Working Papers

No. 16

PALAEOECOLOGICAL EVALUATION OF THE RECENT ACIDIFICATION OF WELSH LAKES

1. Llyn Hir, Dyfed

S. Fritz[1], A.C. Stevenson[2], S.T. Patrick[2], P. Appleby[4], F. Oldfield[3], B. Rippey[5], J. Darley[2] & R.W. Battarbee[2].

Editors: A.C. Stevenson & S.T. Patrick

Palaeoecology Research Unit,
Department of Geography,
University College London

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

Palaeoecological Evaluation of the Recent Acidification of Welsh Lakes. I. Llyn Hir, Dyfed.

S. Fritz[1], A.C. Stevenson[2], S.T. Patrick[2], P. Appleby[4], F. Oldfield[3], B. Rippey[5], J. Darley[2] & R.W. Battarbee[2]
(With Appendices supplied by WWA)

Editors: A.C. Stevenson & S.T. Patrick

Palaeoecology Research Unit
Dept. Geography
University College London
26 Bedford Way
London WC1H 0AP

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

Working Paper No. 16

Palaeoecological Evaluation of the Recent Acidification of Welsh Lakes. I. Llyn Hir, Dyfed.

S. Fritz[1], A.C. Stevenson[2], S.T. Patrick[2], P. Appleby[4], F. Oldfield[3], B. Rippey[5], J. Darley[2] & R.W. Battarbee[2]

[1] Limnological Research Center
University of Minnesota
220 Pillsbury Hall
310 Pillsbury Drive S.E.
Minneapolis, Minnesota 55455

[2] Palaeoecology Research Unit
Dept. Geography
University College London
26 Bedford Way
London WC1H 0AP

[3] Dept. Geography
University of Liverpool
P.O. Box 147
Liverpool L69 3BX

[4] Dept. Applied Mathematics & Theoretical Physics
University of Liverpool
P.O. Box 147
Liverpool L69 3BX

[5] Freshwater Laboratory
University of Ulster
Traad Point
Drumenagh
Magherafelt
N. Ireland.

Contents

Summary

i) The ^{210}Pb Chronology reveals that the sediment accumulation rate in Llyn Hir has been extremely slow. (ca. 6 mg cm^{-2} yr^{-1}, 0.7 mm cm^{-2} yr^{-1})

ii) A clear acidification of Llyn Hir has occurred over the last 120 years, with a distinct accelaration beginning in the early 1940's, similar to the acidification previously described in Galloway.

iii) The core chemistry record demonstrates that trace metal contamination of the lake sediments began at 11 cm (1880's) and parallels the acidification recorded by the diatoms. Similar trends are shown by the carbonaceous cenosphere and magnetic data

iv) The pollen data and documentary evidence demonstrate that apart from phases of small amounts of soil erosion no appreciable land use change has occurred within the catchment since the introduction of sheep by the Cistercian monastery in the 12th century.

v) 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, cenospheres), indicating local deposition of atmospheric pollutants, are consistent with this view.

vi) Llyn Hir is the first Welsh site where recent lake acidification has been clearly demonstrated.

Figures

Tables and Appendices

Tables

1. Lake characteristics
2. Catchment characteristics
3. ^{210}Pb & ^{226}Ra data for the Llyn Hir I core
4. ^{137}Cs data for the Llyn Hir I core
5. Other radioisotope data from the Llyn Hir I core
6. CRS dating model chronology of the Llyn Hir I core
7. CIC dating model chronology of the Llyn Hir I core
8. Diatom based pH reconstruction of the Llyn Hir I core
9. Trace metal flux data for the Llyn Hir 1 core
10. Carbonaceous cenosphere record for the Llyn Hir 1 core
11. Magnetically based core correlation between the lake and pool cores for Llyn Hir

Appendices

A. Bi-weekly chemistry data for Llyn Hir from November 1983-March 1986 (courtesy of WWA)
B. Invertebrate lists from Llyn Hir (courtesy of WWA)
C. Full diatom diagrams for the Llyn Hir I core
D. Full physical and chemical characteristics of the Llyn Hir 1 core
E. Full pollen diagrams for the Llyn Hir I core

Explanation of abbreviations

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

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.

Our approach involves the use of diatom analysis to reconstruct past pH values; ^{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.

Llyn Hir, one of the Teifi pools in mid-Wales (Fig. 1), was the first site chosen in Wales. It has recently been limed (Underwood et al. 1986), but prior to liming it had a mean annual pH of 4.7 and had become fishless in recent years. The catchment is largely undisturbed, comprising upland moorland and rough grazing for sheep. Sediment cores were obtained in May 1984, a year before liming.

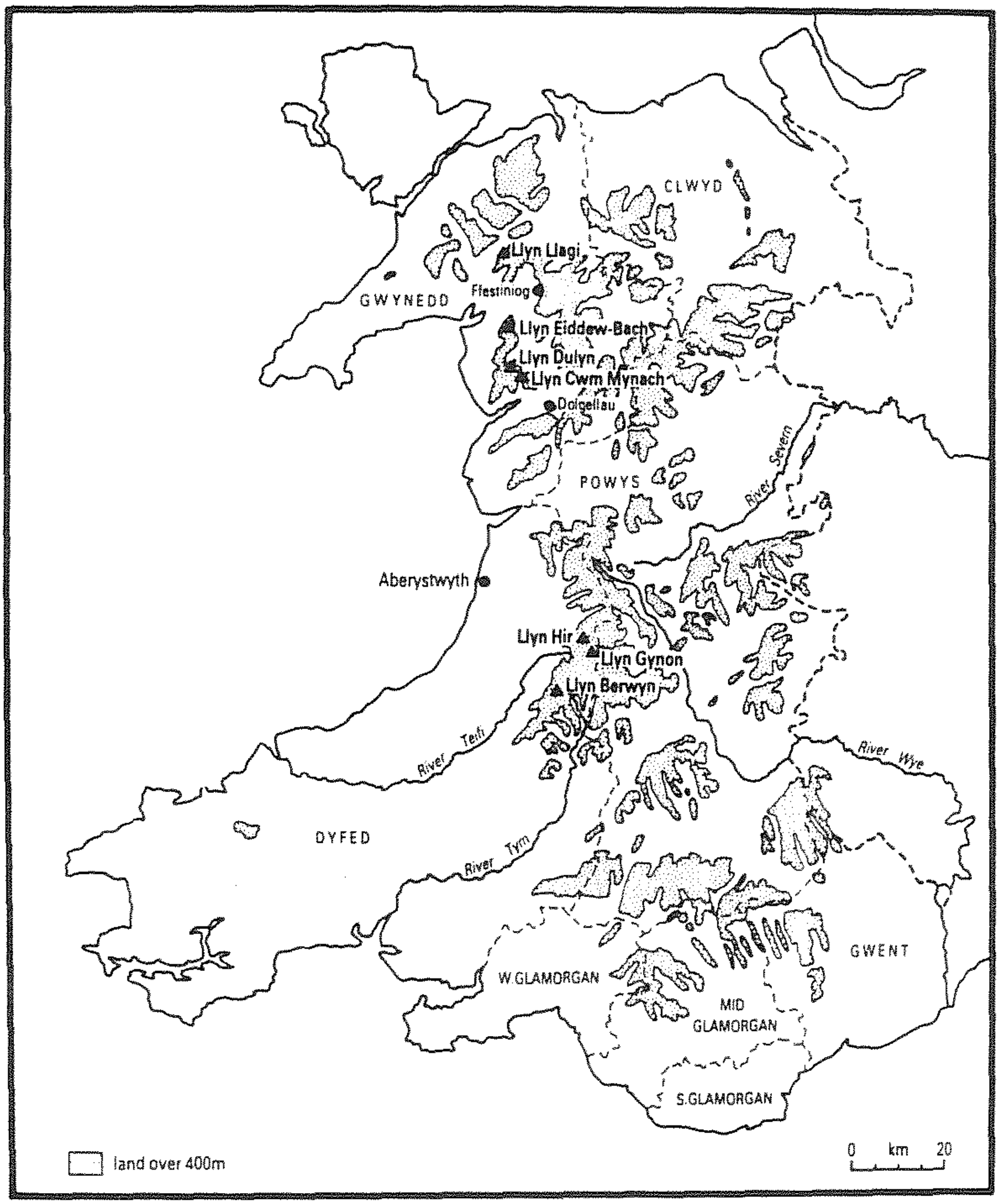


Fig. 1. Llyn Hir location map.

2.0 Site details

2.1 Air quality

Llyn Hir experiences a moderately high acid and sulphate loading (Figs. 2-3). So far insufficient historical data are available to assess whether there has been an improvement in the pollution environment since 1973 associated with falling emissions.

2.2 Lake

The lake lies at an altitude of 435 m in an area which receives a rainfall of 2000 mm yr^{-1}. It is an elongated ('Llyn Hir' = 'long lake') narrow body of water (surface area 0.05 km^2), which drains a small catchment of 0.22 km^2. The detailed bathymetry (Fig. 4) reveals that it is composed of three significant depositional basins two of which are separated by a submerged rocky ridge. Overall, the lake has a mean depth of 2.9 m and volume of ca. 136,000 m^3 (Table 1) and displays minimal variation in water level (Underwood _et al._ 1986). The drainage network is poorly formed and no distinct inflows exist. Most of the water movement is by groundwater and surface flow especially in 2 or 3 areas of very wet flushes dominated by _Eriophorum vaginatum_*. A single outflow drains the southern end of the lake (mean daily flow = 0.13 m^3s^{-1} Underwood _et al._ 1986) feeding the reservoir of Llyn Egnant.

Table 1 LAKE CHARACTERISTICS

Area	48853 m^2
Volume	136367 m^3
Maximum depth	8.8 m
Mean depth	2.79 m

2.2.1 Liming and water chemistry

Llyn Hir, together with Llyn Berwyn, was the subject of a liming experiment conducted by the WWA in the spring of 1985. Detailed results may be found in Underwood _et al._ 1986. Before liming, pH at Llyn Hir varied between 4.5 & 5.1 with zero or very low levels of alkalinity and dissolved calcium (0.5-1.2 mg l^{-1}). After liming on the 1st & 2nd of April 1985 pH, alkalinity and dissolved calcium all increased significantly, while dissolved metal concentrations, especially aluminium, decreased as they precipitated under the higher pH regime (Fig. 5, Appendix A). Subsequently, pH, alkalinity and dissolved calcium all decreased again as calcium rich lake water was lost down the outflow and replaced by acid groundwaters. The lake was re-limed on 12/12/85 to bring the pH back up to 7.0 (Underwood _et al._ 1986). Subsequently pH, alkalinity and dissolved calcium have all decreased again but still remain at a higher level than before liming began in 1985.

2.2.2 Lake vegetation

At Llyn Hir the principal macrophyte in the littoral zone was _Nardia compressa_ with _Sparganium angustifolium_, _Sphagnum acutifolium_ and _Isoetes lacustris_ being recorded to depths of 2-4 m. 44 species of

*Nomenclature follows Tutin _et al._ 1964-1980.

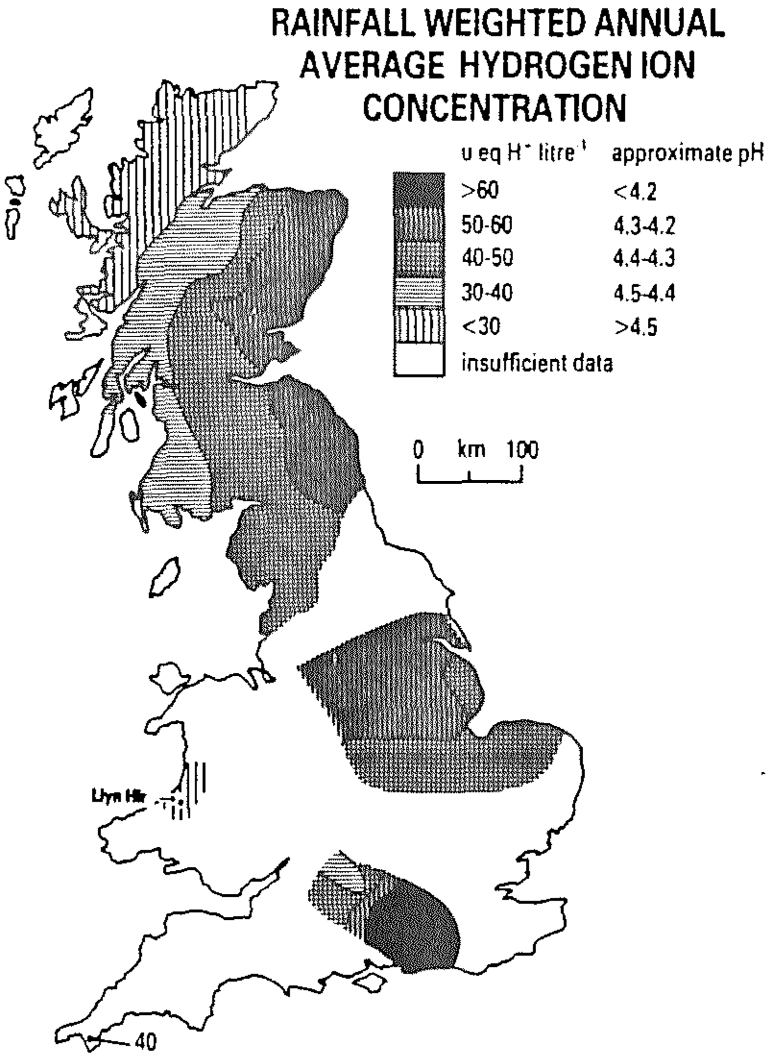


Fig 2. Average annual rainfall weighted Hydrogen ion concentration deposition for the U.K. (Redrawn from Barret et al. 1983).

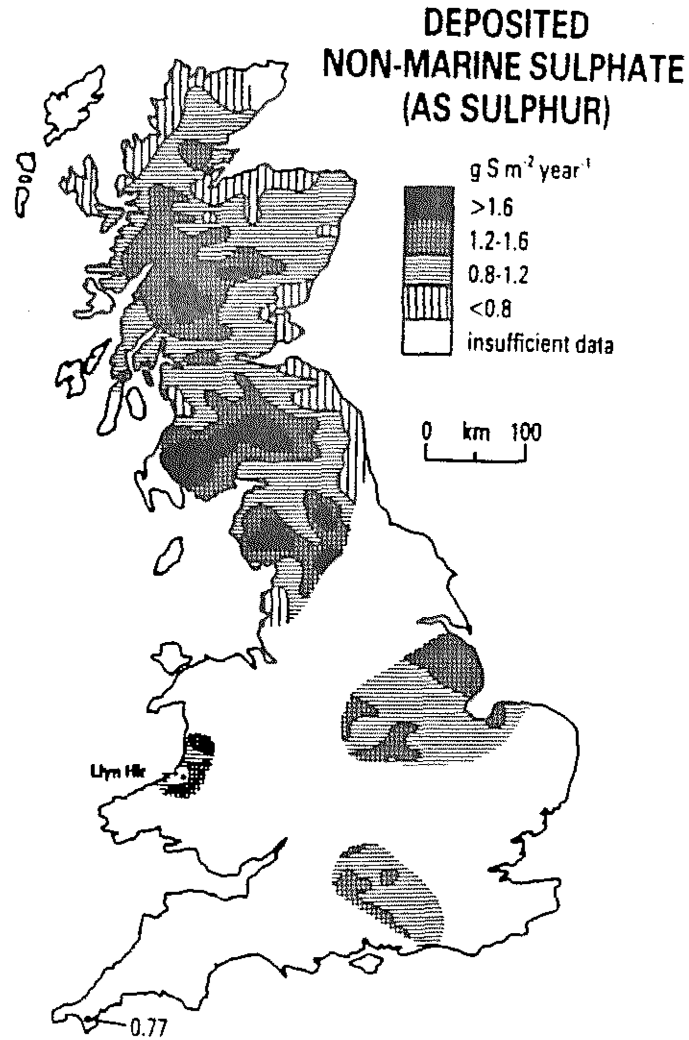


Fig. 3. Average annual deposition of non marine Sulphate for the U.K. (Redrawn from Barret et al. 1983).

Fig. 4. Bathymetry and coring locations for Llyn Hir.

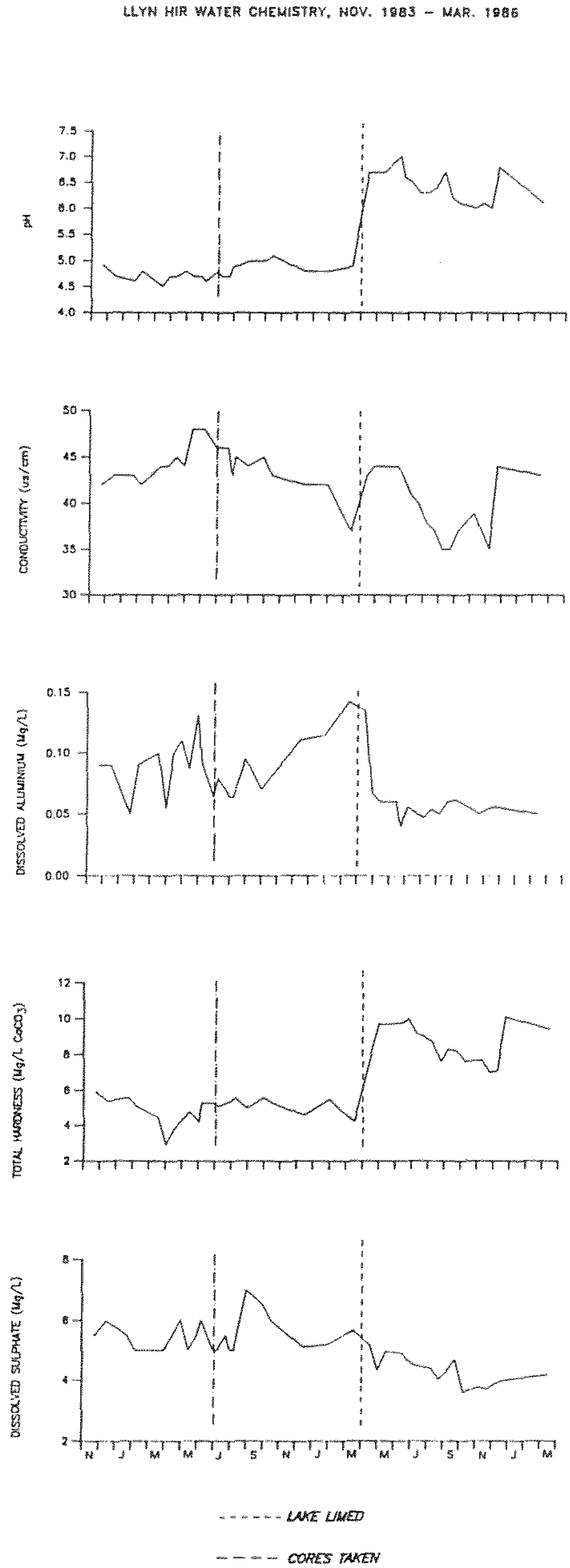


Fig. 5. Bi-weekly lake chemistry results before and after liming (Data supplied by WWA, Dr A. Gee).

macro-invertebrate (Appendix B) were recorded from the lake prior to liming, which are all typical of oligotrophic lakes with a pH of less than 5.0 (B.Morrison pers. comm.)

2.2.3 Fishing history

Before the liming study the lake was regularly stocked, but increasingly with limited success. Attempts to stock from neutral water hatcheries failed (Underwood et al. 1986), as did the introduction of the American Brook Trout in the 1970s (Condry 1981). Serious deterioration of the fishery was recognised by 1982 and by 1984 fish had all but disappeared (G. Jones pers. comm.).

Llyn Hir lies on land that was granted to the Cistercian monks of Strata Florida Abbey in 1184 (Williams 1889). The monks stocked their lakes in this region with trout from Shropshire and other places (Ward 1931). It is therefore possible that Llyn Hir was first 'managed' as a fishery as early as the 12th century.

In the mid 16th century Leland described Llyn Hir as being 'plentiful of trout and eels' (Toulmin Smith 1906).

The lakes above Llyn Teifi were a popular fishery (1) noted for their trout and eels in the 1830s (Leigh 1835). It was the quality of the trout which drew the attention of later commentators. Cliffe (1860) described them as 'large but rather shy', whereas Morgan (1874) considered the trout of the Teifi Pools as being unsurpassed for their flavour (those in Llyn Hir could weigh up to four lbs).

By 1860 the Crosswood Estate of Lord Lisburne had obtained the fishing rights to the lake, although at this date it was suggested that the fishing was not strictly preserved (Cliffe 1860). However, at later dates the Estate is known to have stocked the lake (G. Jones pers. comm.) and maintained a keeper on the lake shore in summer months to protect the Teifi Pool fisheries from unauthorised anglers (2).

The Cardiganshire Water Board (now subsumed into the Welsh Water Authority - WWA) acquired the lake in association with the Llyn Egnant reservoir scheme in the early 1960s. Around this time the lake is remembered by contemporary anglers as supporting a good quality trout population that spawned at the side of the lake and provided catches averaging 0.5 lbs (G. Jones, M. Morgan pers. comm.). The water authority ran the fishing in Llyn Hir for a period before letting the rights to the Teifi Pools Angling Association in 1981 (3).

The late date of the fishery decline may be misleading. It has been suggested (M. Morgan pers. comm.) that increased stocking of the lake from the early 1960s resulted in an enhanced fishing pressure which took its toll on the native stock. This earlier deterioration was however masked by continued stocking.

It is apparent (allowing for the notorious inexactitude of fishing histories) that Llyn Hir supported a healthy and long established fish population. However, in recent years the lake deteriorated as a fishery until by 1984 it was virtually fishless. Possible reasons for the poor fishery status of the lake can be deduced from the water quality data, since fish toxicity arises from combinations of low pH, low calcium & high dissolved aluminium concentrations (O'Donnell et al. 1984).

Following the instigation of the WWA's liming programme in April 1985, the lake was stocked with 300 brown trout and 300 rainbow trout with no apparent mortalities (Underwood et al. 1986).

2.3 Catchment

Llyn Hir has a very small catchment (228,166 m^2) of which the lake occupies some 48,853 m^2 (Table 2, Fig 6). As a consequence Llyn Hir has a relatively large catchment:lake ratio (3.67). Thin soils and vegetation cover most of the catchment but on some of the steeper slopes the underlying rocks are exposed.

Table 2 CATCHMENT CHARACTERISTICS

Total catchment area	228166 m^2
Area of land in catchment	179313 m^2
Area of lake	48853 m^2
Catchment/lake ratio	3.67
Maximum relief	19 m

2.3.1 Geology

Base poor, lower Palaeozoic, Silurian mudstones and shales dominate the catchment (Rudeforth 1970). These largely impermeable rocks are resistant to chemical weathering and the drainage waters are of low hardness (Underwood et al. 1986). Detailed geological mapping is not yet available, but unpublished 1:10,000 maps are held by the BGS at Aberystwyth.

2.3.2 Soils

Soils of the catchment belong to the Hiraethog series of the Hafren association (654a) and are chiefly stagnopodzols and stagnohumic gleys (Rudeforth et al. 1984). Typically these soils, characteristic of the *Nardus* grassland, are thin (30-40 cm) with a wet peaty surface horizon and bleached subsurface horizons, often with a thin ironpan. In places amorphous acid *Sphagnum*/*Eriophorum* peat has accumulated which is being eroded at the southern and eastern sides of the lake.

2.3.3 Present Vegetation

Nardus stricta and *Festuca ovina* grassland dominate the catchment vegetation (Fig. 7). Small areas of *Eriophorum vaginatum* and *Sphagnum* (eg. *S.cuspidatum*, *S.papillosum* and *S.compactum*) bog are restricted to the wettest flushes and incipient drainage channels. *Molinia caerulea* is restricted to the more nutrient rich wet flushes around the edge of the lake. *Polytrichum commune*, *Aulocomnium palustre* and *Tricophorum caespitosus* are also common. Very little *Calluna* is found in the catchment and those plants that are present are very old and almost moribund. *Pteridium* is not present within the catchment.

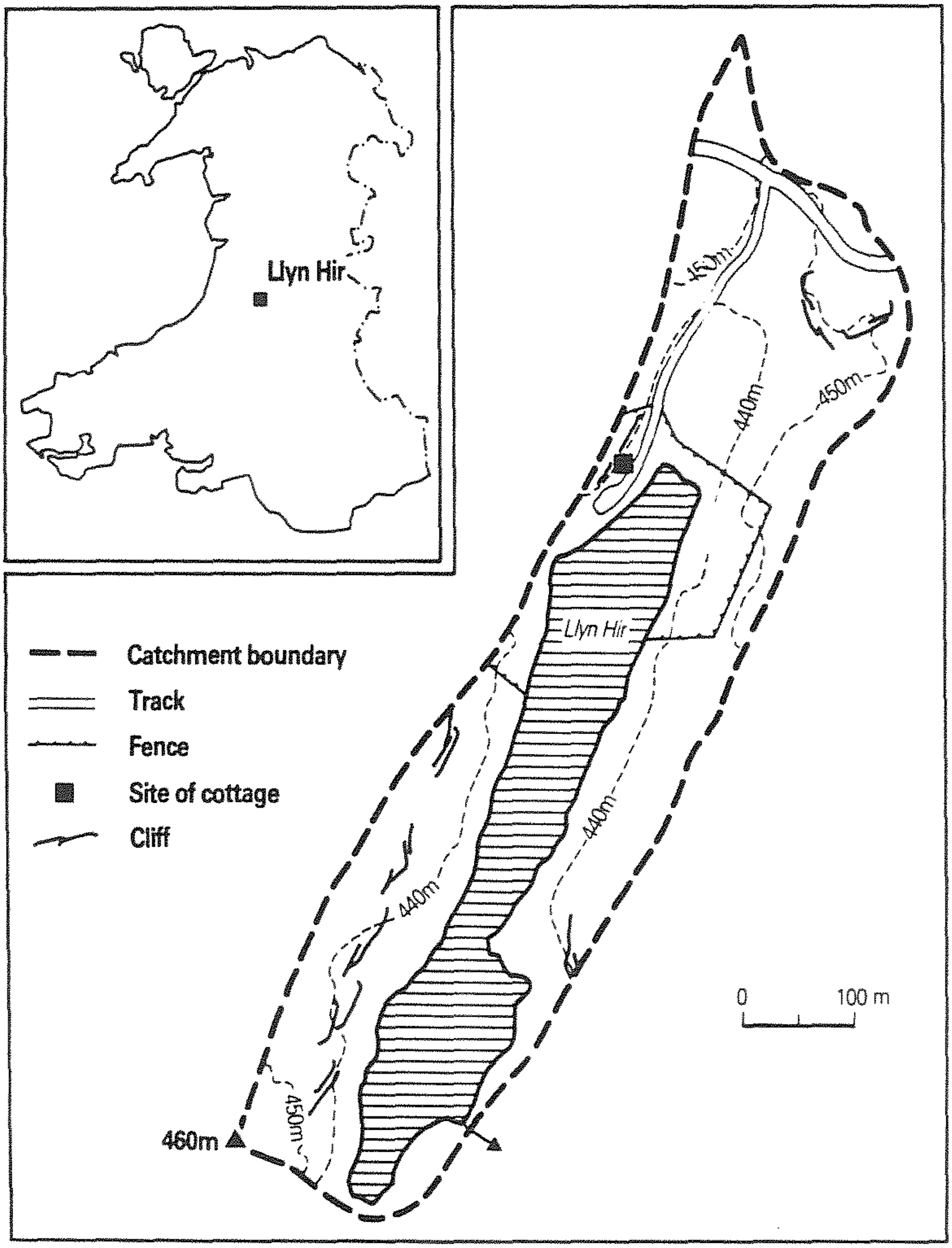


Fig. 6. Catchment diagram showing tracks, fence lines, contours and cottage.

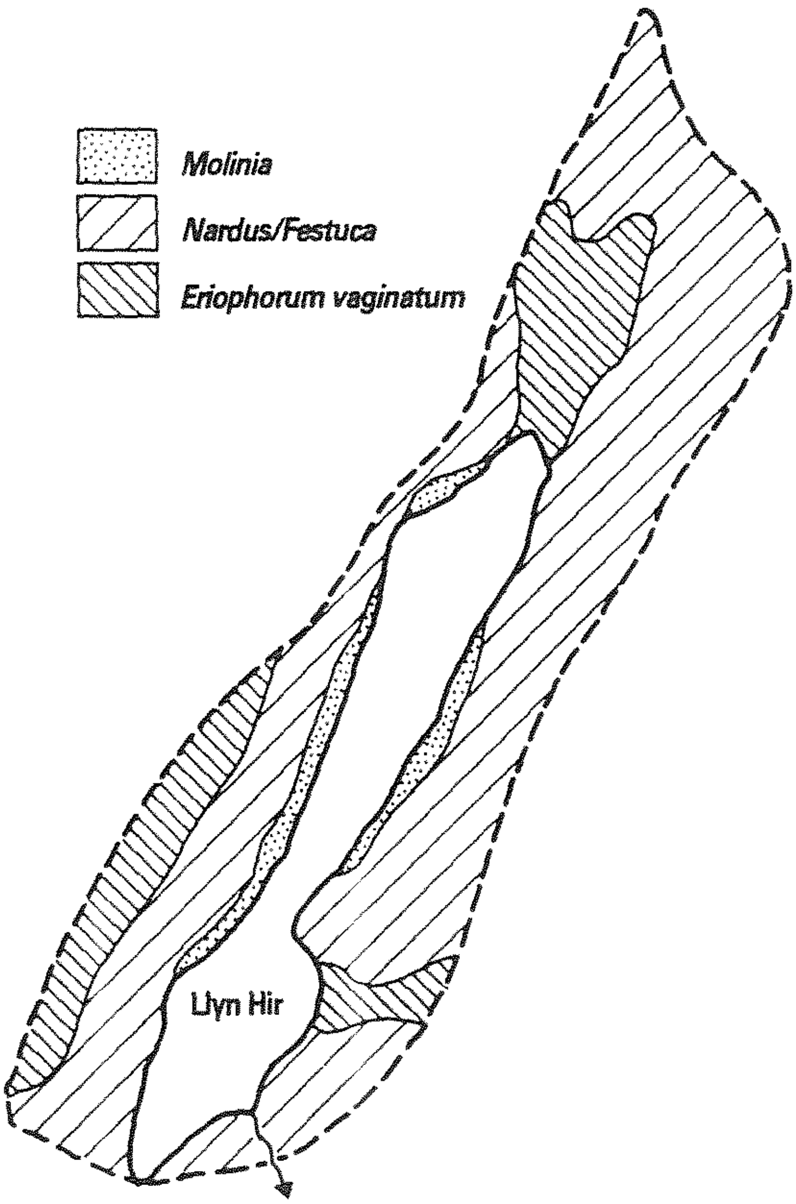


Fig. 7. The catchment vegetation of Llyn Hir.

3.0 Methods

3.1.1. Surveying

The lake was surveyed using the techniques described in Stevenson *et al.* 1986. Shore surveying stations were located on opposite shores at the narrowest section of the lake.

