Research Papers

No. 20

PALAEOECOLOGICAL EVALUATION OF THE RECENT ACIDIFICATION OF WELSH LAKES

4. Llyn Gynon, Dyfed

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

Palaeoecological Evaluation of the Recent Acidification of Welsh Lakes. 4. Llyn Gynon, Dyfed.

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Summary

i) Core studies of diatoms, pollen, chemistry, carbonaceous particles and magnetics together with a land use study have been conducted at Llyn Gynon, Dyfed. An upland, oligotrophic lake situated on the upland plateau east of Aberystwyth.

ii) The ^{210}Pb inventory of the Llyn Gynon core is 2.45 times that at Llyn Hir and indicates possible sediment focussing in Llyn Gynon. A period of disturbance is revealed by a dislocation of the ^{210}Pb profile between 9.75 cm and 11.75 cm dated to around 1930, correlating with a peak in calcium in the core chemistry record.

iii) The diatom based pH reconstructions suggest that the pH of Llyn Gynon was 5.9 - 6.2 throughout most of the history recorded in the core. Planktonic diatoms were absent from the lake and the data suggest a fairly stable flora of attached circumneutral and acidophilous taxa. Acidification of Llyn Gynon, marked by the expansion of *Tabellaria quadriseptata* and *Navicula madumensis*, did not begin until 8 cm ca. 1945. The data suggest a pH decline of 0.4 pH units between 1945 and 1985.

iv) The core chemistry record demonstrates that trace metal contamination of the lake sediments began at 33 cm (1790's). The record also suggests a period of soil erosion (60 cm - 33 cm) before the dated part of the core (pre-1800) which is associated with a depression in values of *Isoetes* and a dilution of the diatom concentrations.

v) The contamination of the sediments by carbonaceous particles commences at 32 cm, concurrent with the beginnings of trace metal contamination. The concentration of these particles increase rapidly from 8cm (1940's) and parallels the recent acidification of the lake as identified by the diatom record. A similar trend is shown by the magnetic data.

vi) The pollen diagram reveals a major hiatus in the core at 60 cm below which sediments dating to approximately the elm decline 'approx 5000 B.P.' occur. Sedimentation has only recommenced within the last 250 years.

vii) No appreciable land use change has occurred within the catchment since the introduction of sheep by the Cistercian monastery. No liming has taken place within the catchment and burning has not been a significant management practice.

viii) The acidification cannot be accounted for by land use changes. Instead, all the data indicate acid deposition as the cause of acidification. The timing of the changes and trends of the atmospheric pollution indicators (trace metals, magnetics, carbonaceous particles), indicating local deposition of atmospheric pollutants, are consistent with this view.

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Explanation of Abbreviations

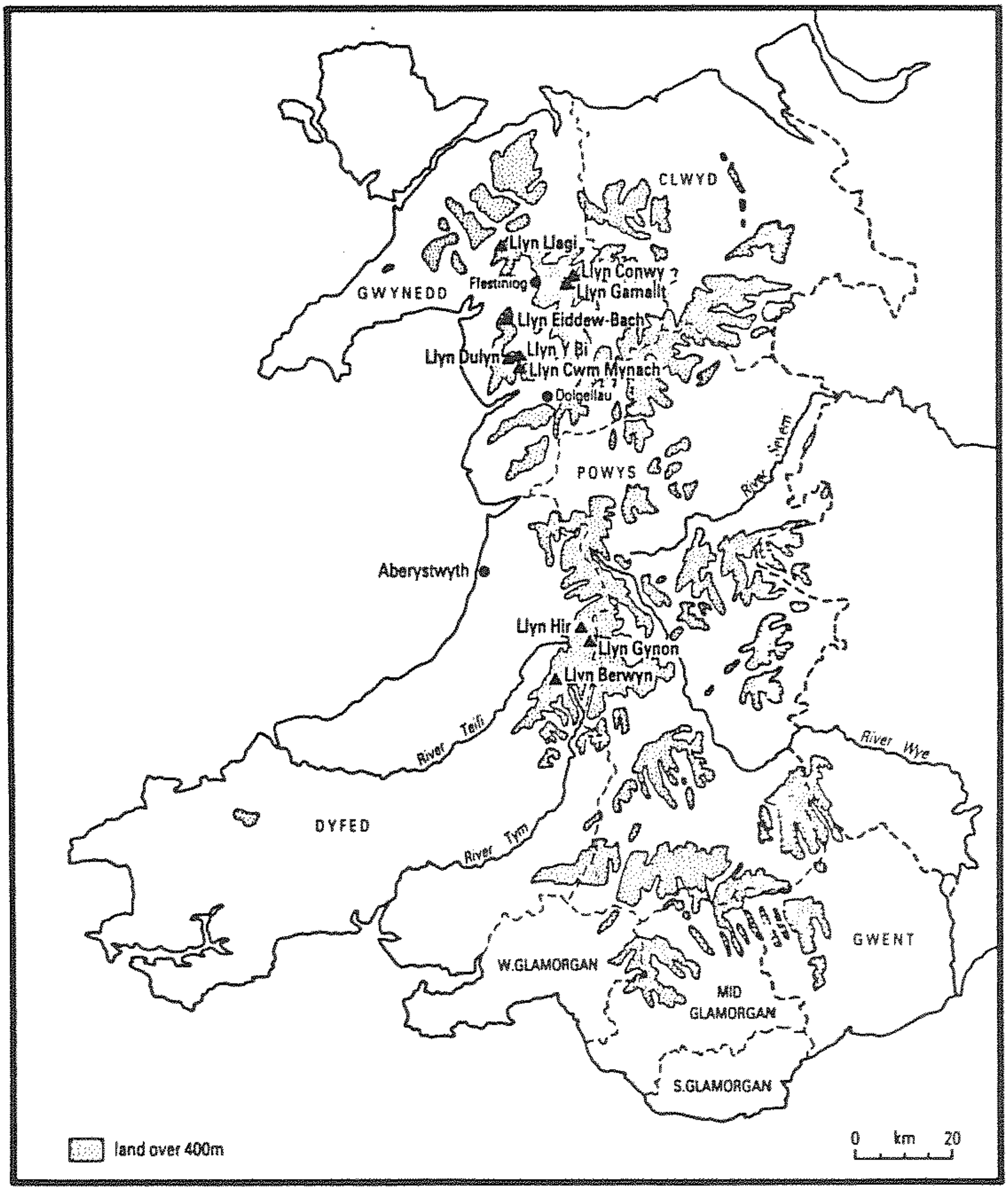
ADAS	Agricultural and Development Advisory Service.
BGS	British Geological Survey
MAFF	Ministry of Agriculture, Fisheries and Food.
NCC	Nature Conservancy Council
NLW	National Library of Wales
PAH	Polyaromatic Hydrocarbons
PRO	Public Record Office
UCL	University College London
WWA	Welsh Water Authority
SSSI	Site of Special Scientific Interest

1.0 Introduction

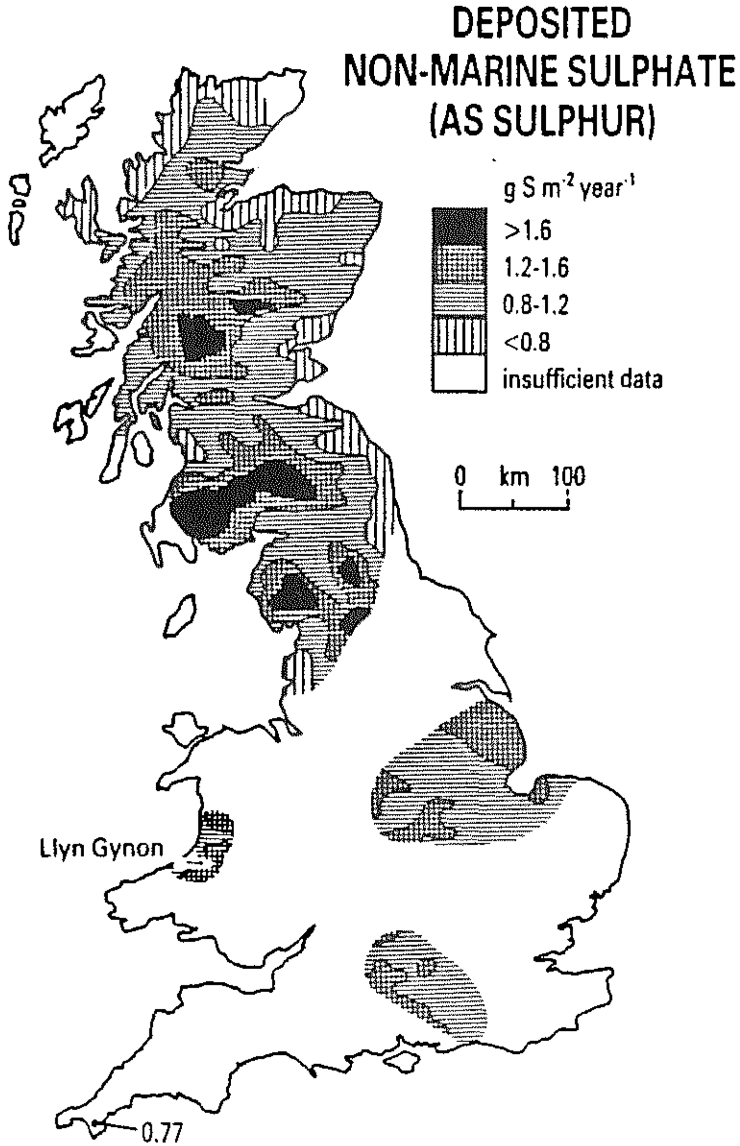
Surface water acidification is recognised as one of the most important environmental problems in Europe and North America, yet despite the pioneering work of Gorham on precipitation chemistry in Cumbria (Gorham 1958) the extent of acidification in the UK is still not known. In earlier papers (Flower and Battarbee 1983, Battarbee et al. 1985, Jones et al. 1986) we established that lakes on granitic rocks in Galloway, South West Scotland, were strongly acidified, and that the most likely cause of the acidification was acid deposition. We have now extended our enquiry to acid lakes in Wales and other parts of Scotland to test the general hypothesis that clearwater lakes with pH values less than 5.5 occurring within areas of high acid deposition are acidified due to an increase in acid deposition over recent decades.

Llyn Gynon (Fig. 1), one of the larger natural lakes on the highland plateau of North Cardiganshire, was the second site chosen in Wales. The mean pH of precipitation is ca. 4.5 and the annual wet sulphate loading is 1.2 - 1.6 g m^{-2} yr^{-1} (Figs. 2 & 3). The catchment is largely undisturbed, comprising upland moorland and rough grazing for sheep. Sediment cores were obtained in May 1985.

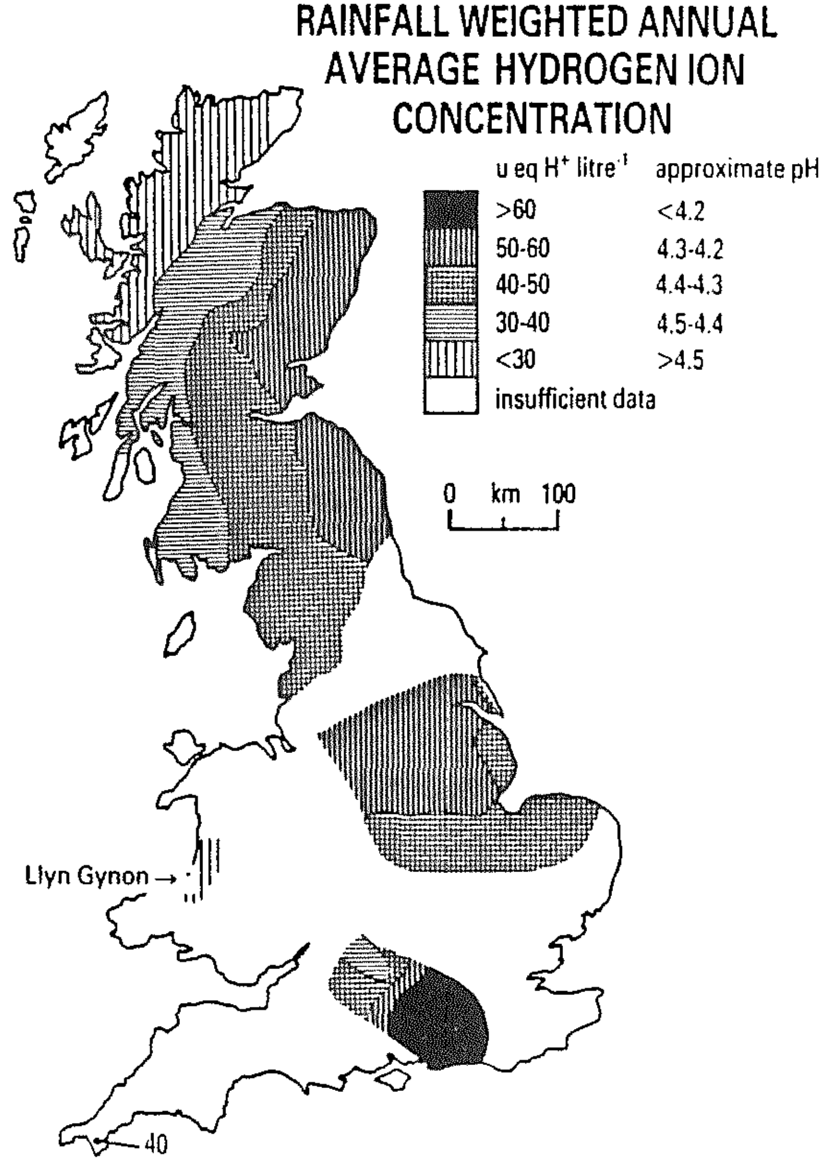
Our approach involves the use of diatom analysis to reconstruct past trends in pH; ^{210}Pb analysis to establish a lake sediment chronology; geochemical, magnetic and "soot" analysis to trace the history of atmospheric contamination; and pollen analysis and land-use history studies to evaluate the influence of catchment changes on the past ecology of the lake.



1. Llyn Gynon location map



3. Average annual deposition of non-marine sulphate for the U.K.
(Redrawn from Barrett et al 1983)



2. Average annual rainfall weighted hydrogen ion
concentration deposition for the U.K. (Redrawn from Barrett et al 1983)

2.0 Site details

2.1 Lake

Llyn Gynon, lying at over 400 m and receiving rainfall in excess of 2000 mm yr^{-1}, lies on the lower Palaeozoic Silurian siltstones on the upland plateau east of Aberystwyth. The lake occupies a broad, irregular basin consisting of two relatively small yet deep basins surrounded by an extensive shallow rim (Fig. 4). The lake has a volume of 533,835 m^3, a mean depth of 2.18 m and displays minimal variation in water level (Table 1). The lake is chiefly fed by a stream from the north, Nant Llethr-du, and groundwater flows. Llyn Gynon is drained by an easterly flowing river, Nant Brwynog, into the Claerwen reservoir.

Table 1 Lake Characteristics

Area	252,550 m^2
Volume	533,835 m^3
Maximum depth	11 m
Mean depth	2.18 m

2.1.1 Water chemistry

Available water chemistry from the lake is extremely limited and is restricted to three spot samples taken in the course of the present study in 1985 and 1986 (Table 2). Lake pH varies from 5.0-5.3 and has very low alkalinities (1.2 - 2.0 mg $CaCO_3$ l^{-1}). Dissolved aluminium levels are half those of Llyn Hir and Berwyn before liming (Underwood et al. 1986).

2.1.2 Lake vegetation and invertebrates

At present no information is available on either the macrophyte vegetation or the invertebrate populations of the lake.

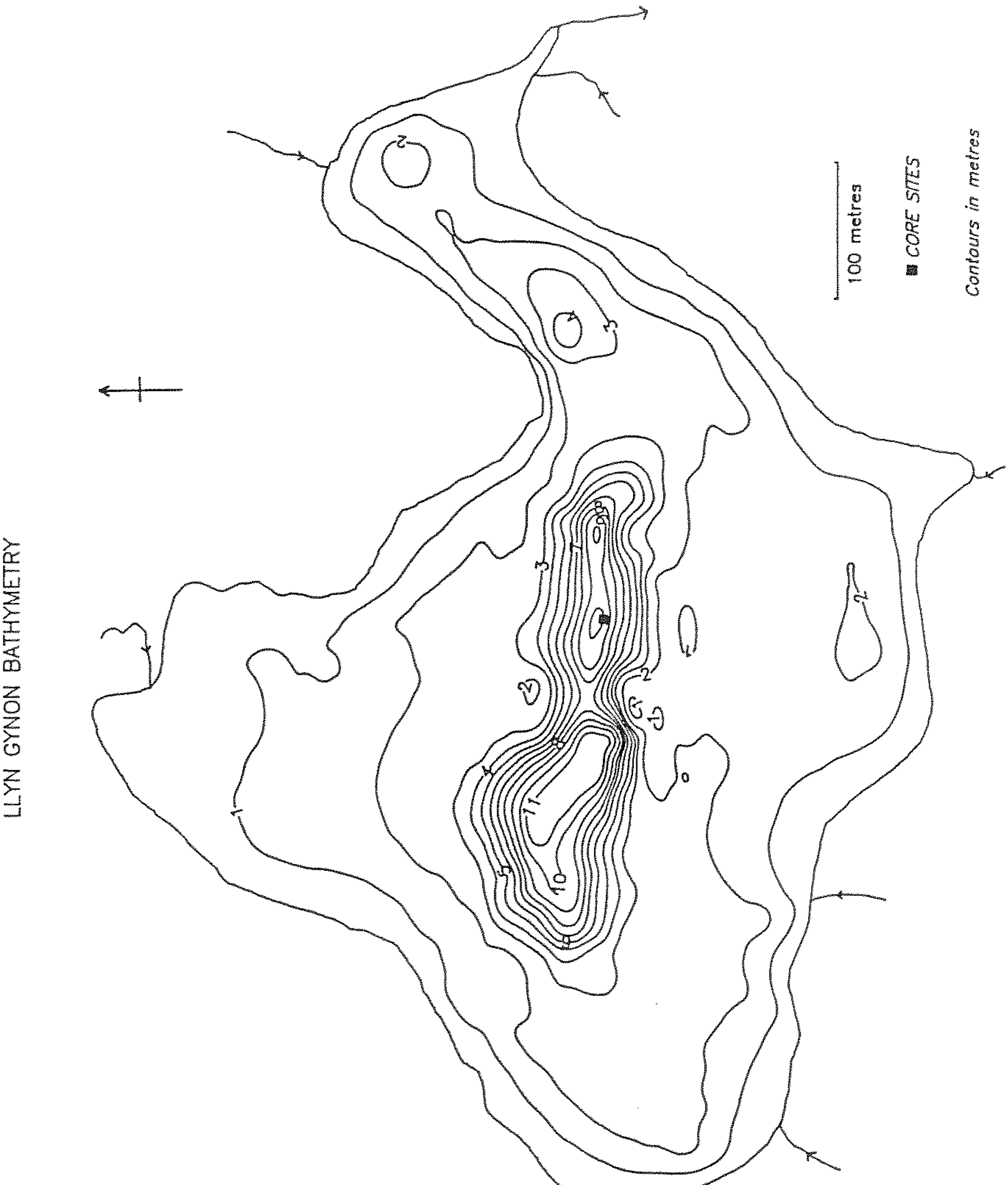
2.1.3 Fishing history

Llyn Gynon has not been stocked within living memory and still supports a wild trout population that migrates up the Nant Brwynog from the Claerwen system and yields catches averaging 0.5 pounds $fish^{-1}$ (G. Jones, M. Morgan pers. comm.).

Lying on the estate of Strata Florida Abbey it is possible that the lake was stocked by the Cistercian monks sometime after the 12th century (Ward 1931). John Leland passed through the area in the 1530s and reported that Llyn Gynon contained both trout and eels (Toulmin Smith 1906). Cliffe (1860) described the lake as 'swarming with trout of excellent quality'. Similar terminology was employed by Ward (1931) to describe the fishing some 70 years later.

Local residents recall that the lake attracted considerable numbers of British and continental anglers before 1940, many of whom would camp at the lake side (E. Davies, E. Edwards pers. comm.).

Owing to its remoteness little control has been exercised over the fishing rights to the lake. The Nanteos Estate kept a boat on the lake in the 19th century (1) but there is no evidence to suggest that the fishing was



4. Bathymetry and coring locations for Llyn Gynon

Table 2. <u>Lake chemistry results for Llyn Gynon 1985/1986</u>

Date	pH	Conductivity 20°C us cm^{-1}	Total Oxidised Nitrogen	Total Hardness	Free Carbon dioxide ($mg\ l^{-1}$)	Total Alkalinity	Chloride
27/02/85	5.1	34.0	0.2	4.5	3.7	1.3	6.0
14/01/86	5.0	29.0	0.1	4.0	3.0	1.2	5.0
23/04/86	5.3	39.0	0.1	---	---	2.0	7.13

Date	Orthophosphate	Dissolved Silica	Dissolved Sulphate ($mg\ l^{-1}$)	Dissolved Sodium	Dissolved Potassium	Dissolved Calcium	Dissolved Zinc
27/02/85	<0.02	0.80	4.57	3.10	0.30	0.83	0.019
14/01/86	<0.02	0.80	2.74	2.86	0.31	0.78	0.029
23/04/86	-----	0.75	----	3.55	0.32	0.80	0.029

Date	Dissolved Copper	Dissolved Cadmium	Dissolved Aluminium ($mg\ l^{-1}$)	Dissolved Lead	Dissolved Chromium	Dissolved Manganese	Dissolved Iron
27/02/85	0.005	0.83	0.068	0.009	<0.003	0.211	0.216
14/01/86	0.006	0.78	0.054	<0.002	<0.003	0.057	0.253
23/04/86	0.005	----	0.050	-----	-----	0.220	0.170

Date	Dissolved Nickel ($mg\ l^{-1}$)	Humic acid
27/02/85	0.005	2.2
14/01/86	-----	2.9
23/04/86	-----	---

preserved. As part of the Claerwen reservoir catchment the fishing rights were passed to Birmingham Corporation and later to the WWA.

2.2 Catchment

Llyn Gynon (252,550 m^2) occupies a shallow depression in the highland plateau east of Aberwystwyth overlooking the Claerwen reservoir. The catchment (3,114,112 m^2) is of low relief (Table 3) and is dominated by acidic blanket peats and small amounts of Nardus* grassland.

Table 3 Catchment Characteristics

Total catchment area	3,114,112 m^2
Area of land in catchment	2,861,562 m^2
Area of lake	252,550 m^2
Catchment/lake ratio	11.33
Maximum relief	10 m

2.2.1 Geology

Base poor, lower Palaeozoic, Silurian mudstones and shales dominate the geology (Rudeforth 1970). Detailed geological mapping by the BGS is not available but surveys are in progress nearby (R. Bazley pers. comm.).

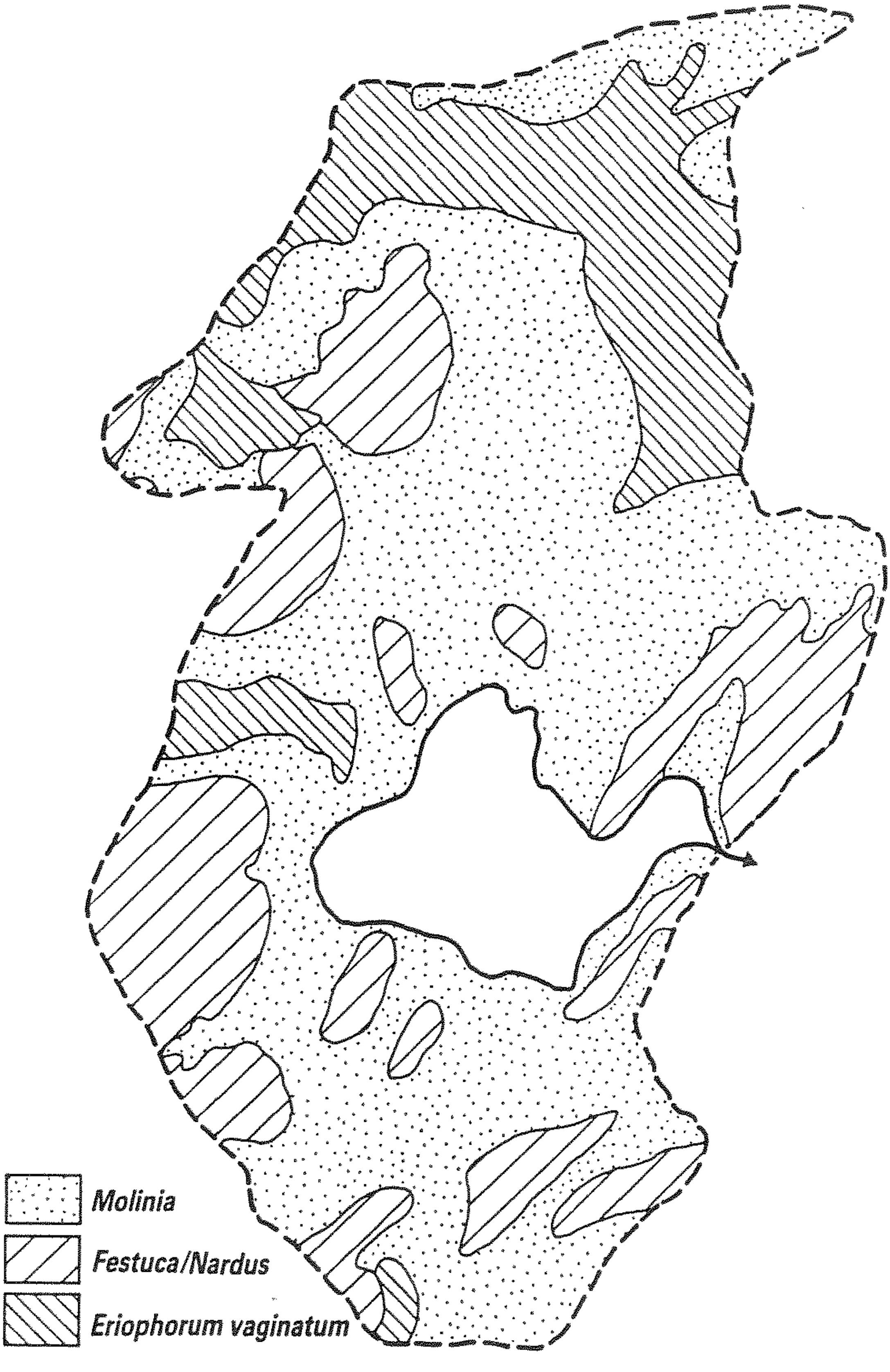
2.2.2 Soils

Soils of the catchment belong to the Crowdy series (1013a) and are chiefly amorphous Molinia/Eriophorum blanket peats. The better drained, Festuca/Nardus, slopes are dominated by soils of the Hiraethog series of the Hafren association (654a) and are chiefly stagnopodzols and stagnohumic gleys (Rudeforth et al. 1984). Typically these soils are thin (30-40 cm) with a wet peaty surface horizon and bleached subsurface horizons, often with a thin ironpan. Extensive peat hagging is noticeable in the east of the catchment by the outflow and a sizeable area of hagging exists on the western side of the lake and may represent old peat cuttings.

2.2.3 Present Vegetation

Catchment vegetation is dominated by blanket peats consisting chiefly of Molinia caerulea in the extensive nutrient-rich flushes and Eriophorum vaginatum & Sphagnum (e.g. S.cuspidatum, S.papillosum & S.compactum) communities in wetter areas (Fig. 5). Polytrichum commune, Aulocomnium palustre and Scirpus caespitosus are also common. Areas of better drained slopes are dominated by Nardus stricta and Festuca ovina grassland. Very little Calluna, Erica and Vaccinium myrtillus is found in the catchment and those plants that are present are very old and almost moribund. Pteridium is not present within the catchment.

* Nomenclature follows Tutin et al (1964-1980).



5. Vegetation map for Llyn Gynon

3.0 Methods

3.1.1 Surveying

The lake was surveyed using the techniques described in Stevenson *et al.* 1987. Shore surveying stations were located by the inflow and outflows.

