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PALAEOECOLOGICAL EVALUATION OF WATER QUALITY CHANGE IN LOCH URR, GALLOWAY, SCOTLAND.

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An evaluation of the recent Palaeoenvironmental history of Loch Urr, a non-acidified Loch in Galloway, south-west Scotland.

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1.0 Introduction

The recent acidification of several lochs on granite bedrock, with afforested and/or moorland catchments, in the Galloway region of south-west Scotland has been documented in detail by the Palaeoecology Research Unit at University College London (eg. Battarbee et al. 1985, Battarbee et al. in press, Flower 1986, Flower and Battarbee 1983, Flower et al. 1987, Jones et al. 1986). To provide a 'control' study to those investigations, this paper examines the palaeoecological and contemporary characteristics of Loch Urr.

Loch Urr is also in the Galloway region and shares the high atmospheric hydrogen ion and sulphate loadings of the acidified Galloway Lochs. However, unlike those lochs Loch Urr drains a catchment which lies on Silurian sedimentary rocks and has a long history of improvement for agriculture. Contemporary water pH of the loch is in the range 6.0 - 7.0. Because of the catchment geology and land use characteristics, surface water acidification is unlikely to have occurred at this site.

2.0 Loch Urr: characteristics

2.1 Loch

Loch Urr lies at 190 m in the Galloway region of south-west Scotland (Fig. 1) and covers an area of 52.3 ha. Two streams flow into the loch in the north-east (Loch Urr Lane) and north-west (Water of Urr). The loch is drained to the south by the Water of Urr (Fig. 2). Loch bathymetry was surveyed in 1903 by Murray and Pullar (1910) and revealed a mean water depth of 3.65 m with a maximum of 12.8 m (Table 1). For the present study the data of Murray and Pullar (1910) have been utilised to construct a map of the loch bathymetry (Fig. 3) using MAPICS (1987) contouring software. Figure 3 shows the loch to have a simple single basin bathymetry which yields a maximum water volume of 1,672,707 m^3 (this compares with Murray and Pullar's estimate of 1,585,836 m^3. Loch water level has been raised (by < 1 m) at sometime in the recent past by a small sluice, probably to facilitate adequate water levels for recreational sailing (Raven 1985). This rise in water level probably accounts for the discrepancy between the maximum water depth recorded by Murray and Pullar (1910) (12.8 m) and that recorded during this survey (13.2 m) (Table 1). A small island lies close to the eastern shore upon which is a ruined castle of some antiquity (Corrie 1910). The island and its ruin are now home to a black-headed gull colony of some 300 pairs (Raven 1985).

Loch water chemistry is presented in Table 2. The analyses of November 1984, July 1985 and December 1987 were made at the laboratories of the Solway River Purification Board. The pH and conductivity measurements of May 1984 were made with portable field instruments, this may explain the low pH reading at that date. The water chemistry indicates that Loch Urr is a mildly acid, brown water loch which retains some bicarbonate alkalinity. The concentration of base cations, particularly Ca^{++} and K^{+} are marginally higher than in other Galloway lochs which are located in granite catchments (Flower et al. 1986) and probably reflects the less resistant Silurian geology of this site. It is of interest to note that in terms of Henrickson's (1979) equation of surface water acidification the pH and calcium values suggest that Loch Urr has not experienced acidification.

Historical descriptions of the loch (eg. Brown 1845), draw attention to the particularly dark colour of the loch water. Secchi disk depth on May 12th 1984 was 2 m. This is probably an exaggerated measurement resulting from the sunny conditions on that afternoon.

Dissolved oxygen and temperature were measured in the loch in May 1984 (Flower et al. 1986). The results are presented in Appendix 1. The loch showed only weak thermal stratification with a poorly developed thermocline between 8 and 10 m depth. This situation may be explained by at least two factors. Sampling was in early summer, well before the thermal maximum and the loch is very exposed so that the thermocline may frequently be broken down during high winds. However, the thermocline was stable enough to permit some deoxygenation of the deeper water.

A detailed survey of loch macrophytes was undertaken in May 1984 (Raven 1985). Littorella uniflora and Myriophyllum alterniflorum dominated the macrophyte community with Callitriche hamulata and Carex rostrata being locally significant. Other macrophyte species recorded were, Isoetes lacustris, Juncus bulbosus var. fluitans, Lobelia dortmanna, Polygonum amphibium, Potamogeton alpinus, Potamogeton natans, Ranunculus peltatus, Eleocharis palustris, Equisetum fluviatile, Phragmites australis and Schoenoplectus lacustris. Unfortunately Loch Urr was not included in the macrophyte survey of West (1910) and there is no historical data to permit a temporal comparison of the macrophyte flora.

2.2 Catchment

The Loch Urr catchment (Fig. 2) covers an area of 778 ha and reaches a maximum altitude of 432 m, giving a net relief of 242 m (Table 1). The land immediately adjacent to the loch consists of 'moss' peat which is particularly wet despite past attempts to drain it (Section 5.0). Tree stumps underlying this area of peat provide evidence of an ancient woodland of uncertain date (the area has been cleared of forest since at least the early-17th century - Section 5.0). All land in the catchment (Fig. 2) has been subjected to improvement of varying intensity. The area of enclosed 'fields' to the north and north-east of the loch still support arable and improved grass cultivation (Section 5.0), whereas the higher land to the north and the poorly drained land to the east and west supports rough grazing moorland characterised by Calluna, Molinia, Scirpus and Juncus species.

The catchment bedrock comprises shales of the Silurian Llandovery series, which fall into the 'medium' category of acid susceptibility (Kinniburgh and Edmunds 1986). Precipitation characteristics are recorded in detail at a site very close to Loch Urr - Waterhead some 1.5 km to the south-west (Barrett et al. 1987). Mean precipitation composition data for the period 1981 - 1985 is presented in Table 3. Of particular note are the high atmospheric hydrogen ion and sulphate loadings.

2.3 Fishing history

Despite relative ease of access, little detail is known of the fishing history of Loch Urr. The information provided by Grierson (1792), that the loch supported pike, some of a large size and a few large trout, is reiterated by Forsyth (1805), Brown (1845) and Cullen and Murray (1845). Lyall (1910) reported that the fishing in the Loch was privately owned and that the pike and trout within the loch did not provide good sport.

Table 1 Loch Urr: loch and catchment characteristics

Loch		Catchment	
Area	52.3 ha	Max. altitude	432 m
Altitude	190 m	Max. relief	242 m
Mean depth	3.65 m	Total area	778 ha
Max. depth	12.8 m [a] 13.2 m [b]	Area afforested	c.5%
Volume	1,672,707 m^3	Annual rainfall	1111 mm
		Annual deposited H^+	33 $\mu eq\ l^{-1}$
		Annual deposited SO_4^{--}	47 $\mu eq\ l^{-1}$

[a] Murray and Pullar (1910)
[b] This survey

Table 2 Loch Urr: water chemistry (outflow samples)
([1] analyses by Solway River Purification Board)

	May 1984	Nov. 1984[1]	July 1985[1]	Dec. 1987[1]
pH	6.0	6.4	7.0	6.9
Alkalinity (mg l^{-1} $CaCO_3$)	*	4.8	10.7	6.9
Conductivity (µS cm^{-1})	65	67	58	47
Na^+ (mg l^{-1})	*	5.15	4.29	3.10
K^+ (mg l^{-1})	*	0.47	0.39	0.46
Ca^{++} (mg l^{-1})	*	2.99	3.86	3.16
Mg^{++} (mg l^{-1})	*	1.70	1.65	1.39
Cl^- (mg l^{-1})	*	12.6	7.8	5.19
SO_4^{--} (mg l^{-1})	*	8.4	6.3	4.33
SiO_2 (mg l^{-1})	*	3.4	0.1	2.3
NO_3^- (mg l^{-1})	*	0.24	0.13	0.30
Al (Tot.) (µg l^{-1})	*	240	320	123
Zn (Tot.) µg l^{-1})	*	13	4	2
Mn (Tot.) (µg l^{-1})	*	16	38	17
Fe (Tot.) (µg l^{-1})	*	139	126	317
Absorbance (250 nm)	*	0.37	0.41	0.405

* missing values

Table 3 Mean precipitation composition in the vicinity of Loch Urr for the period 1981-1985 ($\mu eq\ l^{-1}$) (Barrett *et al.* 1987)

	Waterhead
Distance from Loch Urr	1.5 km
Altitude	200 m
Mean rainfall	1111 mm
H^{+}	33
SO_4^{--}	47
NO_3^{-}	20
NH_4^{+}	23
Na^{+}	78
Cl^{-}	95
Mg^{++}	23
Ca^{++}	18

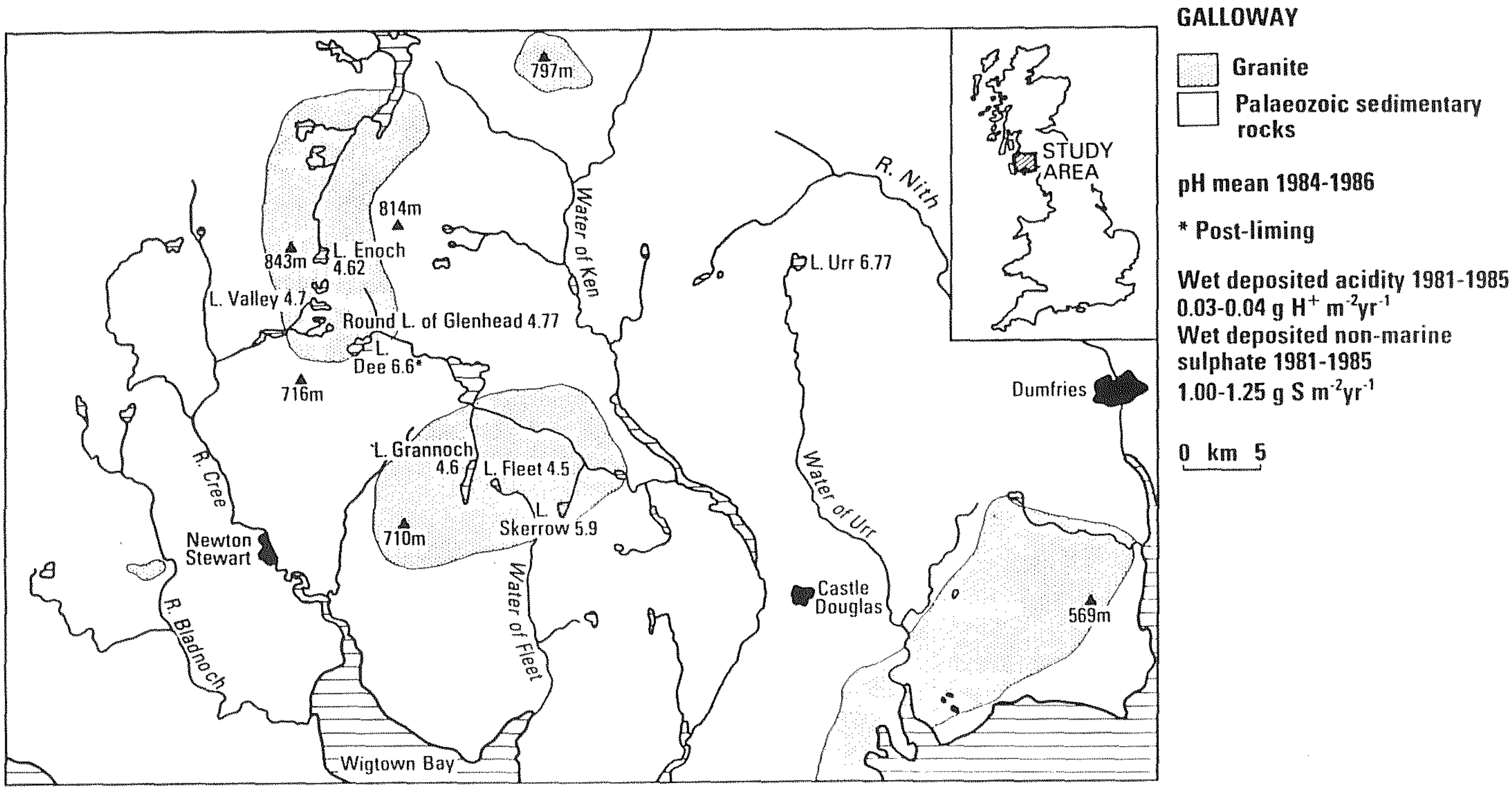


Figure 1. Galloway: the Location of Loch Urr.

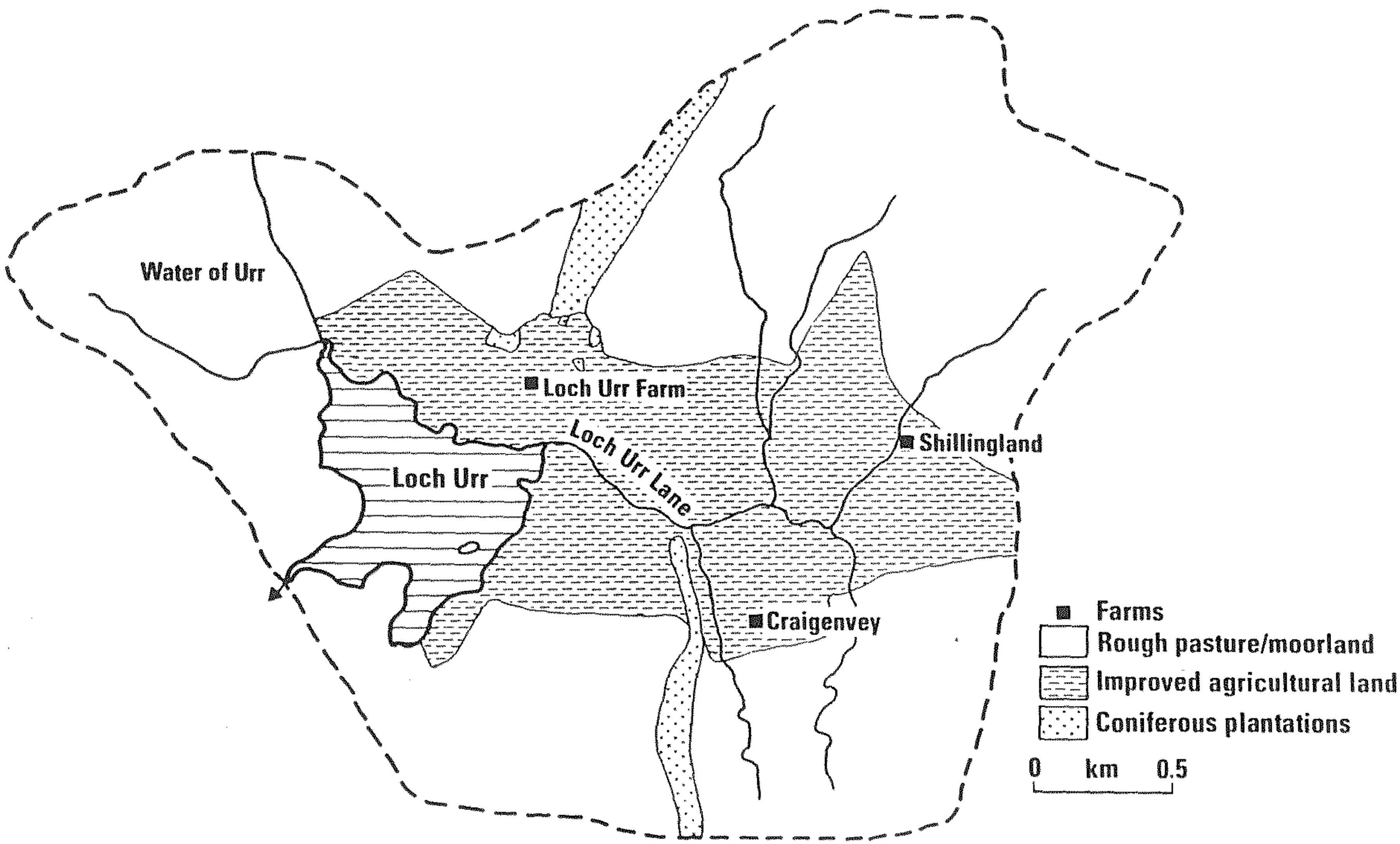


Figure 2 Loch Urr: Catchment.

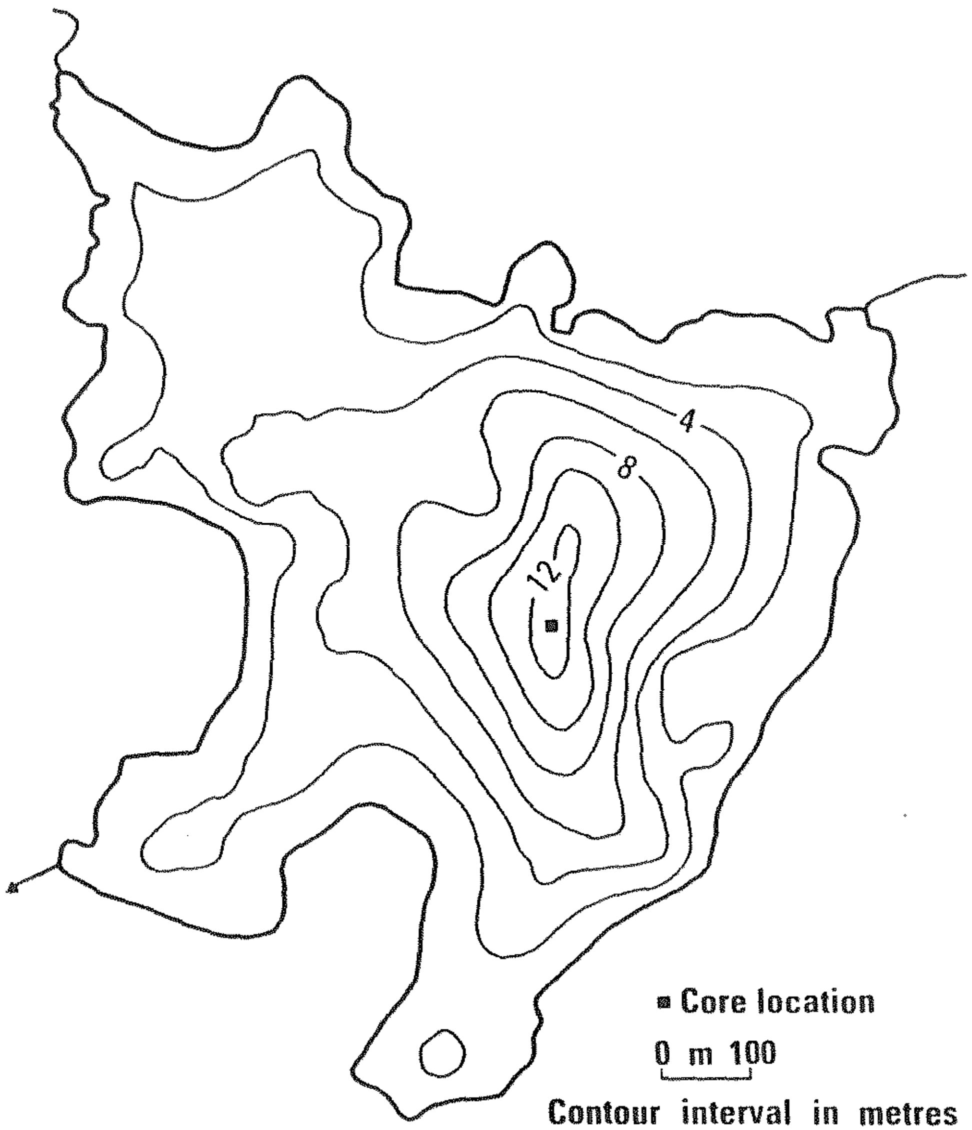


Figure 3 Bathymetric map of Loch Urr showing the core location.

3.0 Methods

Two sediment cores were taken from 12 m water depth (Fig. 3) in May 1984 using a mini-Mackereth corer (Mackereth 1969). Both cores yielded 85 cm of sediment with undisturbed sediment/water interfaces. Sediment core URR1 was extruded in the laboratory at 0.5 cm (top 20 cm) and 1.0 cm (21 cm - base) intervals. The sediment was then sub-sampled for dry weight, loss on ignition (LOI) (at 550°C) and wet density measurements. Subsequent analyses for chemistry, diatoms, carbonaceous particles and pollen were all conducted according to the standard methods set out in Stevenson et al. (1987a). Dating was carried out by the Atomic Energy Research Establishment (AERE) at Harwell according to the techniques set out in Eakins and Morrison (1976).