3.1.2. Collection of sediment cores and routine laboratory measurements of sediment characteristics

Cores were taken from both the north and south basins using a Mackereth mini-corer (Mackereth 1969) operated from an inflatable boat. Sampling was carried out during July 1984. The south basin provided core (HIR 1) which was used for dating and analysis (Fig. 4).

Core HIR 1 (76 cm) was extruded in the laboratory and sliced into 1 cm slices. The top 50 cm of sediment was sub-sampled at 1 cm intervals for dry weight, loss on ignition (at 550°C) and wet density measurements. The remaining 26 slices were subsampled at 2 cm intervals for these analyses.

Analyses for dating, magnetics, chemistry, soot, diatoms & pollen were all conducted according to the standard methods set out in Stevenson *et al.* (1986).

A second core from the south basin, Hir 2, was used for PAH and a third core, Hir 3, from the north basin was used for supplementary magnetic analysis.

4.0 Results

4.1 Lake history

4.1.1. Sediment Description

The changes in the measured sediment characteristics are shown in Fig. 8. The principal component of the sediment is a dark brown mud of organic detritus, with most particles less than 0.1mm in size. In appearance the composition of the sediment seems uniform down the core although small scale fluctuations in the organic content are apparent in the loss on ignition profiles. In the sediment 9-13 cm below the surface there is a small amount of fine sand which is reflected in the slight increase in the dry weight percentages with a corresponding decrease in the percentage lost on ignition.

4.1.2. ^{210}Pb dating

Sediments from Hir 1 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 Fig. 9. The ^{137}Cs results are given in Table 4 and Fig. 10. Table 5 gives values of a range of other radioisotopes determined from the gamma spectra. The ^{210}Pb results show that the unsupported ^{210}Pb (plotted on a logarithmic scale) varies linearly with depth, except for a dislocation of the profile between 10.5 cm and 15.5 cm. Since 15.5 cm is dated 1858 by the CRS ^{210}Pb dating model (Appleby and Oldfield 1978) and 1837 by the CIC model, it would appear that this feature relates to a disturbance in the latter half of the 19th century. Fig. 11 plots the ^{210}Pb chronologies given by both dating models. Except for the period of this disturbance there appears to have been a very slow sediment accumulation rate of ca. 6 mg cm^{-2} yr^{-1} and this is reflected in the high ^{210}Pb concentration in the near-surface sediments of 45.6 pCi g^{-1}. The CRS model indicates accelerated sediment accumulation rates during the period 1875-1910, with a peak accumulation rate of ca. 37 mg cm^{-2} yr^{-1} in 1888, and may be related to the construction of the cottage (see note 2). The CIC dates for this part of the core are older than the CRS dates, indicating possible dilution of the unsupported ^{210}Pb by accelerated sedimentation.

The ^{137}Cs profile (Fig. 10) has a definite peak at 2.5 cm. The ^{241}Am concentrations (Table 4), which also derive from nuclear weapons testing fall-out, have a maximum values at 1.5 cm. Since 2 cm is dated by ^{210}Pb to 1964 it would appear that these features are associated with the 1963 fall-out peak. There are, however, significant ^{137}Cs concentrations down to 15.5 cm, indicating considerable diffusion of this isotope.

The ^{210}Pb inventory of the core represents a mean ^{210}Pb flux of 0.38 pCi cm^{-2} yr^{-1}. This is within the range of values consistent with use of the CRS model. The chronology given in Table 6 is based on the CRS model, although as shown in Fig. 11, there is no significant disagreement with the CIC model except at the lower depths. CIC model results are given in Table 7.

LLYN HIR 1 SEDIMENT DATA PROFILES

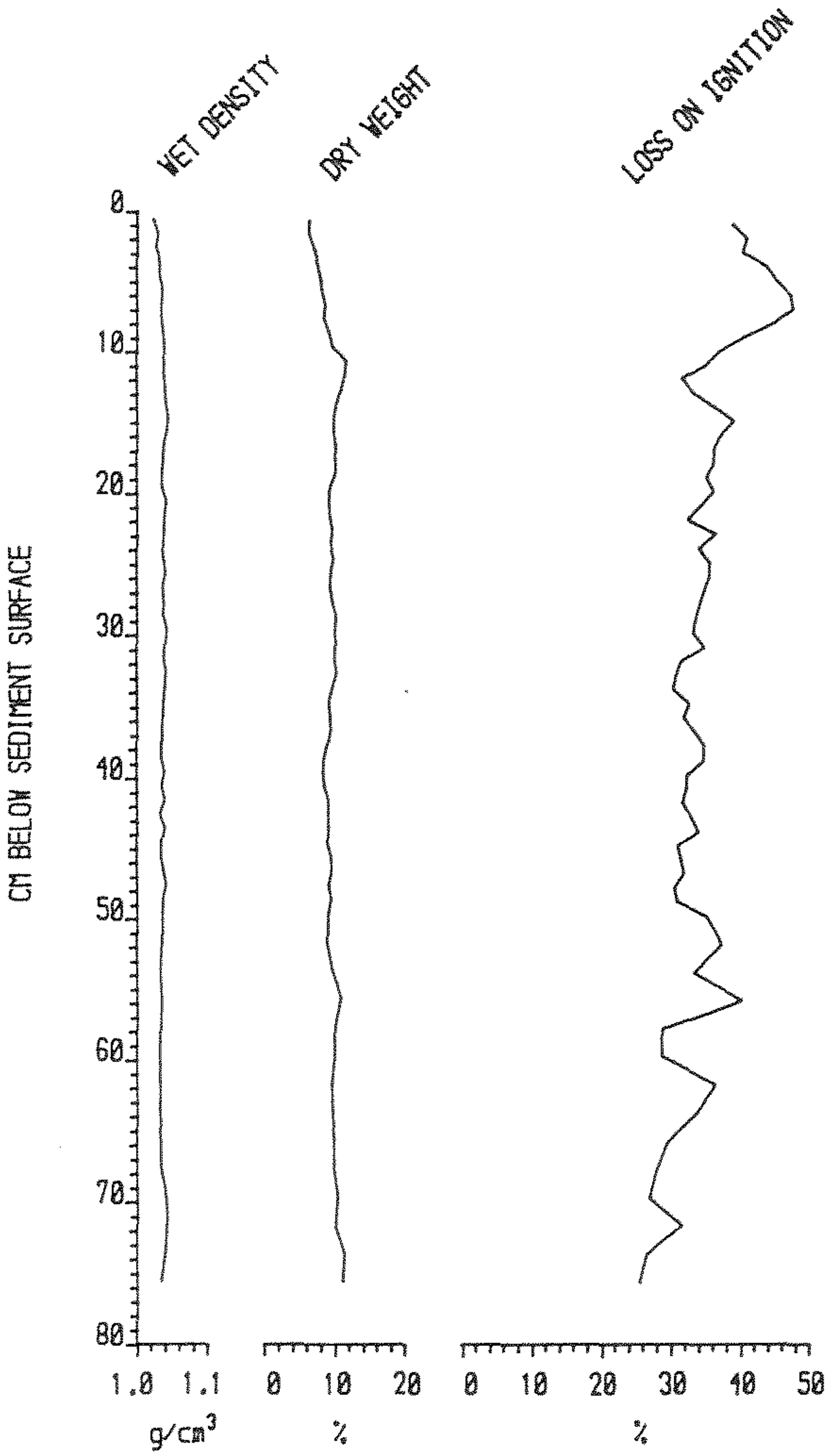


Fig. 8. Profiles of down core variation in dry weight, wet density and loss on ignition for the Llyn Hir I core.

Table 3: ^{210}Pb and ^{226}Ra data for Core Hir 1

Depth	Dry Mass	^{210}Pb Conc Total	^{210}Pb Conc Unsupported	Cum Unsupported ^{210}Pb	Std Errors Conc Total	Std Errors Conc Uns	Std Errors Cum Uns	^{226}Ra Conc
cm	g cm^{-2}	pCi g^{-1}	pCi g^{-1}	pCi cm^{-2}				pCi g^{-1}
0.50	0.0254	45.800	45.800	1.301	2.08	2.08	0.08	0.900
1.50	0.0888	46.440	45.352	4.191	1.62	1.65	0.20	1.088
2.50	0.1561	30.740	30.040	6.691	0.99	1.00	0.26	0.700
3.50	0.2297	19.970	19.473	8.485	0.78	0.79	0.28	0.497
4.50	0.3084	12.110	11.264	9.669	0.54	0.56	0.30	0.846
5.50	0.3907	7.390	6.381	10.379	0.75	0.78	0.30	1.009
7.50	0.5660	2.470	1.807	11.019	0.19	0.20	0.32	0.663
10.50	0.8642	1.540	0.460	11.347	0.23	0.25	0.33	1.080
15.50	1.4130	1.760	0.770	11.683	0.23	0.25	0.35	0.990
20.50	1.9172	1.050	0.110	11.889	0.20	0.22	0.37	0.940
25.50	2.4055	1.020	-0.166	11.875	0.22	0.24	0.38	1.186
53.50	5.0904	0.640	-0.056	11.538	0.16	0.17	0.58	0.696
54.00	5.1393			11.535				

Table 4: ^{137}Cs and ^{241}Am data for Core Hir 1

Depth	^{137}Cs concentration		Cumulative ^{137}Cs		Fract	^{241}Am concentration		Cumulative ^{241}Am		Fract
cm	pCi g^{-1}	+/-	pCi cm^{-2}	+/-		pCi g^{-1}	+/-	pCi cm^{-2}	+/-	
0.50	21.96	0.85	0.56	0.04	0.051	0.24	0.07	0.01	0.00	0.122
1.50	26.76	0.70	2.10	0.10	0.192	0.31	0.06	0.02	0.00	0.469
2.50	27.81	0.54	3.93	0.14	0.360	0.23	0.04	0.04	0.01	0.831
3.50	21.96	0.45	5.76	0.17	0.527	0.00	0.00	0.05	0.01	1.000
4.50	12.51	0.29	7.08	0.19	0.648	0.00	0.00	0.05	0.01	1.000
5.50	6.20	0.31	7.82	0.19	0.715	0.00	0.00	0.05	0.01	1.000
7.50	3.45	0.08	8.64	0.20	0.791	0.00	0.00	0.05	0.01	1.000
10.50	2.43	0.10	9.51	0.21	0.870	0.00	0.00	0.05	0.01	1.000
15.50	1.22	0.08	10.47	0.22	0.958	0.00	0.00	0.05	0.01	1.000
20.50	0.22	0.06	10.77	0.22	0.985	0.00	0.00	0.05	0.01	1.000
25.50	0.14	0.06	10.85	0.22	0.993	0.00	0.00	0.05	0.01	1.000
53.50	0.00	0.00	10.93	0.24	1.000	0.00	0.00	0.05	0.01	1.000

Table 5 Other radioisotope data for core Hir 1

Depth	^{226}Ra	^{238}U	^{235}U	^{228}Ac	^{228}Th	^{40}K
cm			(pCi g^{-1})			
0.50	0.00	0.30	0.26	0.00	0.96	0.00
1.50	1.09	0.00	0.10	0.09	1.93	11.30
2.50	0.70	0.98	0.26	0.70	1.03	7.39
3.50	0.50	0.00	0.23	0.23	0.89	10.17
4.50	0.85	0.00	0.09	0.64	0.85	12.06
5.50	1.01	0.92	0.00	0.62	1.03	3.69
7.50	0.66	0.08	0.11	0.33	0.42	12.48
10.50	1.08	1.02	0.11	0.74	0.61	20.35
15.50	0.99	0.47	0.11	0.71	1.08	19.54
20.50	0.94	0.38	0.09	0.58	1.40	20.96
25.50	1.19	0.72	0.18	0.93	1.39	21.64
53.50	0.70	0.27	0.04	0.42	0.86	11.78

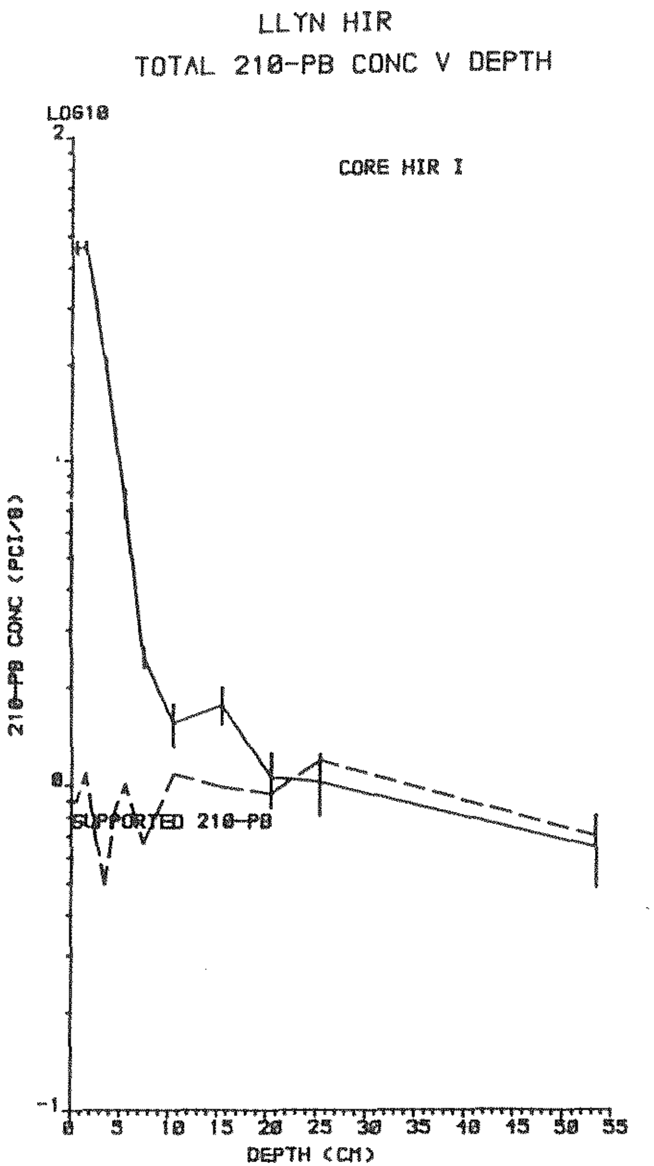


Fig. 9a. Total ^{210}Pb profile for the Llyn Hir I core.

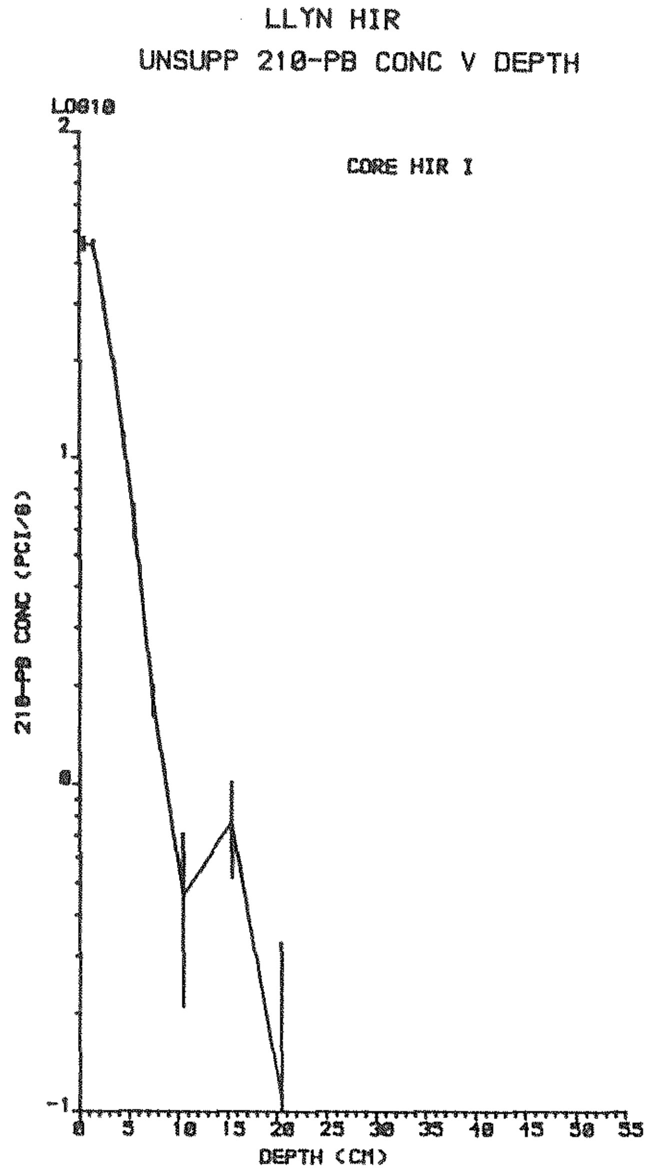


Fig. 9b. Unsupported ^{210}Pb profile for the Llyn Hir I core.

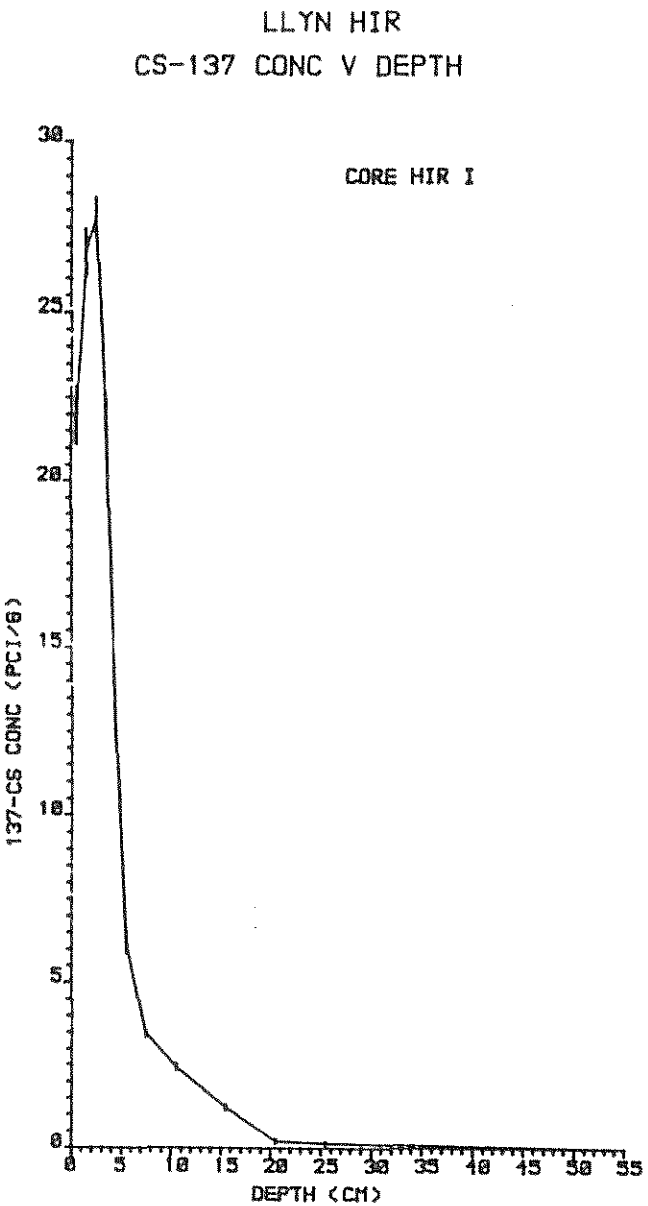


Fig. 10. ^{137}Cs profile for the Llyn Hir I core.

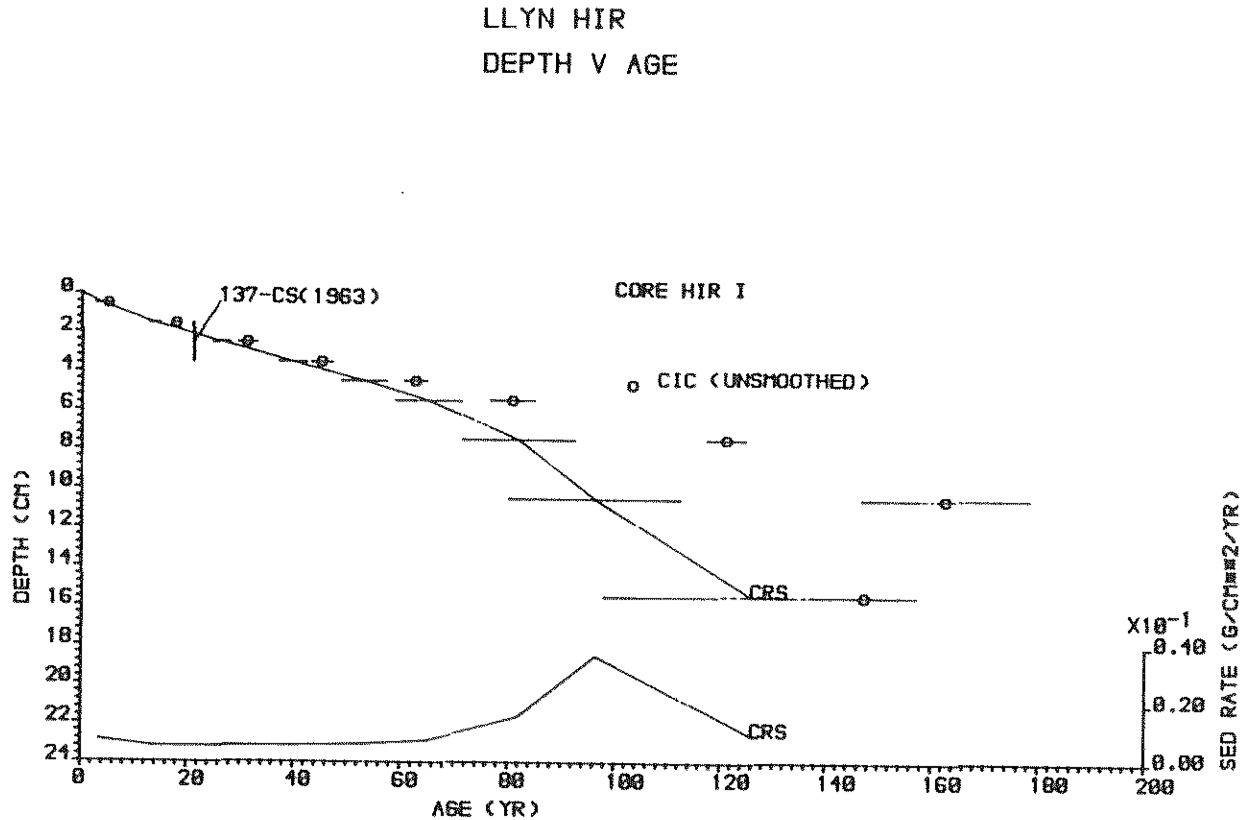


Fig. 11. CRS and CIC ^{210}Pb age/depth chronology for the Llyn Hir I core

Table 6. ^{210}Pb data and CRS calculated sediment age and accumulation rates for the Llyn Hir I sediment core

Depth	Total ^{210}Pb	Cumulative Unsupported ^{210}Pb	Date	Age		Sediment accumulation rate		Standard error	^{226}Ra
cm	pCi g^{-1}	pCi cm^{-2}	AD	yr	S.E.	mg cm^{-2} yr^{-1}	mm yr^{-1}	%	pCi g^{-1}
0.00		12.17	1984	0	-				
0.50	45.800	10.86	1980	4	2	7.4	1.25	5.7	0.900
1.50	46.440	7.94	1970	14	2	5.3	0.82	5.8	1.088
2.50	30.740	5.38	1958	26	2	5.5	0.78	7.4	0.700
3.50	19.970	3.55	1944	40	3	5.6	0.73	10.5	0.497
4.50	12.110	2.34	1931	53	5	6.3	0.78	15.4	0.846
5.50	7.390	1.61	1919	65	7	7.7	0.89	22.0	1.009
6.50	---	1.24	1911	73	9	11.7	1.28	28.6	---
7.50	2.470	0.95	1902	82	11	15.8	1.67	35.2	0.663
8.50	---	0.82	1897	87	13	22.8	2.27	44.5	---
9.50	---	0.71	1893	91	15	29.8	2.88	53.8	---
10.50	1.540	0.61	1888	96	17	36.8	3.48	63.2	1.080
11.50	---	0.50	1882	102	19	31.3	2.96	72.6	---
12.50	---	0.42	1876	108	21	25.7	2.43	82.0	---
13.50	---	0.35	1870	114	24	20.2	1.91	91.4	---
14.50	---	0.29	1864	120	26	14.6	1.39	100.8	---
15.50	1.760	0.24	1858	126	28	9.1	0.86	110.2	0.990
20.50	1.050								0.940
25.50	1.020								1.186
53.50	0.640								0.696
54.00									

Unsupported ^{210}Pb equilibrium depth is 18.1 cm

Table 7. CIC calculated sediment age and accumulation rates for the Llyn Hir I sediment core.

Depth	Cumulative Unsupported ^{210}Pb	Date	Age	Sediment accumulation rate	
cm	pCi cm^{-2}	AD	yr	mg cm^{-2} yr^{-1}	mm yr^{-1}
0.00	56.29	1984	0		
0.50	45.85	1979	5	4.9	8.4
1.50	46.82	1966	18	4.9	7.6
2.50	30.68	1953	31	4.9	7.0
3.50	19.89	1939	45	4.8	6.3
4.50	11.53	1921	63	4.5	5.6
5.50	6.55	1903	81	5.4	6.2
7.50	1.87	1863	121	13.1	13.9
10.50	0.51	1821	163	13.1	12.4
15.50	0.83	1837	147	13.1	12.5

99% equilibrium depth = 15.0 cm

4.1.3. Diatoms and pH reconstruction

The diatom assemblage in the lower part of the Llyn Hir sediments (50 cm - 20 cm) is dominated by Cyclotella kutzingiana, Achnanthes minutissima, and several Fragilaria species, with moderate percentages of Melosira perglabra, M.perglabra var. florineae, Melosira lirata, Anomoeoneis vitrea and a number of small Navicula species (Fig. 12). This flora is very similar to the pre-acidification flora of Round Loch of Glenhead (Flower & Battarbee 1983), but the higher percentages of alkaliphilous taxa, particularly small Fragilaria and Navicula species yield a higher reconstructed pH (6.1 - 6.5) for Llyn Hir (Table 8) in comparison with Round Loch. The only marked change in the flora during this period is the gradual increase in Cyclotella kutzingiana between 35 cm and 25 cm (approximately 1765-1830).

Table 8: Diatom-based pH reconstructions for the base of the Llyn Hir Core

Depth	Index B Renberg & Hellberg	Index B Galloway	Multiple Regression
10	6.1	6.0	6.1
12	6.1	6.0	6.2
14	6.3	6.1	6.4
16	6.5	6.4	6.5
18	6.2	6.1	6.1
20	6.4	6.3	6.4
25	6.3	6.2	6.4
30	6.3	6.2	6.5
35	6.2	6.1	6.5
40	6.3	6.2	6.3
45	6.3	6.2	6.5
50	6.3	6.2	6.4

Early in the 19th century percentages of Cyclotella kutzingiana, the only planktonic taxon in the Llyn Hir sediments, gradually decline, reaching very low values by the end of the century and remaining low throughout subsequent lake history. This loss of diatom plankton has been observed in the early stages of acidification in many lakes, including most of the Galloway sites (Flower et al. in press). A Cyclotella decline occurs at about the same time in Loch Dee and Loch Skerrow, situated partially on non-granitic bedrock but occurs much earlier (ca. 1700 A.D.) at Round Loch of Glenhead, wholly on granites.

pH reconstructions based on Index B (Table 8) do not show a decrease in lakewater pH associated with the Cyclotella decline. This loss of plankton, however, may be associated with a marked loss of alkalinity in response to increased acid loading or alternatively could reflect some other change in water chemistry.

Beginning early in the 20th century a series of changes in the diatom flora suggest a progressive decrease in lake pH. A number of alkaliphilous taxa including Fragilaria brevistriata, F.construens var. venter and Navicula seminulum as well as Navicula cf. vitiosa decline in percent abundance, while Tabellaria flocculosa, Navicula subtilissima and Eunotia veneris, taxa characteristic of acidic water,

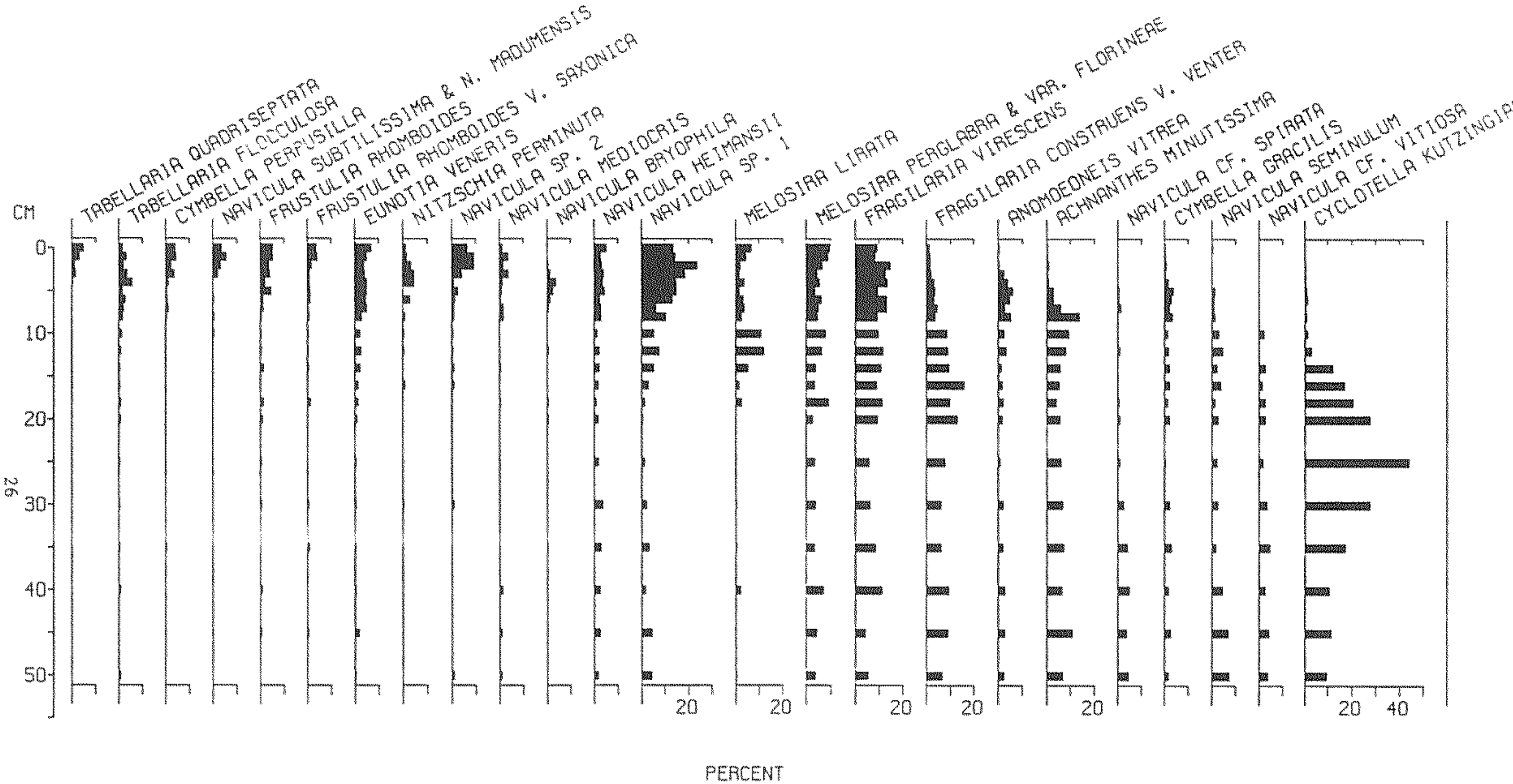


Fig. 12. Diatom summary diagram for the Llyn Hir I core.

increase or first appear. Subsequently, Achnanthes minutissima, Anomoeoneis vitrea, Navicula indifferens, and Navicula cf. spirata, decrease with concurrent increases in Frustulia rhomboides and Nitzschia perpusilla and the appearance of the acidobiontic taxon Tabellaria quadriseptata. A more abrupt change occurs in the upper few cm (post 1944) with distinct increases in Tabellaria quadriseptata, Navicula subtilissima, Frustulia rhomboides var. saxonica, and Cymbella sp. 1 and a decline in Fragilaria virescens and Navicula bryophila. These floristic changes are remarkably similar to those in the uppermost sediments of the Galloway lakes except for the notable absence of Tabellaria binalis.

