Research Papers

No. 29

PALAEOECOLOGICAL EVALUATION OF THE RECENT ACIDIFICATION OF LOCH LAIDON, RANNOCH MOOR, SCOTLAND

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Report to the DOE under Contract PECD 7/7/139

December 1987

Palaeoecological evaluation of the recent acidification of Loch Laidon, Rannoch Moor Scotland.

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Summary

Palaeoecological techniques have been utilised to examine the recent acidification status of Loch Laidon, a large freshwater loch on Rannoch Moor, Scotland.

The rate of sediment accumulation in the Loch Laidon core calculated from unsupported ^{210}Pb concentrations is fairly uniform in terms of dry weight of sediment (0.013 g cm^{-2} y^{-1} since c. 1840) indicating an absence of major physical disturbance in the catchment.

Diatom analysis of the core shows a marked decline in forms characteristic of circumneutral water, with planktonic Cyclotella kutzingiana decreasing in the late 19th century and Anomoeoneis vitrea decreasing in the 1940s. These taxa have been replaced by acidophilous taxa including Eunotia veneris and Tabellaria flocculosa.

Contamination of the sediment by the trace metals lead and zinc from atmospheric sources began in c. 1850, but carbonaceous particles ('soot') are not recorded in the sediment until about 80 years later.

pH reconstructions for the loch based on the sedimentary diatoms indicate that water acidity has decreased by about 0.5 pH units since the mid-19th century, from c. 5.8 (1855) to c. 5.3 (1985).

Pollen analysis of the sediment core reveals no major vegetation change within the catchment, except for a pre-1700 reduction in the Isoetes population within the loch resulting from increased peat erosion.

There is no evidence of significant catchment-wide changes in land use or land management in the last c. 200 years. Localised afforestation and experimental management for deer grazing are not considered to have been important.

Although acidification of Loch Laidon is only moderate the results show that this environmentally important loch, part of which is a National Nature Reserve, has been affected by atmospheric pollution for well over a century.

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1.0 Introduction

Acid deposition has caused strong acidification of several lochs in the Galloway area of south-west Scotland (Flower et al. 1987). Recent acidification of lochs elsewhere in Scotland has yet to be demonstrated. This report investigates the acidification status of a loch in the Rannoch Moor area of the Scottish Central Highlands, Loch Laidon (Fig. 1).

Rannoch Moor is an extensive area of peatland overlying mainly granitic rocks. It possesses an abundance of acid lochs and pools, the largest of which is Loch Laidon, a major loch with an important brown trout fishery. The loch is accorded considerable environmental value and with much of its catchment, has been designated a Site of Special Scientific Interest (SSSI) (Fig. 1). In addition, a section of the southern shore of the loch and adjacent peatland form the Rannoch Moor National Nature Reserve (NNR) (Fig. 1). The loch itself is given grade one status as a large undisturbed, oligotrophic glacially formed loch, by the Nature Conservancy Council (Ratcliffe 1977).

Recent water chemistry data for Loch Laidon (Harriman and Wells 1985) (Table 2), suggest that this important loch is moderately acidified. As the loch lies in an area likely to be sensitive to the effects of acid precipitation (Kinburgh and Edmunds 1986), palaeolimnological analysis is used here to examine the recent history and impact of atmospheric pollution on the loch.

2.0 site details

2.1 Loch

Loch Laidon (Fig. 1) is an elongated (c. 6.5 km * 0.5 km), relatively large (473 ha) oligotrophic loch, lying at an altitude of 282 m. The loch lies wholly on granites and is formed in a glacially scoured rock basin, being an example of a glint lake. Loch bathymetry (Fig. 2) was surveyed by Murray and Pullar (1910) and revealed a maximum depth of 39 m (Table 1). Estimated water residence time (c. 4 months) is comparatively short for a loch of this size and is associated with considerable water level fluctuation (+/- c. 2 m) following heavy precipitation or snow melt.

Water chemistry (Table 2) reflects precipitation and catchment characteristics, being very dilute, acid, low in calcium and moderately coloured. Mean pH, calculated as a geometrical average from 21 measurements (Harriman p. comm.), is 5.41.

The shoreline shelves steeply in most places and consists mainly of coarse-grained boulders and stones with a few sheltered bays in which sand and/or peat debris accumulates. These bays form the main macrophyte habitat where species such as *Juncus bulbosus*, *Eleogiton fluitans*, *Isoetes lacustris*, *Utricularia intermedia*, *Lobelia dortmanna* and *Nitella sp.* are found (NCC 1978).

The zooplankton of the loch is sparse, only *Bosmina coregoni* var. *obstusirostris* occurs in any numbers. The macro-benthos of the deeper water is also sparse, only Chironomidae and Cyrnus flavidus being found. In the littoral, Chironomidae and Naididae predominate (NCC 1978).

2.1.1 Fishing history

Although Weir (1980) suggests that perch were introduced into Loch Laidon and that salmon have only failed to reach the loch since the construction of hydro-electric works downstream, Loch Laidon has always been primarily known for its population of brown and ferox trout.

Despite its reputation (until recently) as one of the best trout lochs in Scotland (eg. Lyall 1910) and although it is still regularly fished, no historical record has been maintained of the quantity and quality of fish caught. Loch 'Laoidean' is mentioned in the New Statistical Account for the parish of Fortingal (MacDonald 1845), as just one of the lochs in the area that were 'well stored with trout'. An angler's diary for the period 1876-1914 reported large catches of trout on the loch including 129 taken by one fisherman in June 1912 (Murray-Smythe 1956). During the same period Groome (1901) described the 'abundance' of trout in the loch, some of which weighed up to 8 lbs. Trout of 3 - 4 lbs were still plentiful in 1940 (Hardie 1940), but in recent years the average size of trout caught has fallen well below 0.5 lbs (M. Pearson, P. Turner p.comms).

The loch is not stocked but on occasion up to 400 trout are put into the small Dubh Loch at the extreme north-east of the catchment. During periods of high water in Loch Laidon Dubh Loch is linked to the main water body.

2.2 Loch catchment

The Loch Laidon catchment is extensive (12,110 ha) and remote (Fig. 1), it attains a maximum altitude of 1108 m (net relief 836 m) towards Glen Coe in the west. The catchment is drained by numerous small streams on its northern and southern flanks, but primarily by an extensive secondary loch system which drains to the River Ba in the west (Fig. 1). The climate is cool and wet. Snow cover can be seasonally extensive and the annual precipitation of 1780 mm is one of the wettest in the UK (Barrett et al. 1987). Deposited sulphur in the region exceeds 1.6 g S m^{-2} y^{-1} (Table 1).

The catchment lies primarily on granite with a confined area of quartz-feldspar-granulite of the Moine series in the far south-west. Blanket peat cover is extensive and deposits of glacial drift are locally significant.

Catchment vegetation consists of acid heath species, particularly Trichophorum caespitosum, Eriophorum vaginatum and Molinia caerulea. Sphagna flourish in wet depressions and Calluna vulgaris and Erica cinerea co-dominate on morainic knolls and better drained areas. Localised erosion of blanket peats has exposed the remains of an extensive Boreal - Atlantic pine-birch forest (Birks 1975, Walker and Lowe 1977). Contemporary mixed woodland is confined to a few small islands in Loch Laidon, Loch

Ba and Lochan na h-Achlaise. Two small coniferous plantations are present, one (c. 30 ha) to the west of Loch Ba, the other (c. 300 ha) adjacent to the north-east shore of Loch Laidon (Fig. 1).

An area in the north-east of the catchment where the topography is of low relief and blanket mire and dystrophic lochans are frequent, comprises part of the Rannoch Moor National Nature Reserve (NNR) (Fig. 1) which is noted for its diverse complex of northern oligotrophic mire types and a rich fauna of moorland insects. Much of the remainder of the catchment is designated as a Site of Special Scientific Interest (SSSI) (Fig. 1). In 1975 the whole area was accorded international importance as a wetland under the 'Ramsar' Convention (Smith 1984)

Table 1 Loch Laidon: loch and catchment characteristics

Loch		Catchment	
Area	473 ha	Max. altitude	1108 m
Altitude	282 m	Max. relief	836 m
Mean depth	10.7 m	Total area	12110 ha
Max. depth	39.0 m	Area afforested	c. 330 ha
Volume	50 * 10^6 m^3	Annual rainfall	1780 mm
Residence time	4 months	Annual deposited H^+	0.1 g m^{-2}
		Annual deposited S	>1.6 g m^{-2}

Table 2 Loch Laidon: water chemistry (outflow samples)

	23.6.1986	19.10.1986	29.3.1987	16.7.1987	Harriman & Wells 1985 Harriman p.comm. 1987
pH	5.52	5.86	5.79	6.01	4.88-5.8
Cond. ($\mu S\ cm^{-1}$)	27	24	20	25	0-16
H^+ ($\mu eq\ l^{-1}$)	3	1	2	1	*
Na^+ ($\mu eq\ l^{-1}$)	140	147	122	119	77-140
K^+ ($\mu eq\ l^{-1}$)	7	7	6	5	1-15
Ca^{++} ($\mu eq\ l^{-1}$)	36	49	37	43	15-48
Mg^{++} ($\mu eq\ l^{-1}$)	31	36	27	30	34-48
Alk ($\mu eq\ l^{-1}$)	14	24	20	25	0-16
Cl^- ($\mu eq\ l^{-1}$)	153	151	116	100	*
SO_4^{--} ($\mu eq\ l^{-1}$)	45	55	46	36	54-79
NO_3^- ($\mu eq\ l^{-1}$)	3	3	2	3	*
Al (Total) ($\mu g\ l^{-1}$)	*	27	26	12	*
Al (non labile) ($\mu g\ l^{-1}$)	*	26	23	8	*
Al (labile) ($\mu g\ l^{-1}$)	*	1	3	4	*
Absorb (250 nm)	0.161	0.188	0.153	0.155	*
TOC ($mg\ l^{-1}$)	*	*	2.6	3.6	*

* missing values

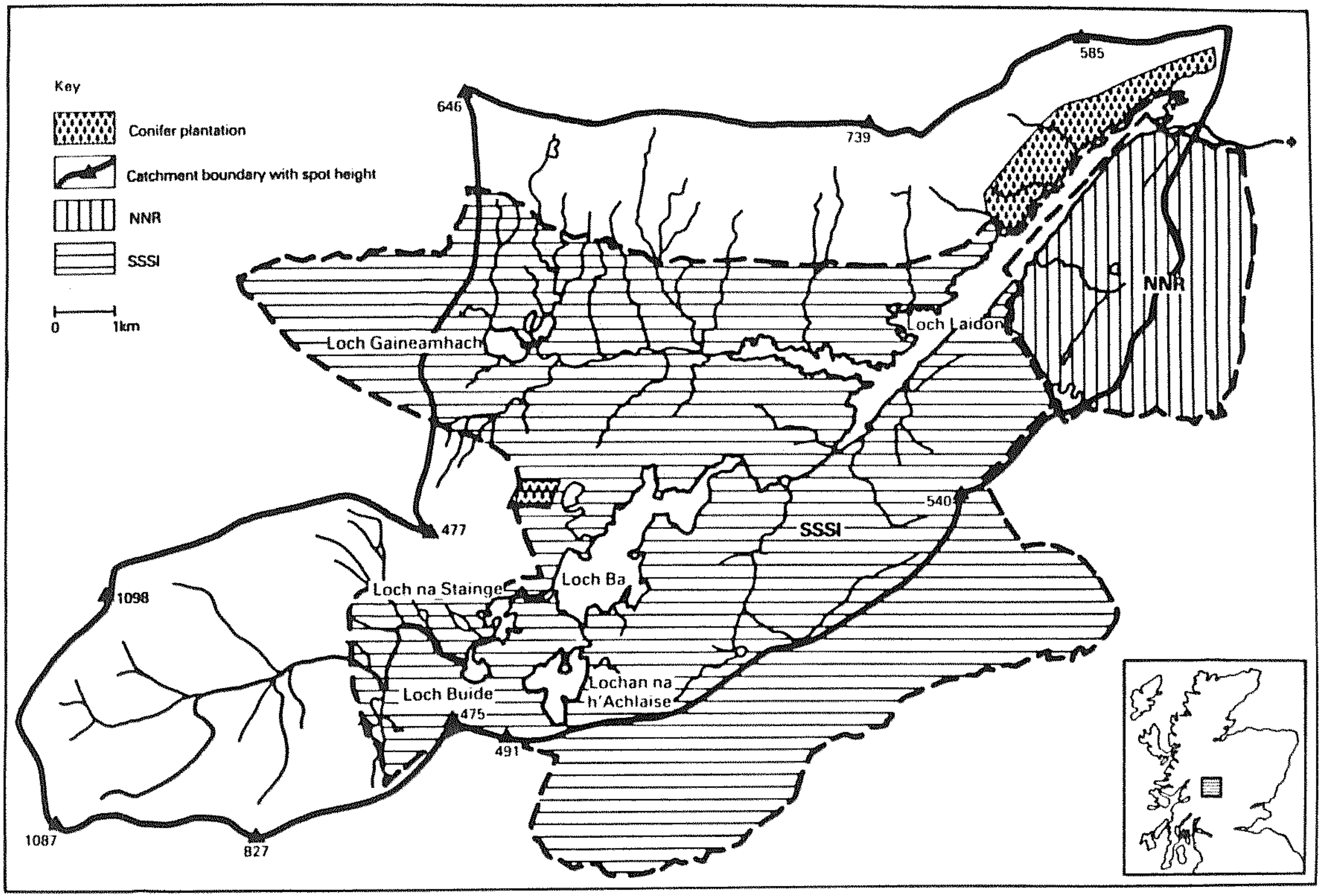


Fig. 1. The Loch Laidon catchment indicating the boundaries of Rannoch Moor NNR and SSSI.

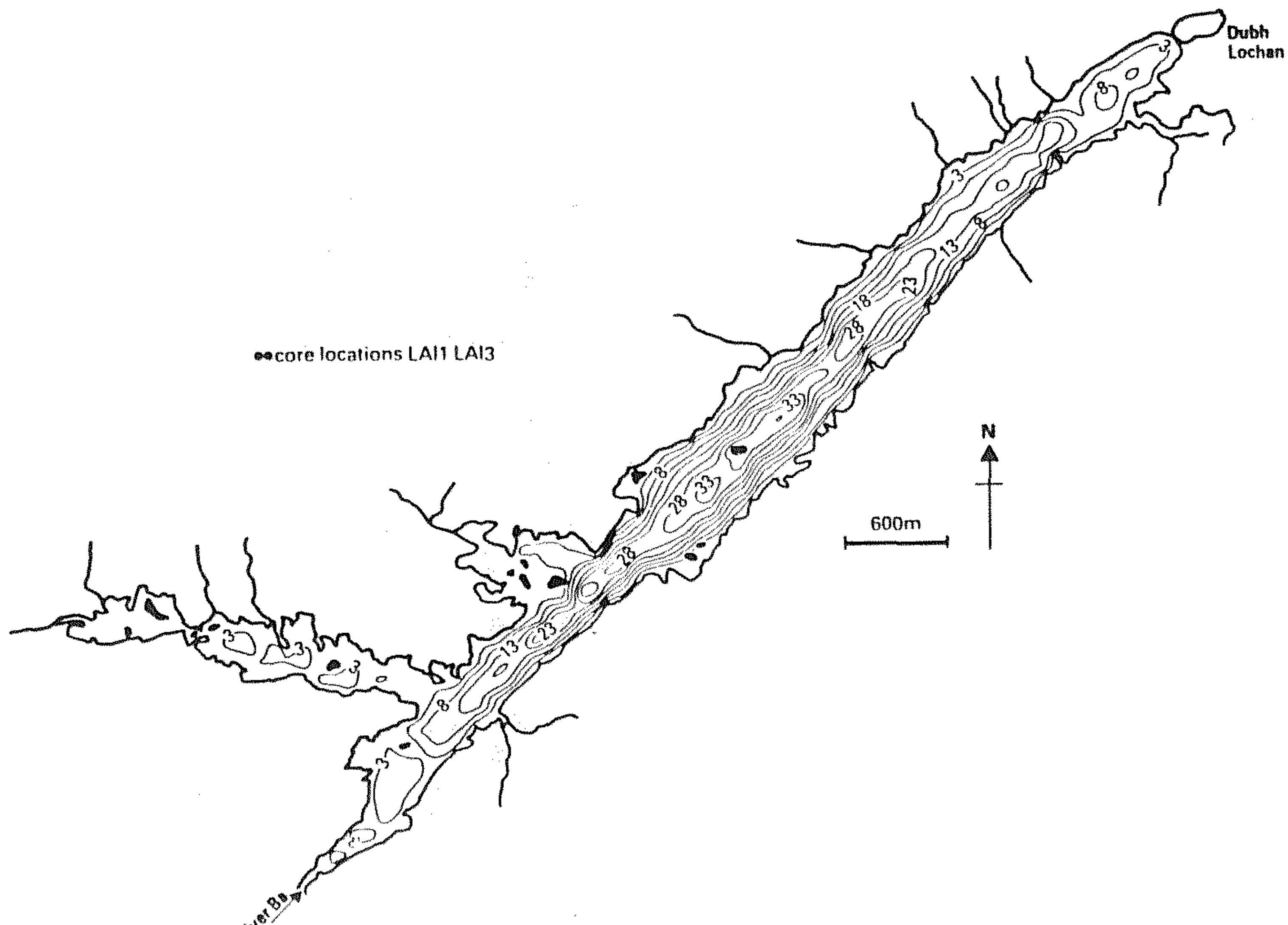


Fig. 2. Loch Laidon bathymetry (contour intervals in metres).

3.0 Methods

The loch bathymetry (Fig. 2) was constructed from the survey undertaken by Murray and Pullar (1910). The techniques employed in drawing the bathymetric map and calculating loch area and volume are described in Stevenson et al. (1987c).

Three sediment cores were taken from the deepest part of the loch (39 m) (Fig. 2) in July 1985, using a mini-Mackereth corer (Mackereth 1969) from an inflatable boat. Two cores, LAI1 ('master' core) and LAI3 were sectioned in the laboratory at 0.5 cm (0 - 22 cm) and 1.0 cm (from 22 cm) intervals. Core LAI1 was sub-sampled for ^{210}Pb, diatoms, pollen, geochemistry and magnetic susceptibility. Carbonaceous particle analysis was performed on core LAI3. These analyses were conducted according to the standard methods set out in Stevenson et al. (1987c).

4.0 Results

4.1 Loch history

4.1.1 Sediment description

The three sediment cores collected from Loch Laidon were all very similar in appearance consisting of fine grained black mud (Munsell colour: 10YR 3/2) with no visual changes in stratigraphy. Basic sedimentological data for wet density, percentage dry weight (at 60° C) and percentage loss on ignition (LOI) (at 550° C) for two of these cores, core LAI1 and LAI3 are shown in Figures 3a,b. Core LAI1 has very uniform wet density and percentage dry weight profile, the only significant change occurs at about 9 cm depth where a small inwash of organic material is indicated. The LOI profile shows an increase from about 60 to 30 cm depth, then lower values between 30 to 20 cm and fairly uniform values from 20 cm to the core top. These changes are possibly evidence of increasing deposition of eroded peat up to 30 cm depth followed by the deposition of less organic material around 25 cm depth. The profiles follow very similar trends in LAI3 and the two cores can be correlated using the LOI curves. A small difference between the two cores is that the relatively low LOI values around 25 cm depth in LAI1 correspond to those at 20 - 23 cm in LAI3 and possibly indicate a slightly higher rate of recent sediment accumulation in the former core.

4.1.2 ^{210}Pb dating

Sediments from core LAI1 were analysed for ^{210}Pb, ^{226}Ra and ^{137}Cs by gamma spectrometry (Appleby et al. 1986). The ^{210}Pb and ^{226}Ra results are given in Table 3 and shown graphically in Figure 4. The ^{137}Cs results are given in Table 4 and Figure 5. Table 5 gives values of a range of other radioisotopes determined from the gamma spectra. The ^{210}Pb inventory of the core is 19.83 pCi cm^{-2} and represents a mean ^{210}Pb supply rate of 0.62 pCi cm^{-2} y^{-1}. This value is comparable with the expected atmospheric flux.

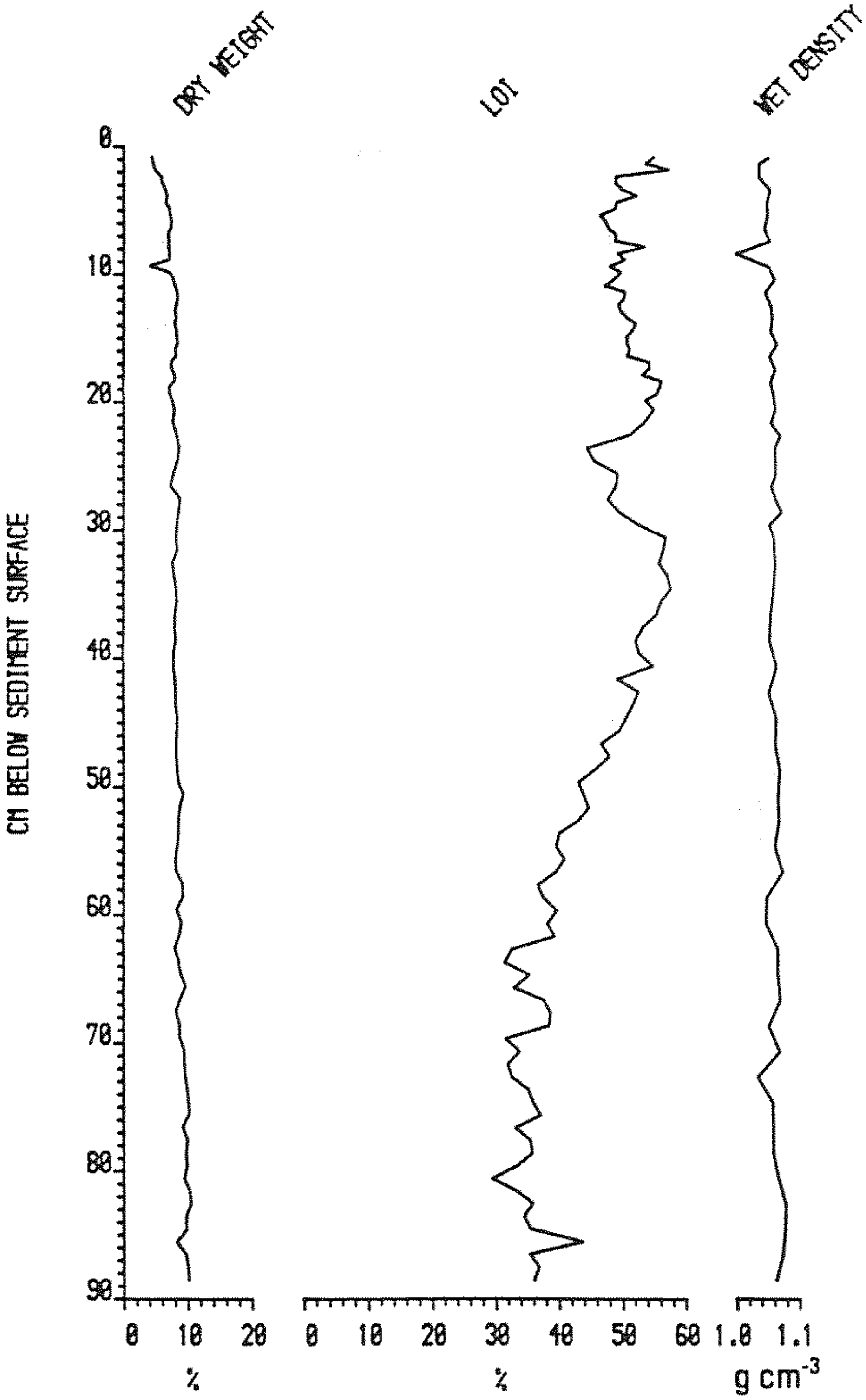


Fig. 3a. Sediment characteristics of Loch Laidon core LAI1.