4.0 Results

4.1 Sediment description

Neither sediment core showed a visual stratigraphy and they consisted throughout of black mud (Munsel colour 10YR). the top c. 0.5 cm comprised brown oxidised sediment containing a few chironomid tubes.

Sediment profiles of wet density, percentage dry weight (at 60°C) and percentage loss on ignition (LOI) (at 550°C) (Fig. 4), show relatively little change throughout the core. Both the wet density and dry weight profiles show a normal decline in the top few cm as water content increases and a minor peak in values around 58 cm depth. Changes are somewhat clearer in the LOI profile although deviation in percentage values never exceeds ±12%. A slight increase is apparent from c. 30% at the base of the core to c. 40% between 62 cm and 25 cm. At 58 cm there is evidence of a small minerogenic inwash event. Values decline to c. 30% again between 25 cm and 20 cm depth and thereafter remain fairly constant to the core top. The increase in LOI values in the lower section of the core could reflect some increased erosion of blanket peat in the catchment whereas the LOI decline at c. 25 cm (early nineteenth century - see Table 5) is probably the result of soil erosion consequent upon agricultural activity (see Section 5.0).

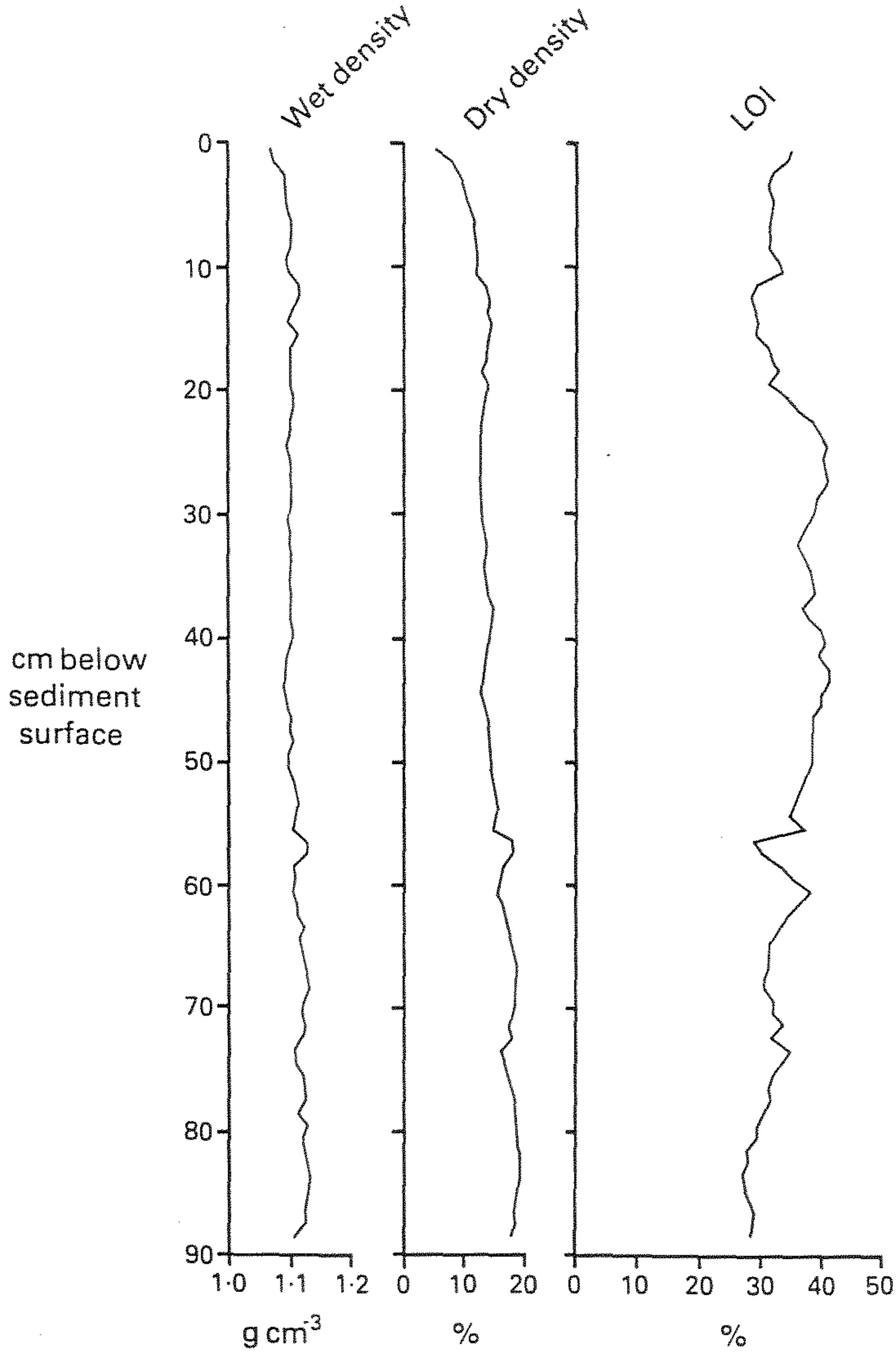


Figure 4 Lithostratigraphic data from Loch Urr.

4.2 ^{210}Pb dating

Sediment samples from core URR1 were analysed for ^{210}Pb and ^{226}Ra by AERE Harwell. The results are given in Table 4 and Figure 5. The unsupported ^{210}Pb inventory of the core was calculated to be 10.4 pCi cm^{-2} and represents a constant ^{210}Pb flux of 0.32 pCi cm^{-2} yr^{-1}. This is a little lower than at other Galloway sites and may indicate a reduced atmospheric flux arising from a lower rainfall. ^{210}Pb chronologies have been calculated using both the CRS and CIC ^{210}Pb dating models (Appleby and Oldfield 1978). In view of the linear nature of the unsupported ^{210}Pb profile (Fig. 5), the two chronologies should be virtually identical. This is confirmed by the results shown in Figure 6. Both indicate a constant sediment accumulation rate of 0.0224 ± 0.0021 g cm^{-2} yr^{-1}.

The CRS model indicates a reduced accumulation rate below 15.5 cm (dated c. 1898) but this can be attributed to errors in estimating the unsupported ^{210}Pb in samples below this depth. The chronology presented in Table 5 has been calculated using a mean accumulation rate, but does not differ significantly from the CIC chronology, or from the CRS chronology above 15 cm.

Table 4 Loch Urr: ^{210}Pb and ^{226}Ra data (core URR1)

Depth	Dry mass	^{210}Pb concentration				^{226}Ra Concentration	
		Total		Unsupported			
cm	g cm^{-2}	pCi g^{-1}	±	pCi g^{-1}	±	pCi g^{-1}	±
1.50	0.0988	13.40	0.90	12.37	0.91	1.03	0.10
5.50	0.5195	7.65	0.50	6.63	0.51		
10.50	1.1664	4.32	0.32	3.32	0.33		
15.50	1.9280	1.90	0.16	0.92	0.19		
20.50	2.6729	1.37	0.12	0.41	0.15		
25.50	3.3828	0.91	0.10	-0.03	0.14		
30.50	4.0814	0.79	0.10	-0.13	0.13	0.92	0.09
40.50	5.5879	0.59	0.08	-0.25	0.12		
50.50	7.0881	0.56	0.07	-0.20	0.10		
60.50	8.8593	0.72	0.10	0.06	0.12	0.66	0.07

Unsupported ^{210}Pb inventory: 10.4 ± 0.6 pCi cm^{-2}

Table 5 Loch Urr: ^{210}Pb chronology (Core Urr1)

Depth cm	Dry mass g cm^{-2}	Date AD	Age yr	±	Sedimentation rate g cm^{-2} yr^{-1}	Sedimentation rate cm yr^{-1}	
0.00	0.0000	1984	0				
1.00	0.0659	1981	3	1		0.317	
2.00	0.1514	1977	7	1		0.243	
3.00	0.2566	1973	11	2		0.216	
4.00	0.3617	1968	16	3		0.204	
5.00	0.4669	1963	21	3		0.195	
6.00	0.5842	1958	26	3		0.181	
7.00	0.7136	1952	32	3		0.174	
8.00	0.8430	1946	38	4		0.171	
9.00	0.9723	1941	43	4		0.170	
10.00	1.1017	1935	49	5	0.0224	0.170	}±9.5%
11.00	1.2426	1929	55	5		0.158	
12.00	1.3949	1922	62	6		0.145	
13.00	1.5472	1915	69	7		0.145	
14.00	1.6995	1908	76	7		0.145	
15.00	1.8518	1901	83	8		0.143	
16.00	2.0025	1895	89	9		0.147	
17.00	2.1515	1888	96	10		0.150	
18.00	2.3004	1881	103	11		0.154	
19.00	2.4494	1875	109	12		0.152	
20.00	2.5984	1868	116	13		0.149	

'5 = 6,800 152

0.0226g =

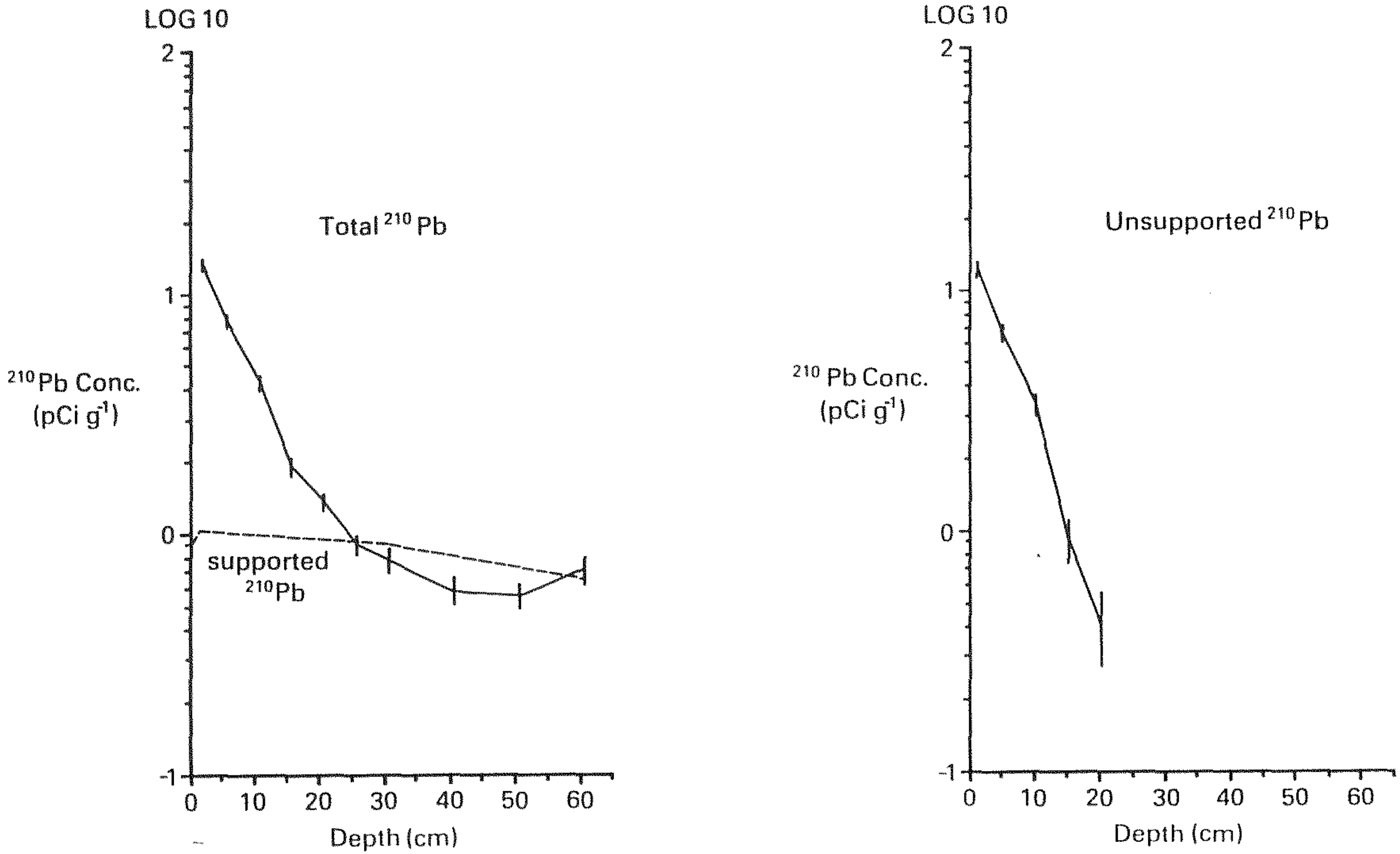


Figure 5 ^{210}Pb Profiles from Loch Urr.

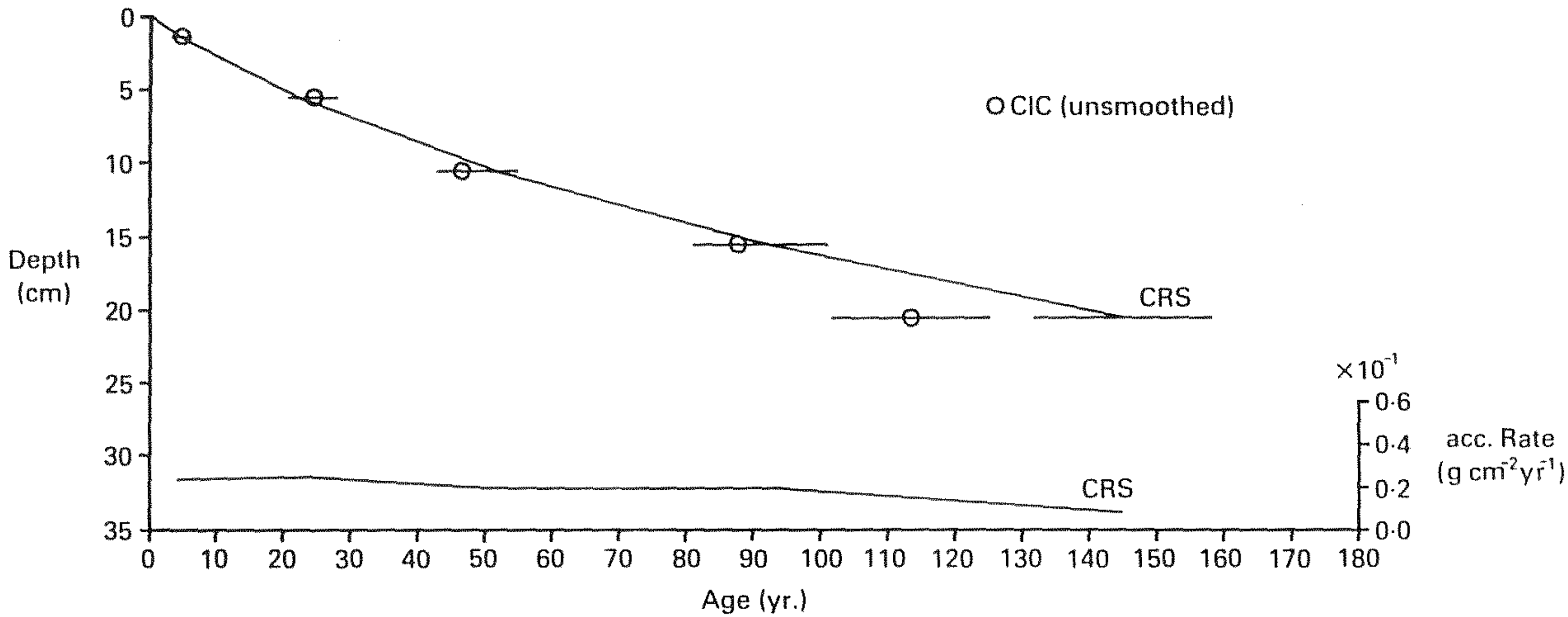


Figure 6 ^{210}Pb chronology for Loch Urr.

4.3 Sediment chemistry

The full geochemical analysis of sediment from core URR1 is presented in Appendix 2.

4.3.1 Major Cations

The major cation concentration-depth profiles show no large changes in the concentrations of potassium, sodium, magnesium and calcium (Fig. 7) over the dated part of core URR1 (0-20 cm- Table 5). All the cations except calcium, behave similarly (correlation coefficients all exceed 0.942).

With the exception of calcium there was an increase in cations around 25 cm, but when the effects of changing organic matter content are removed by expressing the concentrations in terms of per gramme minerals, the concentration changes are less (Fig. 8). The cation results indicate that there has been a change in erosion rates in the catchment, starting around 25 cm core depth, but that they were small. The cation fluxes (Fig. 9) confirm that there has been little change in catchment erosion rates between 20 cm and the core top.

4.3.2 Trace Metals

As there have been no major changes in the sediment accumulation rate above 20 cm depth, the trace metal concentration-depth profiles should reflect the amount of atmospheric contamination to a reasonably accurate degree. Zinc and lead contaminate the sediments above 35 cm (Fig. 10), but there is little contamination by copper and nickel (Fig. 11). The conclusions are the same when the effects of changing organic content are removed (Fig. 12).

35 cm depth precedes the dated section of the core, but as the sediment accumulation rate is fairly steady the date when lead and zinc contamination commenced can be estimated by linear extrapolation. This gives a date of mid to late eighteenth century (Table 5). Similar early dates have been found in other lakes with sediment accumulation rates high enough and steady enough to permit a date of first contamination to be estimated (eg. Fritz <u>et al.</u> 1987, Stevenson <u>et al.</u> 1987b, Patrick <u>et al.</u> 1987). As in the other lakes examined in this project, there are no trace metal bearing effluents entering the lake, so the most probable source of the lead and zinc contamination is deposition from the atmosphere.

The amounts of lead and zinc accumulated in the sediment are higher than in many of the lakes so far investigated (Table 6). Figure 13 shows that Loch Urr has lead and zinc burdens well above all the other lakes with the exception of Llyn Gynon in Wales. Both sediment accumulation rate and lake pH influence the trace metal burdens. There are higher burdens in lakes with high sediment accumulation rates (eg. Patrick <u>et al.</u> 1987), but if the lake pH has fallen low enough to decrease the efficiency of zinc sedimentation, then the zinc burden may be lower than expected (eg. Kreiser <u>et al.</u> 1987). Loch Urr has relatively high amounts of zinc because it is not acidified.

The results presented in Figure 14 show that Loch Urr has been contaminated by lead and zinc deposited from the atmosphere since the eighteenth century.