We are unable to reconstruct quantitatively these 20th century changes in pH because of the high relative abundance (15-35%) of undesignated Navicula species in the uppermost 8 cm of Llyn Hir. These taxa have not been found in the modern sediments of the Galloway lakes or in large quantity in any of the other Welsh lakes so far. Consequently their pH tolerances are unknown, which excludes them from the equations for pH reconstruction. Because these Navicula taxa represent a large proportion of the total flora, their exclusion produces a large error in the pH calculations, and hence we cannot confidently reconstruct pH for these samples. It is quite clear, however, that Llyn Hir has undergone large pH changes from ca. 6.1-6.5 in the 17th - 19th centuries to 4.5-5.1 in the early 1980's. The sharp post-1940 expansion of the acidobiontic taxa Tabellaria quadriseptata and Navicula subtilissima which occur only in highly acidified lakes, indicates that the pH decline has been most marked from this date.

4.1.4 Sediment chemistry

Figs. 13-25 and Appendix D present the whole-core chemistry for the Llyn Hir core.

Major cations

Below the dated part of the core (>20 cm) the basic sediment characteristics (density, dry weight and loss on ignition) change little. However, magnesium, sodium and potassium increase at 36-37 cm depth (Figs. 13-15). This suggests some catchment disturbance at this early date, possibly an increase in erosion rate (Mackereth 1966, Engstrom & Wright 1984). The pollen results also indicate catchment disturbance at this depth (section 4.1.7).

The magnesium, sodium and potassium concentrations decrease above 10-11 cm. This may be a change to a somewhat lower erosion regime. The soil erosion period between 10 and 15 cm, indicated by the dry weight and loss on ignition (4.1.1), ^{210}Pb (4.1.2) and pollen results (4.1.7), is not reflected in the major cations.

Calcium profiles are commonly different from the other major ions, as is the case here (Fig. 16). One feature, the concentration peak at 6-7 cm, is emphasised when the concentrations are expressed per gram minerals and it coincides with a loss on ignition peak (Fig. 8). In dilute waters, natural organic matter preferentially complexes calcium ions (Stumm & Morgan 1981; pp 643-645, Sayles & Mangelsdorf 1977), so it may be that the increase and decrease of sediment organic matter above 10 cm increases and decreases the

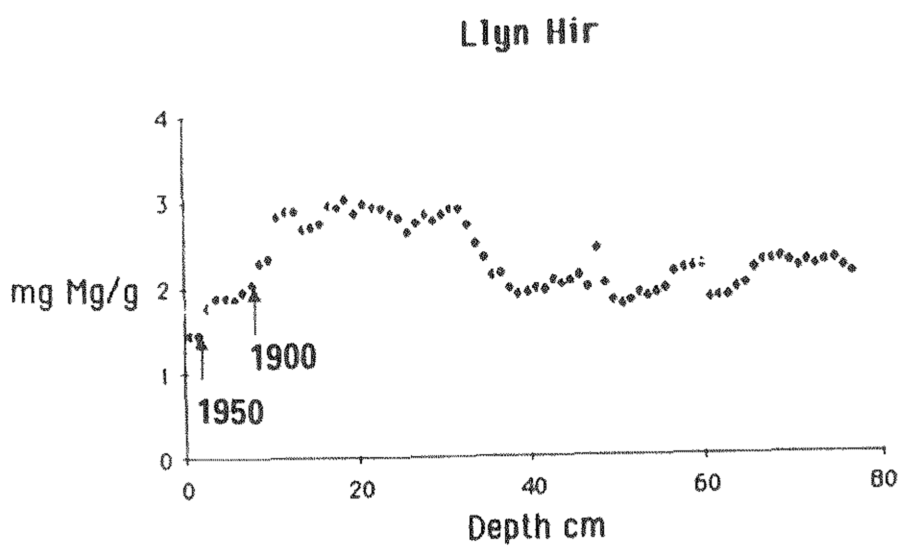


Fig. 13a. Variations in Mg gdw^{-1} for the Llyn Hir I core.

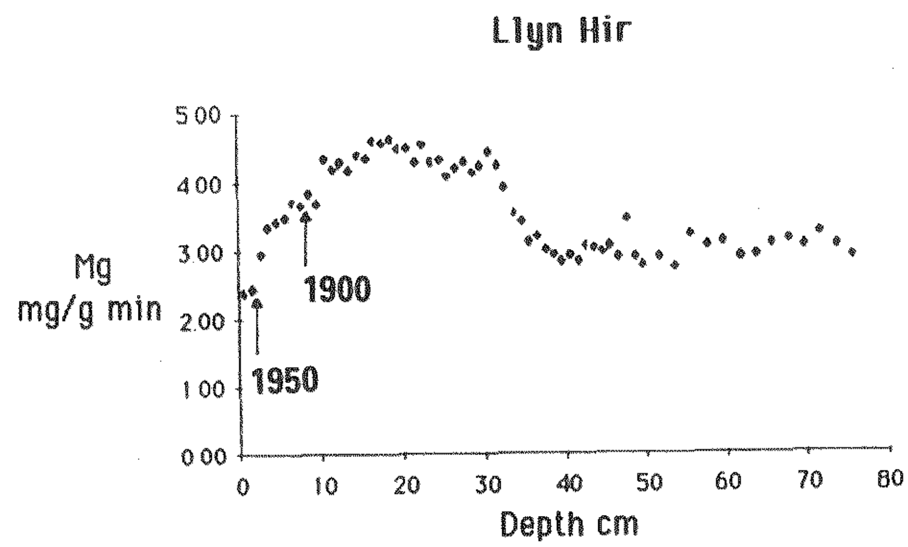


Fig. 13b. Variations in Mg per gram mineral dry weight.

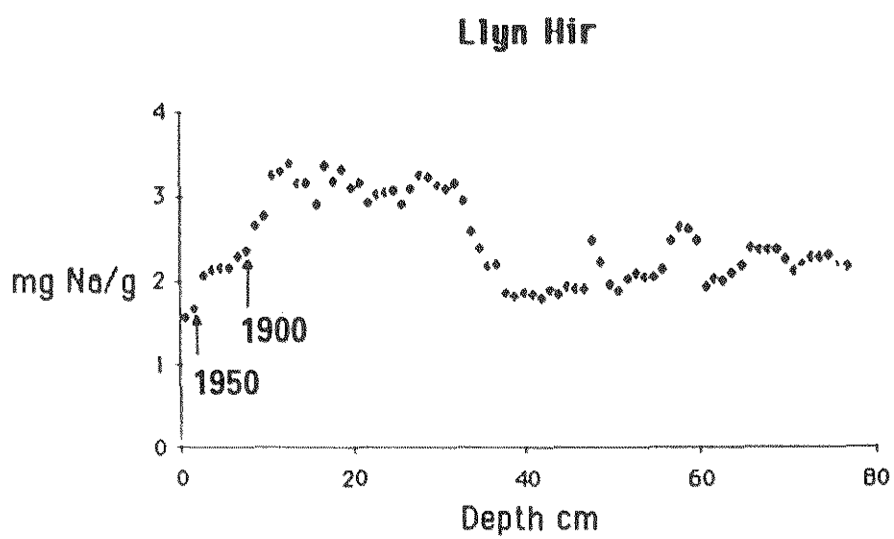


Fig. 14a. Variations in Na gdw^{-1}.

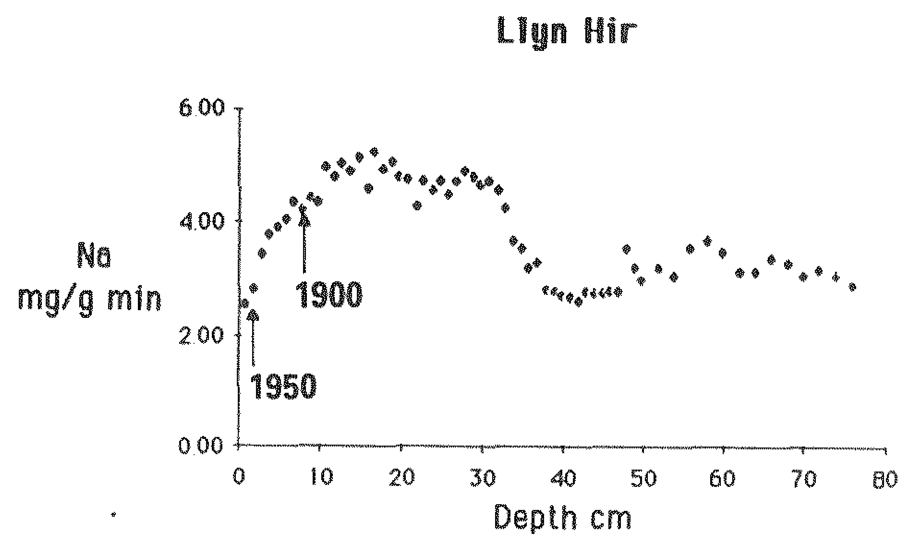


Fig. 14b. Variations in Na per gram mineral dry weight.

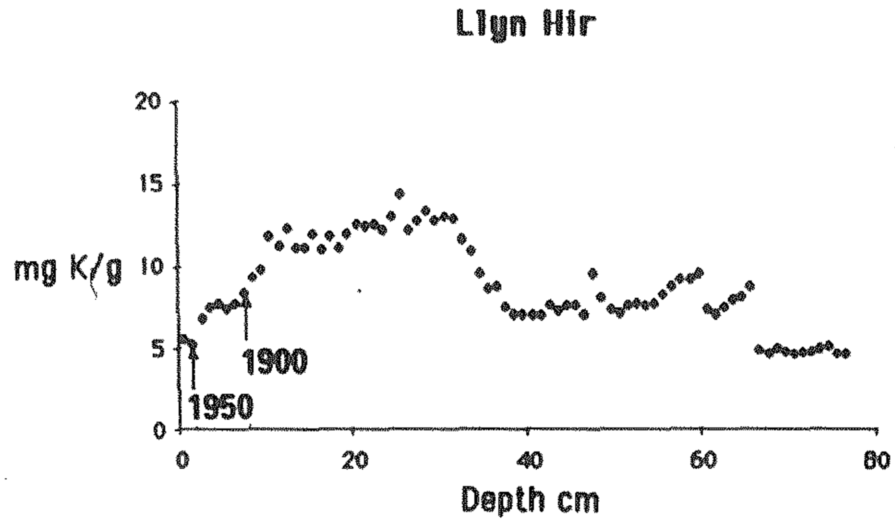


Fig. 15a. Variations in K gdw^{-1}.

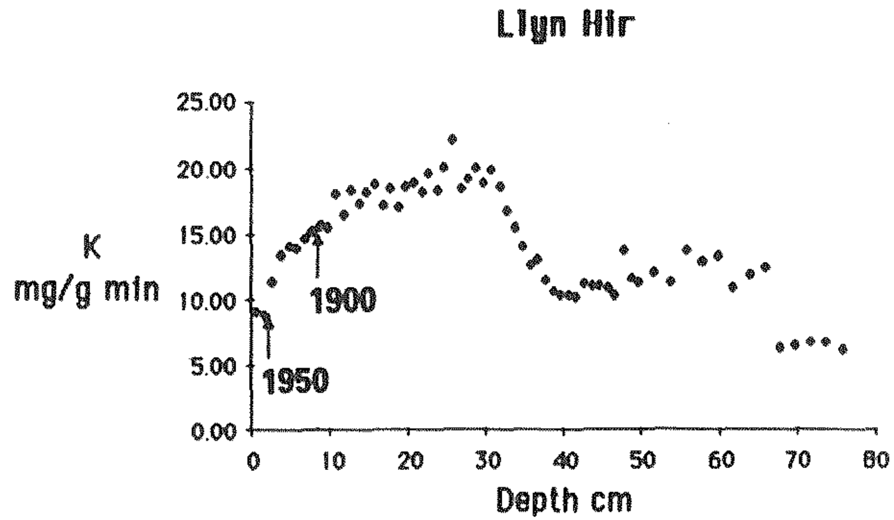


Fig. 15b. Variations in K per gram mineral dry weight.

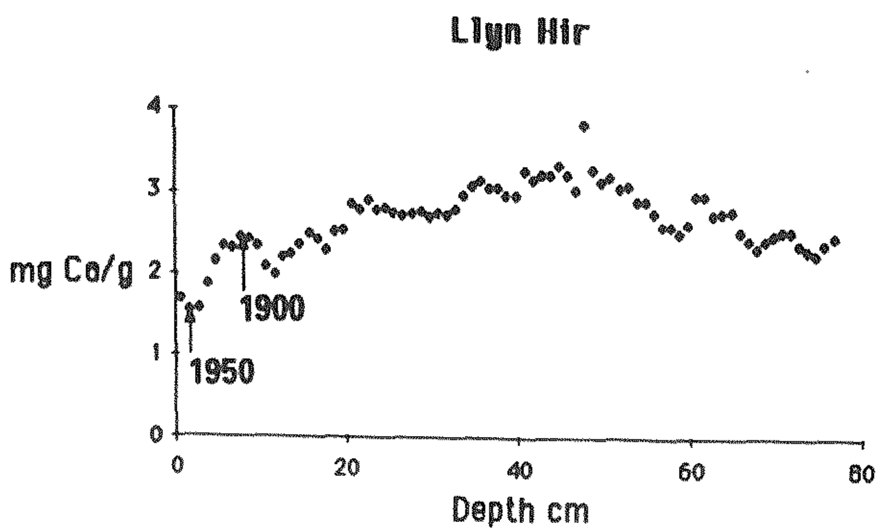
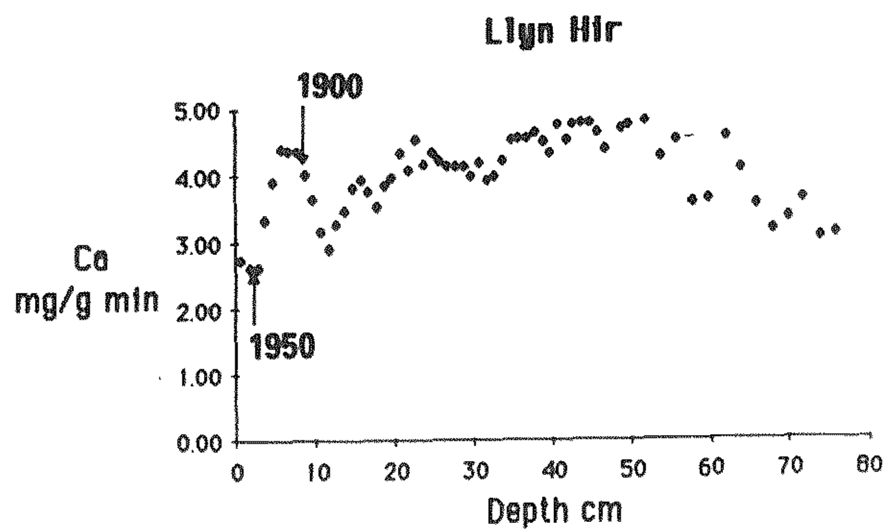


Fig. 16a. Variations in Ca gdw^{-1}.



calcium sedimentation efficiency and so produces this sedimentary calcium feature.

Trace metals

The major cation results indicate that in the absence of inputs of trace metals from the atmosphere the trace metal concentrations might decrease in the upper 10 cm or so of the sediment. The lead, zinc and copper concentrations do, however, increase strongly above 11-12 cm (1882 AD) and indicate contamination of the sediment (Figs. 18-20). The nickel flux from the atmosphere is low but the low sediment accumulation rate in Llyn Hir means that this atmospheric flux is not obscured by a higher catchment flux as is the case in other lakes. So in Llyn Hir, nickel shows a small peak in concentration at 4-5 cm.

The background trace metal concentrations, below 20 cm depth, (136 ug Zn g^{-1}, 23 ug Pb g^{-1} and 23 ug Ni g^{-1}) show that there is no mineralization in the catchment.

In the top 5 cm, the lead, nickel and zinc concentrations either drop or stop increasing. This could be the result of a decrease in the atmospheric flux of these metals and with zinc there could also be a pH-induced decrease in net sedimentation efficiency. This could be by a lower pH in the water column impoverishing sedimenting material in zinc and/or release from the sediment after deposition. We have found this feature at the top of two sediment cores in Galloway.

Iron and Manganese

The iron and manganese concentrations are fairly constant except at the top where there is diagenetic remobilisation (Figs. 21 and 22). The manganese mobilisation extends further into the sediment than with iron and the rise in concentration of both metals towards the sediment surface is roughly exponential. Both these features are expected during anoxic diagenesis.

Sulphur

There was not always enough sediment in the top 10 cm of the core for sulphur analysis on all samples, so the sulphur profile shape is not well defined towards the surface. Nevertheless, within this limitation, the sedimentary sulphur concentrations increase above about 10 cm, which is just a little above the depth at which the trace metal concentrations increase. The depths of peak sulphur and trace metal concentrations are coincident.

In summary, the zinc, lead, copper and sulphur sedimentary profiles indicate that Llyn Hir has received material from the atmosphere beginning at 11-12 cm (1882 AD). The size of these anthropogenic fluxes are given in Table 9 and the trace metal air fluxes are similar to those measured in two Galloway lakes which have been acidified by atmospheric deposition.

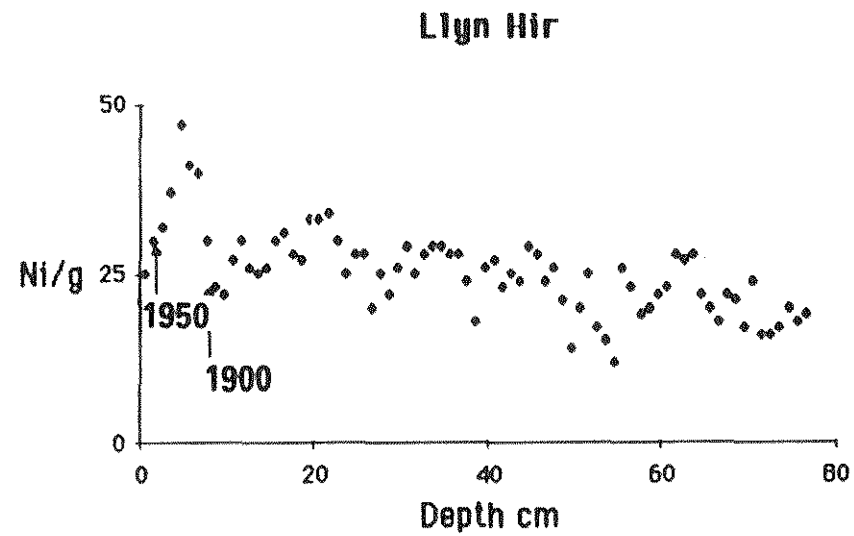


Fig. 17a. Variations in Ni gdw^{-1}.

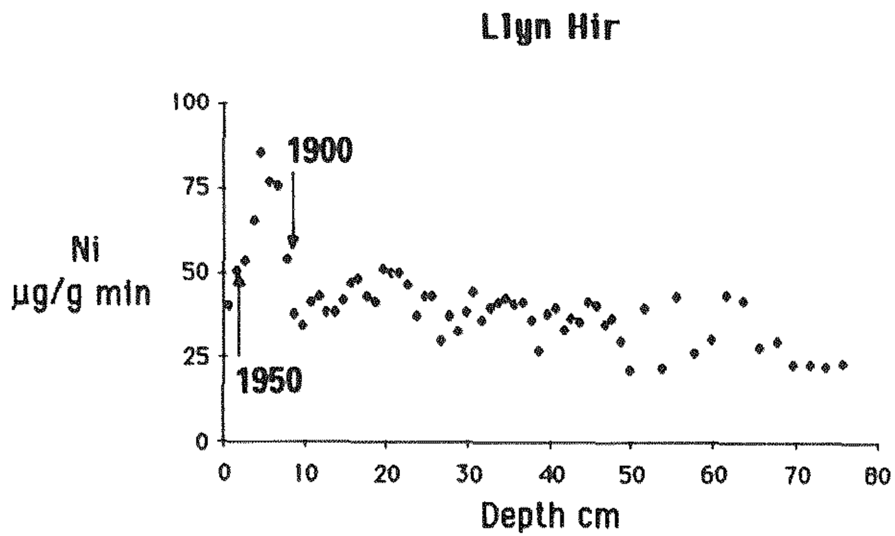


Fig. 17b. Variations in Ni per gram mineral dry weight.

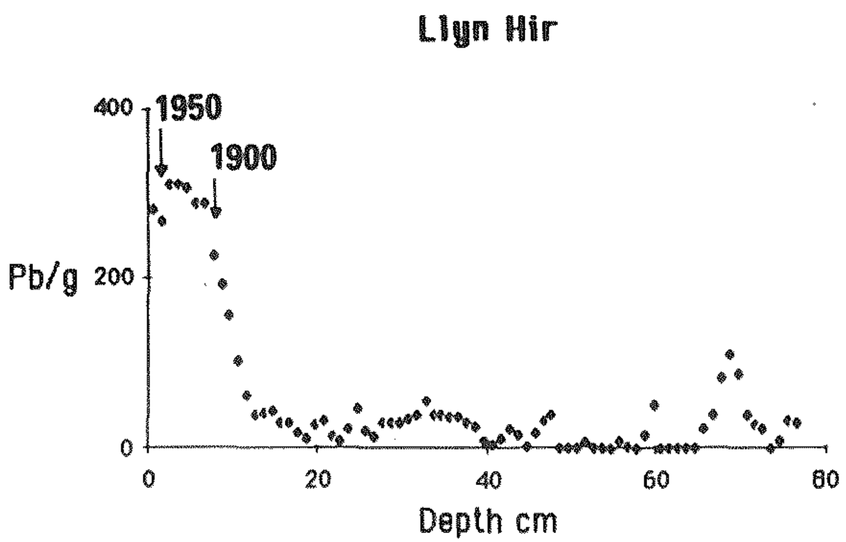


Fig. 18a. Variations in Pb gdw^{-1}.

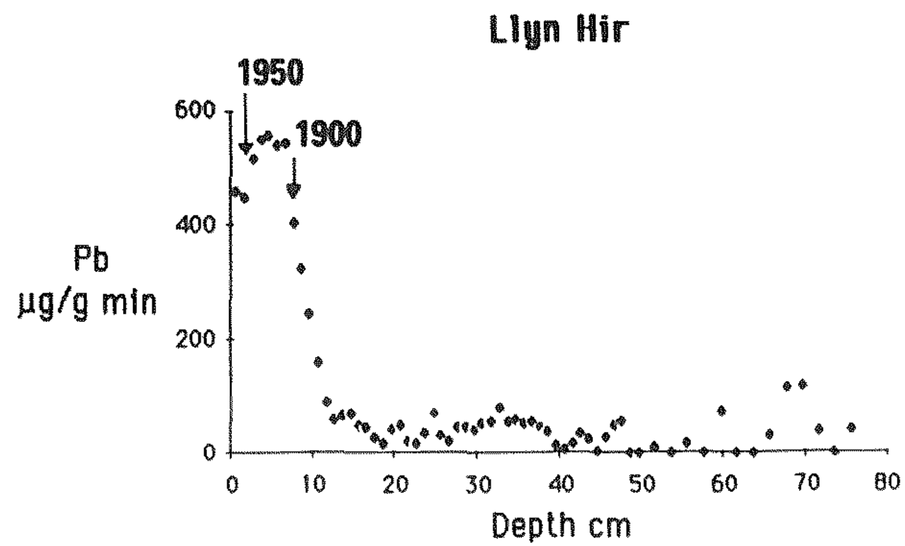


Fig. 18b. Variations in Pb per gram mineral dry weight.

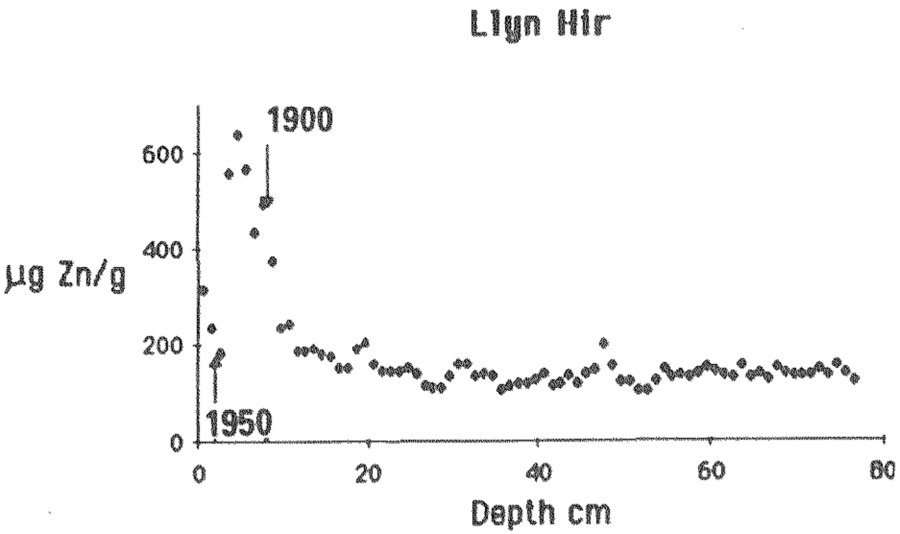


Fig. 19a. Variations in Zn gdw[-1].

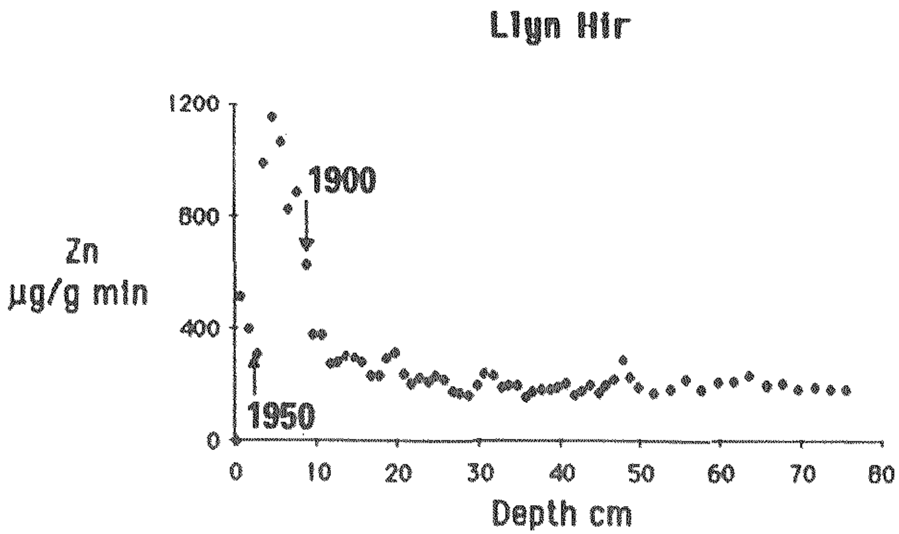


Fig. 19b. Variations in Zn per gram mineral dry weight.

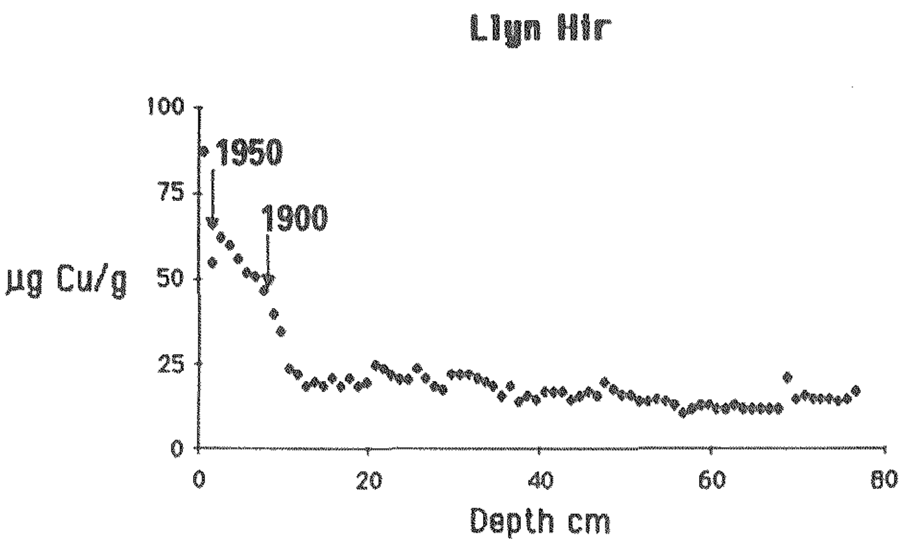


Fig. 20a. Variations in Cu gdw[-1].

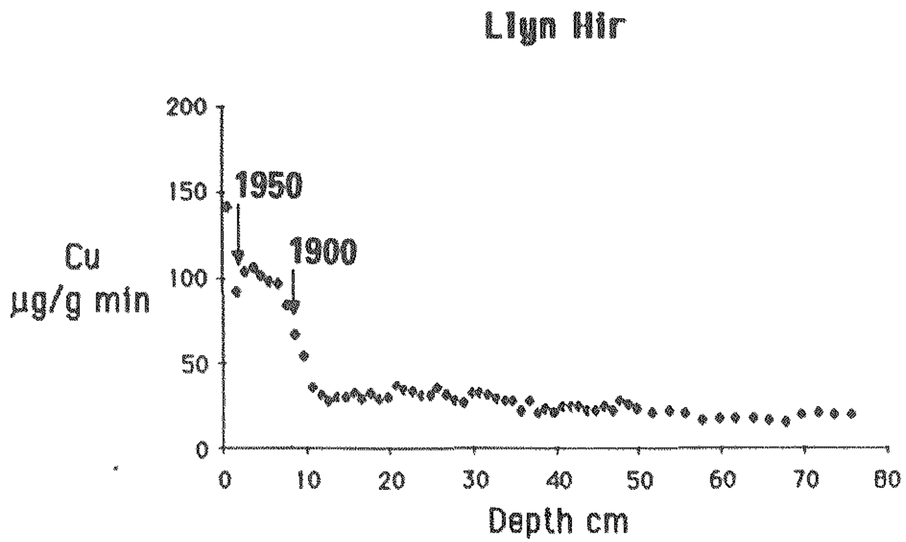


Fig. 20b. Variations in Cu per gram mineral dry weight.