3.1.2 Collection of sediment cores and routine laboratory measurement of sediment characteristics

Cores were taken using a Mackereth mini-corer (Mackereth 1969) operated from an inflatable boat. Sampling was carried out during May 1985. Gynon 3 was used for dating and analysis and Gynon 4 for PAH.

Core Gynon 3 (89 cm) was extruded in the laboratory and the top 20 cm sliced into 1/2 cm slices and the remaining core at 1 cm intervals. The sediment was then sub-sampled for dry weight, loss on ignition (at 550°C) and wet density measurements.

Analyses for dating, magnetics, chemistry, carbonaceous particles, diatom & pollen were all conducted according to the standard methods set out in Stevenson *et al.* (1987).

4.0 Results

4.1 Lake history

4.1.1 Sediment Description

The lowermost sediment in the Llyn Gynon core is a fine dark-brown organic lake mud, with organic content (LOI) ranging from 24% to 31% of the sediment dry weight (Fig. 6). A sharp transition to a silty olive-brown sediment with a lower organic content (11-25%) occurs at 60 cm. Within this silty sediment are several fine bands of rootlets and fibrous plant material. Above 30 cm the organic content of the sediment increases again. Percent organic matter (LOI) ranges from 22 - 42% of the sediment dry weight, with the highest values between 9.0 and 18.5 cm. The contact between the lower silty sediment and the uppermost dark-brown organic sediment is gradual.

4.1.2 ^{210}Pb dating

Sediments from Gynon 3 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 4, and shown graphically in Figs. 7 & 8. The ^{137}Cs results are given in Table 5 and Fig. 9. Table 6 gives values of a range of other radioisotopes determined from the gamma spectra.

Table 7 compares ^{210}Pb and ^{137}Cs parameters for Llyn Gynon with corresponding parameters from nearby Llyn Hir. The unsupported ^{210}Pb concentration of the near surface sediments in Llyn Gynon is half that of Llyn Hir, and indicates a basic sediment accumulation rate in Llyn Gynon twice that of Llyn Hir. The ^{210}Pb inventory of the Llyn Gynon core is 2.45 times that at Llyn Hir, and indicates possible sediment focussing in Llyn Gynon. The combination of these two factors has given rise to a net sediment accumulation rate at the site of core GYN 3 over 5 times that at Llyn Hir. This is reflected in the values of the 90% equilibrium depths, i.e., the depths at which the ^{210}Pb dating parameters have fallen to 10% of the surface value. These depths represent 74 years of sediment accumulation.

The 99% equilibrium depth for the Llyn Gynon core (representing 148 years of sediment accumulation) is about twice the 90% equilibrium depth, and this suggests that over the past 150 years there has been no significant net change in the sediment accumulation rate. The mean accumulation rate given by these figures is 0.035g cm^{-2} yr^{-1}. Within this period there may well have been significant short term fluctuations in sediment accumulation, most notably in association with the non-linear kink in the unsupported ^{210}Pb profile (Fig. 8) between 9.75 cm and 11.75 cm. These depths are dated unambiguously by ^{210}Pb to ca. 1930. This episode has not caused any significant dislocation of the unsupported ^{210}Pb profile, and may represent a discontinuity in the process of sediment focussing due to e.g. a slump. The flattening of the ^{210}Pb profile above 4.75 cm may represent a small post-1964 acceleration in sediment accumulation.

The ^{137}Cs concentrations rise steeply towards the top of the core, with no sign of the expected 1963 peak. The surface concentration is 34 pCi g^{-1}, and is 1.55 times that at Llyn Hir, in spite of the higher sedimentation rate. The ^{137}Cs inventory is 4 times that at Llyn Hir. 50% of the ^{137}Cs inventory should post-date 1963. This would put 1963 at 4.5 cm, and is

6. Profiles of variation in dry weight, wet density and loss on ignition for the Llyn Gynon 3 core

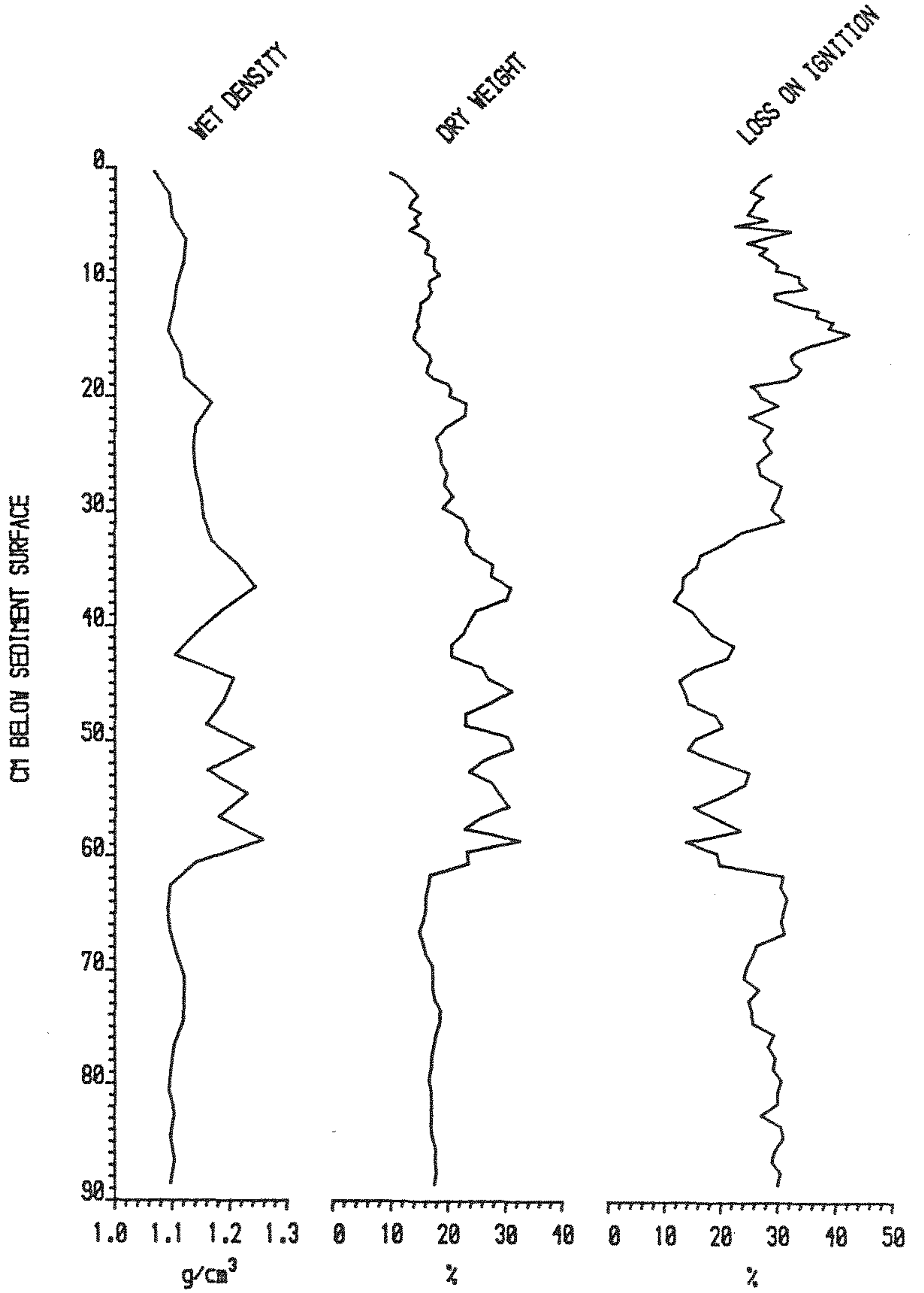


Table 4. ^{210}Pb Data for Core Gynon 3.

Depth	Dry Mass	^{210}Pb Concentration Total	Unsupported	Cumul Unsupp ^{210}Pb	Standard Errors Concent. Total	Uns.	Cumul. Uns.	^{226}Ra concentration	Std. Error
cm	g cm^{-2}	pCi g^{-1}	pCi g^{-1}	pCi cm^{-2}	Total	Uns.	Uns.	pCi g^{-1}	Total
0.75	0.0839	24.210	22.722	1.998	0.90	0.93	0.13	1.488	0.22
2.75	0.3766	21.850	20.480	8.315	1.16	1.20	0.43	1.370	0.29
4.75	0.6845	20.580	19.671	14.494	0.84	0.86	0.63	0.909	0.19
6.25	0.9244	15.390	14.376	18.548	1.10	1.14	0.70	1.014	0.29
7.75	1.2011	9.930	8.533	21.662	0.62	0.65	0.77	1.397	0.19
9.75	1.5939	4.590	3.539	23.900	0.55	0.58	0.81	1.051	0.18
11.75	1.9566	6.220	5.129	25.457	0.55	0.58	0.85	1.091	0.17
14.75	2.4357	5.580	4.566	27.776	0.36	0.38	0.89	1.014	0.11
17.75	2.9625	2.760	1.734	29.349	0.37	0.39	0.91	1.026	0.13
21.50	3.8454	1.690	0.691	30.381	0.22	0.23	0.95	0.999	0.08
25.50	4.7190	0.940	-0.098	30.608	0.21	0.22	0.97	1.038	0.08
29.50	5.6171	1.470	0.502	30.772	0.28	0.30	1.00	0.968	0.10
33.50	6.6698	0.990	-0.233	30.897	0.25	0.27	1.04	1.223	0.10
37.50	8.0543	0.590	-1.027	30.001	0.20	0.22	1.09	1.617	0.09
38.00	8.2190			29.829					

Table 5. ^{137}Cs data for Core Gynon 3

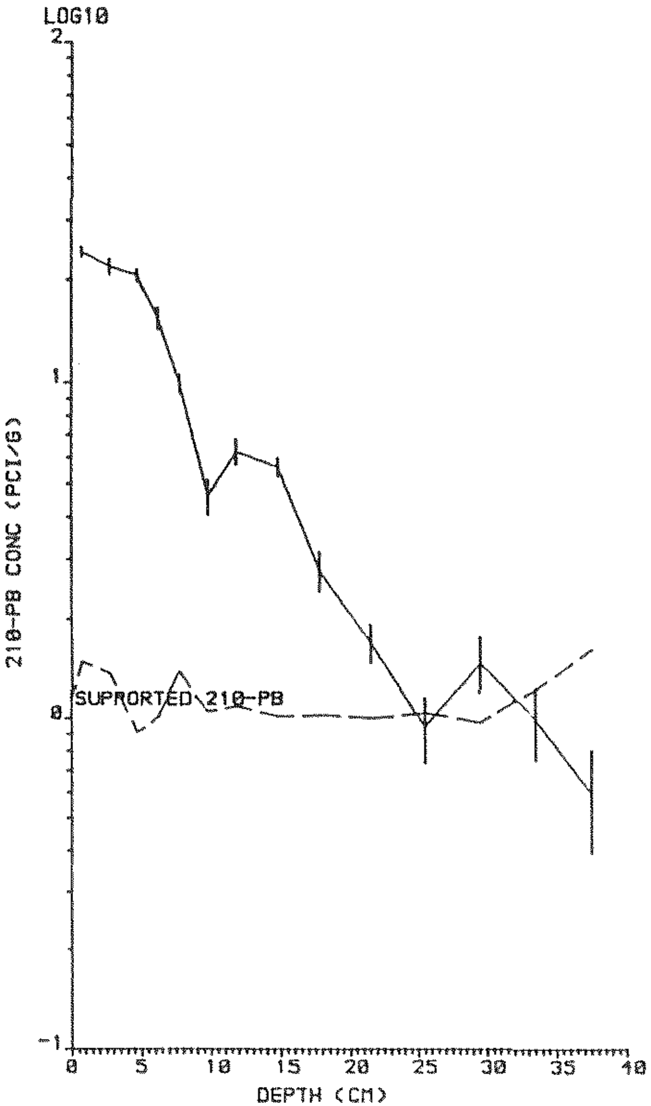
Depth	Dry Mass	^{137}Cs concentration		Cumulative ^{137}Cs		Fract
cm	g cm^{-2}	pCi g^{-1}	+/-	pCi cm^{-2}	+/-	
0.75	0.0839	34.02	0.59	2.85	0.15	0.071
2.75	0.3766	31.97	0.70	12.51	0.53	0.309
4.75	0.6845	28.25	0.50	21.77	0.73	0.538
6.25	0.9244	24.59	0.63	28.10	0.81	0.694
7.75	1.2011	11.76	0.31	32.91	0.86	0.813
9.75	1.5939	4.19	0.22	35.79	0.88	0.884
11.75	1.9566	4.01	0.20	37.28	0.89	0.921
14.75	2.4357	3.46	0.14	39.06	0.90	0.965
17.75	2.9625	0.75	0.11	40.00	0.90	0.988
21.50	3.8454	0.28	0.06	40.42	0.90	0.999
25.50	4.7190	0.00	0.00	40.46	0.91	1.000
29.50	5.6171	0.00	0.00	40.46	0.91	1.000
33.50	6.6698	0.00	0.00	40.46	0.91	1.000
37.50	8.0543	0.00	0.00	40.46	0.91	1.000

Table 6. Other radioisotope data for Core Gynon 3.

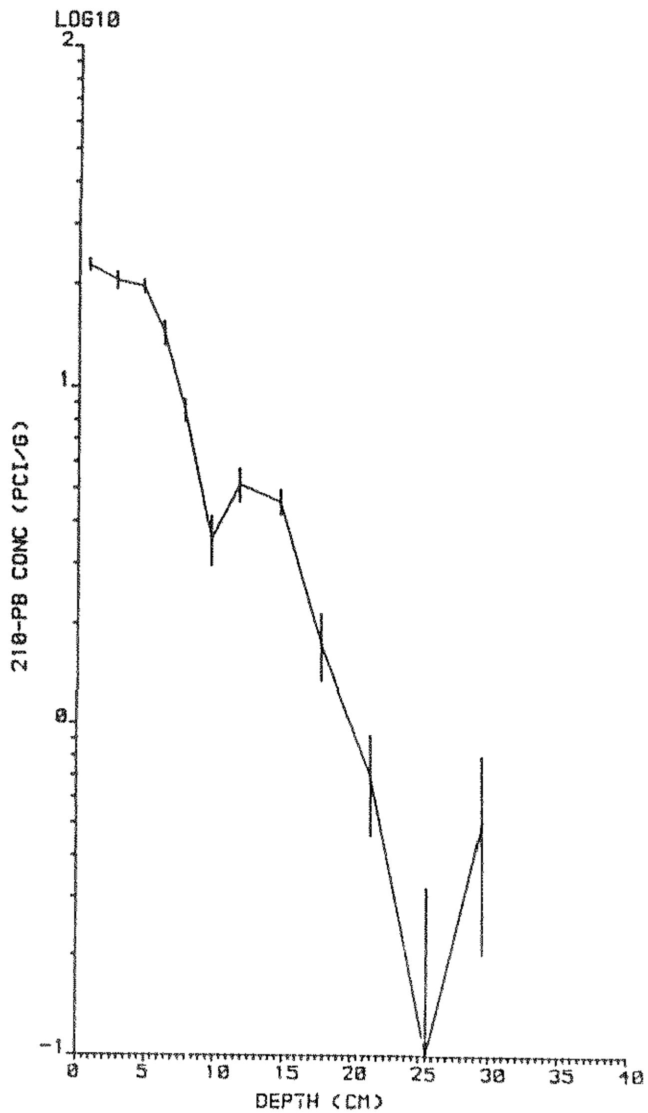
Depth cm	^{226}Ra	^{238}U	^{235}U pCi g^{-1}	^{228}Ac	^{228}Th	^{40}K
0.75	1.49	0.00	0.16	1.13	0.95	16.26
2.75	1.37	1.01	0.00	0.56	1.44	13.82
4.75	0.91	0.00	0.14	0.53	1.26	15.51
6.25	1.01	0.00	0.19	0.00	0.74	17.79
7.75	1.40	0.00	0.16	0.89	0.99	22.19
9.75	1.05	0.00	0.09	0.07	0.75	19.44
11.75	1.09	0.00	0.08	0.48	0.93	20.78
14.75	1.01	0.00	0.18	0.95	0.30	18.20
17.75	1.03	0.15	0.00	1.08	1.34	21.35
21.50	1.00	0.10	0.13	0.95	1.37	19.31
25.50	1.04	0.30	0.13	0.87	1.19	20.81
29.50	0.97	0.54	0.12	0.92	0.35	19.33
33.50	1.22	0.18	0.12	1.14	1.55	29.60
37.50	1.62	0.74	0.05	1.62	1.25	33.62

Table 7. ^{210}Pb and ^{137}Cs parameters for Core Gynon 3.

	Surface unsupp. ^{210}Pb concent. pCi g^{-1}	Unsupp. ^{210}Pb Inventory pCi cm^{-2}	Mean ^{210}Pb Flux pCi cm^{-2} yr^{-1}	^{226}Ra Conc. pCi g^{-1}	90% Equ. Depth g cm^{-2}	99% Equ. Depth g cm^{-2}	Surface ^{137}Cs concentration pCi g^{-1}	^{137}Cs Inventory pCi cm^{-2}
Llyn Gynon	22.1	29.7	0.93	1.16	2.58	5.09	34.0	40.5
Llyn Hir	45.9	12.2	0.38	0.88	0.46	1.51	22.0	10.9



7. Total ^{210}Pb profile for the Llyn Gynon 3 core



8. Unsupported ^{210}Pb profile for the Llyn Gynon 3 core

reasonably consistent with the CRS model ^{210}Pb chronology (Fig. 10). There is a steep rise in ^{137}Cs concentrations between 9.75 cm and 6.25 cm, but significant values are recorded down to 15 cm. This can only be reconciled with the ^{210}Pb chronology by assuming significant downwards diffusion of ^{137}Cs. A puzzling feature is the uniformity of the ^{137}Cs concentrations between 9.75 cm and 14.75 cm. If this uniformity was caused by a slump this feature would be post 1954, raising doubts about the validity of the ^{210}Pb chronology. Unlike Llyn Hir there was no detectable amount of ^{241}Am and this is presumably a further reflection of the generally high accumulation rate in Llyn Gynon.

The chronology given in Table 8 is based on the CRS ^{210}Pb dating model (Appleby and Oldfield 1978). In spite of the relatively high ^{210}Pb inventory the rate of ^{210}Pb supply to the sediments appears to have been reasonably constant. This is shown by the relatively good agreement between the CRS and CIC model dates, except in older sediments where standard errors become large. Where there have been fluctuations in sedimentation the CRS model will generally give more conservative results than the CIC model. CIC model dates are given in Table 9.

4.1.3 Diatoms and pH reconstruction

Diatom analyses were completed on the uppermost 72 cm of the Llyn Gynon core (GYN 3). Summary diatom profiles from Llyn Gynon are illustrated in Fig. 11 a full diagram may be found in Appendix A.

Few floristic changes occur in the lower 60 cm analysed from the Llyn Gynon core. The diatom assemblage is dominated by the circumneutral taxon *Fragilaria virescens*, with moderate percentages of other circumneutral taxa such as *Cymbella gracilis*, *Anomoeoneis vitrea*, of acidophilous taxa including *Tabellaria flocculosa*, *Frustulia rhomboides*, *F.rhomboides* var. *saxonica* and *Eunotia veneris* and of the alkaliphilous taxon *Fragilaria construens* var. *pumila*. The only significant floristic change in these lowermost sediments is the decline of the circumneutral species *Achnanthes minutissima* and *Gomphonema gracile* above 56 cm.

This Llyn Gynon diatom assemblage is quite similar to several of the pre-acidification floras in the Galloway lochs, particularly Loch Valley (Flower *et al.* 1987) and the post-15th century flora of Round Loch of Glenhead (Flower and Battarbee 1983), although the high percentages of *Fragilaria virescens* are not found elsewhere. The near absence of a planktonic flora throughout the core and the relatively low percentages of alkaliphilous species indicate that Llyn Gynon has been moderately acid throughout the history recorded by this core. pH reconstruction suggests a mean pH of between 5.9 & 6.2 (Fig. 11).

Between 40 and 18 cm diatom concentrations are exceedingly low (Fig. 12) suggesting low diatom production and/or a high sediment accumulation rate. The concurrent depression of *Isoetes* percentages (see section 4.1.7) suggests high turbidity in the littoral zone caused by erosion, which shaded macrophytes as well as littoral diatoms and hence depressed production. Loss-on-ignition values increase slightly in this zone of low diatom concentrations and could reflect peat erosion from the catchment. pH reconstructions suggest a depression of lakewater pH between 48 and 24 cm, reflected by slight increases in the abundance of acidophilous taxa such as *Frustulia rhomboides*, *F. rhomboides* var. *saxonica*, *Eunotia faba*

Table 8. CRS Model ^{210}Pb chronology

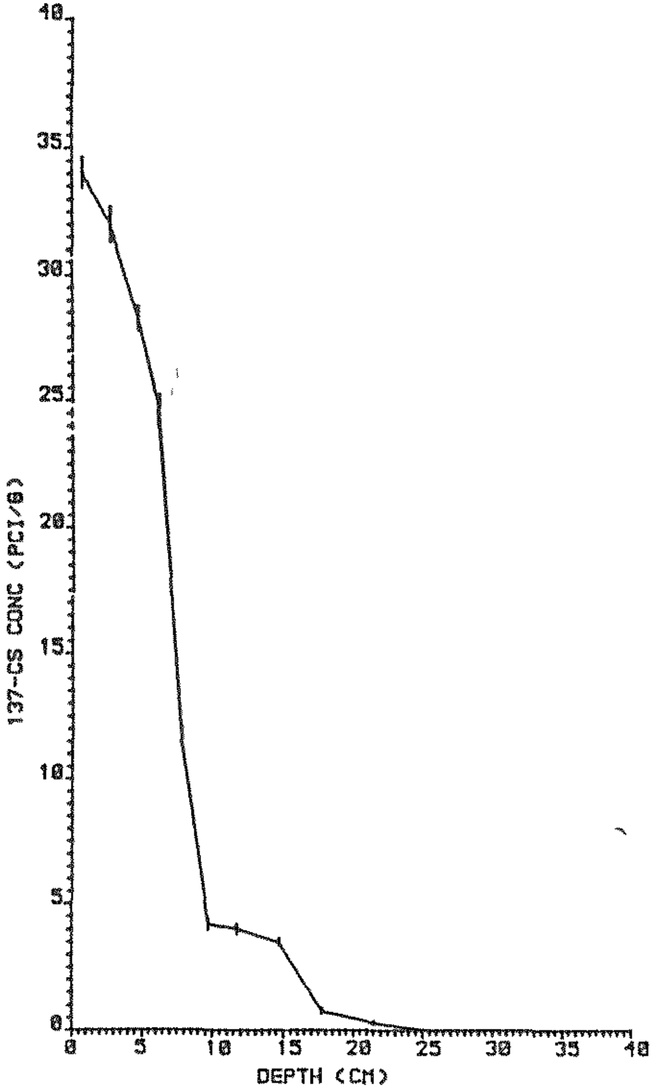
Depth	Dry Mass	Cumul. Unsupp. ^{210}Pb	Chronology			Sedimentation Rate		
			Date	Age	Std. Error			Std. Error
cm	g cm^{-2}	pCi cm^{-2}	AD	Yr		g cm^{-2}	cm yr^{-1}	%
0.00	0.0000	29.72	1985	0				
0.50	0.0559	28.60	1984	1	1	0.0397	0.291	5.0
1.50	0.1937	25.31	1980	5	2	0.0372	0.264	5.6
2.50	0.3400	22.34	1976	9	2	0.0346	0.233	6.3
3.50	0.4921	19.18	1971	14	2	0.0308	0.202	6.3
4.50	0.6460	16.30	1966	19	2	0.0265	0.171	6.2
5.50	0.8044	13.54	1960	25	2	0.0258	0.157	7.5
6.50	0.9705	11.15	1954	31	2	0.0273	0.155	8.9
7.50	1.1550	9.14	1947	38	2	0.0317	0.168	9.4
8.50	1.3484	7.82	1942	43	2	0.0430	0.226	12.5
9.50	1.5448	6.78	1938	47	3	0.0566	0.299	16.6
10.50	1.7299	5.93	1933	52	3	0.0494	0.269	16.0
11.50	1.9113	5.21	1929	56	3	0.0353	0.205	13.7
12.50	2.0764	4.36	1923	62	4	0.0288	0.171	14.0
13.50	2.2361	3.59	1917	68	4	0.0249	0.148	15.0
14.50	2.3958	2.95	1911	74	5	0.0209	0.125	16.0
15.50	2.5674	2.32	1903	82	6	0.0211	0.119	19.0
16.50	2.7430	1.80	1895	90	8	0.0228	0.119	22.7
17.50	2.9186	1.39	1887	98	9	0.0244	0.119	26.3
18.50	3.1391	1.00	1876	109	12	0.0233	0.110	36.5
19.50	3.3745	0.70	1865	120	17	0.0213	0.099	48.6
20.50	3.6100	0.49	1853	132	21	0.0193	0.088	61.1
21.50	3.8454	0.35	1842	143	25	0.0173	0.076	73.4

^{210}Pb Flux = 0.93 +/- 0.03 pCi cm^{-2}
90% Equilibrium Depth = 14.5 cm. or 2.40 g cm^{-2}
99% Equilibrium Depth = 22.6 cm. or 4.09 g cm^{-2}

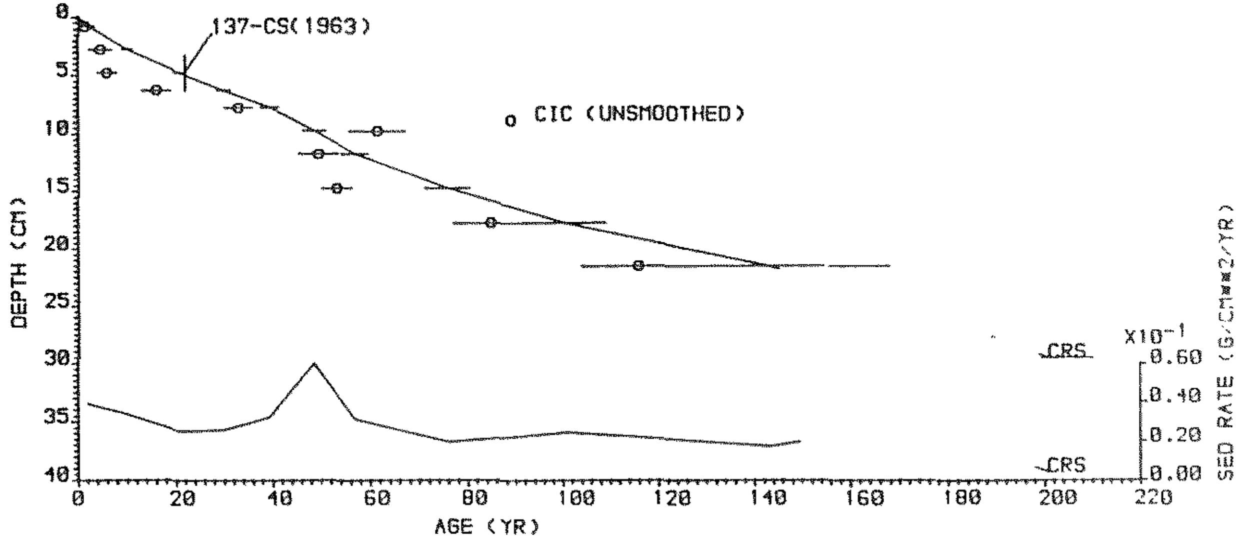
Table 9. CIC Model ^{210}Pb chronology for Core Gynon 3.