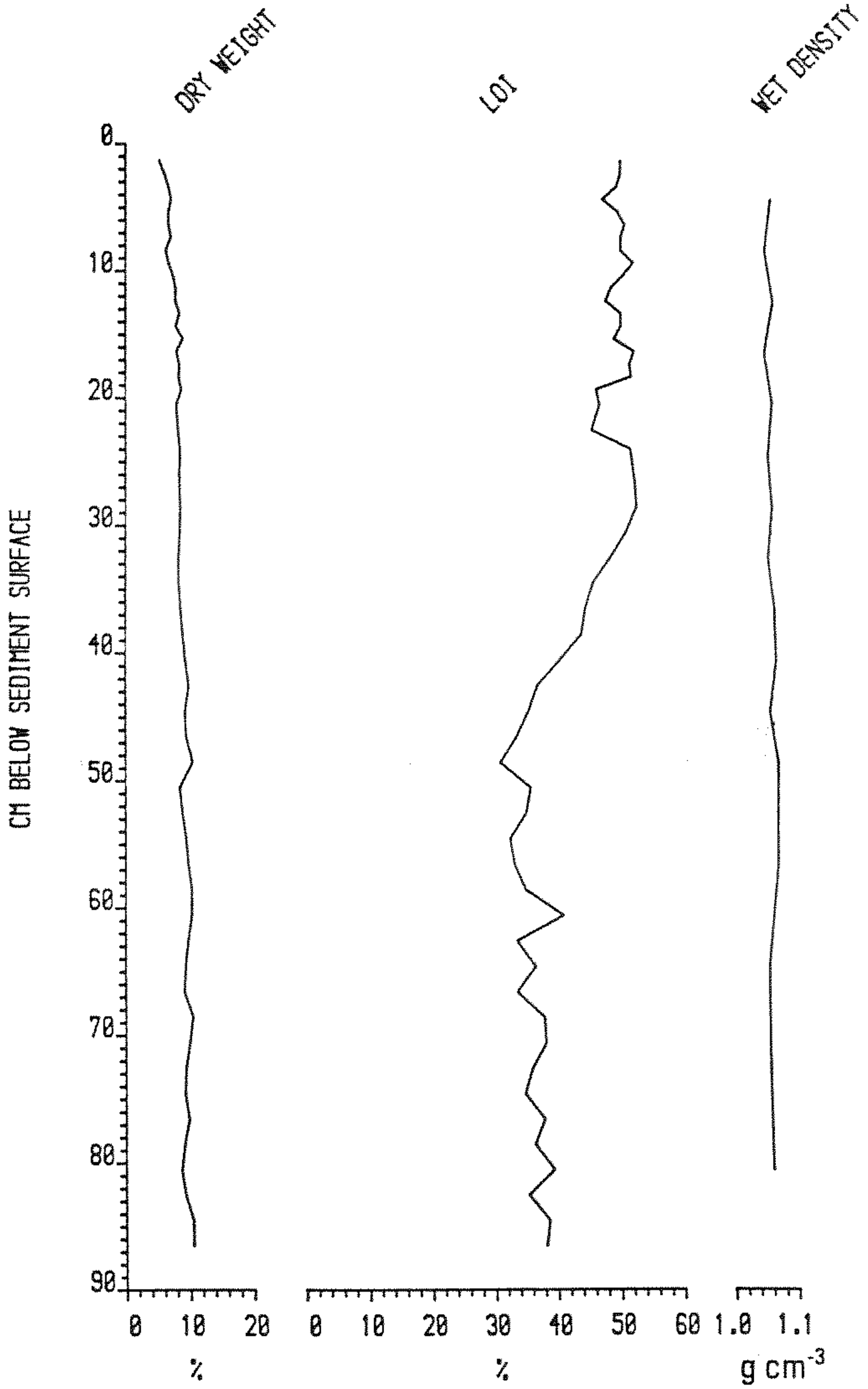


Fig. 3b. Sediment characteristics of Loch Laidon core LAI3

Figure 6 shows the ^{210}Pb chronologies for core LAI1 given by the CRS and CIC ^{210}Pb dating models (Appleby and Oldfield 1978). Both models indicate a small increase in accumulation rates over the past 10 - 20 years and the CIC dates are consequently slightly younger than the CRS dates. In view of the reasonable ^{210}Pb flux and the better date for the peak ^{137}Cs concentration, it would seem preferable to use the CRS model dates. These are given in Table 6. Apart from the recent increase there seems to have been a more or less uniform sediment accumulation rate of c. 0.013 g cm^{-2} y^{-1}.

The ^{137}Cs profile (Fig. 5) shows significant concentrations down to below 15 cm, dated c. 1900, indicating significant downward diffusion. There is maximum ^{137}Cs concentration at 3.75 cm, although the absence of a well defined peak means that this has little chronological significance.

The ^{226}Ra concentrations were generally lower in sediments above 15.25 cm (dated c. 1900), indicating a possible change in sediment type.

Table 3 ^{210}Pb data for Loch Laidon core LAI1

Depth cm	Dry mass g cm^{-2}	^{210}Pb concentration Total pCi g^{-1}	Unsupported pCi g^{-1}	Cumul. unsupp. ^{210}Pb pCi cm^{-2}	Standard errors Concent. Total	Unsupp.	Cumul. Unsupp.	^{226}Ra Concent. pCi g^{-1}	Std. error Total
0.75	0.0308	40.85	40.228	1.315	1.7	1.78	0.09	0.622	0.25
3.75	0.2055	32.980	32.314	7.627	1.27	1.29	0.40	0.666	0.25
6.75	0.4290	21.910	21.288	13.533	1.50	1.52	0.58	0.622	0.25
9.75	0.6320	13.100	12.522	16.888	0.83	0.86	0.67	0.578	0.22
15.25	1.0998	4.250	3.294	20.207	0.46	0.49	0.75	0.956	0.16
20.50	1.5287	2.840	1.730	21.264	0.30	0.32	0.78	1.110	0.12
23.50	1.7844	1.690	0.817	21.577	0.16	0.17	0.79	0.873	0.06
27.50	2.1248	1.590	0.759	21.845	0.23	0.24	0.79	0.831	0.08
30.50	2.3932	1.180	0.179	21.969	0.17	0.18	0.79	1.001	0.07
35.50	2.8197	1.010	0.169	22.042	0.27	0.29	0.80	0.841	0.11
36.00	2.8627			22.049					

Table 4 ^{137}Cs data for Loch Laidon core LAI1

Depth cm	Dry mass g cm^{-2}	^{137}Cs concentration pCi g^{-1}	+/-	Cumulative ^{137}Cs pCi g^{-1}	+/-	Fract
0.75	0.0308	31.69	0.88	0.98	0.06	0.068
3.75	0.2055	31.79	0.72	6.52	0.31	0.455
6.75	0.4290	10.57	0.62	10.83	0.41	0.755
9.75	0.6320	4.20	0.30	12.23	0.44	0.853
15.25	1.0998	1.68	0.16	13.52	0.45	0.942
20.50	1.5387	0.91	0.10	14.05	0.46	0.980
23.50	1.7844	0.33	0.05	14.20	0.46	0.990
27.50	2.1248	0.24	0.06	14.30	0.46	0.997
30.50	2.3832	0.08	0.05	14.34	0.46	0.999
35.50	2.8197	0.00	0.00	14.34	0.46	1.000

Table 5 Other radioisotope data for Loch Laidon core LAI1

Depth cm	^{226}Ra	^{238}U	^{235}U pCi g^{-1}	^{228}Ac	^{228}Th	^{40}K
0.75	0.00	1.28	0.29	0.42	0.96	8.02
3.75	0.67	0.00	0.23	0.00	0.06	4.49
6.75	0.00	1.08	0.14	0.00	0.71	0.00
9.75	0.58	2.07	0.27	0.95	1.50	16.80
15.25	0.96	0.85	0.06	1.06	0.77	8.30
20.50	1.11	1.85	0.23	0.58	1.11	10.20
23.50	0.87	1.34	0.27	0.83	0.57	11.66
27.50	0.83	1.05	0.22	0.60	0.35	8.39
30.50	1.00	1.78	0.36	1.00	0.58	9.16
35.50	0.84	1.70	0.39	1.07	1.17	7.79

Table 6 CRS model ^{210}Pb chronology Loch Laidon core LAI1

Depth	Dry mass	Cumul. unsupp. ^{210}Pb	Chronology			Sedimentation		Std. error
			Date	Age	error			
cm	g cm^{-2}	pCi cm^{-2}	AD	y		g cm^{-2}	cm y^{-1}	%
0.00	0.0000	19.83	1985	0				
1.00	0.0454	18.05	1982	3	2	0.0156	0.281	5.7
2.00	0.1036	15.95	1978	7	2	0.0148	0.253	5.8
3.00	0.1618	14.10	1974	11	2	0.0141	0.225	5.9
4.00	0.2241	12.28	1970	15	2	0.0134	0.201	6.1
5.00	0.2986	10.24	1964	21	2	0.0129	0.189	7.0
6.00	0.3731	8.55	1958	27	2	0.0124	0.177	7.9
7.00	0.4459	7.14	1952	33	2	0.0120	0.167	8.6
8.00	0.5136	5.99	1947	38	2	0.0120	0.162	8.5
9.00	0.5813	5.02	1941	44	3	0.0120	0.157	8.4
10.00	0.6533	4.18	1935	50	3	0.0122	0.154	8.7
11.00	0.7383	3.40	1928	57	3	0.0128	0.160	10.4
12.00	0.8234	2.77	1922	63	4	0.0135	0.166	12.0
13.00	0.9084	2.26	1915	70	4	0.0141	0.172	13.7
14.00	0.9935	1.84	1909	76	5	0.0147	0.178	15.3
15.00	1.0785	1.50	1902	83	5	0.0153	0.184	16.9
16.00	1.1611	1.23	1896	89	6	0.0150	0.180	19.8
17.00	1.2428	1.02	1890	95	7	0.0143	0.171	23.2
18.00	1.3245	0.85	1884	101	8	0.0136	0.163	25.5
19.00	1.4062	0.70	1878	107	19	0.0128	0.155	29.8
20.00	1.4879	0.58	1872	113	10	0.0121	0.146	33.1
21.00	1.5713	0.48	1865	120	12	0.0123	0.147	38.7
22.00	1.6565	0.39	1859	126	14	0.0133	0.158	46.5
23.00	1.7418	0.32	1852	133	17	0.0143	0.169	54.1
24.00	1.8269	0.25	1844	141	19	0.0136	0.160	59.7
25.00	1.9120	0.18	1835	150	20	0.0112	0.131	63.2

^{210}Pb flux = 0.62 +/- 0.02 pCi cm^{-2}
90% equilibrium depth = 14.2 cm or 1.01 g cm^{-2}
99% equilibrium depth = 25.3 cm or 1.94 g cm^{-2}

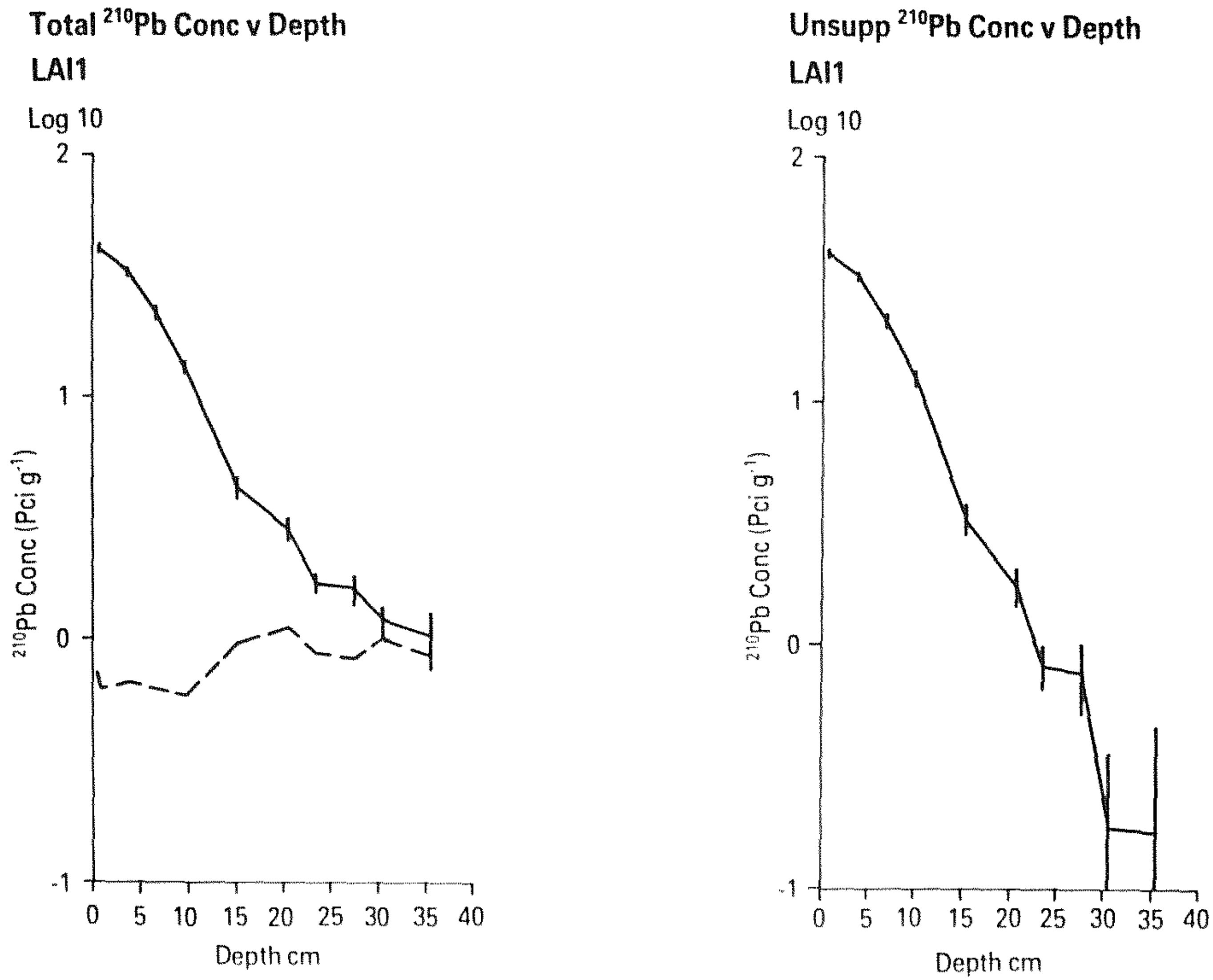


Fig. 4. Loch Laidon: ^{210}Pb profile.

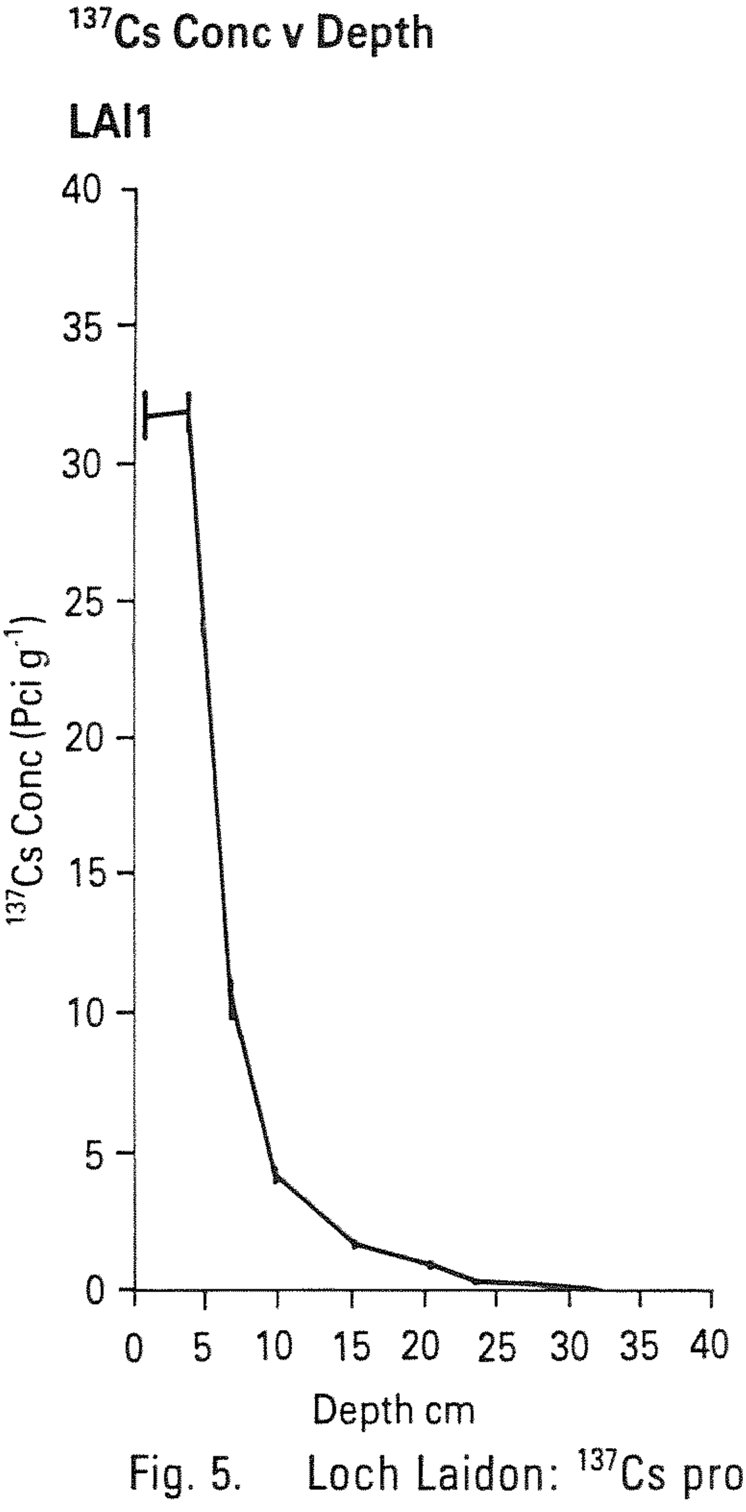


Fig. 5. Loch Laidon: ^{137}Cs profile.

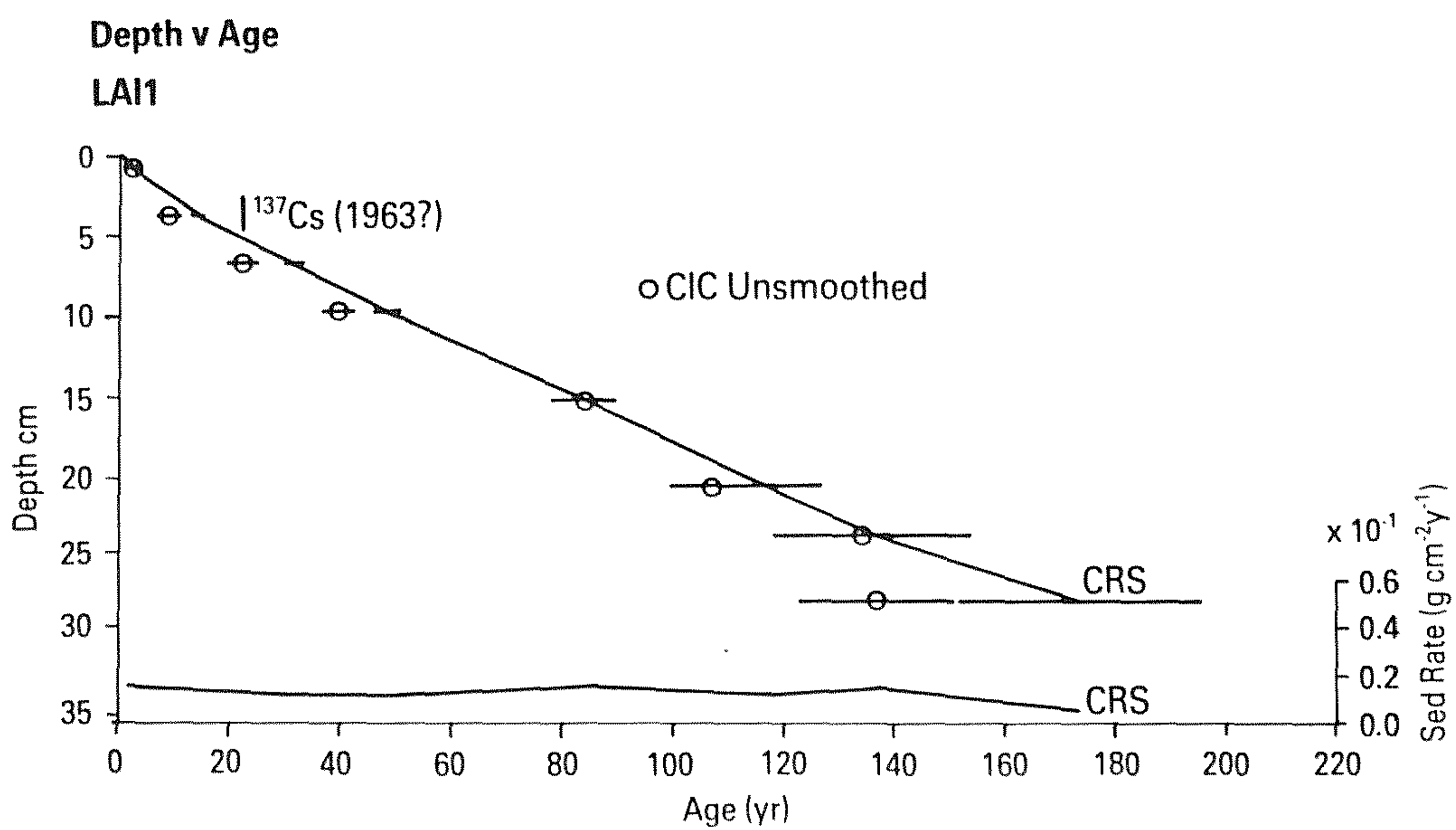


Fig. 6. Loch Laidon: ^{210}Pb chronology.

4.1.3 Diatom analysis

The diatom percentage frequency summary diagram constructed for the Loch Laidon core (LAI1) together with ^{210}Pb dates are shown in Figure 7. The full diatom percentage frequency diagram is presented in Appendix 1 and the full diatom species list in Appendix 2. Below 22 cm depth in the sediment (c. 1850 AD) diatom frequencies change little, the two most common species being Brachysira vitrea and the planktonic species Cyclotella kutzingiana. Above this depth however the flora begins to change markedly as C. kutzingiana declines and the frequency of Tabellaria flocculosa increases. Small increases in less common species such as Eunotia veneris and the acidobiontic Tabellaria quadriseptata also occur above this depth. By 12 cm (c. 1922) C. kutzingiana virtually disappears from the diagram, B. vitrea begins to decline and Frustulia rhomboides v. saxonica increases. Less common species such as Achnanthes pseudoswazi and Cymbella cesatii also disappear at about this level. The trend in frequency changes of the common species is broadly maintained to the core top (1985).

4.1.4 pH reconstruction

The temporal change in loch pH can be reconstructed from the core by including the diatom pH preference group data into the three available pH reconstruction models; Index B (Scandinavia), Index B (Galloway) and Multiple Regression of pH preference groups against pH (Galloway) (Flower 1986). Loch pH histories calculated using all three reconstruction methods (Fig. 7) give similar results although pH values calculated using Index B with coefficients from the Scandinavian data set are consistently between 0.1 and 0.2 pH units higher than those calculated by the other two methods. pH values calculated using the multiple regression method are probably most reliable (Charles 1985, Flower 1986) and for Loch Laidon show that pH has declined in a gradual manner from about pH 5.8 in c. 1855 to 5.3 by 1985. This represents a change of 0.5 pH units or an increase of 3.4 u eq H^+ l^{-1} over about 130 years.