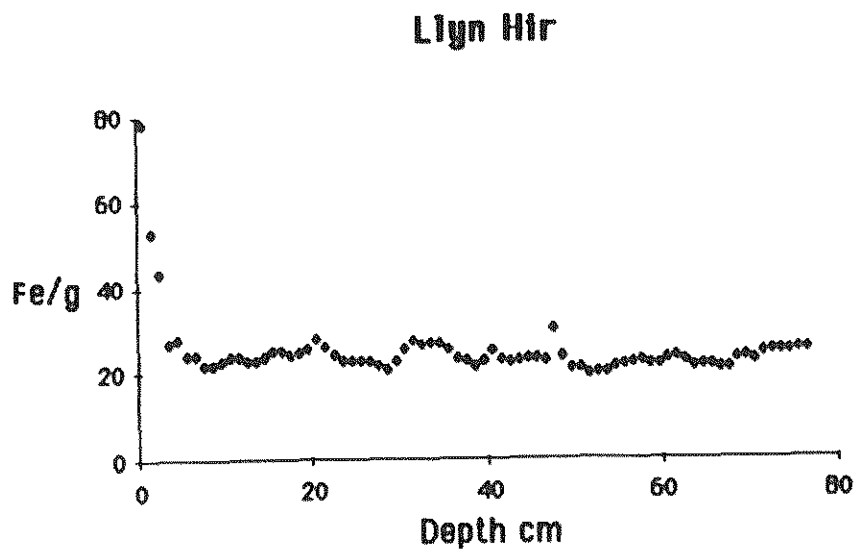


Fig. 21. Variations in Fe gdw^{-1}.

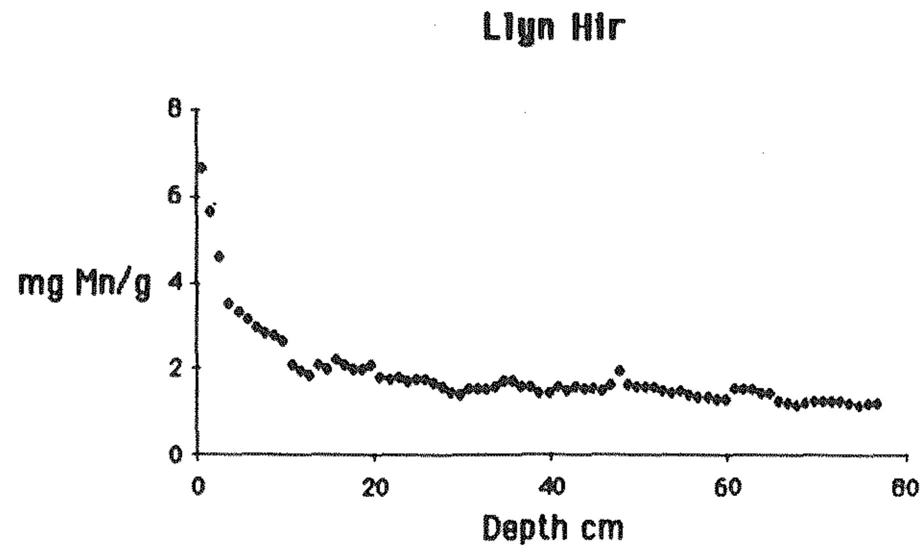


Fig. 22. Variations in Mn gdw^{-1}.

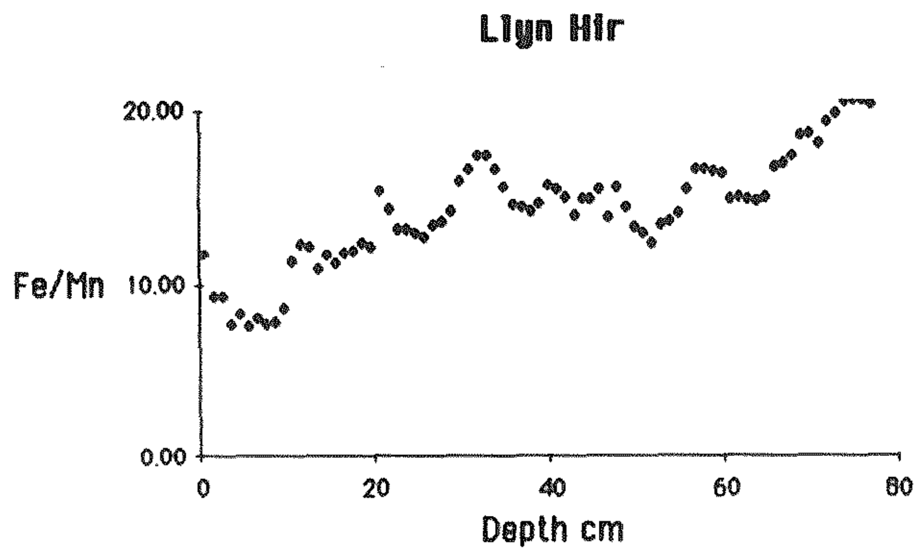


Fig. 23. Variations in the Fe/Mn ratio.

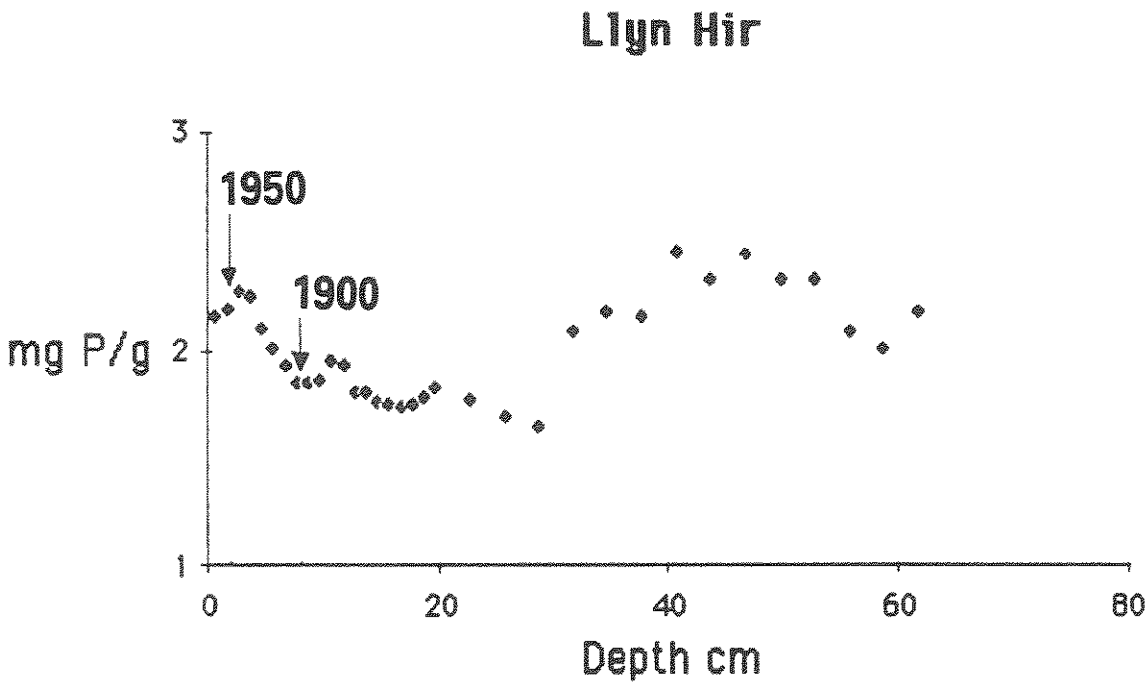


Fig. 24. Variations in the total acid soluble P gdw^{-1}.

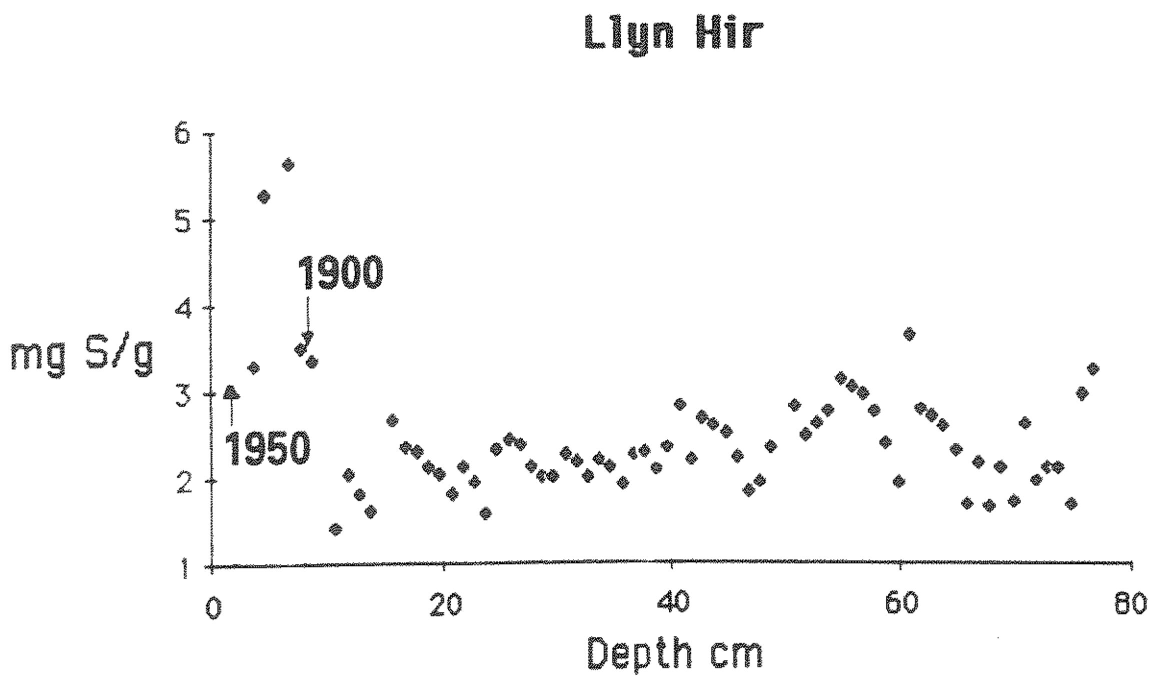


Fig. 25. Variations in S gdw^{-1}.

Table 9. Enhancement of trace metal fluxes caused by anthropogenic activities

Element	Background flux mg m^{-2} yr^{-1}	Maximum flux mg m^{-2} yr^{-1}	Anthropogenic flux mg m^{-2} yr^{-1}
zinc	17	85	68
lead	3	42	39
copper	2.2	9.3	7.1
sulphur	220	740	520

PAH

As yet the analyses for PAH have not been completed and the results will follow.

4.1.5. Carbonaceous cenospheres "Soot"

The "soot" pattern for Llyn Hir, illustrating the number of particles per gram dry sediment is given in Fig. 26 and Table 10. It shows the presence of soot in small numbers at a depth of 25 cm. There is a slight peak at 17-18 cm. Another increase is marked at 7-8 cm, and the onset of a trend of rapidly increasing counts commences at 4 cm, continuing to the surface.

The pattern for the soot count in terms of the organic content of dry sediment is given in Fig. 27. Soot 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 soot pattern, and this can be observed for Llyn Hir. Otherwise, the pattern is very similar to that in Fig. 26.

4.1.6. Magnetic Measurements

Magnetic measurements were carried out on two lake sediment cores (Fig. 28) and on two short cores of peat (Fig. 29) taken from an area of blanket bog growing within the Llyn Hir catchment. Profiles were measured by R. Callow as part of an undergraduate honours dissertation (Callow 1986).

Lake sediment profiles

The profile from the south basin of Llyn Hir (Fig. 28a) is based on samples from the same core that has yielded the chronological, geochemical and palaeoecological results from the site. Below 10 cm, magnetic measurements are exceptionally low (SIRM 200 x 10^{-6} Am^{-2} kg^{-1}). SIRM/ARM is also low though rising gently above 22 cm. The reverse field 'S' ratios each vary within rather narrow limits and with few significant trends over more than 2-3 samples. These results point to an exceptionally low and relatively constant flux of catchment derived magnetic minerals to the sediment.

Above 8-10 cm SIRM values rise at first rather gently up to 3 cm, and then more suddenly to peak values. Coincident with the intermediate values around 4-7 cm there is a peak in SIRM/ARM values together with distinctive

Table 10: "Soot" Analysis for Hir 1

Depth (cm)	No. Carbonaceous Cenospheres per g dry sed x 10^3	No. Carbonaceous Cenospheres per g organic content x 10^3
0-1	26.12	67.7
1-2	24.77	60.9
2-3	10.05	25.1
3-4	10.04	23.1
4-5	4.90	10.9
5-6	4.10	8.7
6-7	-	-
7-8	1.72	3.9
8-9	0.83	2.1
9-10	0.45	1.2
10-11	0.30	0.9
11-12	0.40	1.3
12-13	0.06	0.2
13-14	0.14	0.4
14-15	0.04	0.1
15-16	0.25	0.7
16-17	0.06	0.2
17-18	0.82	2.3
18-19	0.53	1.5
19-20	0.24	0.7
20-21	0.23	0.7
21-22	0.39	1.2
22-23	0.28	0.8
24-25	0.36	1.0

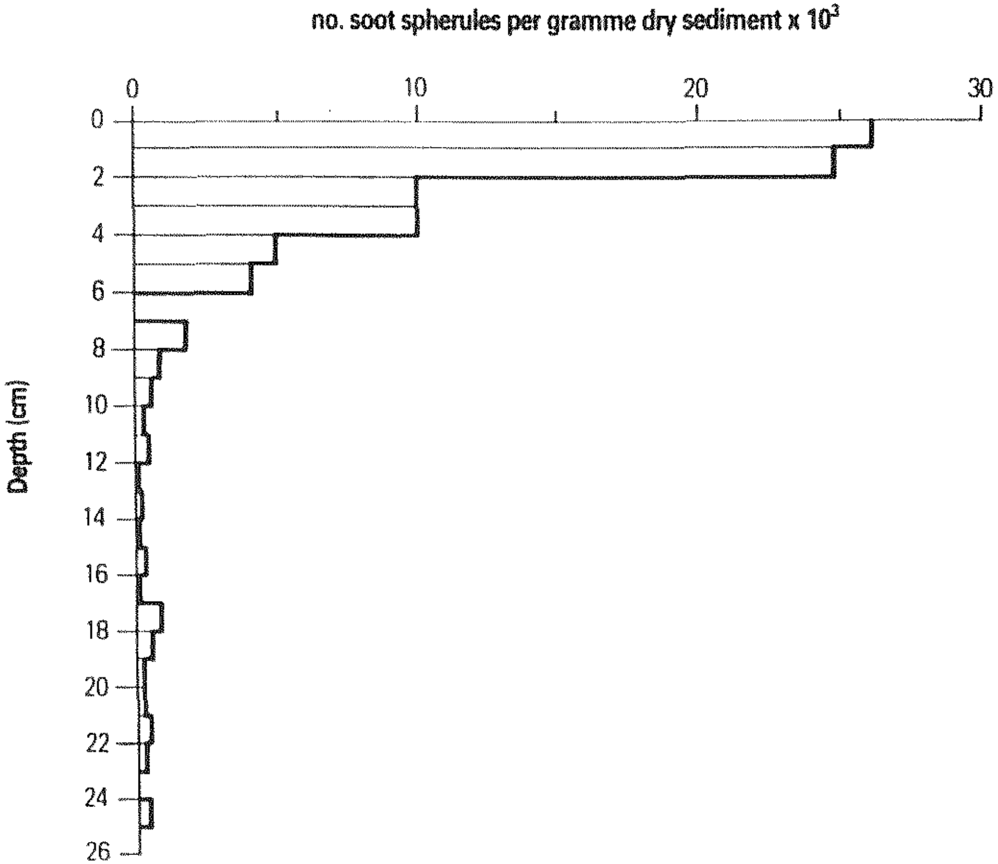


Fig. 26. Carbonaceous cenosphere record gdw⁻¹ for the Llyn Hir I core.

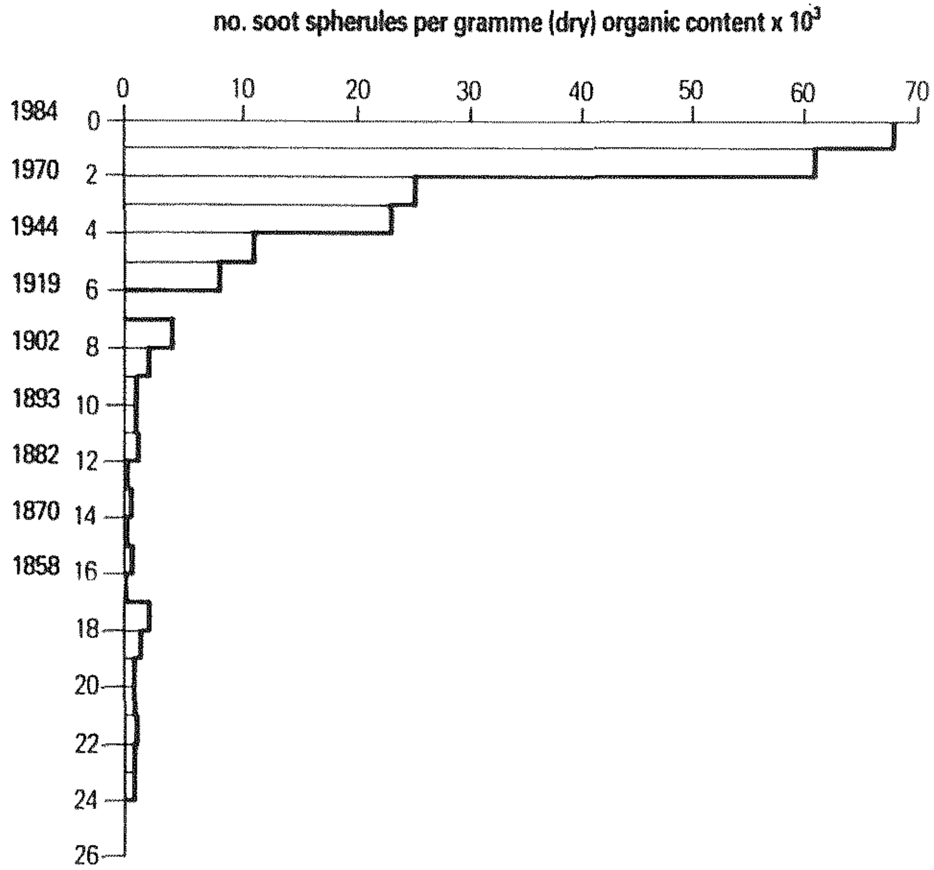


Fig. 27. Carbonaceous cenosphere record per gram mineral dry weight for the Llyn Hir I core.

variations in 'S' (IRM/SIRM) involving peaks of hardness, especially in IRM_{-100mT}/SIRM. SIRM/ARM peaks again at the surface and the reverse field ratios decline to low values.

The profile from the north basin (Fig. 28b) has higher and more variable SIRM values below the near-surface increase. The peak values around 20cm are associated with higher SIRM/ARM and relatively hard remanence, suggesting the relatively greater importance of a haematite component in the catchment derived magnetic minerals. Above ca. 7 cm, the changes in SIRM, SIRM/ARM and 'S' parallel very closely those above 8 cm in the north basin core and correlation may be proposed as follows (Table 11).

Table 11. Magnetic correlations between Hir I and Hir III sediment cores

South (cm)	North (cm)
0	1
1.5	2-3
4.5	5-6
7.5	8

The peak SIRM/ARM values which mark the surface sample in the north basin core are absent from that in the south basin. The possibility that the most recent sediment is missing in that core cannot be excluded.

According to the chronology calculated from ^{210}Pb analyses on the south basin core, these parallel changes in the top centimetre or less of each core begin around the first decade of this century. The softening of the reverse field ratios and final SIRM rise to peak values in the top 3 cm begins around 1950 AD. These recent changes are tentatively interpreted below in the light of the data from the two peat profiles.

Peat profiles

Both profiles (Figs. 29a & 29b) show minimum values at the very base (60 x 10^{-6} Am^{-2} kg^{-1}). Above this, slightly increased values are accompanied by higher SIRM/ARM and harder 'S' ratios, between 22-28 cm in the 'Pool' profile and 24-28 cm in the 'Hummock'. Above this, in the hummock, SIRM values remain rather low, then rise gently to a point of steep increase at 11 cm. This feature coincides with an increase in SIRM/ARM which peaks, along with SIRM in the top 4 cm. The same general features are present in the pool profile though the inflexion in the rising SIRM values is less marked. Once more SIRM/ARM peaks in the topmost samples. In each profile there is at least one sample marked by quite high SIRM and very soft 'S' values (8-9 cm in the hummock, and 4-6 cm in the pool) .

In view of the large volume of unpublished data from upland peat sites throughout most of northwest England, the major features above 28 cm in both peat profiles can be interpreted as the effects of the deposition from the atmosphere of particles resulting from industrial processes such as fossil (largely solid) fuel combustion, iron and steel manufacture and non-ferrous metal smelting. Sites in northern England and southwest Scotland for which direct chronologies are available suggest that the phase up to 11 cm in the hummock and ca. 10 cm in the pool dates from the 19th and first half of the 20th century. The characteristic steep rise to peak SIRM and SIRM/ARM values at that depth has been dated to around 1950 AD at these sites. The single samples with exceptionally soft 'S' values are comparable

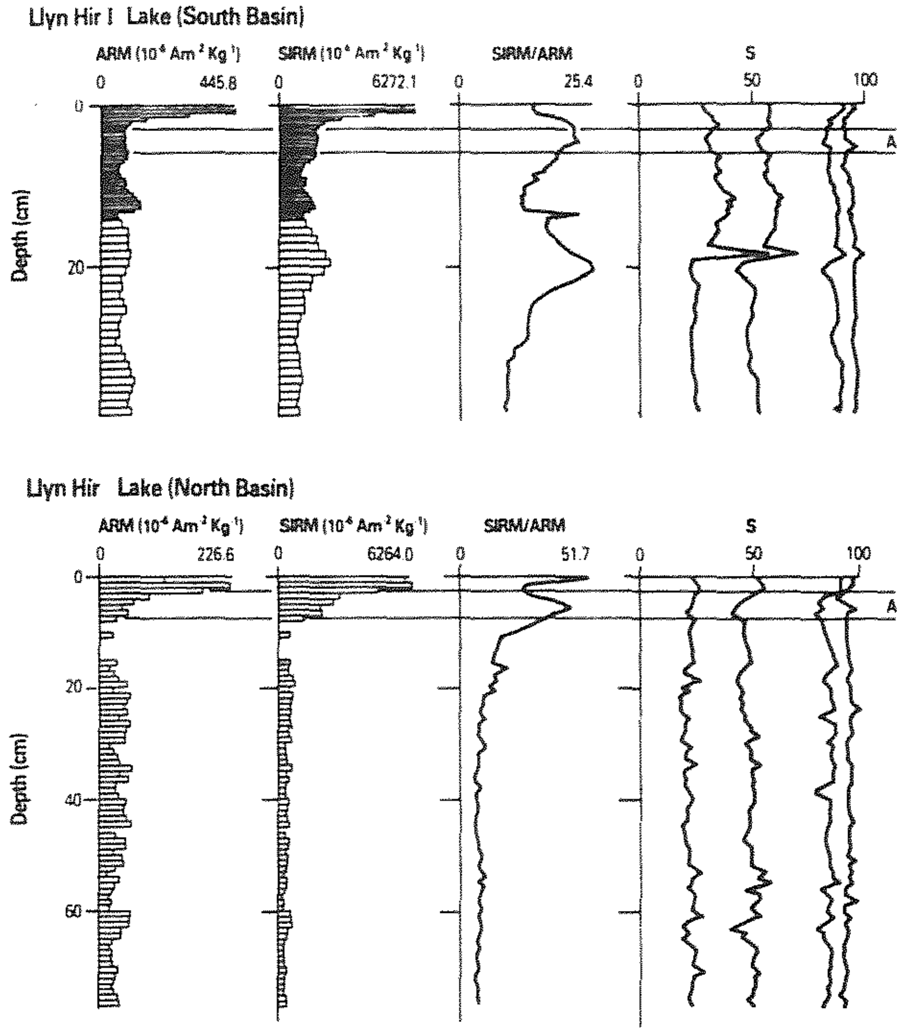


Fig.28 Magnetic measurements for the Llyn Hir I and III lake cores.

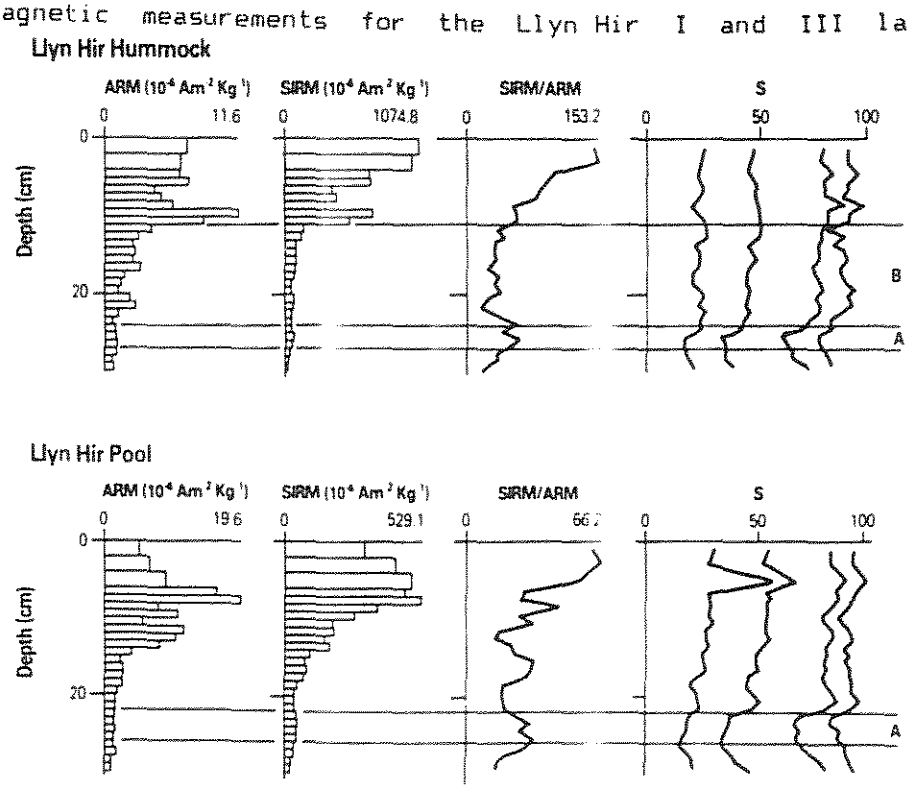


Fig. 29. Magnetic measurements for pool and hummock peats in the Llyn Hir catchments

Susceptibility values as 10^{-6} Gcm^3 Oe^{-1} g^{-1}.
Remanence values are 10^{-6} Gcm^3 g^{-1}. 'S' ratios plot
IRM_{-20mt}/SIRM, IRM_{-40mt}/SIRM, IRM_{-100mt}/SIRM, and IRM_{-300mt}/SIRM.
Measurements - 100 = full reverse saturation, 50 = zero remanence.

to those elsewhere affected by _in situ_ burning, although the documentary evidence does not appear to support this.

Lake-Peat comparisons

Clearly there is a marked parallelism between the magnetic measurements from the top 8 cm of the lake sediment profiles and those from the top 28 cm of the blanket peat. Despite the much more rapid accumulation rate in the peats, an apparently similar sequence of changes is recorded in all the cores. Such chronological evidence as is available - direct for lake sediments, but indirect only for the peats - is compatible with the hypothesis that these changes are synchronous between profiles. This prompts the inference that in the case of the lake, and especially the north basin, the flux of catchment derived magnetic minerals is so low that the 20th century record is dominated by atmospherically derived deposition reflecting the industrial history of areas quite remote from the site. Despite the parallels and the strong circumstantial evidence, this hypothesis requires more direct confirmation through examination of magnetic extracts from the recent lake sediments by means of Scanning Electron Microscopy. This allows unambiguous identification of the industrially derived component in the magnetic record.

4.1.7. Pollen

Figs. 30 and 31 present summary pollen diagrams of the Llyn Hir core. Appendix E contains the full pollen diagram.

The tree pollen diagram from Llyn Hir shows remarkably little change over the course of the core. The pine rise from 15-20 cm towards the top is the only major change. This rise reflects initially the _ad hoc_ reafforestation of some of upland central Wales (Malkin 1807) followed by an accelerated programme of afforestation with pine, primarily lodgepole pine, (_Pinus contorta_) by the Forestry Commission from the early 1940's onwards. The rise is in direct agreement with the available ^{210}Pb dating of the core. Most of the record of _Fagus_ pollen appears to be derived from hedgerows rather than mature woodland stands, for _Fagus_ is the dominant component of hedgerows in the area.

Catchment derived pollen changes throughout the core are limited and agree well with the overall lack of change identified by the current land-use survey. Throughout the core, however, three phases of disturbance can be identified. Two of these correlate well with disturbances indicated by the ^{210}Pb and core chemistry data. Within the dated portion of the core, 0-25 cm, a peak of the pastoral indicator, _Plantago lanceolata_ is correlated with a dislocation of the ^{210}Pb profile, a phase of increased sediment accumulation rate and a decline in values of _Isoetes_ pollen, a combination consistent with a phase of soil erosion.

