Research Papers

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PALAEOLIMNOLOGICAL EVIDENCE FOR THE ACIDIFICATION OF LOCH FLEET

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SUMMARY

1. Sediment distribution in Loch Fleet is more complex in space and time than at other Galloway sites.

2. Despite these complexities it has been possible to identify a mastercore (LF L3) by use of a multi-coring strategy. Although various analyses suggest that **this core has a hiatus between c. 5000 yrs BP and about 1800 AD,** it has a conformable sequence over about the last 200 years. This period has been successfully dated using 210-Pb.

3. **The diatom assemblage is remarkably constant** until 1960 and is similar to that at other pre-acidification Galloway sites. The lake had a plankton flora dominated by *Cyclotella kutzingiana*, and this together with other circumneutral taxa **results in a reconstructed pH of 5.8-6.0 until about 1960** when part of the catchment was afforested. There is no tendency towards acidification at Loch Fleet during this period, unlike other Galloway sites, despite the probable increase in acid loading that took place through the 19th and 20th centuries. The **implication of this is that there must be one or a number of sources of alkalinity in the Loch Fleet catchment that do not occur or are not as important at other sites.**

4. The ploughing of the catchment prior to afforestation, and the associated inwash of peats led to the rapid decline of the planktonic diatom *Cyclotella kutzingiana*. There was a small drop in the inferred pH value at this time, but this could be an artefact if the *Cyclotella* decline was due to habitat disturbance from peat inwash rather than to acidification. **Since non-planktonic circumneutral taxa do not decline at this time it is probable that the ploughing and early stages of forest growth caused little change in water quality.**

5. **A very sudden and acute acidification of the lake occurred from about 1975-6.** The diatom changes that took place are identical to those observed at other sites over much longer time periods. Typically *Anomoeoneis vitrea* and *Achnanthes minutissima* decline and *Eunotia veneris* increases, and then as the lake permanently loses its alkalinity, *Tabellaria quadriseptata*, *T.binalis* and other acidiobiontic taxa takeover. In Loch Fleet this sequence is compressed into a 10-15 year period and is more reminiscent of the rapid changes that have taken place in Sweden and Finland than in Galloway. It is **even more remarkable that it occurs at a time when acid deposition is decreasing.**

6. It is clear from these data that the initial fish decline of the mid-1950's predates any acidification of the lake. However, **the second decline coincides with the start of the inwash in c. 1961-62 and the loss of fish coincides with the mid 1970's** acidification.

7. Despite increased atmospheric loadings no acidification of Loch Fleet took place until at least 1960. Acute acidification of approximately 1 pH unit from about 5.6 to 4.6 occurred in the mid to late-1970's, at a time when emissions were declining but when the forest canopy was beginning close. It is known that maturing

Sitka spruce stands, both at this site and elsewhere, can result in the further acidification of throughflow and stemflow. If the neutralising capacity of the underlying soils is low this acidity will be passed on to the surface waters. **It is necessary to conclude that the increased acidification associated with forest growth was sufficient to exceed the neutralising capacity of the catchment and cause the rapid acidification of the lake.**

8. **We also observed that the peat inwash from catchment ploughing caused very organic peaty sediment to accumulate over areas of the lake bottom that were previously covered by late-glacial silts and clays.** This development may have reduced the internal neutralising capacity of the lake and contributed to the acidification described above. It is possible to calculate the area of lake bed covered in this way, but so far we have made no effort to do so since further field work would be necessary.

9. If these inferences about the importance of the forest are correct, then the natural way to restore a viable fish population to the lake is not to lime or burn the non-afforested part of the catchment, but to carefully clear the catchment of trees or to increase the neutralising capacity of the soils beneath the trees. If the spread of peaty sediments on the lake bottom is important these could be removed by dredging or could be neutralised by liming.

ACKNOWLEDGEMENTS

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1. INTRODUCTION

1.1 Aims

This paper forms the final report of our study of the sediments of Loch Fleet carried out for the SSEB/CEGB Loch Fleet project. The contract period was from July 1984-November 1985 and our specific aims were as follows:

1. to make a new bathymetric map of Loch Fleet and to compute lake dimensions,

2. to make a map of the distribution of different types of surface sediment,

3. to assess variations in recent sediment stratigraphy using core correlation techniques,

4. to establish a sediment chronology for selected cores using 210Pb analysis,

5. to assess the variability of the surface sediment diatom record and to reconstruct the timescale and rate of acidification of the loch using diatom analysis.