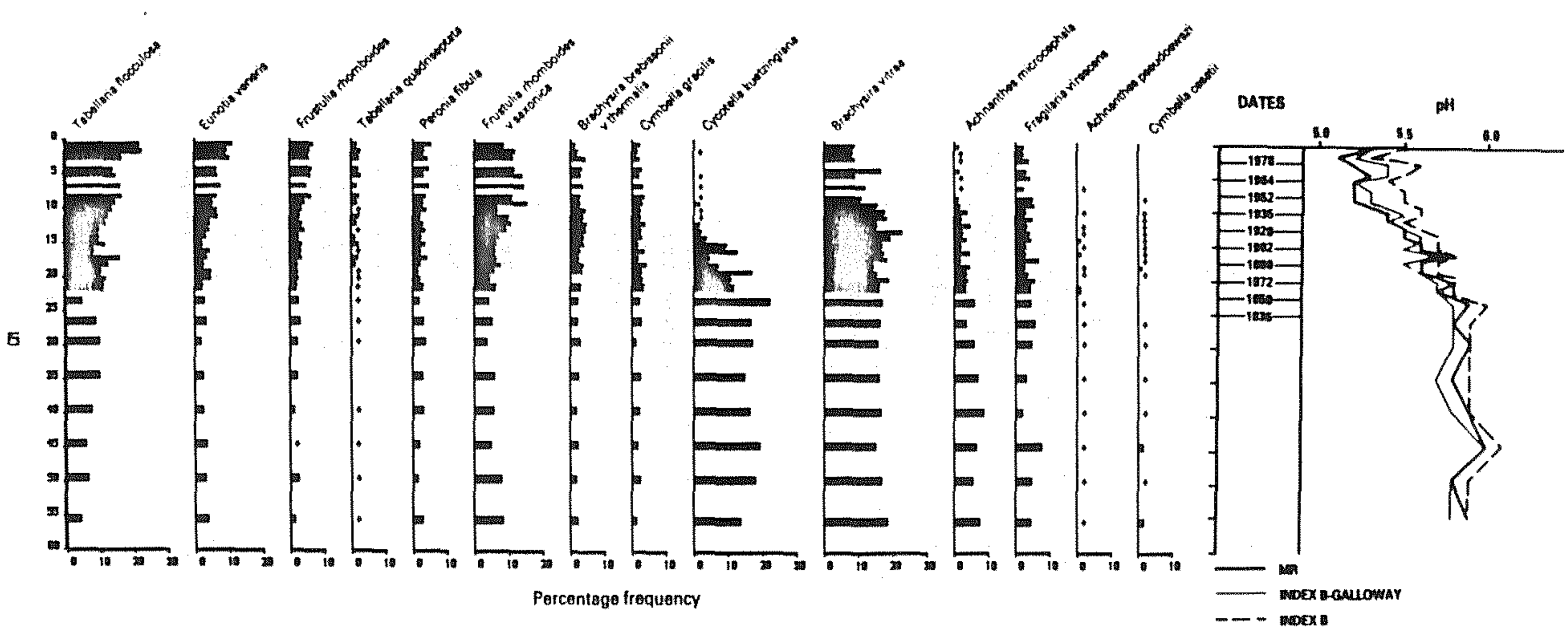


Fig. 7. Loch Laidon: diatom summary diagram and pH reconstruction.

4.1.5 Sediment chemistry

There are no major changes in the density, dry weight, organic content (Fig. 3a) and major ion composition of the sediment in the dated part of core LAI1 (above 25 cm, Fig 8, Appendix 3). Below the dated part there is an increase in organic content while the major cation concentrations decrease. Overall, the behaviour of sodium, magnesium and potassium is similar (correlation coefficients are all over 0.87).

When the effect of the organic content changes on element concentration is removed, by expressing the concentration per gramme of minerals, the increase in major cation concentration is almost removed (Fig. 9). The concentrations actually increase a little from the base of the core to 20 cm and then decrease (Fig. 9).

The small drop in major cation concentration , when expressed per gramme minerals, suggests that there has been a decrease in the erosion rate of material from the catchment during the 0 - 30 cm depth interval (Mackereth 1966, Engstrom and Wright 1984). This change in erosion rate may be small as the sediment accumulation rate is fairly constant in the dated part of the core, except for a small increase in the upper 5 cm (Table 6).

Overall, the catchment was not greatly disturbed over the depth interval 0 - 25 cm (the last 150 years) (Table 6) so it is to be expected that in the absence of any contamination the trace metal concentrations would be fairly constant.

The sedimentary zinc, lead and to a lesser extent copper concentrations increase around 25 cm, while the nickel concentration is fairly constant (Fig. 10, Appendix 3). This is so even although the major ion concentrations decrease above 20 cm. The increases in the three trace metals is more pronounced when the concentrations are expressed per gramme minerals (Fig. 11).

The trace metal profiles indicate that the sediment has been contaminated. As there are no trace metal bearing effluents in the Loch Laidon catchment it is probable that the contamination is from material deposited from an industrially polluted atmosphere.

Three pieces of evidence indicate that this contamination started around 23 cm depth. Firstly, the concentrations per gramme minerals increase at 23.5 cm for zinc and copper and although the lead concentration always rises slowly from the base of the core, it increases strongly at 22.5 cm. Secondly, the sedimentary fluxes of zinc, lead and copper increase around 22.5 cm depth (Fig. 12). Finally, when the zinc and lead concentrations are plotted against the major cations they are positively correlated below 23 cm but the relationship is destroyed above this depth. Figure 13 shows this for zinc/sodium and zinc/potassium. Below 23 cm the concentrations of the trace metals and major cations vary according to the inputs from the catchment, but above this depth the relationship is destroyed because there is an additional source of trace metals - contamination from the atmosphere. Similar contamination has been found in Welsh lakes (eg. Stevenson _et al._ 1987a, b, Patrick _et al._ 1987a). In Loch Laidon the contamination starting at 23 cm depth is dated to c. 1852.

The size of the contamination fluxes are shown in Table 7. There is no measurable nickel contamination. The background fluxes are estimated from the mean in the interval 30 - 89 cm and assume that the dry mass accumulation rate is constant below 25 cm at 13 mg cm^{-2} y^{-1} (Table 6). The contamination fluxes in Loch Laidon are similar to those in certain Welsh lakes where it was found that the dry mass accumulation rate was an important influence on the sedimentary flux of trace metals when there is contamination (Patrick et al. 1987b). When the rate is relatively low there is insufficient material falling through the water column to sediment out all the trace metals added to the lake from the atmosphere.

The dry mass accumulation rate in Loch Laidon (1015 mg cm^{-2} since 1900) is close to the high rates in Wales, but the sedimentary fluxes of zinc and lead (1542 mg Zn m^{-2} and 1746 mg Pb m^{-2} since 1900) are closer to those in lakes with lower accumulation rates (Patrick et al. 1987b). Although this is preliminary evidence it suggests that the trace metal deposition rate in central Scotland is lower than in Wales.

Table 7 Trace metal contamination fluxes in Loch Laidon

Metal	Background	Maximum	Contamination (Max.-background)
		(mg m^{-2} y^{-1})	
Zinc	7.4	24.5	17.1
Lead	4.2	28.1	13.9
Copper	1.5	2.8	1.3

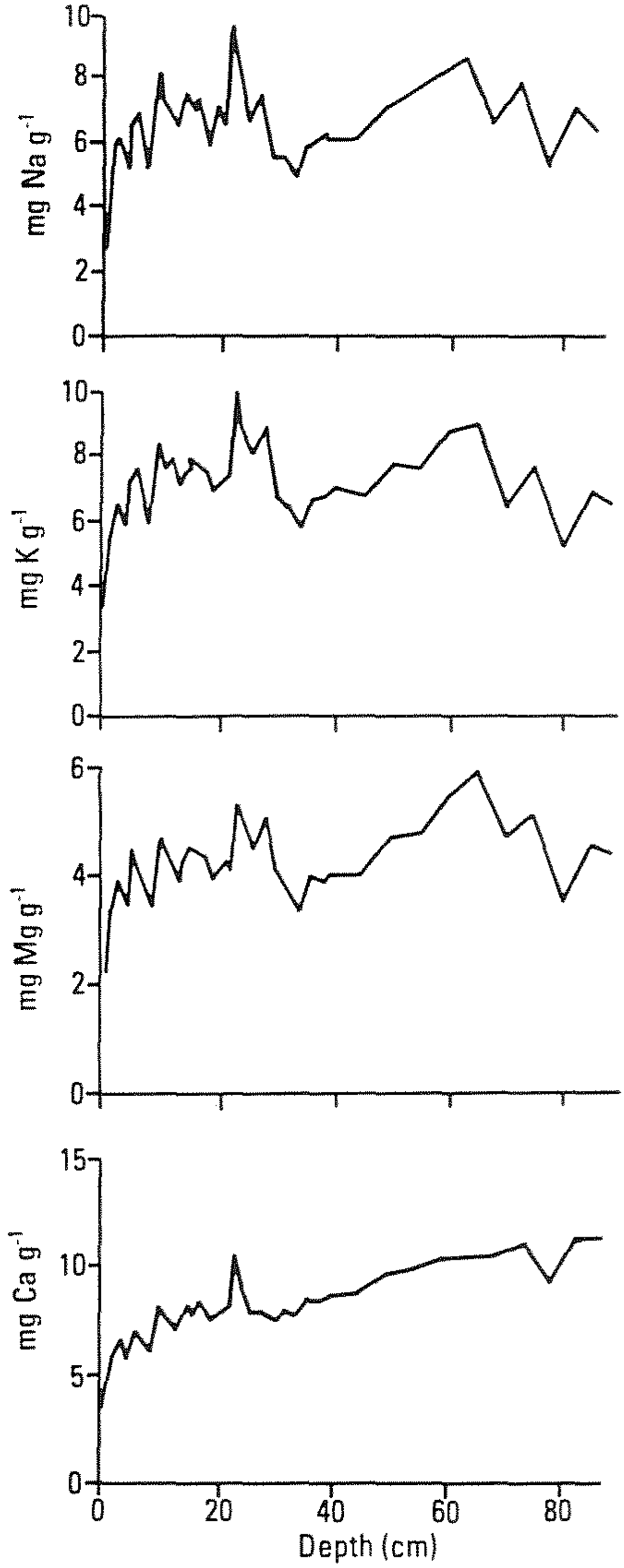


Fig. 8. Variation of sodium, potassium, magnesium and calcium concentrations in the sediments of Loch Laidon.

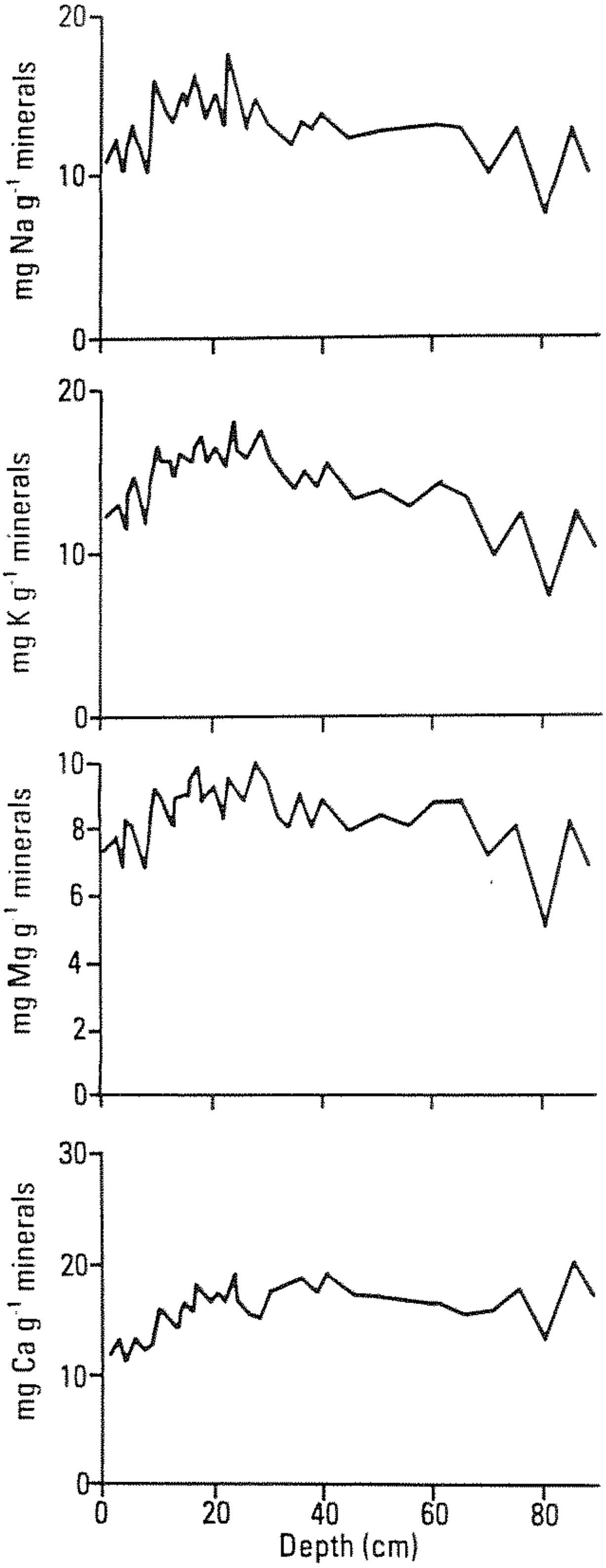


Fig. 9. Variation of sodium, potassium, magnesium and calcium concentrations in the sediments of Loch Laidon, expressed per gramme minerals.

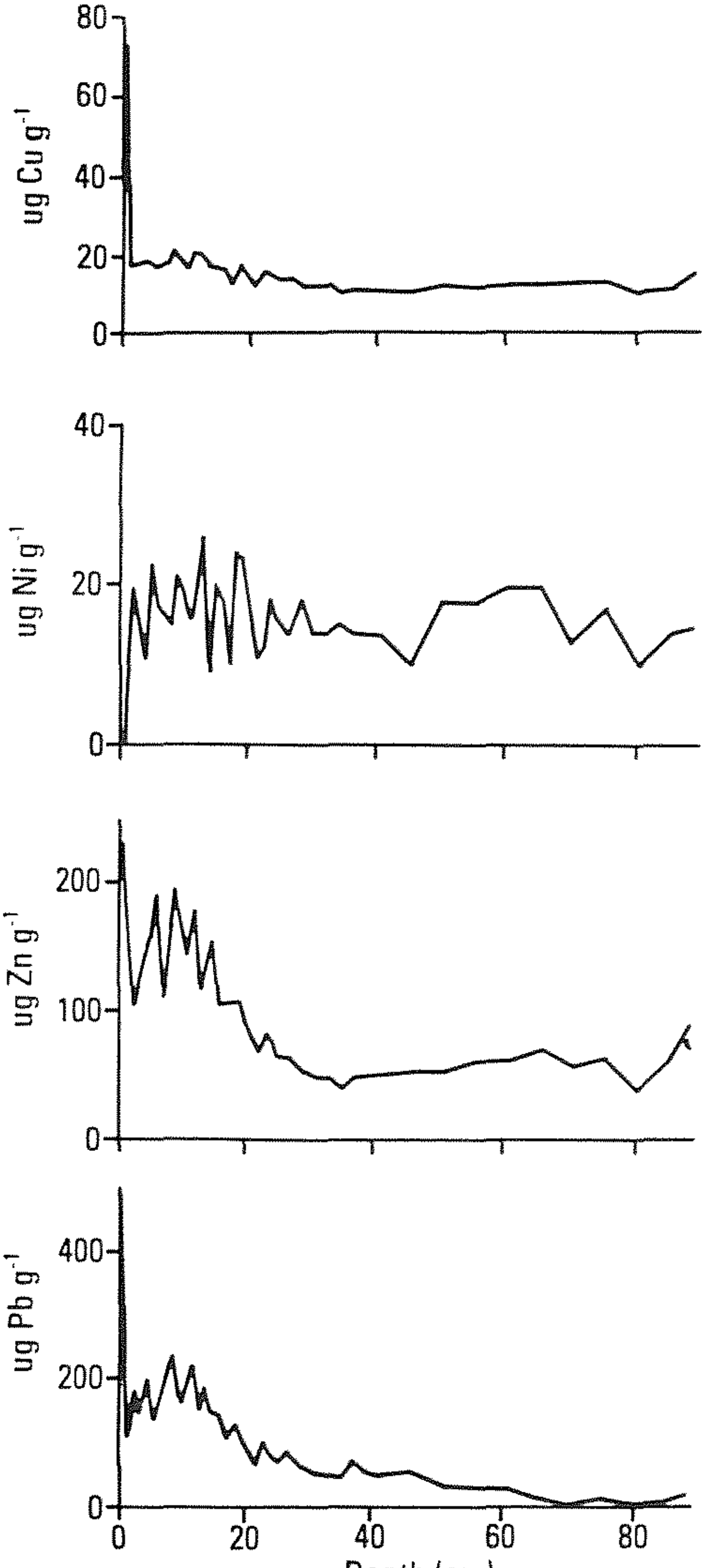


Fig. 10. Variation of zinc, lead, copper and nickel concentrations in the sediments of Loch Laidon.

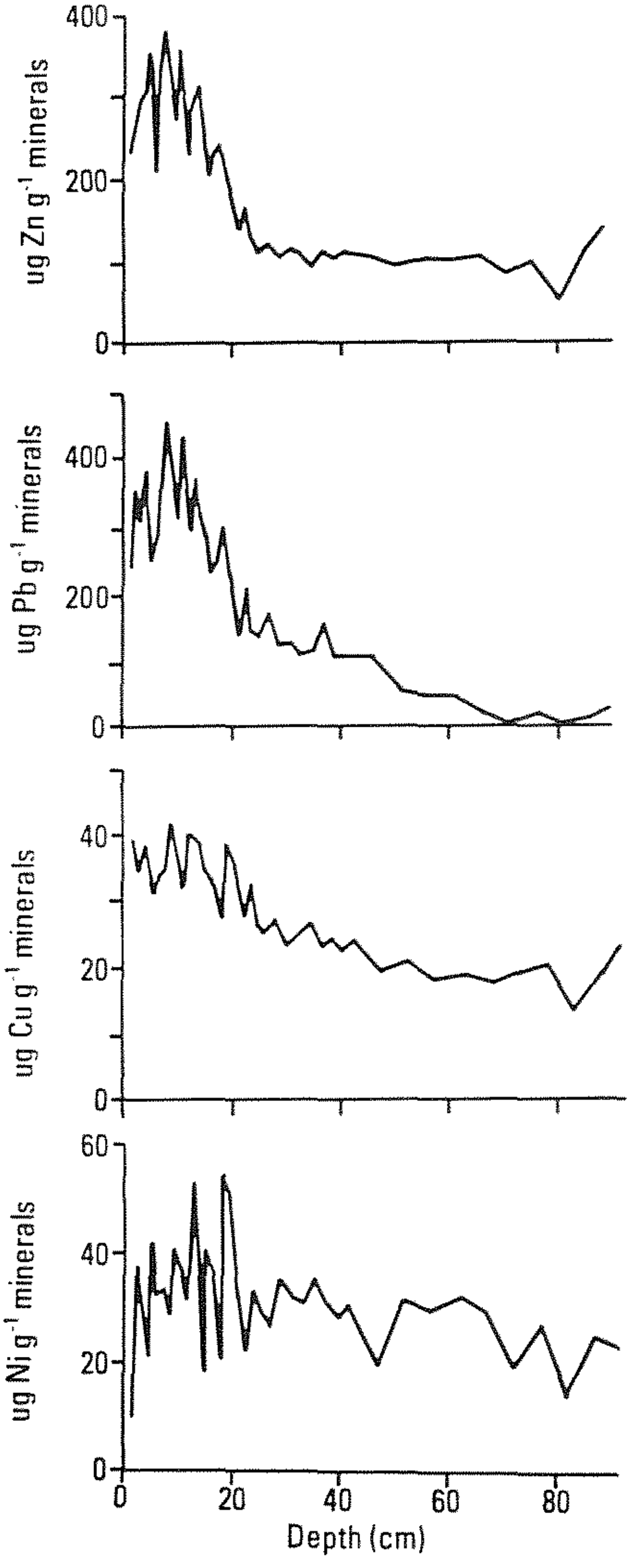


Fig. 11. Variation of zinc, lead, copper and nickel concentrations in the sediments of Loch Laidon, expressed per gramme minerals.

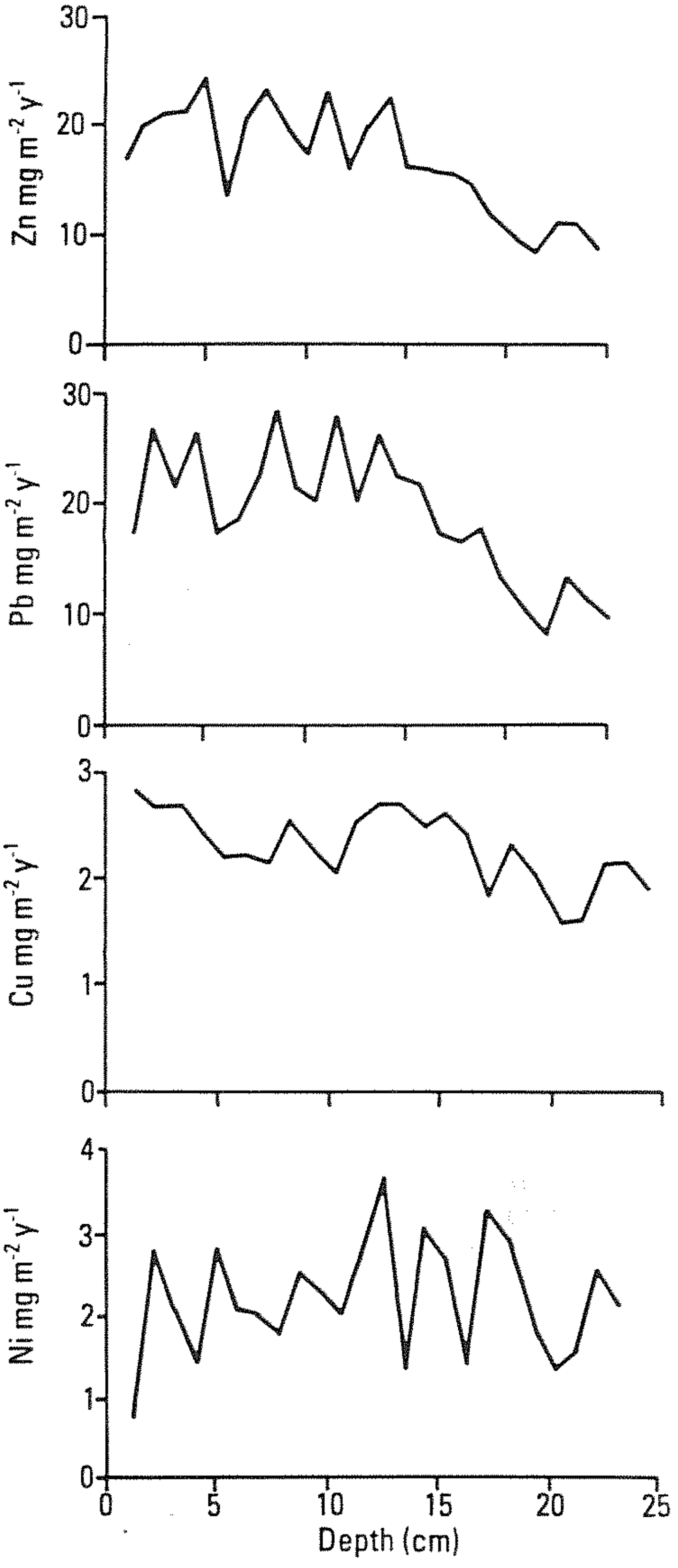


Fig. 12. Variation of zinc, lead, copper and nickel fluxes to the sediments of Loch Laidon.