An earlier phase of disturbance, below the dated portion of the core, is also indicated by a second peak in the pastoral indicator, _Plantago lanceolata_, beginning at 40 cm while values of the aquatic macrophyte _Isoetes_ decline markedly. This feature is also picked up by the whole core chemistry with enhanced values of sodium, potassium and magnesium. The combination of these events is again consistent with a phase of disturbance including soil erosion which increased the turbidity of the lake, thereby,

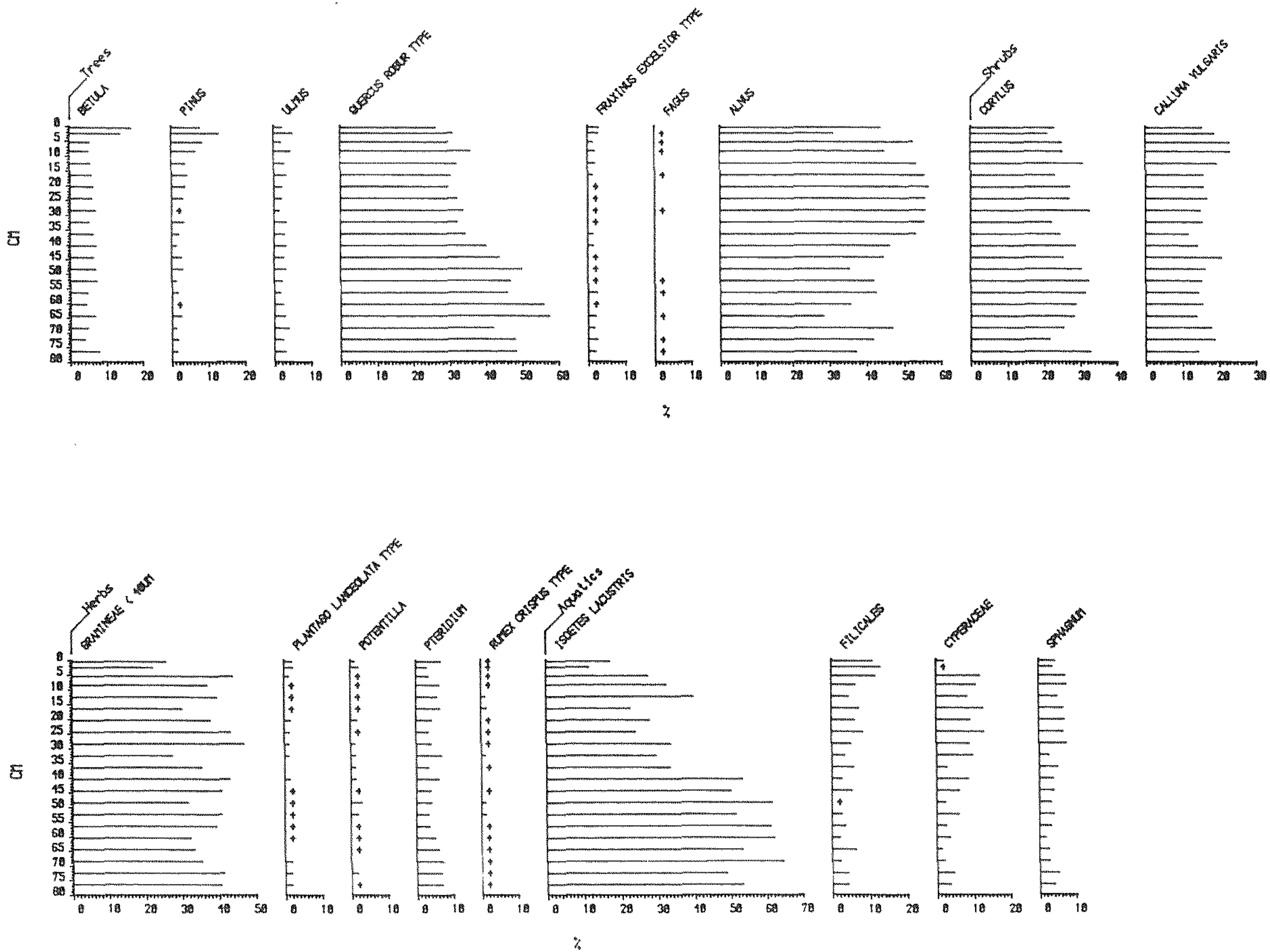


Fig. 30. Summary pollen diagram for the Llyn Hir I core. Trees expressed as a percentage of the Arboreal pollen. All other groupings as a percentage of the Arboreal pollen plus peatland indicators.

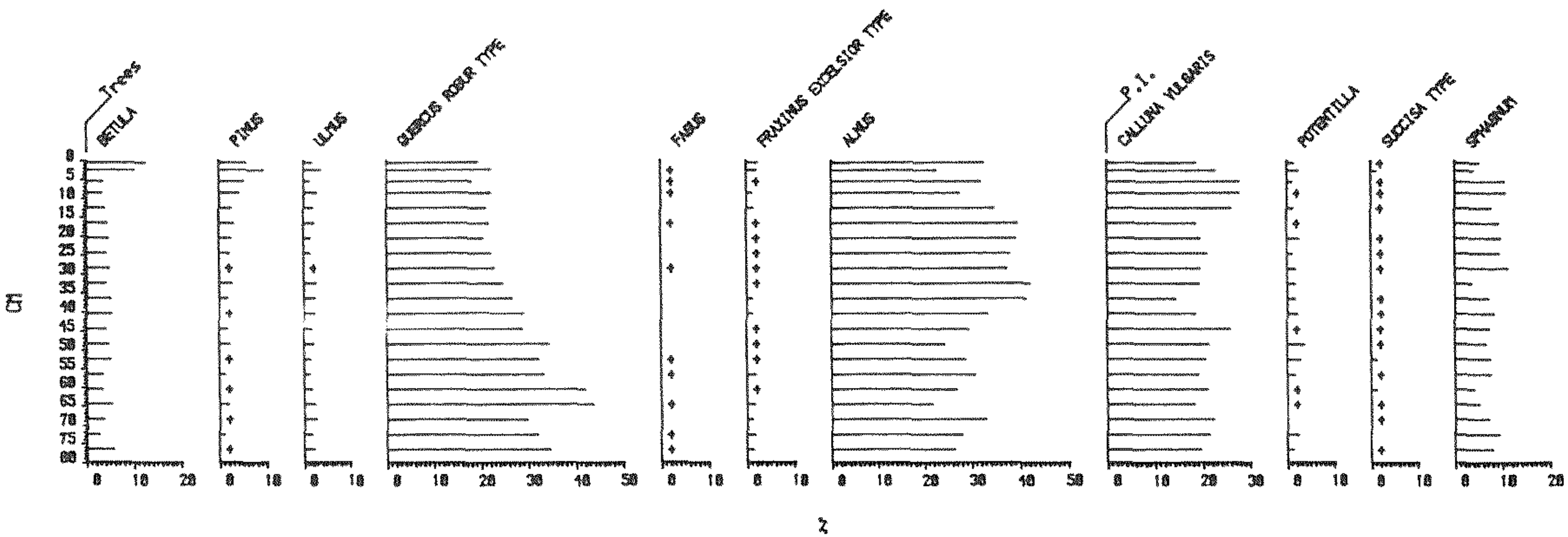


Fig. 31. Summary pollen diagram for the Llyn Hir I core. All taxa expressed as a percentage of the Arboreal pollen plus peatland indicators.

adversely affecting the Isoetes populations. A further peak of Plantago lanceolata at 80 cm does not appear to have resulted in a phase of soil erosion as values of sodium, magnesium and potassium remain low and the Isoetes pollen record remains high.

4.2 Land-use and Management (4)

4.2.1 Land-use

At over 400 m and on acidic soils, the Llyn Hir catchment consists of unimproved, unenclosed moorland utilised for rough grazing. In terms of vegetational composition (see Section 2.3.3) it may be categorised as 'grassy heath' (eg. King 1977, Ball et al. 1982).

There is no evidence to associate the original deforestation of the catchment with the well documented clearance of woodland ordered by Edward I after the Welsh rebellion at the end of the 13th century (5). Moore and Chater (1969) consider this to have been a lowland and foothill clearance. It is probable that land at the elevation of Llyn Hir had been open moorland for a far longer period.

In terms of the ADAS (6) Land Capability Classification the catchment comprises land of category H3 - 'improvements generally severely limited but of moderate or high grazing value' (MAFF 1980).

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 Hir 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 unlikely that any attempt was made to improve the acid moorland soils with lime. There was no limestone in Cardiganshire, and furthermore the high cost of lime in the early 19th century (Davies 1815), together with the cost of carriage over bad roads, deterred farmers from utilising lime on the home farm, let alone on the remoter hills (cf. Rees 1815, Howell 1946) (7). Contemporary farmers (eg. H. Owen and W. Owen pers. comms.) and authorities (eg. R. Davies and C. Evans pers. comms.) confirm that agricultural lime has not been applied to the catchment in living memory.

Documentary evidence (8)

In the 16th century Leland described the Teifi pools as 'gloomy llyns' situated high up among 'dreary morasses and mountain solitudes' surrounded by 'nothing but wilderness' (Ward 1931). Descriptions of the vicinity of Llyn Hir from 19th and 20th century travellogues suggest a landscape free from the improving effects of Man (eg. 'a desolate scene' - Malkin 1807; 'naked, lofty uplands, desolate in the extreme' - Cliffe 1860).

The catchment lies within the parishes of Upper Gwnnws and Caron-Uwch-Cladd (Fig. 32). The tithe maps and schedules of the parishes of Caron (Caron-Is-Clawdd and Caron-Uwch-Clawdd combined) (9) and Gwnnws (Upper

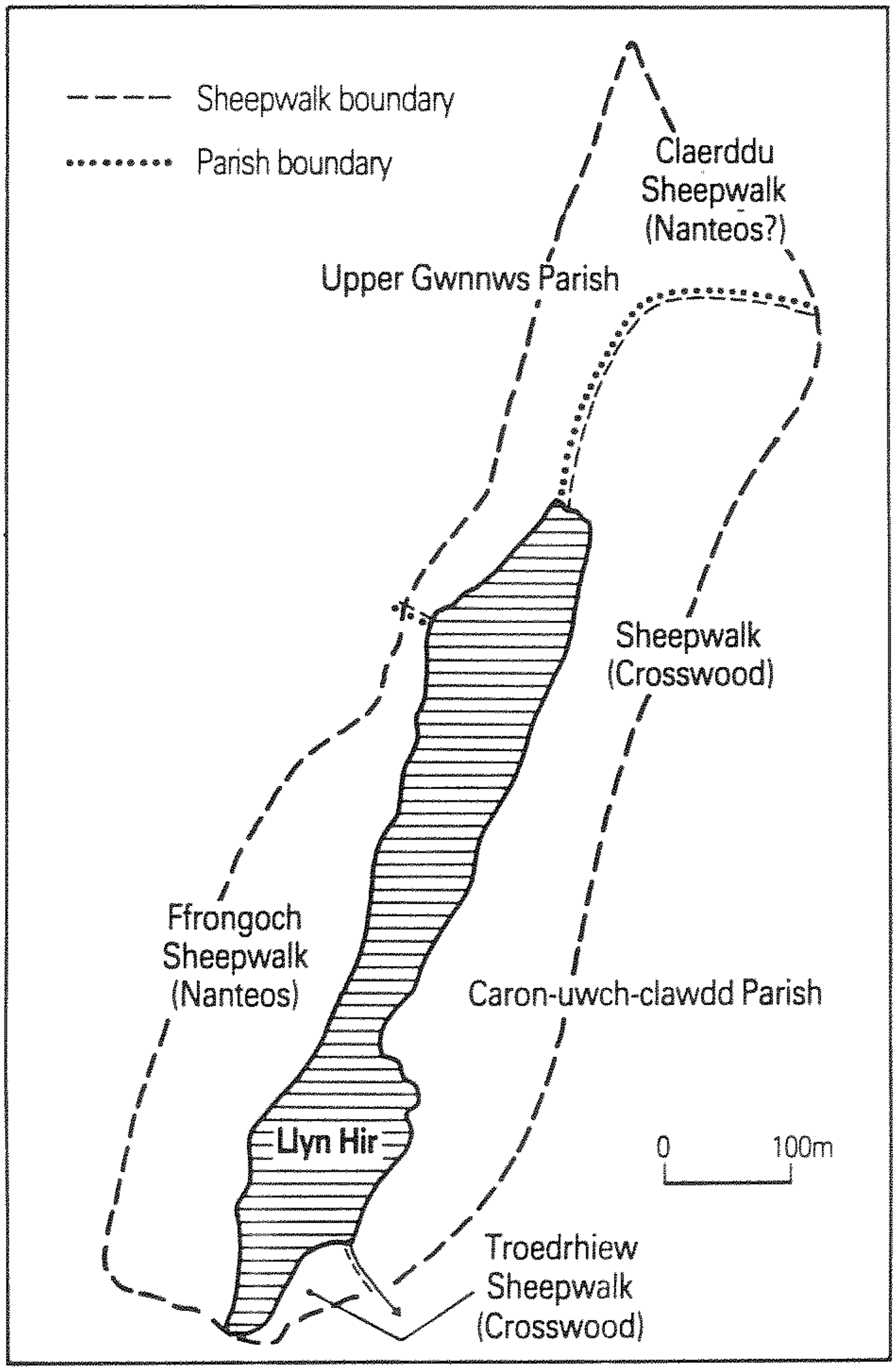


Fig. 32. Parish and sheepwalk boundaries within the Llyn Hir catchment.

Gwnnws and Lower Gwnnws combined) (10) indicate that in the mid 19th century the catchment comprised sheepwalks associated with farms belonging to the Nanteos (Powell) and Crosswood (Lisburne) Estates (Fig. 32).

An 1813 valuation of the Nanteos estate (11) described Ffrongoch (the farm associated with land in the west of the catchment - Fig. 32) as a 'wild, high place, all unenclosed'.

The first edition six inch Ordnance Survey map (surveyed 1886) and subsequent editions (12) of the area, show the catchment to consist of 'rough or heathy pasture'.

The First Land Utilisation Survey six inch manuscript map of 1934 (13) provides no detail of the immediate lake catchment, but adjacent areas to the north are described as 'bent fescue with some Molinia and Nardus, used as sheep grazing'.

The Second Land Utilisation Survey six inch manuscript map of 1970 (14) indicates a vegetational cover identical to the contemporary situation, with Nardus and Festuca on the drier ground and Eriophorum vaginatum dominating the wetter areas (Fig. 7).

Analysis of primary data (15), from which the Countryside Commission's Mid-Wales Upland Study (Parry and Sinclair 1985) was compiled, confirms that the Llyn Hir catchment has remained consistently within the 'moorland core' of unimproved rough pasture since 1948.

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. 'Esgair y Mwyn' lead mine to the north-west of Llyn Teify was probably the closest mine to the catchment (16).

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 Hir catchment was too high and remote to have been grazed by other than transient herds (see below). Evidence concerning Tynddole Sheepwalk (to the west of the Llyn Hir catchment) suggests that cattle grazed the lower land adjacent to the farm in summer, whilst sheep dominated the higher slopes (17).

It is possible that until their decline after c.1750 (Condry 1981), goats would have roamed the vicinity of the Llyn Hir catchment (cf Leland 1536 in Toulmin Smith 1906). It is known that numbers of ponies were grazed in the area in summer months well into the 20th century (C. Evans, H. Owen pers. comms.).

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 (Bowen 1950, Jones Pierce 1950).

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

Part of the Llyn Hir 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' (18). 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 (19). By 1885 the Crosswood Estate had consolidated and enlarged its grazing area, obtaining in the process grazing rights throughout the Llyn Hir catchment (20).

Until the railway opened up mid Wales in the 1860s, sheep and cattle were driven to the markets and fattening pastures of England along drove roads (Skeel 1926, Davies 1934, 1936). These routes cut across country, avoiding tolls and providing as much free grazing along the way as possible (Davies 1936). One such track passed immediately to the north of Llyn Hir (Fig. 6) (Condry 1981). Contemporary accounts (21) describe how the drovers and dealers grazed their stock along unenclosed sections of this road, thus imparting a grazing pressure in addition to that of the indigenous flocks.

In the early 20th century the old drove route immediately to the north of Llyn Hir was utilised by shepherds from the Rhayader region of central Wales to drive their summer flocks to the wintering grounds of the Cardiganshire coastal plateau (Davies 1935).

As the droving trade rapidly declined from its peak in 1860 and as the Crosswood Estate obtained complete control and jealously guarded its grazing rights in the catchment in the 1880s, it is probable that the catchment experienced a less intense and better regulated grazing regime in the last quarter of the 19th century. It is from this period that quantitative data relating to sheep numbers are available at the parish level.

Sheep numbers

Data relating to sheep numbers were drawn from the annual parish returns of Caron and Gwnnws (22) at quinquennial intervals and are presented in Figure 33. Between 1867-1910 (Gwnnws) and 1867-1905 (Caron), the data relate to combined parishes (Caron = Caron-Uwch-Clawdd and Caron-Is-Clawdd; Gwnnws = Upper Gwnnws and Lower Gwnnws). Not until the early 20th century is information specifically available for Caron-Uwch-Clawdd and Upper Gwnnws, the two parishes across which the Llyn Hir catchment lies (Fig. 32). Although they represent the source of information most applicable to the Llyn Hir 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 only a limited account of changes in sheep type and no account of changes in grazing regime (Patrick 1986).

In general, a significant increase in total sheep numbers (Upper Gwnnws, Gwnnws combined, Caron combined) or no overall trend towards an increase or

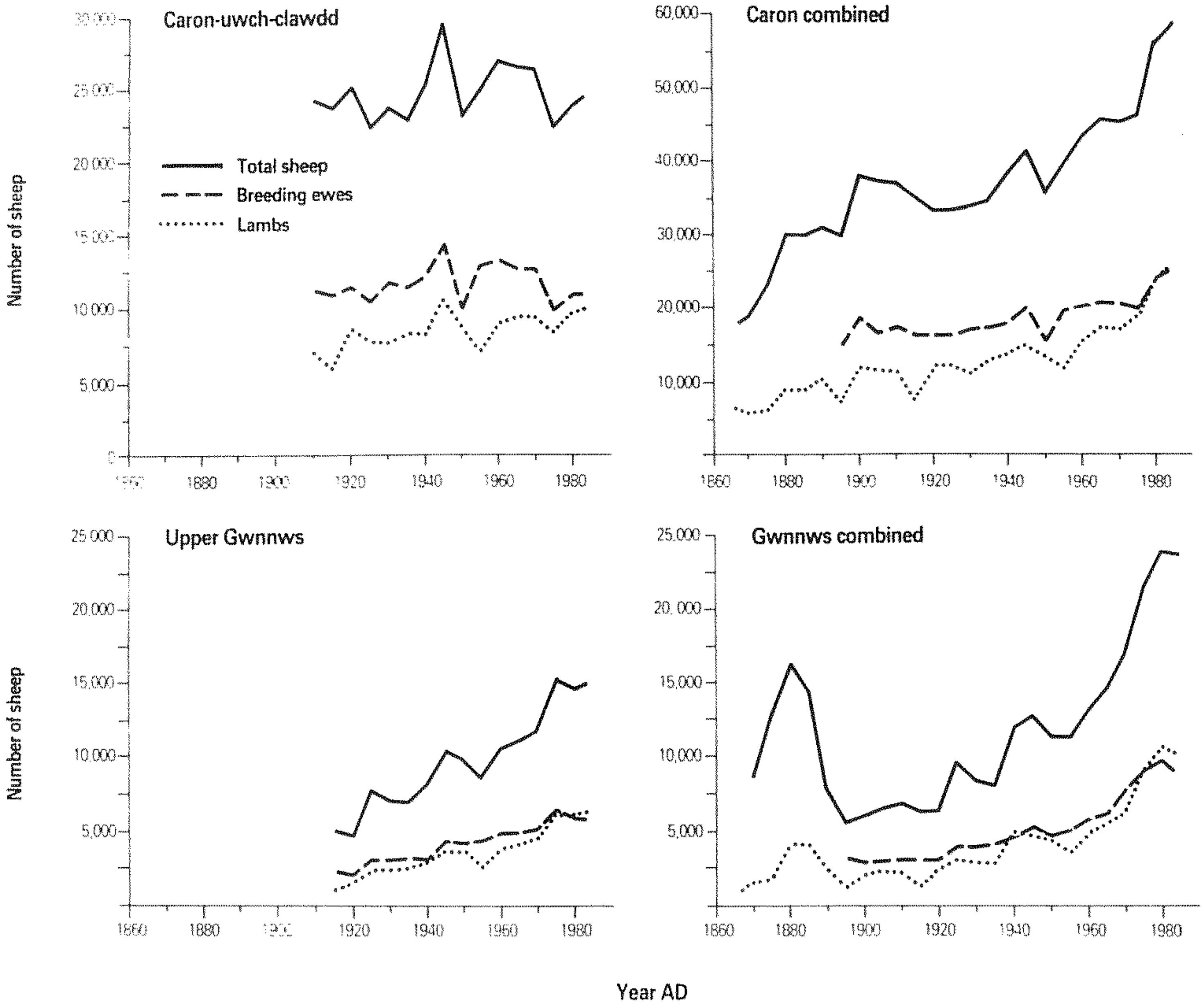


Fig. 33. Sheep numbers in Caron and Gwnnws Parishes 1867 1983.

decline (Caron-Uwch-Clawdd) is discernible from Figure 33 (23). Furthermore, the increasing significance of ewes and lambs at the expense of wether sheep over the last century (cf. Patrick 1986), is suggested from the trends in Figure 33.

Within the Llyn Hir catchment a broad increase in sheep numbers has been recognised (R. Davies, C. Evans, G. Jones, H. Owen, W. Owen pers. comms). Estimates of the extent of this increase vary between two-fold since ca. 1930 (W. Owen pers. comms.) to three-fold since ca. 1945 (C. Evans pers. comms.).

Also apparent over this time scale has been a change in grazing regimes. The transition from hardy wethers to ewes and lambs, the declining viability and eventual abandonment of the highest farms 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 1986) (24).

Manipulation of data relating to sheep numbers (Fig. 33) and area of rough grazing from the parish statistics, allow the calculation of a very crude trend of changing stocking rates on unimproved land in the Llyn Hir locality (Fig. 34). 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 Hir may have significantly increased through the 20th century (at least in summer months).

The close cropped Nardus/Festuca grassland indicates that the catchment supports a significant sheep population today. The evidence above suggests that this is not a recent phenomenon.

Llyn Hir 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

Management of grassland by burning has not been a regular feature in the catchment within living memory (R. Davies, C. Evans, H. Owen, W. Owen, K. Stokes pers. comms.). Air photographs flown in 1946 and 1947 (25) show no evidence of burnt patches. 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.

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 Hir for game. The keeper maintained at Pen-Llyn in summer was responsible solely for

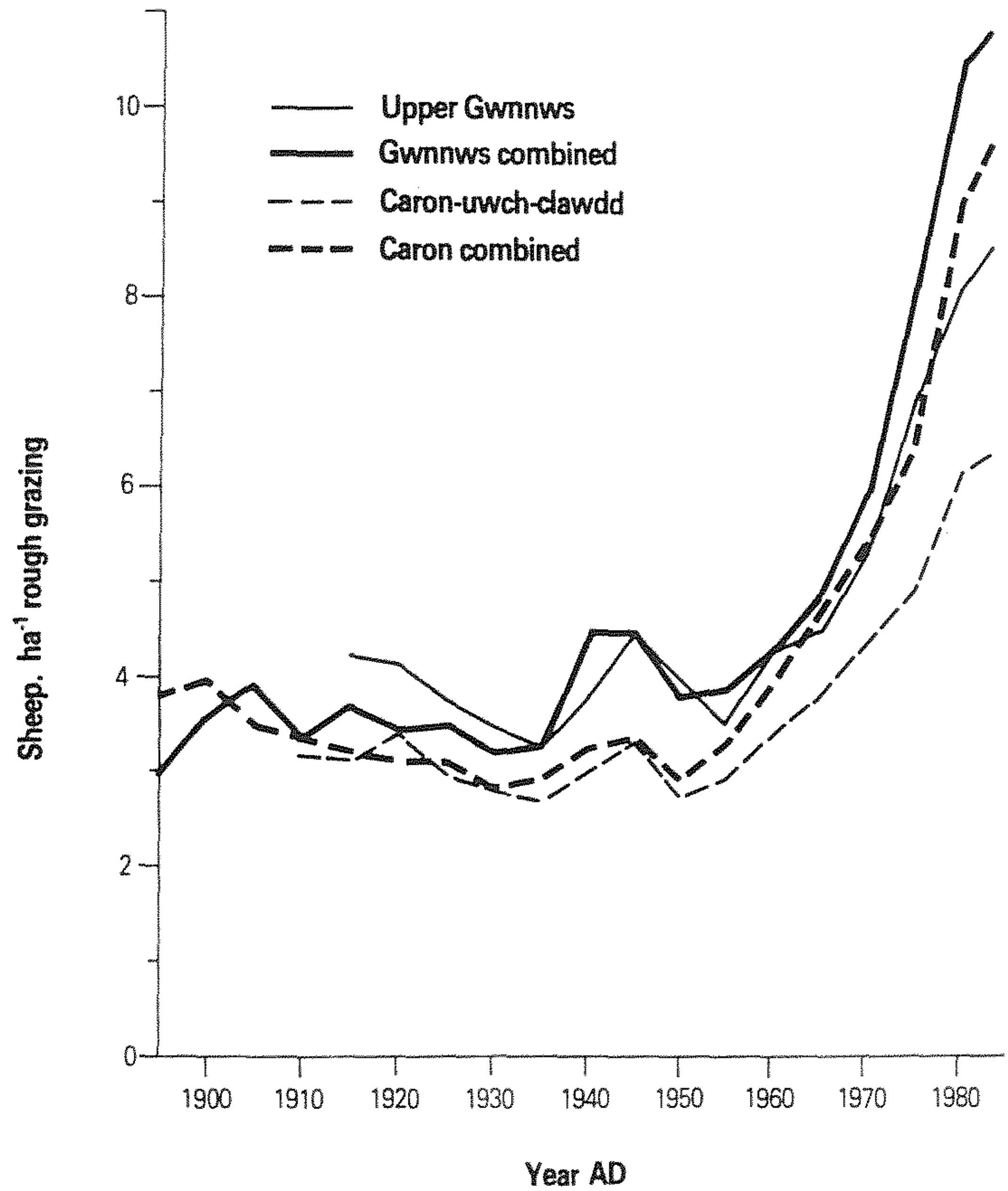


Fig. 34. Crude sheep/rough grazing stocking densities in Caron and Gwnnws Parishes 1895-1993.

preserving the fishing of the Teify Pools, his role as gamekeeper was realised in winter on the lower lands, particularly on Tregaron bog (Cors Goch).

In the 19th century turbaries were established by right or default on the peat areas adjacent to the Llyn Hir catchment (26). These peat cuttings may still be observed. However, there is no evidence of such excavation on the (limited) peat within the catchment.

5.0 Conclusions

i) The ^{210}Pb Chronology reveals that the sediment accumulation rate in Llyn Hir has been extremely slow (ca. 6 mg cm^{-2} yr^{-1}, 0.7 mm cm^{-2} yr^{-1}) throughout the dated part of the core. A period of disturbance is revealed by a dislocation of the ^{210}Pb profile between 10.5cm and 15.5cm dated to between 1875 and 1910, correlating with a peak in disturbance indicators in the pollen record. However, this does not appear to be reflected in the core chemistry record.

ii) The diatom flora shows major changes beginning at 25 cm (early 19th century associated with the loss of the circumneutral planktonic Cyclotella flora, and subsequently the replacement of alkaliphilous taxa by acidophilous and eventually acidobiontic taxa such as Tabellaria quadriseptata. A clear acidification of Llyn Hir has occurred over the last 120 years, with a distinct accelaration beginning in the early 1940's, similar to the acidification previously described in Galloway.

iii) The core chemistry record demonstrates that trace metal contamination of the lake sediments began at 11 cm (1880's) and parallels the acidification recorded by the diatoms. The record also suggests a period of soil erosion (40 cm-35 cm) before the dated part of the core (pre-1800) which is associated with disturbance indicators in the pollen record.

iv) The concentration of carbonaceous cenospheres from fossil fuel combustion increases rapidly from the early 1900's to the present. A similar trend is shown by the magnetic data.

v) The pollen diagram reveals three significant disturbance events characterised by peaks in the pastoral indicator Plantago lanceolata and is associated in the top two with reductions in the spore record from the aquatic fern Isoetes. The topmost event is marked by an increase in sediment accumulation rate while the lower one is also marked in the core chemistry record. It is possible that the lower disturbance event also involved an increase in the accumulation rate but lack of dating prevents any conclusion. An earlier phase of disturbance characterised by an earlier peak of Plantago does not appear to have been recorded in any of the other core variables.

vii) 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.

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, cenospheres), indicating local deposition of atmospheric pollutants, are consistent with this view.

ix) Llyn Hir is the first Welsh site where recent lake acidification has been clearly demonstrated.

6.0 References

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

Appleby, P.G., Nolan, P., Gifford, D.W., Godfrey, M.J., Oldfield, F., Anderson, N.J. & Battarbee, R.W. (In Press) ^{210}Pb dating by low background gamma counting.

Ball, D.F., Dale. J., Sheail, J. & Heal, O.W. (1982) Vegetation change in upland landscapes. Bangor, I.T.E.

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

Barret, C.F., Atkins, D.H.F., Cape, J.N., Fowler, D., Irwin, J.G., Kallend, A.S., Martin, A., Pitman, J.I., Scriven, R.A. & Tuck, A.F. (1983) Acid Deposition in the United Kingdom. Report of the United Kingdom Review Group on Acid Rain, Warren Spring Laboratory.

Bowen, E.C. (1950) the monastic economy of the Cistercians of Strata Florida. Ceredigion, 1 (1), 34-37.

Callow, R. (1986) The magnetic stratigraphy of Llyn Hir, Dyfed. Undergraduate dissertation, Liverpool University.

Cliffe, J.H. (1860) Notes and recollections of an angler. Hamilton, Adams & Co, London.

Colyer, R.J. (1976) The size of farms in the eighteenth and early nineteenth century. Cardiganshire. Bull. Bd. Celtic Studies. 27, 119-126

Condry, W. (1981) The Natural History of Wales. Collins, London.

Davies, W. (1815) General view of the agriculture of South Wales. 2 vols. Sherwood, Neely and Jones, London.

Davies, J.L. (1934) The livestock trade in West Wales in the nineteenth century. Aberystwyth Studies. 8, 85-105.

Davies, E. (1935) Seasonal movements of sheep in Wales. Journal of the Manchester Geographical Society. 45, 24-40.

Davies, J.L. (1936) The livestock trade in West Wales. Aberystwyth Studies. 9, 93-113.

Defoe, D. (1735) A tour through England and Wales Vol II.

Engstrom, D. & Wright, H.E. (1984) Chemical stratigraphy of lake sediments In: Lake Sediments and Environmental History (eds. E.Y. Haworth & J.W.G. Lund), Leicester University Press.

Flower, R.J. & Battarbee, R.W. (1983). Diatom evidence for the recent acidification of two Scottish lochs. Nature. 305, 130-133.

Gorham, E. (1958) The influence and importance of daily weather conditions in the supply of chloride, sulphate and other ions to fresh waters from atmospheric precipitation. Phil. Trans. Royal Soc. London, B, 241, 147.

Howell, E.J. (1946) Cardiganshire: Part 40 in L.D. Stamp (ed) The Land of Britain. Report of the land utilisation survey Geographical Publications, London.

Jones, V., Stevenson, A.C. & Battarbee, R.W. (1986) Lake acidification and the "land-use" hypothesis: a mid-postglacial analogue. Nature. 322, 157-158.

Jones Pierce, T. (1950) Strata Florida Abbey. Ceredigion. 1 (1), 18-33.

King, J. (1977) Hill and upland pasture. pp95-119 in J.Davidson & R. Lloyd (eds) Conservation and Agriculture. Wiley, Chichester.

Leigh (1835) Leigh's guide to Wales and Monmouthshire. Leigh & son, London

Mackereth, F.J.H. (1966) Some chemical observations on post-glacial sediments. Phil. Trans. Royal Soc B. 250, 165-213.

