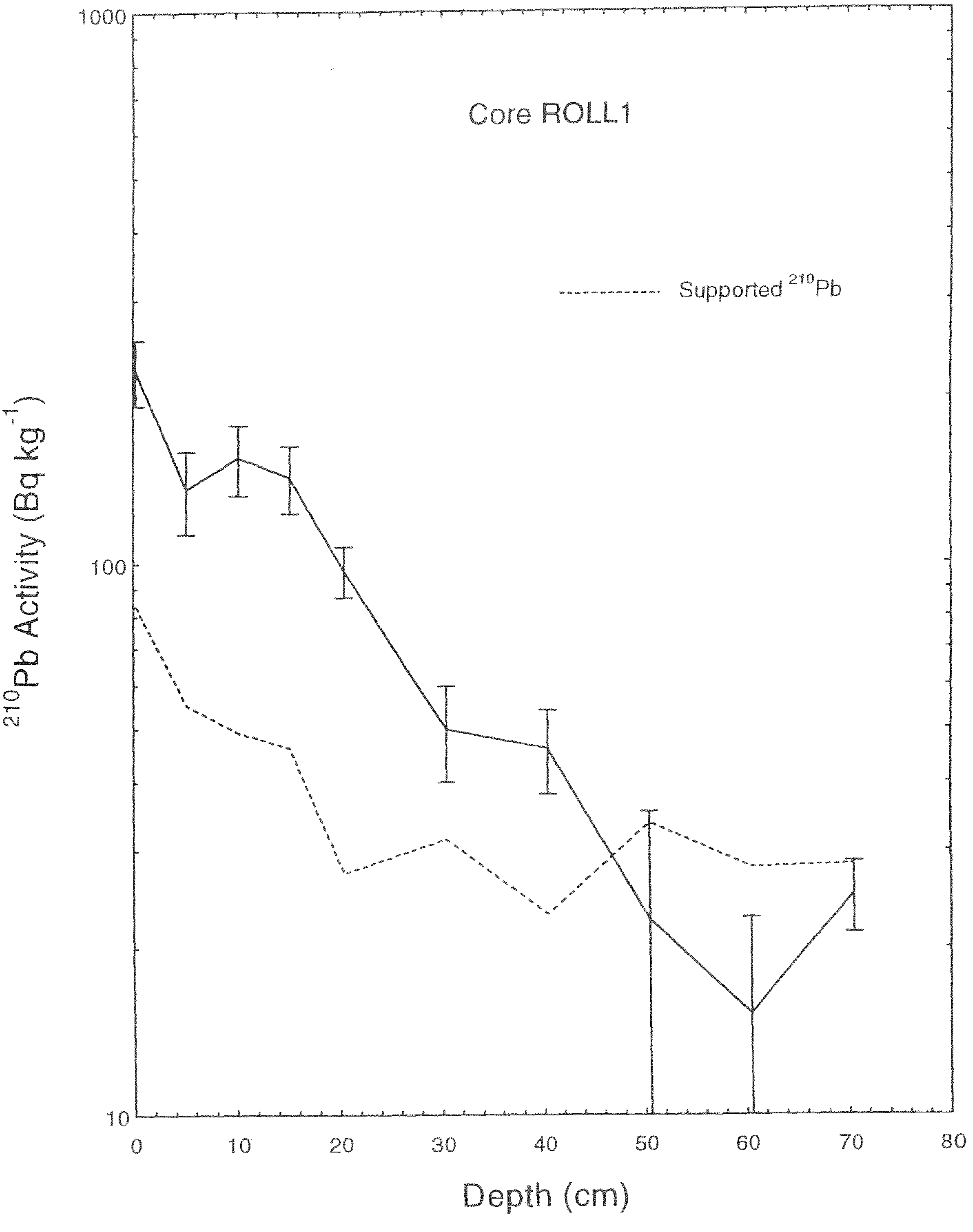


Fig.2b

Rollesby Broad
Unsupported ^{210}Pb Activity versus Depth

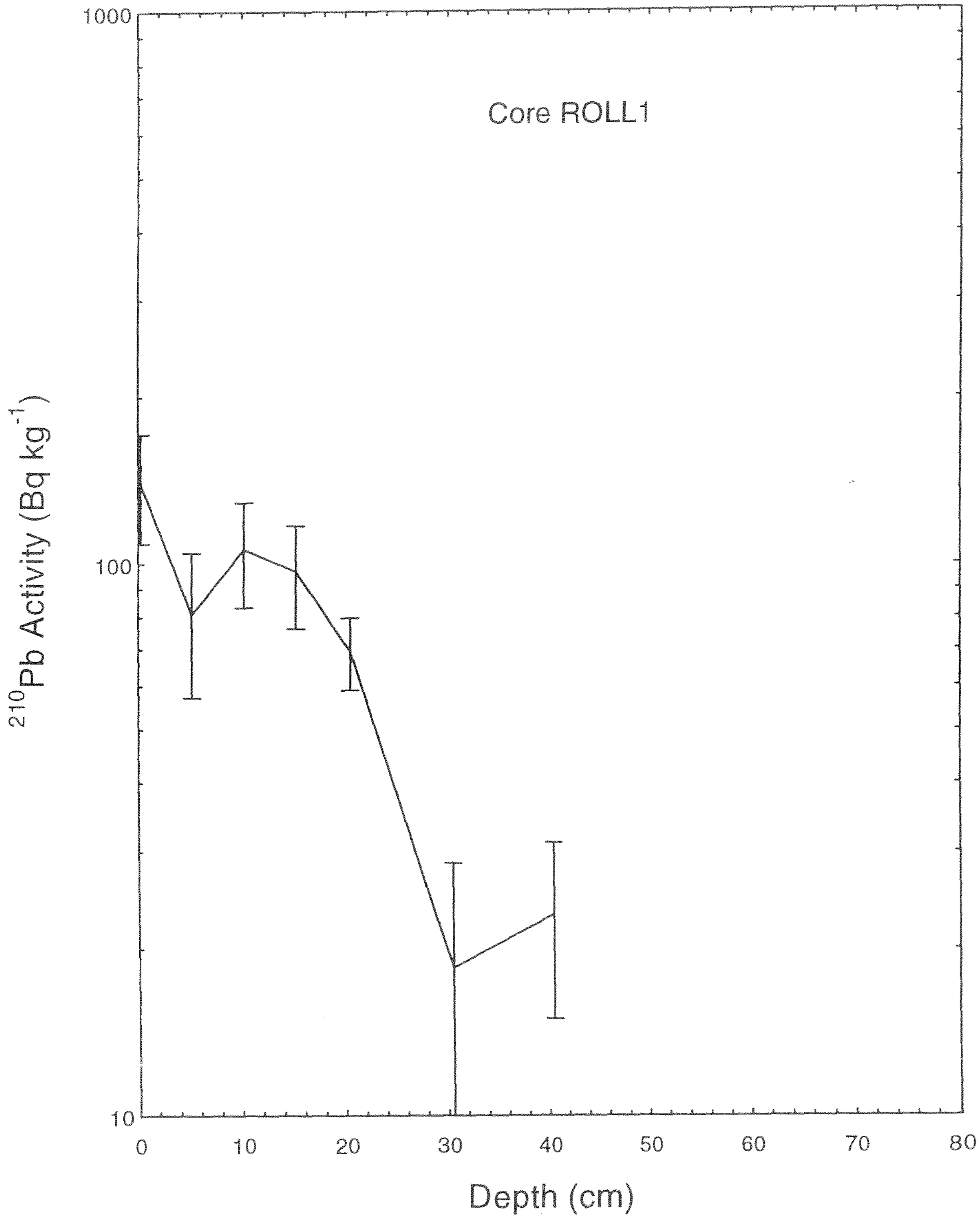


Fig.2c

Rollesby Broad

^{137}Cs Activity versus Depth

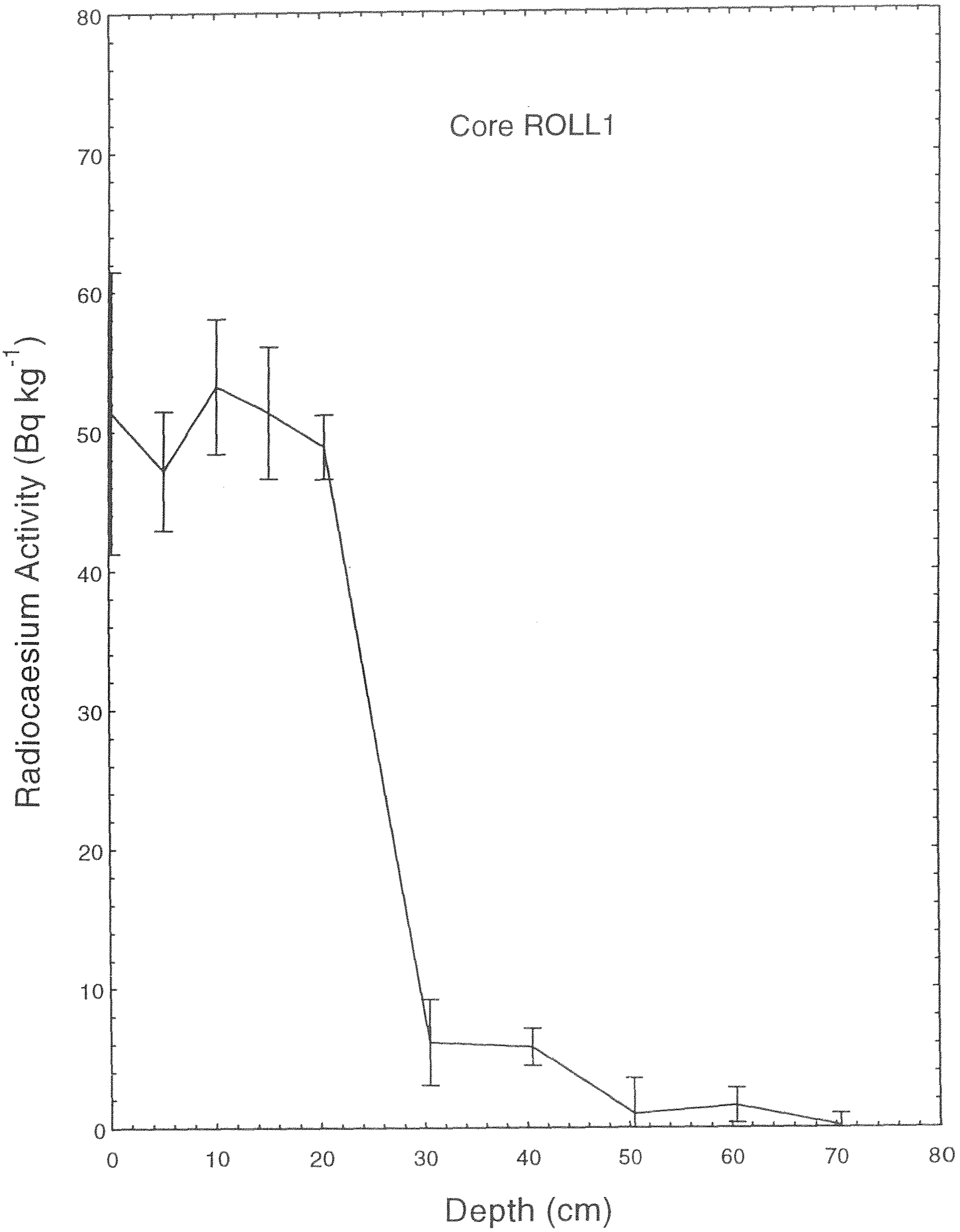


Fig.3a

Wroxham Broad
Total ^{210}Pb Activity versus Depth

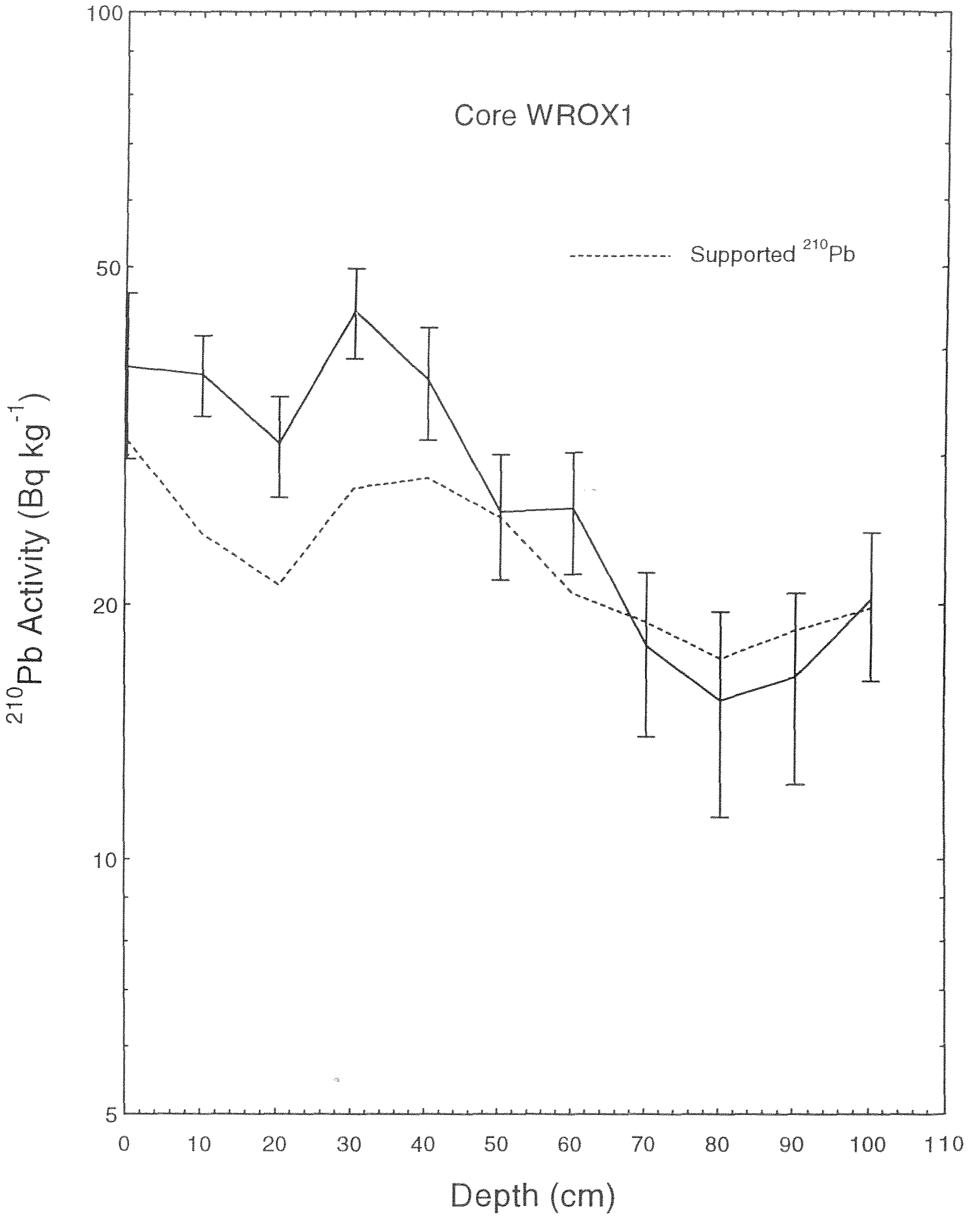


Fig.3b

Wroxham Broad
Unsupported ^{210}Pb Activity versus Depth

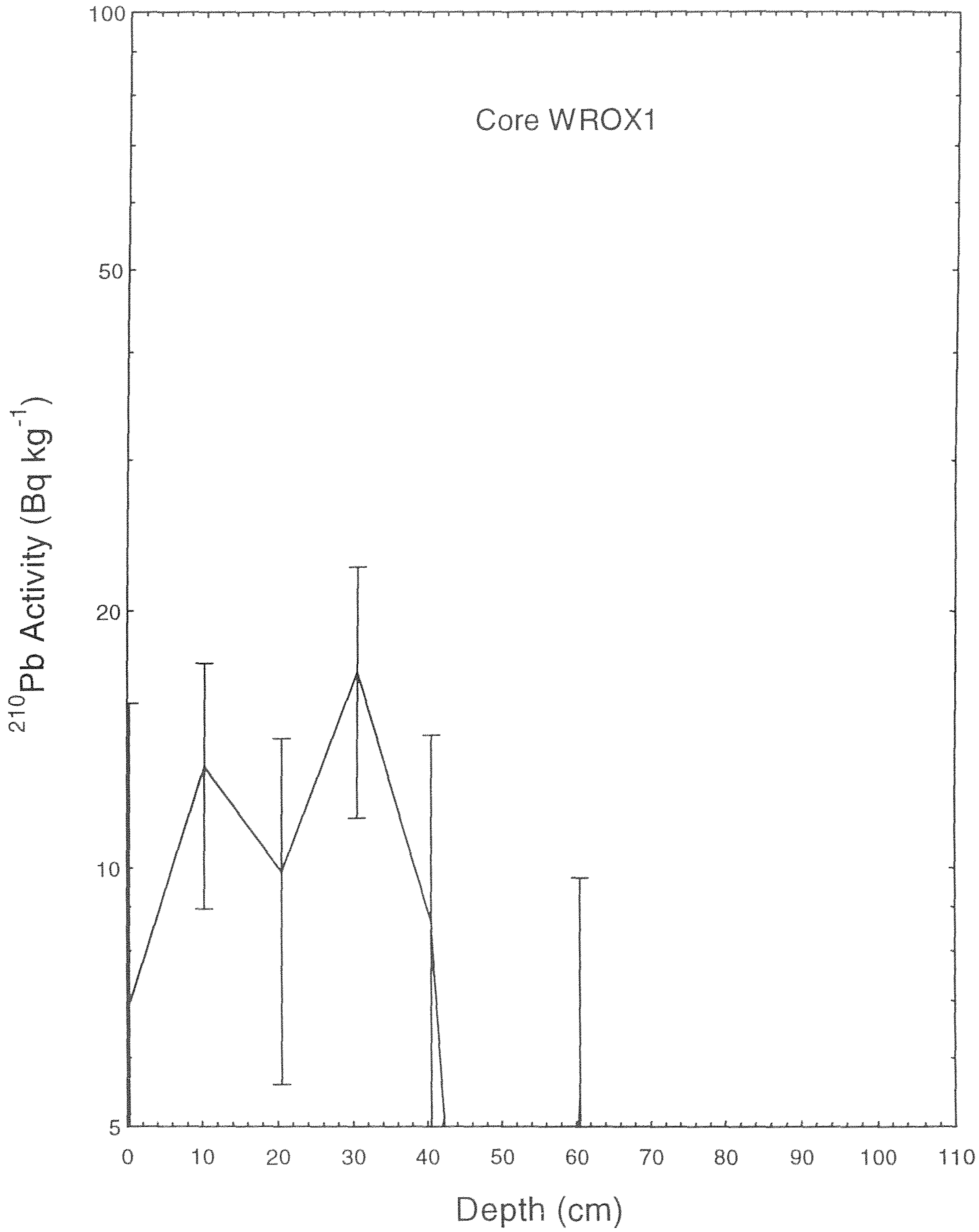


Fig.3c

Wroxham Broad
^{137}Cs Activity versus Depth

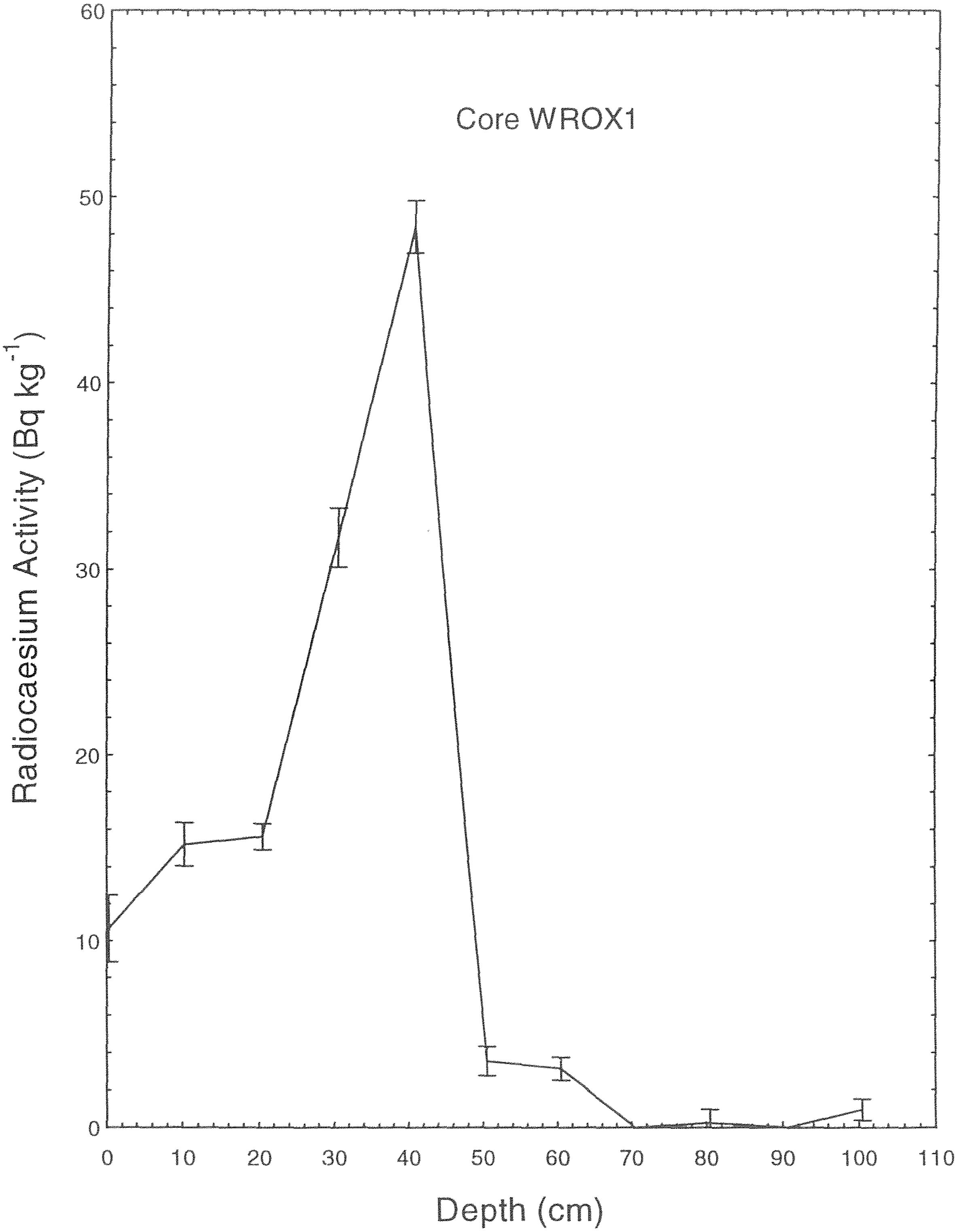


Fig.4

Barton Broad Core BART1
Depth versus Age

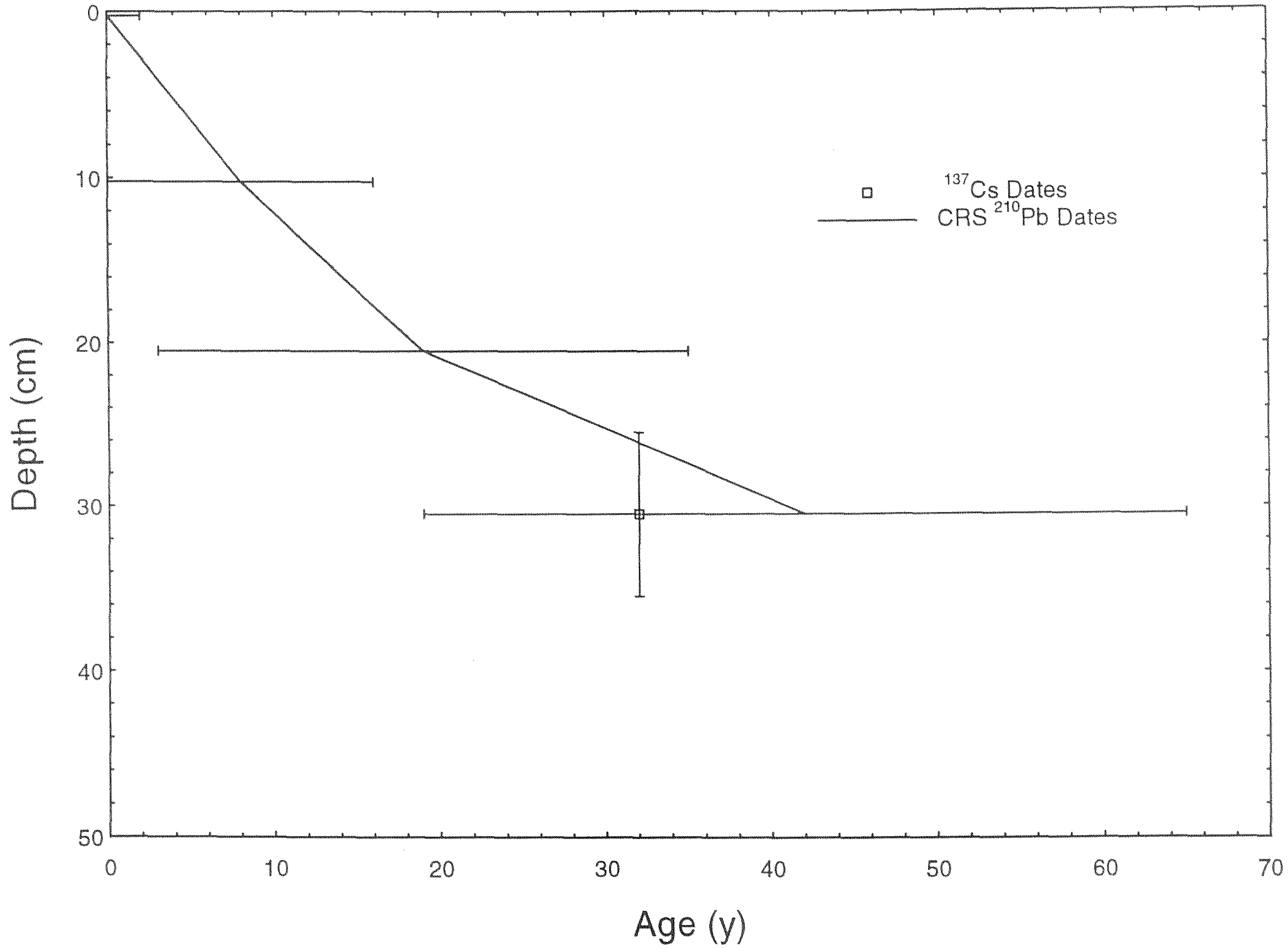


Fig.5

Rollesby Broad Core ROLL1