Table 6 Comparison of amounts of sedimentary lead and zinc deposited in Welsh and Scottish lakes since 1900

Lake	1900 depth cm	Amount deposited since 1900 zinc $mg\ m^{-2}$	lead $mg\ m^{-2}$	dry sed. $mg\ cm^{-2}$	Mean LOI %
Central Wales					
L. Gynon	16	8383	4854	2655	31.0
L. Hir	8	2707	1738	616	43.3
NW Wales					
L. Dulyn	10	1238	728	628	30.1
L. Eiddew Bach	6	1681	509	600	30.1
L. Llagi	16	6245	4623	1543	31.3
L. y Bi	4.25	677	406	250	25.7
L. Cwm Mynach	9	4255	1259	605	31.2
Scotland					
L. Laidon	15	1542	1746	1015	49.6
L. Enoch	18	2695	6336	2018	65.2
Round L. of Glenhead	11	2049	2853	904	39.2
L. Urr	15	9017	3049	1866	31.2

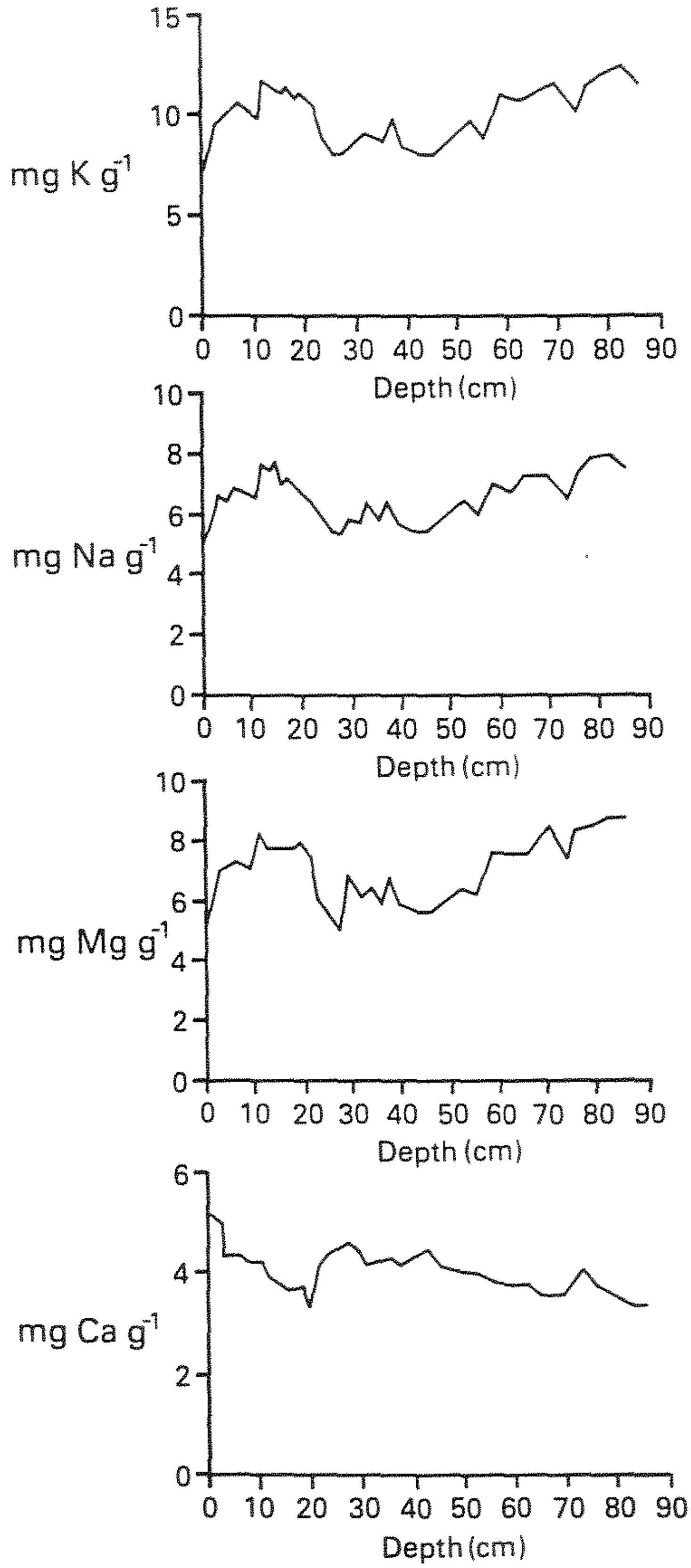


Figure 7 Variations of potassium, sodium, magnesium and calcium concentrations in Loch Urr.

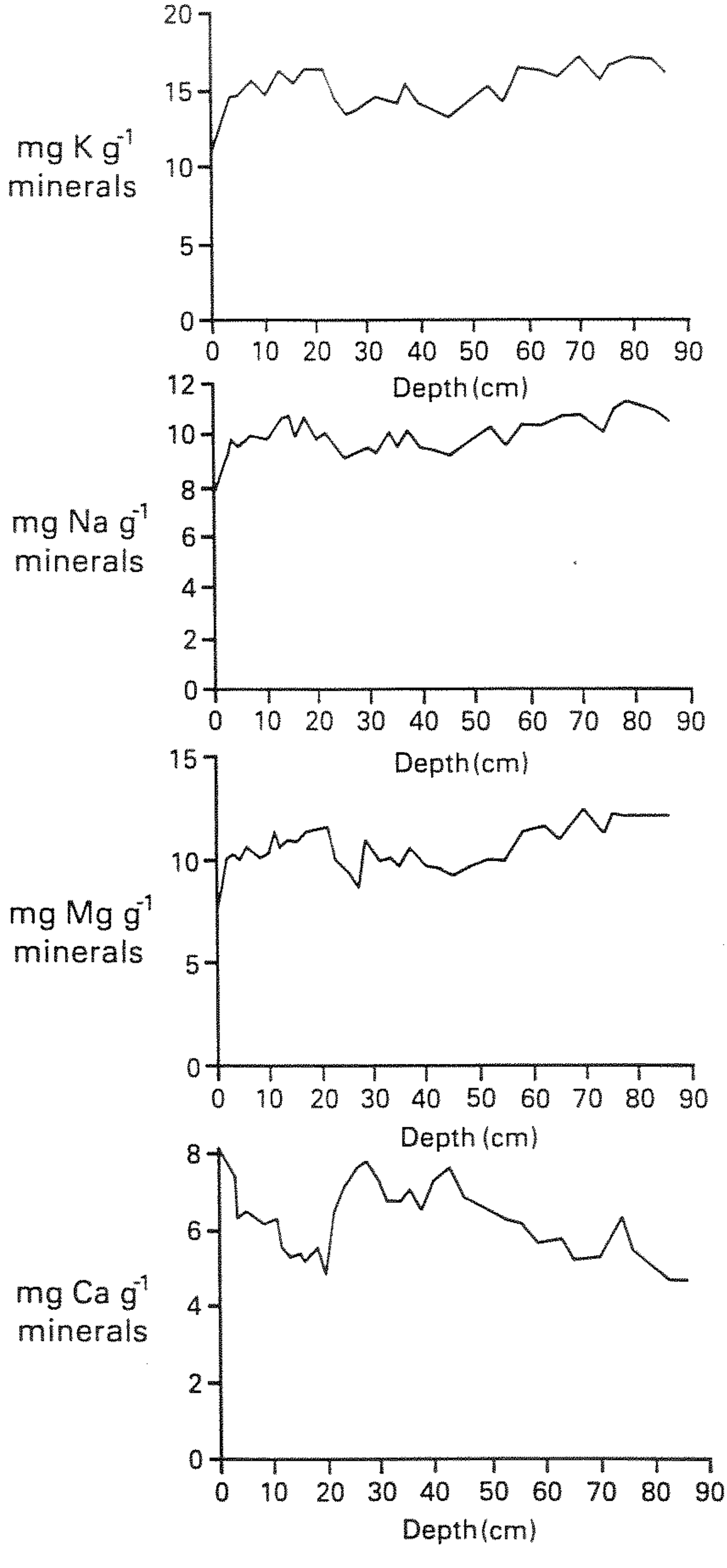


Figure 8 Variations of potassium, sodium, magnesium and calcium concentrations expressed per gramme minerals in Loch Urr.

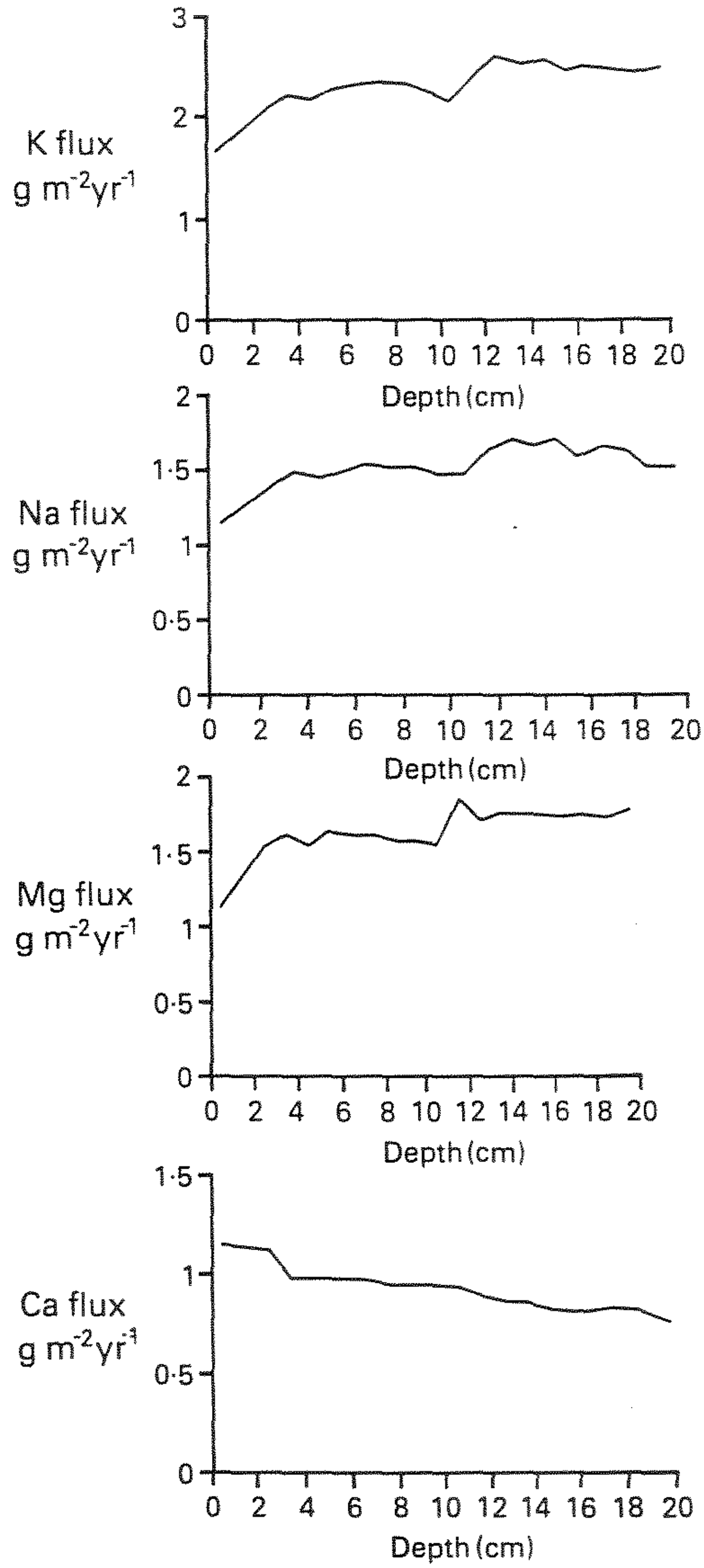


Figure 9 Variations of potassium, sodium, magnesium and calcium fluxes in Loch Urr.

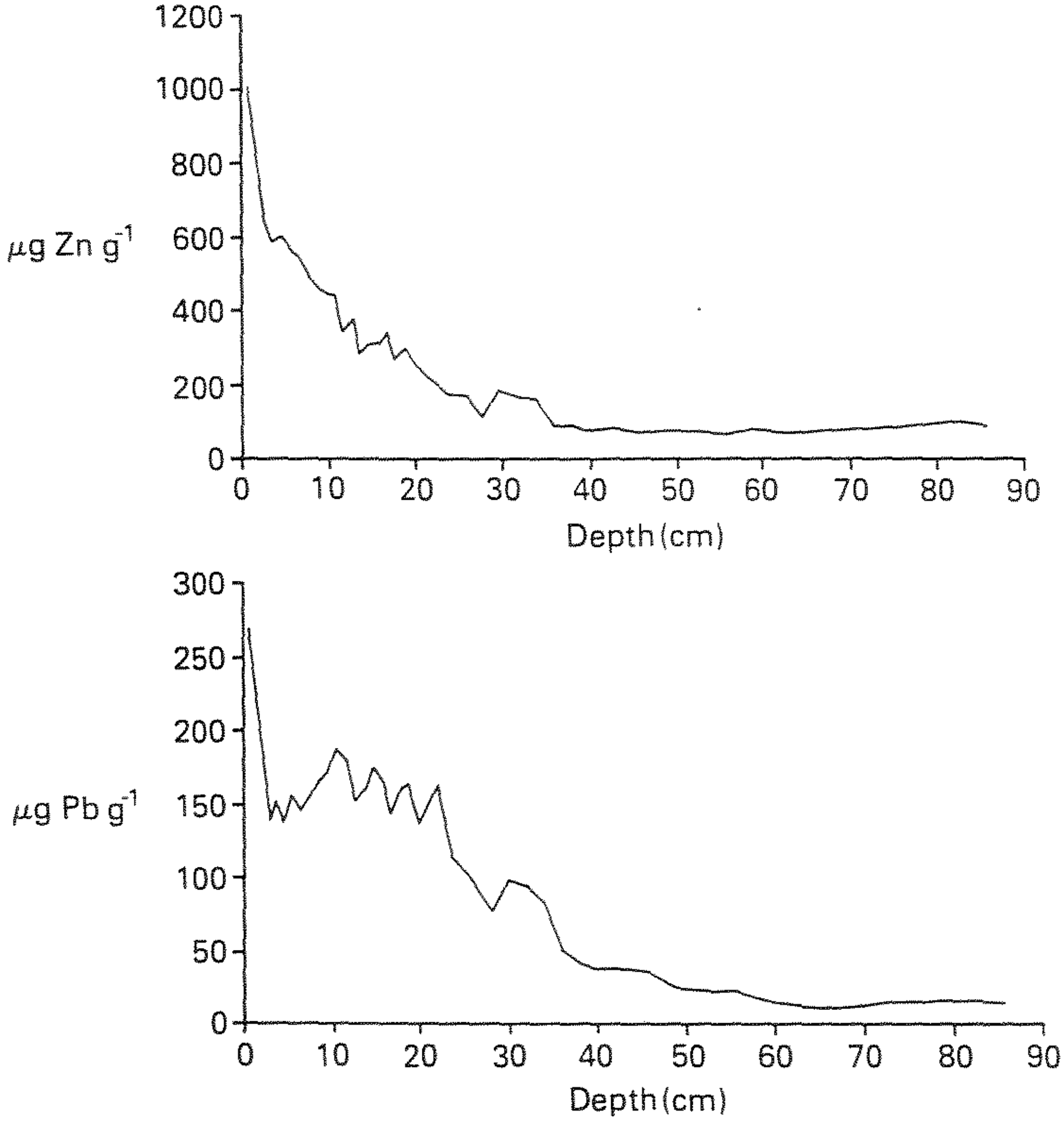


Figure 10 Variations of zinc and lead concentrations in Loch Urr.

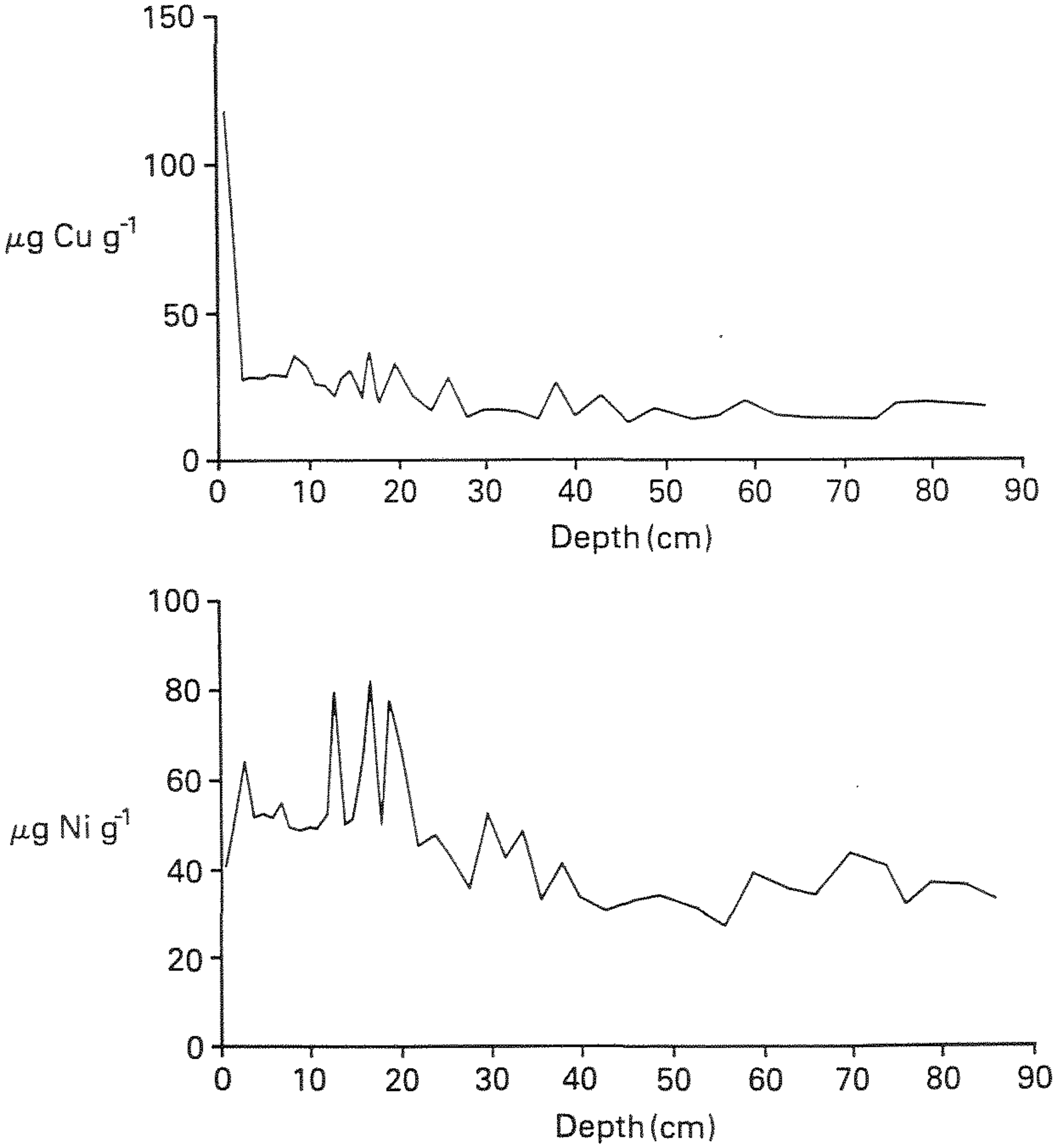


Figure 11 Variations of copper and nickel concentrations in Loch Urr.

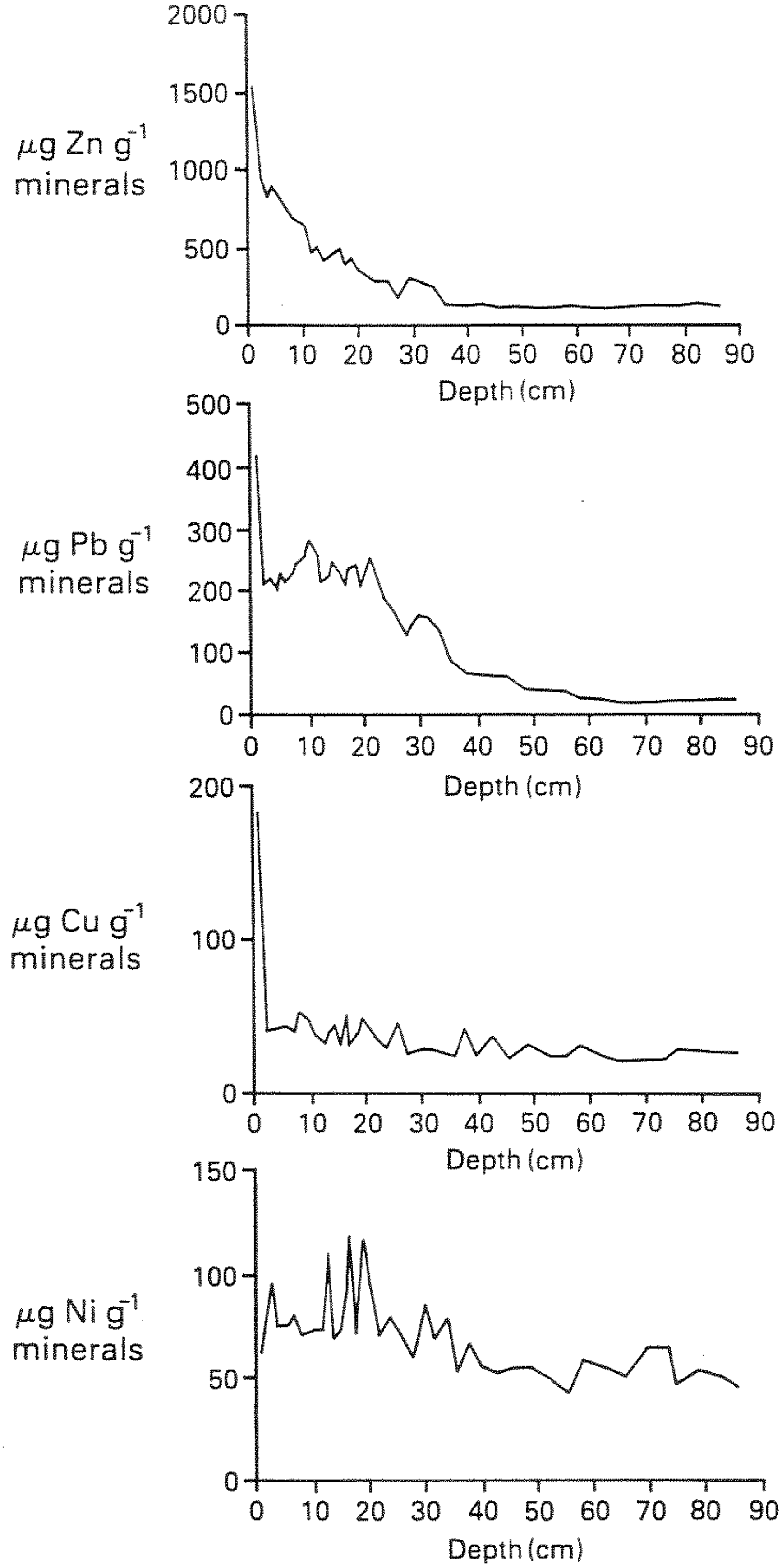


Figure 12 Variation of zinc, lead, copper and nickel concentrations expressed per gramme minerals in Loch Urr.