Mackereth, F.J.H. (1969) A short core sampler for sub-aqueous deposits. Limnol. Oceanogr. 14, 145-151.

MAFF (1980) The classification of land in the hills and uplands of England and Wales. Booklet 2358.

Malkin, B.H. (1807) The scenery, antiquities and biography of South Wales. Vol II. London.

Moore, P.D. & Chater, E.H. (1969) The changing vegetation of west-central Wales in the light of human history. J. Ecol. 57, 361-379.

Morgan, J. (1874) New Guide to Aberystwyth and Neighbourhood. Morgan, Aberystwyth.

O'Donnell, A.R., Munce, L. & Norton, R.C. (1984) A review of the toxicity of aluminium in freshwater. Water Research Centre, Report 541-M

Parry, M & Sinclair, G. (1985) Mid Wales Upland Study. Countryside Commission Report ICP 177.

Patrick, S.T. (in press) Evaluation of the recent acidification of Welsh lakes: land use and land management change. Working paper No. **, Palaeoecology Research Unit, Dept. Geography, University College London.

Raven, P.J. (1986) Occurence of Sphagnum moss in the sublittoral of several Galloway lochs with particular reference to Loch Fleet. Working Paper No. 13 (Palaeoecology Research Unit, University College London)

Rees, T. (1815) The beauties of England and Wales. Vol 18 South Wales, London.

Rudeforth, C.C. (1970) Soils of North Cardiganshire. Memoirs of the Soil Survey of Great Britain. Agricultural Research Council, Harpenden.

Rudeforth, C.C., Hartnup, R., Lea, J.W., Thompson, T.R.E. & Wright, P.S. (1984) Soils and their use in Wales. Soil Survey of England and Wales, Bulletin No. 11. Harpenden.

Sayles, F.L. & Mangelsdorf, P.C. (1977) The equilibration of clay minerals with seawater:exchange reactions. Geochemica et Cosmochimica Acta. 41, 951-960.

Skeel, C., (1926) The cattle trade between Wales and England from the the fifteenth to the nineteenth centuries. Trans. Roy. Hist. Soc. 9, 135-158.

Stevenson, A.C., Patrick, S.T., Kreiser, A., Rippey, B., Darley, J. & Battarbee, R.W. (1986) Palaeoecological evaluation of the recent acidification of Welsh Lakes: Methods. Working Paper No. ** (Palaeoecology Research Unit, University College London.)

Stumm, W. & Morgan, J.J. (1981) Aquatic Chemistry. Wiley, London.

Toulmin Smith, L. (1906) The itinerary of John Leland in or about the years 1536-1539. Bell and Sons, London.

Tutin, T.G., Heywood, V.H., Burges, N.A., Moore, D.M., Valentine, D.H., Walters, S.M. & Webb, A.A. (1964,1968,1972,1976,1980). Flora Europaea volumes 1-5. Cambridge University Press, London.

Underwood, J., Donald, A.P. & Stoner, J.H. (In Press) Investigations into the use of limestone to combat acidification in two lakes in West Wales.

Ward, F. (1931) The lakes of Wales. Jenkins, London.

Williams, S.W. (1889) The Cistercian Abbey of Strata Florida. Whiting and Co., London.

7.0 Acknowledgments

We would like to thank N.J. Anderson, R.J. Flower, S.J. Phethean, D.M. Monteith, A.J. Nicholson, 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 and their comments on an earlier draft of this manuscript. 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 C. Evans and J.R. Davies of ADAS (Trawscoed and Lampeter), Mr W. Owen (Tynddol Farm, Pontrhydfendigaid), Mr H. Owen (Waunfawr Farm, Tregaron), Mr K Stokes (WWA, Brecon), Dr G. Sinclair (Environmental Information Services, Narbeth) and Dr. M.Parry (Dept. Geography, University of Birmingham).

8.0 Notes

1. Cf. an 'historical' article in the Cardiganshire and Tivyside Advertiser of August 9th 1918.

2. The keeper, who was responsible for watching all the Teify Pools, resided in a cottage ('Pen-Llyn') on the shore of Llyn Hir (see Figure 6), which evidence from the first two Ordnance Survey six inch editions, suggests was built between 1886 (First Edition survey) and 1904 (Second Edition survey). Apart from the keeper, overnight accommodation was available for Lord Lisburne and/or his fishing guests. The lake shore buildings were occupied by the army during the Second World War and fell into disrepair (Tregaron RDC file no. SRD/1/466 - Cardiganshire Record Office). However, they were patched up and a keeper's presence was maintained until the late 1950s

3. The Association relinquished these rights in 1986 owing to the demise of the fishery.

4. See Patrick (1986) for definitions of 'land use' and 'land management'.

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

6. ADAS - Agricultural Development Advisory Service (MAFF).

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

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

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

10. Tithe map and schedule for the parish of Gwnnws 1845. PRO Kew IR30 46/22.

11. NLW, Nanteos Estate Papers, unreferenced.

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

13. Held at London School of Economics archive.

14. Held at King's College London Geography Department, sheet no. 385.

15. 1:25,000 land use maps and computer files containing data on land use change, held at the Countryside Commission in Newtown, Powys.

16. This mine was discovered in 1752, but flourished for only a few years (Davies 1815).

17. 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

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

19. See note 1.

20. See eg. NLW, Crosswood I 1988 (undated); I 2016 (c.1870); I 2094 (1884); II 1458 (undated).

21. See note 1.

22. PRO Kew, class MAF 68.

23. Between 1951-1981 these trends are compatible with the broader regional trend in sheep numbers for this part of mid Wales (Parry and Sinclair 1985).

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

25. Air Photograph Office, Welsh Office, Cardiff. Six inch series nos. 532/3215, 532/3216, 532/3217 (December 4th 1946). 1:9870 series nos. 667/2017, 667/2018 (May 28th 1947).

26. See note 1.

Appendices

Appendix A. Bi-weekly lake water chemistry results for Llyn Hir before and after liming
(Courtesy of WWA)

Date	pH	Conductivity 20°C us cm⁻¹	Total Oxidised Nitrogen mg l⁻¹	Total Hardness mg l⁻¹	Free Carbon dioxide mg l⁻¹	Total Alkalinity mg l⁻¹	Chloride mg l⁻¹
21/11/83	4.9	42	0.1	5.9	3.0	1.1	7.0
13/12/83	4.7	43	0.1	5.4	2.8	0.6	14.0
19/01/84	4.6	43	0.1	5.6	2.4	0.4	7.0
02/02/84	4.8	42	0.1	5.1	3.3	1.0	7.0
14/03/84	4.5	44	0.1	4.5	3.8	-	7.0
30/03/84	4.7	44	0.2	2.9	3.5	0.7	7.0
17/04/84	4.7	45	0.1	3.8	-	-	7.0
30/04/84	4.8	44	0.2	-	-	-	8.0
15/05/84	4.7	48	0.2	4.8	4.7	0.3	7.0
31/05/84	4.7	48	0.2	4.2	-	-	8.0
06/06/84	4.6	48	0.1	5.3	6.2	0.4	8.0
26/06/84	4.8	46	0.1	5.3	-	-	7.0
09/07/84	4.7	46	0.1	5.1	-	-	8.0
18/07/84	4.7	46	0.1	5.3	7.8	0.8	8.0
03/08/84	4.9	43	0.1	5.4	-	-	8.0
10/08/84	4.9	45	0.1	5.6	-	-	8.0
07/09/84	5.0	44	0.1	5.0	6.1	1.4	8.0
01/10/84	5.0	45	0.1	5.6	3.9	1.1	8.0
19/10/84	5.1	43	0.1	5.3	3.8	1.2	7.0
10/12/84	4.8	42	0.1	4.6	3.6	0.7	7.0
28/01/85	4.8	42	0.1	5.5	3.8	0.9	7.0
11/03/85	4.9	37	0.2	4.2	2.8	1.0	6.0
10/04/85	6.7	43	0.2	7.9	1.5	6.0	6.0
30/04/85	6.7	44	0.1	9.7	1.9	6.9	7.0
22/05/85	6.7	44	0.2	9.7	2.4	6.8	7.0
11/06/85	7.0	44	0.2	9.8	2.5	6.5	7.0
21/06/85	6.6	43	0.2	10.0	1.8	5.3	6.0
04/07/85	6.5	41	0.2	9.2	2.1	5.9	6.0
18/07/85	6.3	40	0.1	-	-	-	6.0
01/08/85	6.3	38	0.1	8.7	-	-	5.0
15/08/85	6.4	37	0.1	7.6	-	-	5.0
05/09/85	6.7	35	0.2	8.3	1.8	5.9	7.0
19/09/85	6.2	36	0.1	8.2	3.0	4.3	6.0
03/10/85	6.1	37	0.1	7.6	3.5	3.9	6.0
07/11/85	6.0	39	0.1	7.7	3.3	3.4	5.0
21/11/85	6.1	37	0.1	7.0	2.2	3.7	6.0
05/12/85	6.0	35	0.1	7.1	2.3	3.2	5.0
18/12/85	6.8	44	0.1	10.1	2.0	7.1	7.0
14/03/86	6.1	43	0.2	9.4	2.9	5.4	6.0

Date	Orthophosphate	Dissolved Silica	Dissolved Sulphate	Dissolved Sodium	Dissolved Potassium	Dissolved Calcium	Dissolved Zinc
			(mg l^{-1})				
21/11/83	0.02	0.2	5.5	4.0	0.30	1.20	0.019
13/12/83	0.09	0.3	6.0	4.0	0.40	1.00	0.016
19/01/84	0.02	0.4	5.5	3.9	0.27	1.10	0.013
02/02/84	0.02	0.4	5.0	3.9	0.26	0.90	0.019
14/03/84	0.02	0.3	5.0	3.66	0.30	0.80	0.013
30/03/84	0.02	0.3	5.0	2.37	0.18	0.50	0.020
17/04/84	0.02	0.2	5.5	3.01	0.26	0.68	0.022
30/04/84	0.02	0.2	6.0	4.03	0.52	0.94	0.019
15/05/84	0.02	0.2	5.0	3.99	0.39	0.94	0.028
31/05/84	0.02	0.2	5.5	3.38	0.36	0.71	0.031
06/06/84	0.02	0.2	6.0	4.19	0.45	0.99	0.020
26/06/84	0.02	0.2	5.0	4.19	0.43	0.98	0.021
09/07/84	0.02	0.2	5.0	4.34	0.26	0.88	0.017
18/07/84	0.02	0.2	5.5	3.97	0.22	0.99	0.025
03/08/84	0.02	0.2	5.0	4.02	0.25	1.01	0.009
10/08/84	0.02	0.2	5.0	4.48	0.25	1.10	0.026
07/09/84	0.02	0.2	7.0	4.11	0.18	0.85	0.018
01/10/84	0.02	0.2	6.5	4.33	0.26	1.11	0.016
19/10/84	0.02	0.2	6.0	3.91	0.31	0.98	0.023
10/12/84	0.02	0.3	5.1	3.74	0.23	0.86	0.019
28/01/85	0.02	0.5	5.2	4.20	0.49	1.05	0.033
11/03/85	0.02	0.5	5.7	4.30	0.30	0.86	0.026
10/04/85	0.02	0.3	5.2	3.12	0.17	2.35	0.017
30/04/85	0.02	0.2	4.3	3.42	0.25	3.07	0.007
22/05/85	0.02	0.2	5.0	3.56	0.36	2.91	0.006
11/06/85	0.02	0.2	4.9	3.43	0.28	3.08	0.002
21/06/85	0.02	0.2	4.7	3.44	0.19	3.17	0.008
04/07/85	0.02	0.2	4.5	3.41	0.18	2.84	0.015
18/07/85	0.02	0.2	-	--	--	--	-
01/08/85	0.02	0.2	4.4	3.18	0.23	2.66	0.006
15/08/85	0.02	0.2	4.0	3.04	0.28	2.38	0.009
05/09/85	0.02	0.2	4.3	3.00	0.23	2.50	0.011
19/09/85	0.02	0.2	4.7	3.33	0.27	2.46	0.042
03/10/85	0.02	0.2	3.6	3.01	0.18	2.38	0.008
07/11/85	0.02	0.2	3.8	--	--	2.24	0.012
21/11/85	0.02	0.2	3.7	3.10	0.21	1.96	0.007
05/12/85	0.02	0.2	3.9	3.30	0.19	2.00	0.011
18/12/85	0.02	0.2	4.0	3.20	0.19	3.20	0.013
14/03/86	0.02	0.4	4.2	3.20	0.34	2.[illegible]5	0.010

Date	Dissolved Copper	Dissolved Cadmium	Dissolved Aluminium	Dissolved Lead	Dissolved Chromium	Dissolved Manganese	Dissolved Iron
			$(mg\ l^{-1})$				
21/11/83	-	0.0004	0.09	0.002	--	0.148	0.050
13/12/83	-	0.0004	0.09	0.002	--	0.112	0.045
19/01/84	-	0.0004	0.05	0.002	--	0.101	0.046
02/02/84	-	0.0004	0.09	0.002	--	0.102	0.063
14/03/84	-	0.0008	0.10	0.002	--	0.111	0.032
30/03/84	-	0.0008	0.055	0.005	--	0.087	0.022
17/04/84	-	0.0008	0.100	0.005	0.001	0.090	0.085
30/04/84	0.003	0.0008	0.110	0.005	0.001	0.152	0.070
15/05/84	0.001	0.0008	0.087	0.005	0.001	0.179	0.028
31/05/84	0.001	0.0008	0.131	0.005	0.001	0.198	0.017
06/06/84	0.001	0.0008	0.091	0.005	0.001	0.191	0.039
26/06/84	0.001	0.0008	0.064	0.005	0.001	0.183	0.032
09/07/84	0.001	0.0008	0.079	0.005	0.001	0.238	0.040
18/07/84	0.001	0.0008	0.070	0.013	0.001	0.167	0.041
03/08/84	0.001	0.0008	0.064	0.005	0.001	0.200	0.065
10/08/84	0.001	0.0008	0.064	0.006	0.001	0.168	0.060
07/09/84	0.001	0.0008	0.095	0.006	0.001	0.248	0.094
01/10/84	0.002	0.0010	0.070	0.013	0.003	0.211	0.071
19/10/84	0.001	0.0008	0.079	0.021	0.001	0.248	0.090
10/12/84	0.002	0.0010	0.111	0.006	--	0.149	0.090
28/01/85	0.002	0.0010	0.115	0.015	0.003	0.141	0.168
11/03/85	0.002	0.0010	0.143	0.005	0.003	0.130	0.086
10/04/85	0.002	0.001	0.135	0.005	0.002	0.096	0.047
30/04/85	0.002	0.001	0.067	0.005	0.003	0.024	0.058
22/05/85	0.002	0.001	0.060	0.005	0.003	0.025	0.025
11/06/85	0.002	0.001	0.060	0.005	0.003	0.031	0.110
21/06/85	0.003	0.001	0.040	0.005	0.003	0.019	0.072
04/07/85	0.002	0.001	0.056	0.005	0.003	0.015	0.092
18/07/85	--	--	--	--	--	--	--
01/08/85	0.002	0.001	0.047	0.002	0.003	0.010	0.090
15/08/85	0.002	0.001	0.054	0.002	0.003	0.010	0.115
05/09/85	0.002	0.001	0.050	0.002	0.003	0.017	0.149
19/09/85	0.003	0.001	0.060	0.002	0.003	0.011	0.134
03/10/85	0.002	0.001	0.062	0.002	0.003	0.011	0.154
07/11/85	0.002	0.001	0.055	0.002	0.003	0.009	0.108
21/11/85	0.002	0.001	0.050	0.003	0.003	0.009	0.093
05/12/85	0.002	0.001	0.054	0.002	0.003	0.005	0.089
18/12/85	0.002	0.001	0.056	0.002	0.003	0.004	0.081
14/03/86	0.002	0.001	0.050	0.006	0.003	0.010	0.050

Date	Dissolved Nickel mg l^{-1}	Humic acid mg l^{-1}
21/11/83	--	-
13/12/83	--	-
19/01/84	--	-
02/02/84	--	-
14/03/84	--	-
30/03/84	--	-
17/04/84	0.001	0.2
30/04/84	0.001	0.7
15/05/84	0.001	0.4
31/05/84	0.001	0.3
06/06/84	0.001	0.3
26/06/84	0.001	0.3
09/07/84	0.001	0.3
18/07/84	0.003	0.3
03/08/84	0.001	1.0
10/08/84	0.002	0.5
07/09/84	0.002	0.6
01/10/84	0.003	1.1
19/10/84	0.005	1.4
10/12/84	--	1.6
28/01/85	0.003	1.4
11/03/85	0.003	1.2
10/04/85	0.003	1.7
30/04/85	0.003	1.7
22/05/85	0.003	1.5
11/06/85	0.003	1.4
21/06/85	0.012	1.5
04/07/85	0.003	1.8
18/07/85	--	1.6
01/08/85	0.003	2.0
15/08/85	0.003	2.5
05/09/85	0.003	2.7
19/09/85	0.003	6.0
03/10/85	0.003	2.7
07/11/85	0.003	2.2
21/11/85	0.003	2.2
05/12/85	0.003	2.1
18/12/85	0.003	2.2
14/03/86	0.003	1.7

Appendix B. Invertebrate taxa found at Llyn Hir prior to liming
(Courtesy of WWA)

	Log abundance rating
Tricladida	
Polycelis nigra/tenuis	1
Mollusca	
Pisidium sp.	1
Oligochaeta	
Nais communis/variablis	1
Stylaria lacustris	1
Enchytraedae	1
Lumbarius variegatus	3
Stylodrilus heringianus	3
Ephemeroptera	
Leptophlebia vespertina	3
Plecoptera	
Nemoura cinerea	2
Odonata	
Enallagma cyatherigum	2
Aeshna grandis	1
Hemiptera	
Callicorixa praeusta	1
Arctocorisa germari	1
Sigara scotti	2
Coleoptera	
Stictotarsus duodecimpustulatus	1
Hydroporus palustris	1
Megaloptera	
Sialis lutaria	1
Trichoptera	
Plectrocnemia conspersa	2
Polycentropus flavomaculatus	1
P. kingi	2
Cyrnus flavidus	2
Agrypnia varia	2
A. obsoleta	2
Limnemephilus rhombicus	1
Cingulatus latipennis	1
Halesus radiatus	1
H. digitatus	1
Diptera	
Macropelopia sp.	1
Procladius sp.	1
Ablabesymia sp.	1
Arctopelopia sp.	3
Heterotanytarsus apicalis	1
Heterotrissocladius marcidus	1
Zalutschia humphresiae	2
Psectrocladium psilopterus	1
P. limbatellus gp.	2
P. psilopterus	1
P. octomaculatus	2
P. octomaculatus/ limbatellus gp.	3
P. sordidellus	2
Chaetocladius	3

	Log abundance rating
Diptera ctd	
Corynoneura lacustris	2
C. scutellaria	2
Glyptotendipes sp.	1
Dicrotendipes sp.	2
Microtendipes pedellus	3
Microspectra sp.	1
Tantytarsus sp.	1

Abundance categories

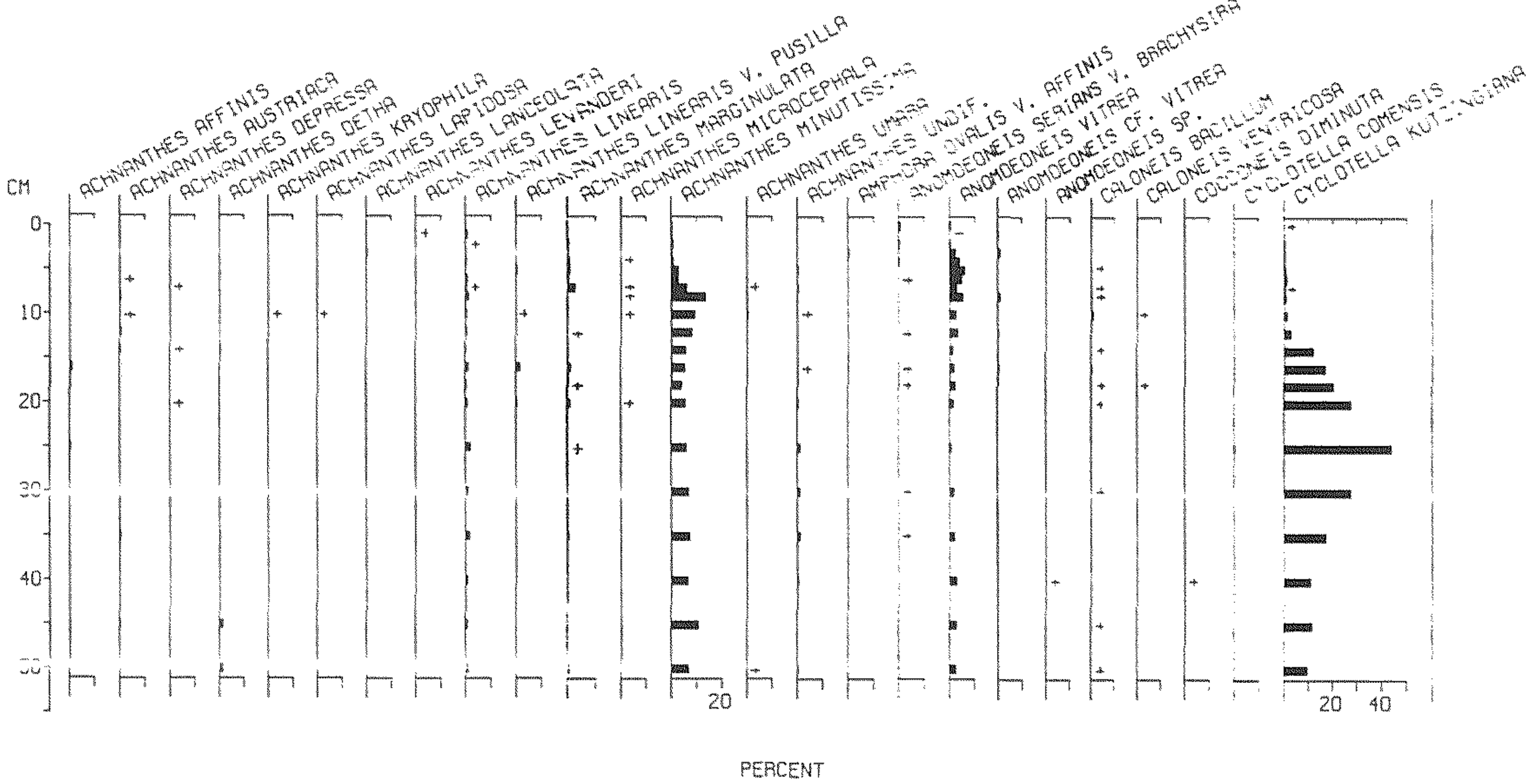
1 = 1 - 10
2 = 11 - 100
3 = 101 - 1000

ACHNANTHES LANCEOLATA	BREB.
ACHNANTHES LINEARIS	W. SMITH
ACHNANTHES LINEARIS V PUSILLA	GRUN.
ACHNANTHES MICROCEPHALA	KUTZ.
ACHNANTHES OESTRUPII	(A. CLEVE) HUST.
ACHNANTHES AFFINIS	GRUN.
ACHNANTHES MINUTISSIMA	KUTZ.
ACHNANTHES AUSTRIACA	HUST.
ACHNANTHES KRYOPHILA	BOYE PETERSON
ACHNANTHES MARGINULATA	GRUN.
ACHNANTHES DEPRESSA	(CLEVE) HUST.
ACHNANTHES UMARA	CARTER
ACHNANTHES DETHA	
ACHNANTHES LAPIDOSA	
ACHNANTHES LEVANDERI	
ACHNANTHES SP 1	L.HIR (SF)
ACHNANTHES SP	
AMPHORA OVALIS V AFFINIS	(KUTZ.) V.H. EX DET.
ANOMOEONEIS SERIANS V BRACHYSIRA	(BREB.) CLEVE
ANOMOEONEIS VITREA	(GRUN.) ROSS
ANOMOEONEIS CF VITREA	L.HIR (SF)
ANOMOENEIS SP	
CALONEIS BACILLUM	(GRUN.) MERESCHKOWSKY
CALONEIS VENTRICOSA	(EHR.) MEISTER
CYMBELLA VENTRICOSA	KUTZ.
CYMBELLA PERPUSILLA	A. CLEVE
CYMBELLA AEQUALIS	SMITH
CYMBELLA CESATII	(RABH.) GRUN.
CYMBELLA HEBRIDICA	(GREGORY) GRUN.
CYMBELLA GRACILIS	(RABH.) CLEVE
CYMBELLA GAEUMANNI	MEISTER
CYMBELLA HETEROPLEURA V MINOR	CLEVE
CYMBELLA MUELLERI	HUST.
CYMBELLA MINUTA V PSEUDOGRACILIS	(CHOLNUKY) REIMER
CYMBELLA ANGUSTATA	(W. SMITH) CLEVE
CYMBELLA SP.	
COCCONEIS DIMINUTA	PANT.
CYCLOTELLA KUTZINGIANA	THWAITES
CYCLOTELLA COMENSIS	GRUN.
DIPLONEIS MARGINESTRIATA	HUST.
EUNOTIA VENERIS	(KUTZ.) O. MULLER
EUNOTIA PECTINALIS	(KUTZ.) RABH.
EUNOTIA PECTINALIS V MINOR	(KUTZ.) RABH.
EUNOTIA TENELLA	(GRUN). HUST.
EUNOTIA LUNARIS	(EHR.) GRUN.
EUNOTIA LUNARIS V SUBARCUATA	(NAEGELI) GRUN.
EUNOTIA BIDENTULA	W.SMITH
EUNOTIA MONODON V MAIOR	(W.SMITH) RABH.
EUNOTIA EXIGUA	(BREB.) RABH.
EUNOTIA FABA	(EHR.) GRUN.
EUNOTIA FABA V INTERMEDIA	
EUNOTIA RHOMBOIDEA	HUST.
EUNOTIA ROBUSTA	RALFS
EUNOTIA ROBUSTA V DIADEMA	(EHR.) RALFS
EUNOTIA FLEXUOSA	KUTZ.
EUNOTIA IATRIAENSIS	FOGED
EUNOTIA MEISTERI	HUST.
EUNOTIA TRINACRIA V UNDULATA	HUST.
EUNOTIA VALIDA	HUST.
EUNOTIA PARALLELA	EHR.
EUNOTIA SP 1	L.HIR (SF)
EUNOTIA SP (INCISA/VANHEURCKII)	L.HIR (SF)
EUNOTIA SP 40	PIRLA
EUNOTIA SP 15	NGLS, L.HIR (SF)
EUNOTIA SP 11	L.HIR (SF)
EUNOTIA SP 9	L.HIR (SF)
EUNOTIA SP 7	L.HIR (SF)
EUNOTIA SP 5	L.HIR (SF)
EUNOTIA SP 3	L.HIR (SF)
EUNOTIA SP 1	PIRLA
EUNOTIA CF SEPTENTRIONALIS	L.HIR (SF)
EUNOTIA SP	
FRAGILARIA PINNATA	EHR.
FRAGILARIA CONSTRUENS	(EHR.) GRUN.
FRAGIALRIA CONSTRUENS V VENTER	(EHR.) GRUN.
FRAGILARIA VIRESCENS	RALFS
FRAGILARIA BREVISTRIATA	GRUN.
FRAGILARIA CF PINNATA V LANCETTULA	L.HIR (SF)
FRUSTULIA RHOMBOIDES	(EHR.) DE TONI
FRUSTULIA RHOMBOIDES V SAXONICA	(RABH.) DE TONI
GOMPHONEMA GRACILE	EHR.
GOMPHONEMA ACUMINATUM	EHR.
GOMPHONEMA PARVULUM	KUTZ.
GOMPHONEMA INTRICATUM	KUTZ.
GOMPHONEMA INTRICATUM V PUMILA	GRUN.
GOMPHONEMA BREBISSONII	KUTZ.
GOMPHONEMA SP (MONTANUM)	L.HIR (SF)
GOMPHONEMA SP	
MELOSIRA AMBIGUA	(GRUN.) O. MULLER
MELOSIRA LIRATA	(EHR.) KUTZ.
MELOSIRA LIRATA V LACUSTRIS	GRUN.
MELOSIRA DISTANS	(EHR.) KUTZ.
MELOSIRA DISTANS V TENELLA	(NYGAARD) FLORIN
MELOSIRA DISTANS V NIVALIS	(W.SM.) KIRCHNER
MELOSIRA DISTANS V NIVALOIDES	CAMBURN
MELOSIRA PERGLABRA	OSTRUP
MELOSIRA PERGLABRA V FLORINIAE	CAMBURN
MELOSIRA NYGAARDII	CAMBURN
MELOSIRA CF LIRATA V TENUISSIMA	L.HIR (SF)
MELOSIRA SP	
NAVICULA JARNEFELTII	HUST.
NAVICULA RADIOSA	KUTZ.
NAVICULA SEMINULUM	GRUN.
NAVICULA MEDIOCRIS	KRASSKE
NAVICULA LANCEOLATA	(AGARDH) KUTZ.
NAVICULA PSEUDOSCUTIFORMIS	HUST.
NAVICULA PUPULA	KUTZ.
NAVICULA INDIFFERENS	HUST.
NAVICULA COCCONEIFORMIS	GREGORY
NAVICULA SUBTILISSIMA	CLEVE
NAVICULA ANGUSTA	GRUN.
NAVICULA ARVENSIS	HUST.
NAVICULA HEIMANSII	VAN DAM & KOOY.
NAVICULA MINIMA	GRUN.
NAVICULA SUBATOMOIDES	HUST.
NAVICULA KRASSKEI	HUST.
NAVICULA ERYOPHILA	PETERSEN
NAVICULA SUBHAMULATA	GRUN.