Depth	Dry Mass	Unsupp. ^{210}Pb concentration	Chronology			Sedimentation Rate	
			Date	Age	Std Error		
cm	g cm^{-2}	pCi g^{-1}	AD	Yr		g cm^{-2} yr^{-2}	cm yr^{-1}
0.00	0.0000	22.95	1985	0			
0.75	0.0839	22.07	1984	1	1	0.0638	0.466
2.75	0.3766	19.89	1980	5	3	0.0638	0.425
4.75	0.6845	19.12	1979	6	2	0.0378	0.242
6.25	0.9244	13.96	1969	16	3	0.0207	0.120
7.75	1.2011	8.24	1952	33	3	0.0247	0.129
9.75	1.5939	3.39	1924	61	6	0.0437	0.232
11.75	1.9566	4.94	1936	49	5	0.0446	0.265
14.75	2.4357	4.40	1932	53	4	0.0356	0.212
17.75	2.9625	1.64	1900	85	8	0.0265	0.127
21.50	3.8454	0.62	1869	116	12	0.0467	0.206
25.50	4.7190	-0.15	1850	135	17	0.0467	0.211
29.50	5.6171	0.44	1858	127	22	0.0467	0.192

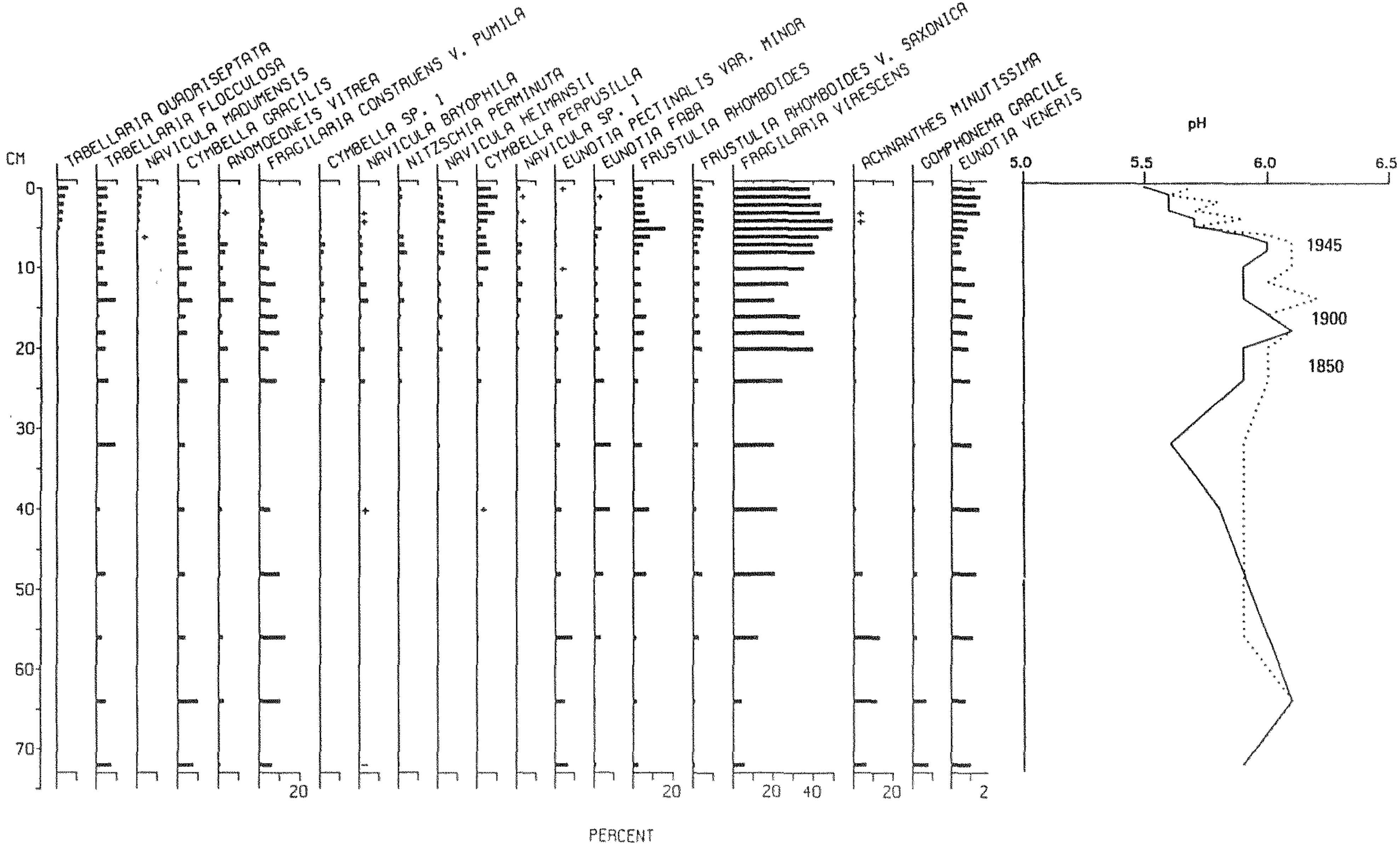
90% Equilibrium Depth = 16.6 cm. or 2.75 g cm^{-2}
99% Equilibrium Depth = 31.3 cm. or 6.09 g cm^{-2}



9. ^{137}Cs profile for the Llyn Gynon 3 core

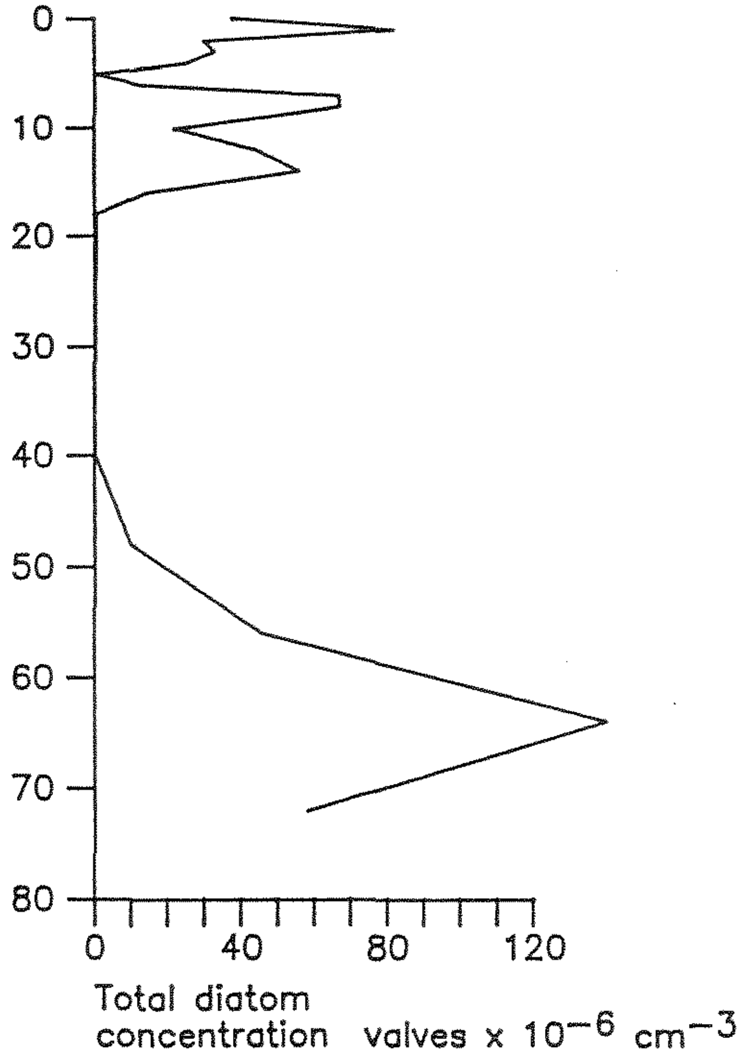


10. CRS and CIC ^{210}Pb age/depth chronology for the Llyn Gynon 3 core



11. Diatom summary diagram for the Llyn Gynon 3 core

······ M.R Preference groups
——— INDEX B – Galloway



12. Diatom concentration diagram for the Llyn Gynon 3 core

and Tabellaria flocculosa. This pH depression could be an artefact of the inwash of acidophilous diatoms living in catchment peats (e.g. Battarbee & Flower 1984).

Above 18 cm diatom concentrations and Isoetes percentages rise, suggesting reduced sediment inwash. The slightly depressed cation concentrations (see section 4.1.4) in these sediments are also consistent with the hypothesis of lowered erosion rates. The magnetic data (section 4.1.5) however, do not provide any evidence for decreased erosion and the historical data (section 4.2.1) do not suggest any late-19th century change in land use that might account for altered sediment inputs from the catchment.

The most significant floristic change occurs in the uppermost portion of the Llyn Gynon core, beginning with an increase in the acidophilous Cymbella perpusilla above 14 cm. Above 6 cm the acidobiontic taxa Tabellaria quadriseptata and Navicula madumensis increase sharply, and Anomoeoneis vitrea, Fragilaria construens var. pumila and Cymbella gracilis decline in abundance. These changes, particularly the expansion of Tabellaria quadriseptata, indicate significant acidification of the lake. pH reconstructions (Fig. 11) suggest that this reflects a decline of 0.4 pH units in the uppermost 8 cm. The high values of Fragilaria virescens found in the top half of the core are thought to be the cause of the over-estimation of reconstructed pH, by 0.2 - 0.3 of a pH unit, by the multiple regression method.

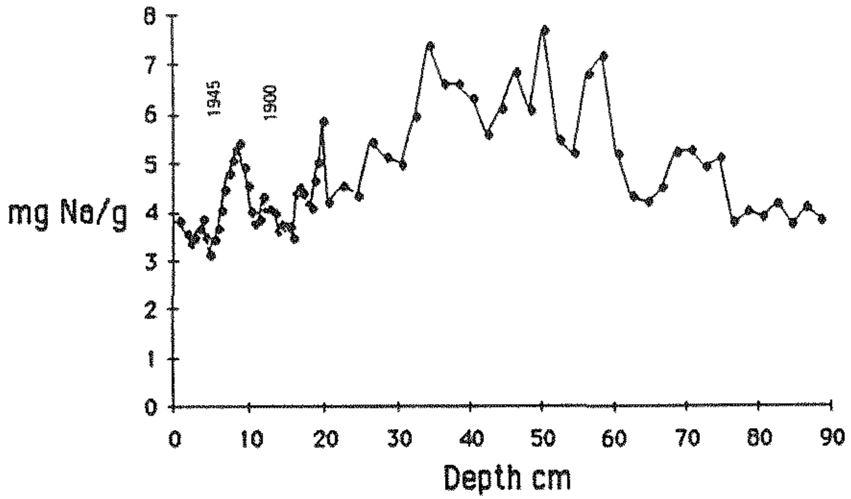
4.1.4 Sediment chemistry

Major Cations

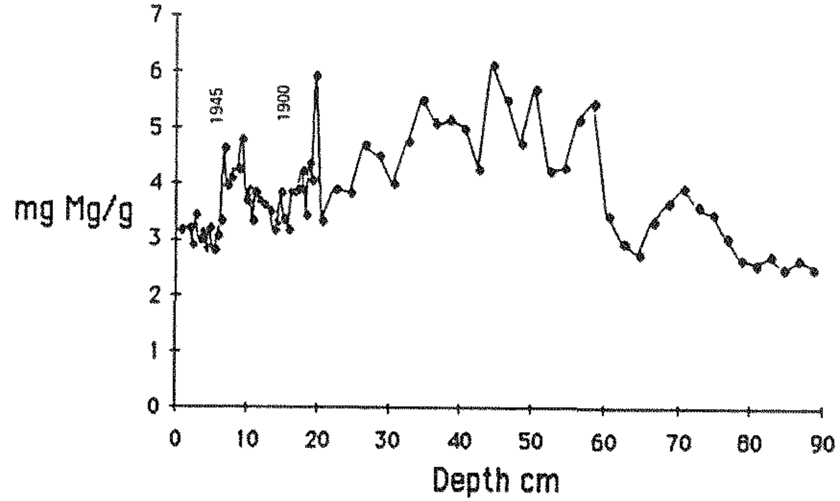
There are major changes in sediment constitution within and below the dated section of the core. Between 33 and 60 cm the sediment has a higher dry weight and lower organic content than in the upper 33 cm (Fig. 6). The sedimentary magnesium, sodium and potassium concentrations are also highest in this interval. This suggests that the rate of erosion of material from the catchment was higher during this period. (Mackereth 1966, Engstrom & Wright 1985, pp27-34). This is before the dated portion of the core.

Within the dated section of the core ($<$ 20 cm) the organic content increases to a peak at 14 cm and then decreases towards the surface (Fig. 6). There is a minor peak at 10 cm. The 10 cm peak in organic content coincides with a peak in dry weight and with peaks in concentration of potassium (Fig. 15) and, especially, sodium and magnesium (Figs. 13 & 14). There is also a very small peak in the calcium profile at this depth (Fig. 16). Usually the calcium profile does not reflect changes in erosion rates from the catchment (Fritz et al. 1986, Kreiser et al. 1986).

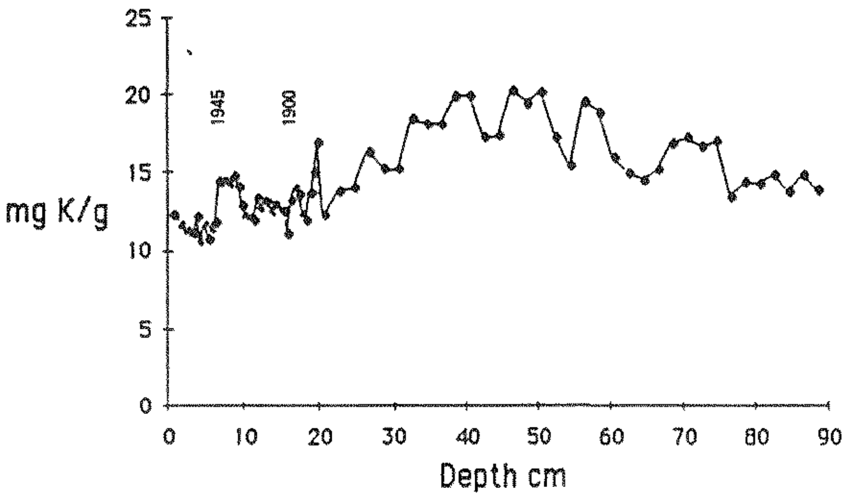
The peaks in magnesium, potassium, sodium and dry weight profiles at 10 cm are usually taken to indicate a period of increased erosion from the catchment (Mackereth 1966, Engstrom & Wright 1984). This is partly supported by a fluctuation in the steady accumulation rate of sediment at 10 cm in Llyn Gynon (Table 8). This may be due to an increase in accumulation rate or a discontinuity in sediment focussing in the lake. If the discontinuity is a slump of material from a shallower area, then the sediment would be coarser (higher dry weight) and would have higher major



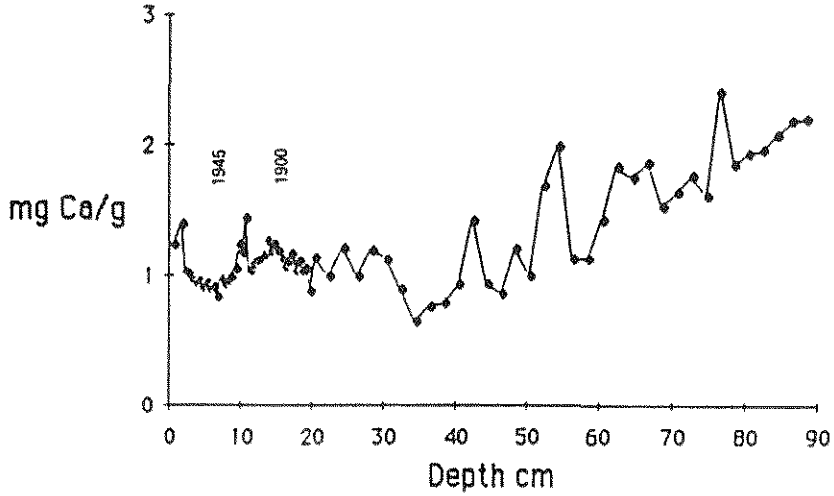
13. Variations in Na gdw[-1] for the Llyn Gynon 3 core



14. Variations in Mg gdw[-1] for the Llyn Gynon 3 core



15. Variations in K gdw[-1] for the Llyn Gynon 3 core



16. Variations in Ca gdw[-1] for the Llyn Gynon 3 core

cation concentrations. The chemical results suggests that a slump might have occurred.

Trace metals

Nickel behaves like potassium in the dated portion of the core (Fig. 17). The peak around 10 cm is the only feature on a fairly constant concentration-depth profile.

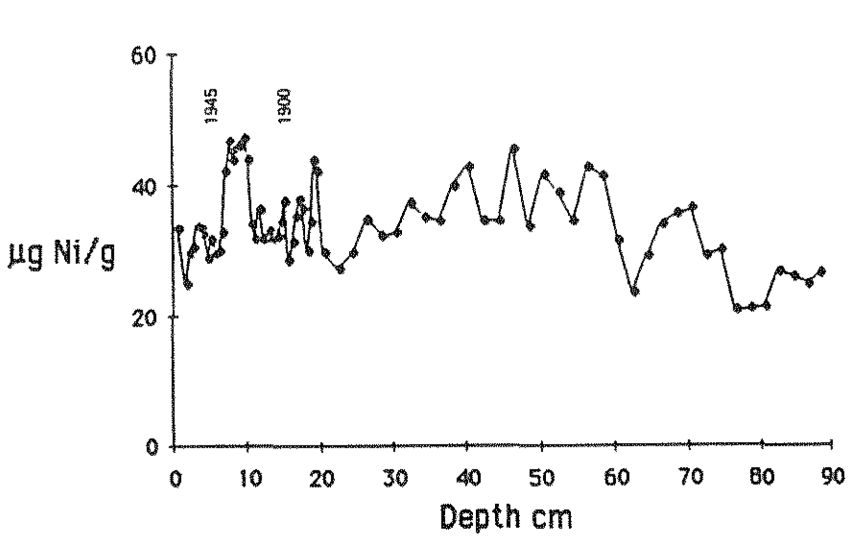
Zinc, lead and copper have similar profiles (Figs. 18 - 20). Below about 30 cm the concentration is constant around background values of 137 ug Zn g^{-1}, 42 ug Pb g^{-1}, 33 ug Ni g^{-1} and 14 ug Cu g^{-1}. These are typical background values for freshwater sediments (Forstner 1977). Using the concentrations expressed per gramme minerals zinc reaches its maximum level of contamination at 9 cm depth, lead at 17 and copper at 14 cm (Figs 21, 22). In the top 6 cm the zinc concentration drops while lead concentrations are constant. Apart from the very sediment surface the copper concentration-depth profile shape is similar to the organic content in the upper 20 cm.

The zinc, lead and to a lesser extent copper profiles indicate that the sediment has been contaminated by these trace metals above 30 cm. This depth is below the dated part of the core but the maximum period of contamination, from 9 to 17 cm corresponds to 1900 to 1935 (Table 8).

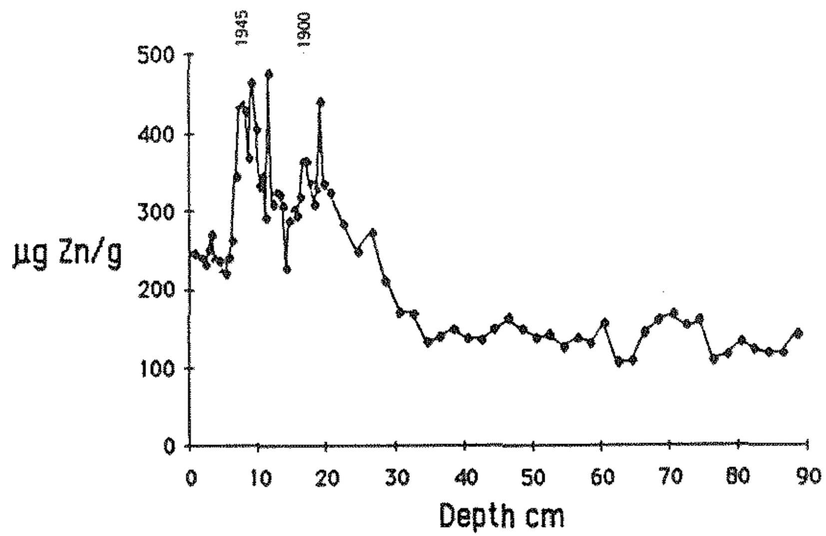
An attempt can be made to ascribe a date to the 30 cm sediment level when the trace metal results suggest contamination commenced. This must be done carefully as three sediment properties (major cations, pollen & diatoms) indicate that the erosion rate of material from the catchment began to decrease at this level. In the absence of contamination, sedimentary trace metal concentrations can increase when erosion rates fall. This has been observed in Loch Dee (Rippey unpublished) and because the erosion rate changes were within the dated part of the core, trace metal fluxes could be used to estimate the start of contamination and its size. This approach, however, cannot be used here as the changes are below the dated part of the core.

Trace metal and major ion concentrations are usually highly correlated in sediments when there is no contamination. This is the case with lead/zinc and potassium below 30 cm depth in Llyn Gynon (Fig. 23). With lead there is an almost immediate change to a new relationship which reflects the contamination regime, whereas, the change is more gradual with zinc. The zinc versus potassium relationship during contamination is established around 24 - 25 cm depth. In both cases, however, the departure from the pre-contamination relationships starts around 30 cm although the initial degree of lead contamination is higher than with zinc. The lead/zinc versus sodium behaviour is identical to lead/zinc versus potassium. This analysis confirms that contamination does commence around 30 cm depth. This depth can only be dated by extrapolation from the dated section of the core (Table 8) and corresponds roughly to 1725 A.D. This is a very early date and needs some comment.

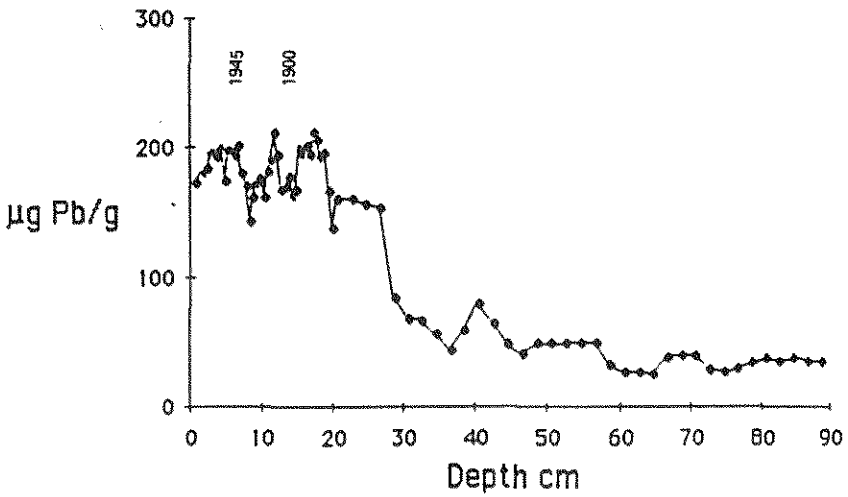
The date is only a rough estimate as the sediment level is below the dated part of the core. It is also at the end of a period when chemical and microfossil evidence indicates that erosion rates from the catchment were higher. The sediment accumulation rates were presumably higher then also



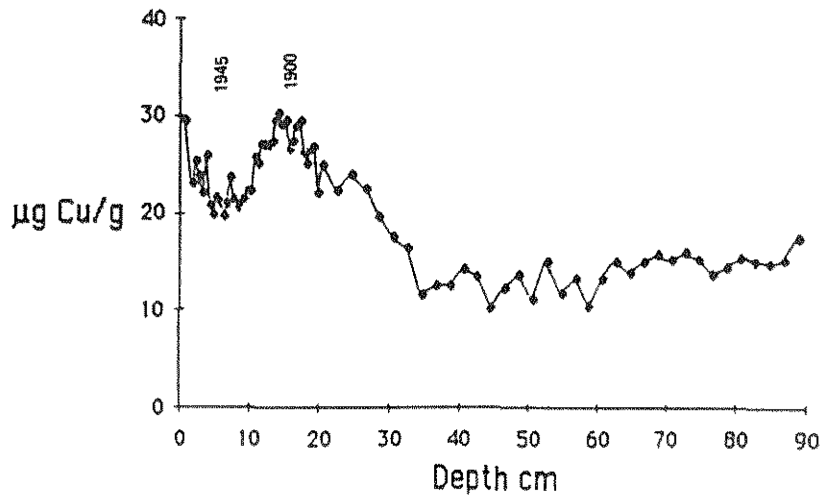
17. Variations in Ni gdw⁻¹ for the Llyn Gynon 3 core



18. Variations in Zn gdw⁻¹ for the Llyn Gynon 3 core



19. Variations in Pb gdw⁻¹ for the Llyn Gynon 3 core



20. Variations in Cu gdw⁻¹ for the Llyn Gynon 3 core

and therefore 30 cm could be later than 1725 A.D. Lead contamination has been recorded in the early 18th century (Fletcher 1985) and it is the lead contamination that is most important just above the 30 cm level. Zinc contamination only becomes important later, around 25 cm.

If the early date is correct then this sensitive record of trace metal contamination may be due to the sediment focussing in Llyn Gynon. Trace metals are incorporated into the fine-grained fraction of sediments (Salomons & Forstner 1984, pp69-76) and if it is this fraction that is selectively focussed at the coring site (as is the case with ^{210}Pb, 4.1.2) the net sedimentary trace metal concentrations would be particularly high there also. The effect is a magnification of the trace metal contamination signal. Without magnification, low level contamination would not be detectable against normal environmental variations of trace metal concentration.

We have found that copper profiles in the Scottish and Welsh lakes examined only show low levels of contamination (Fritz <u>et al</u>. 1986, Kreiser <u>et al</u>. 1986). This is also the case here and above 20 cm at the peak of contamination the profile appears to be more affected by changes in the organic matter content of the sediment. Of the four trace metals determined copper is the one with the most affinity with natural organic compounds (Tipping <u>et al</u>. 1983, Mantoura <u>et al</u>. 1978, Davis & Leckie 1978).

We can use the sediment chronology (Table 8), density (Fig 6), dry weight (Fig. 6) and trace metal concentrations (Figs. 17 - 20) to calculate the contamination fluxes. As the background concentrations are before the dated portion of the core we cannot calculate exact background fluxes. We can use the constant sediment accumulation rate measured in the upper 20 cm (35 mg cm^{-2} yr^{-1}) but this must be done carefully.

Llyn Gynon shows sediment focussing and this may not always have been constant. Furthermore, the measured accumulation rate is quite high because of sediment focussing. The background value, for example, in Llyn Hir is 5 mg cm^{-2} yr^{-1}. We can use the measured accumulation rate in Llyn Gynon and note that the background trace metal fluxes may be lower and so the contamination fluxes may be higher (Table 10).