A report covering the first three of these aims has been issued (Anderson & Battarbee 1985). This report is mainly concerned with aims 4 and 5 but also includes the results of pollen, magnetic, carbonaceous particle, and trace metal analysis carried out by our laboratories but not funded under this contract.

1.2 Background

In 1980 and 1981 when we were planning our earlier work on the acidification history of Galloway lakes (Flower & Battarbee 1983, Battarbee & Flower 1985) we obtained sediment cores from 7 lochs, including Loch Fleet. With the exception of Loch Fleet our strategy of coring at the deepest point of each of these lakes was successful. In the case of L. Fleet our core from the deepest water suggested that this was not the site of most rapid sediment accumulation and the 210Pb dating (see below and Battarbee et al. 1985) indicated that a good chronology could not be established from it, because of a probable hiatus and because of inadequate 226Ra data. In July 1984 a map of surface sediment characteristics was made using information from 86 Ekman grab samples. 24 short cores and 2 long cores were also obtained from within the zone covered by organic sediments (Fig. 1). Lithostratigraphic analysis, 210Pb dating, and pollen analysis of core L1 (see below) showed that the core contained a major hiatus between early post-glacial accumulation (c.9000-5000 BP) and shortly before the very recent and rapid sediment accumulation associated with the post 1961-3 soil erosion from the afforested area of the catchment.

From inspection of the dry weight and loss on ignition data of these 2 long cores and the 24 short cores we deduced that longer and possibly more continuous records of sediment accumulation could be found in relatively shallow areas in the north-east corner and in the sheltered north-west corner of the lake. In May 1985 cores were obtained from both these sites (L3 & L4). In the case of L3 the transition from organic post-glacial sediments to late-glacial clays occurred at 3.10m. Subsequent analysis of this core (see below) has shown that it also contains a major hiatus, but somewhat smaller than for L1, and appears to include a complete record of the most essential period, from the early nineteenth century to the present. In the following sections data for L1, L3 and other cores are presented but L3 is regarded as the master core (Fig. 1).

2. LITHOSTRATIGRAPHY

2.1 Core LF L1

Fig. 2a shows the stratigraphic column and loss on ignition data for core L1. The base of the core comprises grey late-glacial clays that pass upwards at 1.30m into organic post-glacial muds with an organic content of about 25%. Although there was no clear visual stratigraphic change in the core when freshly extruded, reddish minerogenic bands were apparent between 60 and 35 cm after the sediment had been allowed to dry. The loss on ignition data show fluctuating values at these levels and then a sharp increase to about 60% that decline back to about 35% at the sediment surface. It is almost certain (see below) that the changes at about 60 cm and upwards are the result of catchment disturbance associated with the 1961-1963 ploughing and afforestation. It is also clear that the sediments from about 60 cm downwards belong to pre 5000 BP times when undisturbed natural woodland communities occupied the region (see below).

2.2 Core LF L3

Fig. 2b shows similar data for L3. There is an initial increase from low percentages in the late-glacial period to ca. 20% at 312 cm. Between 310 and 240 cm values vary between 25 and 40%, and then decline to about 20% by 110 cm. However, a number of clear peaks occur in this zone particularly above 160 cm. Above 110 cm there is a rapid increase in LOI values to over 70% reflecting the inwash of catchment peat following ploughing. Values in the uppermost zone vary between 60 and 90% but there is a trend towards decreasing percentages after the maximum at 60 cm representing the stabilisation of catchment soils after canopy closure.

2.3 Stratigraphic units

On the basis of these two cores three well-defined stratigraphic units can be established, but, because of the presence of hiatuses, they cannot be used for chronostratigraphic correlation at their boundaries. Unit A is the zone with very high (>40%) organic values often preceded by a mineral inwash of low and fluctuating loss on ignition values corresponding to the recent post-ploughing phase. Unit B is characterised by medium (15-40%) organic values and corresponds to the pre-ploughing post-glacial sediments, whilst unit C comprises grey clays of very low organic content (<10%) and relates to late-glacial sediments. In L3 unit B can be divided by the approximate position of the hiatus into two zones, the upper of which is characterised by a series of organic peaks and troughs (Fig. 2b).