Depth versus Age

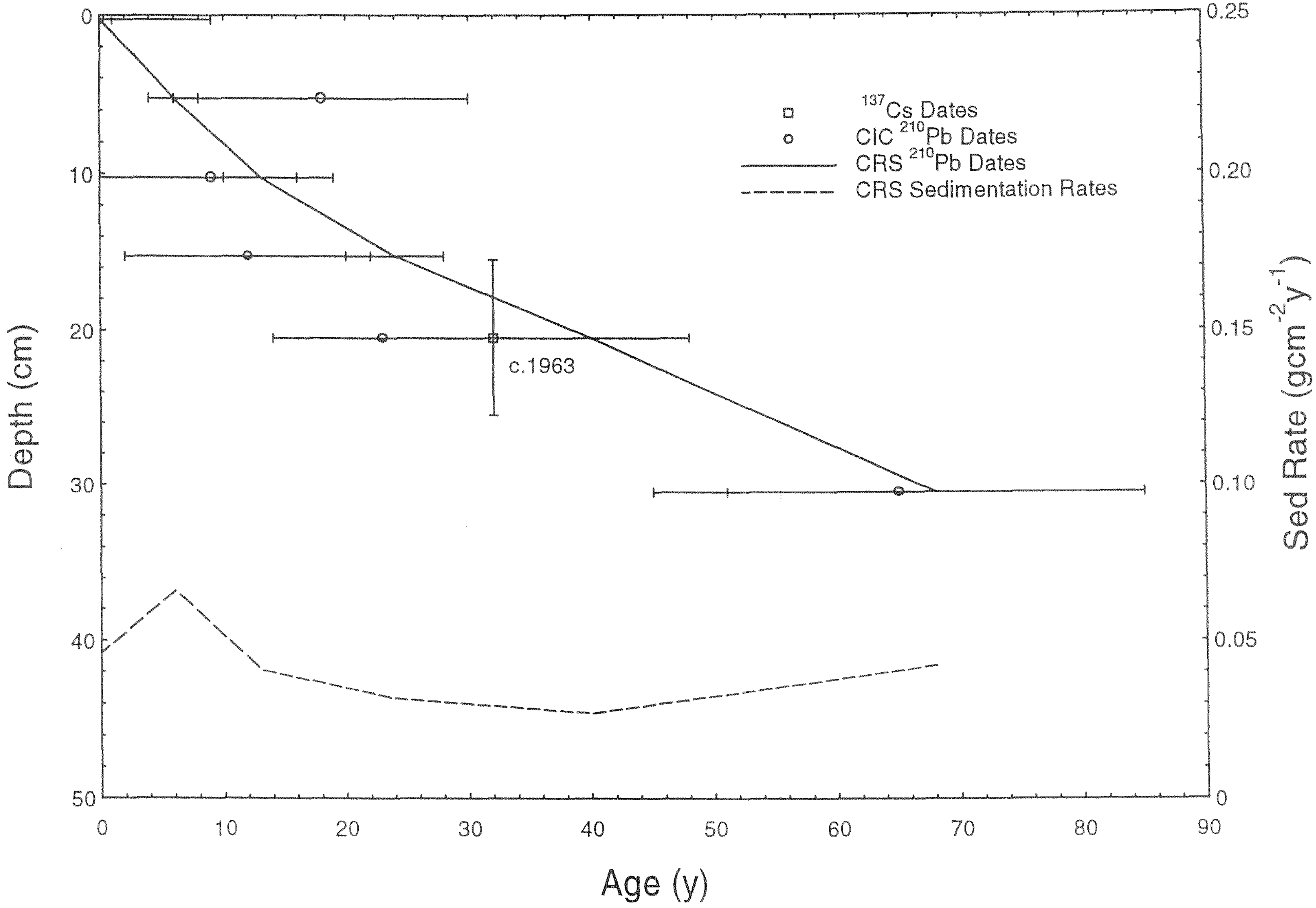
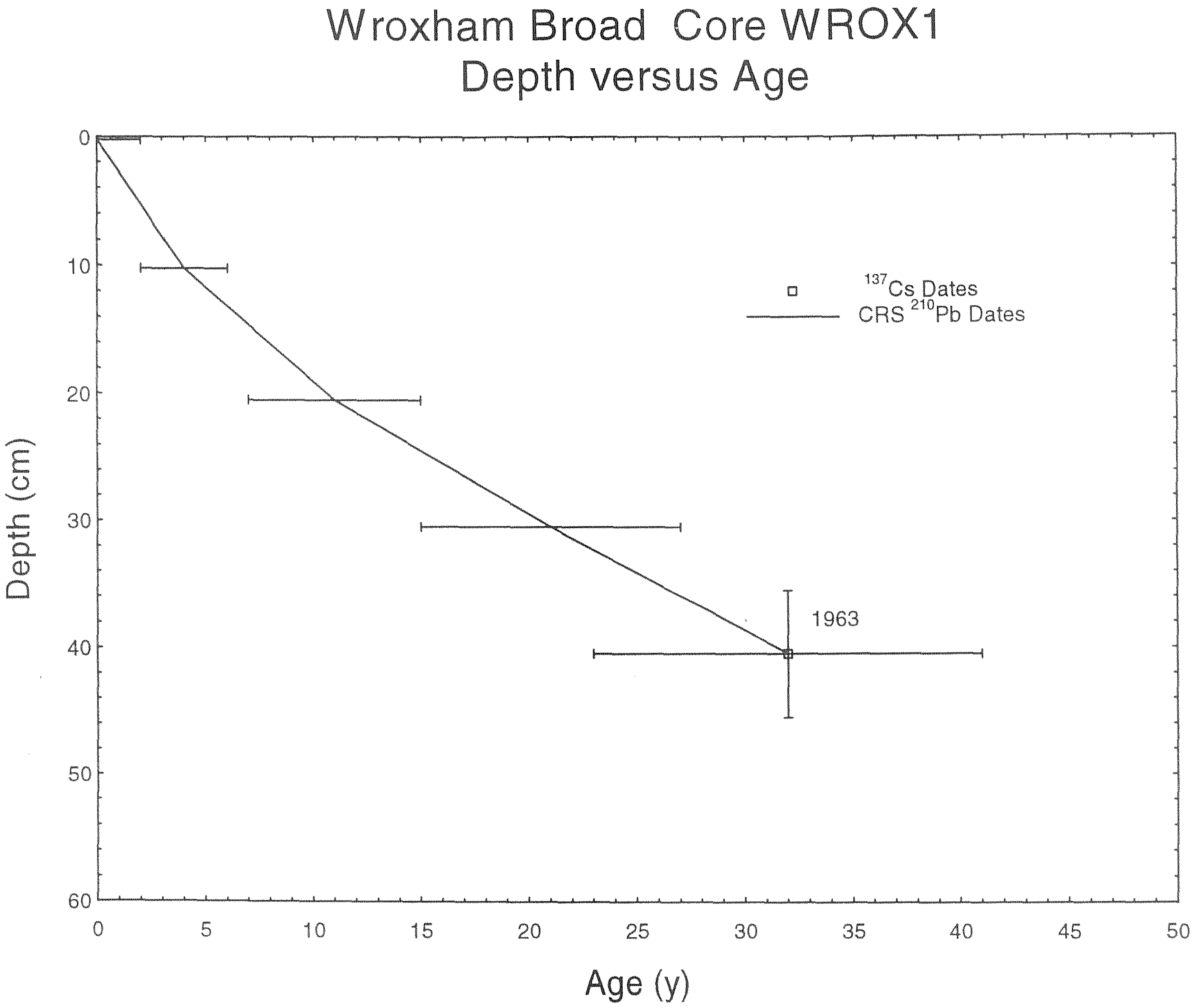


Fig.6


Wroxham Broad Core WROX1
Depth versus Age
^{137}Cs Dates
CRS ^{210}Pb Dates
1963
Depth (cm)
0
10
20
30
40
50
60
Age (y)
0
5
10
15
20
25
30
35
40
45
50

4 Barton Broad (TG 363 215)

Barton Broad on the River Ant system has been the subject of past palaeolimnological investigations (Osborne & Moss, 1977; Moss, 1980) and has been intensively monitored by the NRA since 1977. Phosphorus removal from point sources has been taking place since 1980, resulting in a 90% reduction in load from the catchment. Phosphorus removal is shortly to be enhanced, following substantial investment by Anglian Water, and in addition the majority of the sediment from the lake will be progressively removed by a mud pumping programme which started in October 1995.

4.1 Lithostratigraphy

A 115 cm piston core was taken on 12-10-95 from the Main Broad in 1.2 m of water (location shown in Appendix). The percentage dry weight (%DW) and loss on ignition (%LOI) profiles are shown in Figure 7. The profiles clearly show the presence of a peat layer from c. 70 cm to the base of the core. The material was highly organic with %LOI values of c. 80% and %DW of c. 10%. There was a marked decline in %LOI between the 75 cm and 60 cm samples from 75% to 25% as the material changed to an organic lake mud with some minerogenic clay content. The upper part of the core was homogeneous and %LOI values stabilised at c. 18%.

4.2 Diatom Stratigraphy

The percentage relative frequencies of diatom species in ten levels of the sediment core BART1 were calculated and Figure 8 illustrates the results for the major taxa. Diatom preservation was good down to a depth of 60 cm but diatoms were absent in the peat section below this depth. A total of 64 taxa was observed, 55 of which were present in the TP calibration set. There were no species analogue problems, with 95% or more of the fossil assemblage being used in the TP reconstructions.