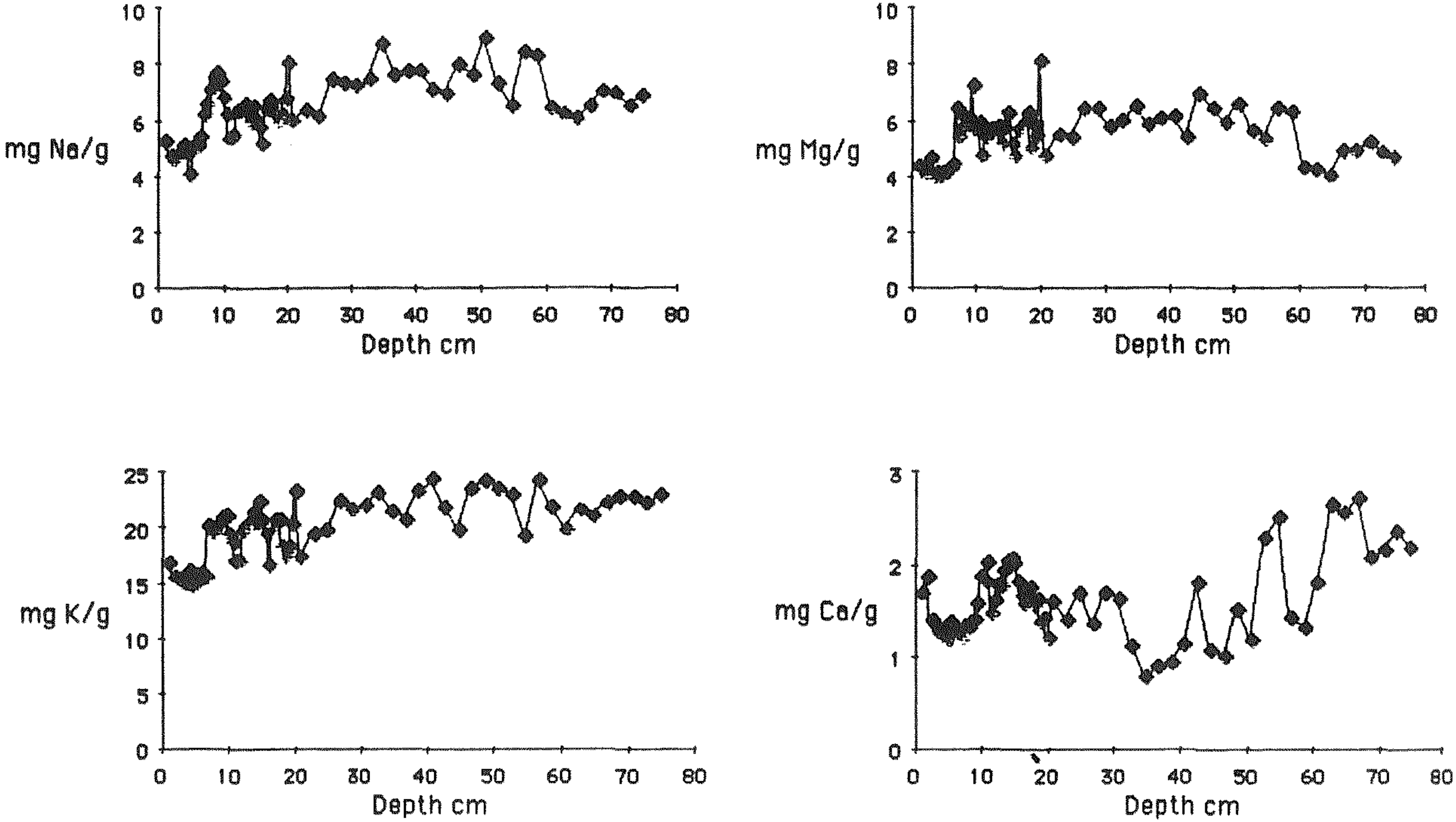
Table 10. Sedimentary trace metal fluxes mg m^{-2} yr^{-1}

	Background	Maximum	Contamination
Zinc	50	137	87
Lead	15	100	85
Copper	11.5	14	2.5

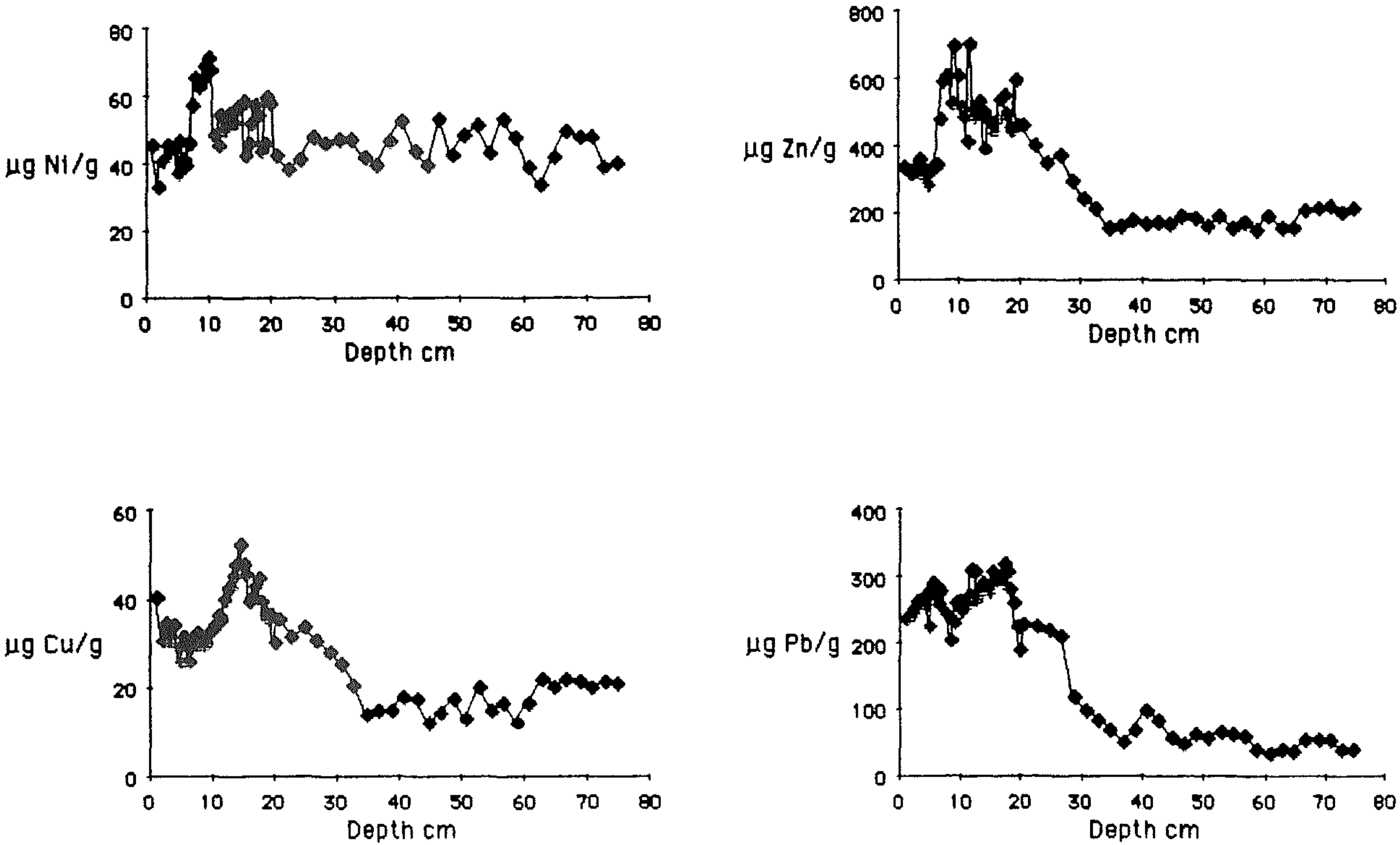
The contamination fluxes are typical of those found in other Welsh and Scottish lakes (Fritz <u>et al</u>. 1986, Battarbee <u>et al</u>. 1985).

The most likely source of metal contamination in Llyn Gynon and the other lakes is atmospheric deposition. Wastewater sources in these remote lakes are most unlikely and the normal background concentrations indicate that there is no mineralization in the Llyn Gynon catchment.

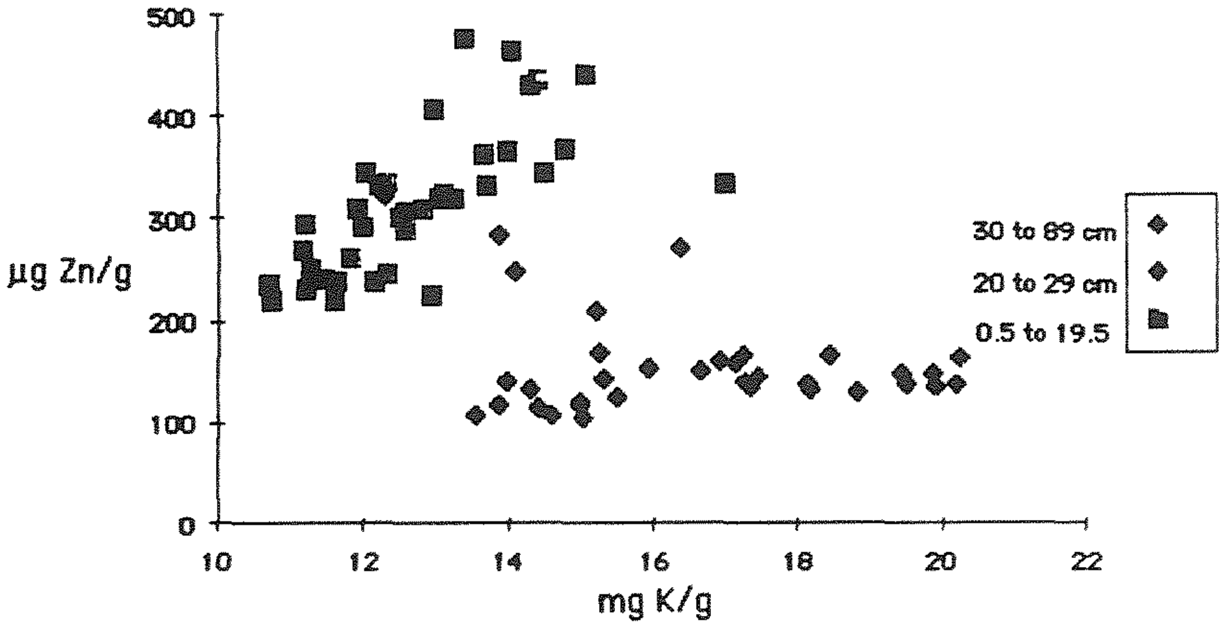
The concentration of zinc falls in the top 6 cm whereas lead is fairly constant. The drop in zinc may be due to a decrease in the flux from the atmosphere and/or a lower pH in the lake. This behaviour has been observed

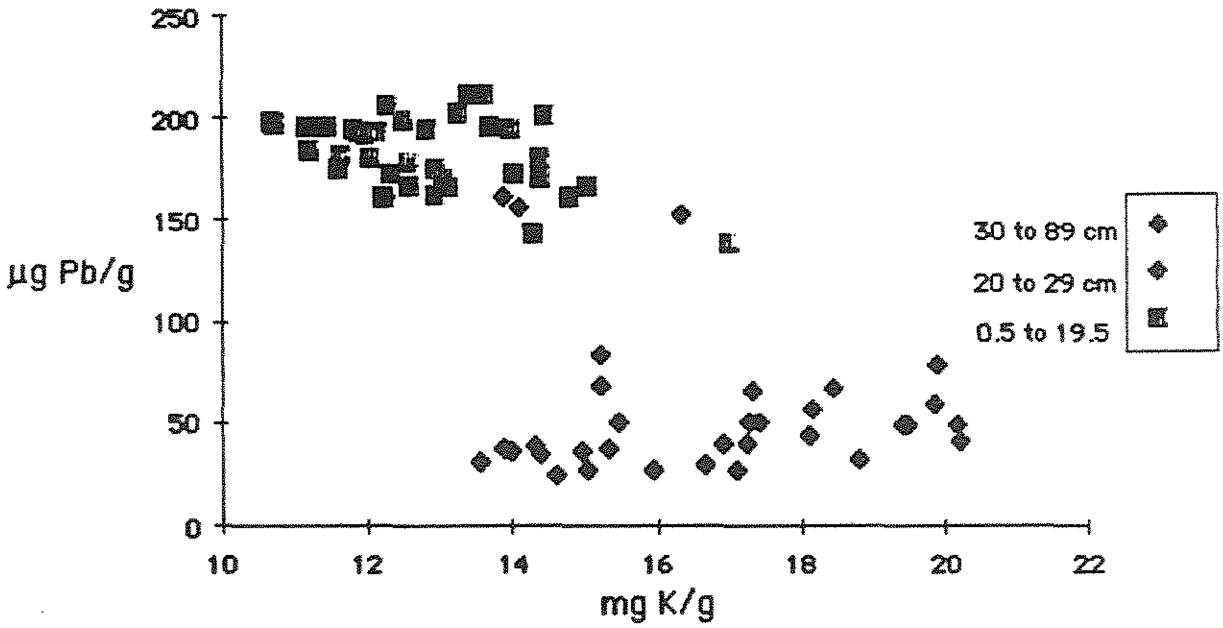


21. Variations in Na, Mg, K & Ca per gramme mineral dry weight for the Llyn Gynon 3 core



22. Variations in Ni, Zn, Pb & Cu per gramme mineral dry weight for the Llyn Gynon 3 core





23. The relationships between lead and potassium concentrations
and zinc and potassium concentrations in the Llyn Gynon 3 core

in two Scottish lakes (Battarbee et al. 1985, Rippey unpublished) and one other Welsh lake (Fritz et al. 1986). A drop in lake pH could cause a drop in the sedimentation efficiency and/or release of zinc from the sediment. No exact pH can be given below which a metal is desorbed from sediment as this depends on the sediment constitution (Benjamin et al. 1982) although it is recognised that zinc is more susceptible to release at lower pH than other trace metals. Zinc tends to be desorbed below pH 4.5 to 5.0 (Mouvet & Borg 1983, Evans et al. 1983, Norton & Hess 1980, White & Driscoll 1987) but as the diatom-inferred pH only drops from 6.0 to 5.5 in the top 6 cm (Fig. 11) it may be that there is a drop in the flux of zinc from the atmosphere.

Sulphur

The sedimentary sulphur concentrations oscillate rapidly, especially in the upper 30 cm (Fig. 24). To assess if there is any pattern in the results the values have been smoothed and this is indicated in the diagram by the continuous line. While there is now an indication that the sulphur concentration rises at 30 cm as with zinc and lead (Figs. 18 & 19) the trends are not very clear.

PAH

Analyses are at present being conducted but the results are not yet available

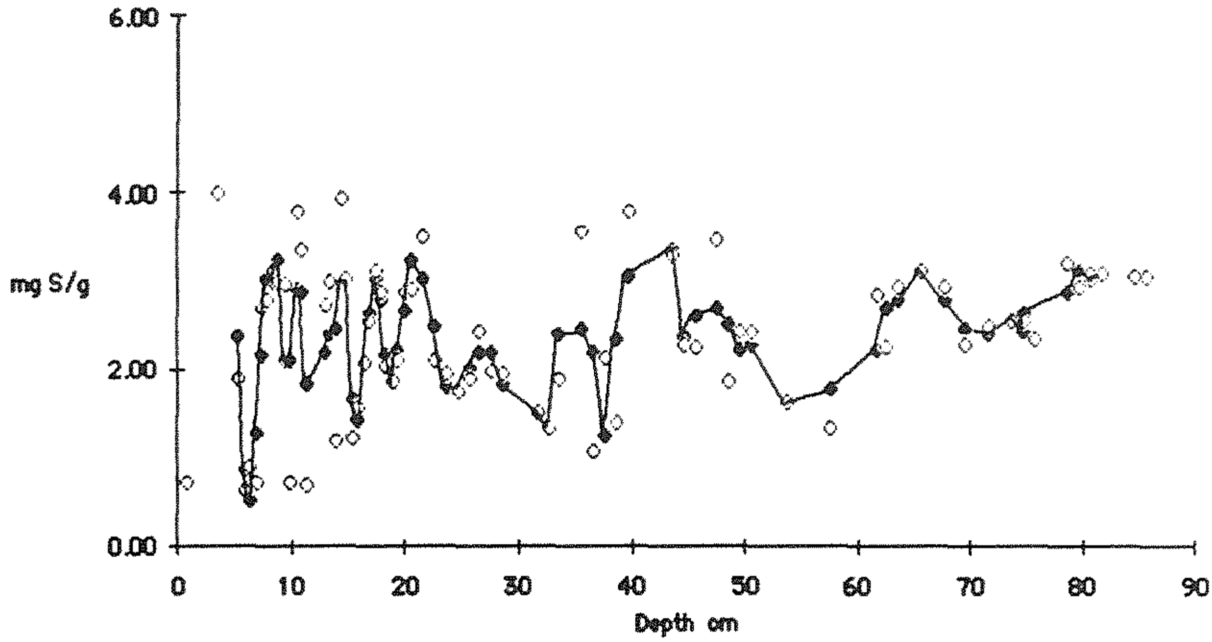
4.1.5. Carbonaceous particles "CP"

The "CP" pattern for Llyn Gynon, illustrating the number of particles per gram dry sediment is given in Fig. 25 & Table 10. It shows the presence of carbonaceous particles in small numbers at a depth of 32 cm (ca. 1750 A.D.). A smooth rise in particles then occurs to 8 cm (1940) subsequently followed by a very steep rise in concentration to the top of the core.

The pattern for the CP count in terms of the organic content of dry sediment is given in Fig. 26. CP patterns expressed in terms of the organic fraction of sediment (using LOI) may be considered to be more precise than expression per gram dry weight as the supply of organic material to the sediment tends to be more uniform over time than the input of mineral matter, which can vary widely. Using LOI as a base has the effect of 'smoothing' the CP pattern, and this can be observed for Llyn Gynon. Otherwise, the pattern is very similar to that in Fig. 25.

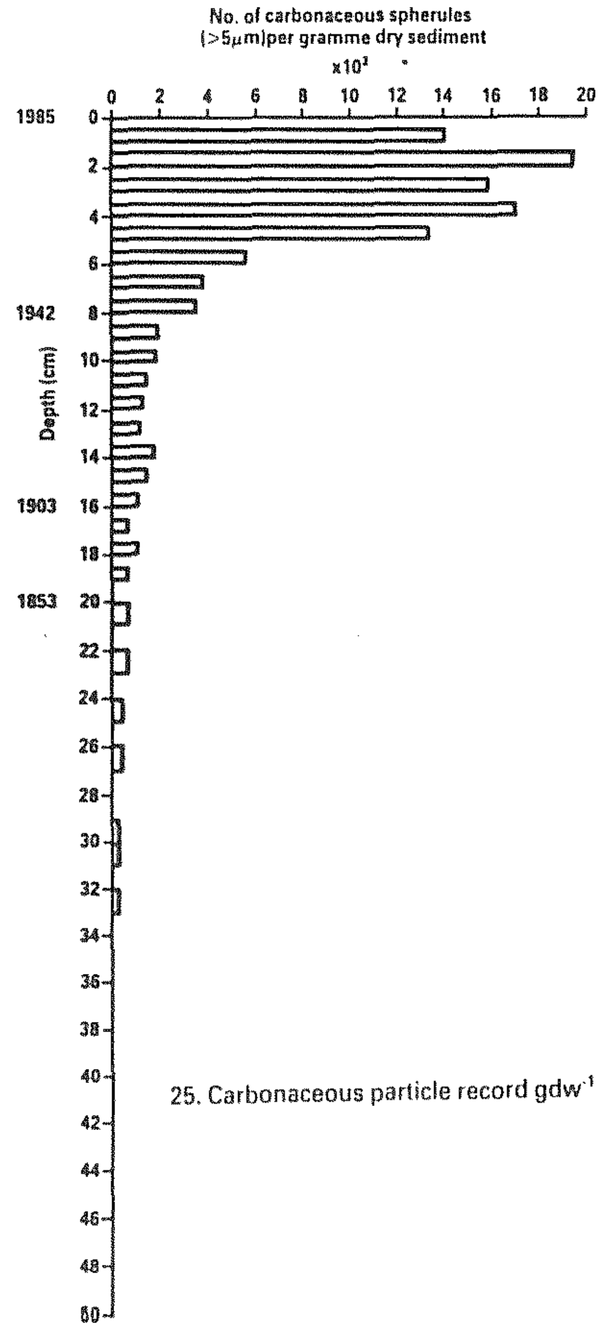
4.1.6 Magnetic Measurements

Fig. 27 plots the results of ARM, SIRM and IRM measurements on the Gynon 3 sediment core. 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 demagnetization at which IRM is zero and 100 represents the point at which IRM/SIRM is -1. Fig. 28 plots $SIRM-IRM_{-20mT}$ as a mass specific remanence versus depth. This is the best available (albeit imperfect) estimate of the changing concentration of multidomain 'magnetite' in the core. Our unpublished evidence indicates that this is often the best single 'magnetic' indicator of recent anthropogenically derived atmospheric deposition. Fig. 29 plots $SIRM+IRM_{-300mT}$ also as a mass specific remanence versus depth. This is the

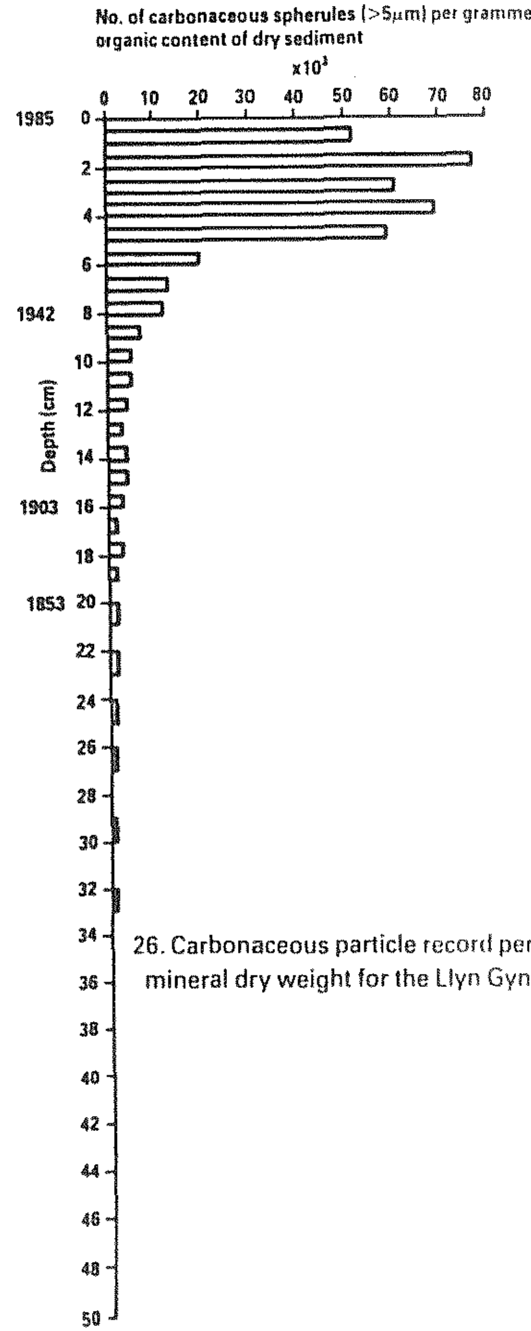


24. Variations in S gdw^{-1} for the Llyn Gynon 3 core

Sheppard five-term smoothing



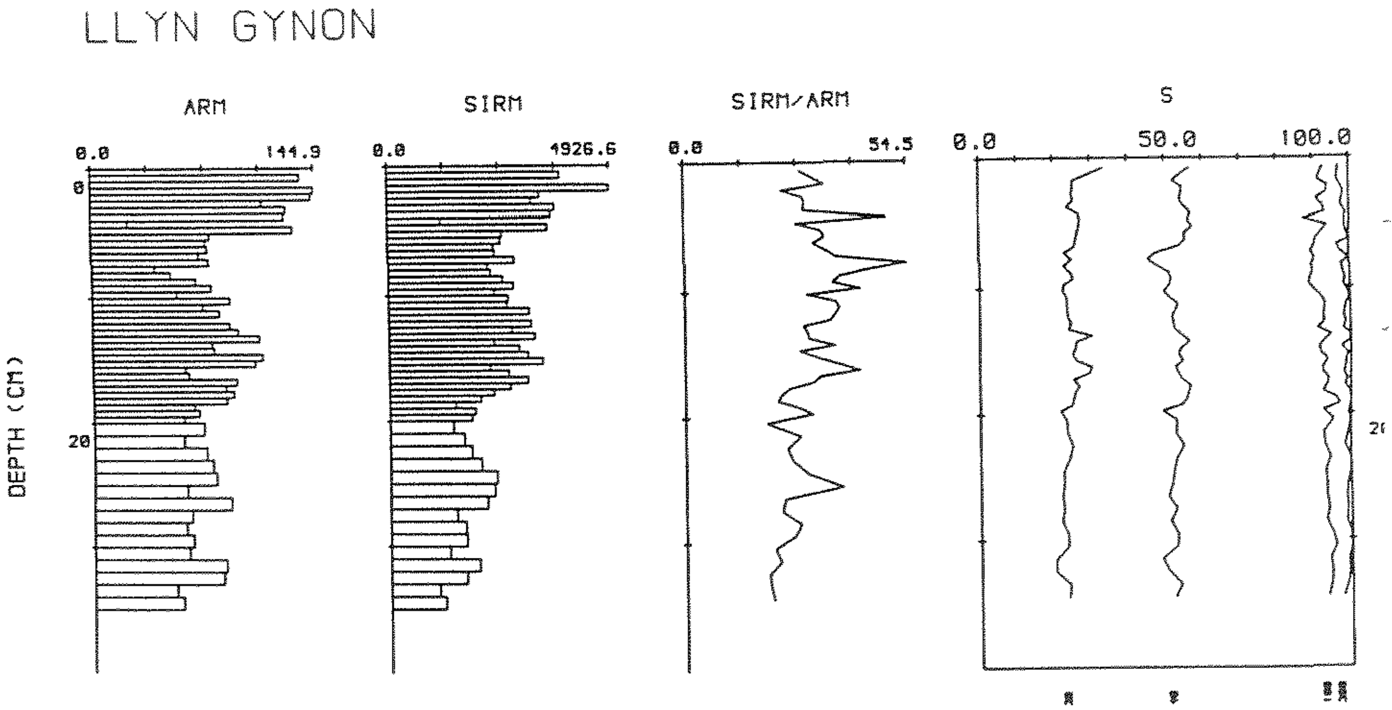
25. Carbonaceous particle record gdw[-1] for the Llyn Gynon 3 core



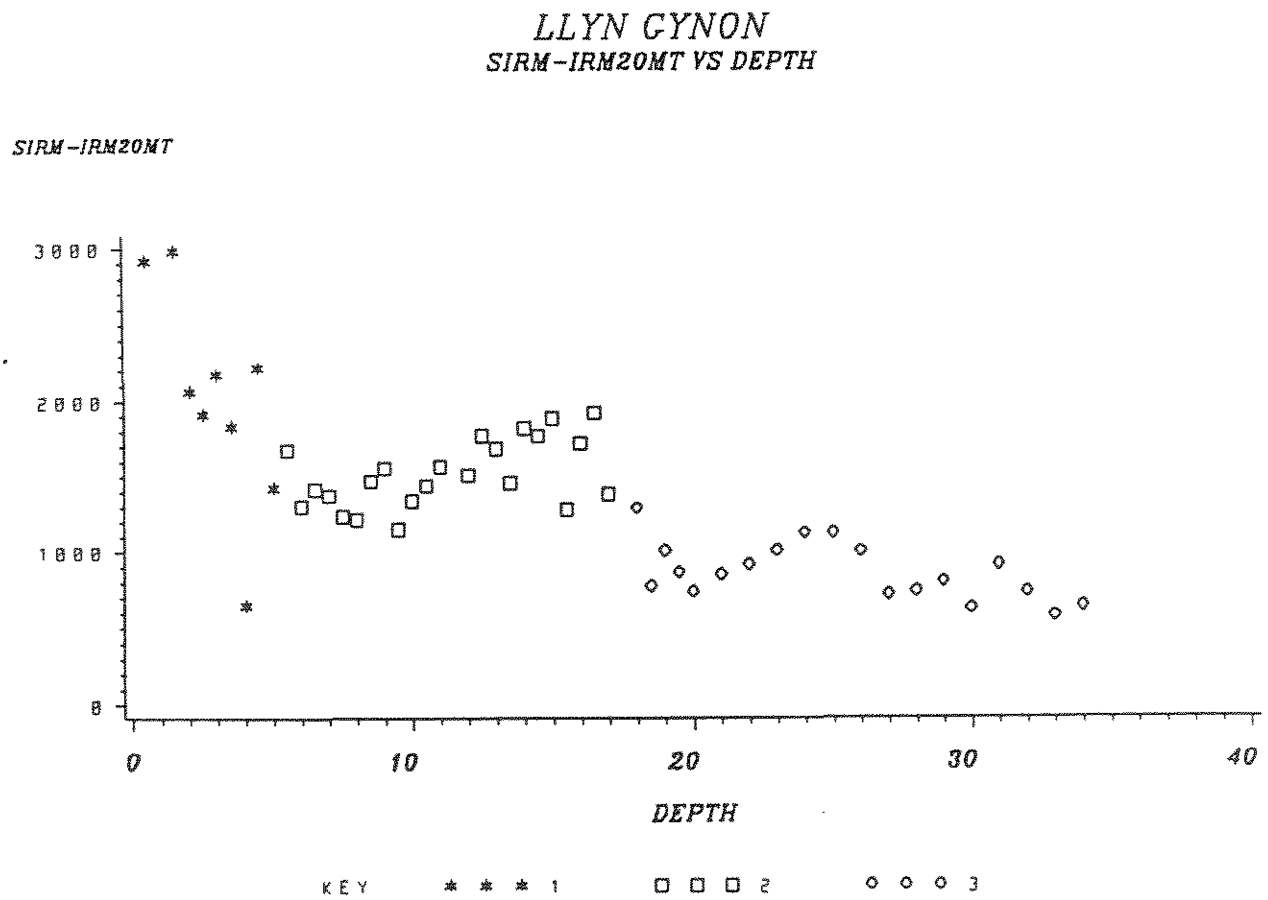
26. Carbonaceous particle record per gramme mineral dry weight for the Llyn Gynon 3 core