L3 illustrates the most complete core so far obtained from the lake and thereby allows the LOI profiles of the short cores to be correlated with it. The 12 profiles available are shown in Fig. 3 (redrawn from Fig. 9a in Anderson &

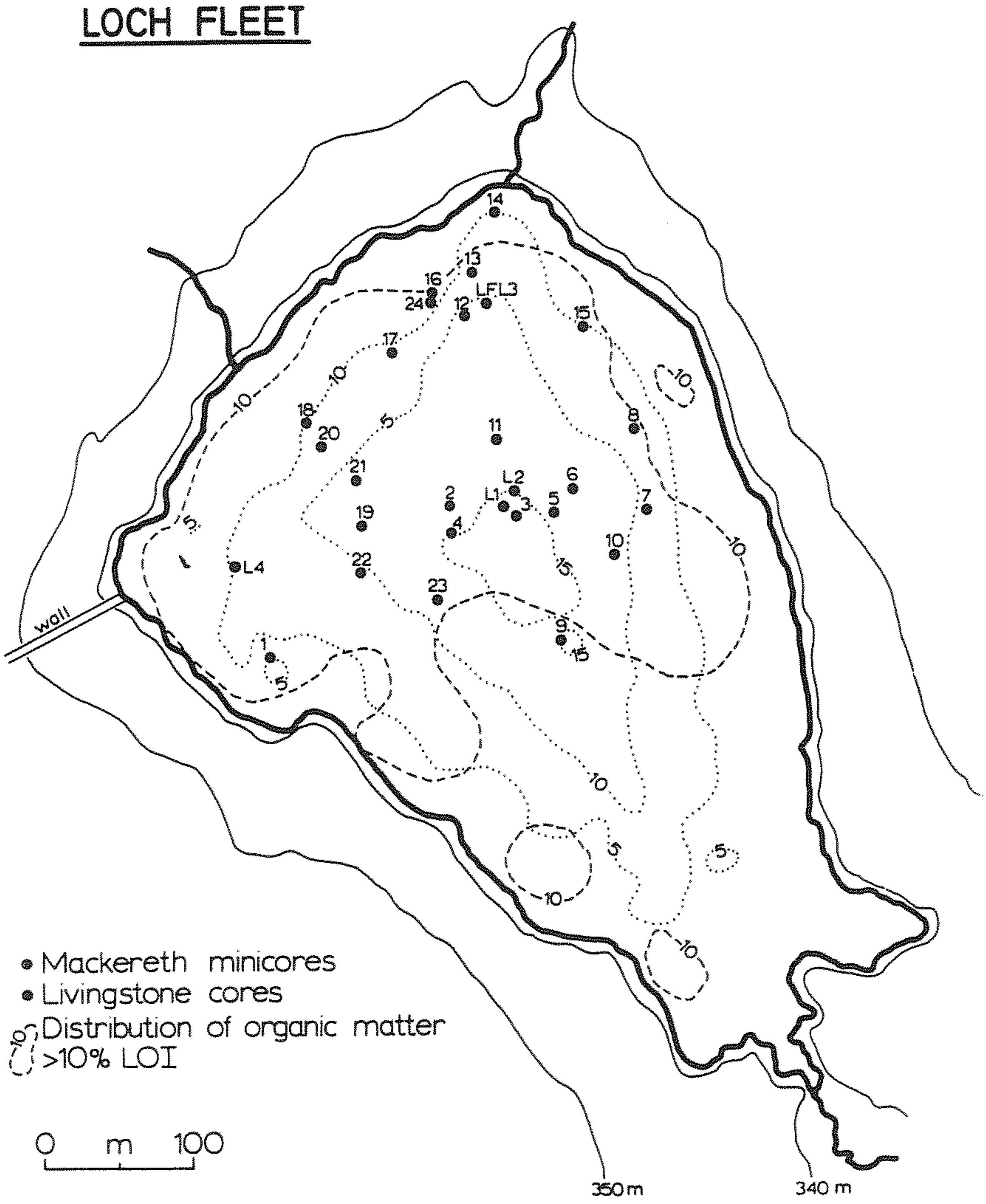


Fig. 1 Mini-core and Livingstone core lbcation; with the limit of organic accumulation.

Battarbee 1985). Although of varying thickness all cores contain a highly organic upper section (unit A), some however pass directly to grey clays of unit C (eg 15, 24, 10, and 4), whilst others (1, 5, 6, and 11) pass into the unit B type sediments.