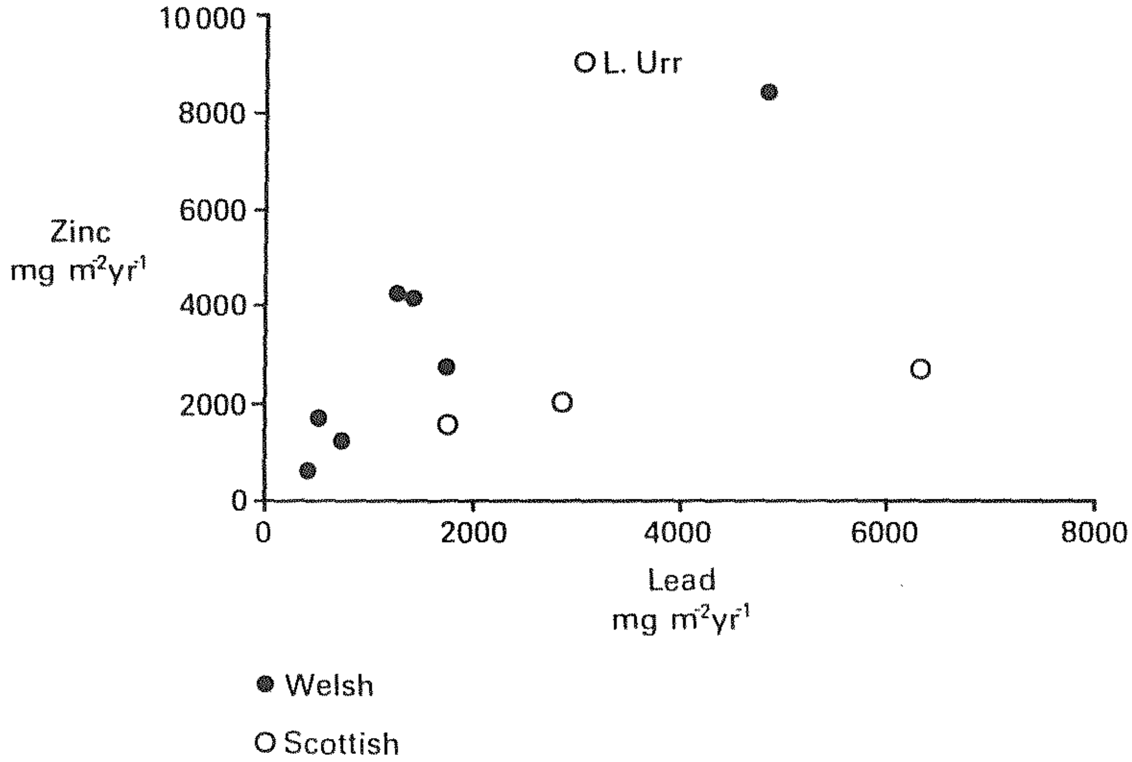


Figure 13 Comparison of the amounts of zinc and lead deposited since 1900 in some Scottish and Welsh lakes.

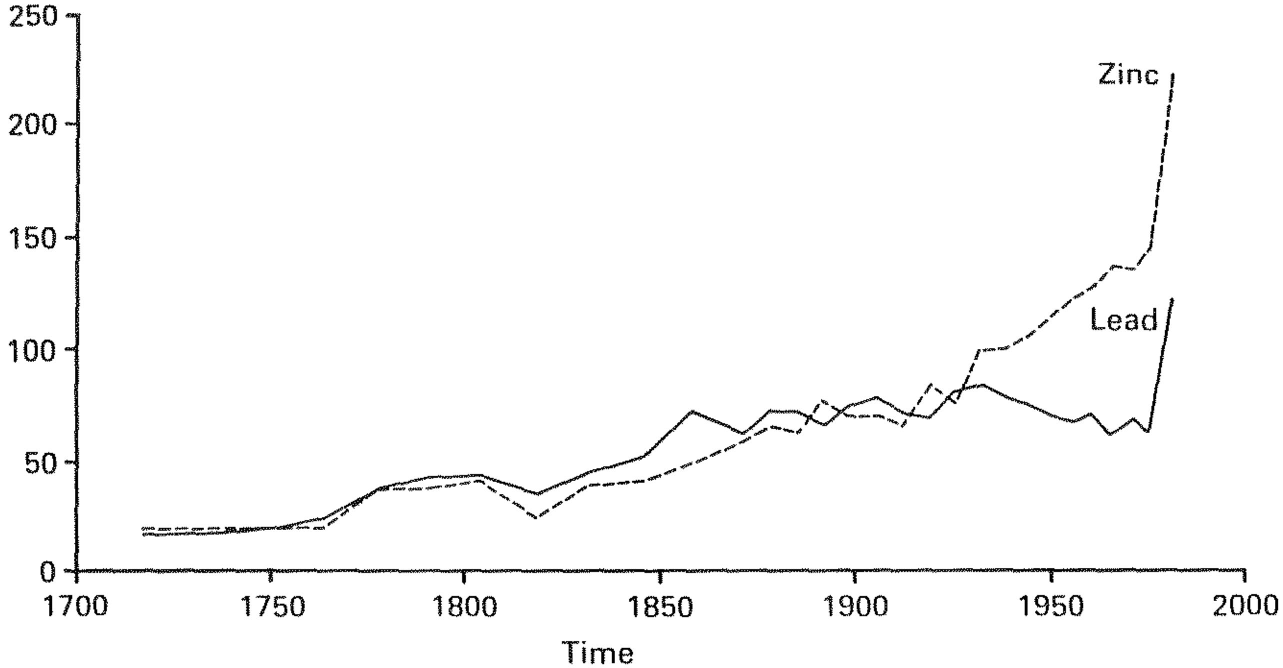


Figure 14 Variations of zinc and lead fluxes (mg $m^{-2}yr^{-1}$) with time in Loch Urr.

4.4 Sedimentary diatom assemblages

The percentage frequency profiles of all the diatoms counted at selected levels in core URR1 are given in Appendix 3. The summary diagram (Fig. 15) shows the major floristic changes recorded in the core. Between the core base and 25 cm depth the diatom flora shows little change and is dominated by a small form of *Cyclotella kutzingiana* var. *planteophora*, *C. comensis* and *Achnanthes minutissima*. These species are typical of mildly oligotrophic, circumneutral to acid upland lakes. The main diatom change in the core occurs between 25 cm and 15 cm as *C. kutzingiana* declines and *C. pseudostelligera* increases. These are both planktonic diatoms and the proliferation of *C. pseudostelligera* indicates some enrichment of the lake during the nineteenth and early twentieth centuries, possibly related to agricultural improvements at this time (Section 5.0). Above about 10 cm depth (1940s) *C. pseudostelligera* begins to slowly decline in abundance and small increases in less common diatoms such as *Synedra acus* and *Navicula indifferens*, occur in the most recent sediment of the core top.

The diatoms provide no evidence of recent acidification of the loch, on the contrary they indicate that enrichment of the loch has occurred in the recent past.

4.4.1 Diatom concentration

The concentration of diatom cells in the Loch Urr sediment core was determined using the latex microsphere method (Battarbee and Kneen 1982). The down-core variation in diatom concentration is shown in Figure 16. The diatom concentration is relatively high ($> 1 \times 10^{-8}$ cells g^{-1} dry sediment) throughout the upper 35 cm of sediment. The main feature of the concentration curve is a marked decline from the core base to 18 cm depth which corresponds with a decline in sediment LOI (Fig. 4). This possibly relates to increased catchment soil erosion in the pre-nineteenth century period causing dilution of the sedimentary diatoms. Between 18-12 cm depth diatom concentration increases and coincides with the expansion of *Cyclotella pseudostelligera* in the diatom assemblage. This could be accounted for by reduced erosion as well as agricultural enrichment. Except for one level (at 7 cm depth), the diatom concentration remains at $>2.5 \times 10^{-8}$ cells g^{-1} over the top 12 cm of sediment.

4.4.2 pH reconstruction

Two methods of pH reconstruction were applied to the Loch Urr sediment core (Stevenson *et al.* 1987a). Index B using Galloway coefficients and Multiple Regression of pH preference groups (Flower 1986) gave similar results (Fig. 17).

The results show that there has been little change in the pH of Loch Urr since 35 cm depth (pre-nineteenth century) and there is no clear evidence of water acidification. pH shows a slight increase between 35 and 12 cm followed by a decline at 10 cm (c. 1935). Above 10 cm pH remains stable at 6.5 - 6.6.

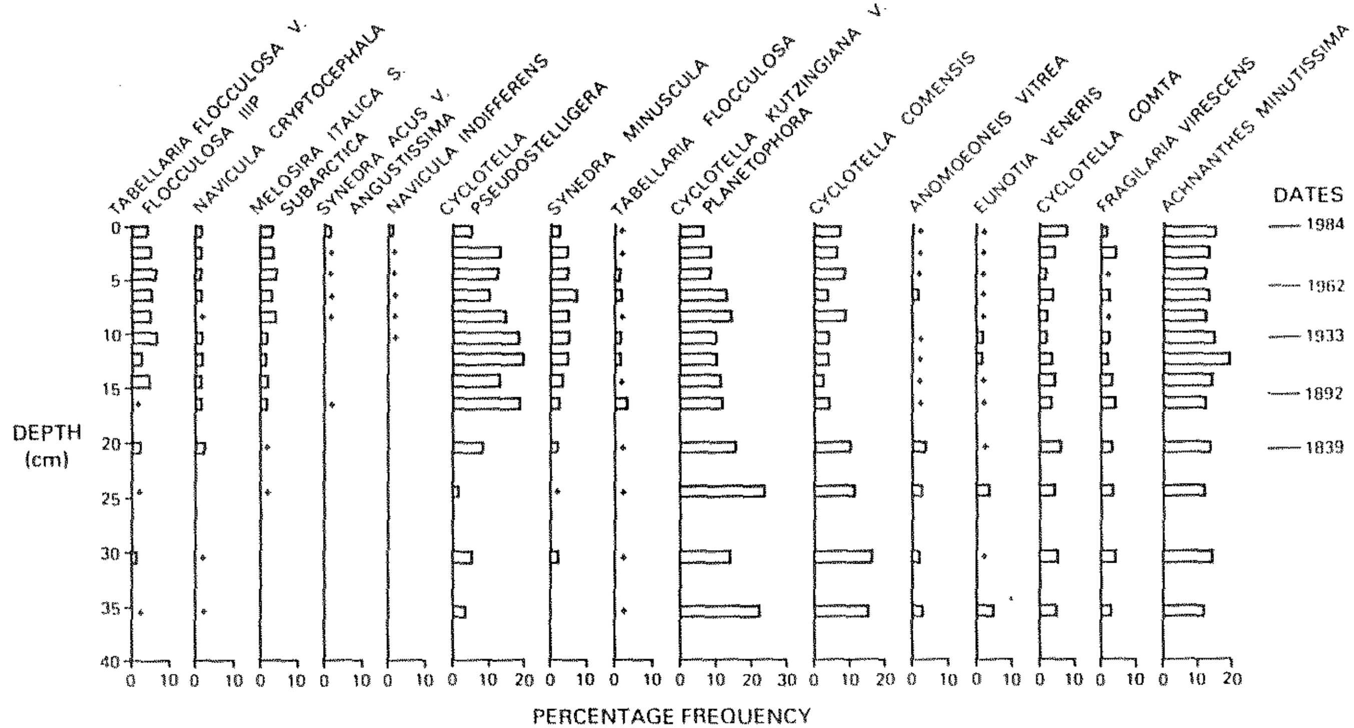


Figure 15 Summary Diatom diagram Loch Urr.

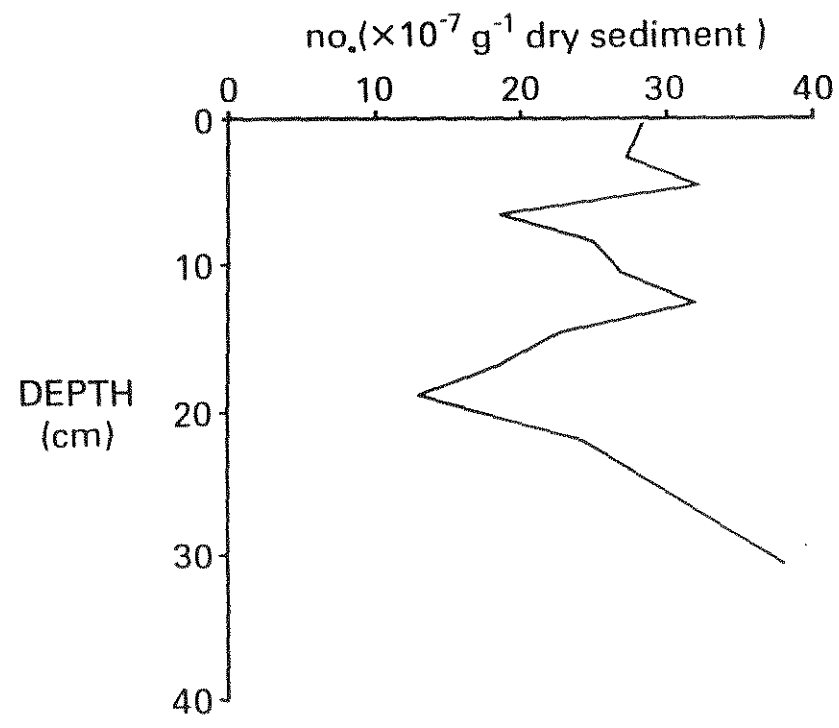


Figure 16 Loch Urr: diatom concentration.

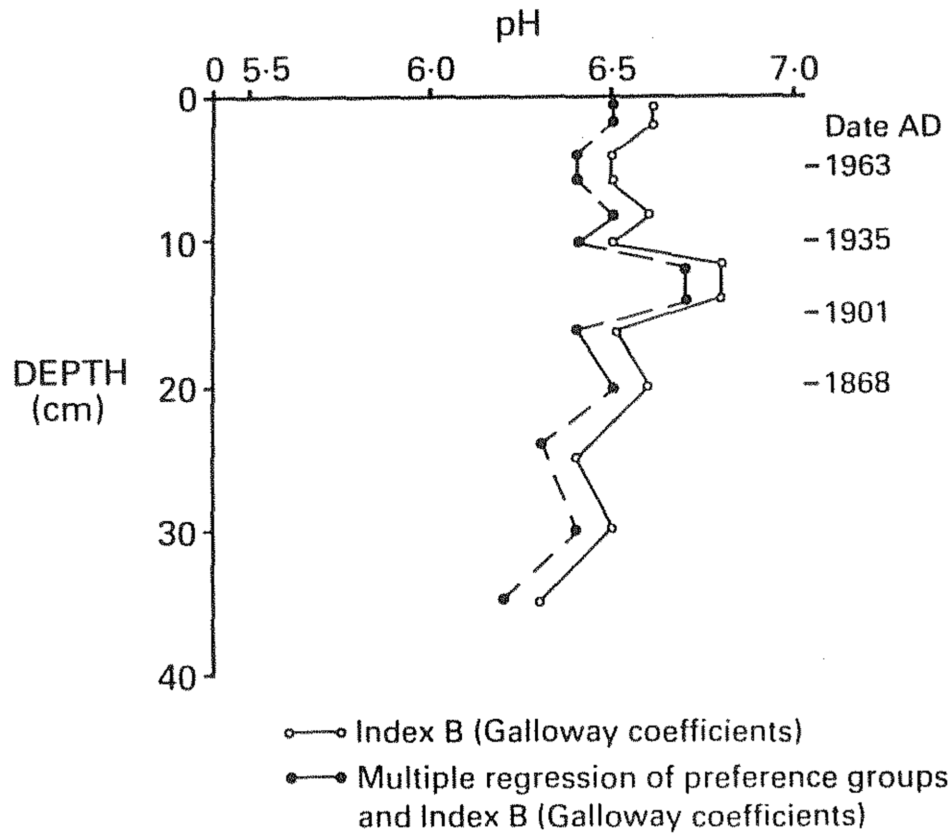


Figure 17 Loch Urr pH reconstruction.

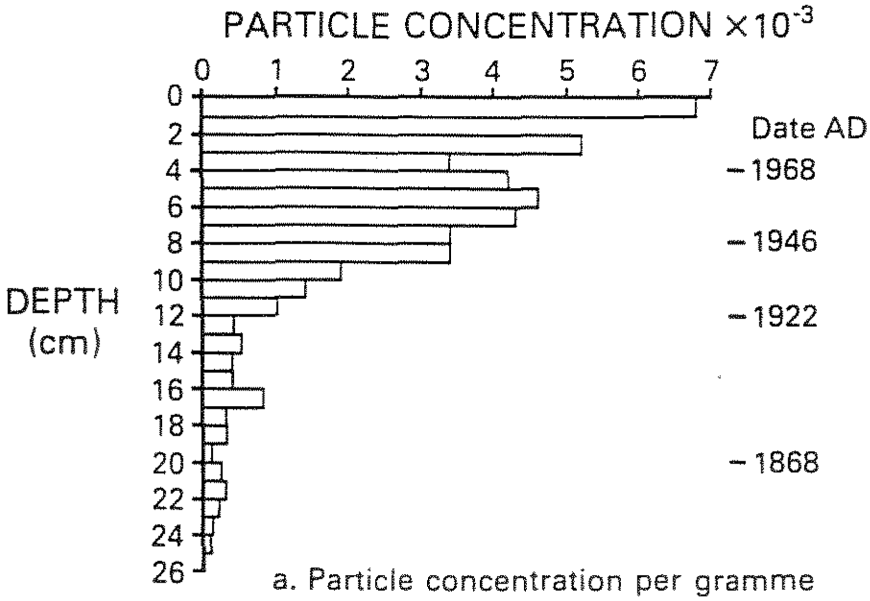
4.5 Carbonaceous particles

Samples of sediment from core URR1 were analysed for spherical carbonaceous particles (SCPs). 24 sub-samples were taken down to 25 cm depth. the results are given in Table 7 and shown graphically in Figure 18. SCPs were observed in all levels analysed.