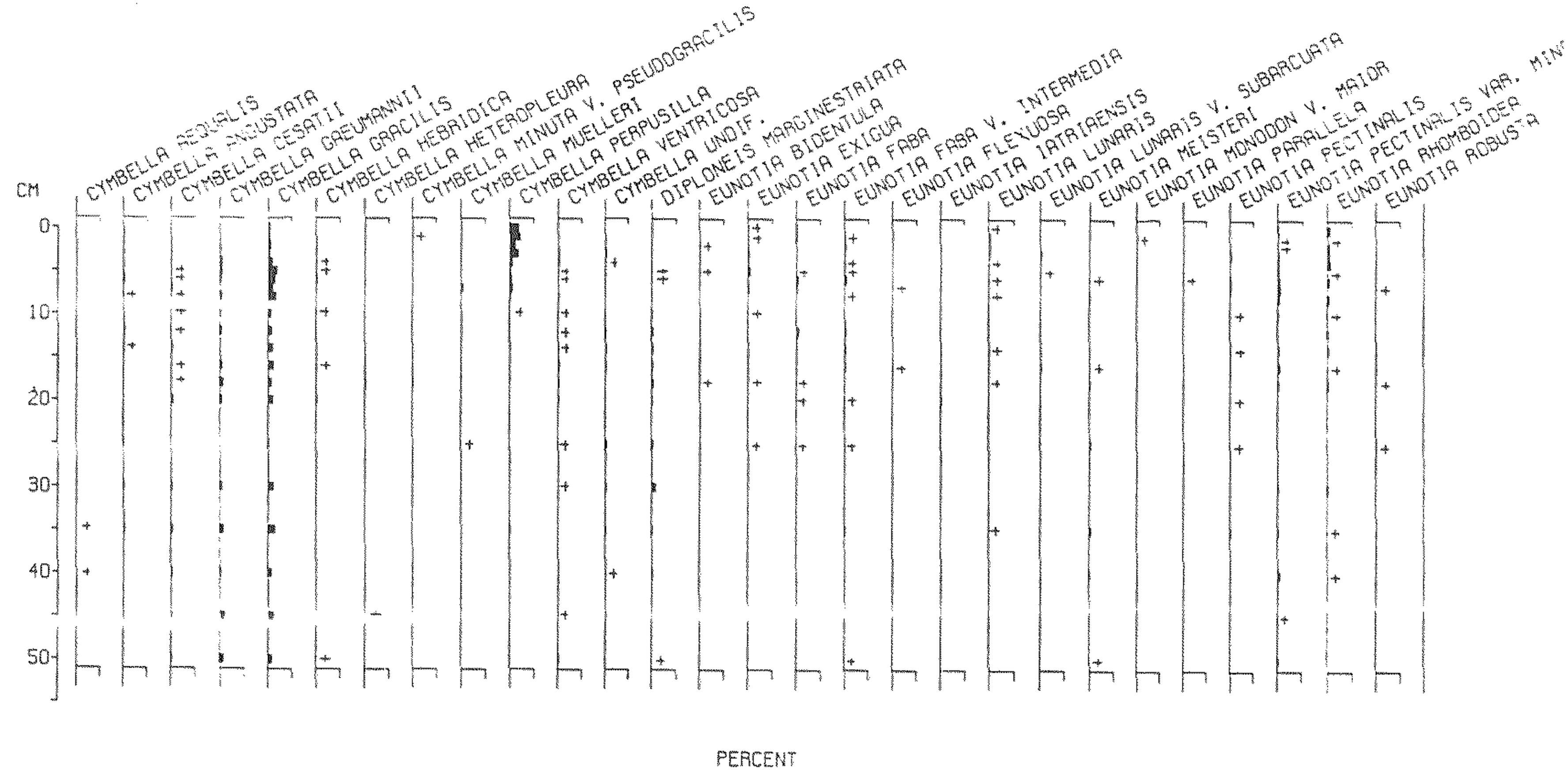
Appendix C

NAVICULA MURALIS	GRUN
NAVICULA ATOMUS	(KUTZ.) GRUN.
NAVICULA MINUSCULA	GRUN.
NAVICULA SUBROTUNDATA	HUST.
NAVICULA PSEUDOMURALIS	HUST.
NAVICULA SEMINULOIDES	HUST.
NAVICULA TENUICEPHALA	HUST.
NAVICULA MADUMENSIS	JORGENSEN
NAVICULA DISJUNCTA	HUST.
NAVICULA MEDIOCONVEXA	HUST.
NAVICULA SCUTIFORMIS	GRUN.
NAVICULA UTERMOHLII	HUST.
NAVICULA SP 3 (MUCICOLA)	L.HIR (SF)
NAVICULA DENTATA/SUBARVENSIS	L.HIR (SF)
NAVICULA CF VITIOSA	L.HIR (SF)
NAVICULA CF SUBMOLESTA	L.HIR (SF)
NAVICULA CF SCHASSMANNII	L.HIR (SF)
NAVICULA SP 24	PIRLA
NAVICULA SP 11	L.HIR (SF)
NAVICULA SP 8	L.HIR (SF)
NAVICULA SP 4	L.HIR (SF)
NAVICULA SP 2	L.HIR (SF)
NAVICULA SP 1	L.HIR (SF)
NAVICULA CF SPIRATA	L.HIR (SF)
NAVICULA PELLICULOSA/PERMITIS	L.HIR (SF)
NAVICULA IMPEXA/INVICTA	L.HIR (SF)
NAVICULA SP	
NEIDIUM IRIDIS V AMPLIATA F VERNALIS	REICHELT
NEIDIUM AFFINE	(EHR.) CLEVE
NEIDIUM AFFINE V LONGICEPS	(GREGORY) CLEVE
NEIDIUM BISULCATUM	(LAGERSTEDT) CLEVE
NEIDIUM ALPINUM	HUST.
NEIDIUM SP	
NITZSCHIA PERMINUTA	GRUN.
NITZSCHIA PALEA	(KUTZ.) W. SMITH
NITZSCHIA AMPHIBIA	GRUN.
NITZSCHIA DISSIPATA	(KUTZ.) GRUN.
NITZSCHIA RECTA	HANTZSCH
NITZSCHIA GANDERSHEIMIENSIS	KRASSKE
NITZSCHIA SIGMOIDEA	(EHR.) W.SMITH
NITZSCHIA CF ROMANA	L.HIR (SF)
NITZSCHIA CF GRACILIS	L.HIR (SF)
NITZSCHIA CF FONTICOLA	L.HIR (SF)
NITZSCHIA SP	
OPEPHORA MARTYI	HERIBAUD
PERONIA FIBULA	(BREB. ex KUTZ.) ROSS
PINNULARIA ACUMINATA	SMITH SYN.PI003A
PINNULARIA MAIOR	KUTZ
PINNULARIA DIVERGENS	W. SMITH
PINNULARIA SUBLINEARIS	GRUN.
PINNULARIA MICROSTAURON	(EHR.) CLEVE
PINNULARIA BOREALIS	EHR.
PINNULARIA BOREALIS V BREVICOSTATA	
PINNULARIA APPENDICULATA	(AGARDH) CLEVE
PINNULARIA ABAUJENSIS	([illegible]) ROSS
PINNULARIA BICEPS	GREGORY
PINNULARIA UNDULATA	GREGORY
PINNULARIA HILSEANA	(JANISCH) MULL
PINNULARIA SUBCAPITATA	GREGORY
PINNULARIA BRAUNII	(GRUN.) CLEVE
PINNULARIA BRAUNII V AMPHICEPHALA	(A. MAYER) HUST

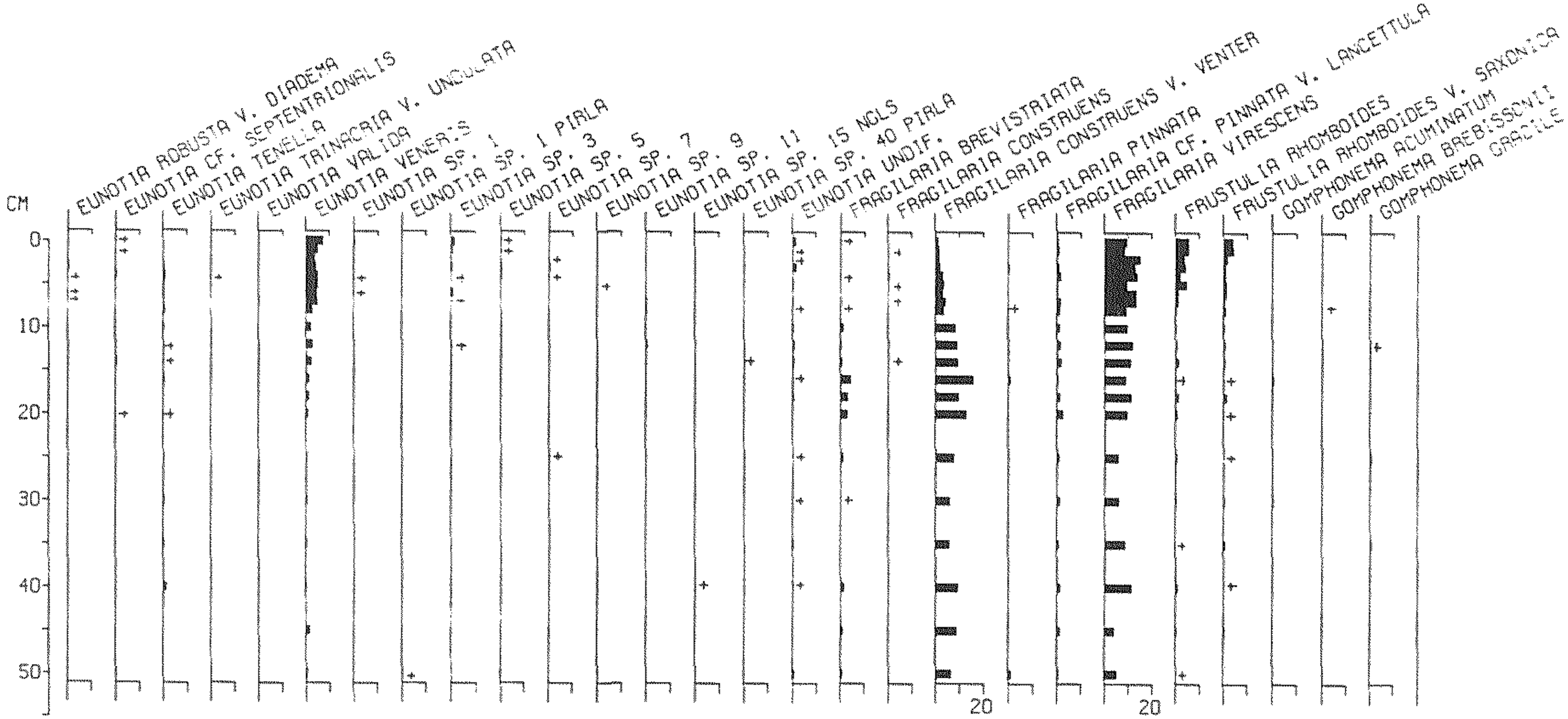
PINNULARIA SUBSTOMATOPHORA	HUST.
PINNULARIA SP 13	PIRLA
PINNULARIA SP 11	PIRLA
PINNULARIA SP 4	L.HIR (SF)
PINNULARIA CF PSEUDOMICROSTAURON	L.HIR (SF)
PINNULARIA CF DIVERGENS V ELLIPTICA	L.HIR (SF)
PINNULARIA CF TERMITINA	L.HIR (SF)
PINNULARIA SP	
STAURONEIS ANCEPS	EHR.
STAURONEIS ANCEPS F GRACILIS	(EHR.) CLEVE
STAURONEIS ALPINA	HUST.
STAURONEIS PHOENICENTERON	(NITZSCH) EHR.
STAURONEIS ANCEPS V 1	L.HIR (SF)
STAURONEIS SP	
STENOPTEROBIA INTERMEDIA	LEWIS
SURIRELLA LINEARIS	W. SMITH
SURIRELLA SP	
SYNEDRA RUMPENS	KUTZ.
SYNEDRA PARASITICA	W. SMITH
SYNEDRA PARASITICA V SUBCONSTRICTA	GRUN.
SYNEDRA DELICATISSIMA V ANGUSTISSIMA	GRUN.
SYNEDRA TENERA	W. SMITH
SYNEDRA SP	
TABELLARIA FLOCCULOSA	(ROTH) KUTZ.
TABELLARIA QUADRISEPTATA	KNUDSON
TABELLARIA SP	


ACHNANTHES AFFINIS
ACHNANTHES AUSTRIACA
ACHNANTHES DEPRESSA
ACHNANTHES DETHA
ACHNANTHES KRYOPHILA
ACHNANTHES LAPIDOSA
ACHNANTHES LANCEOLATA
ACHNANTHES LEVANDERI
ACHNANTHES LINEARIS
ACHNANTHES LINEARIS V. PUSILLA
ACHNANTHES MARGINULATA
ACHNANTHES MICROCEPHALA
ANOMOEONEIS SERIANS V. BRACHYSIRA
ANOMOEONEIS VITREA
ANOMOEONEIS CF. VITREA
ANOMOEONEIS SP.
CALONEIS BACILLUM
CYCLOTELLA COMENSIS
CM
0
10
20
30
40
20
20
40
PERCENT

Appendix C

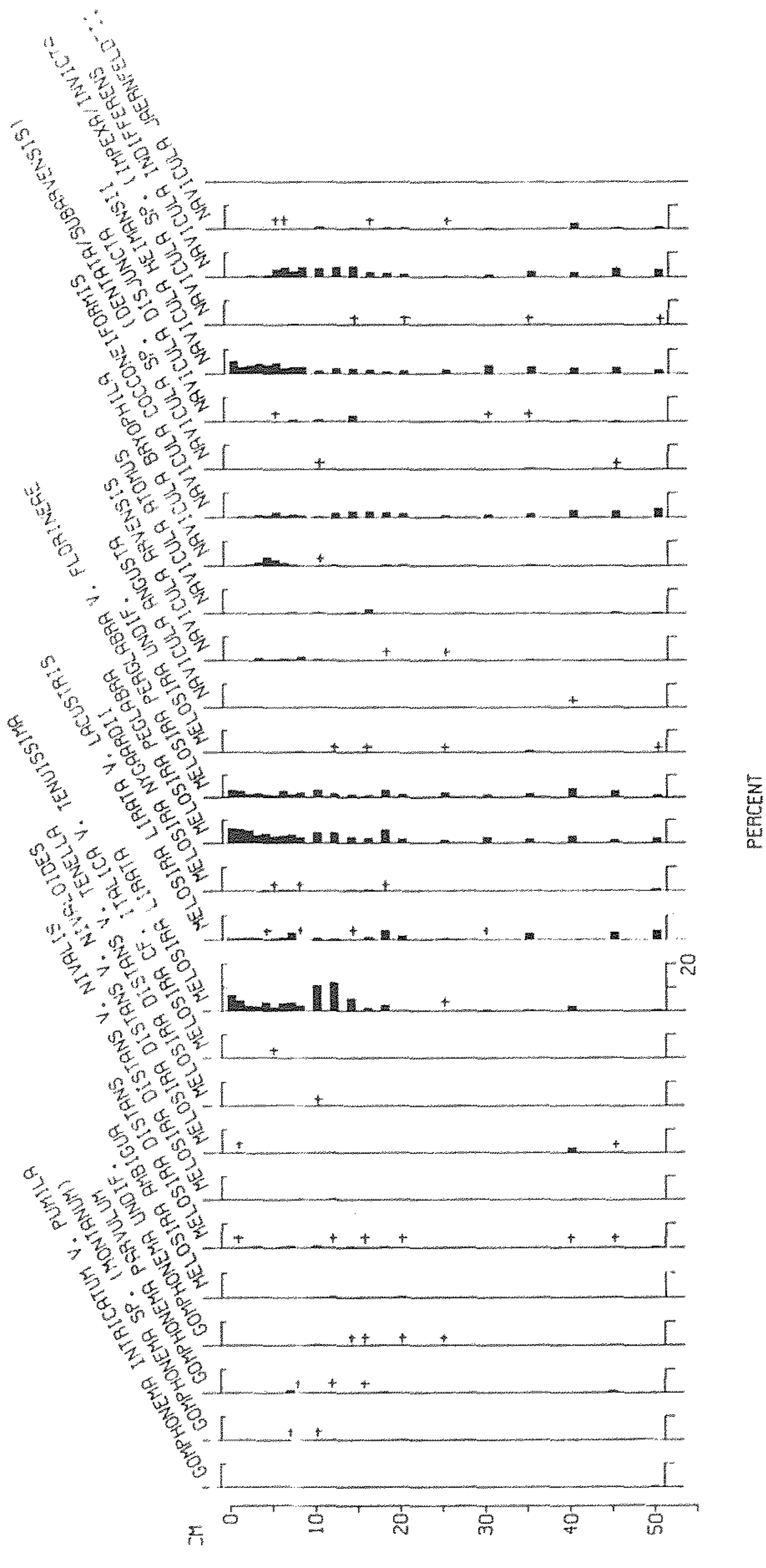

CYMBELLA AEQUALIS
CYMBELLA ANGUSTATA
CYMBELLA CESATII
CYMBELLA GAEUMANNII
CYMBELLA GRACILIS
CYMBELLA HEBRIDICA
CYMBELLA HETEROPLEURA
CYMBELLA MINUTA V. PSEUDOGRACILIS
CYMBELLA MUELLERI
CYMBELLA PERPUSILLA
CYMBELLA VENTRICOSA
CYMBELLA UNDIF.
DIPLONEIS MARGINESTRIATA
EUNOTIA BIDENTULA
EUNOTIA EXIGUA
EUNOTIA FABA
EUNOTIA FABA V. INTERMEDIA
EUNOTIA FLEXUOSA
EUNOTIA IATRIAENSIS
EUNOTIA LUNARIS
EUNOTIA LUNARIS V. SUBARCUATA
EUNOTIA MEISTERI
EUNOTIA MONODON V. MAIOR
EUNOTIA PARALLELA
EUNOTIA PECTINALIS
EUNOTIA PECTINALIS VAR. MIN
EUNOTIA RHOMBOIDEA
EUNOTIA ROBUSTA
CM
0
10
20
30
40
50
PERCENT

Appendix C

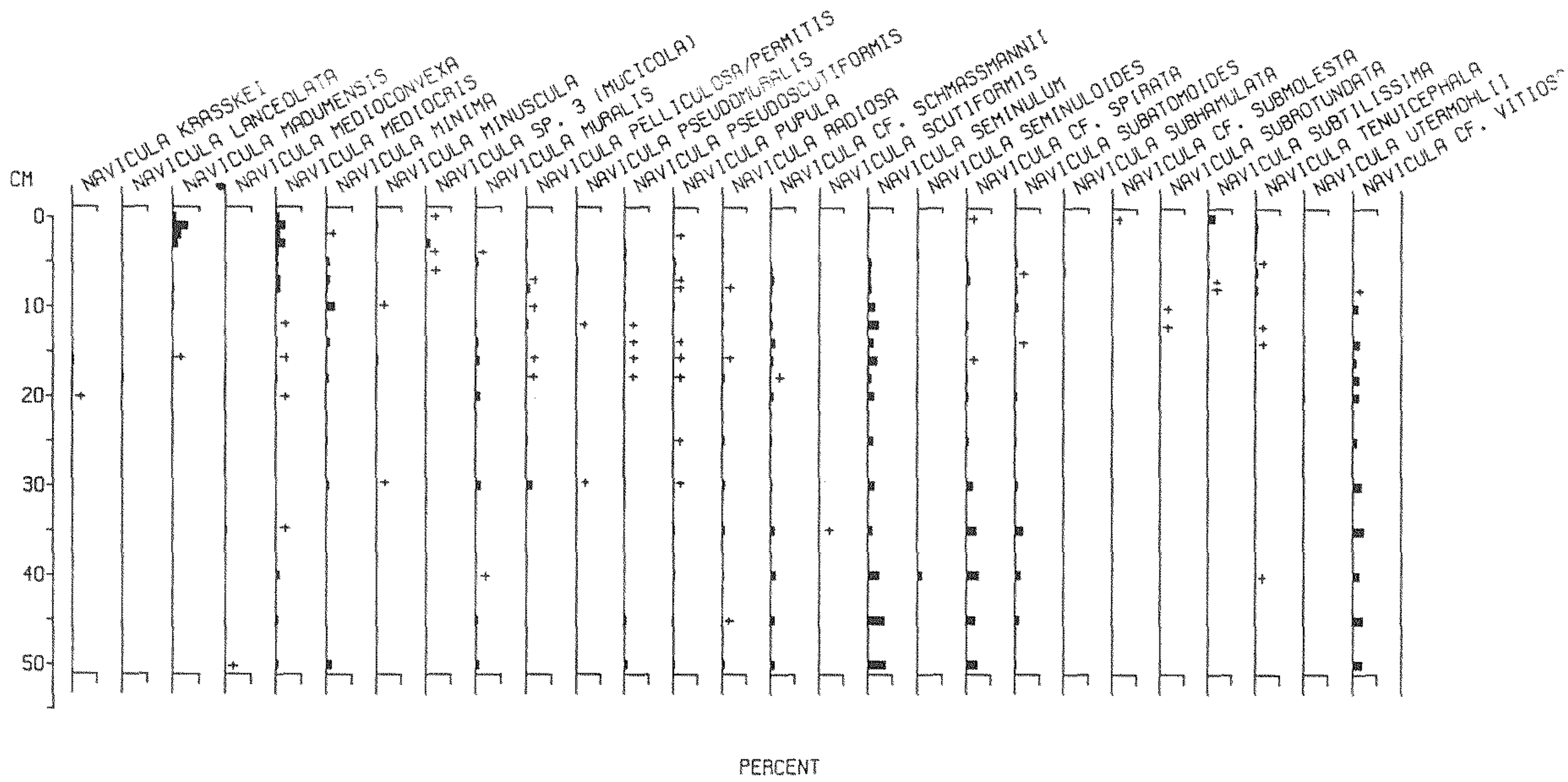


PERCENT

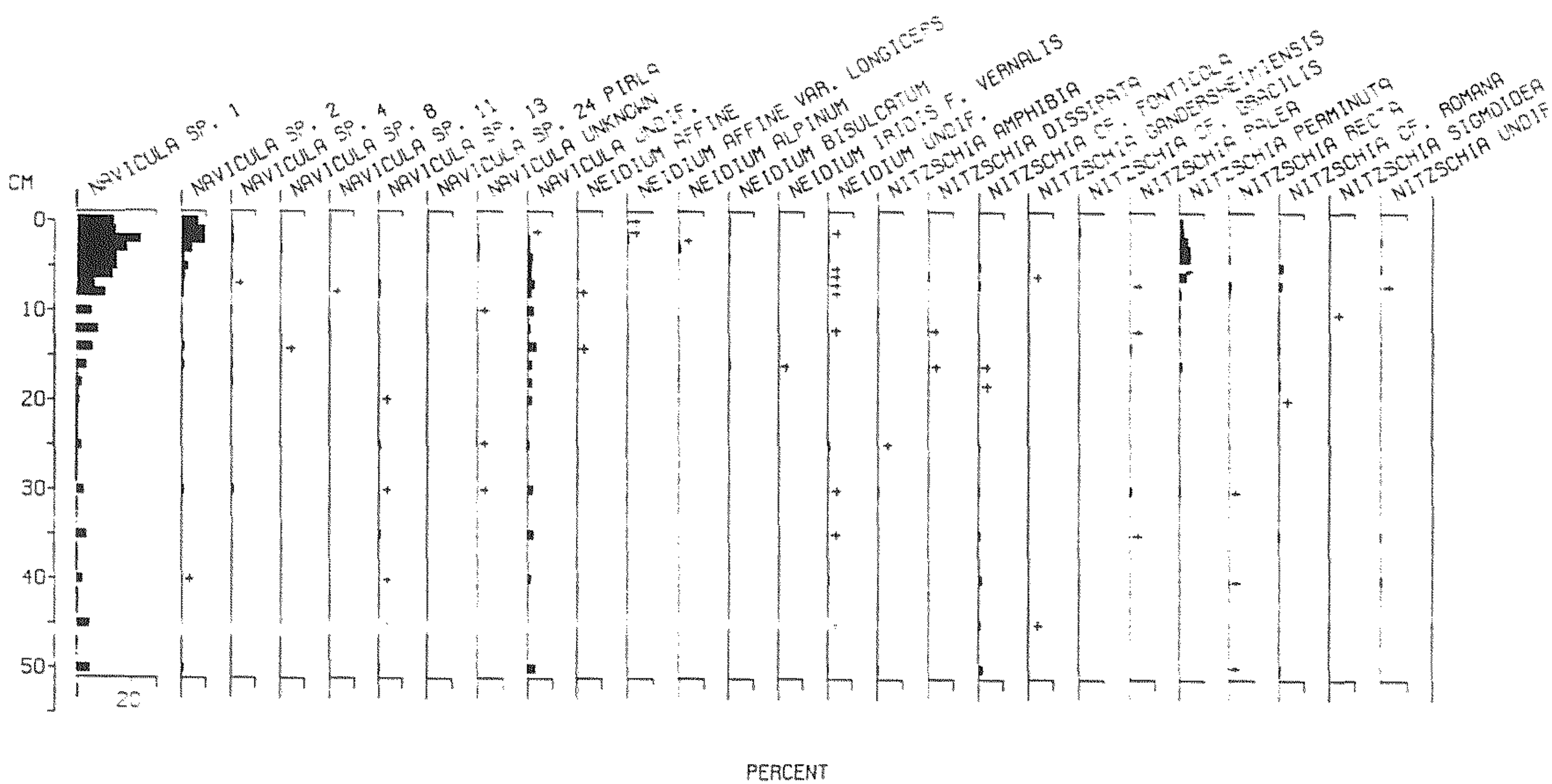
Appendix C



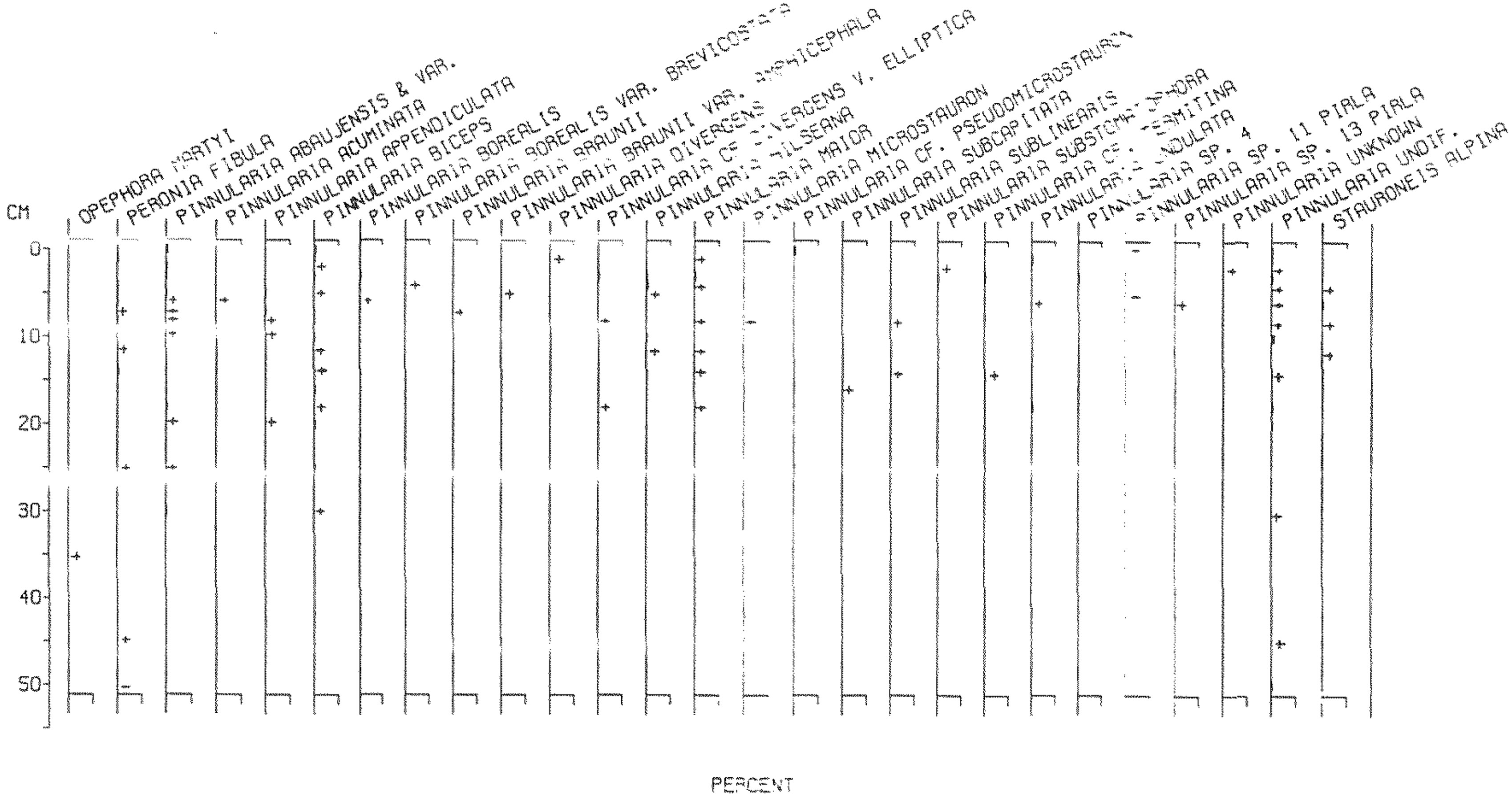
Appendix C


NAVICULA KRASSKEI
NAVICULA LANCEOLATA
NAVICULA MADUMENSIS
NAVICULA MEDIOCONVEXA
NAVICULA MEDIOCRIS
NAVICULA MINIMA
NAVICULA MINUSCULA
NAVICULA SP. 3 (MUCICOLA)
NAVICULA MURALIS
NAVICULA PELLICULOSA/PERMITIS
NAVICULA PSEUDOMURALIS
NAVICULA PSEUDOSCUTIFORMIS
NAVICULA PUPULA
NAVICULA RADIOSA
NAVICULA CF. SCHMASSMANNII
NAVICULA SCUTIFORMIS
NAVICULA SEMINULUM
NAVICULA SEMINULOIDES
NAVICULA CF. SPIRATA
NAVICULA SUBATOMOIDES
NAVICULA SUBHAMULATA
NAVICULA CF. SUBMOLESTA
NAVICULA SUBROTUNDATA
NAVICULA SUBTILISSIMA
NAVICULA TENUICEPHALA
NAVICULA UTERMOHLII
NAVICULA CF. VITIOSA
CM
0
10
20
30
40
50
PERCENT