Table 11: Carbonaceous particle analysis for Gynon 3

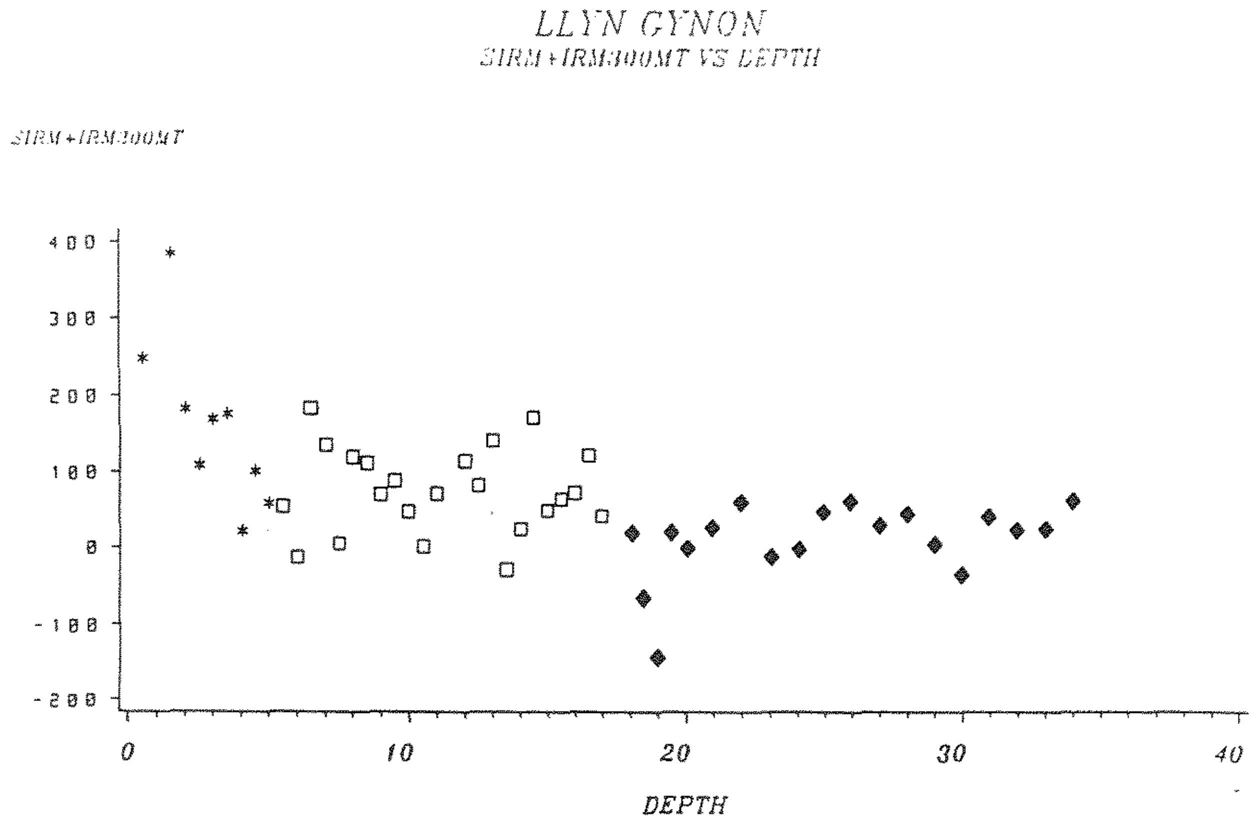
Depth (cm)	No. Carbonaceous Particles per g dry sed $\times 10^3$	No. Carbonaceous Particles per g organic content $\times 10^3$
0.5 - 1.0	14.06	51.9
1.5 - 2.0	19.39	77.0
2.5 - 3.0	15.86	61.1
3.5 - 4.0	17.00	69.2
4.5 - 5.0	13.26	59.3
5.5 - 6.0	5.49	19.7
6.5 - 7.0	3.66	13.0
7.5 - 8.0	3.54	12.4
8.5 - 9.0	1.92	6.5
9.5 - 10.0	1.83	5.4
10.5 - 11.0	1.38	4.7
11.5 - 12.0	1.32	4.1
12.5 - 13.0	1.09	3.0
13.5 - 14.0	1.69	4.4
14.5 - 15.0	1.39	3.5
15.5 - 16.0	0.98	3.0
16.5 - 17.0	0.54	1.7
17.5 - 18.0	0.95	2.9
18.5 - 19.0	0.56	2.2
20.0 - 21.0	0.60	2.0
22.0 - 23.0	0.51	1.8
24.0 - 25.0	0.25	0.9
26.0 - 27.0	0.31	1.1
29.0 - 30.0	0.11	0.4
30.0 - 31.0	0.09	0.3
32.0 - 33.0	0.13	0.6
34.0 - 35.0	-	-
37.0 - 38.0	-	-
40.0 - 41.0	0.06	0.3
43.0 - 44.0	-	-
46.0 - 47.0	0.04	0.3
49.0 - 50.0	-	-
52.0 - 53.0	-	-



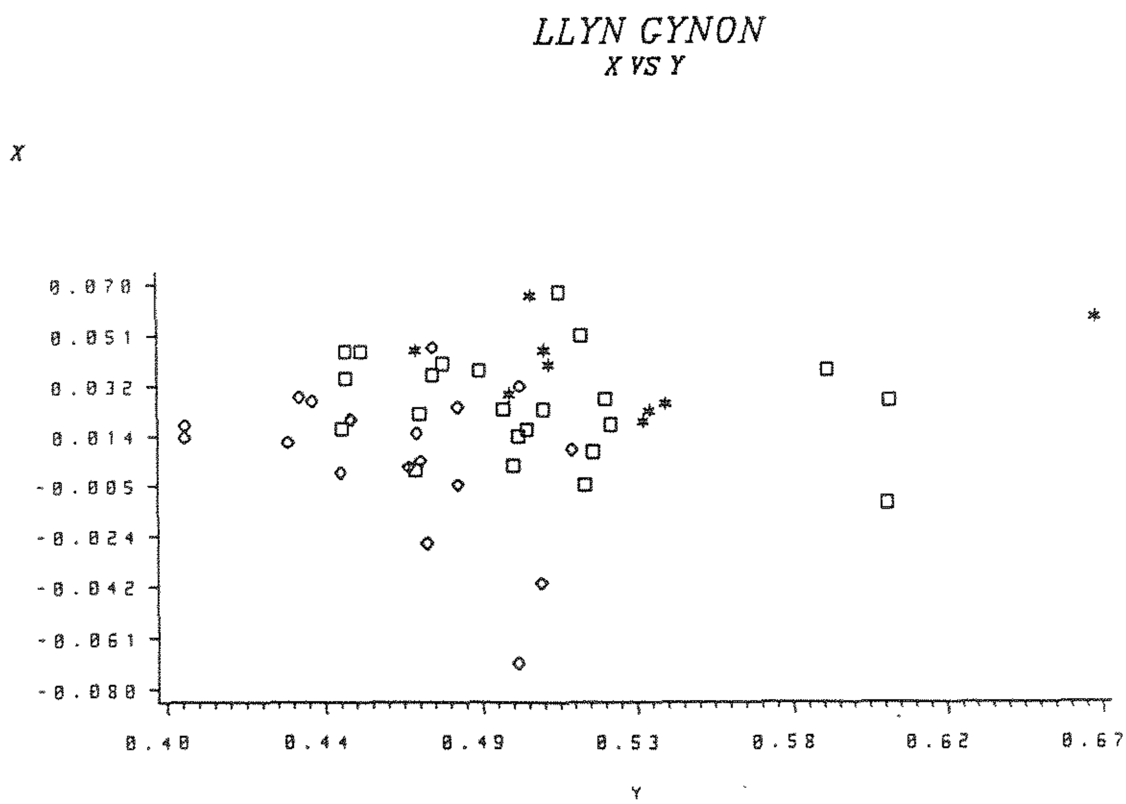
27. Magnetic measurements for the Llyn Gynon 3 core



28. Mass specific remanence variation in SIRM - IRM_{20mT} for the Llyn Gynon 3 core



29. Mass specific remanence variation in SIRM - IRM_{300mT} for the Llyn Gynon 3 core



30. Cross plots of normalised magnetic parameters for Llyn Gynon

best available estimate of the changing concentration of 'haematite' in the core. $SIRM-IRM_{-20mT}$ increases significantly between 20 cm and 17 cm and is the main component in the SIRM increase. There are less significant and/or less consistent increases in $SIRM+IRM_{-300mT}$ and ARM. The CRS ^{210}Pb model dates suggest that this increase takes place between 1860 and 1890 AD. Around 5 cm, ARM, SIRM, $SIRM-IRM_{-20mT}$ and $SIRM+IRM_{-300mT}$ all increase sharply. This level is dated to ca. 1960 AD.

In order to test the hypothesis that the magnetic properties of the most recent sediments can be ascribed in part to an anthropogenically derived component distinguishable from pre-industrial catchment inputs, several cross-plots of normalized magnetic parameters were compiled (Figs. 30-32). In each plot, samples below 17.5 cm, those from 5 to 17.5 cm and those above 5 cm are separately distinguished.

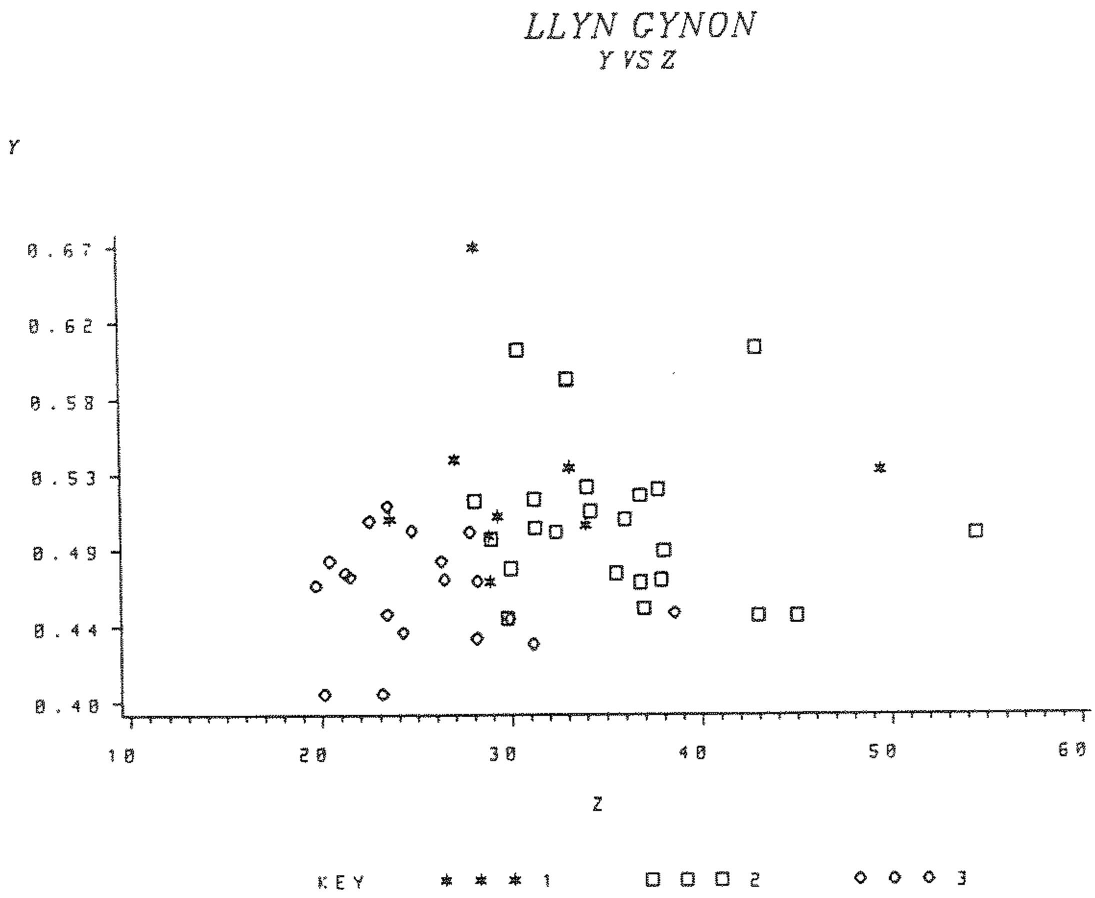
Parameter X is $$\frac{SIRM + IRM_{-300mT}}{SIRM}$$

Parameter Y is $$\frac{SIRM - IRM_{-20mT}}{SIRM}$$

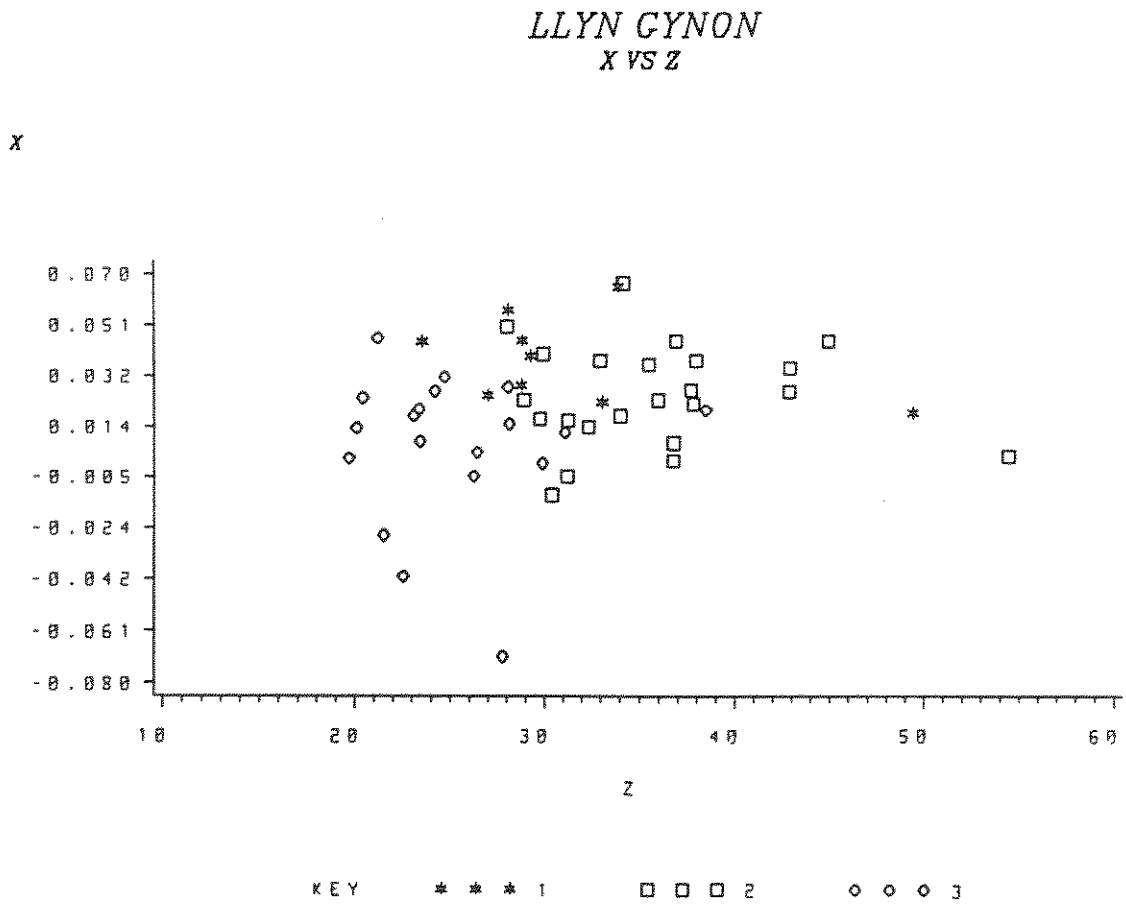
and Z is SIRM/ARM. In all cases the envelope of values for samples above 5 cm is indistinguishable from that for samples between 17.5 cm and 5 cm. However, both upper samples sets are relatively well distinguished from the lowest. This is reflected most clearly in lower SIRM/ARM values below 17.5 cm, though the extreme values of parameters X and Y are also lowest below this depth. In rock magnetic terms, these changes point to a proportionally higher stable single domain contribution in the lowest part of the core and a proportionally greater multidomain ferrimagnetic (cf. magnetite) and canted anti-ferromagnetic (cf. haematite) contribution above. These observations, coupled with the observed increases in the concentrations of these components, are consistent with a distinctive and additional magnetic input from the mid-late nineteenth century onwards. The magnetic properties themselves are consistent with the hypothesis that this contribution is at least in part anthropogenically derived. 'background' magnetic deposition from the catchment gives SIRM values of ca. 1×10^{-3} Am^2 kg^{-1}. Such values are between one and two orders of magnitude higher than those recorded in pre-industrial ombrotrophic peats. It is therefore difficult, from these measurement alone, to confirm and quantify an anthropogenic input. The magnetic accumulation rates calculated using the ^{210}Pb sedimentation rate are within the range obtained for recent peats from upland Britain through ca. 4 times the rates obtained for nearby Llyn Hir. For the post-1980 sediments the 'multidomain magnetite' accumulation rate per m^2, as approximated by $SIRM-IRM_{-20mT}$, is around 1×10^{-3} Am^2. This is between 6 and 7 times the values for the early 19th century sediments at the site (Fig. 33). Present evidence does not preclude the hypothesis that this increase is at least in part, a function of anthropogenically derived deposition especially since ca. 1960.

4.1.7 Pollen

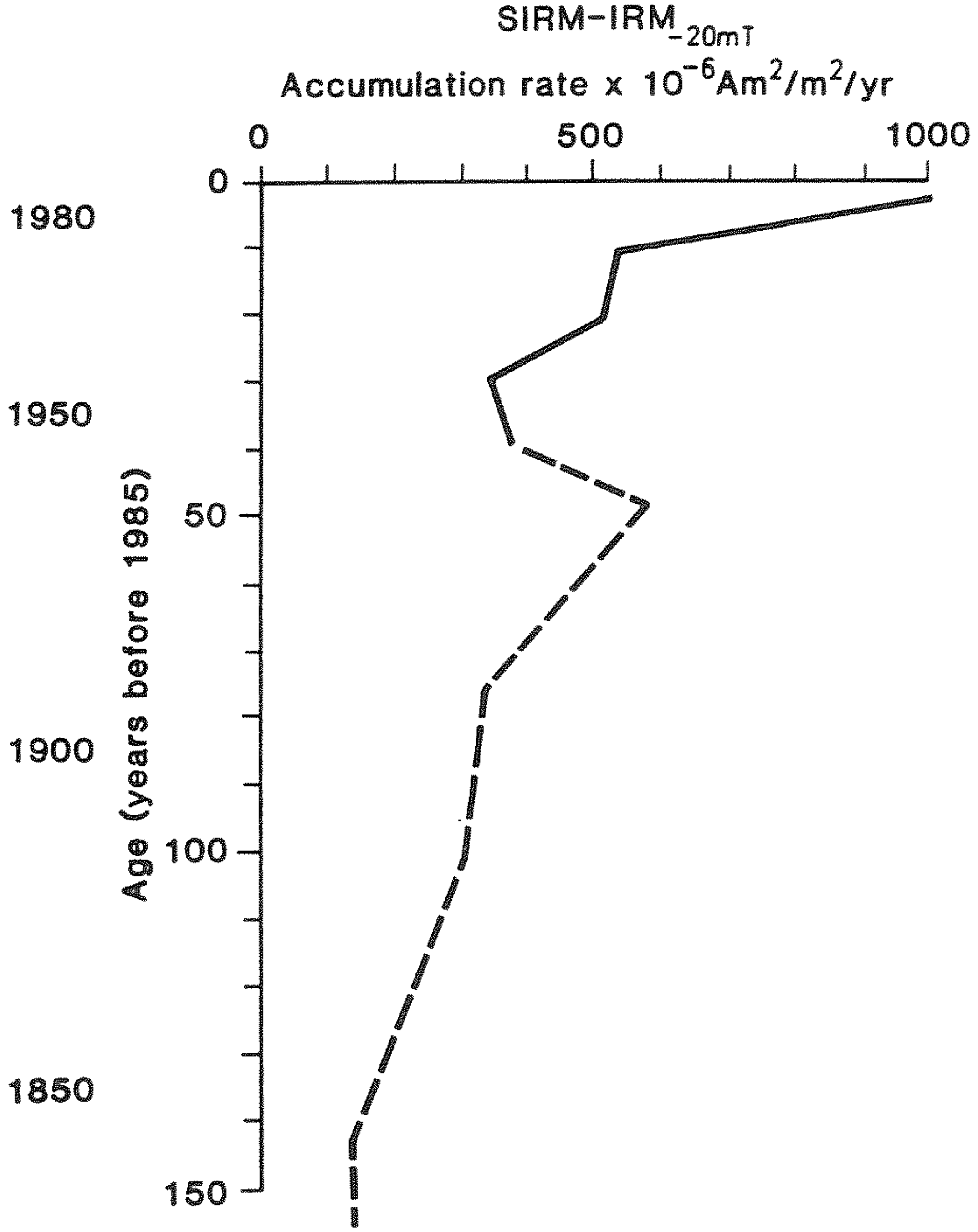
Early work on a blanket peat section from a site located on the northern shore of the lake (Fig. 34) enables insights to be gained into the Holocene vegetational history of the area (Moore 1966, Moore & Chater 1969).



31. Cross plots of normalised magnetic parameters for Llyn Gynon

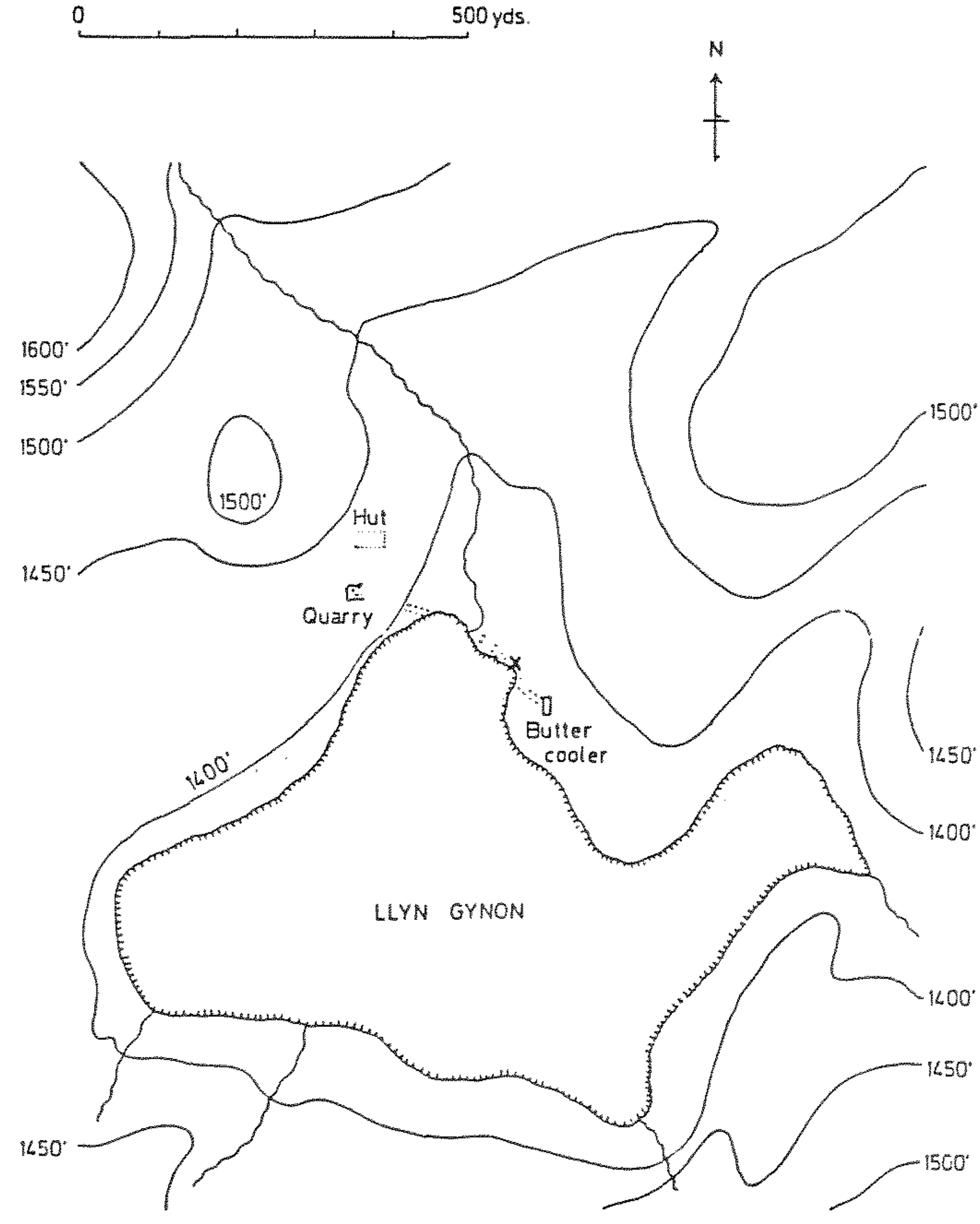


32. Cross plots of normalised megnetic parameters for Llyn Gynon



33. Multidomain magnetite accumulation rate for Llyn Gynon 3

Llyn Gynon showing position of trackway



34. Catchment map showing butter cooler, trackway and quarry

Stratigraphic investigations reveal a detailed story of plant succession within the catchment (Moore 1966). Initially, a Phragmites/Juncus rich community became established on an old stream bed. Subsequently Carex rostrata invaded and became dominant. The sediment at this time is also rich in macrofossils of Betula and Pinus and appears to date from the Boreal period (ca. 8500 B.P.). Around 7000 B.P., an extensive alder carr developed over the sedge community but gradually became less abundant as acid bog vegetation, dominated by Molinia and Eriophorum, developed. A hiatus caused by the emplacement of a medieaval trackway across the peat surface then exists in the section. A Nardus/Festuca grassland peat is developed directly over the trackway, representing the present vegetation of the better drained, drier slopes.

The pollen diagram provides not only a detailed picture of the local vegetation but also an overview of the early-mid-Holocene vegetation of the region. The initial sediments date from early Boreal times and are characterised by high pollen values of Betula, Pinus and Ulmus. Quercus values are low throughout. Locally, the early Phragmites / Cyperaceae communities are reflected in high values of Gramineae and Cyperaceae pollen. A more mesotrophic macrophyte vegetation existed in the lake than at present with Myriophyllum alterniflorum, M.verticillatum, Nymphaea and Sparganium pollen recorded.

The late Boreal part of the diagram shows a period of increasing oak forest as values of Quercus pollen rise at the expense of Ulmus and Pinus. Salix becomes dominant in the local marsh community. The onset of Atlantic times (7000 B.P.) is reflected by the characteristic rise in Alnus eventually dominating the local marsh vegetation. Throughout this rise ruderal pollen indicators such as Plantago lanceolata, P. major & Rumex are also prominent. This occurrence of ruderal plants with the alder rise has been noted elsewhere and it has been suggested that anthropogenic interference in the vegetation aided the spread of Alnus from its normal coastal and wet marsh habitats (Smith 1984).