In some cases (12, and perhaps 3 & 7), the entire core comprises sediments of unit A. Where sediments with a highly organic upper section (unit A) pass directly to clays a hiatus between 8-9000 BP and 1963 AD is implied. Other hiatuses are less obvious but can be detected by other techniques (see below).

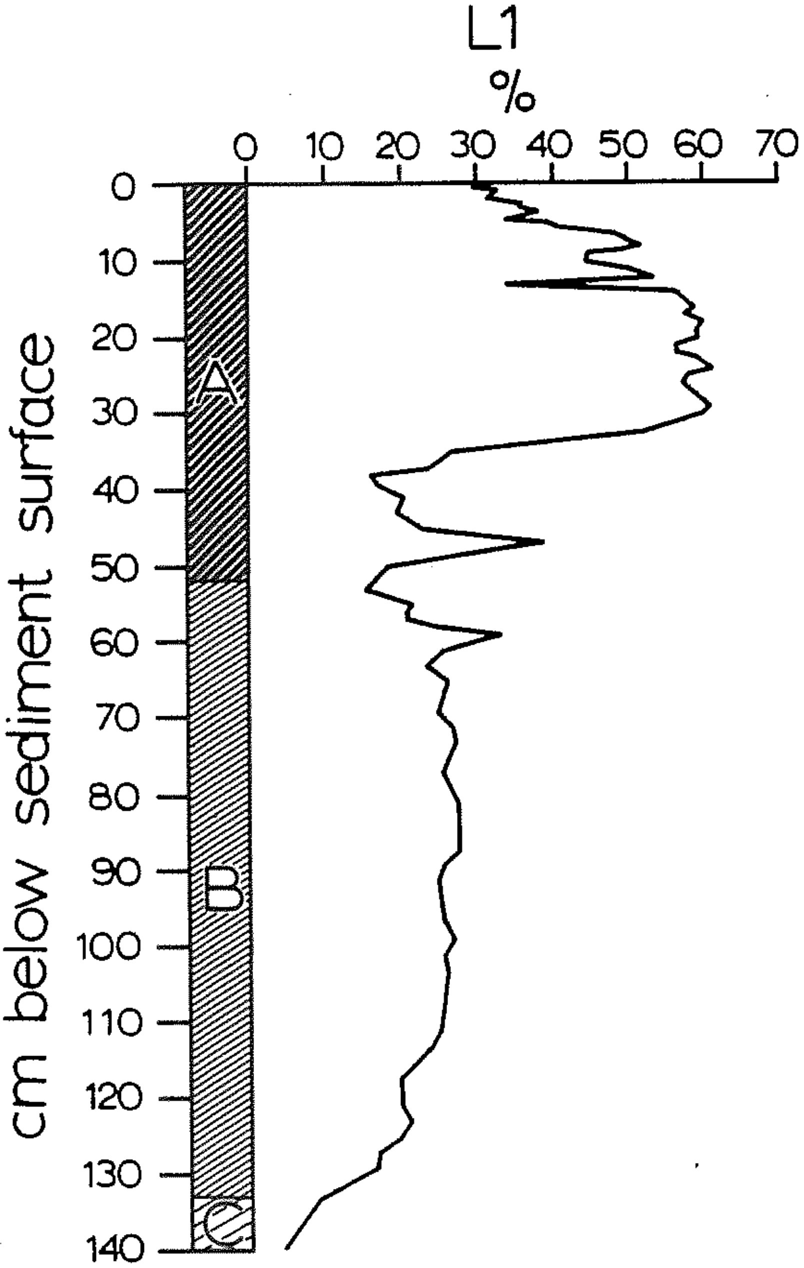


Fig. 2.a L1 LOI profile and stratigraphic units.