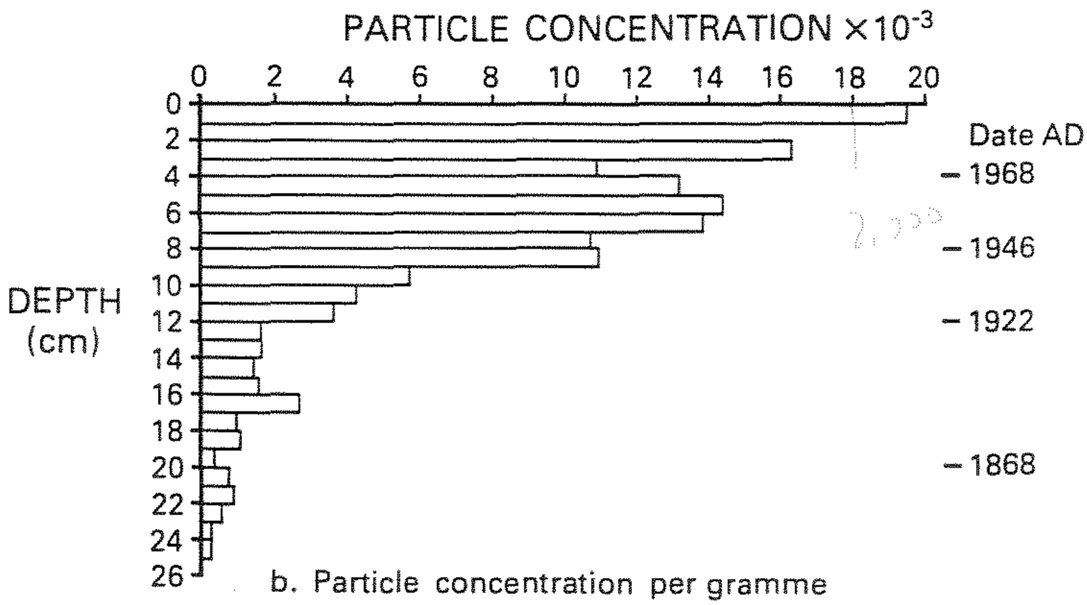
The concentration of SCPs as depicted in Figure 18a remains very low in the older sediment and up to a depth of 12 cm (c. 1922). Above this level they increase rapidly, with the highest concentrations being in the most recent sediment. When expressed in terms of the organic fraction of the dry sediment (determined by LOI) (Fig. 18b) the concentrations give a pattern of distribution similar to that described in Figure 18a.

Table 7 Loch Urr: carbonaceous particle analysis (core URR1)

Depth cm	Number of SCPs g^{-1} (dry sediment) x 10^{-3}	g^{-1} (organic content dry sediment) x 10^{-3}
0- 1	6.79	19.48
2- 3	5.17	16.25
3- 4	3.36	10.86
4- 5	4.19	13.18
5- 6	4.57	14.42
6- 7	4.29	13.81
7- 8	3.36	10.71
8- 9	3.38	10.85
9-10	1.85	5.69
10-11	1.38	4.16
11-12	1.05	3.58
12-13	0.44	1.56
13-14	0.45	1.56
14-15	0.40	1.41
15-16	0.42	1.45
16-17	0.79	2.56
17-18	0.28	0.89
18-19	0.32	0.97
19-20	0.10	0.32
20-21	0.25	0.74
21-22	0.31	0.87
22-23	0.21	0.55
23-24	0.07	0.18
24-25	0.10	0.24



a. Particle concentration per gramme dry weight of sediment



b. Particle concentration per gramme organic content of dry sediment

Figure 18 SCP record for core URRI.

4.6 Pollen

Figure 19 presents a summary pollen diagram from Loch Urr. Although this is a lowland lake and surrounded by a mixture of agriculture and agroforestry, the characteristics of the pollen curves are very similar to those seen in other Galloway sites (Battarbee et al. 1985). Indeed, the most notable change is that in the Calluna : Gramineae ratio which shows increasing amounts of Gramineae through the diagram, confirming a change that has been seen in all the other Galloway cores studied (Battarbee et al. 1985). This Suggests that the 'land use hypothesis' as currently formulated (eg. Rosenqvist 1977, 1978 and see Patrick 1987) is untenable within the Galloway region.

An erosion period within the sediment record would seem to occur from 40 cm as values of Isoetes decline and reach a minima at 20 cm. Afforestation of the region is indicated by the rise in Pinus values from 4 cm.

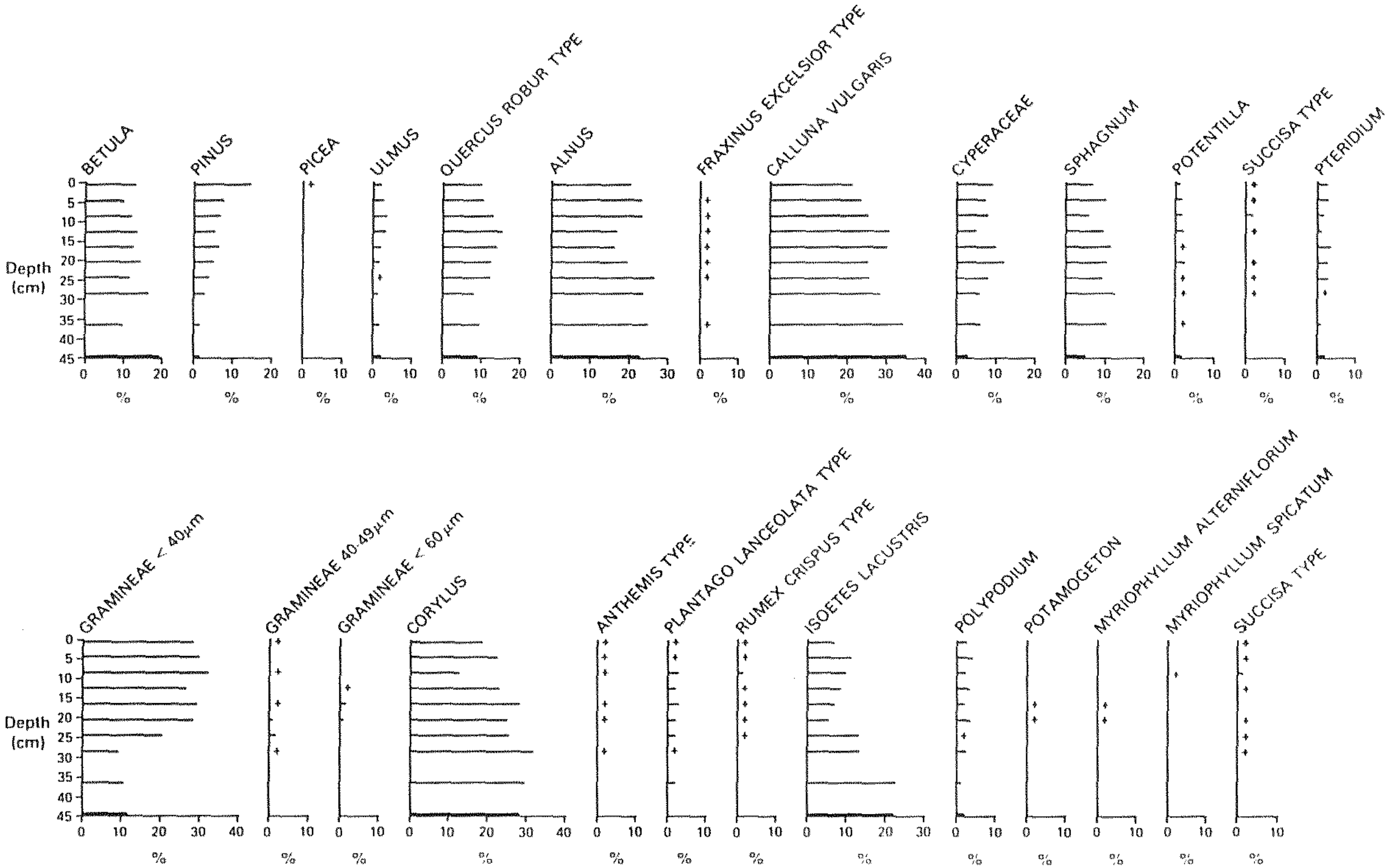


Figure 19 Summary Pollen diagram for Loch Urr.

5.0 Land use and management history

Alone, among the lakes investigated under DoE contract PECD 7/7/139 the Loch Urr catchment has a long history of land improvement and intensive management for agriculture. It is uncertain when land in the catchment was first improved, but a farm has existed at Loch Urr (Fig. 2) since 1605 (Kennedy Moffat p.comm.) and is recorded in Blaeu's (1654) atlas of Scotland. The ruined castle on the island in the Loch may indicate a sporadic, low-intensity exploitation of the catchment even before the seventeenth century.

All land in the catchment is enclosed, either in small fields adjacent to the loch and farm buildings, or as broad sheepwalks on the higher ground. The date of enclosure is uncertain. The adjacent farms of 'Loch Urr', 'Shillingland' and 'Craigenvey' and the associated enclosures were in existence by 1820[1]. Enclosure of the higher common grazing land presumably dates from the mid-eighteenth century as elsewhere in the region (eg. Webster 1794, Singer 1812, Corrie 1910).

Between 1876 and 1895 the three farms in the catchment were amalgamated under one farmer. The grandson of that farmer is the current occupant of 'Loch Urr Farm'. A particularly detailed history, from diaries and personal experience, is thus available for the catchment over the last century.

Although arable land reached a peak in the mid-nineteenth century the central core of enclosed fields has a long and continuous history of exploitation for arable or improved grassland.

All improved land was originally brought into economic use by burning, liming and drainage[2]. Lime applications in this locality date from the late-eighteenth century (Kirkpatrick 1790) when shell lime comprised the dominant 'manure'. The early-twentieth century lease to 'Loch Urr Farm' specified that three wagons of burnt lime were to be applied to the farm land every year. Since that period lime applications have fluctuated according to economic conditions and the rate of lime subsidy, reaching a peak in the late-1970s. Representative twentieth century lime applications have averaged a total of 100 tons yr^{-1} at a rate of 0.8 tons ha^{-1} on hill land, with lower applications on ploughland and improved grassland (Kennedy Moffat p.comm.). Contemporary practice supplements lime with applications of organic manure (approximately 16 tons yr^{-1}) and chemical 20:10:10 fertiliser (approximately 5 tons yr^{-1}).

All fields in the vicinity of 'Loch Urr Farm' have been ploughed and cultivated within the past 15 years, during which period all cultivatable land has been re-drained. cultivation has consisted

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[1] Scottish Record Office plan <u>RHP 37503</u>: Map of Dumfriesshire c. 1820, surveyed by W. Crawford.

[2] The catchment-wide extent of old drainage is apparent from air photographs of the area: Scottish Development Department, Air Photographs Unit; 106G/Scot/UK 150, 1:10,000, August 1946; F21 543/RAF/2333, 1:10,500, June 1963; V39 RAF/4720, 1:25,000, May 1975.

primarily of an oats/turnip rotation with most land put to sown grasses. Enclosed land in the vicinity of 'Shillingland' and 'Craigenvey' has not been ploughed since 1964 (Kennedy Moffat p.comm.).

Since 1964, Agricultural Census returns for 'Loch Urr Farm' provide a unique catchment-specific insight into cultivation acreages and animal numbers in the area. Figure 20 indicates a decline in the area of sown grass and crops since the late-1970s.

Sheep and cattle have comprised the focus of the economy of the catchment. Sheep were predominant by the late-eighteenth century (Forsyth 1805). Disused sheepfolds provide evidence of the extensive nature of previous sheep grazing regimes. A major increase in sheep numbers occurred in the late 1940s and levels have been sustained at around 3000 sheep and 250 cattle since that date (cf. Figure 21).

Burning, once a major management practice has declined since the late-1970s owing to the proximity of large forestry plantations. burning is now confined to 12-16 ha of roughland each year (Kennedy Moffat p.comm.).

Shelter belts of coniferous and mixed woodland have long been a feature of the catchment. Several new plantations have been laid down for this purpose in recent years (Fig. 2).

In addition to agriculture the catchment has been exploited in the past for its mineral resources - early Ordnance Survey maps and air photographs indicate the presence of disused gravel pits and small quarries. Peat has also been extensively cut, particularly on the poorly drained land close to the loch shore[3].

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[3] This is most apparent from air photograph evidence - see note [2].

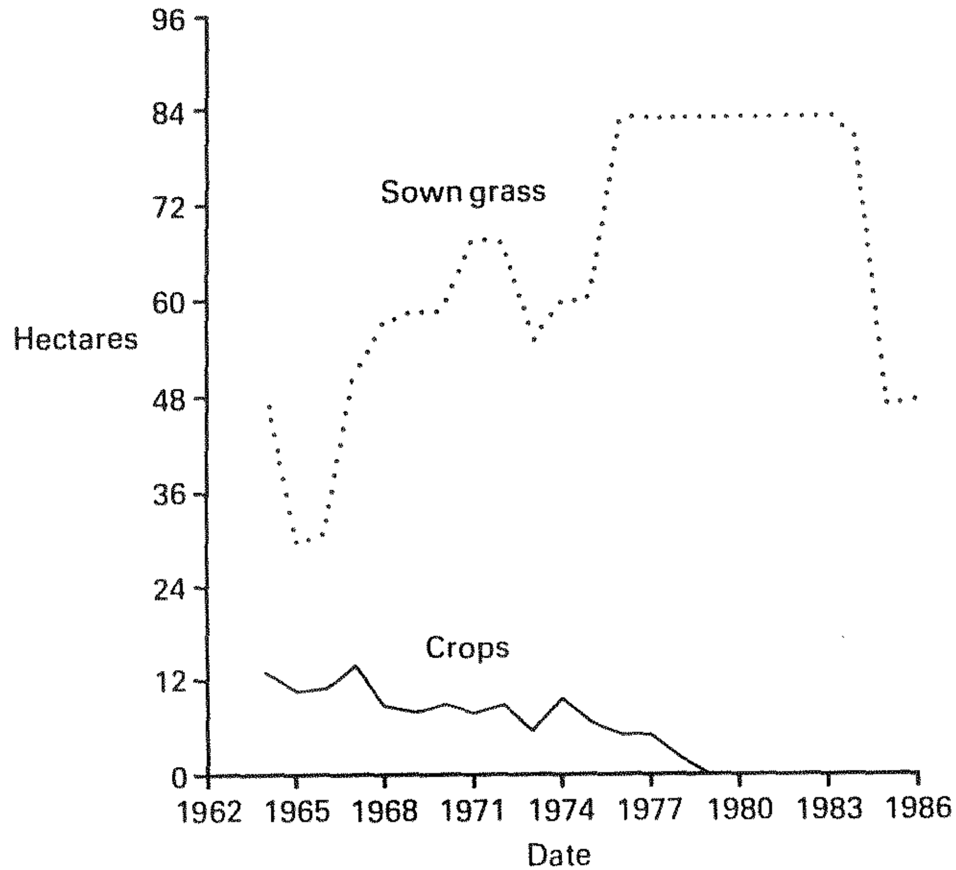

Figure 20 Cultivated Land in the Loch Urr Catchment
1964-1984 (Agriculture Census data)

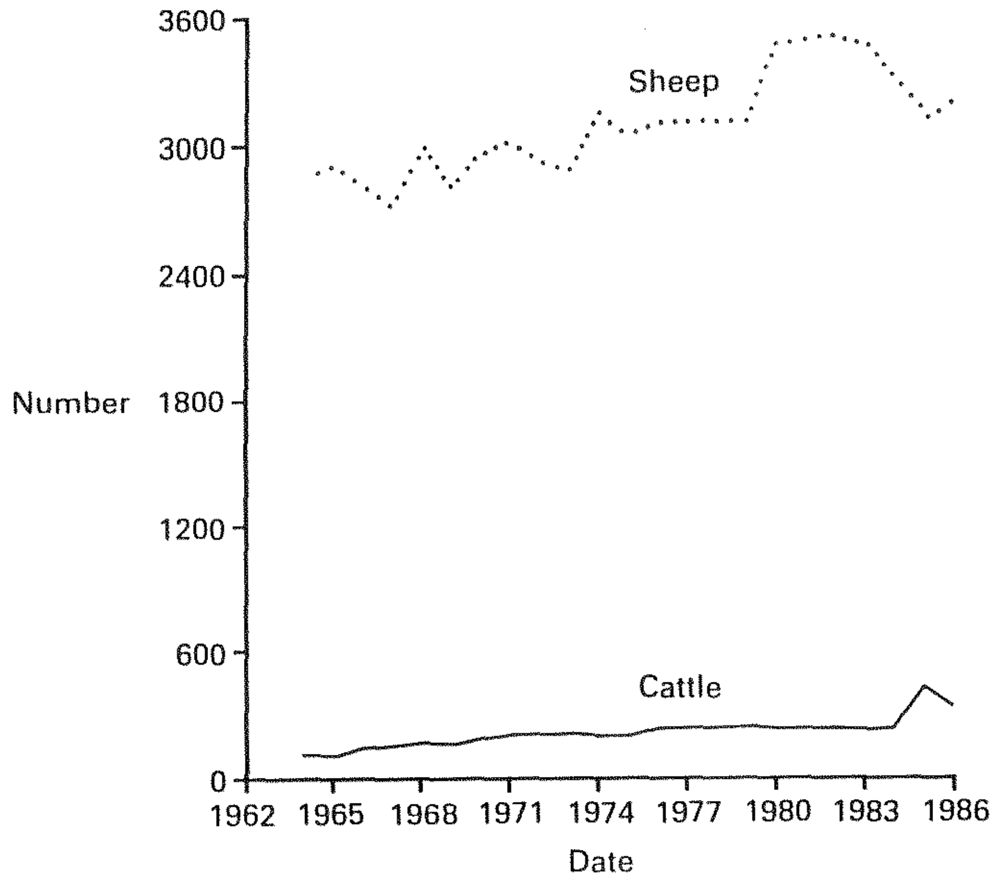

Figure 21 Livestock numbers in the Loch Urr Catchment 1964-1986 (Agriculture Census data)

6.0 Conclusions

Loch Urr was chosen as a control site for lake acidification investigations in Galloway. It shares the high atmospheric deposition loadings of the region but lies on less resistant Silurian sedimentary rocks as opposed to granite, and drains a catchment that has been extensively improved for agriculture.

The influence of catchment geology is reflected in the water chemistry of the loch. It is mildly acidic with base cation concentrations higher than lochs in the region which lie in granite catchments. Similarly, Loch Urr possesses a more diverse macrophyte flora.

The ^{210}Pb method was successfully employed to date a lake sediment core. 20 cm core depth was dated to the 1860s. Sediment accumulation in the loch has been relatively high. This together with the lack of major erosional events in the dated component of the sediment core provides a good resolution for sediment-based analyses.

Pollen analysis indicates an erosion period at 40 cm core depth, and lithostratigraphic and base cation analyses suggests a change in erosion rates at 25 cm depth. Both these changes may relate to agricultural improvements in the catchment which first date from the early seventeenth century.

The only significant change in the sedimentary diatom assemblage occurs at c. 25 cm core depth and is indicative of lake water enrichment during the nineteenth century. This enrichment is probably related to agricultural improvements in the catchment, notably the regular application of lime from the early nineteenth century.

The diatom record and associated pH reconstruction provides no evidence of a recent acidification of the loch, on the contrary they indicate a stable pH and an enrichment of the loch in the recent past.

The trace metal-time profiles accurately record the deposition of trace metals from the atmosphere. These results indicate that Loch Urr has been contaminated by lead and zinc deposited from the atmosphere since the eighteenth century.

Atmospheric contamination is confirmed by the SCP record which reveals low-level contamination throughout the dated core, with much higher levels in the top 12 cm (1920s - 1980s).

The improvement of the catchment for agriculture from the seventeenth century is documented from historical sources and further confirmed by pollen analysis of the lake sediments which shows an increase in the Gramineae component since that time.

Loch Urr experiences similar levels of atmospheric contamination to acidified lochs elsewhere in Galloway and reveals a similar atmospheric deposition history. However, the loch has not acidified, thus revealing the importance of catchment geology and the associated acid neutralising capacity, in lake acidification.

Acknowledgements

This research was funded by the Department of the Environment under project PECD 7/7/139. Permission to work on the Loch and much valuable background information about the loch and its catchment was kindly provided by Mr Kennedy Moffat of 'Loch Urr Farm'. The sediment core was dated by AERE at Harwell. Diagrams were prepared by Lauren McClue.

References

Appleby, P.G. and Oldfield, F. 1978 The calculation of ^{210}Pb dates assuming a constant rate of supply of unsupported ^{210}Pb to the sediment. Catena. 5, 1-8.

Barrett, C.F., Atkins, D.H.F., Cape, J.N., Crabtree, J., Davies, T.D., Derwent, R.G., Fisher, B.E.A., Fowler, D., Kallend, A.S., Martin, A., Scriven, R.A., Irwin, J.G., Cottrill, S.M. and Jenkins G.J. 1987 Acid deposition in the United Kingdom 1981-1985. A second report of the United Kingdom Review Group on Acid Rain. Warren Spring Laboratory, Stevenage.