Figure 8 illustrates that there have been marked changes in the diatom species composition over the period represented by the upper 60 cm of the core (*c.* post-1910). Prior to the 25 cm level (*c.* pre-1966), the assemblages were dominated by non-planktonic taxa, the major taxa being *Fragilaria brevistriata, Fragilaria construens* var. *venter*, *Fragilaria pinnata, Fragilaria construens, Amphora pediculus, Navicula [cf. seminulum], Navicula vitabunda* and *Gomphonema minutum*, all species commonly found attached to either the sediments, stones or macrophyte surfaces of shallow, alkaline waters (e.g. Bennion, 1994; 1995).

Although the non-planktonic *Fragilaria* taxa were present in high abundances throughout the core, there was a clear switch at the 25 cm level, where percentages of the other non-planktonic forms declined and were replaced by a number of planktonic diatom taxa not previously observed in the lake. The major planktonic species in the upper 25 cm were *Aulacoseira ambigua, Aulacoseira granulata, Stephanodiscus hantzschii, Cyclostephanos dubius, Cyclostephanos invisitatus, Cyclotella atomus* and *Asterionella formosa* (in the upper 5 cm only), species commonly found in shallow, eutrophic lakes (e.g. Bennion, 1994; 1995).

Figure 7 **Lithostratigraphic data for Barton Broad**

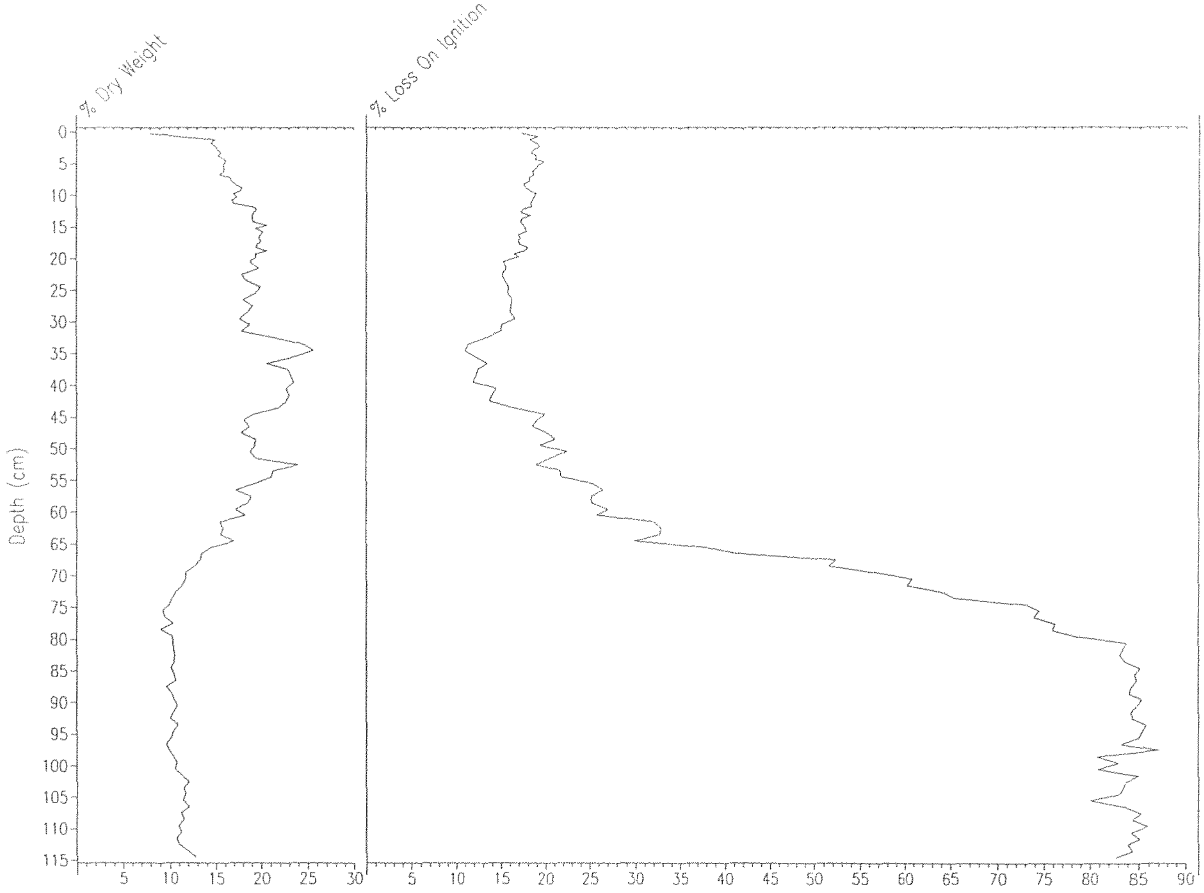
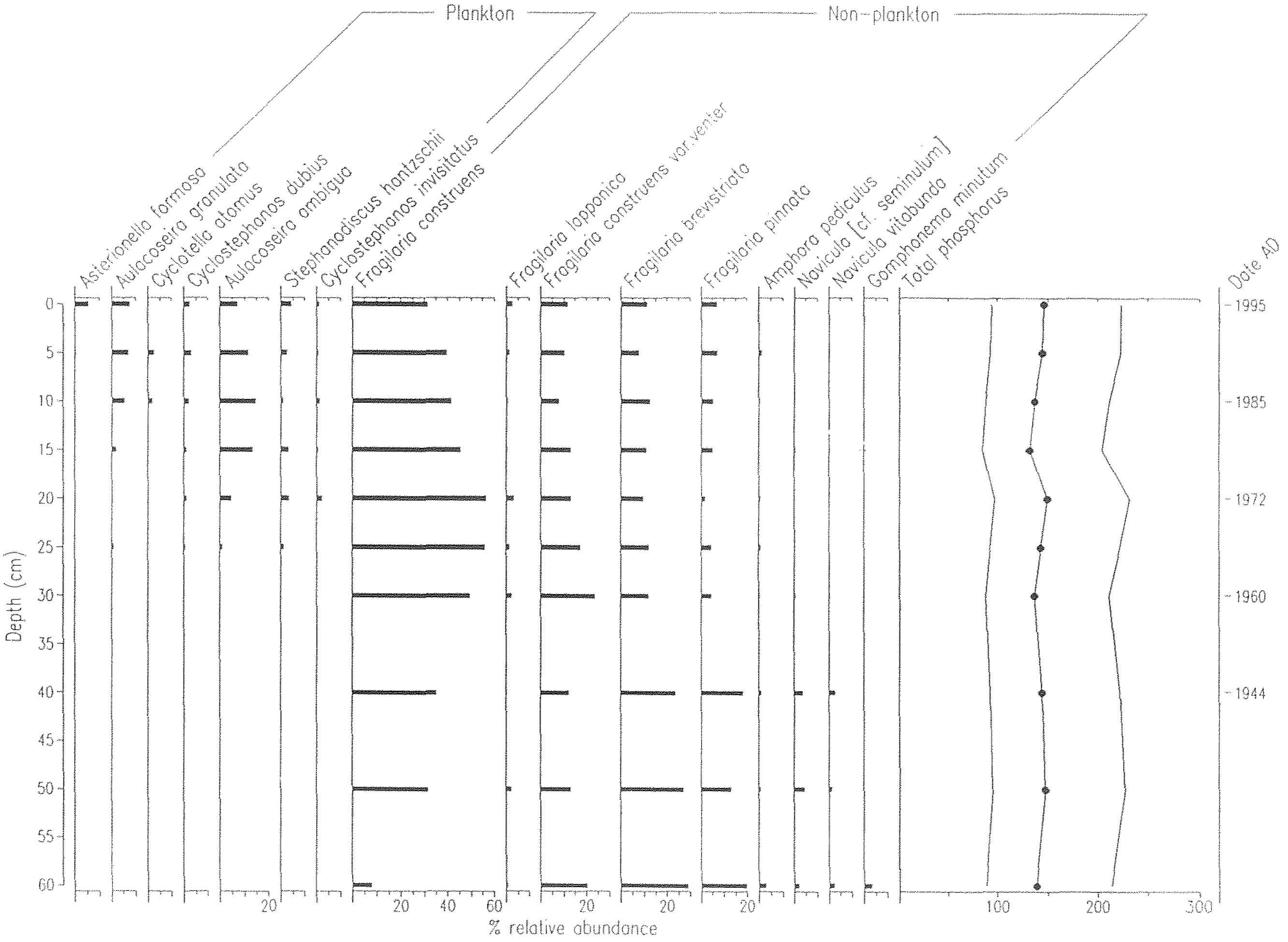


Figure 8 **Summary diatom diagram and TP reconstruction for Barton Broad**

(TP = annual mean TP in μg l^{-1} shown by line with filled circles;
standard errors of prediction are shown by solid lines)



4.3 TP Reconstruction

The diatom-inferred TP (DI-TP) reconstruction (Fig 8) shows that the lake has had high TP concentrations throughout the period represented by the sediment core (*c.* post-1910), which would place the lake in the hypertrophic category (> 100 μg TP l^{-1}) following the OECD classification scheme (OECD, 1982). The DI-TP concentrations ranged from 132 μg TP l^{-1} to 149 μg TP l^{-1} but without any clear trend over time.