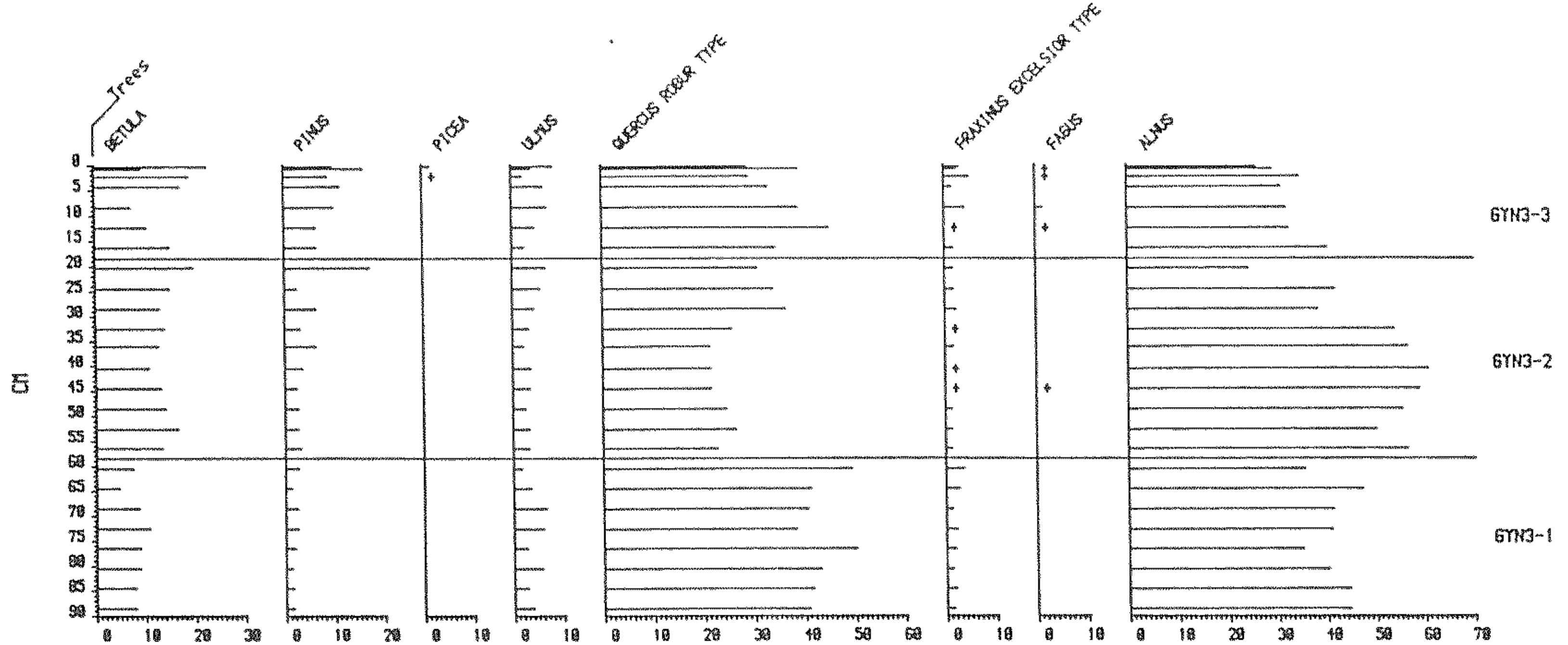
The local dominance of alder appears to be short lived and values decline once more as values of peat-indicative pollen types increase eg. Cyperaceae, Sphagnum, Potentilla, Succisa and Ericaceae. At the same time the elm decline occurs and weed pollen values, e.g. Plantago lanceolata, P.major increase dramatically, reflecting the clearance of woodland from the catchment.

The mediaeval trackway then prevents any further insights into the vegetation development save for sediments above the trackway which are similar to the present day pollen rain from the current peat forming communities.

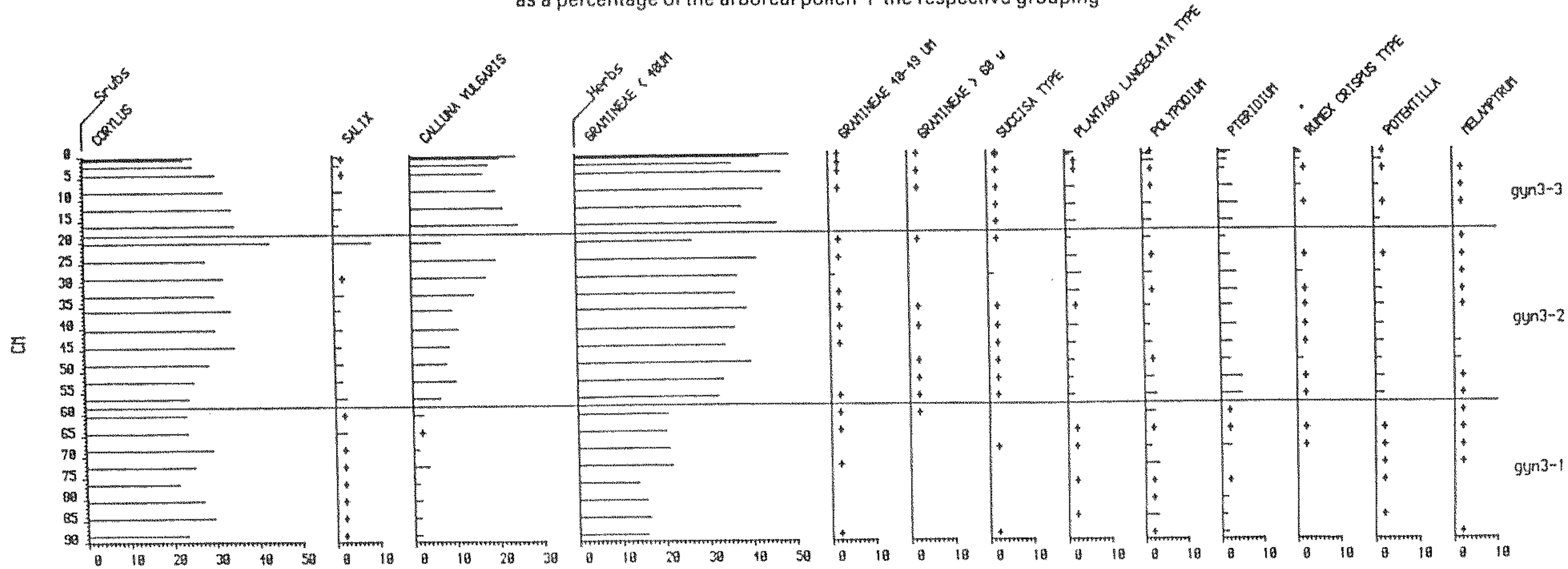
Gynon 3 lake core

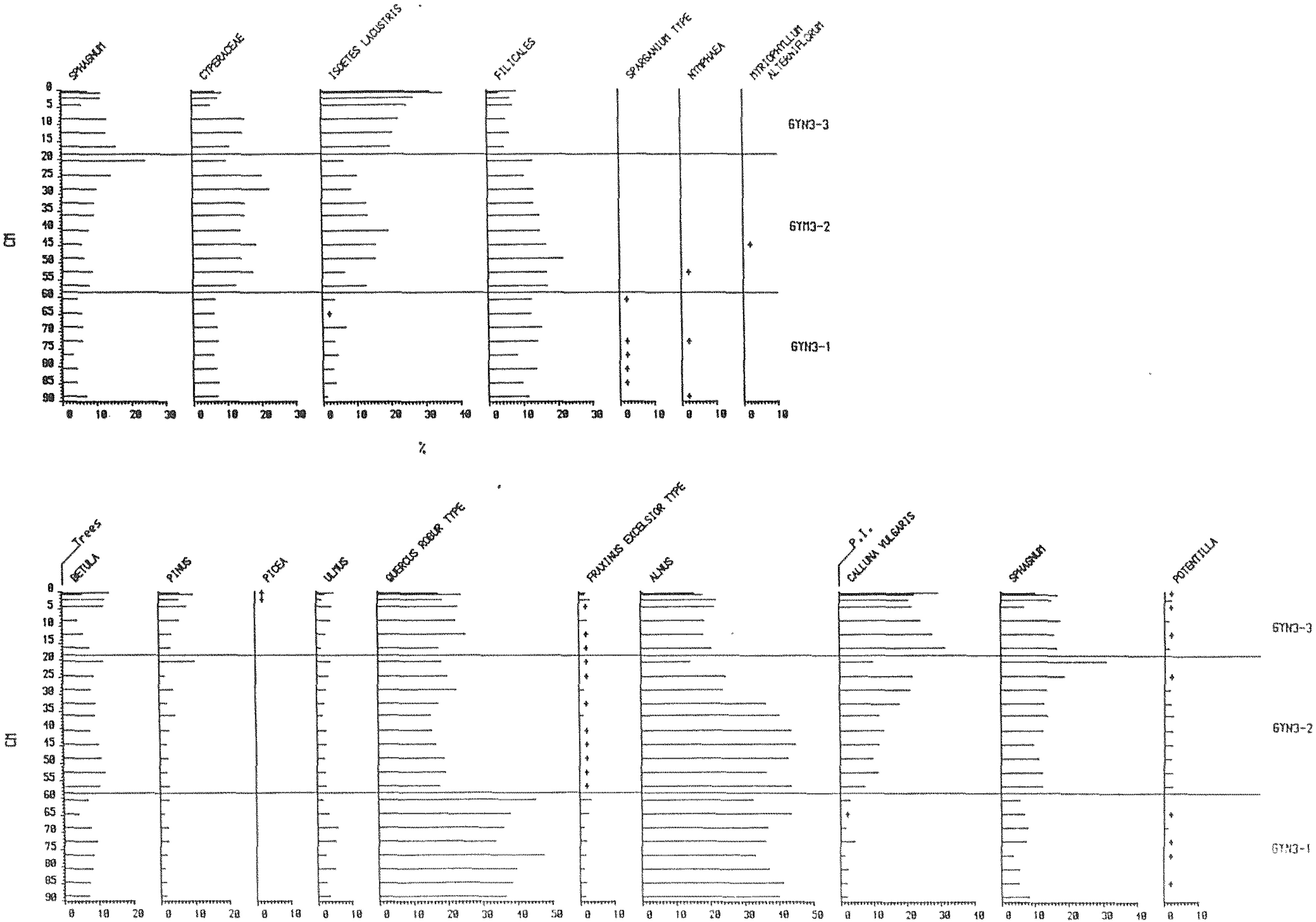
The summary pollen diagrams for the Gynon 3 sediment core is shown in Figs. 35 & 36 and concentration diagram for total pollen in Fig. 37. Full pollen diagrams may be found in Appendix C.

A zonation of the diagram was achieved using the procedures of Gordon & Birks (1972) and produced a threefold zonation, the most important of which, 58 cm, indicates that a hiatus may exist in the sediment record.

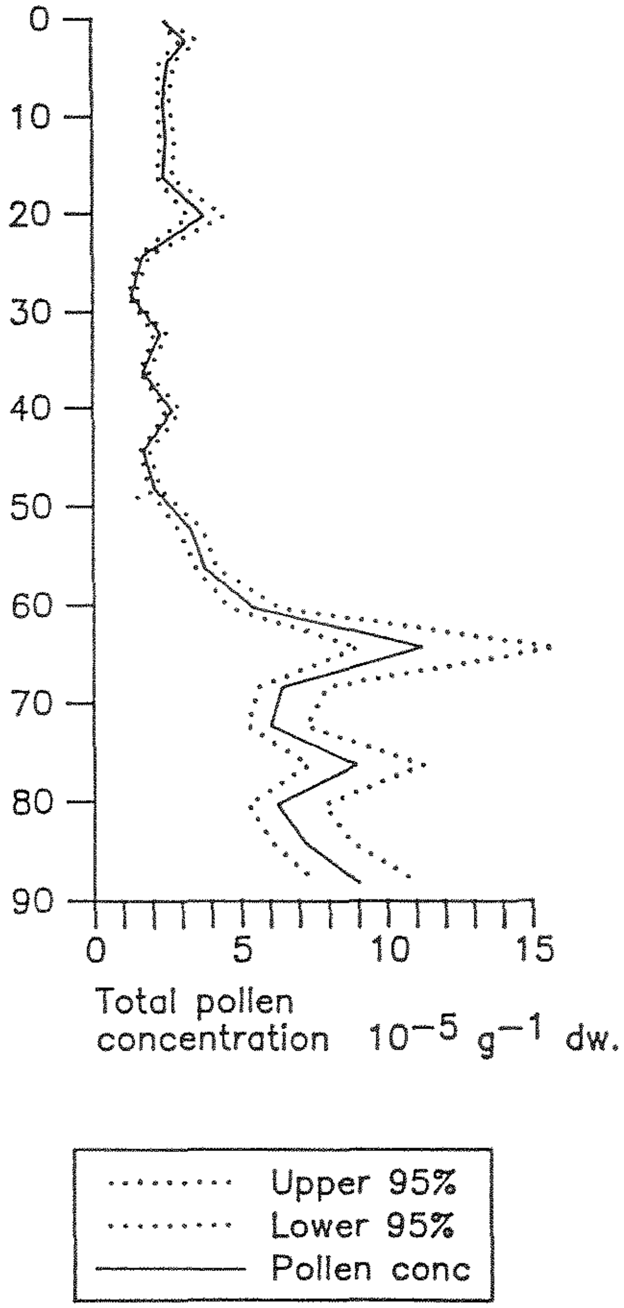


35. Summary pollen diagram for the Llyn Gynon 3 core. Trees expressed as a percentage of the arboreal pollen. All other groupings as a percentage of the arboreal pollen + the respective grouping





36. Summary pollen diagram for the Llyn Gynon 3 core. All taxa expressed as a percentage of the arboreal pollen + peatland indicators sum



37. Pollen concentration diagram

GYN3-1

This zone is characterised by very high values of Quercus in association with Ulmus. Examination of the peatland summary diagram suggests that the catchment at this period was still forested with an open acid Quercus woodland. Dating of this zone is relatively imprecise but must post date the alder rise at 7000 B.P. However, the high values of Quercus both on the relative and concentration diagrams, together with the lack of evidence of extensive blanket peats within the catchment and the high Ulmus values, tends to suggest a period just before the elm decline, with the fall in elm at the very end of the zone.

Pollen records of macrophytes are common throughout the zone and suggest the local presence of a mesotrophic Sparganium / Nymphaea community and correlate well with the late Atlantic portion of the peat diagram.

The termination of the zone is marked by abrupt changes in the major pollen types with values of Quercus falling some 20% as values of Calluna, Cyperaceae and Sphagnum all increase. This feature is shown also on the peatland summary diagram and is even more marked on the total concentration diagram where total pollen concentrations decline twofold. The zone boundary represents a hiatus in the sedimentary record with sedimentation and pollen accumulation only recommencing relatively recently (ca. 1700 A.D.).

GYN3-2

Throughout this zone values of Quercus and Ulmus are low. The pollen is dominated by blanket peat indicators such as Calluna, Cyperaceae, Sphagnum, Potentilla and Succisa, a feature also demonstrated by the peatland summary diagram. Bouts of anthropogenic interference are shown by the large peaks in the ruderal indicators, Plantago lanceolata and Rumex, associated with probable upland Napoleonic growing of cereals as shown by the large cereal peaks.

The mesotrophic aquatic indicators are progressively lost during the zone and values of the oligotrophic indicator, Isoetes, increase. A possible erosion feature is demonstrated by the depression in Isoetes values from 40 cm - 20 cm associated with high peatland values, a feature commonly found in many of the other lakes in this study (Fritz et al. 1986, Anderson et al. 1986, Stevenson unpublished data)

GYN3-3

The very recent sediments show a distinct Pinus rise from 8 cm, together with the presence of grains of Picea, presumably derived from the Towy forest lying some 4 km to the south west. A spike in the Pinus and Sphagnum curves at 20 cm could indicate a possible inwash horizon but does not appear to be reflected in the ^{210}Pb results. Betula values increase and Quercus values undergo a concomitant decline mid-way through the zone and could reflect further clearance and regeneration in the valley bottoms. Throughout, ruderal pollen values are high and a further phase of nearby cereal growing is indicated by the cereal peak at 8 cm.

Increasing oligotrophication of the lake or the relaxation of the inwash could explain the increasing values of Isoetes which now dominates the aquatic pollen values.

4.2 Land use and management (2)

4.2.1 Land use

At over 400 m, on acidic soils, the Llyn Gynon catchment consists of unenclosed unimproved moorland utilised for rough grazing. The vegetation is dominated by Molinia and Festuca/Nardus grassland with Eriophorum vaginatum characterising the wetter areas (see Section 2.1.3, Fig. 5) and may be characterised as 'grassy heath' (eg. King 1977, Ball et al. 1982).

In terms of the ADAS land capability classification (MAFF 1980) the land is dominated by class 'H3' (improvements generally severely limited but of moderate or high present grazing value), with some areas classed as 'H4' (generally not improvable and of low present grazing value) (3).

This area of Wales witnessed a well documented woodland clearance at the behest of Edward I following the Welsh rebellion at the end of the 13th century (4). However, Moore and Chater (1969) consider this to have been a lowland and foothill clearance. It is probable that land at the altitude of Llyn Gynon has been moorland for a far longer period.

During investigations in the peat deposits at the north shore of the lake, Moore (1966) identified the remains of a stone slab trackway leading from what he interpreted as a 'mediaeval farmhouse' to a 'butter cooler' (constructed not earlier than the 12th century) (Fig. 33). Building material for the trackway was probably obtained from a rudimentary quarry adjacent to the 'farmhouse' (Fig. 33). The broad chronology of these features coincides with the early exploitation of the area as grazing land by the Cistercians of Strata Florida from the late 12th century (Williams 1889).

If the function of these remains has been correctly interpreted and some permanent or semi-permanent habitation was maintained in the catchment during the medieaval period, then a limited improvement of the moorland from enhanced grazing pressure on land in the immediate vicinity of the 'dwelling', may have occurred perhaps regulated by enclosure(s).

The frontiers of cultivation and improved pasture reached their upper limit in Cardiganshire during the agricultural boom of the Napoleonic wars. The rise in rents on the Crosswood and Nanteos Estates (the holders of grazing rights over the Llyn Gynon catchment at this time) bears witness to such expansion locally (Colyer 1976).

However, there is no evidence from documentary sources (see below), from air photographs or on the ground (of relict enclosures, drainage or cultivation features) to suggest that the catchment has ever supported a land use other than rough moorland grazing.

It is unreasonable to expect any attempt to have been made towards improving the acid moorland soils with lime. There was no limestone in Cardiganshire and in the early 19th century lime cost 16d. bushel^{-1} at Aberystwyth (Davies 1815), a price which together with the cost of carriage over bad roads, deterred the farmer from utilising lime on the home farm, let alone on the remoter hills (cf. Rees 1815, Howell 1946) (5). Contemporary farmers (eg. E. Edwards, W. Jones, V. Lloyd pers. comm.) confirm that agricultural lime has not been applied to the catchment in living memory.

Documentary evidence (6)

The catchment lies within the parish of Caron-Uwch-Clawdd. The tithe map and schedule of the combined parish of Caron (Caron-Is-Clawdd and Caron-Uwch-Clawdd combined) (7) indicate that in the mid-19th century the catchment comprised sheepwalks associated with farms belonging to the Nanteos (Powell) and Crosswood (Lisburne) Estates.

The first edition six inch Ordnance Survey map of the area (surveyed 1886), and subsequent editions (8) show the catchment to consist of 'rough or heathy pasture'.

The first Land Utilisation Survey 6 inch manuscript map of 1933 (9) provides no detail within the lake catchment, describing the area as 'typical hill sheepwalk' characterised by bent fescue, Molinia and Nardus.

The Second Land Utilisation Survey 6 inch manuscript map of 1970 (10) indicates a vegetational cover identical to the contemporary situation, with Festuca and Nardus on the drier ground and Eriophorum vaginatum dominating the wetter areas (Fig. 5).

Analysis of primary data (11) from which the Countryside Commission's 'Mid-Wales Uplands Study' (Parry and Sinclair 1985) was compiled, confirms that the Llyn Gynon catchment has remained consistently within the 'moorland core' of unimproved rough pasture since 1948. The closest land to have experienced any documented change in land use lies 0.6 km. to the west of the catchment.

Non-agricultural land use

Although it lies in the broad vicinity of the north Cardiganshire lead mining region, there is no evidence from documentary sources or on the ground, to suggest that any mineral was ever mined or prospected for, within the lake catchment.

4.2.2 Land management

Pastoralism

For much of the 18th and 19th centuries Welsh black cattle were an important part of the pastoral economy of Cardiganshire (eg. Defoe 1735, Davies 1934). Although some moorland areas were grazed by cattle, it seems probable that the Llyn Gynon catchment was too high and remote to have regularly fulfilled such a function.

It is possible that until their decline after ca. 1750 (Condry 1981), goats would have roamed the vicinity of the Llyn Gynon catchment (cf Leland 1536 in Toulmin Smith 1906).

In the early 20th century it was a common practice for flocks of geese to be driven from 'Pen-ddol-fawr' farm (some 4 km to the west of the lake), for summer grazing (E. Davies, V. Lloyd pers. comm.).

However, the central issue of land management in the catchment concerns its utilisation for sheep grazing. This practice dates to at least the late 12th century when the Cistercians of Strata Florida acquired the area and used it as rangeland for their flocks.

In the 1530s Leland described how the land in the vicinity was treated as common grazing - 'everyman thereabouts putting his beasts upon it without paying money' (Toulmin Smith 1906).

Part of the Llyn Gynon catchment comprised sheepwalk of the Crosswood Estate. In 1814 the Estate's sheepwalks were surveyed and considered of 'good quality, good and healthy for sheep' but 'ill stocked and managed' (12).

However, in 1857 witnesses affirmed the practice of the Crosswood Estate of strictly preserving its grazing rights, keeping unauthorised graziers and even those with common rights off its sheepwalks (13).

Sheep numbers

Data relating to sheep numbers were drawn from the annual parish returns of Caron (14) at quinquennial intervals and are presented in Fig. 38. Between 1867-1905 the data relate to the combined parish of Caron (Caron-Uwch-Clawdd and Caron-Is-Clawdd). Not until the early 20th century is information specifically available for Caron-Uwch-Clawdd, the parish within which the Llyn Gynon catchment lies.

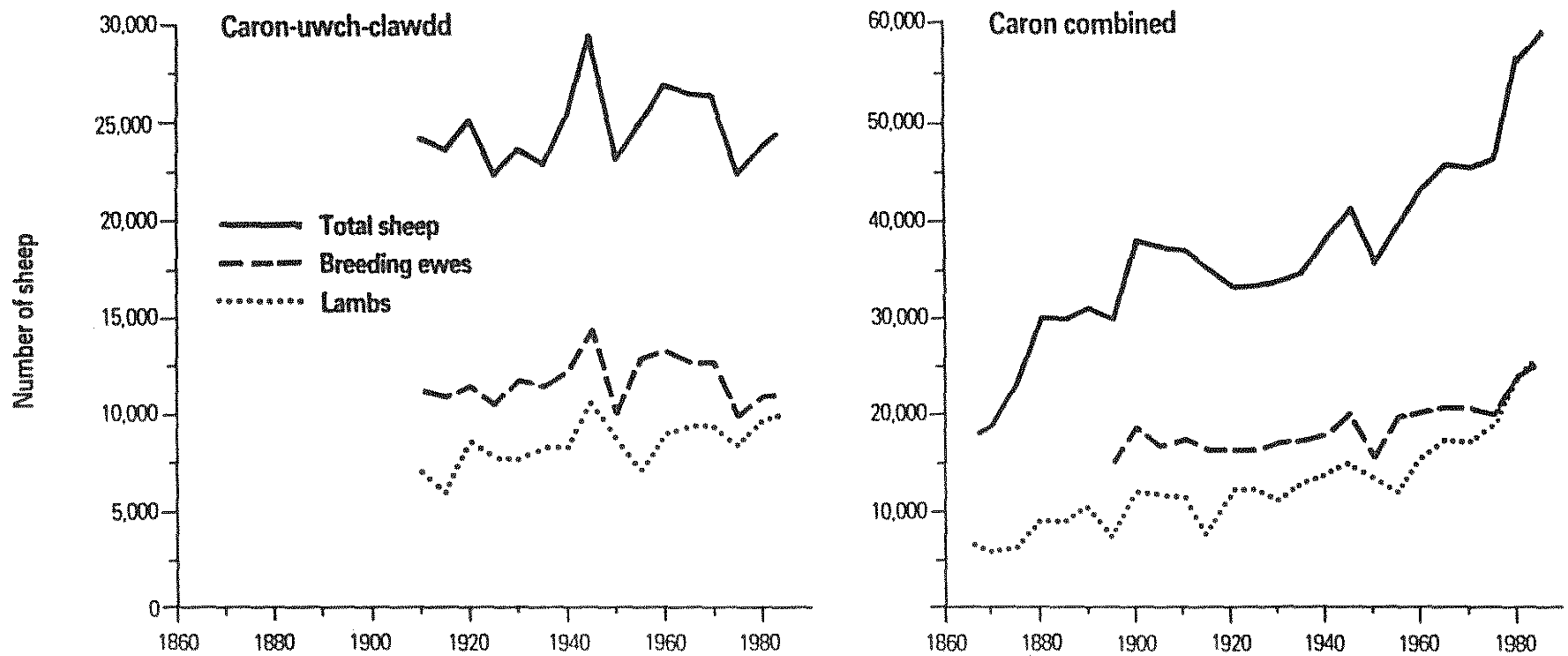
Although they represent the source of information most applicable to the Llyn Gynon catchment, the spatial resolution of these data do not permit catchment-specific assertions to be drawn and their interpretation is hindered by several other constraints. In particular they take a limited account of changes in sheep type and no account of changes in grazing regime (Patrick 1987).

No overall trend towards an increase or decline in total sheep numbers is discernible from Fig. 38. Furthermore, the increasing significance of ewes and lambs at the expense of wether sheep over the last century, is not really suggested from the trends in Fig. 38.

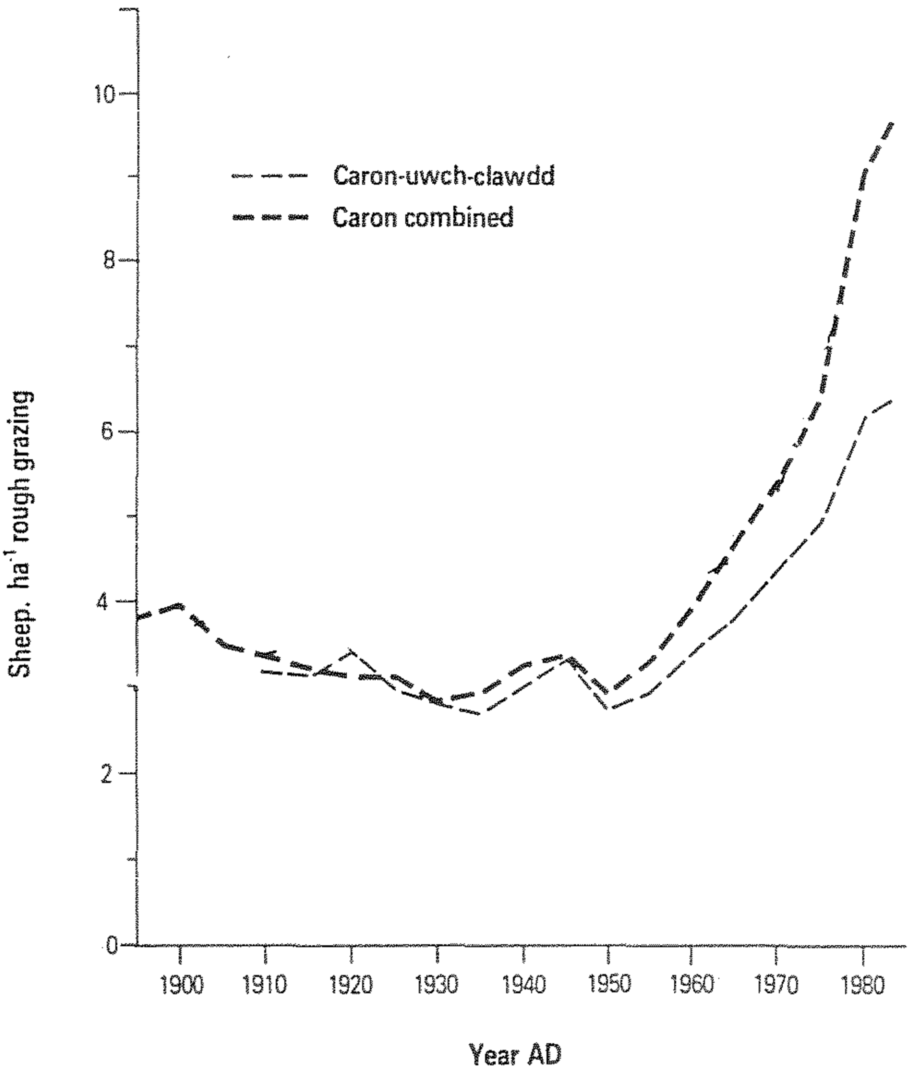
Within the Llyn Gynon catchment a broad increase in sheep numbers has been recognised since ca. 1945 (E. Davies, R.J. Davies, E. Edwards, W. Jones, V. Lloyd pers. comm.). It is estimated that the western part of the catchment currently supports 1800 ewes and 1500 lambs between May and November (V. Lloyd pers. comm.).