Battarbee, R.W. and Kneen, M. 1982 The use of electronically counted microspheres in absolute diatom analysis. Limnol. Oceanogr. 27, 184-188

Battarbee, R.W., Flower, R.J., Stevenson, A.C. and Rippey, B. 1985 Lake acidification in Galloway: a palaeoecological test of competing hypotheses. Nature. 314, 350-352

Battarbee, R.W., Stevenson, A.C., Rippey, B., Fletcher, C., Natkanski, J., Wik, M. and Flower, R.J. in press Causes of lake acidification in Galloway, south-west Scotland: a palaeoecological evaluation of the relative roles of atmospheric contamination and catchment change for two acidified sites with non-afforested catchments. Journal of Ecology.

Blaeu. 1654 Atlas of Scotland.

Brown, J. 1845 Glencairn. New statistical account of Scotland. Vol. IV, 330-336.

Corrie, J. 1910 Glencairn the annals of an inland parish. Hunter and Co., Dumfries.

Cullen, G. and Murray, G. 1845 Balmaclellan, New statistical account of Scotland. Vol. IV, 98-107.

Eakins, J.D. and Morrison, R.T. 1976 A new procedure for the determination of lead-210 dating in lake and marine sediments. International Journal of Applied Radioactive isotopes. 29, 531-536.

Flower, R.J. 1986 The relationship between surface sediment diatom assemblages and pH in 33 Galloway lakes: some regression models for reconstructing pH and their application to sediment cores. Hydrobiologia. 143, 93-105.

Flower, R.J. and Battarbee, R.W. 1983 Diatom evidence for recent acidification of two Scottish Lochs. Nature. 305, 130-133.

Flower, R.J., Rippey, B. and Tervet, D. 1986 34 Galloway lakes: bathymetries, water quality and diatoms. Palaeoecology Research Unit, University College London, Research Paper. 14.

Flower, R.J., Battarbee, R.W. and Appleby, P.G. 1987 The recent palaeolimnology of acid lakes in Galloway, southwest Scotland: diatom analysis, pH trends and the role of afforestation. J. Ecol. 75, 797-824.

Forsyth, R. 1805 The beauties of Scotland (5 Vols). Edinburgh

Fritz, S.C., Stevenson, A.C., Patrick, S.T., Appleby, P.G., Oldfield, F., Rippey, B., Darley, J., Battarbee, R.W., Higgitt, S.R. and Raven, P.J. 1987 Palaeoecological evaluation of the recent acidification of Welsh Lakes. VII. Llyn y Bi, Gwynedd. Palaeoecology Research Unit, University College London, Research Paper, 23.

Grierson, W. 1792 Glencairn. Statistical account of Scotland. Sinclair, J. (ed.) Vol. II. 339-344. William Creek, Edinburgh.

Henrickson, A. 1979 A simple approach for identifying and measuring acidification of freshwater. Nature. 278, 542-545.

Jones, V.J., Stevenson, A.C. and Battarbee R.W. 1986 Lake acidification and the land-use hypothesis: a mid-post-glacial analogue. Nature. 322, 157-158

Kinniburgh, D.G. and Edmunds, W.M. 1986 The susceptibility of United kingdom groundwaters to acid deposition. British Geological Survey, NERC. Wallingford.

Kirkpatrick, J. 1790 Dunscore. Statistical account of Scotland. Sinclair, J. (ed.) Vol. III, 140-144. William Creek, Edinburgh.

Kreiser, A., Patrick, S.T., Stevenson, A.C., Appleby, P.G., Rippey, B., Oldfield, F., Darley, J., Battarbee, R.W., Higgitt, S.R. & Raven P.J. 1987 Palaeoecological evaluation of the recent acidification of Welsh lakes. X, Llyn Cwm Mynach, Gwynedd. Palaeoecology Research Unit, University College London, Research Paper. 27.

Lyall, W. (ed.). 1910 The sportsman's and tourists guide to the rivers, lochs, moors and deer forests of Scotland. Lyall and Co. London.

Mackereth, F.J.H. 1969 A short core sampler for subaqueous deposits. Limnol. Oceanogr. 14, 145-151

MAPICS 1987 MAPICS reference manual. MAPICS Ltd. London.

Murray, J. and Pullar, L. 1910 Bathymetrical survey of the fresh water lochs of Scotland. Vol. III. Challenger Office. Edinburgh.

Patrick, S.T. 1987 Palaeoecological evaluation of the recent acidification of Welsh lakes. V, The significance of land use and land management. Palaeoecology Research Unit, University College London, Research Paper. 21.

Patrick, S.T., Stevenson, A.C., Fritz, S.C., Appleby, P.G., Rippey, B., Oldfield, F., Darley, J., Higgitt, S., Battarbee, R.W. and Raven, P.J. 1987b Palaeoecological investigations of the recent acidification of Welsh lakes: ix. Llyn Llagi, Gwynedd. Palaeoecology Research Unit, University College London, Research Paper. 25.

Raven, P.J. 1985 The use of aquatic macrophytes to assess water quality changes in some Galloway Lochs: an exploratory study. Palaeoecology Research Unit, University College London, Research Paper. 9.

Rosenqvist, L. Th. 1977 Acid Soil Acid Water. Oslo.

Rosenqvist, L. Th. 1978 Alternative sources for acidification of river water in Norway. The Science of the Total Environment. 10, 39-49.

Singer, Dr. 1812 General view of the agriculture in the county of Dumfries. Board of Agriculture, Edinburgh.

Stevenson, A.C., Patrick, S.T., Kreiser, A. and Battarbee R.W. 1987a Palaeoecological evaluation of the recent acidification of susceptible lakes: methods utilised under DoE contract PECD 7/7/139 and the Royal Society SWAP project. Palaeoecology Research Unit, University College London, Research Paper. 26.

Stevenson, A.C., Fritz, S.C., Patrick, S.T., Appleby, P.G., Rippey, B., Oldfield, F., Darley, J., Higgitt, S., Battarbee, R.W. and Raven, P.J. 1987b Palaeoecological investigations of the recent acidification of Welsh lakes: iv. Llyn Gynon, Dyfed. Palaeoecology Research Unit, University College London, Research Paper. 20.

Webster, J. 1794 General view of the agriculture of Galloway. Board of Agriculture, Edinburgh

West, G. 1910 A further contribution to a comparative study of the dominant phanerogamic and higher cryptogamic flora of aquatic habitats in scottish lakes. Proc. Roy. Soc. Edin. 30, 65-81

Appendix 1 Dissolved oxygen and temperature profile for Loch Urr (sample taken May 12th 1984)

Depth m	Temperature °C	Oxygen %
0	13.0	93
1	12.5	86
2	12.5	90
3	12.5	89
4	12.0	86
5	12.0	86
6	12.0	84
7	12.0	82
8	11.5	81
9	9.5	68
10	8.5	64
11	8.5	59
12	8.0	52
13	8.0	47

Appendix 2 Geochemical analyses of sediment from core URR1

Depth cm	Zn	Pb µg g-1	Cu	Ni	Ca	Mg mg g-1	Na	K
0.5	1002	270	118	41	5.18	5.09	5.16	7.49
2.5	649	140	28	64	5.02	6.87	6.25	9.40
3.5	594	152	29	52	4.41	7.19	6.69	10.05
4.5	605	139	28	52	4.40	6.91	6.52	9.92
5.5	565	155	30	52	4.40	7.33	6.64	10.18
6.5	543	148	29	55	4.34	7.26	6.89	10.41
7.5	498	156	30	50	4.24	7.28	6.78	10.59
8.5	467	166	36	49	4.25	7.04	6.79	10.42
9.5	442	173	33	50	4.26	7.06	6.57	10.15
10.5	442	186	26	49	4.21	6.96	6.57	9.85
11.5	346	180	26	52	4.00	8.21	7.30	10.99
12.5	376	153	23	79	3.84	7.69	7.61	11.69
13.5	293	160	28	50	3.84	7.85	7.48	11.46
14.5	313	174	31	51	3.76	7.80	7.63	11.52
15.5	317	166	22	63	3.65	7.83	7.09	11.05
16.5	346	146	36	82	3.72	7.77	7.38	11.34
17.5	277	160	21	50	3.77	7.83	7.25	11.17
18.5	293	163	25	78	3.70	7.75	6.91	10.99
19.5	266	140	33	67	3.44	7.94	6.78	11.21
21.5	218	162	24	46	4.20	7.50	6.49	10.54
23.5	182	116	18	48	4.41	6.11	5.76	8.86
25.5	178	100	28	43	4.57	5.70	5.51	8.09
27.5	113	79	16	36	4.61	5.05	5.49	8.18
29.5	187	98	18	53	4.47	6.73	5.86	8.79
31.5	168	95	18	43	4.23	6.16	5.77	9.07
33.5	164	86	17	49	4.30	6.37	6.34	9.19
35.5	90	53	15	34	4.34	5.97	5.87	8.79
37.5	91	45	26	42	4.19	6.71	6.41	9.75
39.5	77	39	16	34	4.35	5.91	5.76	8.55
42.5	86	40	22	31	4.49	5.72	5.54	8.16
45.5	72	37	14	33	4.19	5.65	5.56	8.02
48.5	78	28	19	34	4.12	6.00	5.98	8.81
52.5	70	24	15	31	4.04	6.44	6.61	9.72
55.5	69	24	16	27	3.92	6.26	6.04	8.94
58.5	85	20	21	39	3.79	7.61	6.99	10.96
62.5	73	15	17	36	3.82	7.66	6.85	10.81
65.5	76	14	15	35	3.59	7.64	7.35	11.05
69.5	82	15	15	44	3.61	8.50	7.34	11.72
73.5	89	16	15	41	4.11	7.39	6.62	10.25
75.5	87	17	19	32	3.79	8.29	7.43	11.29
78.5	94	18	20	37	3.65	8.47	7.85	11.96
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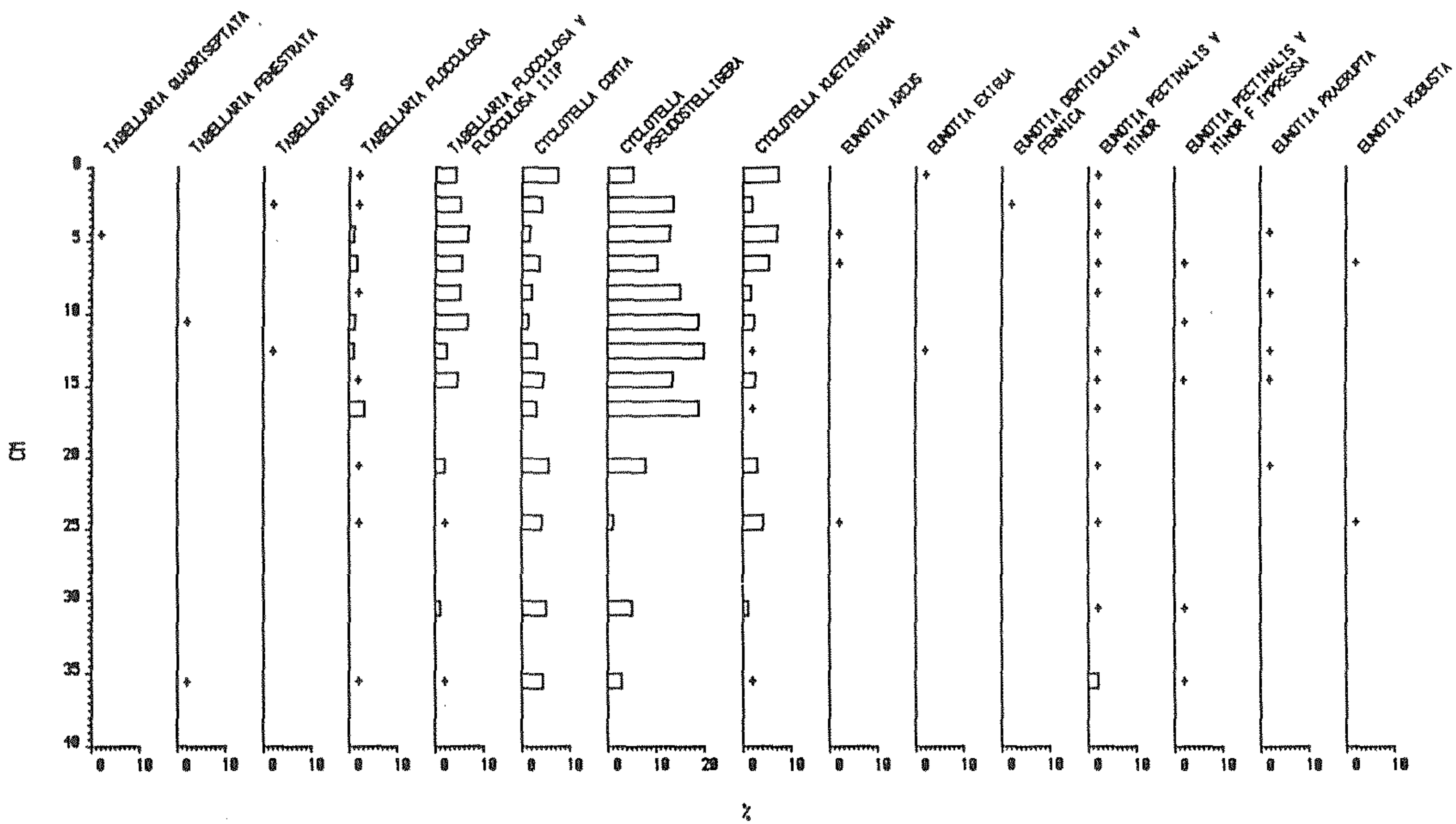
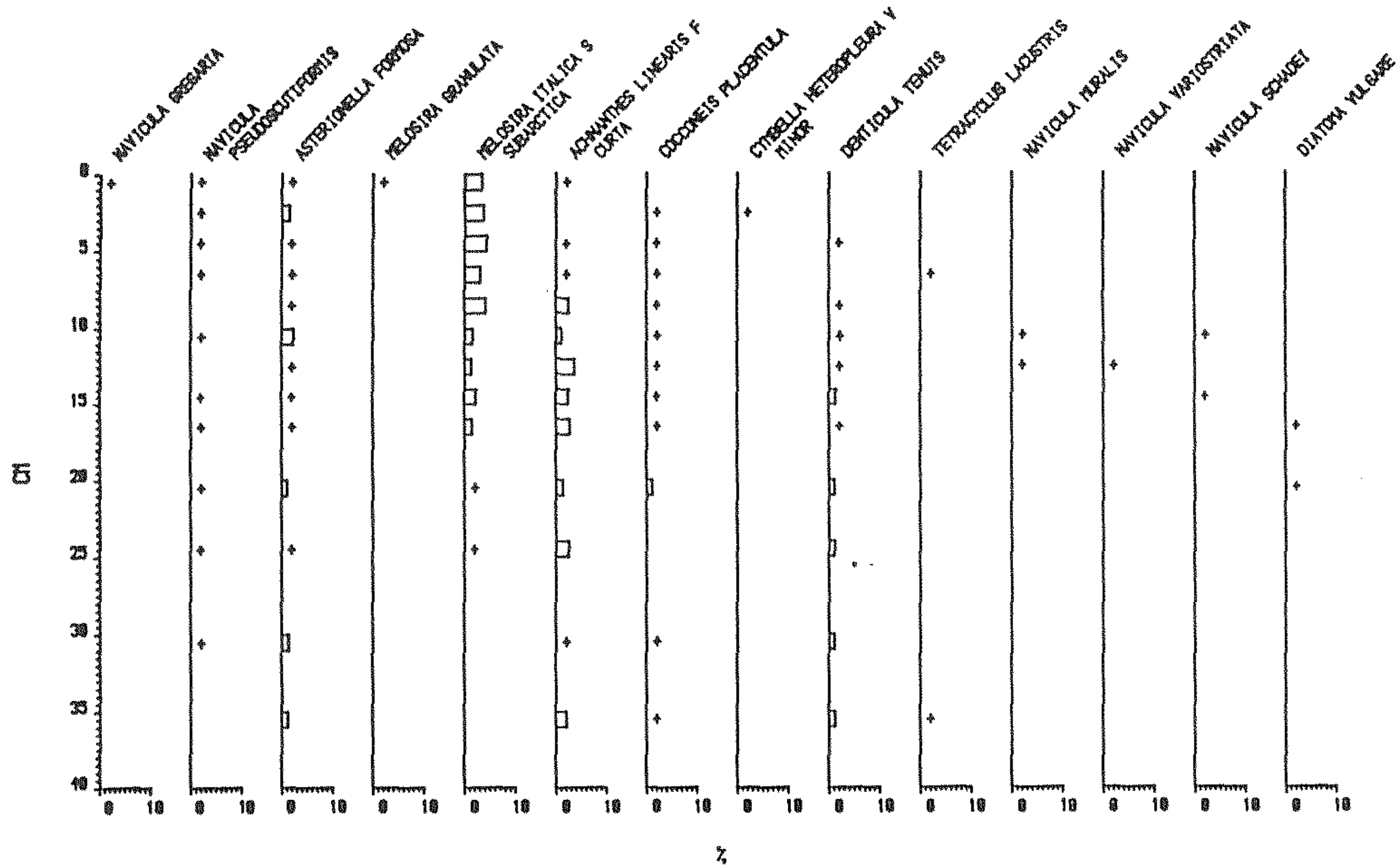


Appendix 3. Full diatom diagram for Loch Urr, Loch Urr 1



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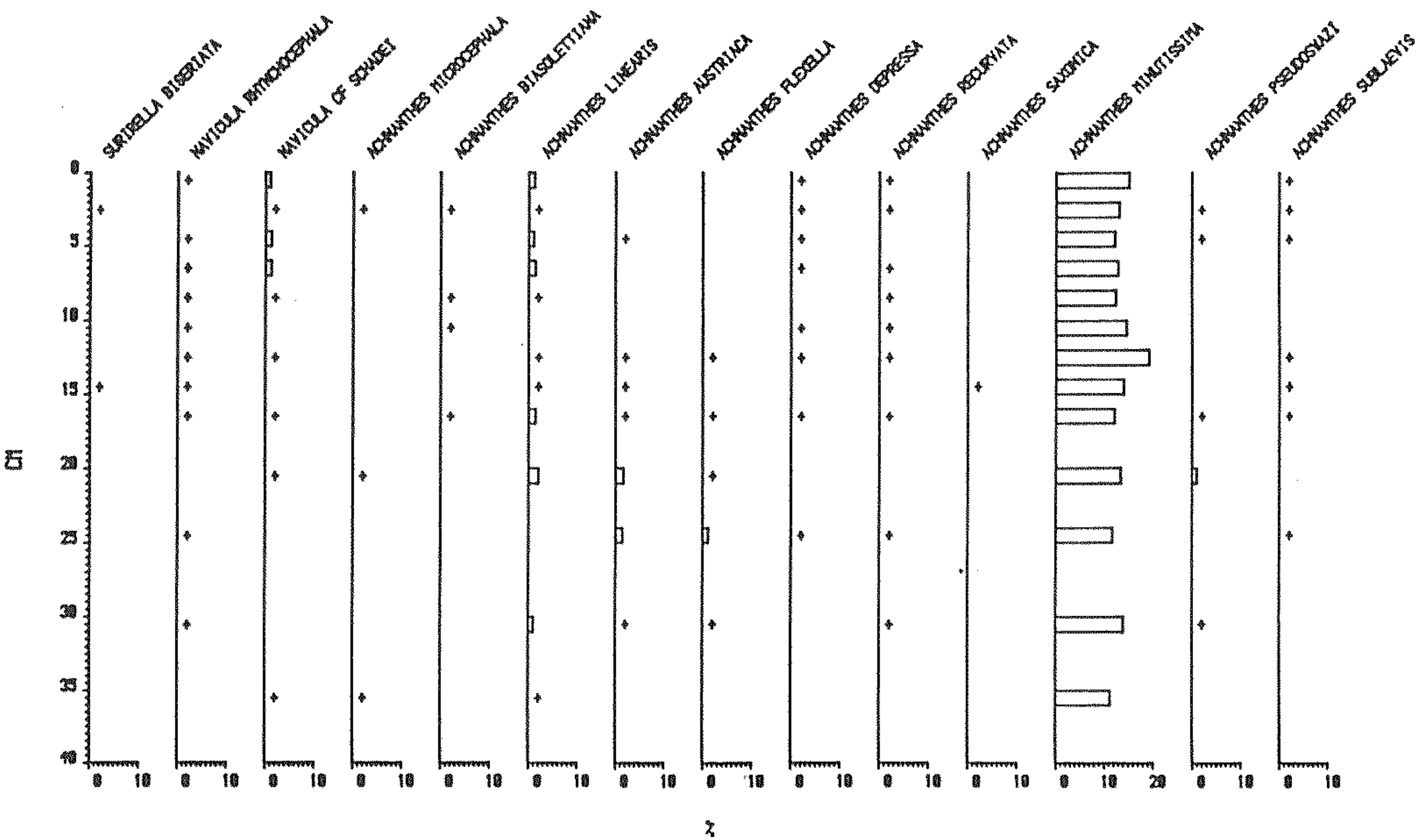