4.4 Discussion

The qualitative data, that is the actual floristic changes in the diatom communities of the Barton Broad core, indicate that there has been a significant shift from a non-planktonic diatom assemblage to a plankton dominated one, occurring at the 25 cm level which is calculated to represent c. 1966 (although the dates must be viewed with caution, see chapter 3). This corresponds with the observations of Moss (1980) who reported dominance by *Fragilaria* spp. in the lower core and a rapid increase in planktonic diatoms since approximately 1960. These species shifts reflect the increasing fertility of the lake from the expanding agricultural activity and population in the catchment. It is thought that enrichment from sewage effluent may have occurred since as early as 1920-30 but it would appear that the high nutrient concentrations in the lake did not affect the stability of the community until the 1960s. By the 1960s, the harmful affects of eutrophication were observed in many of the Broads, for example increased water turbidity, loss of once extensive stands of submerged and floating aquatic macrophytes, and increased sediment accumulation rates (e.g. Moss, 1980). Osborne & Moss (1977) noted that by 1968 only floating leaved macrophytes were present in Barton Broad and that these had completely disappeared by 1972, resulting in a phase 3 broad. Barton Broad is currently classed as a late phase 3/phase 4 broad (Kennison & Prigmore, 1994). This loss of submerged macrophytes arises from the competitive shading of the higher plants by the algae and is clearly reflected in the fossil diatom assemblages both in this study and in earlier palaeolimnological work (e.g. Osborne & Moss, 1977; Moss, 1980).

The dominance of the non-planktonic *Fragilaria* taxa in the lower core section is indicative of an epiphyte-dominated community based on abundant aquatic macrophyte crops. The diatom species composition in the early period of Barton Broad is analogous to the current diatom flora of Upton Broad, one of the few Broads that still has clearwater, sparse phytoplankton and supports a diverse submerged macrophyte flora, largely due to it's isolation from nutrient sources (H. Bennion, unpublished data). These *Fragilaria* taxa remain relatively abundant in the upper core section (also observed by Osborne & Moss, 1977) which may be due to their growth on the bottom sediments or transport of organic matter from the marginal reed swamps. However, a number of other taxa, such as *Navicula [cf. seminulum], Navicula vitabunda* and *Gomphonema minutum*, indicative of an epiphytic dominated community, disappeared from the lake by the 1960s. These were replaced by planktonic taxa which reflect eutrophication and elimination of the aquatic macrophyte community. The major planktonic species in the upper 25 cm of the core were *Aulacoseira ambigua, Aulacoseira granulata, Stephanodiscus hantzschii, Cyclostephanos dubius, Cyclostephanos invisitatus, Cyclotella atomus* and *Asterionella formosa* (in the upper 5 cm only), species commonly found in shallow, eutrophic lakes (e.g. Bennion, 1994; 1995).

Owing to the problems associated with the dating of the Barton Broad core, the exact timing of this community switch could not be ascertained. Very low ^{210}Pb activities mean that the chronology must be viewed with caution and the extrapolation of results to sample depths below 40 cm must be interpreted with extreme caution. Only a mean sedimentation rate of 7.8 mm yr^{-1} could be calculated and therefore the increase in sedimentation rates observed in earlier cores from the lake could not be detected in BART1. Osborne & Moss (1977) reported an increase from c. 1 mm yr^{-1} in the 1800s to c. 5 mm yr^{-1} by the 1950s, further increasing to 12 mm yr^{-1} by the 1970s. It may be possible that the BART1 core is mixed, although the clear floristic changes would suggest that this is not the case. Rapid throughflow of water in the Broad may be an alternative explanation for the dilute ^{210}Pb records because the rapid flushing gives the radionuclides little chance to be incorporated into the sediments. However, despite the dating difficulties, it would appear that the sediment accumulation rate is similar to those estimated for other Barton Broad cores, placing the floristic shift (25 cm) at c. 1966. The timing of this event is consistent with the observed epiphyton-plankton switch in other studies (e.g. Osborne & Moss, 1977; Moss, 1980).

The quantitative diatom transfer function results, unfortunately however, do not follow the pattern of progressive enrichment indicated by the qualitative diatom analysis. Indeed the DI-TP data suggest that Barton Broad has been a nutrient-rich lake for the whole of the period represented by the 60 cm core (extrapolated date c.1910) and has not experienced any major change in TP concentrations since that time. The DI-TP values fluctuated at around 140 µg TP l^{-1} for the whole core length, placing Barton Broad in the hypertrophic category following the OECD lake classification system (1982). The DI-TP value for the surface sample is in close agreement with the current measured TP concentrations of Barton Broad, values being 145 and 180 µg TP l^{-1} respectively. It is unlikely, however, that the very high DI-TP values estimated by the model for the lower part of the core are realistic. Past phosphorus budgets estimated for Barton Broad by Moss (1980) produced an epilimnetic TP concentration of 52 µg TP l^{-1} for 1900 increasing to 120 µg TP l^{-1} by 1940, and therefore it seems that the diatom transfer function over-estimates TP for Barton Broad during the early twentieth century.

The diatom phosphorus transfer function results must be interpreted with caution in view of the dominance of the non-planktonic *Fragilaria* taxa in the core which are known to cause problems with quantitative diatom analysis (see Bennion, 1995 for a full account). One problem is that non-planktonic forms are less sensitive to changes in epilimnetic water chemistry than plankton. The *Fragilaria* taxa are distributed along the whole length of the TP gradient in the northwest European transfer function illustrating that these taxa are not particularly good indicators of lake trophic status.

Clearly, benthic taxa are likely to be affected by factors in addition to epilimnetic water chemistry, for example variations in substrate, and epiphytic taxa are influenced by the extent of macrophyte development. The relationship between non-planktonic taxa and epilimnetic nutrient concentrations is complicated by the availability of alternative sources of nutrients for these forms. For example, *Fragilaria* spp. growing *in situ* on the sediment surface in very shallow waters may have access to enhanced nutrient levels at the sediment-water interface, and epiphytic diatoms may derive nutrients from their hosts, although release of P from growing macrophytes is considered to be minimal in lakes with high epilimnetic TP concentrations, in comparison with the amount of P that epiphytes obtain from the water (Granéli & Solander, 1988).