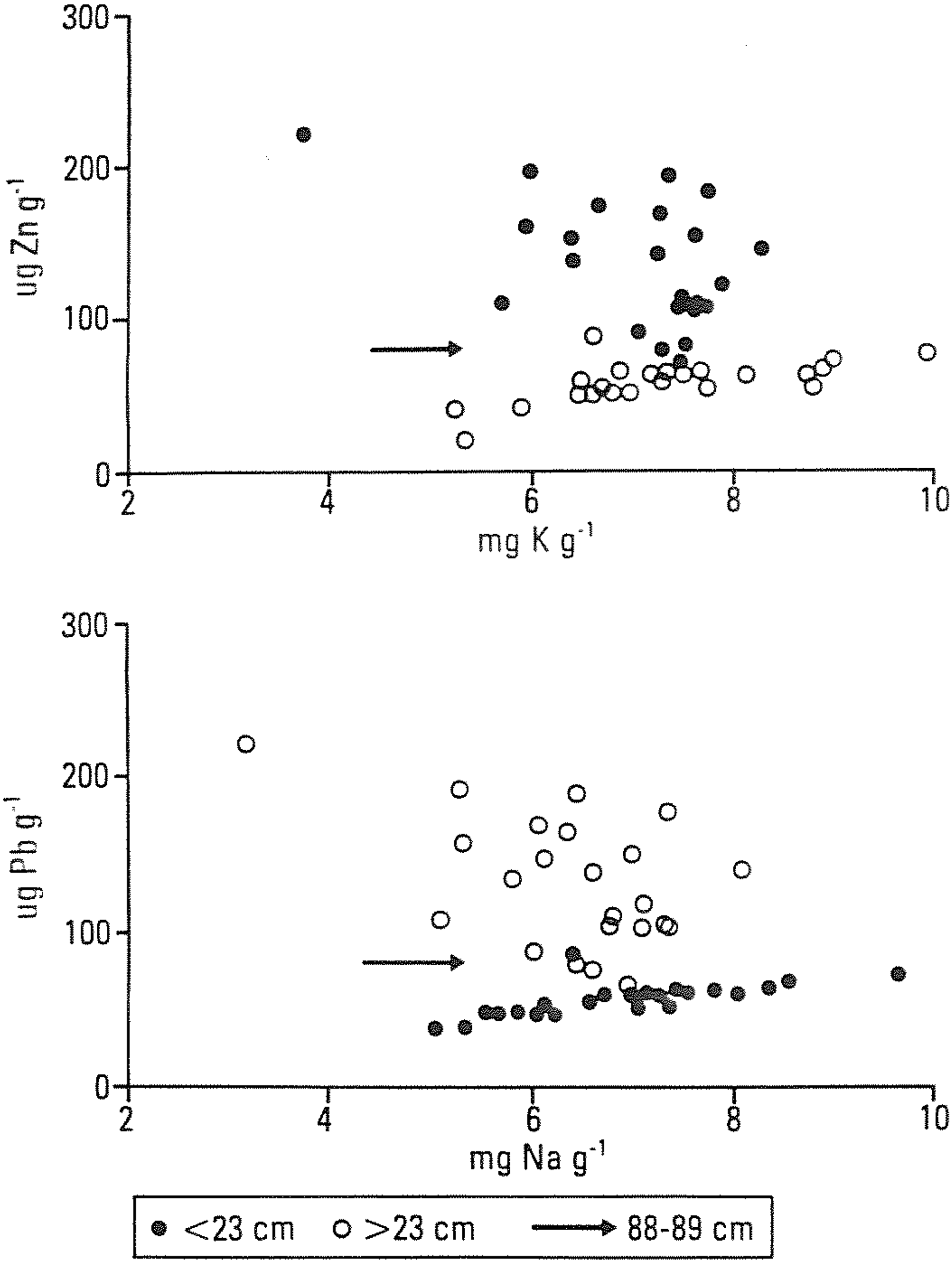


Fig. 13. Relationships between zinc and potassium and lead and sodium in the sediments of Loch Laidon.

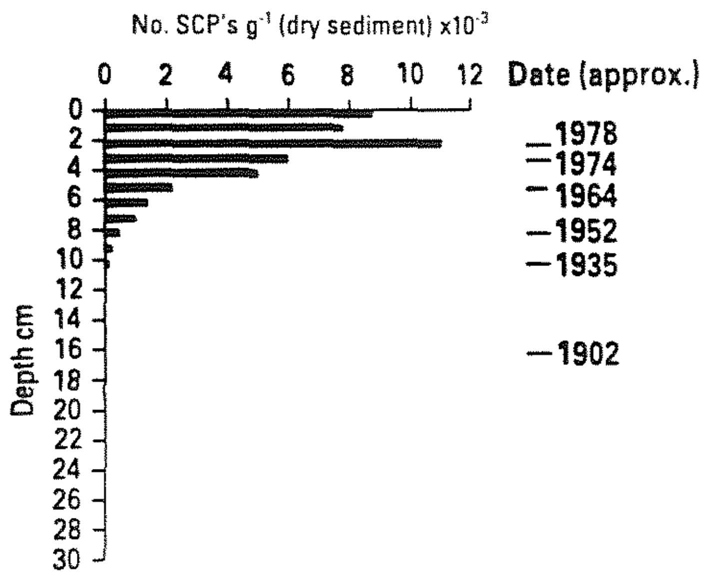
4.1.6 Spherical carbonaceous particles (SCPs)

Sediment samples from core LAI3 were analysed for concentration of SCPs. 25 sub-samples were taken down to 29 cm depth. The results are given in Table 8 and shown graphically in Figure 14. The dating on the SCP diagrams is inferred by cross correlation, on the basis of loss on ignition data, with core LAI1 (see Section 4.1.1).

The concentration of SCPs in the core (Fig. 14) is virtually zero in the sediment below 10 cm depth or prior to c. 1930. In the upper 10 cm or post 1930s section of the core the concentration of these particles increases rapidly, particularly between 4.5 and 2.0 cm depth which corresponds to the 1970s period. At 2.5 - 2.0 cm depth particle concentration achieves a maximum value of 22,000 spherules g^{-1} dry sediment before declining to 16,000 spherules g^{-1} dry sediment in the top sample which represents the early 1980s period.

Table 8 Spherical Carbonaceous Particle analysis for Loch Laidon core LAI3

	No. SCPs	
Depth cm	g^{-1} (dry sediment) * 10^{-3}	g^{-1} (Organic content of dry sediment) * 10^{-3}
0- 0.5	8.84	
1- 1.5	7.84	15.7
2- 2.5	11.06	22.1
3- 3.5	5.94	12.0
4- 4.5	4.96	10.5
5- 5.5	2.16	4.4
6- 6.5	1.42	2.8
7- 7.5	0.97	1.9
8- 8.5	0.49	1.0
9- 9.5	0.24	0.5
10-10.5	0.11	0.2
11-11.5	0.00	0.0
12-12.5	0.00	0.0
13-13.5	0.00	0.0
14-14.5	0.00	0.0
15-15.5	0.00	0.0
16-16.5	0.13	0.3
17-17.5	0.10	0.2
18-18.5	0.00	0.0
19-19.5	0.00	0.0
20-21.0	0.00	0.0
22-23.0	0.00	0.0
28-29.0	0.00	0.0



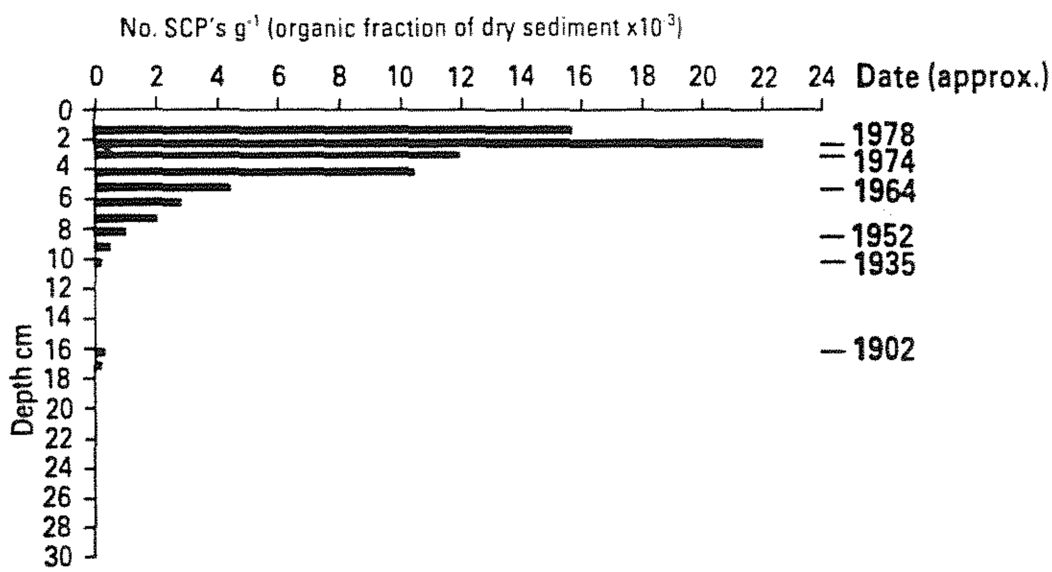


Fig. 14. Carbonaceous particle profiles in the sediments of Loch Laidon (core LAI3).

4.1.7 Pollen

A summary pollen diagram for Loch Laidon is presented in Figure 15. Further pollen information is contained in Appendix 4.

Within the regional pine/birch forest very little change occurs throughout the pollen diagram. A distinct pine expansion, associated with the afforestation of the uplands, is not present. The only indication of present day afforestation is a very small peak in Picea pollen recorded at 8 cm (1947 AD). The local pollen spectra throughout is dominated by Calluna/Sphagnum and Cyperaceae, reflecting blanket peat domination of the catchment.

The only major change within the pollen diagram is an increase in Sphagnum and a decrease in Isoetes spore values between 70-40 cm. This reduction in Isoetes is a common feature of many sites examined in this present study (eg. Fritz et al. 1986, 1987, Patrick et al. 1987b, Stevenson et al. 1987a, b) and generally indicates increased catchment erosion and reduction of Isoetes populations in the loch as a result of decreased transparency. This is confirmed by the LOI data which show a progressive increase, indicative of blanket peat erosion over the 60 - 30 cm depth section.

4.1.8 Magnetic measurements

Sediments from core LAI1 were packed into previously screened styrene sample pots and subjected to the sequence of magnetic measurements outlined in Stevenson et al. 1987c.

All remanences were measured on a Minispin slow-speed spinner fluxgate magnetometer. Susceptibility was not measured as the combination of small sample size and relatively weak magnetisation made the samples unsuitable.

Figure 16 plots the results of these measurements. The right hand graph shows reverse field ratios (IRM_{-n}/SIRM) plotted against a horizontal scale of percentage reverse-saturation. Thus 50 represents the point during DC demagnetisation at which IRM is zero and 100 represents the point at which IRM/SIRM is -1.

The higher SIRM and ARM values coupled with the low SIRM/ARM quotient, especially above 15 cm, confirm that the magnetic record is dominated by catchment derived materials. The changes from 23 cm to the sediment surface could be indicative of shifts in sediment source type, possibly related to disturbance or land use change. Any such shift must have been very small as there is no appreciable change in sediment accumulation rates through this part of the core (Table 6). Similarly, there is no indication of land use or significant management change from documentary sources (See section 4.2)

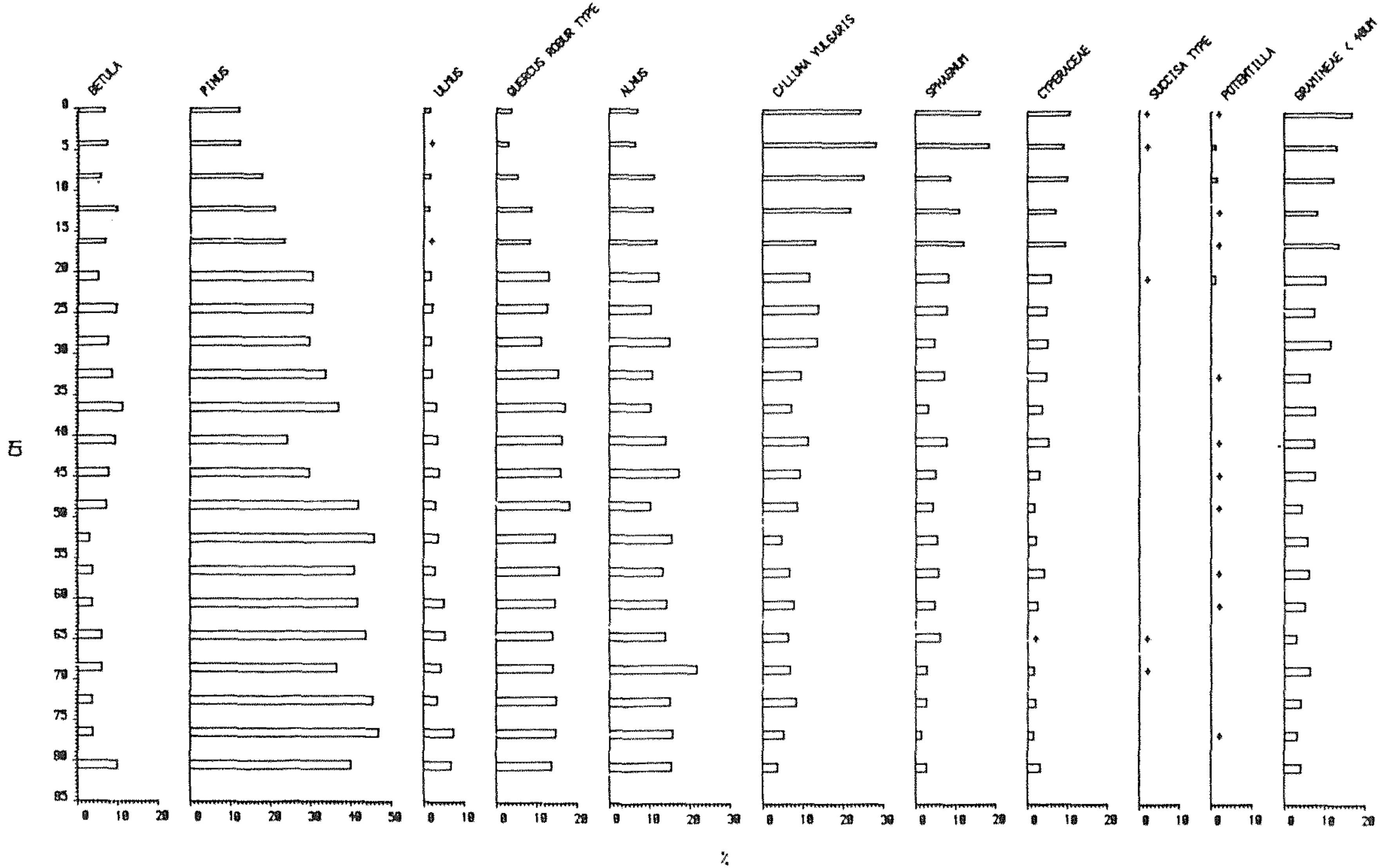


Fig. 15. Summary pollen diagram for Loch Laidon core LAI1. All taxa expressed as a percentage of the Arboreal pollen plus peatland indicators.

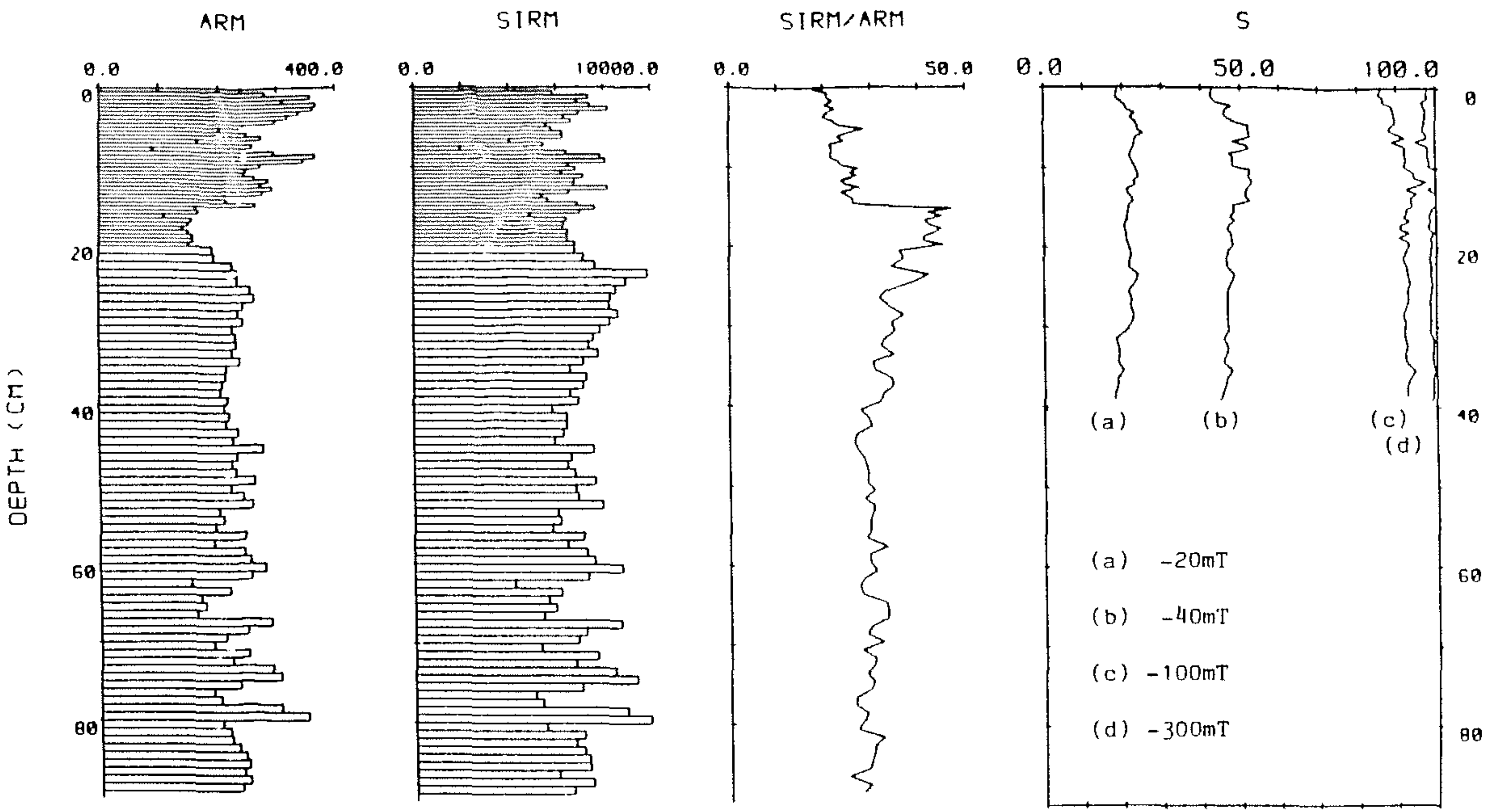


Fig. 16. Magnetic measurements for Loch Laidon core LAI1.

4.2 Land use and management history

4.2.1 Land use

The catchment is characterised by heathland vegetation (see Section 2.2). The birch dominated woodland which characterised the last woodland phase in the catchment had been largely cleared by c. 600 BP (NCC 1978). However, 18th and 19th century plans[1] and 19th century views (Anon. 1844, Anon. 1894) indicate the presence of deciduous woodland along the northern and (more sparsely) the southern shore of Loch Laidon and around Loch Ba. Today such woodland is confined to islands in Loch Laidon, Loch Ba and Lochan na h-Achlaise.

Travellers and writers from Dorothy Wordsworth in the early 19th century (Shairip 1974) onwards (eg. Groome 1901, Stewart 1928, Miles 1930), have described central Rannoch Moor as the most desolate, unimprovable tract of land in Scotland. With the exception of two small coniferous plantations (Fig. 1), there is no evidence on the ground, from cartographic sources [2] or from air photographs [3], to suggest that the wet, exposed and acid peats and soils of the catchment have supported a land use other than rough moorland grazing. Despite the local availability of limestone (MacDonald 1845, Maclean 1845, Vince 1944) and a lime mill and kiln established on the Struan Estate in the mid-18th century (Marshall 1794, Robertson 1799), the only attempt (by the Commissioners of Annexed Estates in the late-18th century) to improve land in the region (50 ha at the head of Loch Rannoch - the 'soldiers trenches'), by liming, draining and burning, yielded poor results and was soon abandoned (MacDonald 1845, Stewart 1928).

The only recorded habitation in the catchment apart from seasonal shealings, has been at 'Ba Cottage' (now deserted) at the far western end, off the old Tyndrum - Fort William military road. This routeway was superseded in 1929 by a new paved trunk road, the A 82, built to the east of the old road and skirting the eastern shore of Lochan na h'Achlaise (Fig. 18).

Of the two coniferous plantations in the catchment, only the block adjacent to the north of Loch Laidon is of a significant size (c. 300 ha). This area of sitka spruce (*Picea sitchensis*)

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[1] Scottish Record Office, West Register House plans:
RHP 772, Plan of the counties of Perth and Clackmannan 1787, surveyed by James Stroble.
RHP 3664, Plan of the counties of Perth and Clackmannan 1783, surveyed by James Stroble.
RHP 13609 Plan of Lorn, Ardgour and Locheil 1801.
RHP 46256 Plan of the county of Argyll engraved for Dr Smith's agricultural survey 1799.

[2] Earliest large scale Ordnance Survey coverage = Six inch first edition, surveyed 1864 (Perthshire), 1870 (Argyllshire).

[3] Scottish Development Department, Air Photographs Unit: Series 541/A/400 1:10,000, flown May 21st 1948. Series OS/59/67 1:24,000, flown June 14th 1959. Series OS/68/267 1:27,000, flown August 8th 1968. Series OS/80/086 1:26,000, flown May 17th 1980.

and lodgepole pine (Pinus contorta) was planted in the early 1960s by the Forestry Commission, but is now privately owned.

It has been suggested (NCC 1978) that peat has been cut for fuel in the catchment. However, there is no evidence for this on the ground.

There has been no exploitation of mineral resources within the catchment.

4.2.2 Land management

The general progression in the grazing history of the Central Highlands involved the replacement of the traditional mixed, semi-feudal, transhumant agriculture by large sheep flocks in the mid-18th century (the 'clearances') (eg. Robson 1794, Smith 1798, Forsyth 1805). As sheep became increasingly less profitable through the 19th century, sheep numbers declined in favour of deer and sporting interests came to the fore (eg. Stewart 1928, Vince 1944). However, this simplified chronology whereby the balanced grazing ecology of cattle (in summer) and native sheep (and goats on the highest land) was replaced by a monoculture of superior breeds of sheep and later sheep and deer, does not hold true over much of the Loch Laidon catchment. Most of the western and southern sections of the catchment lay on the Breadalbane Estate and comprised low-intensity deer forest well before the 1750s. Sheep were introduced to this area in the late-18th century, but by the 1820s sheep numbers were massively reduced in favour of a reversion to deer forest (McLeod 1892).

Only in the area to the north and far north-east of the catchment (the 'Cruach' region of the old Struan - Robertson Estate) is there evidence of old sheilings, which subsequently in the 18th century became shepherds retreats as sheep replaced cattle. Deer were introduced in significant numbers to this area in the late 19th century and the land managed primarily for deer stalking and grouse shooting. Figure 17 indicates the broad decline in sheep numbers in Fortingal Parish, within which this area of the Laidon catchment lies. These data are not catchment-specific (sheep have been excluded from most of the north-eastern section of the catchment since the mid-1950s - see below [4]) and can serve only to illustrate the local trend.

With the exception of recent developments to the north of Loch Laidon, management in the catchment has been confined to burning the moorland vegetation primarily for the benefit of grouse. Some areas were burnt as frequently as every four years until the 1930s (M. Pearson p. comm.) and heather fires were common on the moor through the 1940s (Ratcliffe-Barnet 1946). In recent years the frequency of burning has declined owing to the expense of game keeping, poor grouse returns and NCC policy.