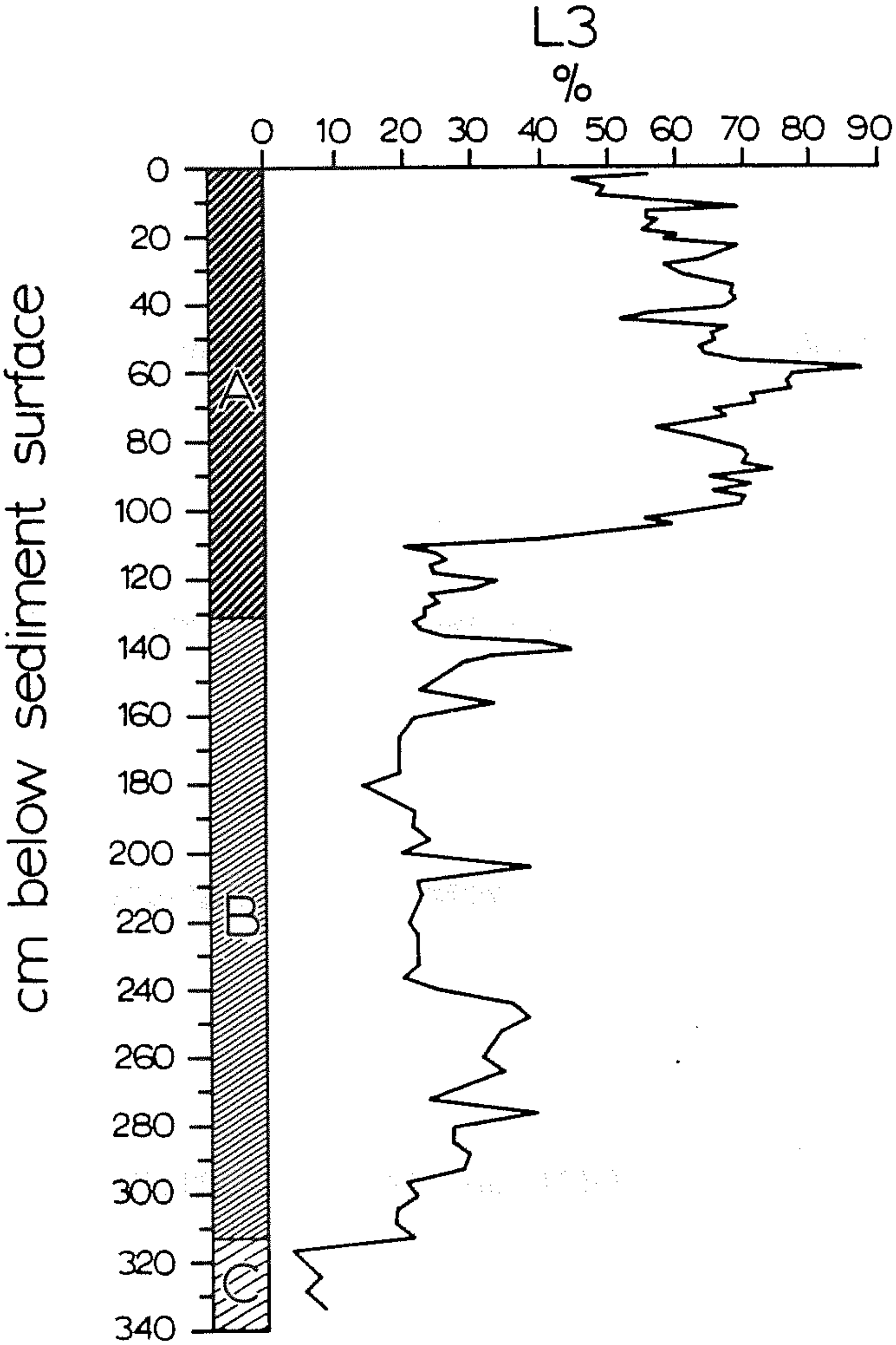


Fig. 2.b L3 LOI profile and stratigraphic units.