Figure 9 Lithostratigraphic data for Rollesby Broad

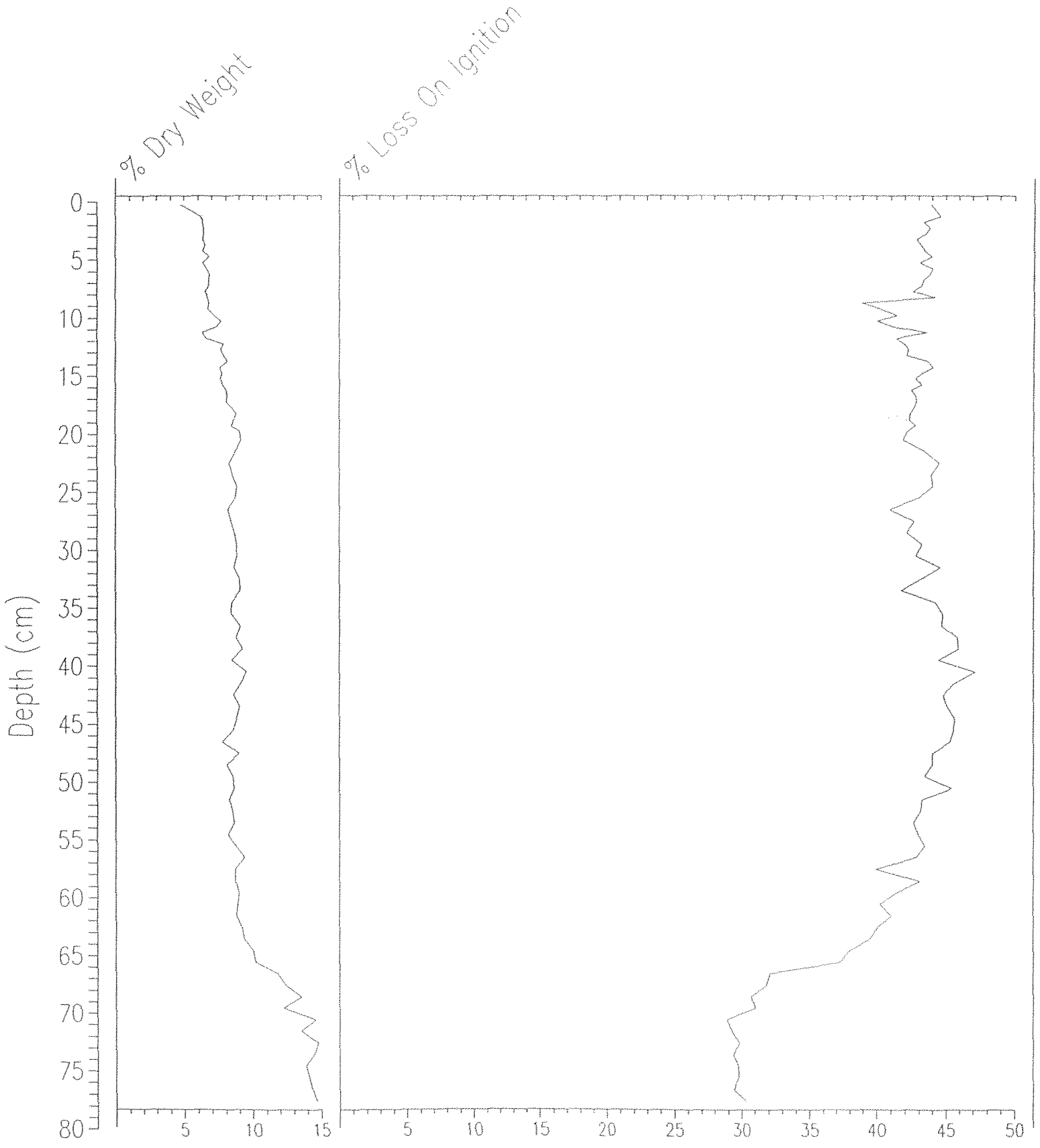
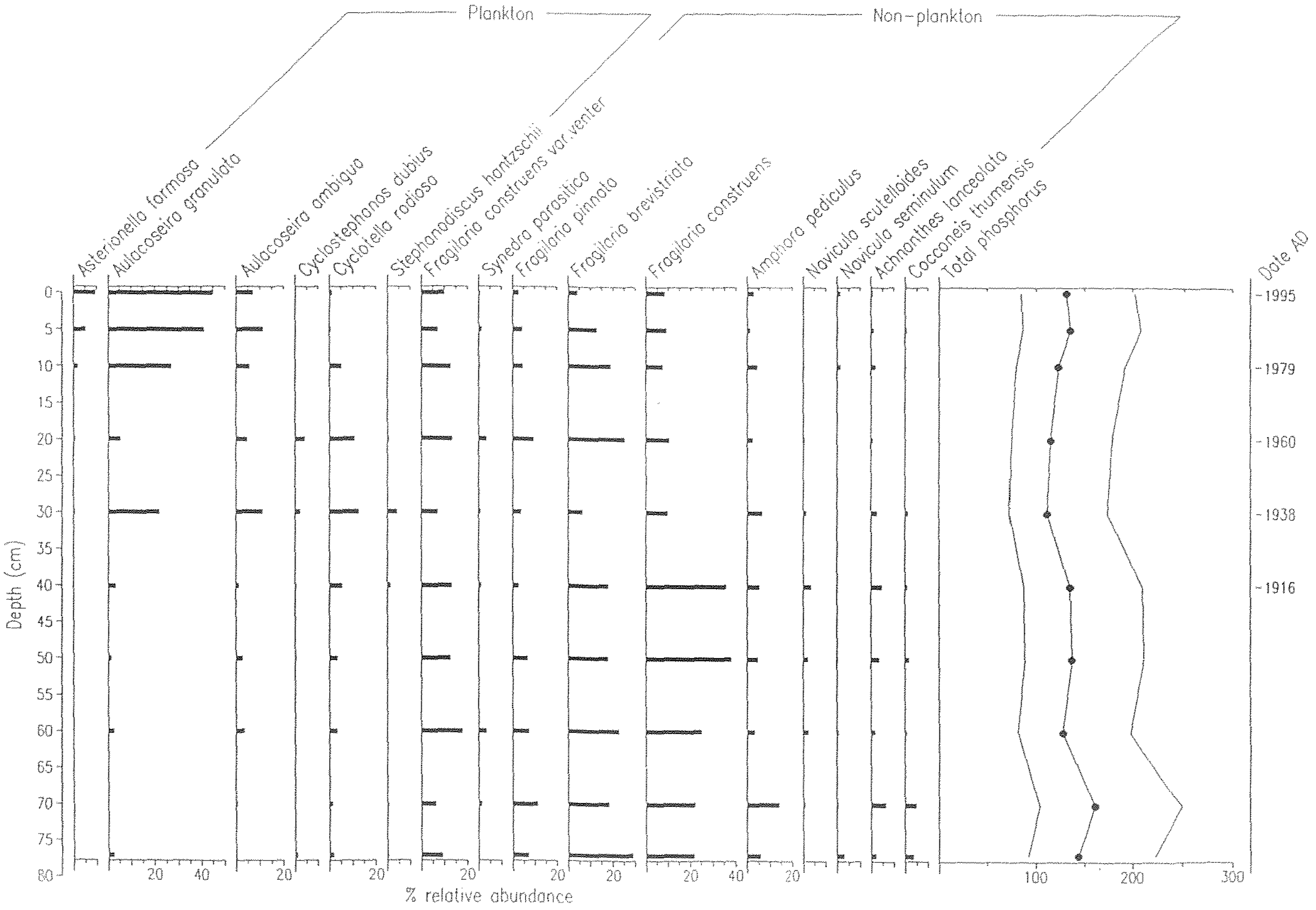


Figure 10 **Summary diatom diagram and TP reconstruction for Rollesby Broad**
(TP = annual mean TP in µg l^{-1} shown by line with filled circles;
standard errors of prediction are shown by solid lines)



5.4 Discussion

The species shifts observed in the Barton Broad core were also a feature of the Rollesby Broad core, with a marked switch from an epiphytic diatom community to a plankton dominated one. In Rollesby Broad this switch occurred at the 30 cm sample, calculated to represent 1938, somewhat earlier than the 1966 shift in Barton. However, given the uncertainties surrounding the radiometric dates in Barton Broad, a direct comparison of the timing of events in the two cores is not recommended here. Similarly to the Barton Broad core, the *Fragilaria* taxa remain relatively abundant throughout the core but a number of other important epiphytic taxa, in particular, *Amphora pediculus, Navicula seminulum, Achnanthes lanceolata* and *Cocconeis thumensis* decline in relative abundance, reflecting the loss of submerged macrophytes in the lake.

The upper 30 cm of the core, that is the post-1938 period, was dominated by planktonic taxa. *Aulacoseira granulata* was the most abundant taxon, a species commonly forming large blooms in nutrient-rich lakes. *Aulacoseira ambigua* and *Cyclotella radiosa* were also common. These taxa are generally indicative of slightly lower nutrient concentrations than taxa from the genera *Stephanodiscus* and *Cyclostephanos*. Species from the latter genera were only present in low relative abundances, which may reflect the slightly less fertile nature of Rollesby Broad compared to Barton and Wroxham Broad. Unlike the other two sites, Rollesby Broad does not receive direct sewage effluent and is still classed as a late phase 2 to early phase 3 broad (Kennison & Prigmore, 1994).

The DI-TP values, however, do not reflect the lower trophic status of Rollesby Broad relative to the other two study lakes. The results suggest that Rollesby Broad has always been a hypertrophic lake with TP concentrations > 100 µg TP l^{-1}. The DI-TP concentrations ranged from 112 µg TP l^{-1} to 161 µg TP l^{-1} but displayed no clear direction of change over time. The lowest DI-TP values were for the period 1938-1979 when *Cyclotella radiosa* was present in relatively high abundances.

As for the Barton Broad core, the DI-TP values must be interpreted in light of the problems associated with high percentages of non-planktonic taxa in the fossil assemblages. The nutrient-enrichment which brought about the observed switch in diatom species composition was not reflected by the model because of the continuing dominance of *Fragilaria* spp. throughout the core. The DI-TP values for the early part of the core are likely to be over-estimates of actual epilimnetic TP concentrations, as the assemblages are more indicative of the available habitats and light conditions than the in-lake nutrient levels. Therefore, similarly to Barton Broad the quantitative data are not reliable enough to determine the TP threshold for achieving community stability. However, the complete ^{210}Pb record in the Rollesby Broad core provides reliable dates and allows us to conclude with reasonable confidence that the switch to a plankton dominated community occurred at around 1938.

6 Wroxham Broad (TG 308 165)

Wroxham Broad is the first major lake on the River Bure system and is likely to be the first to respond to the reduction in phosphorus discharges that were initiated in 1986. As for the River Ant, phosphorus removal from sewage effluent is about to be improved and knowledge of the history of the lake would be useful for management.

6.1 Lithostratigraphy

A 106 cm core was taken on 12-10-95 in 2 m of water (see Appendix). The %DW and %LOI profiles are shown in Figure 11. The results show that the %LOI was similar throughout the whole period represented by the core with values of approximately 10-15%. The %DW also showed little variation, although there was a relatively more organic section from c. 70 cm to 30 cm where %DW values declined slightly and %LOI simultaneously increased. A small increase in organic matter was also observed in the upper 10 cm of the core.