The south-east section of the catchment was declared a NNR in

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[4] It is unlikely that stocking levels have been high enough to warrant the NCC's assertion (1978) that enhanced peat erosion in the catchment may have resulted from over-grazing in the catchment.

1958 and extended to the area shown in Figure 1 in 1969. More recently much of the remainder of the catchment was designated a SSSI (Fig. 1) NCC policy (NCC 1978) is to minimise anthropogenic interference with the area, thus grazing intensity is strictly controlled and burning rarely sanctioned.

Sheep have been excluded from the north-east section of the catchment in favour of deer since 1953. A deer fence was erected around the area of mixed conifers adjacent to the loch. In an attempt to improve the habitat for grouse, by drawing deer away from the more intensively grazed parts of this area, some 30 ha were limed and reseeded with rye grass and clover in 1972. In the summer of 1984 cattle were introduced to the area and a fertiliser mix of trace elements, phosphate and potash applied to an area of some 260 ha. In September 1986 over 2,000 ha were fertilised from the air in 12 m wide strips at 1.25 tonnes ha^{-1} (M. Pearson p. comm.).

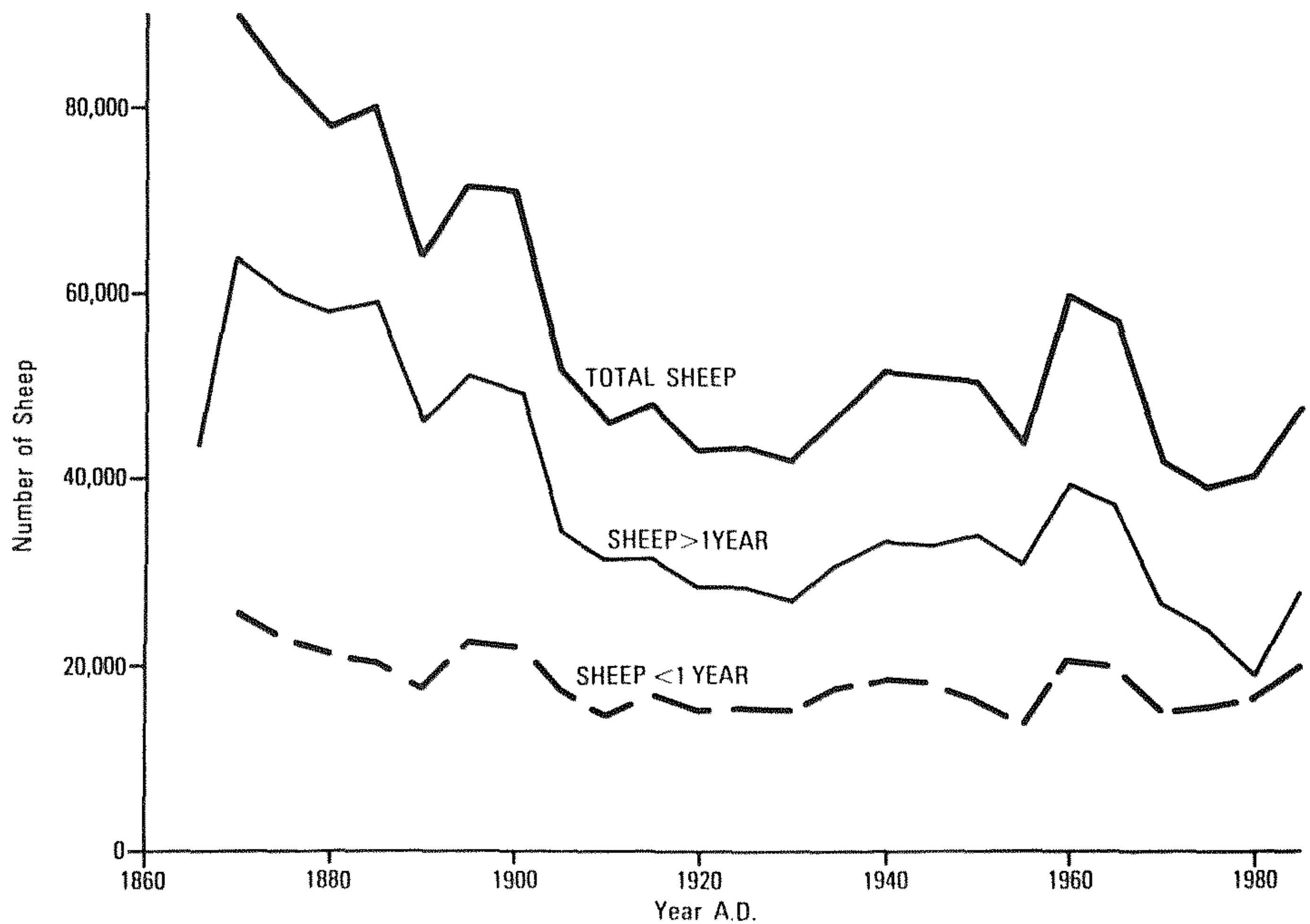

Fig. 17. Variation in sheep numbers in the parish of Fortingal 1866-1985. (Source = Annual Agricultural Census returns).

5.0 Discussion

The planktonic diatom decline, particularly the fall in the frequency of Cyclotella taxa (Charles 1985, Flower et al. 1987) and subsequent frequency increases of acidophilous benthic diatoms in the Loch Laidon sediments offer strong evidence that the water acidity of the loch has increased in the past 130 years. The phytoplankton of the loch was sampled in July 1946 by Lind (1950) and the absence of Cyclotella taxa on that occasion supports the sedimentary evidence.

The pH reconstructions applied to the Loch Laidon surface sediment diatom assemblage, produce inferred pH values of between 5.3 and 5.5 (Fig. 7) and compare well with the geometric mean measured pH for the loch water of 5.41. The longer term pH history shows a gradual and sustained decline beginning in the mid-19th century and is similar to that calculated for Loch Dee, a moderately acidified loch in Galloway, south-west Scotland (Flower et al. 1987). The magnitude of the pH decline in Loch Laidon is typical of an impacted site where the catchment possesses some acid neutralising capacity but insufficient to prevent loch acidification.

It has previously been established that acid deposition is the most probable cause of loch acidification in south-west Scotland (Battarbee 1984, Battarbee et al. 1985, Flower et al. 1987, Harriman et al. 1987). The timing of pH decline in Loch Laidon is compatible with this hypothesis and the carbonaceous particle record is direct evidence for the impact of atmospheric pollution. Similarly, the trace metals lead and zinc are well documented contaminants in precipitation (Galloway et al. 1982) and their elevated concentration in recent (post 1850 AD) Loch Laidon sediment, which coincides with increasing water acidity, is further evidence of pollution from atmospheric sources.

Although the pH of Loch Laidon has decreased by the relatively small amount of 0.5 pH units, the change is of considerable relevance to the loch biota since it occurs in the range over which alkalinity is lost. This range, defined as a pH shift from 5.7-6.0 to 5.0-5.3 (Sutcliffe and Carrick 1986), marks the distributional limits of many freshwater invertebrates (Macan and Worthington 1951, Sutcliffe and Carrick 1986). Effects of acidification on other biota in Loch Laidon are unknown, but studies elsewhere indicate the probability that other algae (eg. Lazarek 1982, Smol et al. 1984), aquatic macrophytes (eg. Roelofs 1983) and fish (eg. Schofield 1976, Harriman et al. 1987) are adverely affected.

When the Rannoch Moor NNR and SSSI were established the undisturbed nature of the area was a key aspect and the peatland and aquatic communities therein were considered to be stable and relatively unaffected by anthropogenic influences (Ratcliffe 1977, Smith 1984). However, diatom analysis has shown that major floristic change has developed within the loch ecosystem and that acidification has occurred over the past 130 years, almost certainly as a result of pollution from acid deposition. Since NNRs and SSSIs receive statutory protection (eg. Nature Conservancy Council Act 1973, Wildlife and Countryside Act 1981), ecological change of this extente raises important questions concerning the control of atmospheric pollution.

6.0 Conclusions

1) The rate of sediment accumulation in the Loch Laidon core calculated from unsupported ^{210}Pb concentrations is fairly uniform in terms of dry weight of sediment (0.013 g cm^{-2} y^{-1} since c. 1840) indicating an absence of major physical disturbance in the catchment.

2) Diatom analysis of the core shows a marked decline in forms characteristic of circumneutral water, with planktonic *Cyclotella kutzingiana* decreasing in the late 19th century and *Anomoeoneis vitrea* decreasing in the 1940s. These taxa have been replaced by acidophilous taxa including *Eunotia veneris* and *Tabellaria flocculosa*.

3) Contamination of the sediment by the trace metals lead and zinc from atmospheric sources began in c. 1850, but carbonaceous particles ('soot') are not recorded in the sediment until about 80 years later.

4) pH reconstructions for the loch based on the sedimentary diatoms indicate that water acidity has decreased by about 0.5 pH units since the mid-19th century, from c. 5.8 (1855) to c. 5.3 (1985).

5) Pollen analysis of the sediment core reveals no major vegetation change within the catchment, except for a pre-1700 reduction in the *Isoetes* population within the loch resulting from increased peat erosion.

6) There is no evidence of significant catchment-wide changes in land use or land management in the last c. 200 years. Localised afforestation and experimental management for deer grazing are not considered to have been important.

7) Although acidification of Loch Laidon is only moderate the results show that this environmentally important loch, part of which is a National Nature Reserve, has been affected by atmospheric pollution for well over a century.

Acknowledgements

This research was funded by the Department of the Environment (grant no. PECD 7/7/139). Assistance with fieldwork was provided by Stuart Phethean. Annette Kreiser supervised the extrusion and initial preparation of sediment cores. Water analyses were performed by Dr R. Harriman of the DAFS Laboratory, Pitlochry. Much local information was provided by Rosalind Smith of the NCC, Perth and by Mr M. Pearson of Rutland Gate, London SW7. Diagrams were drawn by Lauren McClue and reproduced by Chris Cromarty.

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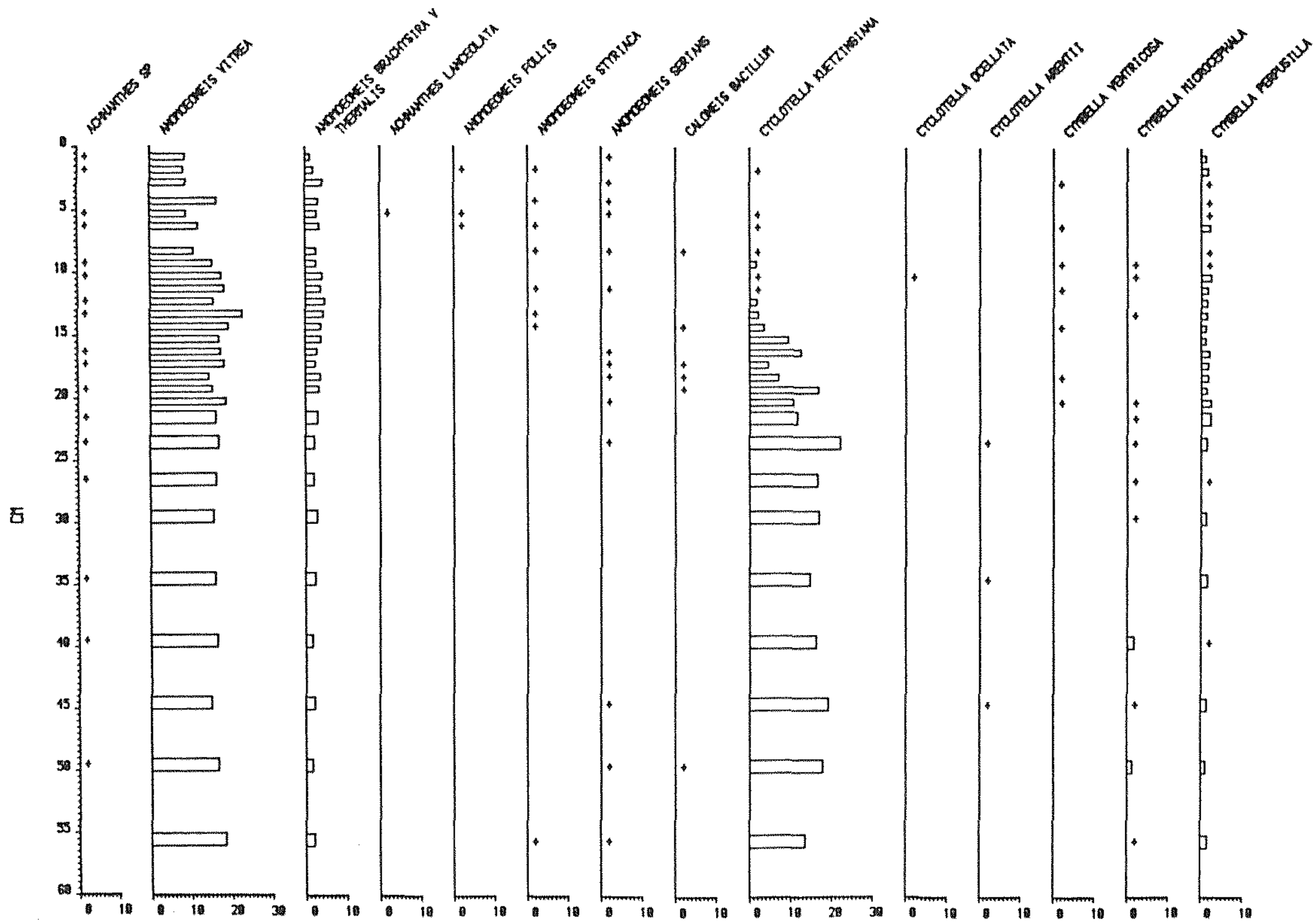
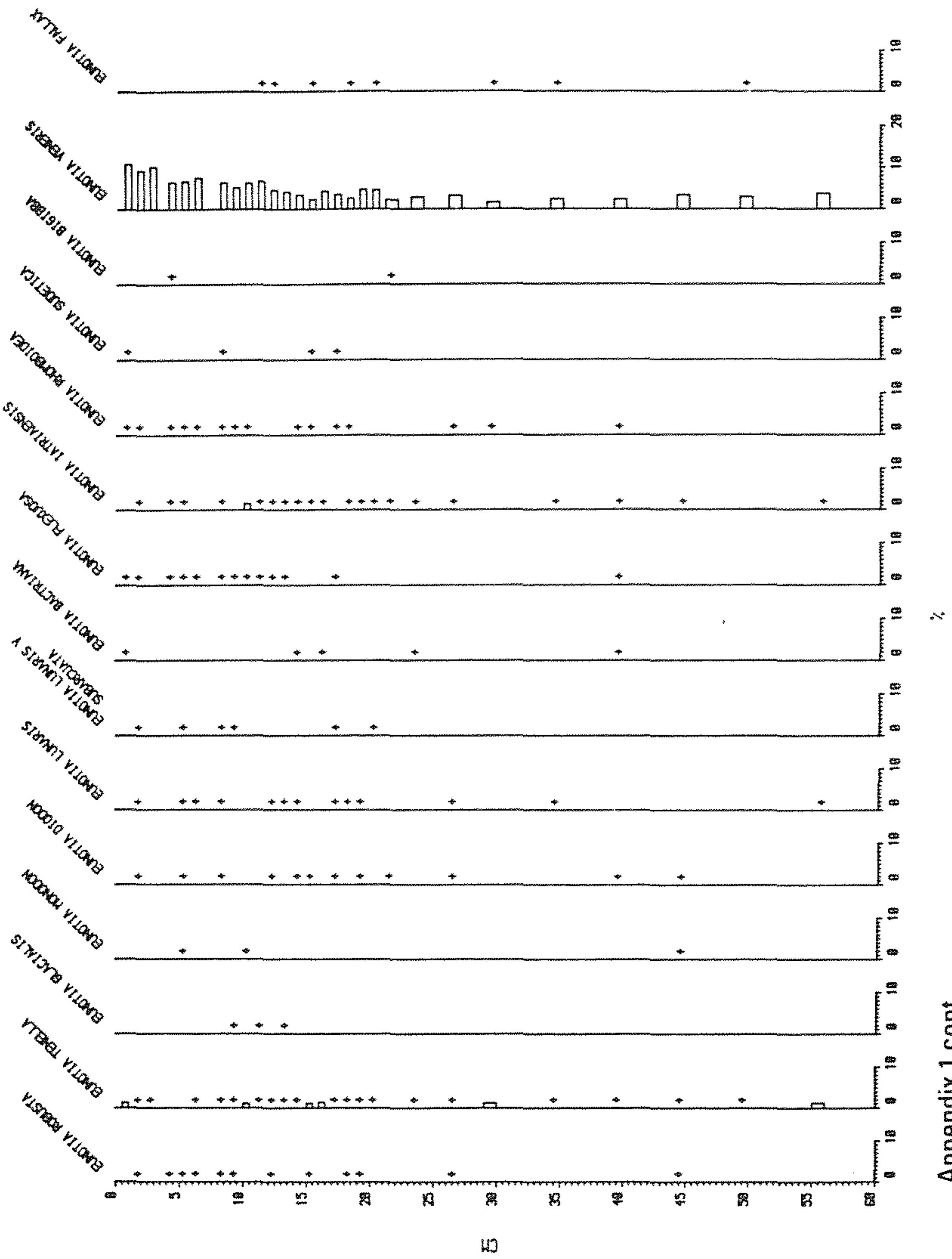


Appendix 1. Loch Laidon: full diatom diagram.



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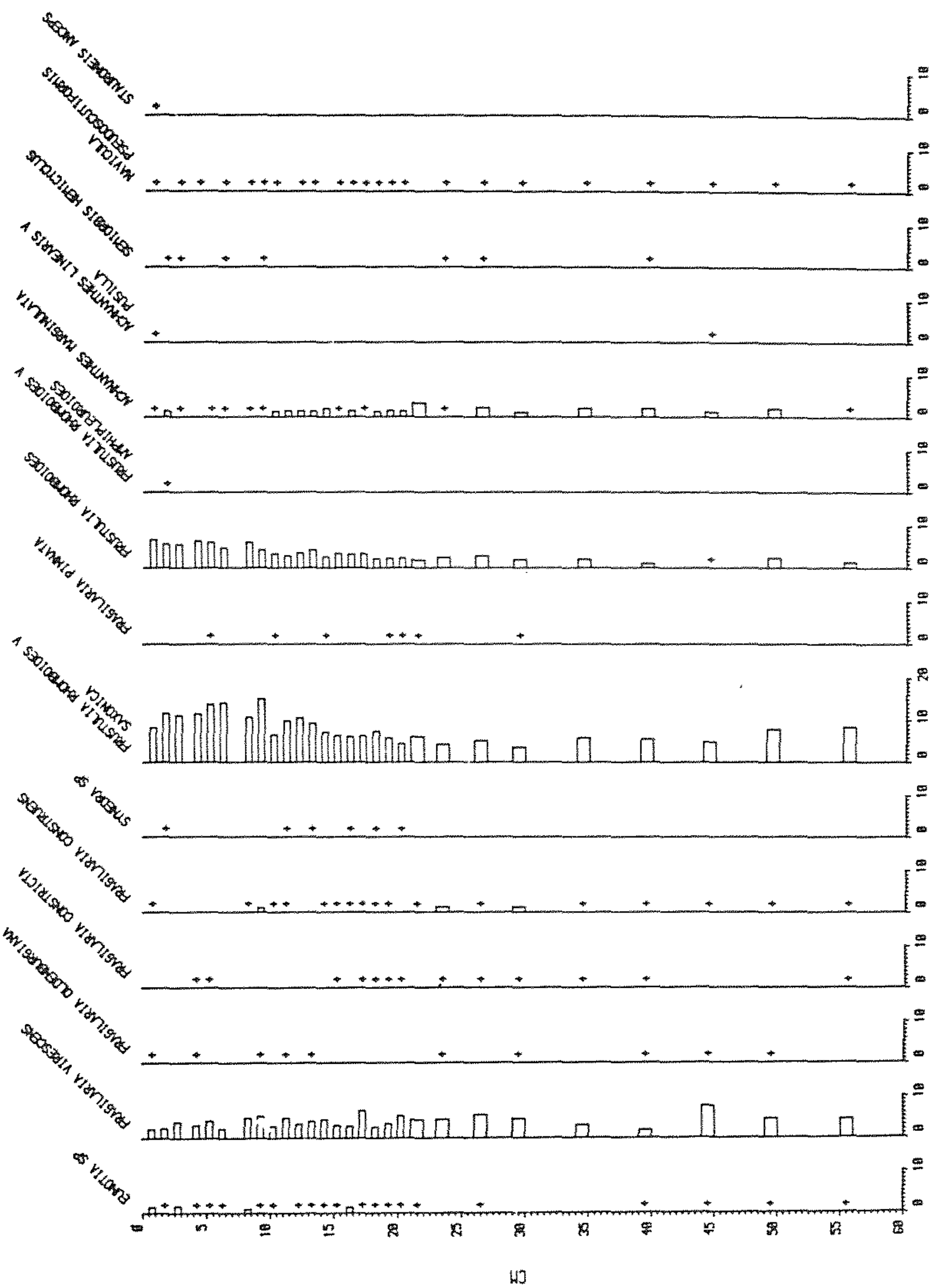

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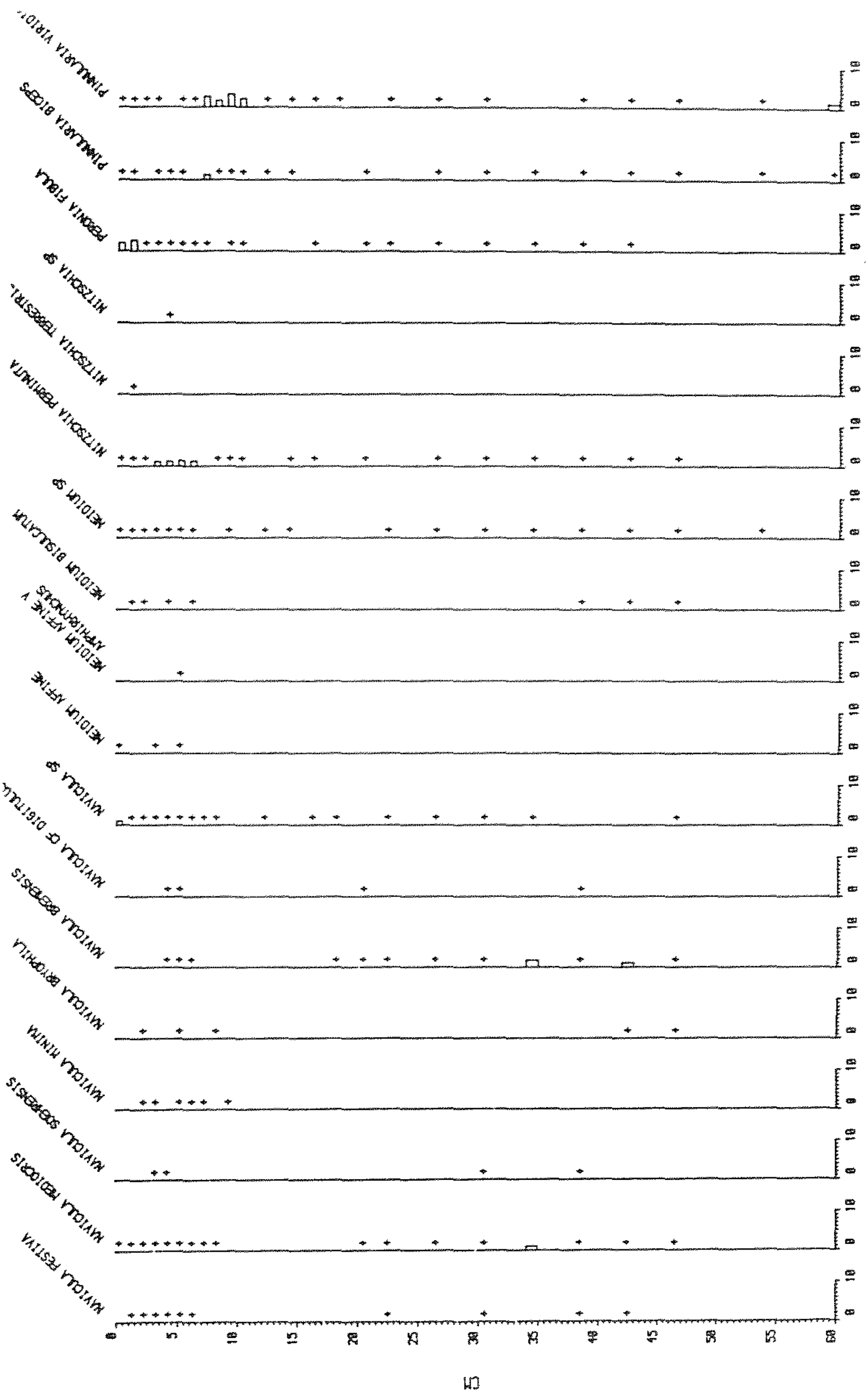