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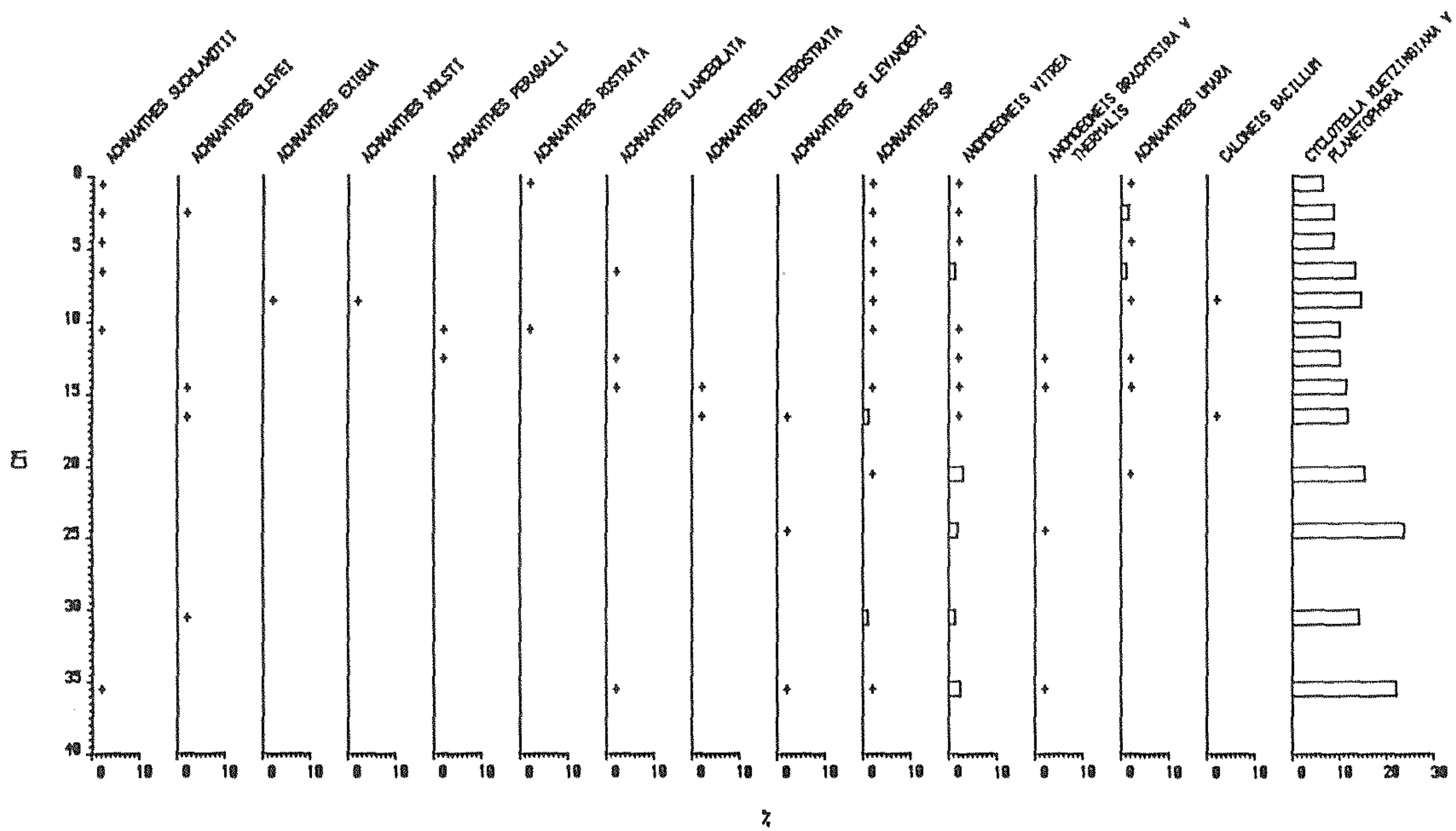

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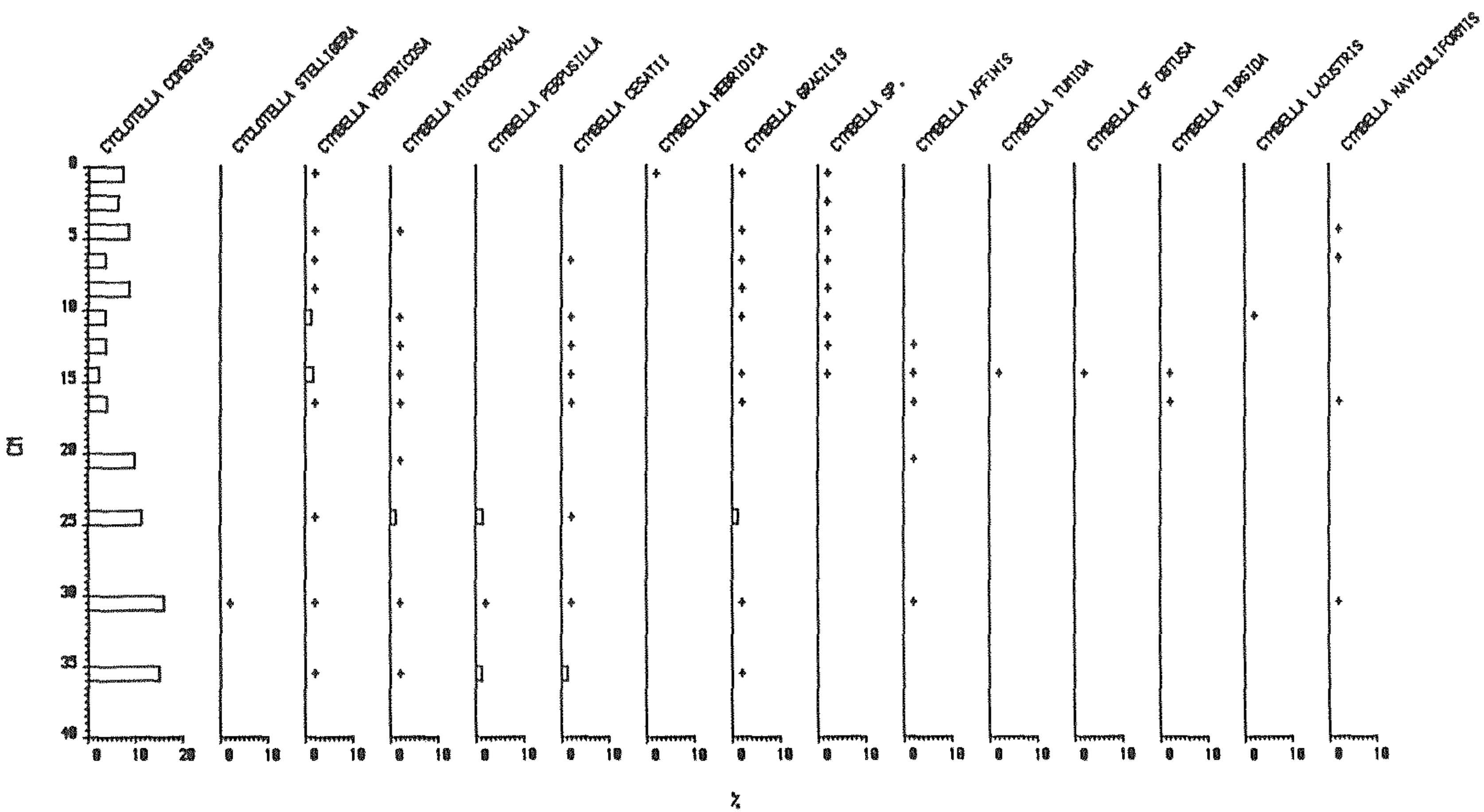

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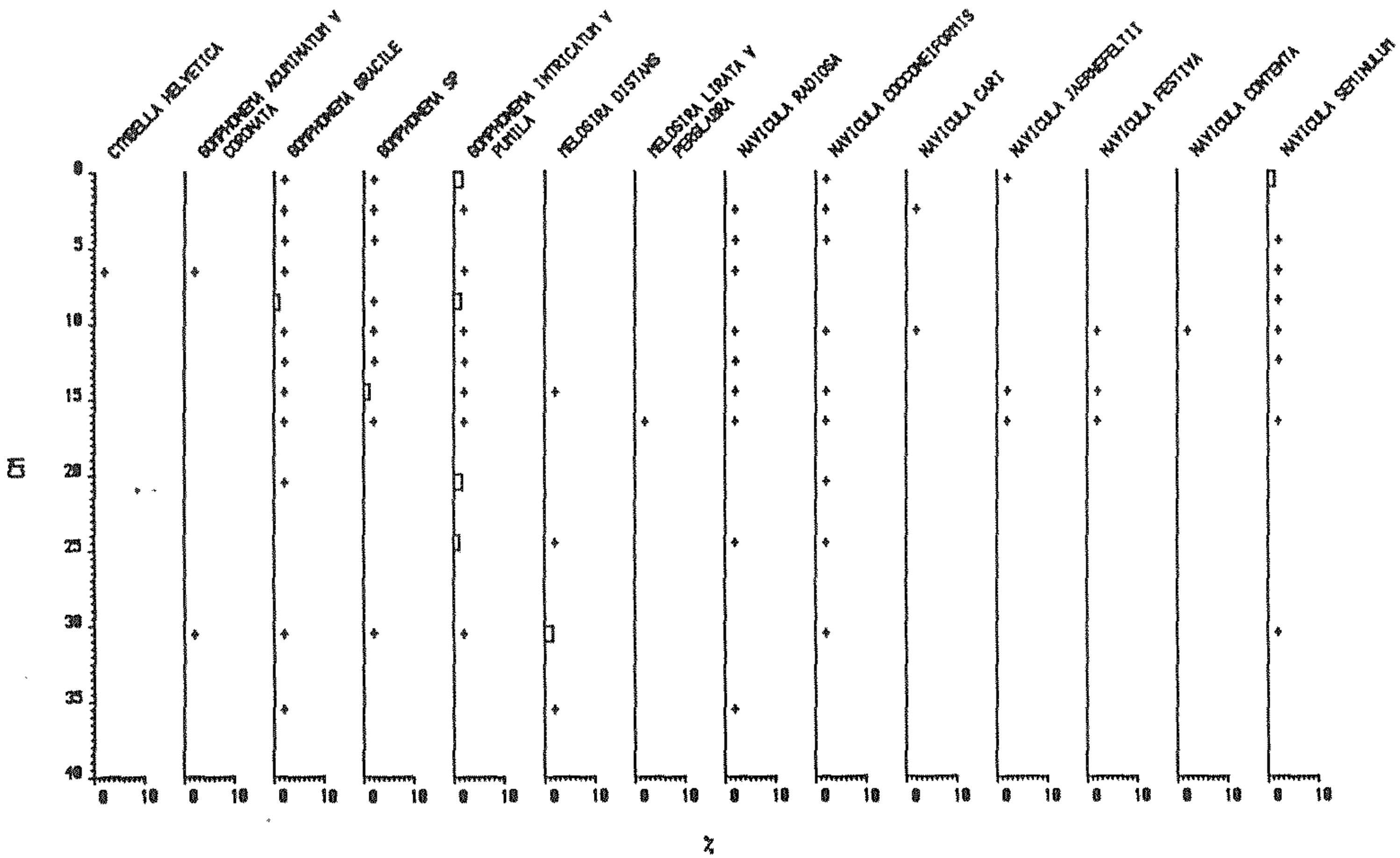

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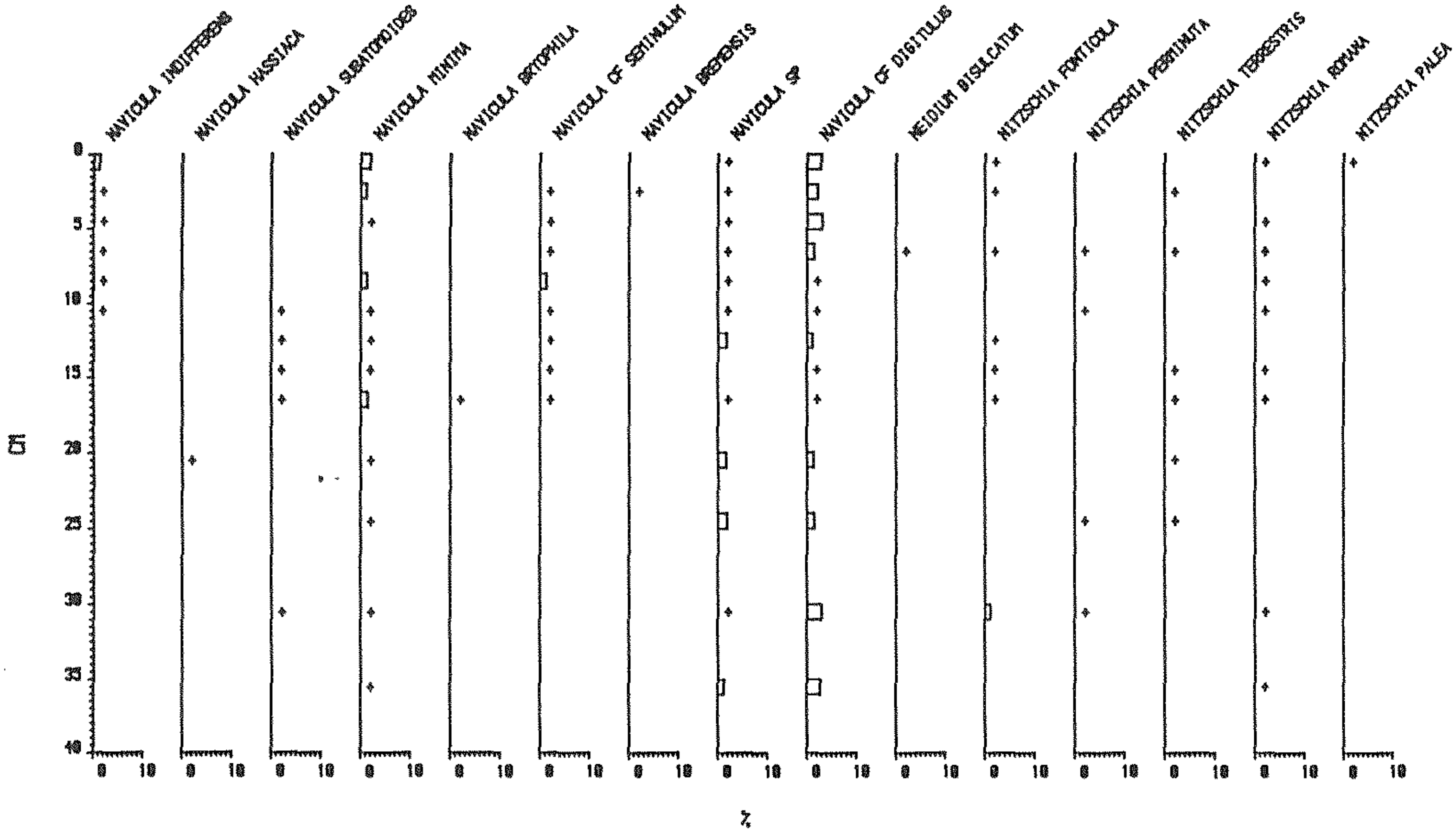

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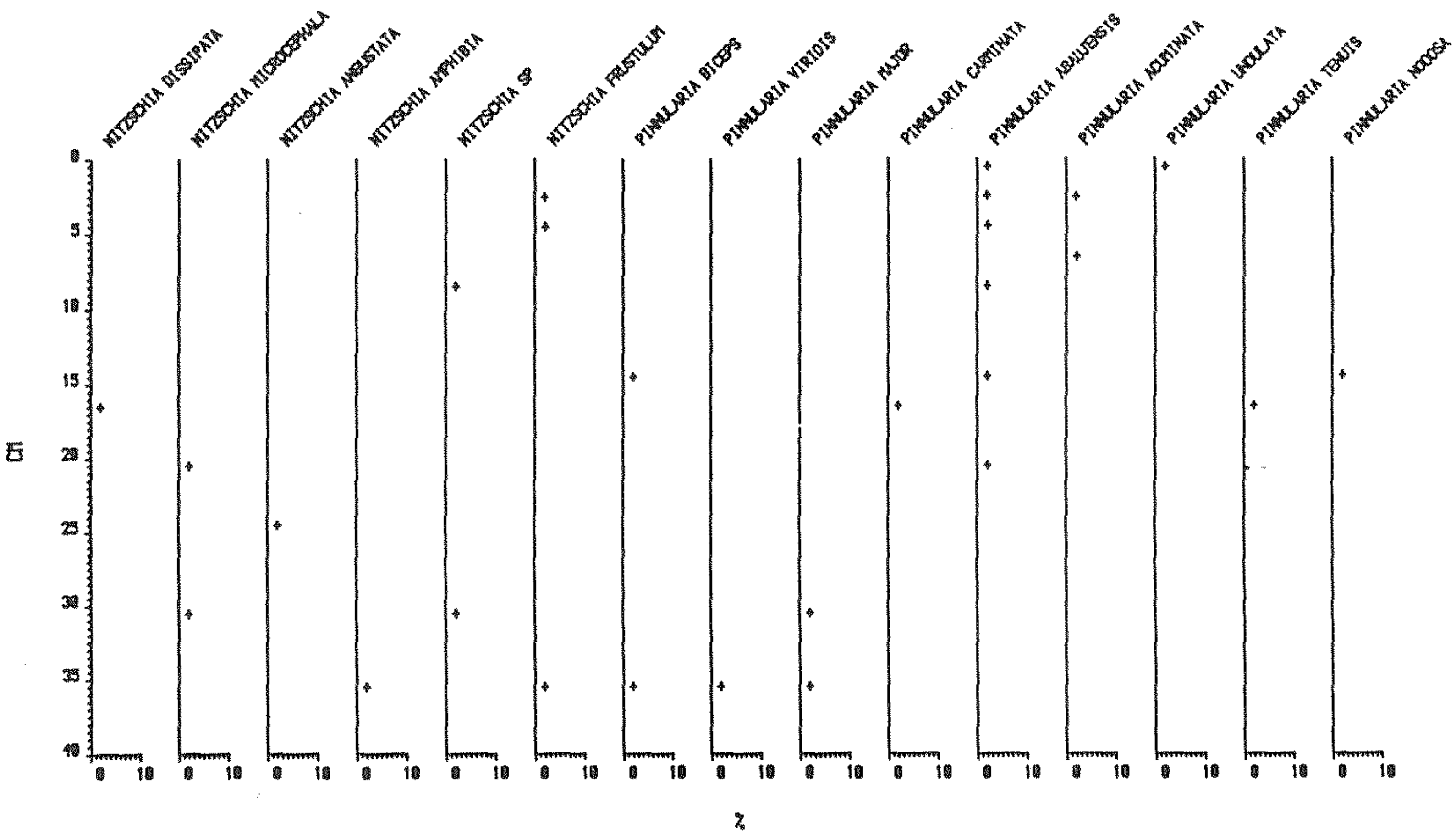