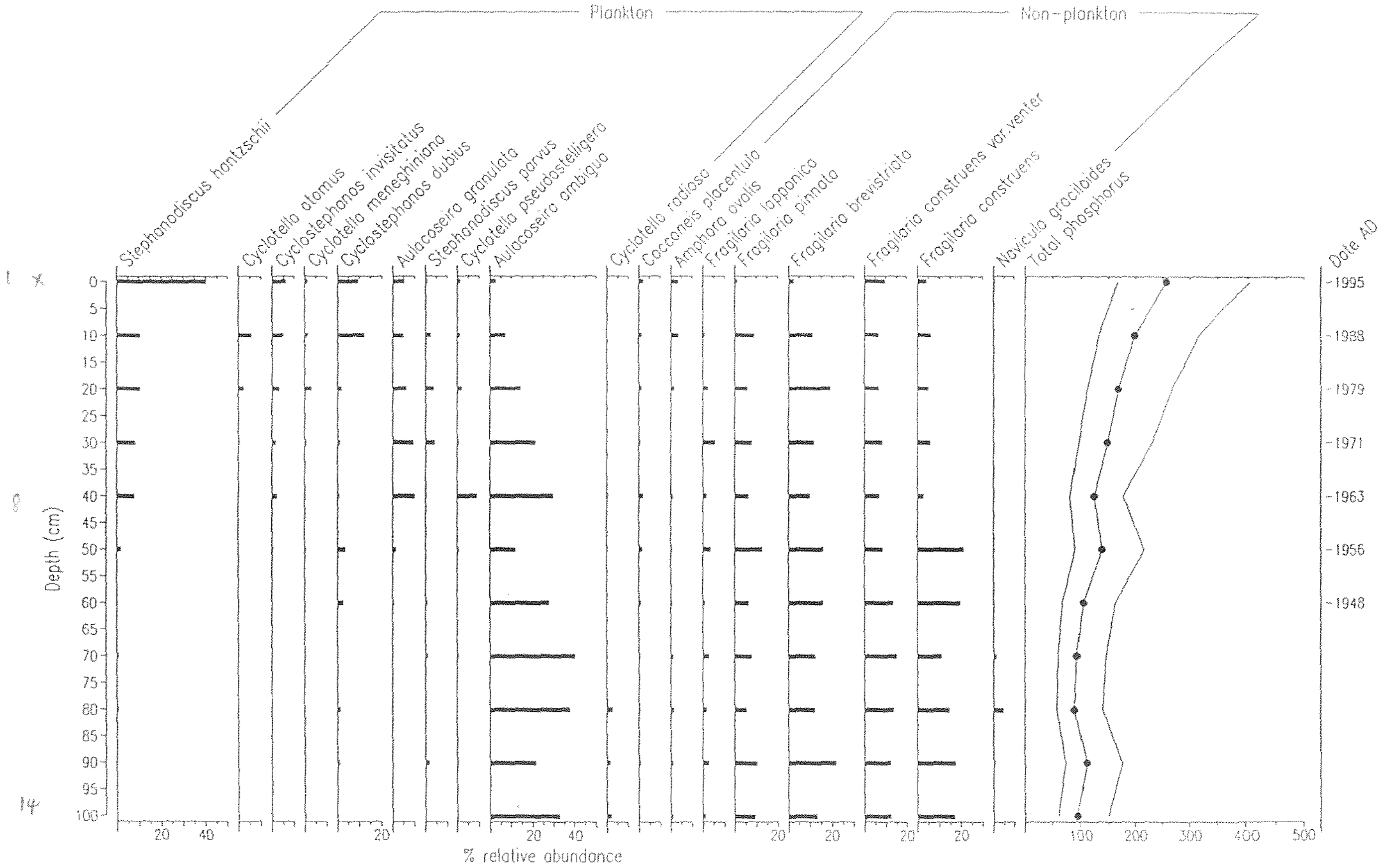
6.2 Diatom Stratigraphy

The percentage relative frequencies of diatom species in eleven levels of the sediment core WROX1 were calculated and Figure 12 illustrates the results for the major taxa. Diatom preservation was good throughout the core. A total of 84 taxa was observed, 74 of which were present in the TP calibration set. There were no species analogue problems, with 98% or more of the fossil assemblage being used in the TP reconstructions.

Figure 12 illustrates that there have been marked changes in the diatom species composition over the period represented by the 100 cm core (*c.* post-1920). Prior to the 40 cm level (c. pre-1963), the assemblages were dominated by the non-planktonic taxa, *Fragilaria brevistriata, Fragilaria construens* var. *venter, Fragilaria pinnata* and *Fragilaria construens,* but unlike the other two sites also supported a high relative abundance of the planktonic species *Aulacoseira ambigua* in the early period of the lake's history. The non-planktonic *Fragilaria* taxa were also an important part of the diatom assemblage in the upper 40 cm of the core but relative abundances declined. There was a progressive decrease in the percentage of *Aulacoseira ambigua* from 40 cm to the surface and *Cyclotella radiosa* disappeared. In contrast, the assemblages became dominated by a number of planktonic species indicative of more eutrophic conditions in the upper 40 cm. In particular, *Stephanodiscus hantzschii* increased in importance from less than 10% of the total assemblage before the 40 cm sample (c. 1963) to 40% at the surface (1995). Other common taxa in the upper core section were *Aulacoseira granulata, Cyclostephanos dubius, Cyclostephanos invisitatus, Cyclotella atomus, Stephanodiscus parvus, Cyclotella meneghiniana* and *Cyclotella pseudostelligera.*

Figure 12 Summary diatom diagram and TP reconstruction for Wroxham Broad

(TP = annual mean TP in µg l^{-1} shown by line with filled circles;
standard errors of prediction are shown by solid lines)



6.3 TP Reconstruction

The DI-TP reconstruction shows that the lake has had high TP concentrations throughout the period represented by the sediment core (*c.* post-1920), which would place the lake in the hypertrophic category (> 100 μg TP l^{-1}). In contrast to Barton Broad and Rollesby Broad, however, there was a clear trend in the DI-TP concentrations with an increase from c. 90 μg TP l^{-1} at the base of the core to 257 μg TP l^{-1} at the surface. The DI-TP values for the samples below 50 cm were on average much lower than those above this level (ie. range 89-112 μg TP l^{-1}, mean 99 μg TP l^{-1} and range 123-257 μg TP l^{-1}, mean 172 μg TP l^{-1} respectively), corresponding to the switch in the diatom community from one dominated by non-plankton to one dominated by planktonic species indicative of high TP concentrations. The most marked change in the DI-TP concentrations was the steady rise from the 40 cm (c. 1963) sample to the surface during which values increased two-fold.

6.4 Discussion

Similarly to the other two study sites, there were clear species shifts in the Wroxham Broad core reflecting a switch from a largely epiphytic community to one dominated by planktonic forms. Prior to the 40 cm level (c. pre-1963), the assemblages were dominated by the non-planktonic taxa, *Fragilaria brevistriata, Fragilaria construens* var. *venter, Fragilaria pinnata* and *Fragilaria construens,* but unlike the other two sites also supported a high relative abundance of the planktonic species *Aulacoseira ambigua* in the early period of the lake's history. The non-planktonic *Fragilaria* taxa remained an important part of the diatom assemblage in the upper 40 cm of the core, as in Barton and Rollesby Broad, although relative abundances declined.

A clear change was observed at 40 cm with the percentage of *Aulacoseira ambigua* progressively decreasing towards the surface and *Cyclotella radiosa* disappeared from the lake. These two species have relatively low TP optima (68 and 36 μg TP l^{-1} respectively) and are indicative of slightly less rich conditions than the small, centric plankton, and thus their decline clearly signals the start of enrichment. The assemblages became dominated by a number of planktonic species indicative of more eutrophic conditions in the upper core section. In particular, *Stephanodiscus hantzschii* increased in importance from less than 10% of the total assemblage below the 40 cm sample (c. 1963) to 40% at the surface (1995). Other common taxa in the upper core section were *Aulacoseira granulata, Cyclostephanos dubius, Cyclostephanos invisitatus, Cyclotella atomus, Stephanodiscus parvus, Cyclotella meneghiniana* and *Cyclotella pseudostelligera,* taxa which have high TP optima of > 130 μg TP l^{-1}. These qualitative data confirm the current classification of Wroxham Broad as a late phase 3 broad (Kennison & Prigmore, 1994).

The quantitative diatom results support the above findings. In contrast to Barton Broad and Rollesby Broad, there was a clear trend in the DI-TP concentrations with an increase from c. 90 μg TP l^{-1} at the base of the core to 257 μg TP l^{-1} at the surface. The model performs better when applied to the Wroxham Broad core than the other two sites in this study because of the higher percentage of plankton throughout the core. The DI-TP values for the samples below 50 cm were on average much lower than those above this level (ie. range 89-112 μg TP l^{-1}, mean 99 μg TP l^{-1} and range 123-257 μg TP l^{-1}, mean 172 μg TP l^{-1} respectively). This is the core depth at which the diatom community switches from one dominated by non-plankton to one dominated by planktonic species indicative of high TP concentrations, and therefore a TP concentration of c. 100 μg TP l^{-1} appears to be the threshold value below which stability is maintained. Given the problems associated with the abundance of non-planktonic *Fragilaria* taxa in fossil diatom assemblages, it may be possible that this is an over-estimate of the past TP concentrations.

The recent eutrophication process in Wroxham Broad is clearly shown by the diatom-TP reconstruction. The most marked change in DI-TP concentrations has occurred since c. 1963 during which values have increased two-fold. The planktonic diatom taxa constituted over 70% of the total assemblage in the surface sample. There is no evidence, therefore, that the water quality has begun to improve following a reduction in phosphorus discharges to the lake and Wroxham Broad would be classed as hypertrophic, following the OECD scheme (1982).

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Appendix: Maps showing the core locations in Barton, Rollesby and Wroxham Broad