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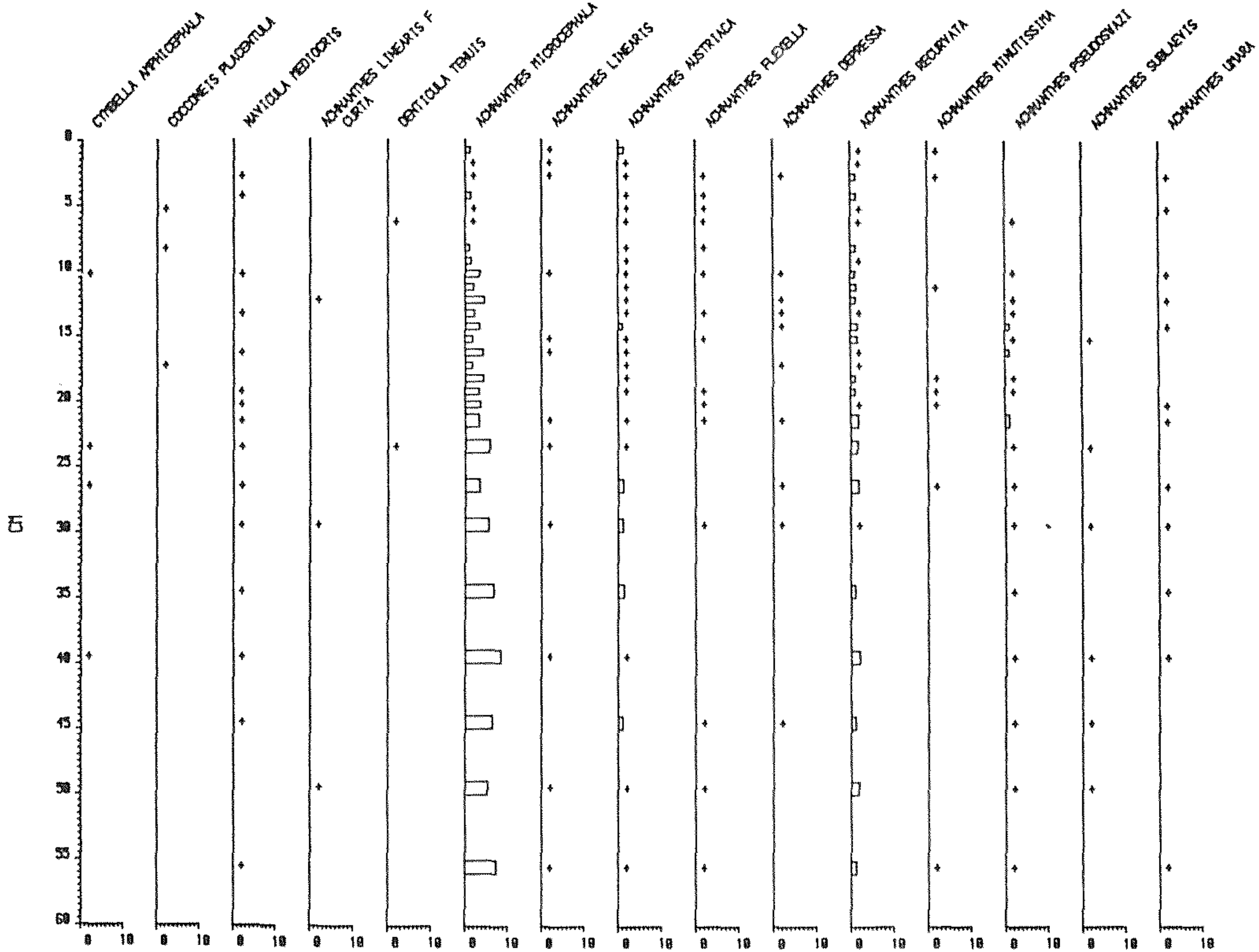

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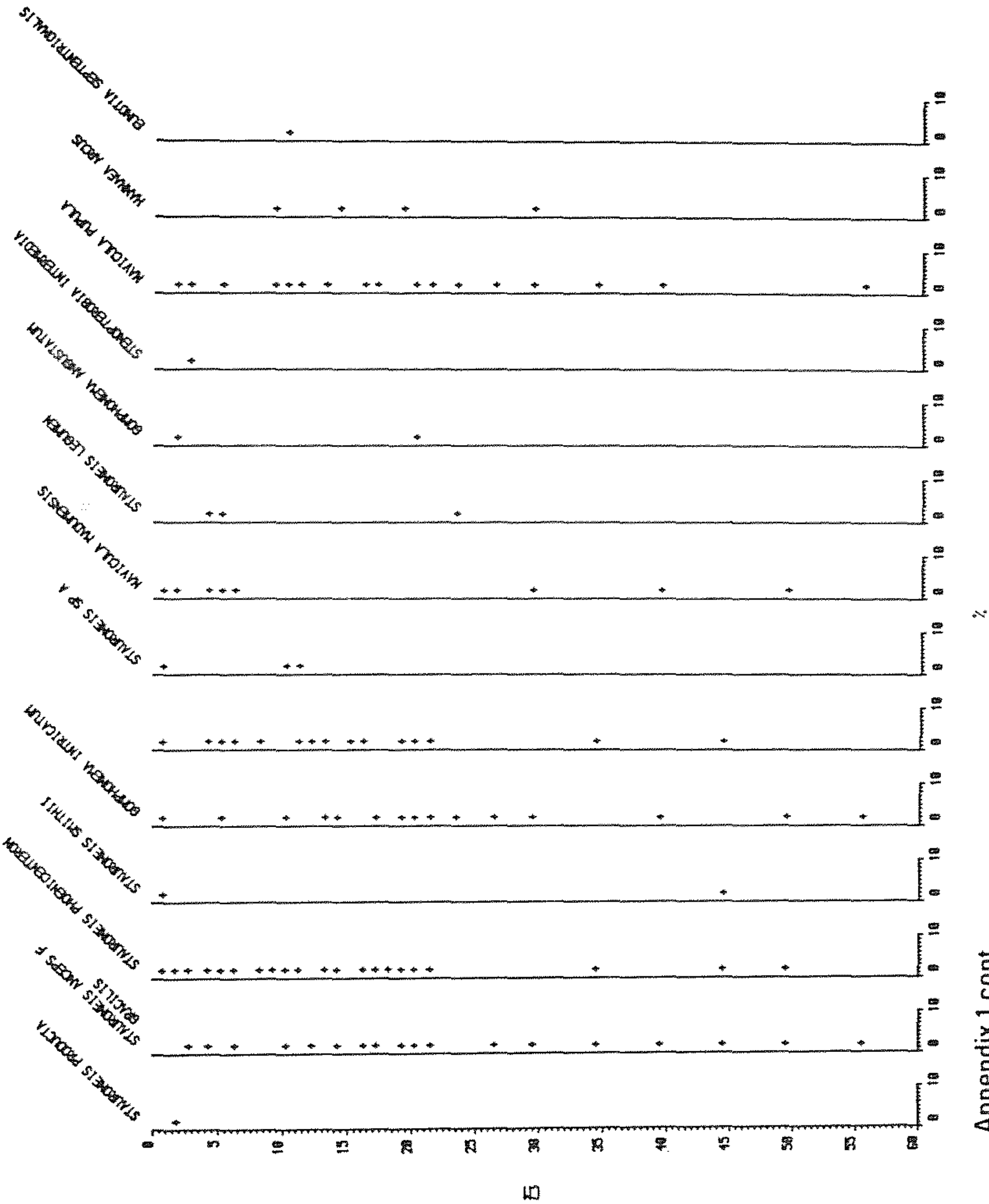

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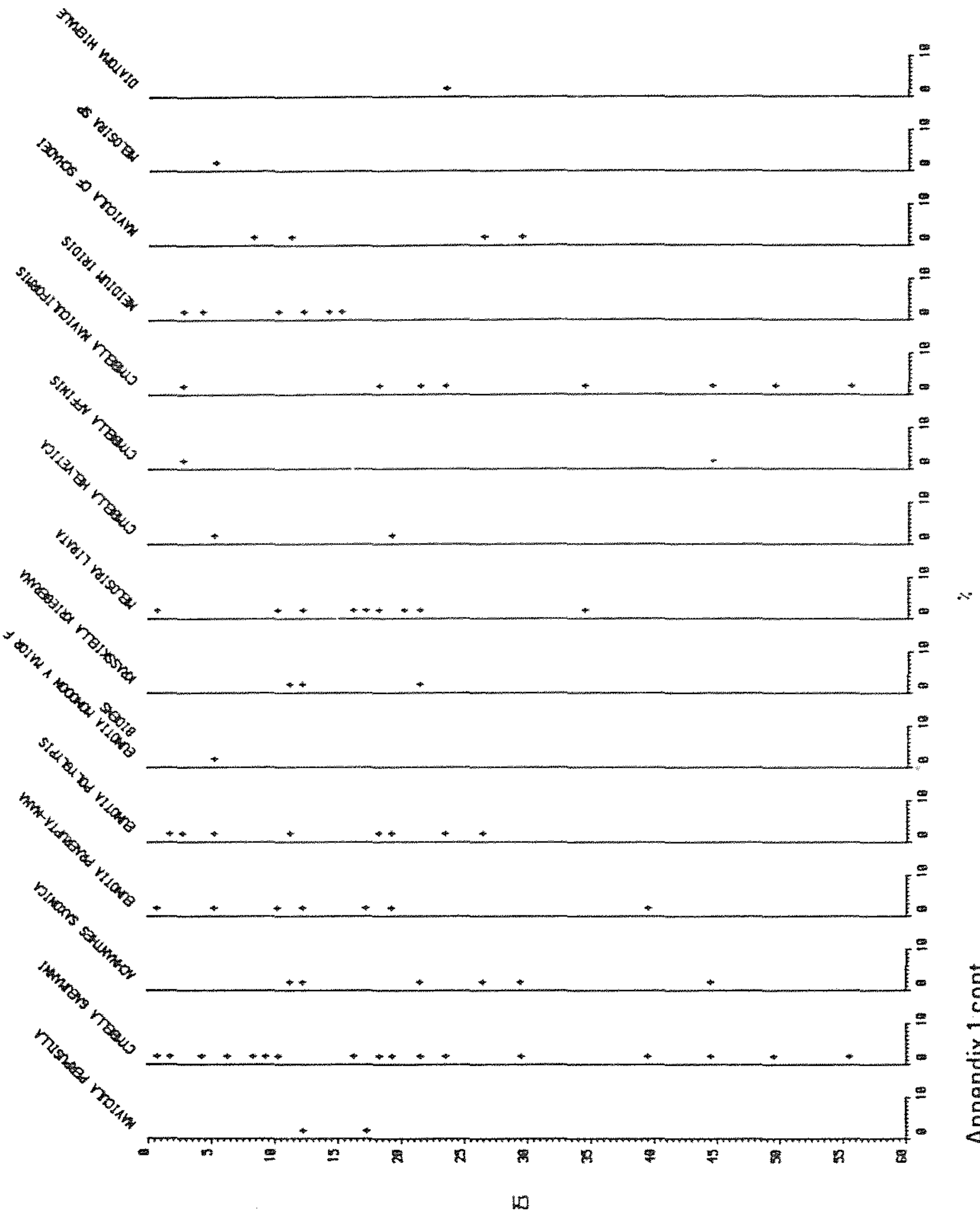

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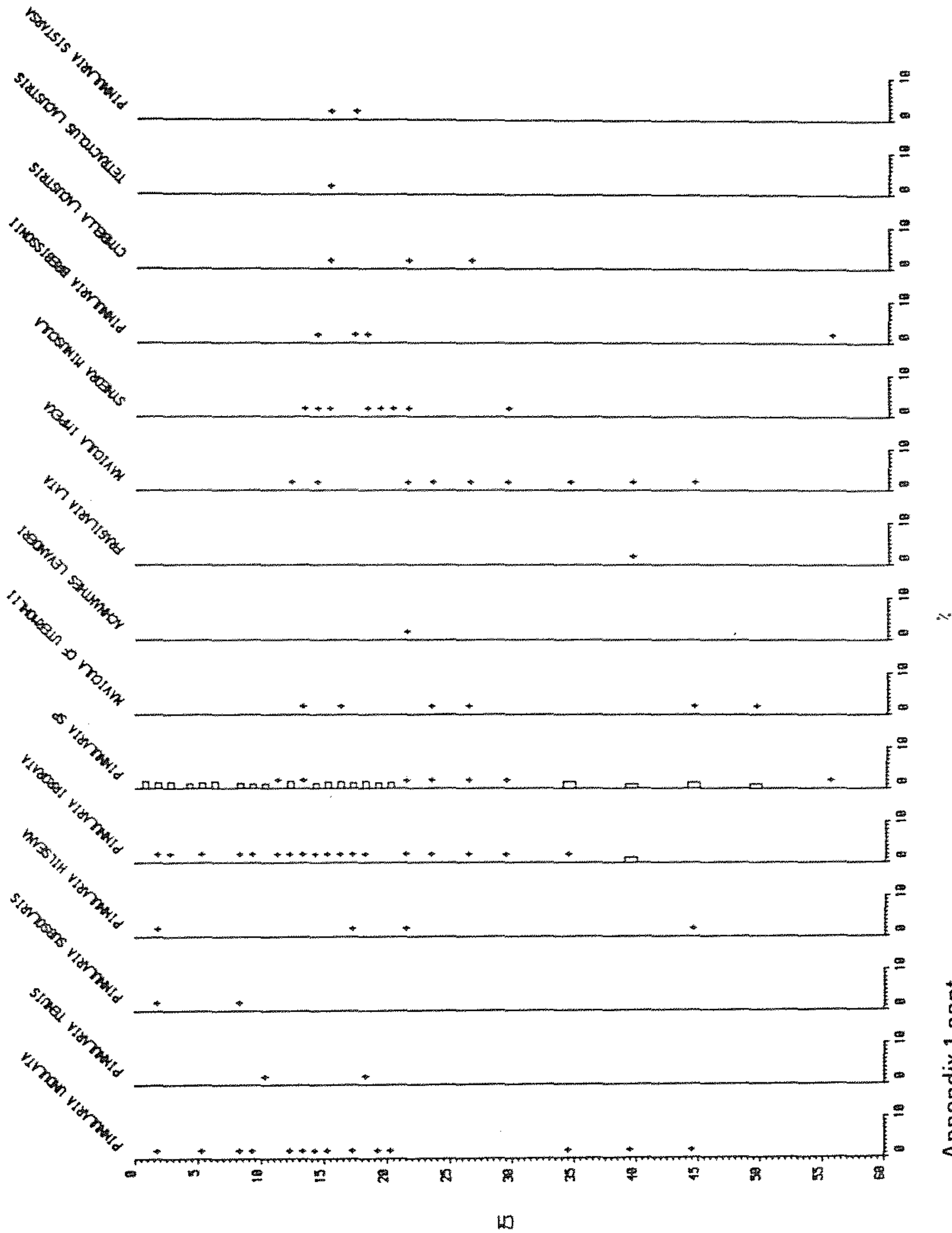

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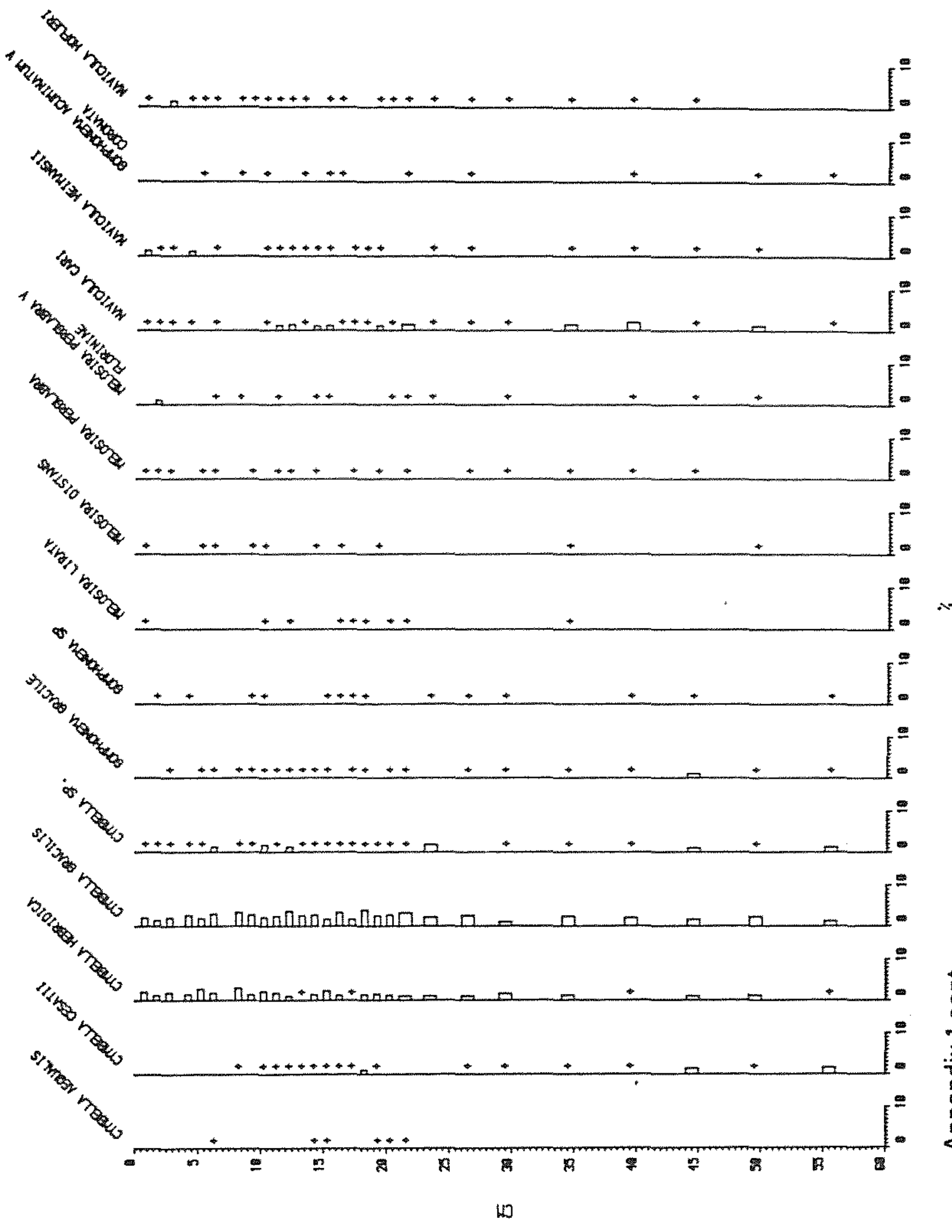

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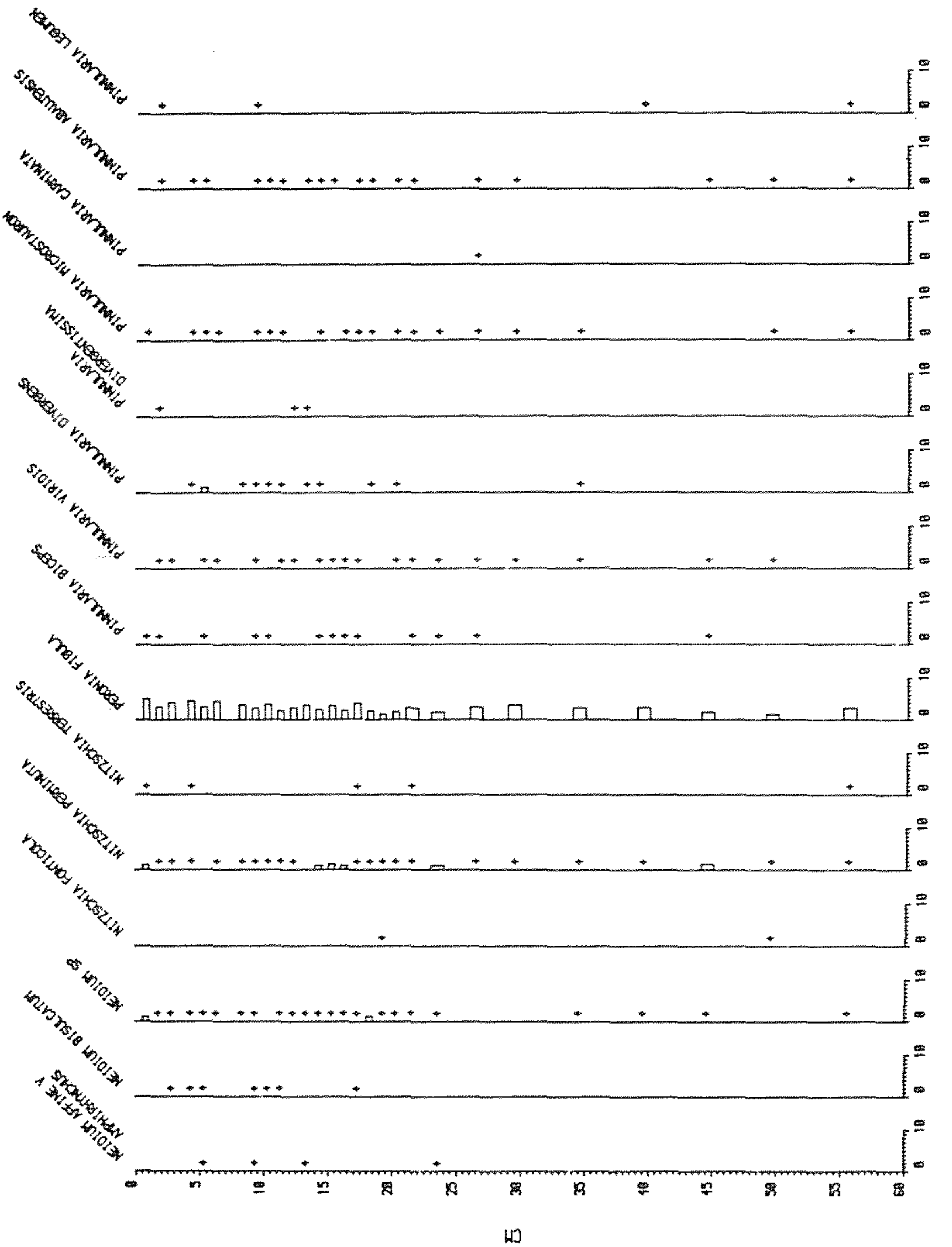