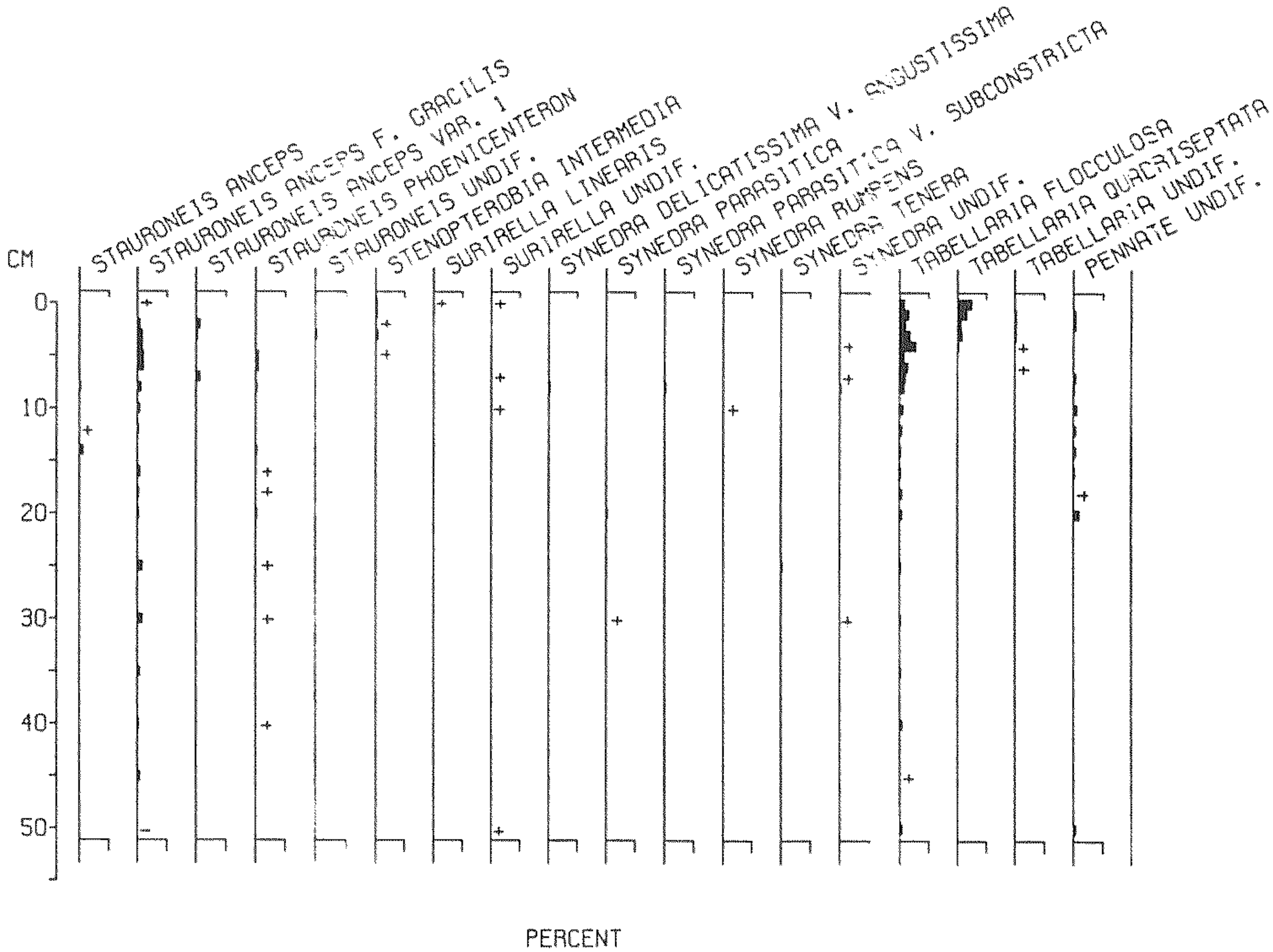
Appendix C


CM
0
10
20
30
40
50
20
NAVICULA SP. 1
NAVICULA SP. 2
NAVICULA SP. 4
NAVICULA SP. 8
NAVICULA SP. 11
NAVICULA SP. 13
NAVICULA SP. 24 PIRLA
NAVICULA UNKNOWN
NAVICULA UNDIF.
NEIDIUM AFFINE
NEIDIUM AFFINE VAR. LONGICEPS
NEIDIUM ALPINUM
NEIDIUM BISULCATUM
NEIDIUM IRIDIS F. VERNALIS
NEIDIUM UNDIF.
NITZSCHIA AMPHIBIA
NITZSCHIA DISSIPATA
NITZSCHIA CF. FONTICOLA
NITZSCHIA GANDERSHEIMIENSIS
NITZSCHIA CF. GRACILIS
NITZSCHIA PALEA
NITZSCHIA PERMINUTA
NITZSCHIA RECTA
NITZSCHIA CF. ROMANA
NITZSCHIA SIGMOIDEA
NITZSCHIA UNDIF.
PERCENT

Appendix C


CM
0
10
20
30
40
50
OPEPHORA
PERONIA FIBULA
PINNULARIA ABAUJENSIS & VAR.
PINNULARIA ACUMINATA
PINNULARIA APPENDICULATA
PINNULARIA BICEPS
PINNULARIA BOREALIS
PINNULARIA BOREALIS VAR. BREVICOS
PINNULARIA BRAUNII
PINNULARIA BRAUNII VAR.
PINNULARIA DIVERGENS
PINNULARIA CF
PINNULARIA MAIOR
PINNULARIA MICROSTAURON
PINNULARIA CF. PSEUDOMICROSTAURON
PINNULARIA SUBCAPITATA
PINNULARIA SUBLINEARIS
PINNULARIA CF.
PINNULARIA SP. 11 PIRLA
PINNULARIA SP. 13 PIRLA
PINNULARIA UNKNOWN
PINNULARIA UNDIF.
STAURONEIS ALPINA
PERCENT

Appendix C

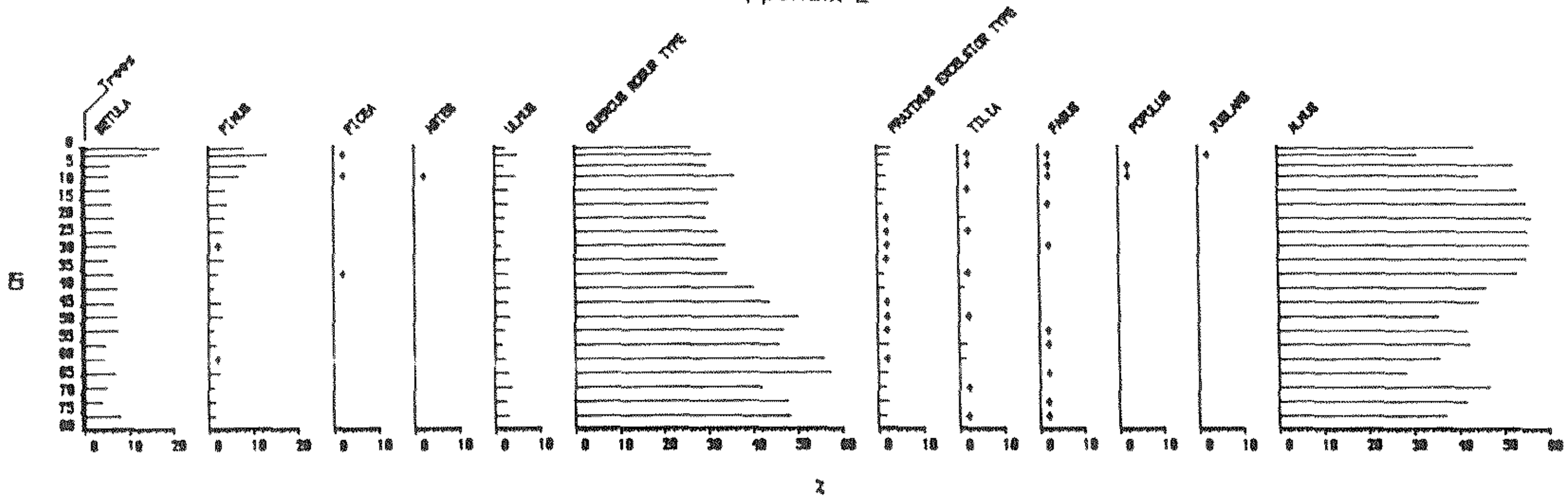

CM
STAURONEIS ANCEPS
STAURONEIS ANCEPS F. GRACILIS
STAURONEIS ANCEPS VAR. 1
STAURONEIS PHOENICENTERON
STAURONEIS UNDIF.
STENOPTEROBIA INTERMEDIA
SURIRELLA LINEARIS
SURIRELLA UNDIF.
SYNEDRA DELICATISSIMA V. ANGUSTISSIMA
SYNEDRA PARASITICA
SYNEDRA PARASITICA V. SUBCONSTRICTA
SYNEDRA RUMPENS
SYNEDRA TENERA
SYNEDRA UNDIF.
TABELLARIA FLOCCULOSA
TABELLARIA QUADRISEPTATA
TABELLARIA UNDIF.
PENNATE UNDIF.
0
10
20
30
40
50
PERCENT

Appendix C

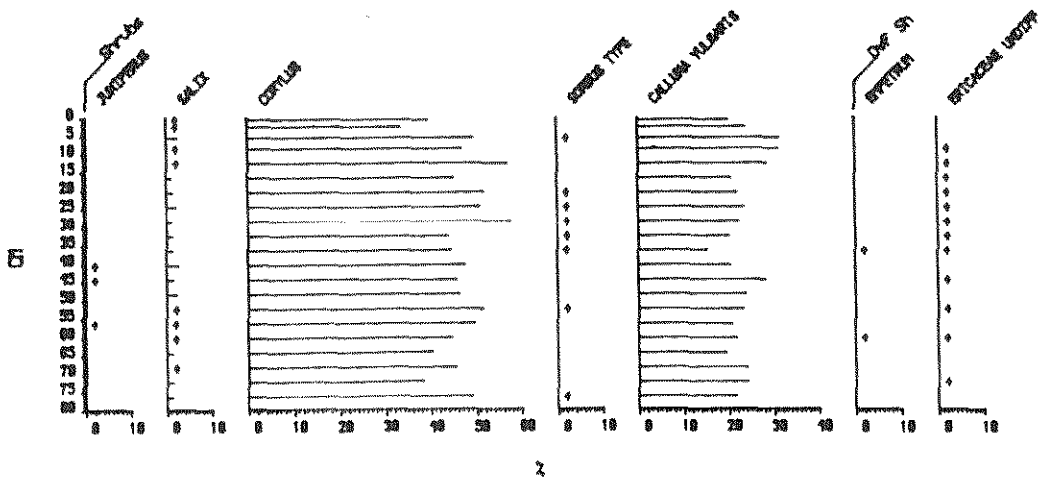
Appendix D: Hir 1 physical and chemistry core data

Depth cm	Density g cm⁻³	Dry Wt g	LOI %	Zn	Pb (ug gdw⁻¹)	Cu	Ni	Ca	Mg	Na	K (mg gdw⁻¹)	Fe	Mn	S	P	Fe/Mn
0.5	1.022	6.2	38.6	316	281	87	25	1.68	1.47	1.57	3.58	78.19	6.64		2.16	11.78
1.5	1.029	6.2	40.7	737	266	55	30	1.56	1.46	1.68	5.25	52.98	5.66		2.2	9.36
2.5	1.025	6.9	40.0	185	309	62	32	1.58	1.77	2.08	6.88	43.14	4.61		2.28	9.36
3.5	1.032	7.41	43.6	559	310	60	37	1.88	1.9	2.14	7.56	27.08	3.51	3.3	2.25	7.72
4.5	1.032	7.85	45.0	637	306	56	47	2.15	1.9	2.17	7.78	27.78	3.33	5.26	2.11	8.34
5.5	1.036	8.08	46.9	566	287	52	41	2.33	1.86	2.16	7.42	24.25	3.16		2.02	7.67
6.5	1.034	8.55	47.2	436	287	51	40	2.3	1.97	2.31	7.78	24.02	2.97	5.65	1.93	8.09
7.5	1.034	8.28	44.4	493	225	47	30	2.43	2.05	2.36	8.46	22.13	2.85	3.51	1.85	7.76
8.5	1.036	9.1	40.1	375	192	40	23	2.41	2.3	2.67	9.4	21.9	2.79	3.37	1.85	7.85
9.5	1.038	9.53	36.5	237	154	35	22	2.32	2.35	2.77	9.84	22.75	2.63		1.87	8.65
10.5	1.038	11.58	34.7	245	103	24	27	2.07	2.84	3.25	11.84	23.86	2.1	1.42	1.96	11.36
11.5	1.038	11.38	31.2	189	61	22	30	1.99	2.9	3.31	11.33	23.93	1.95	2.05	1.93	12.27
12.5	1.039	10.86	32.8	189	39	19	26	2.2	2.9	3.4	12.37	22.86	1.88	1.82	1.81	12.16
13.5	1.04	10.13	35.8	193	41	20	25	2.23	2.68	3.17	11.17	22.68	2.08	1.64	1.81	10.90
14.5	1.044	9.76	38.6	181	43	19	26	2.34	2.72	3.17	11.21	23.62	2.01		1.76	11.75
15.5	1.042	9.69	36.7	176	30	21	30	2.49	2.75	2.92	11.93	25.31	2.25	2.67	1.75	11.25
16.5	1.036	9.98	35.8	151	29	19	31	2.42	2.97	3.38	11.05	25.2	2.12	2.38	1.74	11.89
17.5	1.037	10.06	35.8	151	18	21	28	2.27	2.95	3.19	11.9	24.1	2.02	2.3	1.75	11.93
18.5	1.035	10.04	34.8	191	11	19	27	2.5	3.02	3.32	11.15	24.79	2.0	2.14	1.79	12.40
19.5	1.035	9.16	35.8	203	27	20	33	2.54	2.88	3.1	11.94	25.65	2.11	2.07	1.83	12.16
20.5	1.041	9.08	33.9	159	32	25	33	2.86	2.98	3.17	12.5	27.84	1.81	1.82		15.38
21.5	1.038	9.21	32.0	142	13	24	34	2.77	2.93	2.94	12.41	25.8	1.8	2.14		14.33
22.5	1.037	9.52	36.1	143	10	22	30	2.89	2.92	3.04	12.52	24.1	1.83	1.97	1.77	13.17
23.5	1.036	9.28	33.6	143	22	21	25	2.77	2.86	3.05	12.23	22.99	1.74	1.6		13.21
24.5	1.038	9.81	35.3	151	45	21	28	2.81	2.8	3.08	13.03	23.04	1.77	2.33		13.02
25.5	1.041	9.36	35.2	141	21	24	28	2.74	2.65	2.92	14.4	22.77	1.78	2.45	1.7	12.79
26.5	1.036	9.24	34.4	118	14	21	20	2.71	2.76	3.11	12.19	22.76	1.69	2.41		13.47
27.5	1.038	9.6	33.7	112	29	19	25	2.74	2.85	3.27	12.76	21.72	1.59	2.14		13.66
28.5	1.037	10.11	33.2	112	31	18	22	2.76	2.77	3.23	13.37	21.1	1.48	2.02	1.65	14.26
29.5	1.42	9.89	32.8	134	29	22	26	2.68	2.85	3.14	12.75	22.87	1.43	2.04		15.99
30.5	1.04	10.05	34.4	158	34	22	29	2.74	2.92	3.11	13.04	25.46	1.53	2.28		16.64
31.5	1.038	9.94	31.2	160	38	22	25	2.71	2.92	3.16	12.84	27.31	1.57	2.21	2.1	17.39
32.5	1.042	10.25	30.3	136	55	21	28	2.78	2.74	2.97	11.68	26.62	1.53	2.03		17.40
33.5	1.039	9.58	30.0	141	39	20	29	2.95	2.5	2.59	10.89	26.87	1.61	2.23		16.69
34.5	1.038	9.07	32.3	136	40	19	29	3.06	2.34	2.4	9.52	26.89	1.72	2.13	2.19	15.63
35.5	1.037	9.23	31.5	107	36	16	28	3.12	2.14	2.2	8.69	25.38	1.74	1.94		14.59
36.5	1.035	9.36	33.1	118	36	19	28	3.04	2.16	2.22	8.75	23.23	1.61	2.29		14.43
37.5	1.036	8.89	34.5	122	30	14	24	3.04	1.98	1.86	7.56	23.05	1.62	2.32	2.16	14.23
38.5	1.035	8.39	34.4	122	26	16	18	2.95	1.92	1.83	7.05	21.39	1.45	2.1		14.75
39.5	1.04	8.25	32	130	10	15	26	2.94	1.94	1.86	7.11	22.79	1.45	2.36		15.72
40.5	1.035	8.46	31.9	141	6	17	27	3.23	1.99	1.84	7.12	24.91	1.61	2.85	2.46	15.47
41.5	1.04	9.06	31.3	115	11	17	23	3.12	1.96	1.81	7.06	22.74	1.51	2.23		15.06
42.5	1.032	9.0	32.6	120	23	17	25	3.2	2.07	1.89	7.63	22.58	1.61	2.71		14.02
43.5	1.04	9.01	33.6	134	16	15	24	3.18	2.02	1.84	7.34	22.91	1.53	2.64	2.33	14.97
44.5	1.034	8.89	30.7	121	2	16	29	3.31	2.07	1.93	7.68	23.34	1.56	2.53		14.96
45.5	1.035	9.5	31.2	138	19	17	28	3.19	2.11	1.92	7.59	23.5	1.52	2.25		15.46
46.5	1.038	9.52	31.6	148	33	16	24	3.0	1.98	1.91	7.11	22.67	1.63	1.86	2.45	13.91
47.5	1.042	9.04	30.2	201	39	20	26	3.8	2.43	2.48	9.62	30.2	1.94	1.97		15.57
48.5	1.037	9.47	30.6	157	0	18	21	3.26	2.02	2.23	8.14	23.77	1.64	2.36		14.49
49.5	1.036	9.01	34.8	123	0	16	14	3.1	1.83	1.96	7.4	21.2	1.59		2.33	13.33
50.5				126	0	16	20	3.16	1.77	1.89	7.17	20.92	1.61	2.84		12.99
51.5	1.036	8.87	37	106	7	14	25	3.03	1.83	2.02	7.66	19.83	1.59	2.51		12.47
52.5				106	0	14	17	3.05	1.91	2.09	7.78	20.09	1.49	2.65	2.33	13.48
53.5	1.033	9.63	33	125	0	15	15	2.87	1.8	2.06	7.64	20.14	1.47	2.8		13.70
54.5				148	0	14	12	2.88	1.91	2.05	7.71	21.41	1.52	3.16		14.09
55.5	1.035	10.86	39.8	132	10	13	26	2.73	1.95	2.14	8.35	22.05	1.42	3.08	2.1	15.53
56.5				136	2	11	23	2.58	2.15	2.48	8.82	22.42	1.35	3.01		16.61
57.5	1.034	9.93	28.5	133	0	12	19	2.57	2.2	2.65	9.28	22.76	1.37	2.79		16.61
58.5				141	17	13	20	2.49	2.21	2.63	9.24	21.74	1.32	2.43	2.01	16.47
59.5	1.033	10.01	28.6	153	51	13	22	2.61	2.23	2.48	9.57	21.81	1.33	1.98		16.40
60.5				143	0	12	23	2.95	1.85	1.94	7.43	23.22	1.56	2.68		14.88
61.5	1.033	9.52	36.1	134	0	12	28	2.93	1.86	2.02	7.06	23.56	1.57	2.83	2.19	15.01
62.5				132	0	13	27	2.72	1.88	2.0	7.55	22.98	1.54	2.75		14.92
63.5	1.033	9.59	33.3	157	0	12	28	2.74	1.95	2.09	7.97	21.57	1.46	2.62		14.77
64.5				131	0	12	22	2.75	2.0	2.19	8.2	21.93	1.46	2.35		15.02
65.5	1.034	9.84	29.4	141	22	12	20	2.51	2.19	2.39	8.83	21.76	1.3	1.7		16.74
66.5				127	38	12	18	2.4	2.29	2.36	4.96	20.77	1.22	2.19		17.02
67.5	1.035	9.81	27.6	151	83	12	22	2.31	2.28	2.38	4.66	21.08	1.21	1.69		17.42
68.5				138	109	21	21	2.4	2.31	2.36	5.0	23.08	1.24	2.14		18.61
69.5	1.041	10.3	26.6	137	86	15	17	2.46	2.26	2.25	4.81	23.62	1.26	1.74		18.75
70.5				137	39	16	24	2.5	2.2	2.11	4.67	22.83	1.26	2.65		18.12
71.5	1.043	9.94	31.3	134	27	15	16	2.5	2.25	2.19	4.75	24.78	1.28	2.01		19.36
72.5				146	22	15	16	2.35	2.22	2.27	4.77	25.24	1.27	2.13		19.87
73.5	1.04	11.36	26.3	136	0	15	17	2.27	2.26	2.27	5.02	24.99	1.22	2.15		20.48
74.5				157	10	14	20	2.23	2.28	2.3	5.15	24.99	1.21	1.71		20.65
75.5	1.034	11.03	25.2	138	32	15	18	2.34	2.18	2.17	4.7	25.52	1.24	2.99		20.58
76.5				124	31	17	19	2.43	2.13	2.17	4.72	25.44	1.25	3.27		20.35

Appendix E

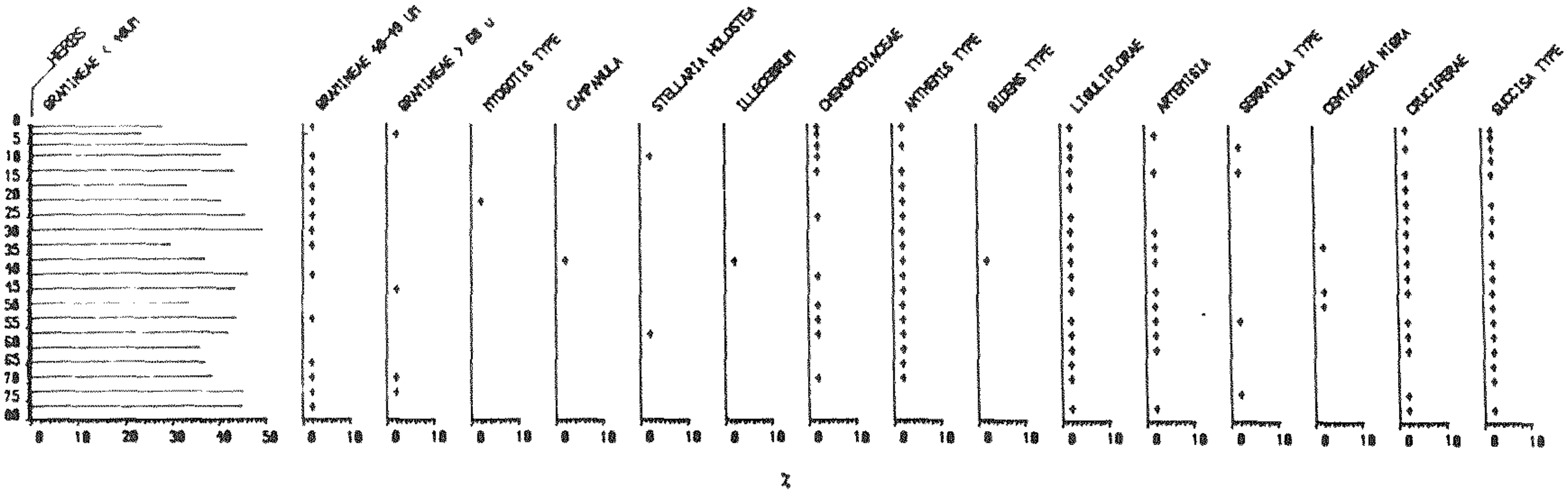


Llyn Hir full diagram %ap

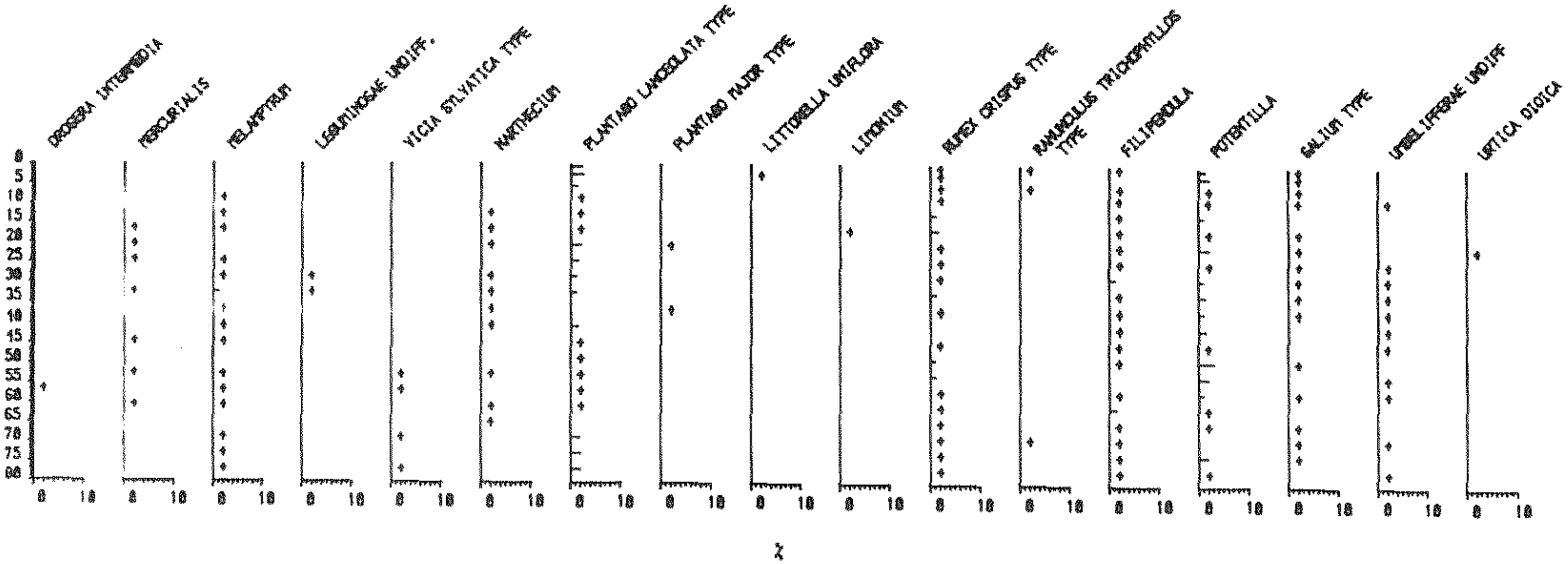


Llyn Hir full diagram %ap+shrubs %ap+dwf shrubs

Appendix E

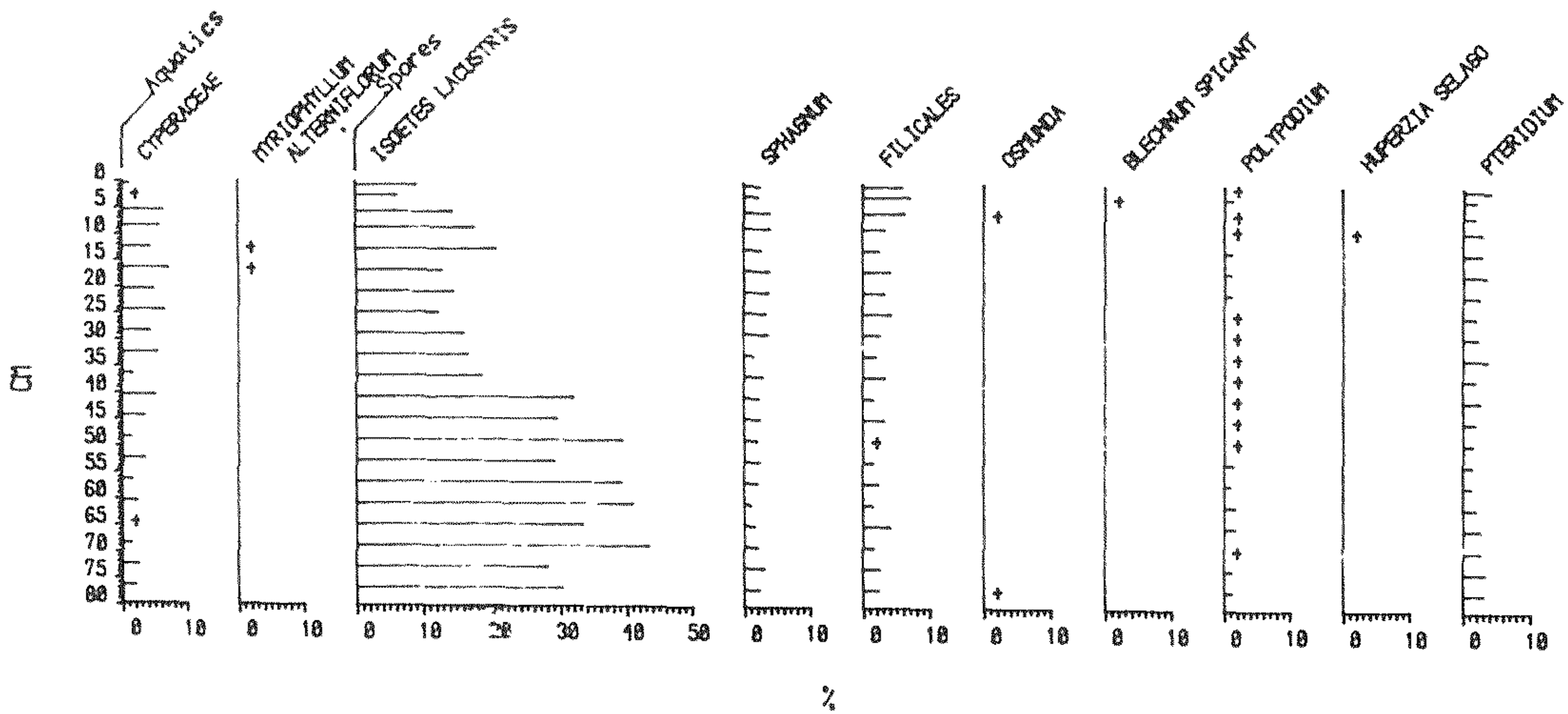


Llyn Hir Full diagram %ap+herbs



Llyn Hir Full Diagram Herbs %

Appendix E



Llyn Hir Full diagram %Total pollen

PALAEOECOLOGY RESEARCH UNIT
WORKING PAPERS

No. 1 Patrick, S. & 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. 43 pp.

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. 18 pp.

No. 3 Patrick, S. & Battarbee, R.W. 1983 Rural sanitation in the Lough Erne catchment: History and influence on phosphorous loadings. 26 pp.

No. 4 Patrick, S. 1983 The calculation of per capita phosphorous outputs from detergents in the Lough Erne catchment. 23 pp.

No. 5 Patrick, S. 1983 Phosphorous loss at sewage works in the Lough Erne region. 36 pp.

No. 6 Flower, R.J. & Battarbee, R.W. 1983 Acid lakes in the Galloway uplands, South West Scotland: catchments, water quality and sediment characteristics. 56 pp.

No. 7 Patrick, S. 1984 The influence of industry on phosphorous loadings in the Loch Erne region. 46 pp

No. 8 Battarbee, R.W. & Flower, R.J. 1985 Palaeoecological evidence for the timing and causes of lake acidification in Galloway, South West Scotland. 79 pp.

No. 9 Raven, P.J. 1985 The use of aquatic macrophytes to assess water quality changes in some Galloway lochs: an exploratory study. 76 pp.

No. 10 Anderson, N.J. & Battarbee, R.W. 1985 Loch Fleet: bathymetry and sediment distribution. 18 pp.

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

No. 12 Battarbee, R.W. and Renberg, I. 1985 Royal Society Surface Water Acidification Project (SWAP) Paleeolimnology Programme. 18 pp.

No. 13 Raven, P.J. 1986 Occurrence of Sphagnum moss in the sublittoral of several Galloway lochs, with particular reference to Loch Fleet. 40 pp.

No. 14 Flower, R.J., Rippey, B. & Tervet. 1986 34 Galloway Lakes: Bathymetries, Water quality & Diatoms.

No. 15 Flower, R.J. & Nicholson, A. 1986 Batymetries, water quality and diatoms of lochs on the island of South Uist, The Outer Hebrides, Scotland. 42pp

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

No. 17 Anderson, N.J.A., 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.

For copies of Working Papers or further information, please contact Dr. R.W. Battarbee, Palaeoecology Research Unit, Department of Geography, University College London, 26 Bedford Way, London WC1H 0AP.