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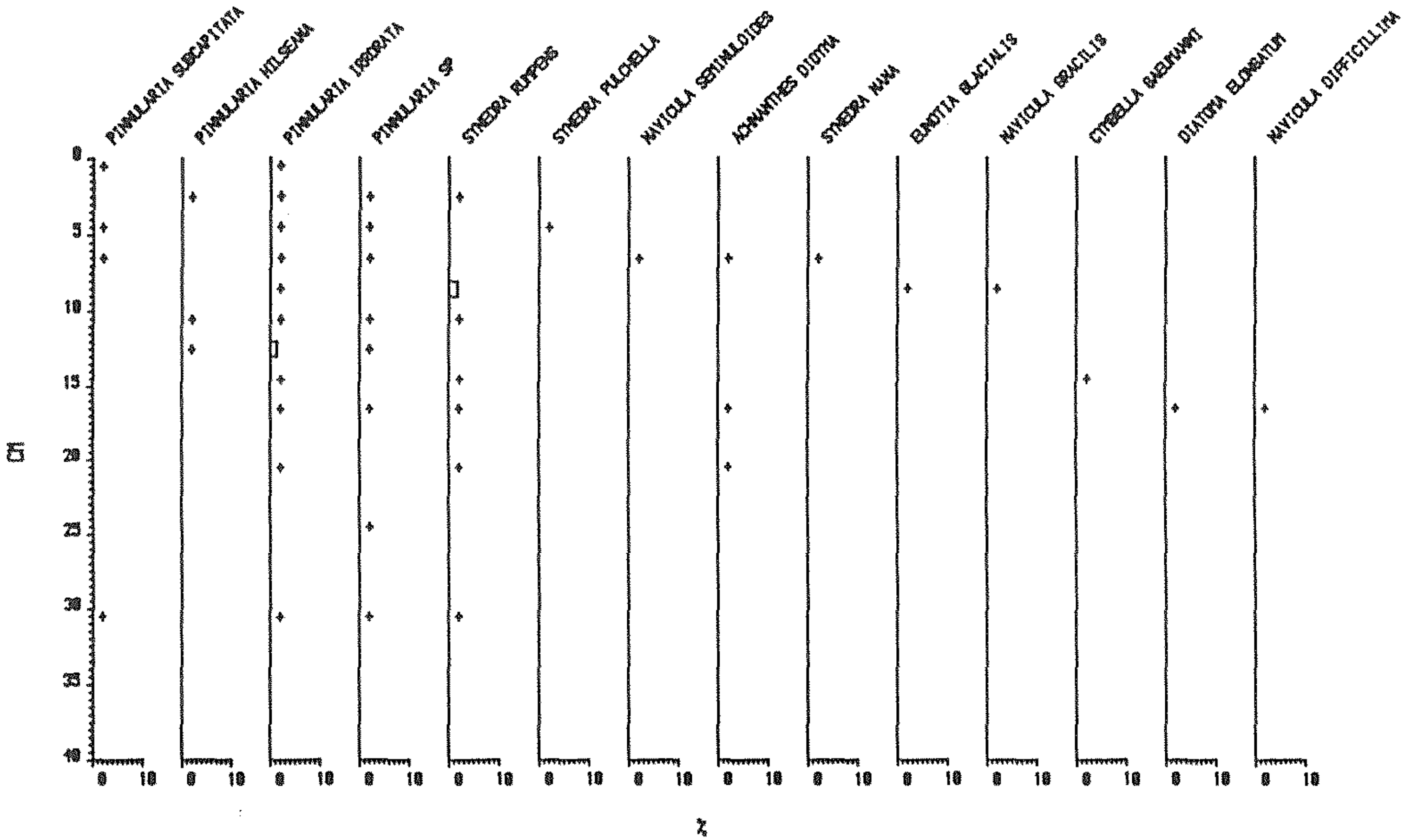

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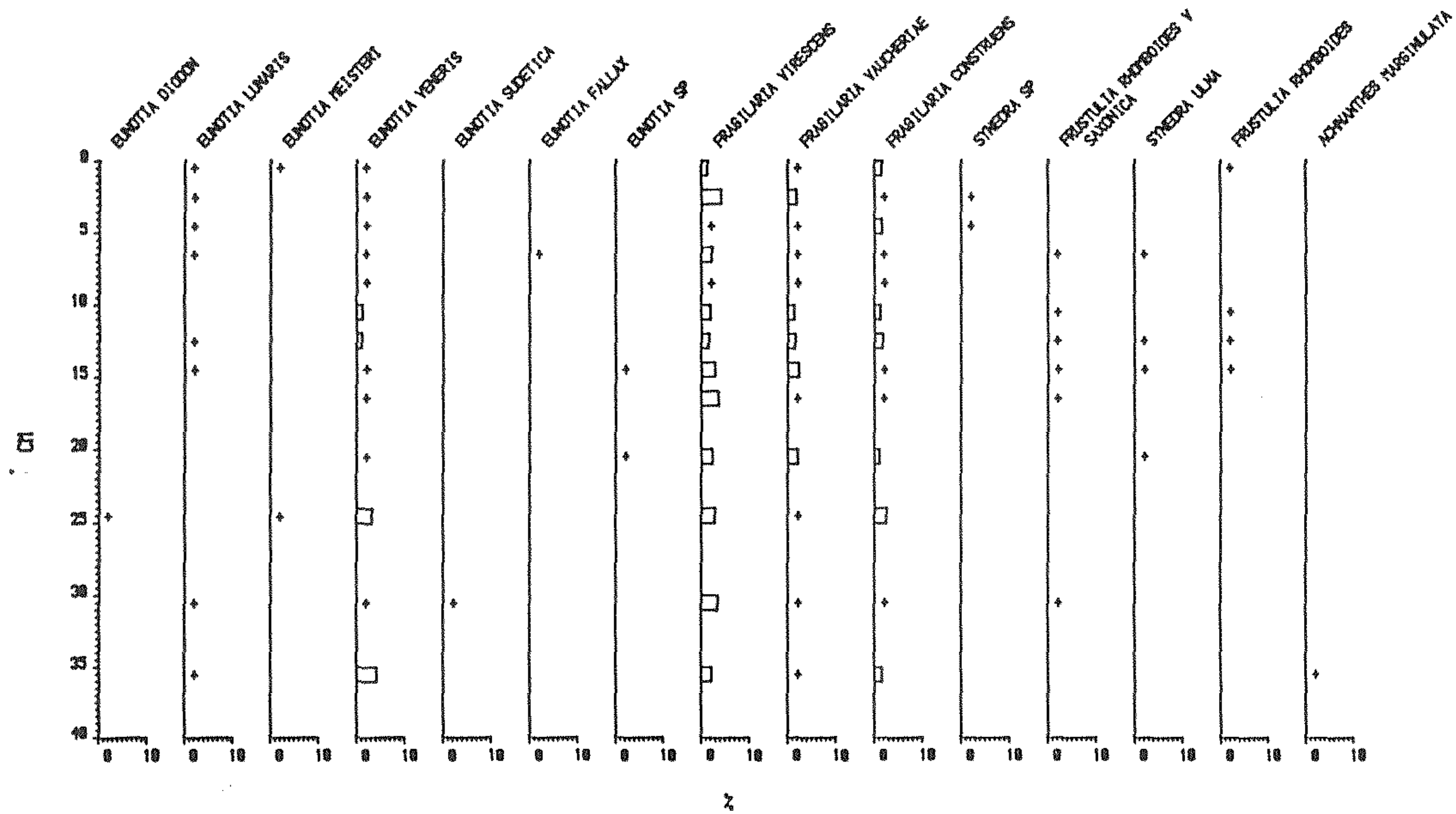

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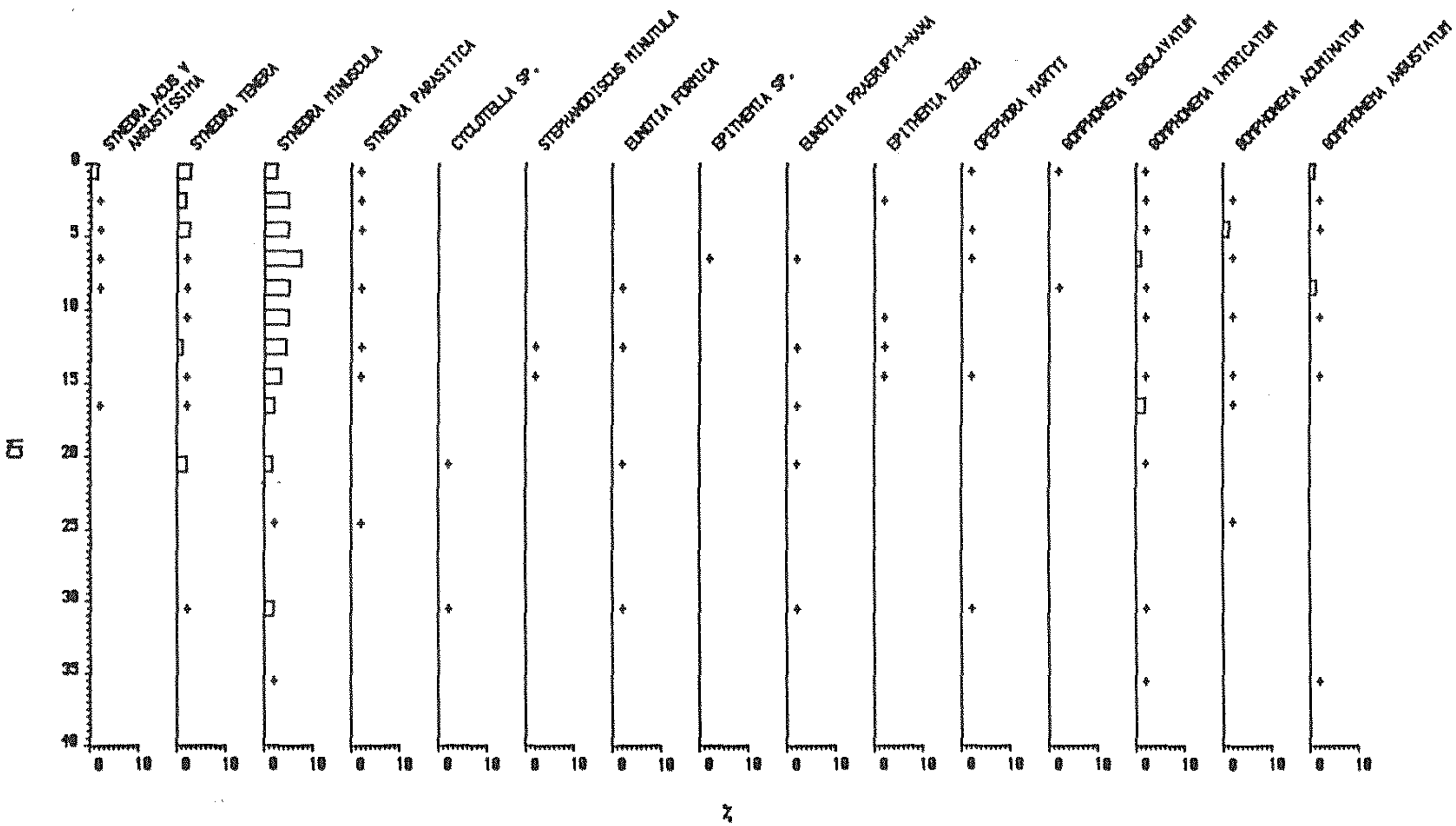

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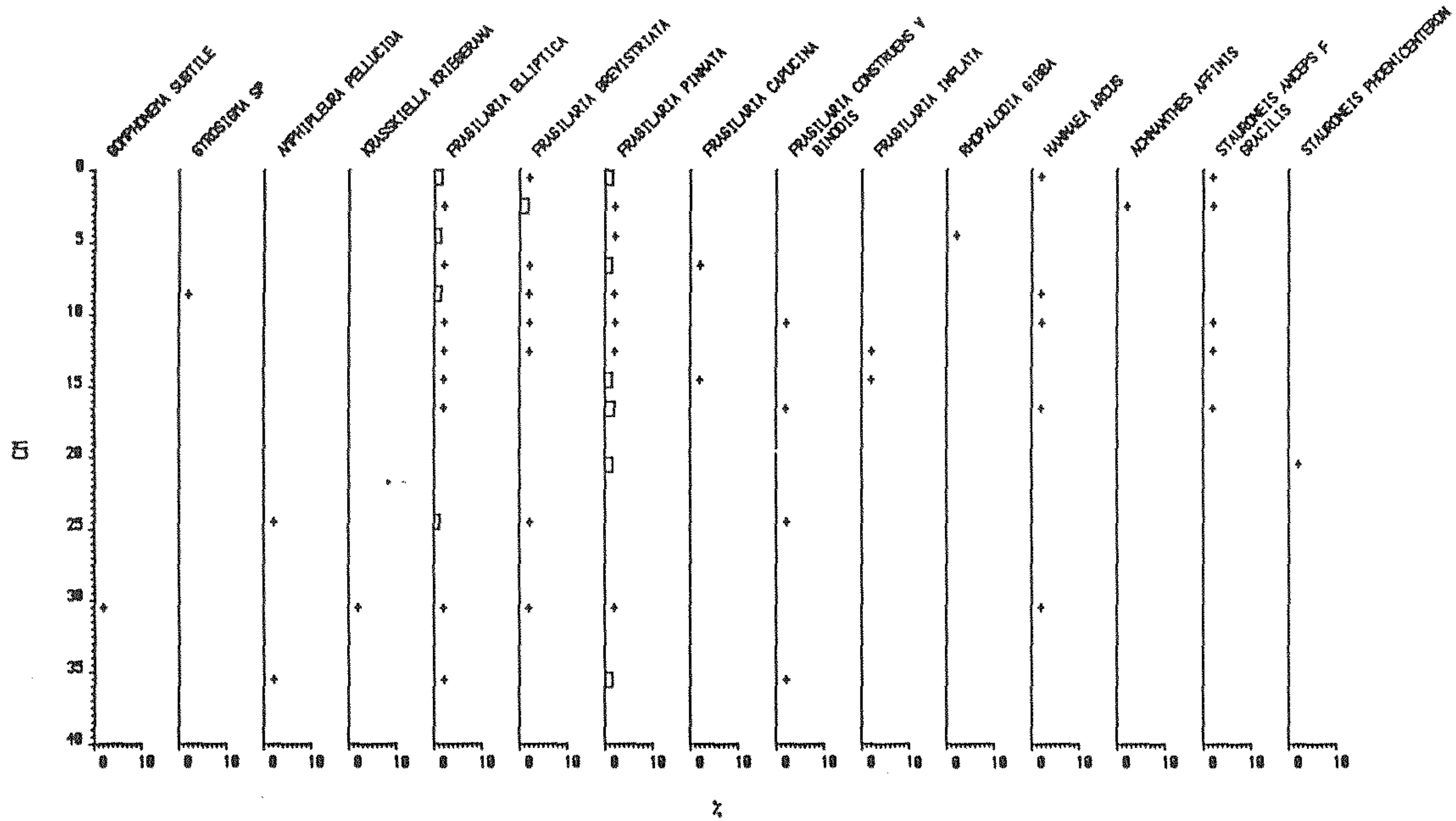
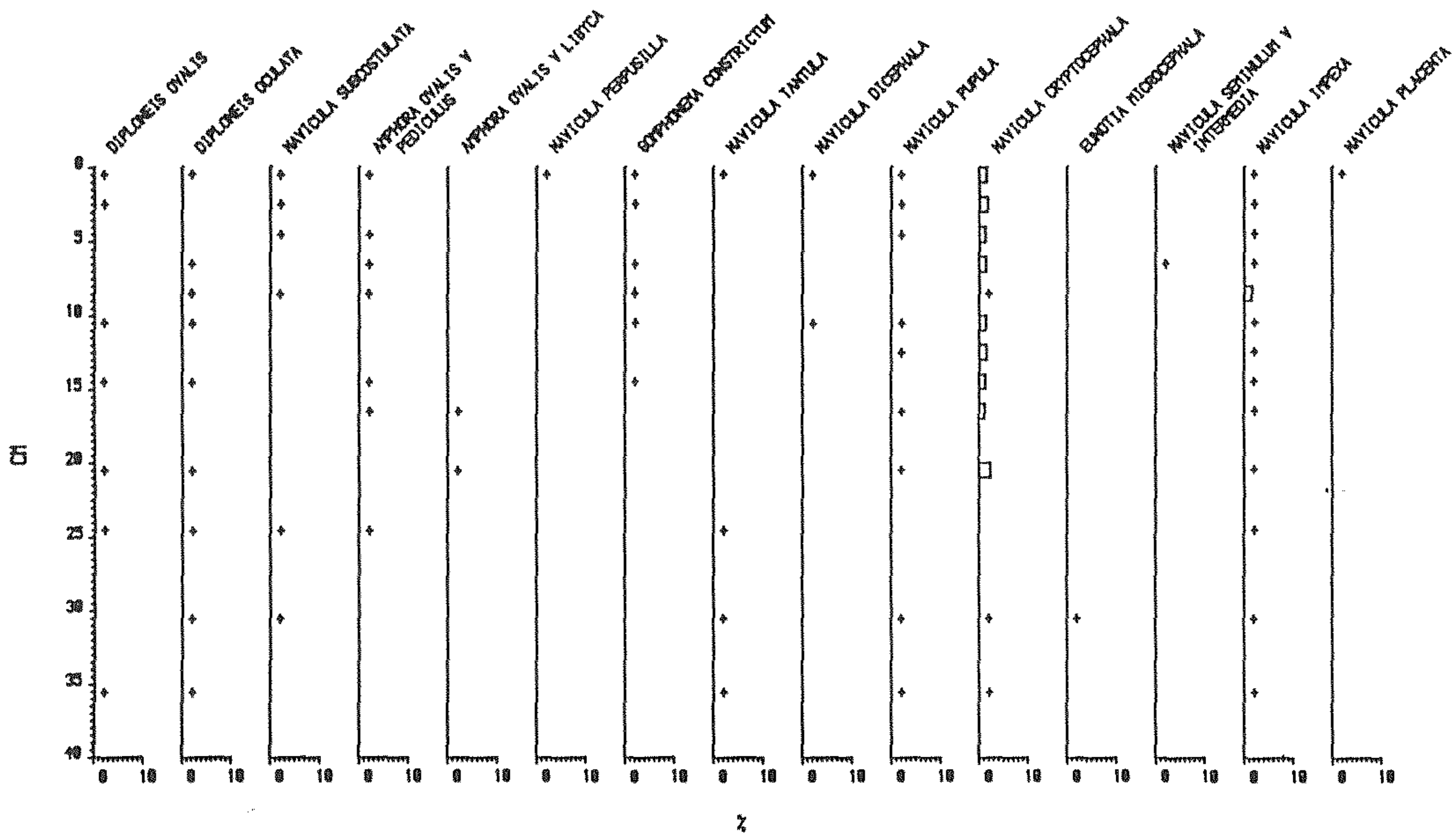
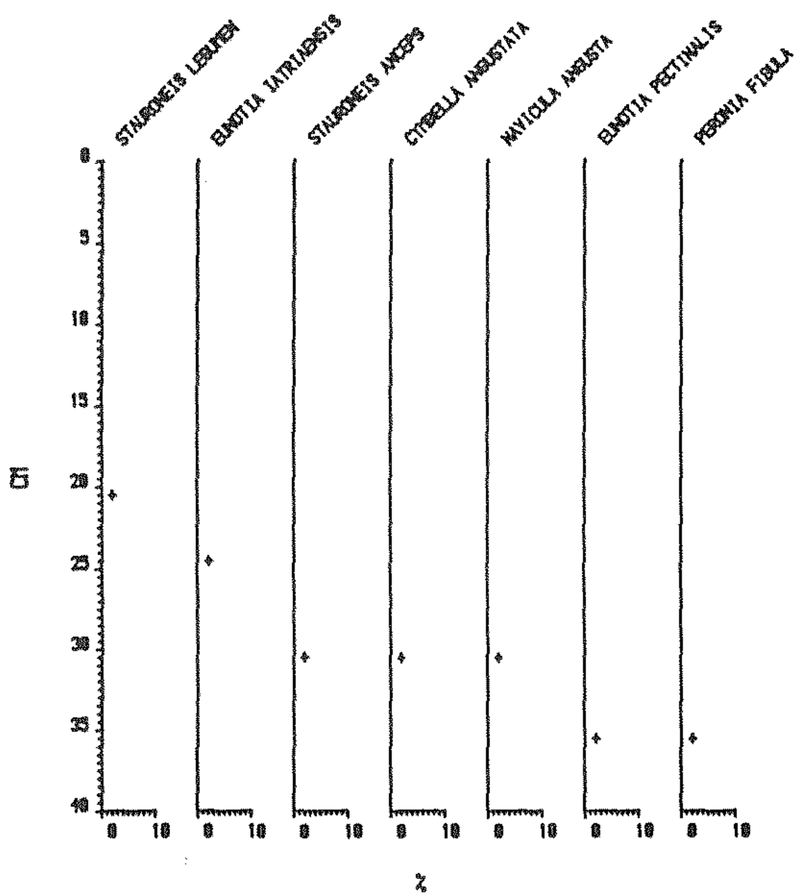


Appendix 3 Cont.



Appendix 3 Cont.



Appendix 3 Cont.