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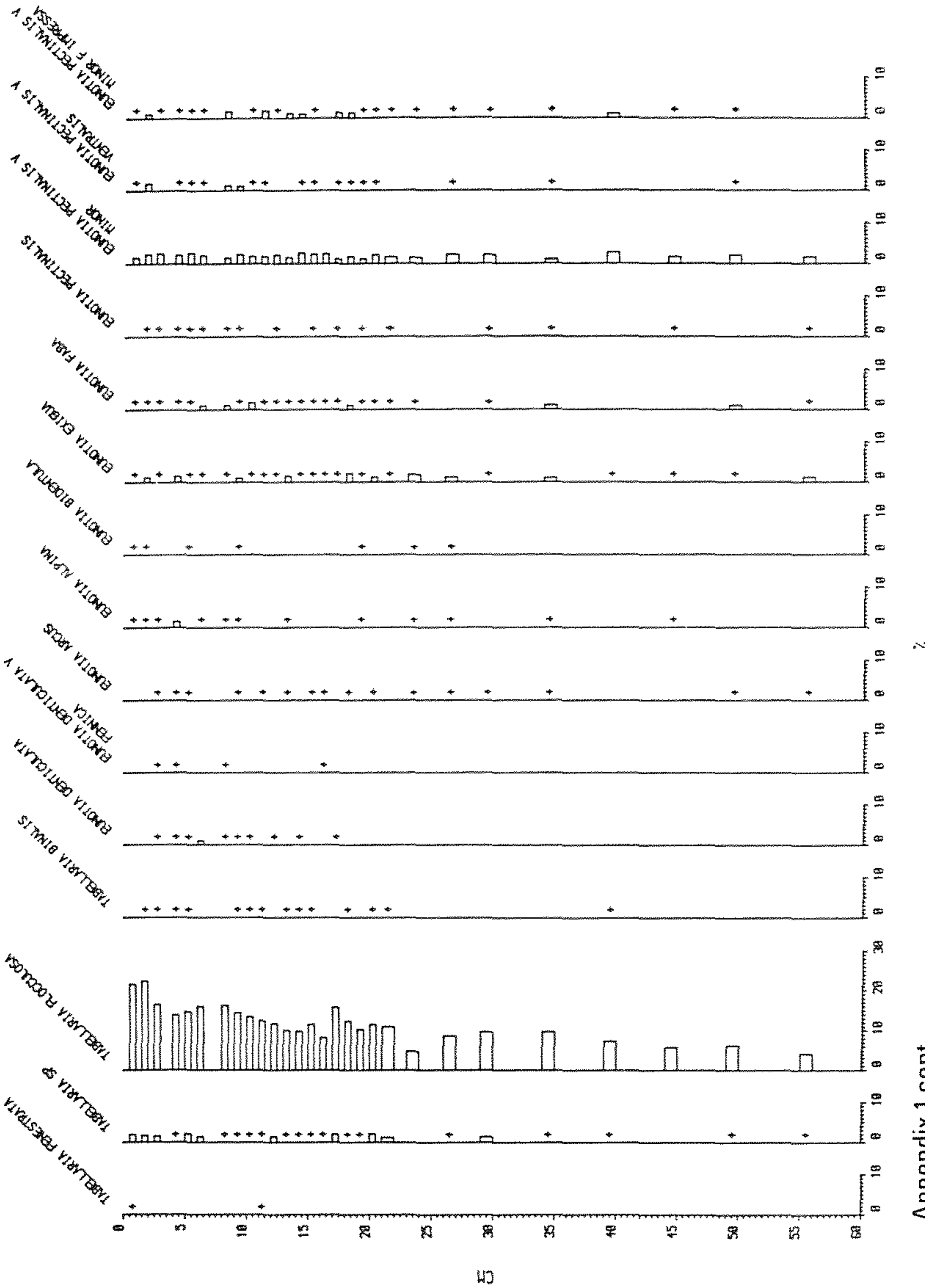

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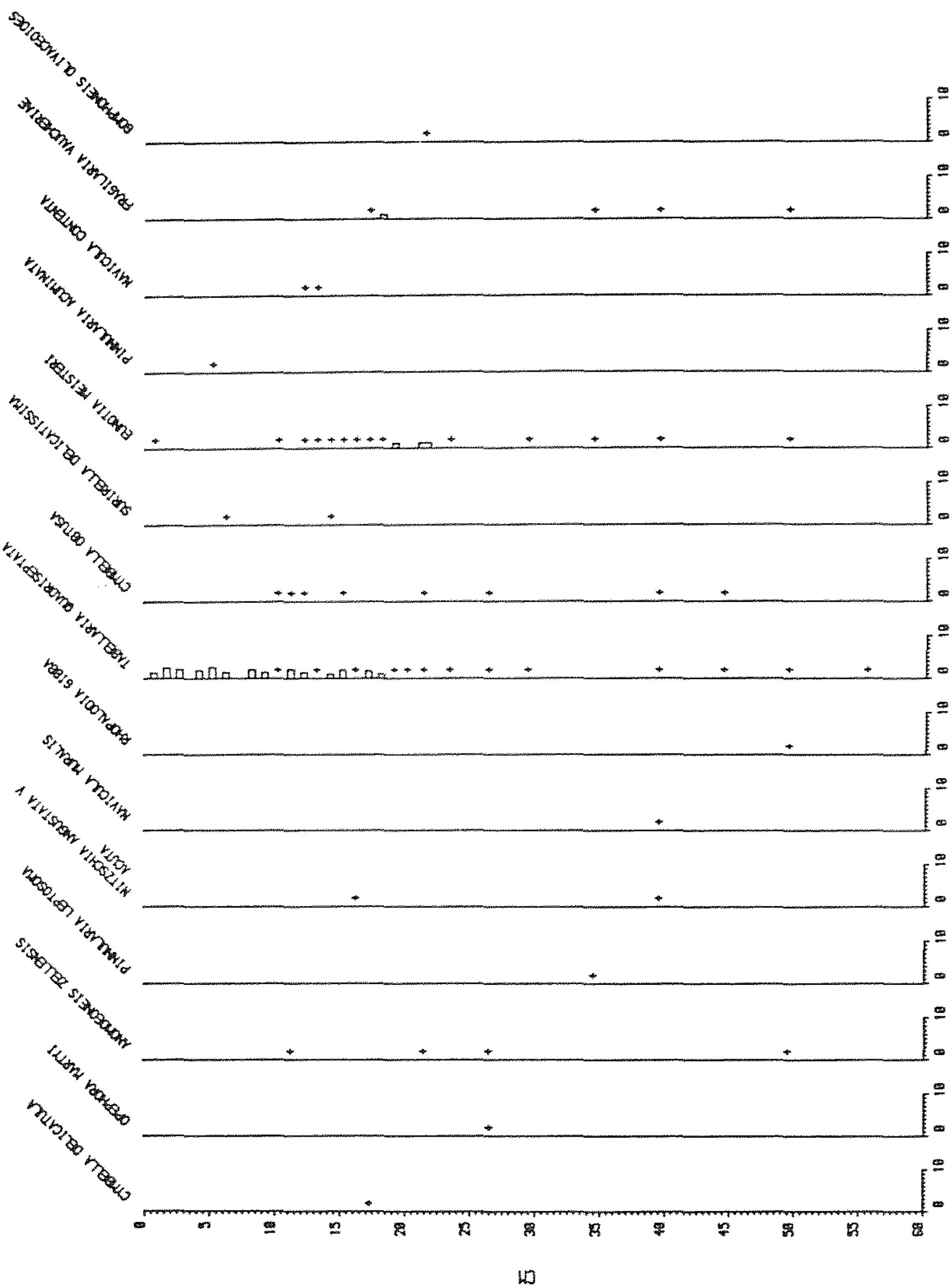


Appendix 1 cont.

Appendix 2. Loch Laidon: diatom species list.

AC001A	ACHNANTHES LANCEOLATA	BREB.
AC002A	ACHNANTHES LINEARIS	W. SMITH
AC002B	ACHNANTHES LINEARIS F CURTA	H.L. SMITH
AC002C	ACHNANTHES LINEARIS V PUSILLA	GRUN.
AC003A	ACHNANTHES MICROCEPHALA	KUTZ.
AC004A	ACHNANTHES PSEUDOSWAZI	CARTER
AC009A	ACHNANTHES RECURVATA	HUST.
AC013A	ACHNANTHES MINUTISSIMA	KUTZ.
AC014A	ACHNANTHES AUSTRIACA	HUST.
AC014B	ACHNANTHES AUSTRIACA V MINOR	L.GRANNOCH (RJF)
AC022A	ACHNANTHES MARGINULATA	GRUN.
AC024A	ACHNANTHES DEPRESSA	(CLEVE) HUST.
AC025A	ACHNANTHES FLEXELLA	(KUTZ.) GRUN
AC028A	ACHNANTHES SAXONICA	KRASSKE
AC029A	ACHNANTHES SUBLAEVIS	HUST.
AC030A	ACHNANTHES UMARA	CARTER
AC044A	ACHNANTHES LEVANDERI	
AC9999	ACHNANTHES SP	
AN002A	ANOMOEONEIS FOLLIS	(EHR.) CLEVE
AN003A	ANOMOEONEIS SERIANS	(BREB.) CLEVE
AN004A	ANOMOEONEIS VITREA	(GRUN.) ROSS
AN006A	ANOMOEONEIS STYRIACA	(GRUN.) HUST.
AN007A	ANOMOEONEIS ZELLENSIS	(GRUN.) CLEVE
AN008A	ANOMOEONEIS BRACHYSIRA	(BREB.) GRUN.
AN008B	ANOMOEONEIS BRACHYSIRA V THERMALIS	NOV. COMB.
CA002A	CALONEIS BACILLUM	(GRUN.) MERESCHKOWSKY
CM001A	CYMBELLA VENTRICOSA	KUTZ.
CM004A	CYMBELLA MICROCEPHALA	GRUN.
CM009A	CYMBELLA NAVICULIFORMIS	AUERSWALD
CM010A	CYMBELLA PERPUSILLA	A. CLEVE
CM013A	CYMBELLA HELVETICA	KUTZ.
CM014A	CYMBELLA AEQUALIS	SMITH
CM015A	CYMBELLA CESATII	(RABH.) GRUN.
CM016A	CYMBELLA AMPHICEPHALA	NAEGELI
CM017A	CYMBELLA HEBRIDICA	(GREGORY) GRUN.
CM018A	CYMBELLA GRACILIS	(RABH.) CLEVE
CM019A	CYMBELLA LACUSTRIS	(AGARDH) CLEVE
CM020A	CYMBELLA GAEUMANNI	MEISTER
CM022A	CYMBELLA AFFINIS	KUTZ.
CM035A	CYMBELLA ANGUSTATA	(W. SMITH) CLEVE
CM036A	CYMBELLA OBTUSA	GREGORY
CM038A	CYMBELLA DELICATULA	(KUTZ.) HUST.
CM043A	CYMBELLA NAVICULACEA	GRUN.
CM9999	CYMBELLA SP.	
CO001A	COCCONEIS PLACENTULA	EHR.
CY006A	CYCLOTELLA KUETZINGIANA	THWAITES
CY009A	CYCLOTELLA OCELLATA	PANT.
CY016A	CYCLOTELLA ARENTII	KOLBE
DE001A	DENTICULA TENUIS	KUTZ.
DT002A	DIATOMA HIEMALE	(LYNGBYE) HEIBERG
EU001A	EUNOTIA VENERIS	(KUTZ.) O. MULLER
EU002A	EUNOTIA PECTINALIS	(KUTZ.) RABH.
EU002B	EUNOTIA PECTINALIS V MINOR	(KUTZ.) RABH.
EU002C	EUNOTIA PECTINALIS V VENTRALIS	(EHR.) HUST.
EU002E	EUNOTIA PECTINALIS V MINOR F IMPRESSA	(EHR.) HUST.
EU003A	EUNOTIA PRAERUPTA	EHR.
EU004A	EUNOTIA TENELLA	(GRUN). HUST.

Appendix 2 cont.

EU005A EUNOTIA ALPINA	(NAEGELI) HUST.
EU006A EUNOTIA LUNARIS	(EHR.) GRUN.
EU006B EUNOTIA LUNARIS V SUBARCUATA	(NAEGELI) GRUN.
EU007A EUNOTIA BIDENTULA	W.SMITH
EU008A EUNOTIA MONODON	EHR.
EU008B EUNOTIA MONODON V MAIOR F BIDENS	W. SMITH
EU009A EUNOTIA EXIGUA	(BREB.) RABH.
EU010A EUNOTIA FABA	(EHR.) GRUN.
EU011A EUNOTIA RHOMBOIDEA	HUST.
EU012A EUNOTIA ROBUSTA	RALFS
EU013A EUNOTIA ARCUS	EHR.
EU014A EUNOTIA BACTRIANA	EHR.
EU015A EUNOTIA DENTICULATA	(BREB.) RABH.
EU015B EUNOTIA DENTICULATA V FENNICA	HUST.
EU016A EUNOTIA DIODON	EHR.
EU017A EUNOTIA FLEXUOSA	KUTZ.
EU019A EUNOTIA IATRIAENSIS	FOGED
EU020A EUNOTIA MEISTERI	HUST.
EU021A EUNOTIA SUDETICA	(O. MULLER) HUST.
EU022A EUNOTIA BIGIBBA	KUTZ.
EU024A EUNOTIA GLACIALIS	MEIST.
EU025A EUNOTIA FALLAX	CLEVE
EU026A EUNOTIA PRAERUPTA-NANA	BERG
EU031A EUNOTIA SEPTENTRIONALIS	OSTRUP
EU038A EUNOTIA POLYGLYPIS	GRUN.
EU039A EUNOTIA TRIODON	EHR.
EU040A EUNOTIA PALUDOSA	SENSU HOPEL
EU9999 EUNOTIA SP	
FR001A FRAGILARIA PINNATA	EHR.
FR002A FRAGILARIA CONSTRUENS	(EHR.) GRUN.
FR002D FRAGILARIA CONSTRUENS V EXIGUA	(W.SMITH) SCHULZ
FR005A FRAGILARIA VIRESCENS	RALFS
FR007A FRAGILARIA VAUCHERIAE	(KUTZ.) BOYE PETERSON
FR010A FRAGILARIA CONSTRICTA	EHR.
FR013A FRAGILARIA OLDENBURGIANA	HUST.
FR015A FRAGILARIA LATA	RENBERG
FU002A FRUSTULIA RHOMBOIDES	(EHR.) DE TONI
FU002B FRUSTULIA RHOMBOIDES V SAXONICA	(RABH.) DE TONI
FU002D FRUSTULIA RHOMBOIDES V AMPHIPLEUROIDES	GRUN.
GM002A GOMPHONEIS OLIVACEOIDES	(HUST.) CARTER
GO003A GOMPHONEMA ANGUSTATUM	(KUTZ.) RABH.
GO004A GOMPHONEMA GRACILE	EHR.
GO006C GOMPHONEMA ACUMINATUM V CORONATA	(EHR.) W. SMITH
GO014A GOMPHONEMA INTRICATUM	KUTZ.
GO9999 GOMPHONEMA SP	
HN001A HANNAEA ARCUS	(EHR.) PATRICK
KR001A KRASSKIELLA KRIEGERANA	(KRASSKE) ROSS & SIMS
ME004A MELOSIRA LIRATA	(EHR.) KUTZ.
ME004C MELOSIRA LIRATA V LACUSTRIS	GRUN.
ME005A MELOSIRA DISTANS	(EHR.) KUTZ.
ME010A MELOSIRA PERGLABRA	OSTRUP
ME010B MELOSIRA PERGLABRA V FLORINIAE	CAMBURN
ME9999 MELOSIRA SP	
NA002A NAVICULA JAERNEFELTII	HUST.
NA005A NAVICULA SEMINULUM	GRUN.
NA006A NAVICULA MEDIOCRIS	KRASSKE
NA013A NAVICULA PSEUDOSCUTIFORMIS	HUST.
NA014A NAVICULA PUPULA	KUTZ.
NA015A NAVICULA HASSIACA	KRASSKE
NA016A NAVICULA INDIFFERENS	HUST.
NA032A NAVICULA COCCONEIFORMIS	GREGORY

Appendix 2 cont.

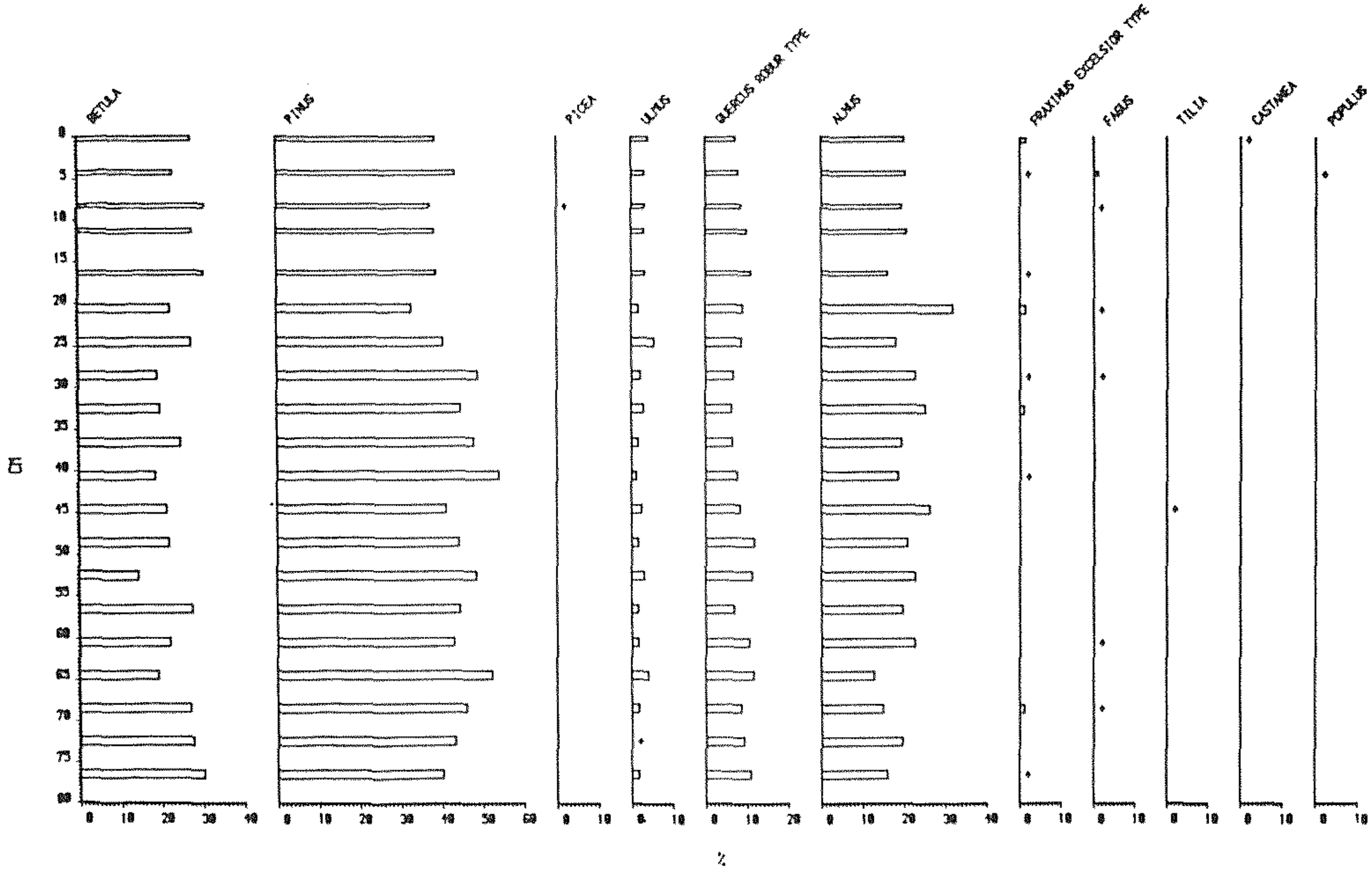
NA036A	NAVICULA PERPUSILLA	GRUN.
NA037A	NAVICULA ANGUSTA	GRUN.
NA039A	NAVICULA FESTIVA	KRASSKE
NA040A	NAVICULA HOFLERI	CHOLNOKY
NA041A	NAVICULA HEIMANSII	VAN DAM & KOOY.
NA042A	NAVICULA MINIMA	GRUN.
NA043A	NAVICULA SUBATOMOIDES	HUST.
NA044A	NAVICULA KRASSKEI	HUST.
NA045A	NAVICULA BRYOPHILA	PETERSEN
NA046A	NAVICULA CONTENTA	GRUN.
NA048A	NAVICULA SOEHRENSIS	KRASSKE
NA051A	NAVICULA CARI	EHR.
NA068A	NAVICULA IMPEXA	HUST.
NA082A	NAVICULA MURALIS	GRUN.
NA086A	NAVICULA TANTULA	HUST.
NA099A	NAVICULA BREMENSIS	HUST.
NA140A	NAVICULA MADUMENSIS	JORGENSEN
NA9953	NAVICULA CF UTERMOHLII	L.LAIDON (RJF)
NA9955	NAVICULA CF VITIOSA	L.HIR (SF)
NA9973	NAVICULA CF DIGITULUS	L.URR (RJF)
NA9976	NAVICULA CF SCHADEI	OCHILTREE (RJF)
NA9999	NAVICULA SP	
NE001A	NEIDIUM IRIDIS	(EHR.) CLEVE
NE003C	NEIDIUM AFFINE V AMPHIRHYNCHUS	(EHR.) CLEVE
NE004A	NEIDIUM BISULCATUM	(LAGERSTEDT) CLEVE
NE9999	NEIDIUM SP	
NI002A	NITZSCHIA FONTICOLA	GRUN.
NI005A	NITZSCHIA PERMINUTA	GRUN.
NI020B	NITZSCHIA ANGUSTATA V ACUTA	GRUN.
NI029A	NITZSCHIA TERRESTRIS	(PETERSEN) HUST.
OP001A	OPEPHORA MARTYI	HERIBAUD
PE002A	PERONIA FIBULA	(BREB. ex KUTZ.) ROSS
PI002A	PINNULARIA ACUMINATA	SMITH SYN.PI003A
PI005A	PINNULARIA MAJOR	(KUTZ.) W.SMITH
PI007A	PINNULARIA VIRIDIS	(NITZSCH) EHR.
PI008A	PINNULARIA DIVERGENS	W. SMITH
PI011A	PINNULARIA MICROSTAURON	(EHR.) CLEVE
PI012A	PINNULARIA BOREALIS	EHR.
PI013A	PINNULARIA SISTARSA	CARTER
PI015A	PINNULARIA ABAUJENSIS	(PANT.) ROSS
PI016A	PINNULARIA DIVERGENTISSIMA	(GRUN.) CLEVE
PI017A	PINNULARIA CARMINATA	BARBER & CARTER
PI018A	PINNULARIA BICEPS	GREGORY
PI019A	PINNULARIA LEGUMEN	EHR.
PI020A	PINNULARIA UNDULATA	GREGORY
PI021A	PINNULARIA HILSEANA	(JANISCH) MULL.
PI023A	PINNULARIA IRRORATA	(GRUN.)HUST.
PI026A	PINNULARIA TENUIS	GREGORY
PI028A	PINNULARIA SUBSOLARIS	(GRUN.) CLEVE
PI036A	PINNULARIA LEPTOSOMA	GRUN.
PI042A	PINNULARIA NODOSA	EHR.
PI048A	PINNULARIA BREBISSONII	(KUTZ.) RABENH.
PI9999	PINNULARIA SP	
RH001A	RHOPALODIA GIBBA	(EHR.) O. MULLER
SA001A	STAURONEIS ANCEPS	EHR.
SA001B	STAURONEIS ANCEPS F GRACILIS	(EHR.) CLEVE
SA003A	STAURONEIS SMITHII	GRUN.
SA005A	STAURONEIS LEGUMEN	EHR.
SA006A	STAURONEIS PHOENICENTERON	(NITZSCH) EHR.
SA008A	STAURONEIS PRODUCTA	GRUN.
SA9997	STAURONEIS SP A	

Appendix 2 cont.