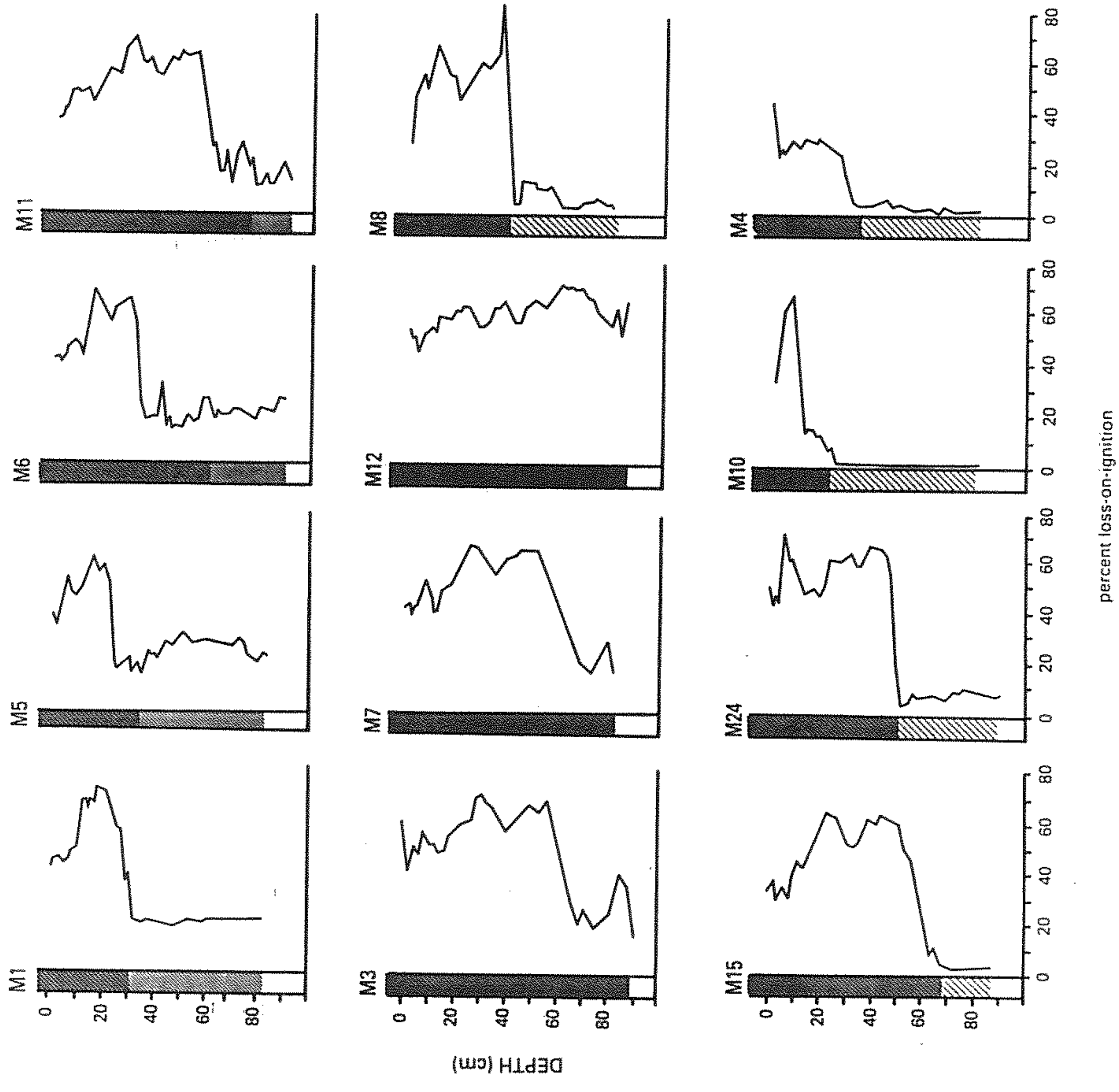


Fig. 3 LOI profiles and stratigraphic units for Mackereth minicores.

3 CHRONOLOGY AND SEDIMENT ACCUMULATION RATES.

3.1 General

Cores L1 and L3 were analysed for 210Pb, 226Ra and 137Cs by gamma spectrometry, using a low background well-type Ortec Ge-Li detector (Appleby et al. 1986). A limited number of additional measurements were also carried out on the earlier core LFV (Battarbee et al. 1985). Figs. 4-8 show the 210Pb profiles for all three cores. Figs. 9-11 show the 137Cs profiles. 210Pb and 137Cs parameters for each core are given in Table 1. The dominant feature of the 210Pb profiles is that, except in the near-surface sediments, variations in the 210Pb concentrations are largely governed by variations in the parent isotope 226Ra. In all three cores the 226Ra concentrations vary from 1-2 pCig-1 in the most recent sediments to ca 11 pCig-1. The mean 210Pb flux of 1.15 pCi cm2 yr-1 compares quite well with the mean value of 1.12 pCi cm-2 yr-1 for all the Galloway lakes. The high unsupported 210Pb concentrations found in the near-surface sediments of all three cores indicates that current sediment accumulation rates are very low. Using the 210Pb flux value the mean present day accumulation rate for Loch Fleet is estimated to be about 0.035 g cm-2 yr-1, or 0.35 cm yr-1. If this value had prevailed throughout the levels of unsupported 210Pb activity, 210Pb equilibrium would be reached at depths of about 50 cm. The actual mean equilibrium depth of 95 cm is some indication of the extent of the enhanced erosion rates presumably associated with the 1961-63 afforestation programme.