Apparent over a somewhat longer time scale has been a change in grazing regimes. A transition from hardy wethers to ewes and lambs, the declining viability and eventual abandonment of the highest farms (15), and the greater availability and improved quality of winter grazing on lower lands, has possibly resulted in fewer sheep over-wintering on the higher hills and a shortening of the grazing season at these altitudes (Patrick 1987) (16).

Manipulation of data relating to sheep numbers (Fig. 39) and area of rough



38. Sheep numbers in Caron-Uwch-Clawdd & Caron-Is-Clawdd 1867-1905



39. Crude sheep/rough grazing stocking densities in Caron-Uwch-Clawdd

grazing from the parish statistics, allow the calculation of a very crude trend of changing stocking rates on unimproved land in the Llyn Gynon locality (Fig. 39). These trends are not catchment-specific and they assume that all sheep are turned on to the hills (not an unreasonable assumption in the summer). Furthermore, they take no account of the changing impact on grazing intensities consequent upon the replacement of larger wethers by ewes and lambs. However, they do suggest that as the area of rough grazing has declined (primarily through afforestation - there has been little improvement of grassland in the parishes concerned) and the numbers of sheep have risen, then the potential stocking density of sheep on the land surrounding Llyn Gynon may have significantly increased through the 20th century (at least in summer months).

Grassland management

Llyn Gynon lies within the Cwm Ystwyth SSSI. In terms of land management the NCC act in a consultative and advisory capacity, but there is no evidence to suggest that contemporary management practices have been significantly altered as a result.

Burning of grassland was a regular practice in the catchment until the 1950s (E. Davies, W. Jones, V. Lloyd pers. comms.). Burning patterns may be faintly distinguished from aerial photographs flown in 1948 (17). The proximity of the extensive Towy forest to the south has made grassland fires an inappropriate and rarely sanctioned method of land management in the area since the early 1960s.

While the farm of 'Gareg Lwyd' was occupied areas of Molinia in the catchment were occasionally cut for hay to provide winter fodder.

Subsidiary management practices

Despite their reputation as sporting estates through the 19th and early 20th centuries, there is no evidence to suggest that the Crosswood or Nanteos estates actively managed the high land in the vicinity of Llyn Gynon for game.

In the 19th century turbaries were established on the peats at the west of the Llyn Gynon catchment. These peat cuttings are depicted on a map of 'Gareg Lwyd' of 1831 (19) and were utilised by the tenants of that farm (E. Davies, E.Edwards, V. Lloyd pers. comm.). Evidence of their existence may still be observed.

5.0 Conclusions

i) The unsupported ^{210}Pb concentration of the near surface sediments in Llyn Gynon is half that of Llyn Hir and indicates a basic accumulation rate of 2x that in Llyn Hir. The ^{210}Pb inventory of the Llyn Gynon core is 2.45 times that at Llyn Hir and indicates possible sediment focussing in Llyn Gynon. The combination of these two factors has given rise to a net sediment accumulation rate (2.1mm yr^{-1}) at the site of core GYN 3 over 5 times that at nearby Llyn Hir. A period of disturbance is revealed by a dislocation of the ^{210}Pb profile between 9.75 cm and 11.75 cm dated to around 1930, correlating with a peak in calcium in the core chemistry record.

ii) The diatom based pH reconstructions suggest that the pH of Llyn Gynon was 5.9 - 6.2 throughout most of the history recorded in the core. Planktonic diatoms were absent from the lake and the data suggest a fairly stable flora of attached circumneutral and acidophilous taxa. Acidification of Llyn Gynon, marked by the expansion of Tabellaria quadriseptata and Navicula madumensis, did not begin until 8 cm ca. 1945. The data suggest a pH decline of 0.4 pH units between 1945 and 1985.

iii) The core chemistry record demonstrates that trace metal contamination of the lake sediments began at 33 cm (1790's). The record also suggests a period of soil erosion (60 cm - 33 cm) before the dated part of the core (pre-1800) which is associated with a depression in values of Isoetes and a dilution of the diatom concentrations.

iv) The contamination of the sediments by carbonaceous particles commences at 32 cm, concurrent with the beginnings of trace metal contamination. The concentration of these particles increase rapidly from 8cm (1940's) and parallels the recent acidification of the lake as identified by the diatom record. A similar trend is shown by the magnetic data.

v) The pollen diagram reveals a major hiatus in the core at 60 cm below which sediments dating to approximately the elm decline 'approx 5000 B.P.' occur. Sedimentation has only recommenced within the last 250 years. The initial period of sedimentation is associated with a period of increasing erosion from the catchment as identified by depressions in values of Isoetes and associated with elevated levels of calcium and dramatic reductions in diatom concentrations from 60 cm to 18 cm.

vi) No appreciable land use change has occurred within the catchment since the introduction of sheep by the Cistercian monastery. While sheep numbers have increased in the area in recent years the documentary evidence is not precise enough to assess whether the catchment has experienced a significant increase in grazing pressure. No liming has taken place within the catchment and burning has not been a significant management practice.

vii) The acidification cannot be accounted for by land use changes. Instead, all the data indicate acid deposition as the cause of acidification. The timing of the changes and trends of the atmospheric pollution indicators (trace metals, magnetics, carbonaceous particles), indicating local deposition of atmospheric pollutants, are consistent with this view.

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7.0 Acknowledgments

We would like to thank N.J. Anderson, R.J. Flower, S.J. Phethean, D.M. Monteith, A.J. Nicholson and A. Kreiser for their invaluable help in the field and in the laboratory; Karen Phethean for typing and Alick Newman for diagram production; in particular the staff of WWA: J. Underwood, N.Milner, R. Hemsworth, M.Mills, J.Stoner and A.Gee are thanked for allowing us access to unpublished data. Furthermore, the following people are thanked for allowing us to discuss the local history of the area with them: G. Jones, M.Morgan (Tregaron Angling Society), Mr J.R. Davies of ADAS (Lampeter), Mrs E. Davies (Pontrhydfendigaid, formerly of 'Gareg Lwyd' farm), Mr E. Edwards (Pontrhydfendigaid, formerly of 'Gareg Lwyd' farm), Mr V. Jones ('Tyn y Cwm' Farm, Pontrhydfendigaid, Mr V. Lloyd, Pontrhydfendigaid Dr G. Sinclair (Environmental Information Services, Narbeth) and Dr. M.Parry (Dept Geography, University of Birmingham).

8.0 Notes

1. NLW Nanteos papers. Correspondence, uncatalogued.

2. See Patrick (1987) for definitions of 'land use' and 'land management'.

3. ADAS - Agricultural Development Advisory Service (MAFF). Manuscript 1:25,000 land capability maps accessed at ADAS Aberystwyth.

4. This clearance was described by Leland in 1536. He further described how grazing by goats prevented the regeneration of woodland (Toulmin Smith 1906).

5. A valuation of the Crosswood Estate in 1814 (NLW, Crosswood I 1223, II 660) suggested that no lime was used anywhere on the estate.

6. See Patrick (1986) with regards to sources (and their interpretation) used in documenting land use and land management change.

7. Tithe map and schedule for the parish of Caron 1842. PRO Kew, IR30 46/10 map D.

8. First edition surveyed 1887 published 1891.
   Second edition surveyed 1904 published 1906.
   Provisional edition ammended 1948 published 1953.

9. Manuscript held at London School of Economics archive.

10. Manuscript held at KQC Geography Department, sheet no.___.

11. 1:25,000 land use maps and computer files containing data on land use change, held at the Countryside Commission in Newtown, Powys.

12. NLW, Crosswood I 1233; II 660. 'Valuation of the Crosswood Estate by John Murray'. May 1814.

13. NLW, Crosswood I 1721 'Depositions by different persons touching the Tynddole sheepwalk in the parish of Gwnnws belonging to the Earl of Lisburne and disputed by the Crown'. ca. 1857.

14. PRO Kew, class MAF 68.

15. In the 1930s 5-6 farms on the track from Strata Florida to below Llyn Gynon were permanently occupied (W. Jones, V. Lloyd pers. comms.). Today only 'Tyn y' Cwm' is inhabited.

16. These trends may currently be reversing as the use of winter feed blocks and silage bags becomes increasingly prevalent in the Llyn Gynon area.

17. Air Photograph Office, Welsh Office, Cardiff. Six inch series nos. 532/1213, 532/1214 (December 4th 1946). 885/3124, 885/3125, 885/3126, 885/4064, 885/4065 (May 19th 1948).

18. 'Gareg Lwyd' lies 0.75 km. to the west of the lake and was last inhabited ca. 1940.

19. NLW 14, p.61. Field plan and schedule of Gareg Lwyd by Thomas Griffiths 1831.

LLYN GYNON (3) SPECIES LIST

AC002A	ACHNANTHES LINEARIS	W. SMITH
AC002C	ACHNANTHES LINEARIS V PUSILLA	GRUN.
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AC012A	ACHNANTHES AFFINIS	GRUN.
AC013A	ACHNANTHES MINUTISSIMA	KUTZ.
AC014A	ACHNANTHES AUSTRIACA	HUST.
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AN007A	ANOMOEONEIS ZELLENSIS	(GRUN.) CLEVE
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CM010A	CYMBELLA PERPUSILLA	A. CLEVE
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CY010A	CYCLOTELLA CUMENSIS	GRUN.
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EU002D	EUNOTIA PECTINALIS V UNDULATA	(RALFS) RABH.
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EU006B	EUNOTIA LUNARIS V SUBARCUATA	(NAEGELI) GRUN.
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EU008C	EUNOTIA MONODON V MAIOR	(W.SMITH) RABH.
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EU025A	EUNOTIA FALLAX	CLEVE