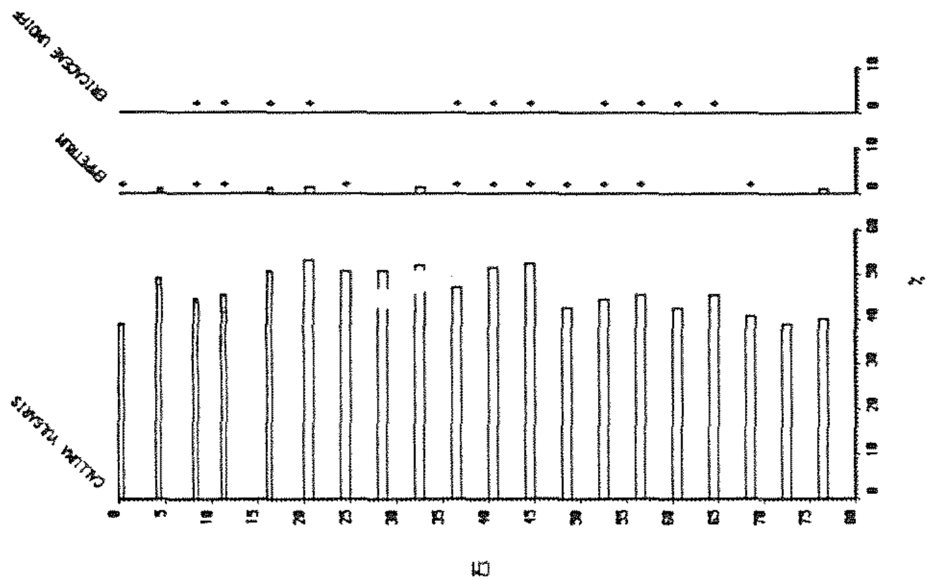
SE001A	SEMIORBIS HEMICYCLUS	(EHR.) PATRICK
SP001A	STENOPTEROBIA INTERMEDIA	LEWIS
SU004A	SURIRELLA BISERIATA	BREB.
SU006A	SURIRELLA DELICATISSIMA	LEWIS
SY018A	SYNEDRA MINUSCULA	GRUN.
SY9999	SYNEDRA SP	
TA001A	TABELLARIA FLOCCULOSA	(ROTH) KUTZ.
TA001B	TABELLARIA FLOCCULOSA V FLOCCULOSA IIIP	KOPPEN
TA002A	TABELLARIA FENESTRATA	(LYNGBYE) KUTZ.
TA003A	TABELLARIA BINALIS	(EHR.) GRUN.
TA004A	TABELLARIA QUADRISEPTATA	KNUDSON
TA9999	TABELLARIA SP	
TE001A	TETRACYCLUS LACUSTRIS	RALFS

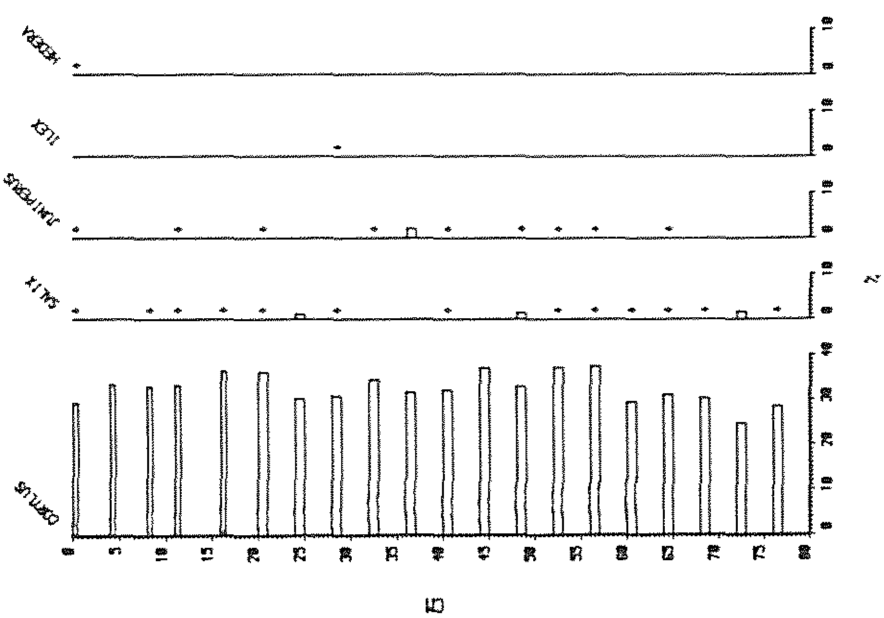
Appendix 3 Geochemical data for Loch Laidon core LAI1 (all figures expressed as mg g^{-1})

Depth	Zn	Cu	Ni	Pb	Ca	Mg	K	Na
0.25	221	73	0	500	4.15	2.32	3.76	3.17
1.25	109	18	5	111	5.54	3.40	5.69	5.09
2.25	136	18	19	180	6.21	3.83	6.41	5.82
3.25	149	19	15	155	6.32	3.83	6.39	6.11
4.25	159	18	11	195	5.77	3.54	5.96	5.30
5.25	190	17	22	136	6.80	4.38	7.38	6.44
6.25	111	18	17	150	6.86	4.20	7.48	6.78
7.25	171	18	17	184	6.50	3.75	6.65	6.04
8.25	193	21	15	234	6.23	3.49	6.02	5.27
9.25	165	19	21	177	6.72	4.04	7.28	6.32
10.25	144	17	19	165	7.99	4.68	8.29	8.08
11.25	179	20	16	217	7.70	4.45	7.75	7.36
12.25	120	20	20	152	7.54	4.32	7.88	7.09
13.25	141	19	26	184	7.20	4.03	7.26	6.61
14.25	152	17	9	152	7.50	4.34	7.63	6.98
15.25	106	17	20	142	8.02	4.47	7.73	7.35
16.25	106	16	18	115	7.82	4.44	7.62	7.10
17.25	108	13	10	116	8.23	4.38	7.63	7.29
18.25	107	17	24	129	7.70	4.34	7.43	6.76
19.25	91	16	23	103	7.66	3.99	7.03	6.03
20.50	79	13	15	85	7.85	4.14	7.29	6.58
21.50	69	13	11	67	8.07	4.25	7.47	6.91
22.50	82	16	12	100	8.17	4.13	7.52	6.43
23.50	75	15	18	80	10.46	5.27	9.94	9.65
24.50	65	14	16	73	9.09	4.97	8.86	8.38
26.50	63	14	14	86	7.90	4.50	8.13	6.69
28.50	55	12	18	63	7.79	5.05	8.78	7.35
30.50	50	11	14	54	7.52	4.10	6.79	5.64
32.50	49	12	14	48	7.81	3.73	6.45	5.56
34.50	41	10	15	48	7.76	3.42	5.86	5.05
36.50	49	11	14	69	8.37	4.02	6.59	5.84
38.50	50	11	14	52	8.38	3.95	6.71	6.10
40.50	51	11	14	48	8.58	4.04	6.95	6.18
45.50	54	10	10	54	8.76	4.07	6.68	6.13
50.50	54	12	18	31	9.65	4.74	7.72	7.04
55.50	62	11	18	27	9.93	4.82	7.54	7.54
60.50	63	12	20	28	10.24	5.49	8.73	8.03
65.50	72	12	20	12	10.39	5.94	8.97	8.53
70.50	58	13	13	3	10.52	4.78	6.47	6.58
75.50	64	13	17	12	11.04	5.12	7.66	7.80
80.50	39	10	10	2	9.38	3.63	5.22	5.35
85.50	63	11	14	8	11.33	4.62	6.85	6.97
88.50	88	15	15	17	11.34	4.50	6.60	6.41

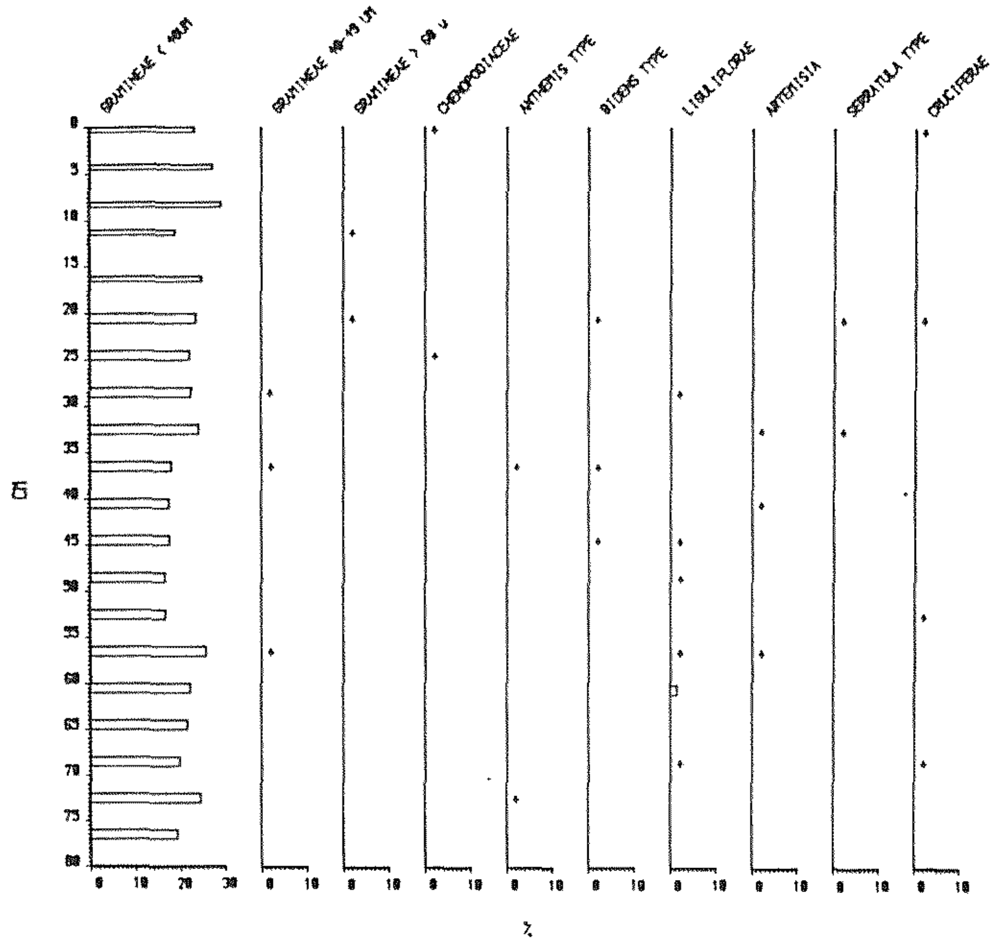


Appendix 4. Summary pollen diagram for Loch Laidon core LAI1. Trees expressed as a percentage of the Arboreal pollen. All other groupings expressed as a percentage of the Arboreal pollen plus the respective grouping.





Appendix 4 cont.



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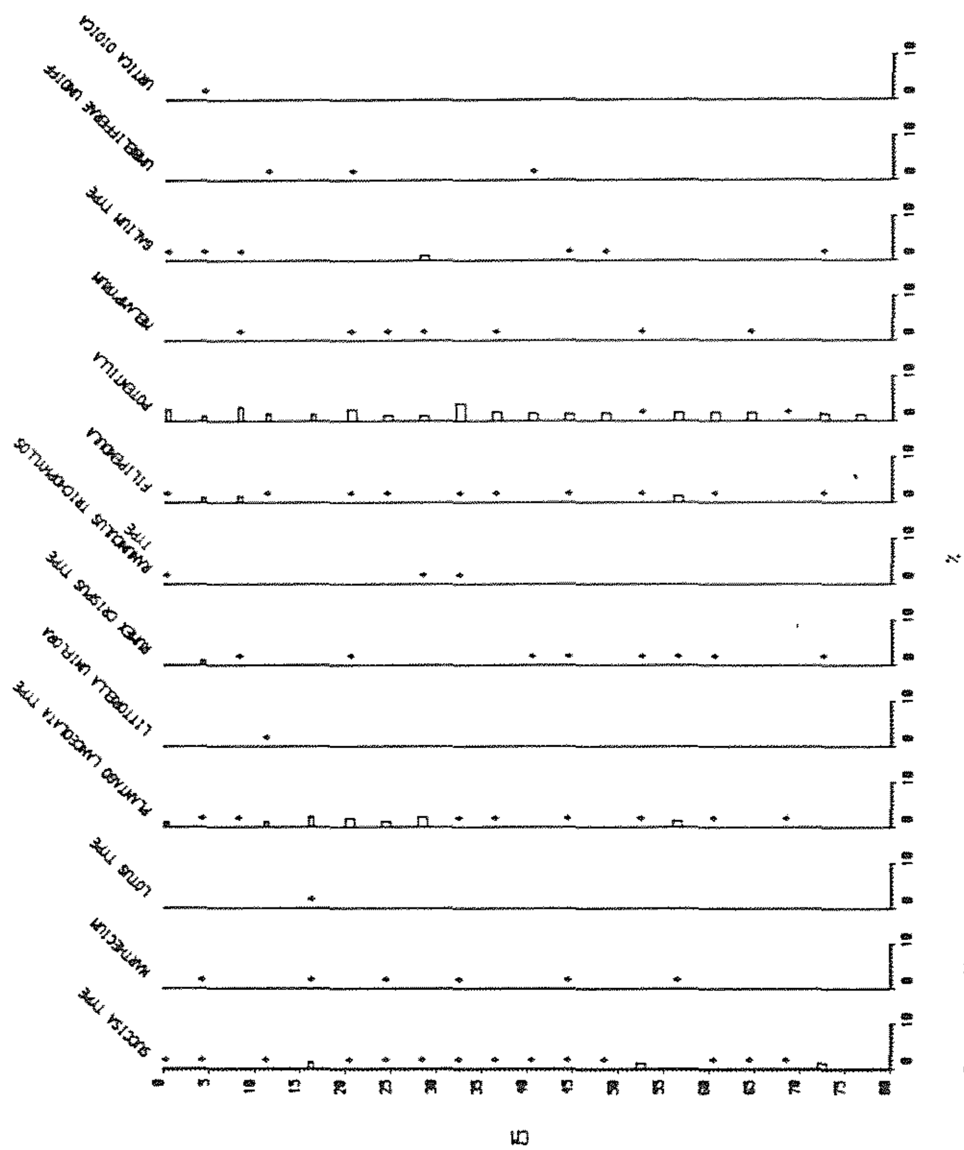

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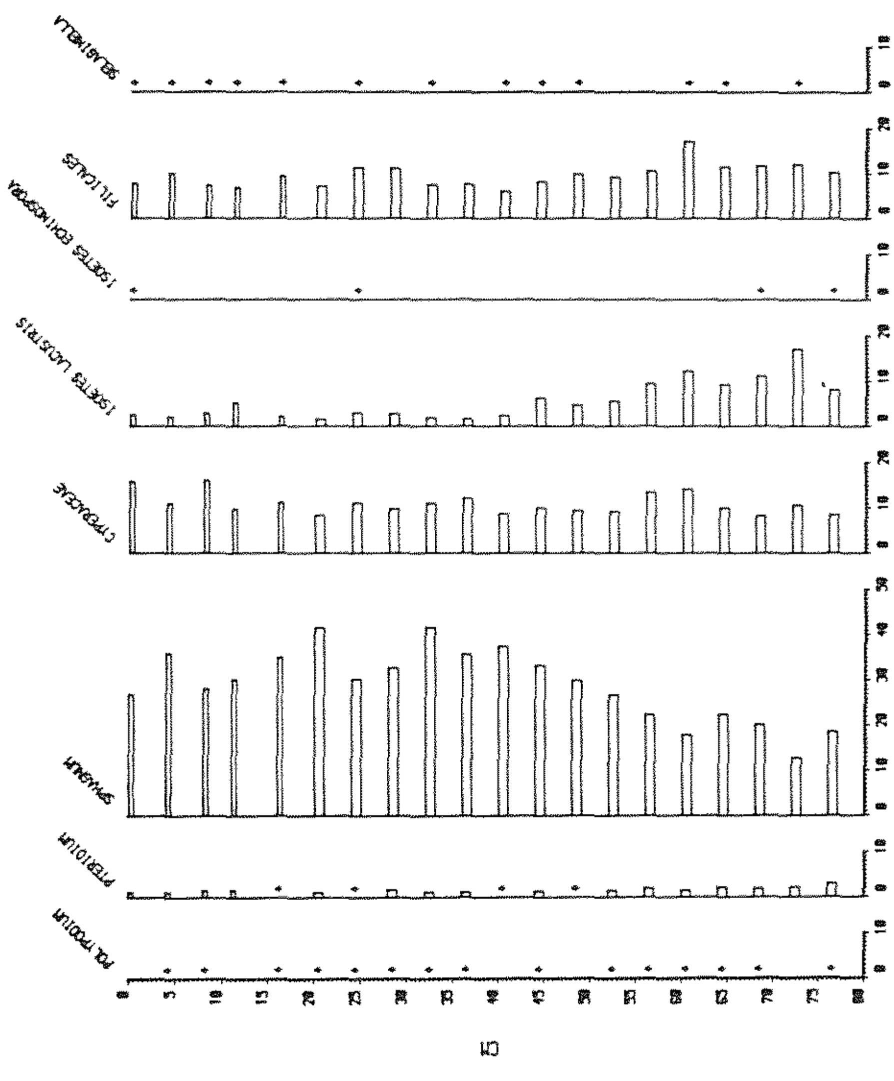
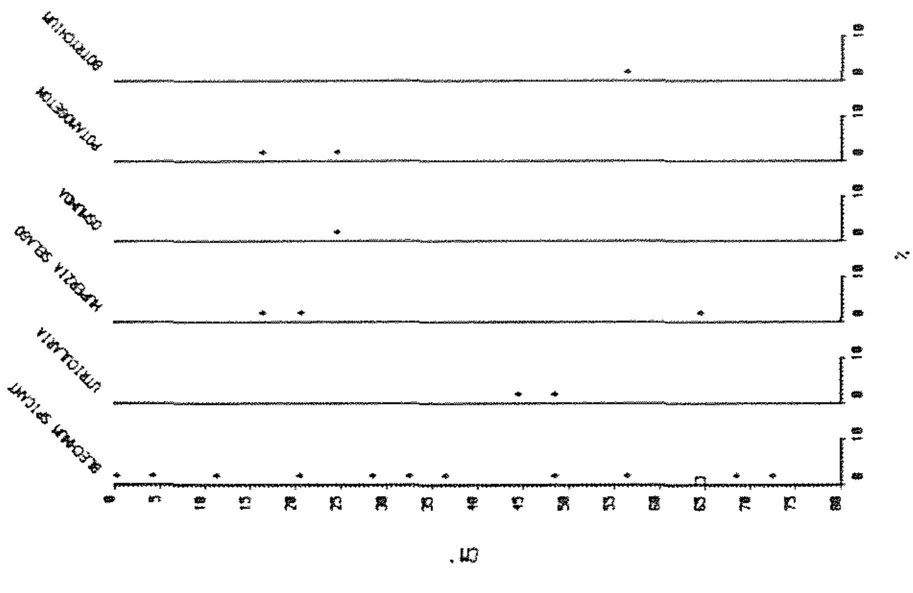


Appendix 4 cont.



Appendix 4 cont.

Palaeoecology Research Unit: Research papers

No. 1 **Patrick, S.T. & Battarbee, R.W. 1981**
The influence of sanitary and other social changes on the eutrophication of Lough Erne since 1850: project introduction and a consideration of the potential role of metabolic wastes.

No. 2 **Battarbee, R.W. 1983**
Diatom analysis of River Thames foreshore deposits exposed during the excavation of a Roman waterfront site at Pudding Lane, London.

No. 3 **Patrick, S.T. & Battarbee, R.W. 1983**
Rural sanitation in the Lough Erne catchment: history and influence on phosphorus loadings.

No. 4 **Patrick, S.T. 1983**
The calculation of per capita phosphorus outputs from detergents in the Lough Erne catchments.

No. 5 **Patrick, S.T. 1983**
Phosphorus loss at sewage works in the Lough Erne region.

No. 6 **Flower, R.J. & Battarbee, R.W. 1983**
Acid lakes in the Galloway uplands, south west Scotland: catchments, water quality and sediment characteristics.

No. 7 **Patrick, S.T. 1984**
The influence of industry on phosphorus loadings in the Lough Erne region.

No. 8 **Battarbee, R.W. & Flower, R.J. 1985**
Palaeoecological evidence for the timing and causes of lake acidification in Galloway, south west Scotland.

No. 9 **Raven, P.J. 1985**
The use of aquatic macrophytes to assess water quality changes in some Galloway Lochs: an exploratory study.

No. 10 **Anderson, N.J. & Battarbee, R.W. 1985**
Loch Fleet: bathymetry and sediment distribution.

No. 11 **Battarbee, R.W. 1985**
Diatoms and acid lakes: proceedings of a workshop.

No. 12 **Battarbee, R.W. & Renberg, I. 1985**
Royal Society Surface Water Acidification Project (SWAP) palaeolimnology programme.

No. 13 **Raven, P.J. 1986**
Occurrence of Sphagnum moss in the sublittoral of several Galloway lochs, with particular reference to Loch Fleet.

No. 14 **Flower, R.J., Rippey, B. & Tervet, D. 1986**
34 Galloway lakes: bathymetries, water quality and diatoms.

No. 15 **Flower, R.J. & Nicholson, A. 1986**
Bathymetries, water quality and diatoms of lochs on the island of South Uist, the Outer Hebrides, Scotland.

No. 16 Fritz, S.C., Stevenson, A.C., Patrick, S.T., Appleby, P.G., Oldfield, F., Rippey, B., Darley, J. & Battarbee, R.W. 1986
Palaeoecological evaluation of the recent acidification of Welsh lakes. I, Llyn Hir, Dyfed.

No. 17 Anderson, N.J., Battarbee, R.W., Appleby, P.G., Stevenson, A.C, Oldfield, F., Darley, J. & Glover, G. 1986
Palaeolimnological evidence for the recent acidification of Loch Fleet, Galloway.

No. 18 Kreiser, A., Stevenson, A.C., Patrick, S.T., Appleby, P.G., Rippey, B., Darley, J. & Battarbee, R.W. 1986
Palaeoecological evaluation of the recent acidification of Welsh lakes. II, Llyn Berwyn, Dyfed.

No. 19 Patrick, S.T. & Stevenson, A.C. 1986
Palaeoecological evaluation of the recent acidification of Welsh lakes. III, Llyn Conwy and Llyn Gamallt, Gwynedd (site descriptions, fishing and land use/management histories).

No. 20 Stevenson, A.C., Patrick, S.T., Fritz, S.C., Rippey, B., Oldfield, F., Darley, J., Higgitt, S.R., & Battarbee. 1987
Palaeoecological evaluation of the recent acidification of Welsh lakes. IV, Llyn Gynon, Dyfed.

No. 21 Patrick, S.T. 1987
Palaeoecological evaluation of the recent acidification of Welsh lakes. V, The significance of land use and land management.

No. 22 Stevenson, A.C., Patrick, S.T., Fritz, S.C., Rippey, B., Appleby, P.G., Oldfield, F., Darley, J., Higgitt, S.R., Battarbee, R.W. & Raven, P.J. 1987
Palaeoecological evaluation of the recent acidification of Welsh lakes. VI, Llyn Dulyn, Gwynedd.

No. 23 Fritz, S.C., Stevenson, A.C., Patrick, S.T., Appleby, P.G., Oldfield, F., Rippey, B., Darley, J., Battarbee, R.W., Higgitt, S.R. & Raven, P.J. 1987
Palaeoecological evaluation of the recent acidification of Welsh lakes. VII, Llyn y Bi, Gwynedd.

No. 24 Patrick, S.T., Fritz, S.C., 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. VIII, Llyn Eiddew Bach, Gwynedd.

No. 25 Patrick, S.T., Stevenson, A.C., Fritz, S.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. IX, Llyn Llagi, Gwynedd.

No. 26 Stevenson, A.C., Patrick, S.T., Kreiser, A. & Battarbee, R.W. 1987
Palaeoecological evaluation of the recent acidification of susceptible lakes: methods utilised under DoE contract PECD 7/7/139 and the Royal Society SWAP project.

No. 27 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.

No. 28 Jones, V.J., Stevenson, A.C. & Battarbee, R.W. 1987
A palaeolimnological evaluation of peatland erosion. Report (First phase) to the NCC.

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