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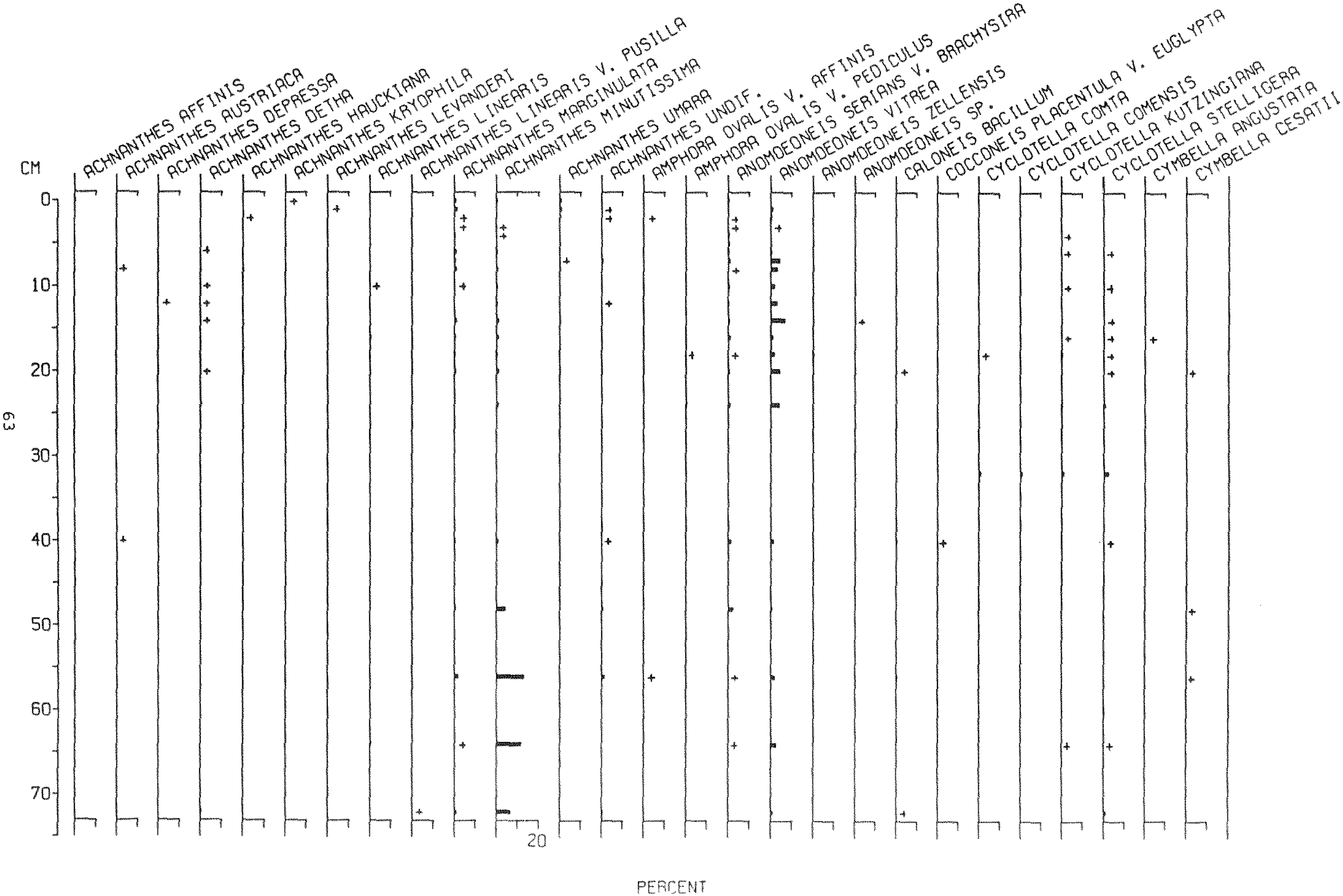
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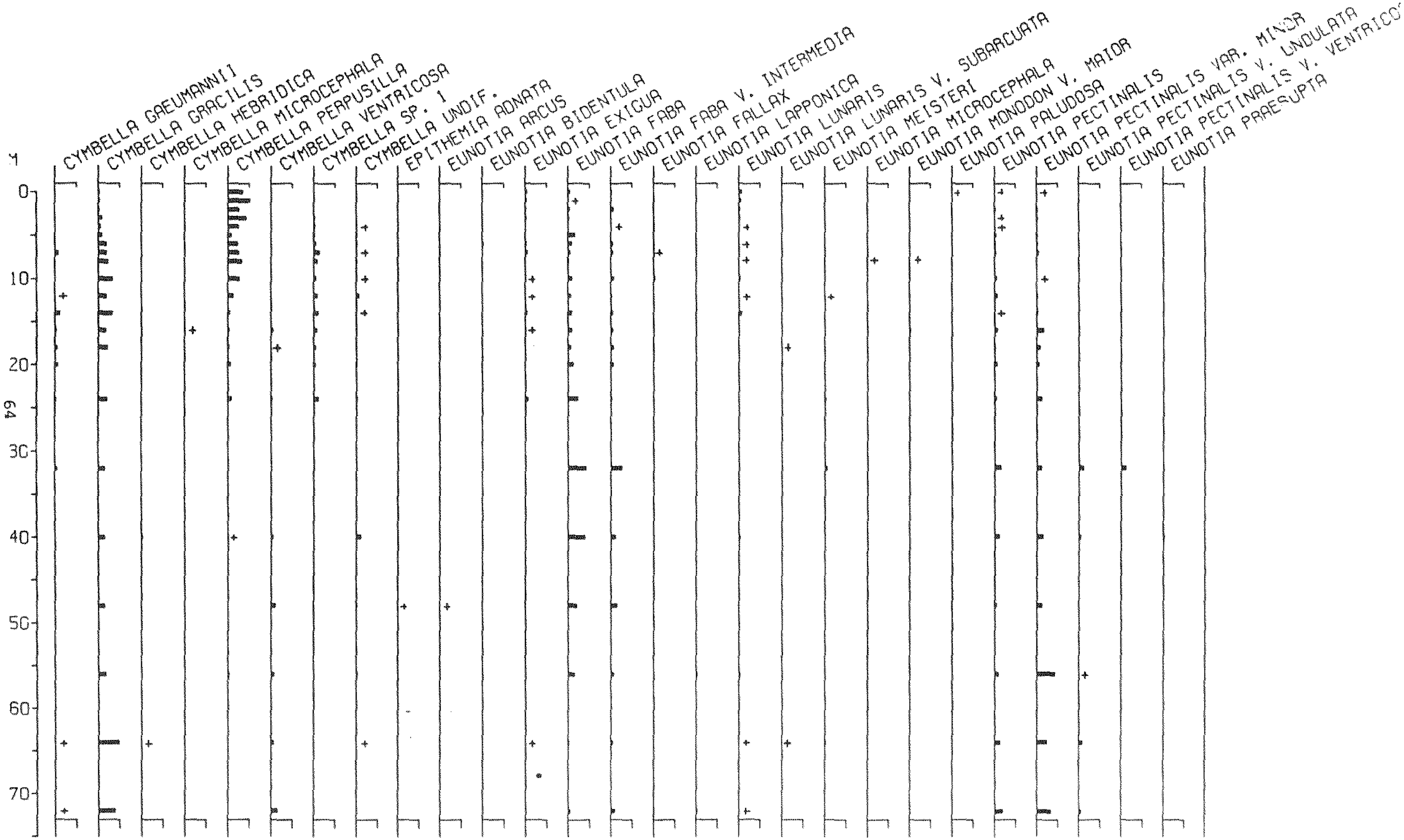
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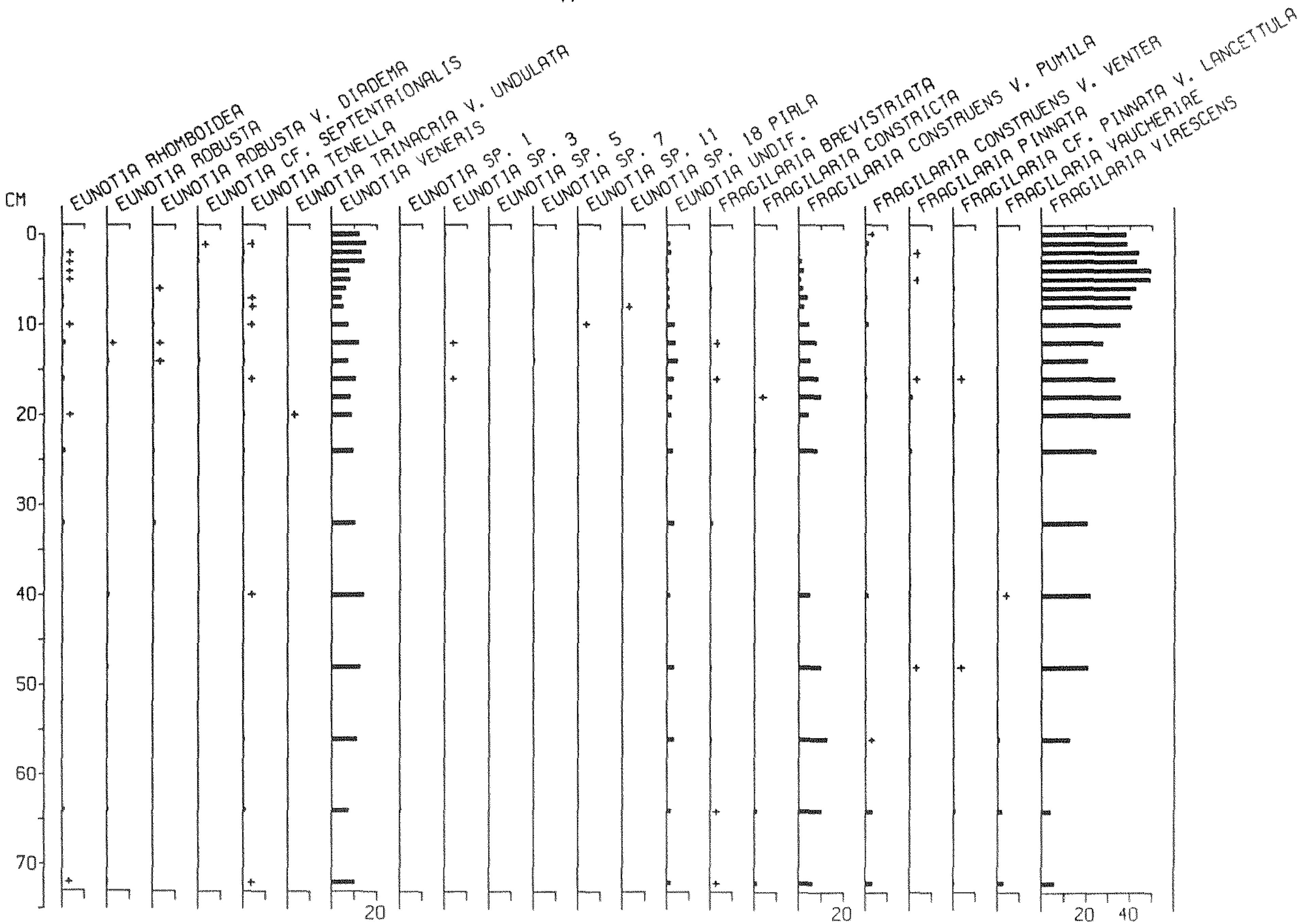
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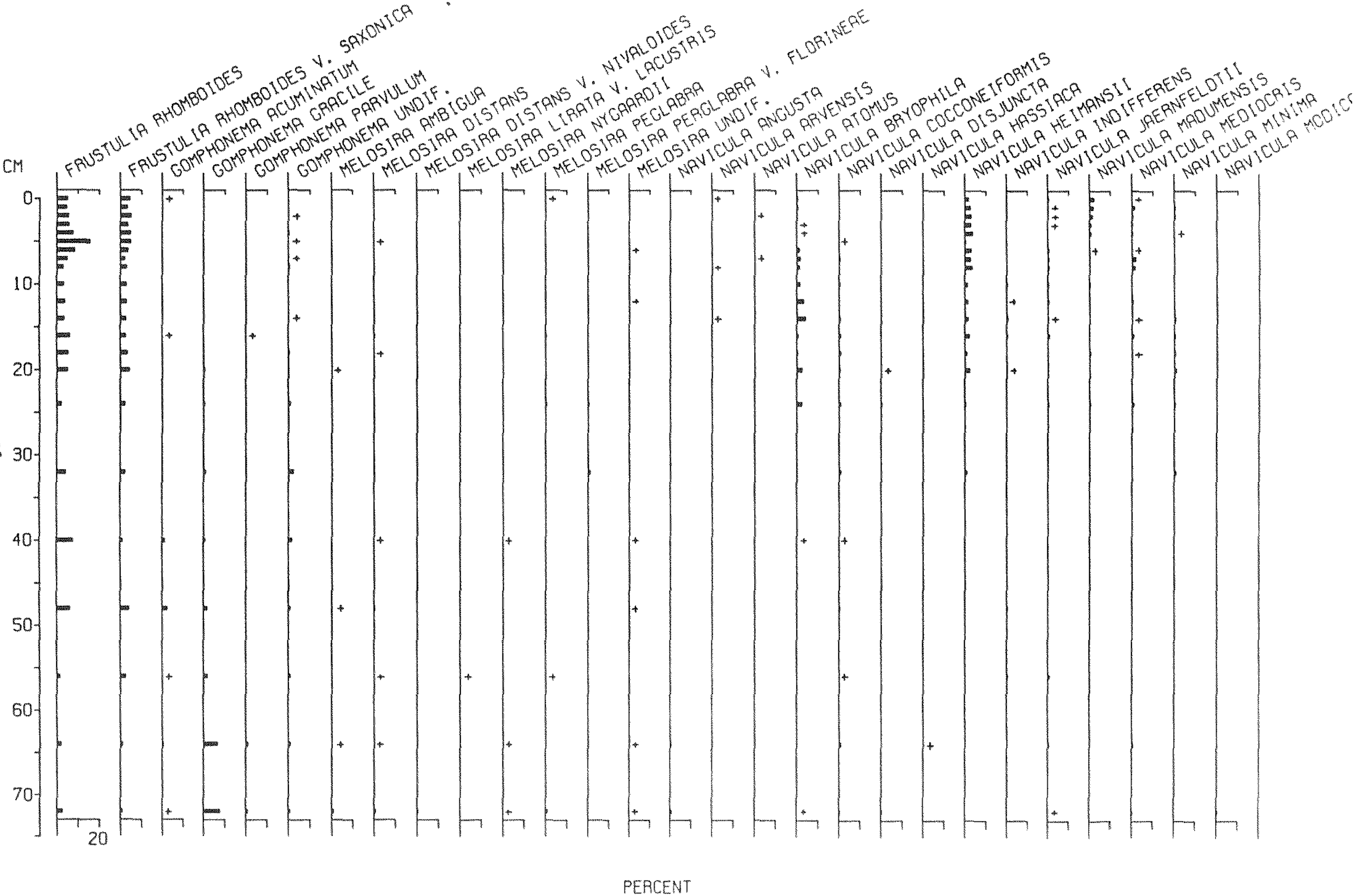
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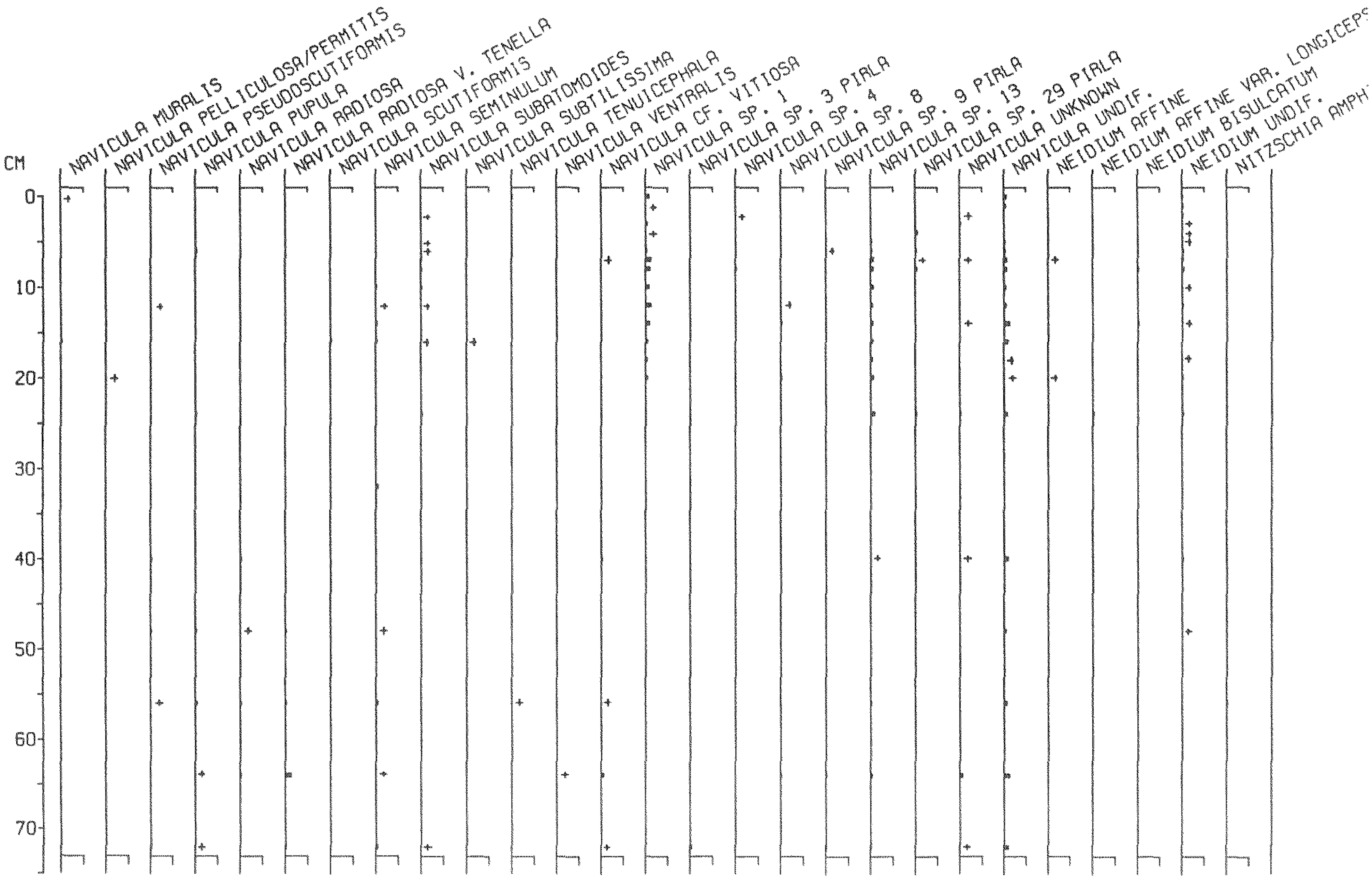
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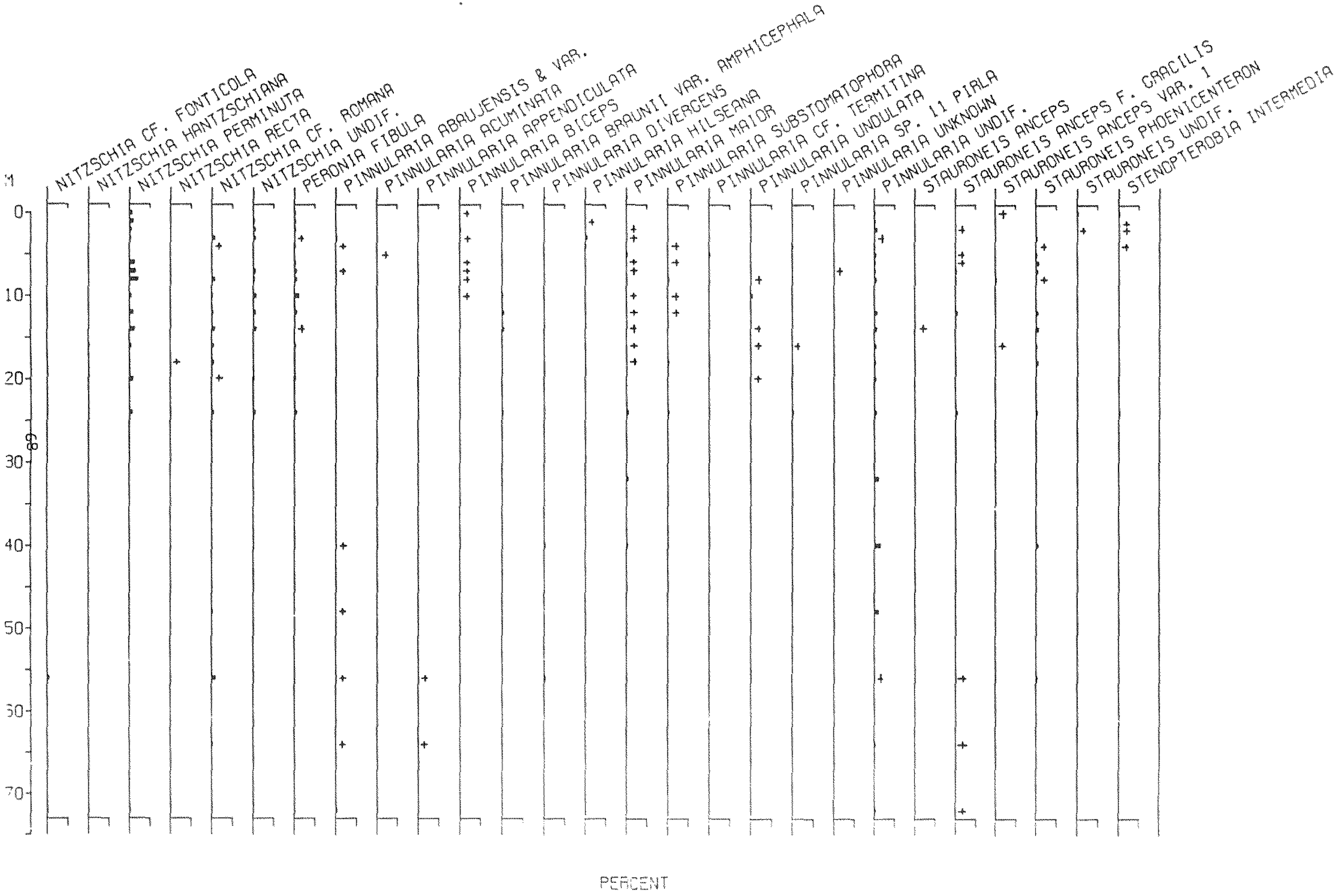
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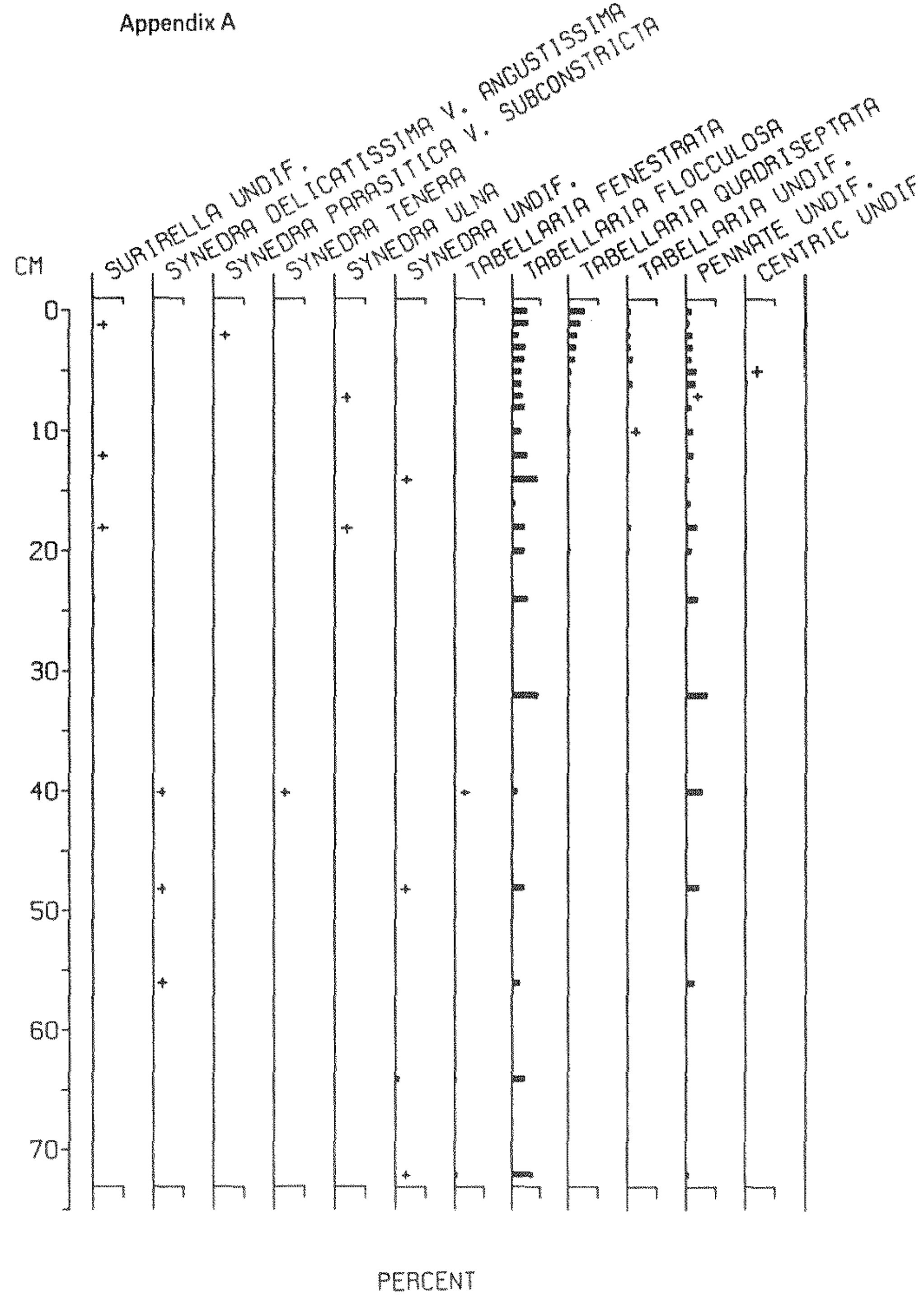
Appendix A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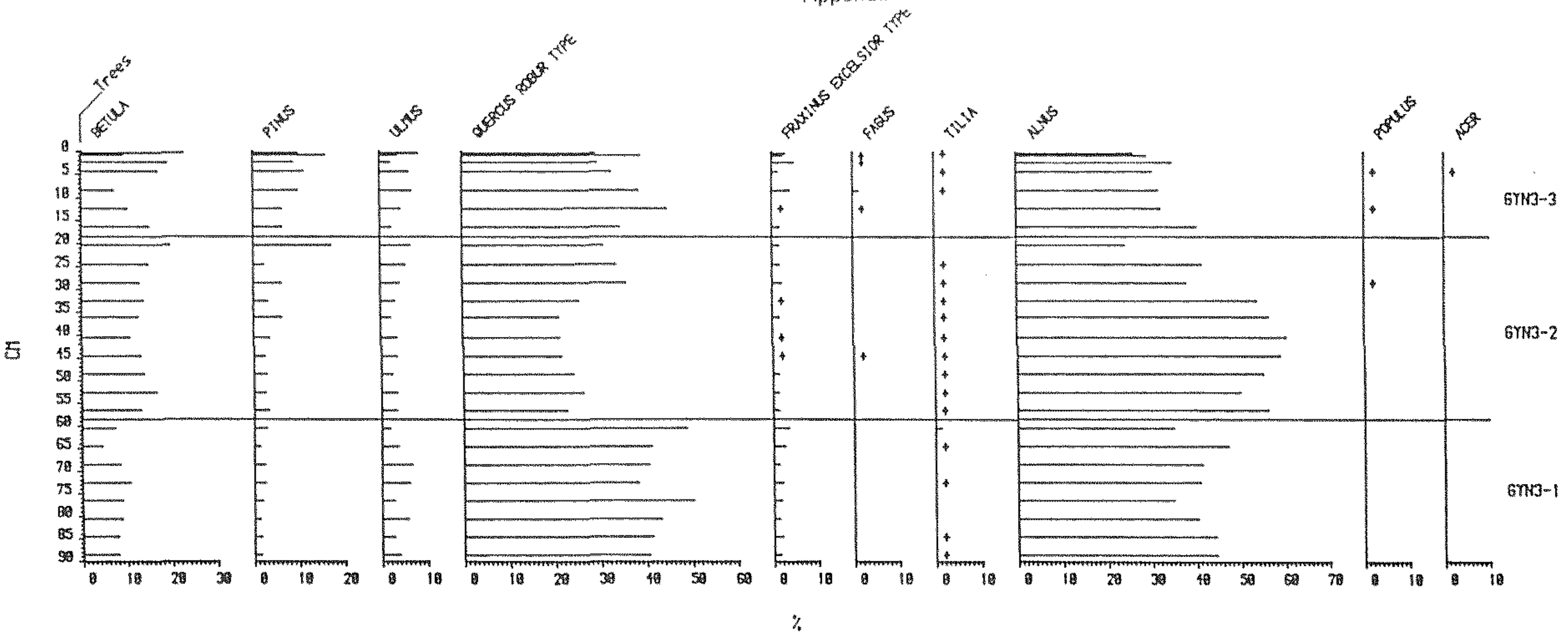
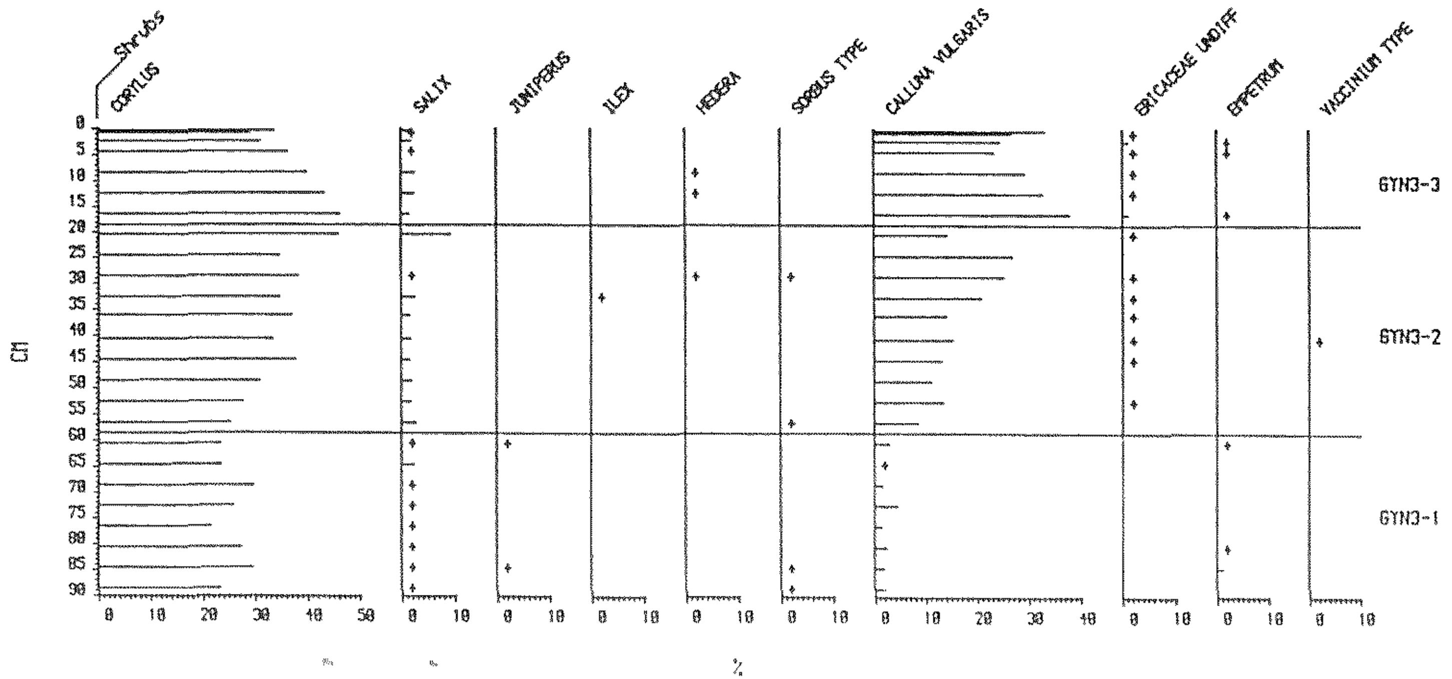
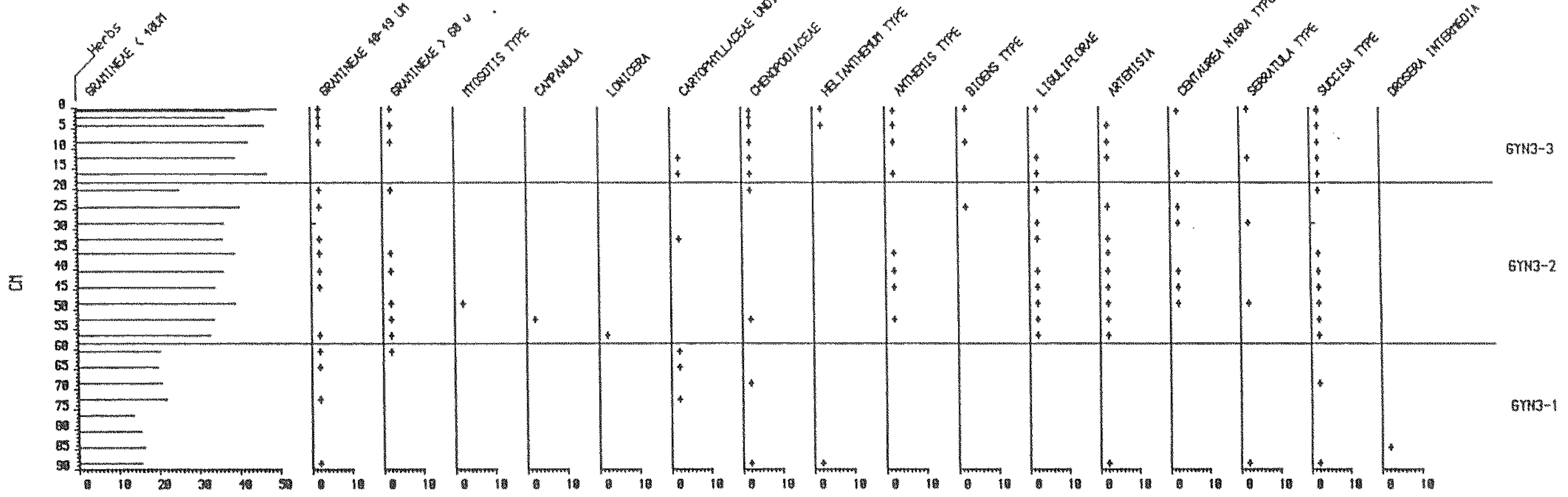
TABELLARIA FLOCCULOSA
TABELLARIA QUADRISEPTATA
TABELLARIA UNDIF.
PENNATE UNDIF.
CENTRIC UNDIF.
CM
0
10
20
30
40
50
60
70
PERCENT

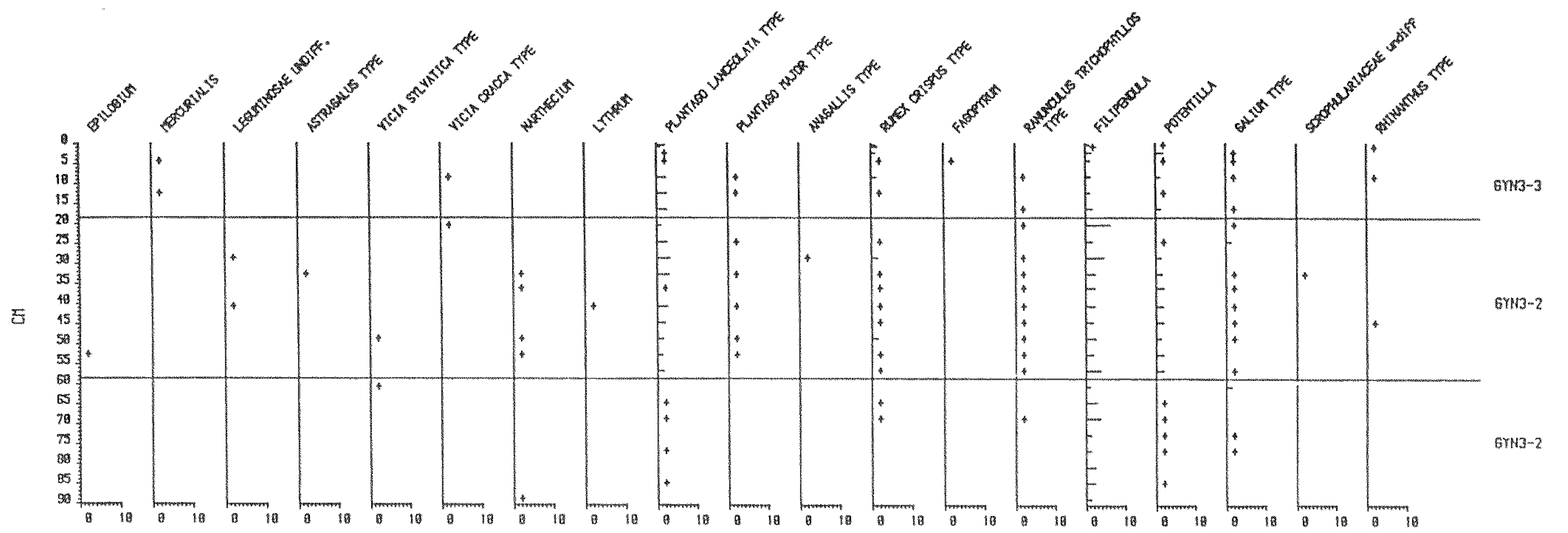
Appendix B


Trees
BETULA
PINUS
ULMUS
QUERCUS ROBUR TYPE
FRAXINUS EXCELSIOR TYPE
FAGUS
TILIA
ALNUS
POPULUS
ACER
CM
%
GYN3-3
GYN3-2
GYN3-1

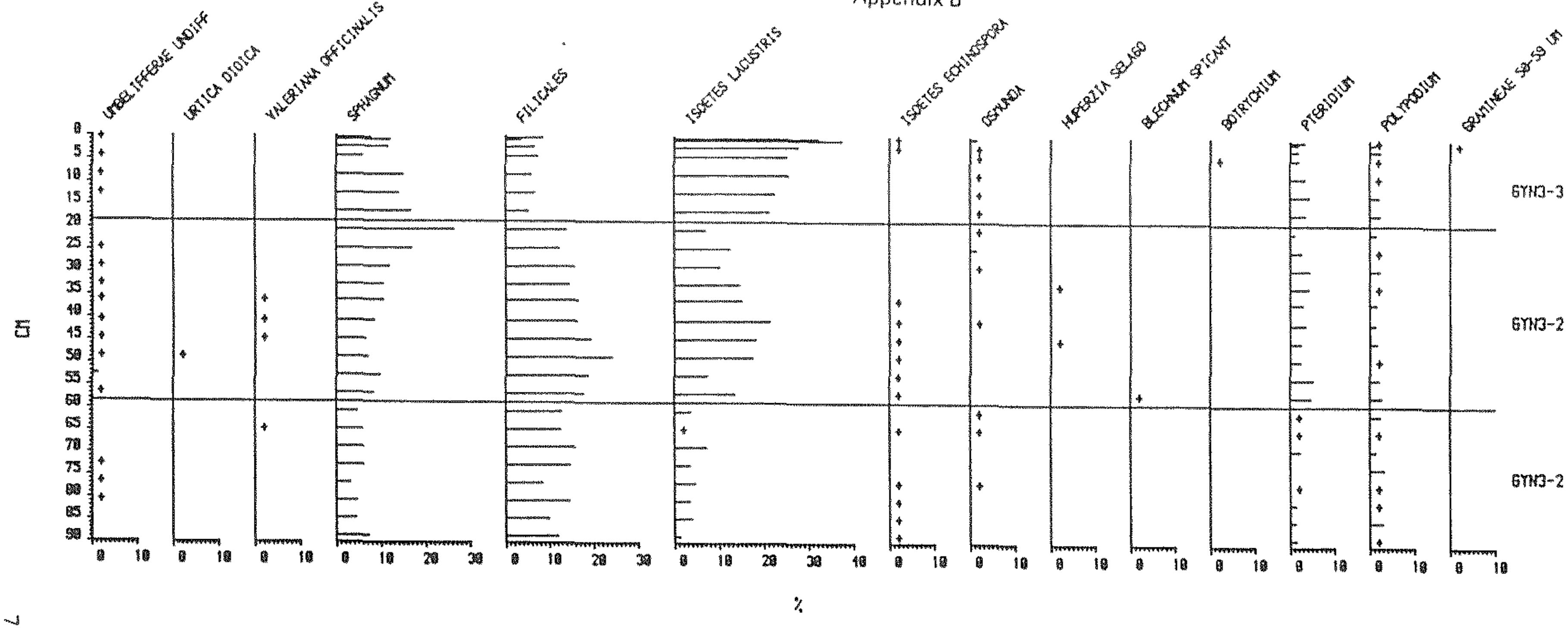

Shrubs
CORYLUS
SALIX
JUNIPERUS
ILEX
HEDERA
SORBUS TYPE
CALLUNA VULGARIS
ERICACEAE UNDIFF
EMPETRUM
VACCINIUM TYPE
CM
%
GYN3-3
GYN3-2
GYN3-1

Appendix B

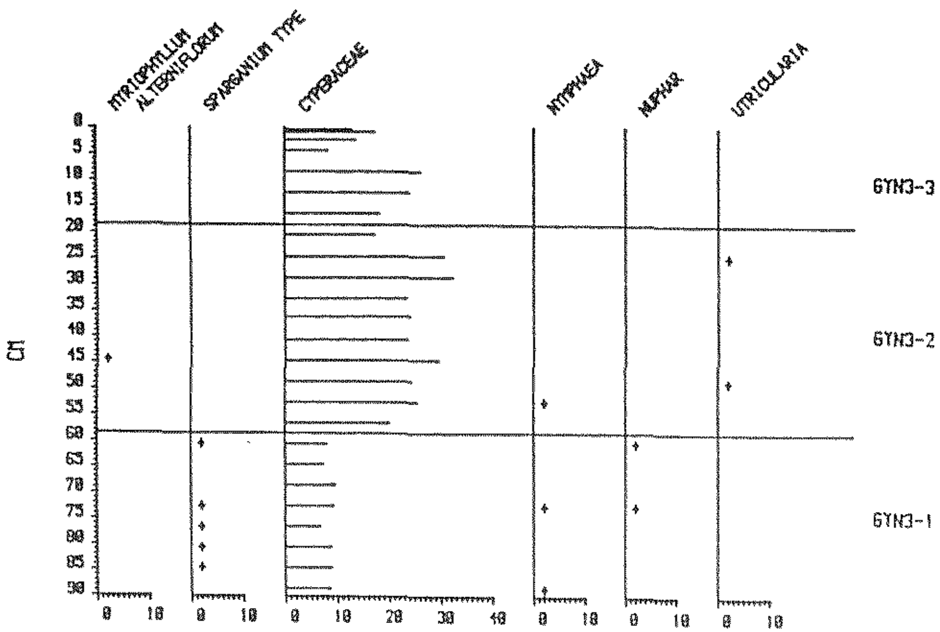

Herbs
GRAMINEAE < 40UM
GRAMINEAE 40-49 UM
GRAMINEAE > 60 u
MYOSOTIS TYPE
CAMPANULA
LONICERA
CARYOPHYLLACEAE UNDIFF.
CHENOPODIACEAE
HELIANTHEMUM TYPE
ANTHEMIS TYPE
BIDENS TYPE
LIGULIFLORAE
ARTEMISIA
CENTAUREA NIGRA TYPE
SERRATULA TYPE
SUCCISA TYPE
DROSERA INTERMEDIA
GYN3-3
GYN3-2
GYN3-1
CM
%


EPILOBIUM
MERCURIALIS
LEGUMINOSAE UNDIFF.
ASTRAGALUS TYPE
VICIA SYLVATICA TYPE
VICIA CRACCA TYPE
NARTHECIUM
LYTHRUM
PLANTAGO LANCEOLATA TYPE
PLANTAGO MAJOR TYPE
ANAGALLIS TYPE
RUMEX CRISPUS TYPE
FAGOPYRUM
RANUNCULUS TRICHOPHYLLOS TYPE
FILIPENDULA
POTENTILLA
GALIUM TYPE
SCROPHULARIACEAE undiff
RHINANTHUS TYPE
GYN3-3
GYN3-2
GYN3-2
CM

Appendix B



UMBELLIFERAE UNDIFF
URTICA DIOICA
VALERIANA OFFICINALIS
SPHAGNUM
FILICALES
ISOETES LACUSTRIS
ISOETES ECHINOSPORA
OSMUNDA
HUPERZIA SELAGO
BLECHNUM SPICANT
BOTRYCHIUM
PTERIDIUM
POLYPODIUM
GRAMINEAE 50-59 UM
CM
%
GYN3-3
GYN3-2
GYN3-2



MYRIOPHYLLUM ALTERNIFLORUM
SPARGANIUM TYPE
CYPERACEAE
NYMPHAEA
NUPHAR
UTRICULARIA
CM
GYN3-3
GYN3-2
GYN3-1

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