Chronologies for cores L1 and L3 are given in Table 2. In the case of L3 the chronology is largely based on the CRS model dates, with some small amendments based on the discussion below. For L1 the chronology is based on the CRS model, using the dated reference point of 1961 for 50.5 cm.

3.2 Chronology for LF L3

The 210Pb inventory of L3 (see Table 1) is twice that at L1, and indicates the extent of sediment focussing at this site. The unsupported 210Pb profile (Fig. 8) shows strongly non-monotonic features reminiscent of those seen in 210Pb data from Loch Grannoch (Battarbee et al. 1985). Fig. 12 shows the 210Pb depth v age curve and accumulation history for LF3, based on the CRS 210Pb dating model (Appleby & Oldfield 1978). This dates the A/B horizon at 108 cm to 1960, and confirms the association of this horizon with the onset of inwashed peat derived from the 1961-3 ploughing. Significantly, this transition to sediments with high organic values is also marked by a large reduction in 226Ra concentrations, and also in the concentrations of a range of other radio-isotopes such as 238U, 235U and 40K. The validity of the CRS model date in spite of the enhanced 210Pb flux suggests that the extent of sediment focussing at L3 has been reasonably steady.

The unsupported 210Pb concentration in L3 above 108 cm has a

Table 1. Loch Fleet (a) ^{210}Pb Parameters

Core	Surface ^{210}Pb Conc.	^{210}Pb Inventory	Mean ^{210}Pb Flux	^{226}Ra Conc	99% Equ. Dep
	pCig^{-1}	pCi cm^{-2}	pCi cm^{-2}yr^{-1}	pCig^{-1}	cm
LF1	45.9	29.2	0.91	1.9-11.2	51.3
LF3	21.1	63.7	1.98	1.1-11.4	201.0
LFTV	24.7	18.3	0.57	2.0-10.6	32.2
	Mean	37.1	1.15		

(b) ^{137}Cs Parameters

	Surface ^{137}Cs Conc.	^{137}Cs Inventory
	pCig^{-1}	pCi cm^{-2}
LF1	13.35	12.64
LF3	21.20	14.66
LFTV	14.31	7.58

TABLE 2 LOCH FLEET PB-210 CHRONOLOGY

CORE LF1

DEPTH	DRYMASS	CHRONOLOGY			SEDIMENTATION RATE		
		DATE	AGE	STD			% STD
CM	G/CM**2	AD	YR	ERROR	G/CM**2YR	CM/YR	ERROR
0.00	0.0000	1984	0				
0.50	0.0448	1983	1	1	0.032	0.28	4.2
1.50	0.1565	1981	3	2	0.048	0.41	4.8
3.50	0.3946	1976	8	2	0.078	0.69	6.1
5.50	0.6296	1972	12	2	0.137	1.26	7.5
7.50	0.8427	1971	13	2	0.270	2.60	10.0
9.50	1.0553	1970	14	2	0.397	3.89	12.4
11.50	1.2565	1970	14	2	0.424	4.18	12.2
13.50	1.4555	1969	15	2	0.410	4.06	11.7
15.50	1.6545	1969	15	2	0.396	3.94	11.1
17.50	1.8535	1968	16	2	0.382	3.81	10.5
19.50	2.0525	1968	16	2	0.388	3.85	10.0
21.50	2.2524	1967	17	2	0.471	4.52	12.8
25.50	2.6522	1966	18	2	0.676	6.17	18.6
29.50	3.0520	1966	18	2	0.882	7.24	24.3
33.50	3.5673	1965	19	2	0.651	5.34	21.8
41.50	4.6724	1963	21	2	0.569	3.80	21.4
50.50	6.1971	1961	23	2	0.930	5.22	23.4

CORE LF3

DEPTH	DRYMASS	CHRONOLOGY			SEDIMENTATION RATE		
		DATE	AGE	STD			% STD
CM	G/CM**2	AD	YR	ERROR	G/CM**2YR	CM/YR	ERROR
0.50	0.0226	1985	0	2	0.114	1.47	5.1
1.50	0.1083	1984	1	2	0.124	1.43	5.1
3.50	0.3026	1982	3	2	0.144	1.39	5.5
5.50	0.5221	1981	4	2	0.168	1.53	6.4
7.50	0.7440	1980	5	2	0.194	1.78	6.6
9.50	0.9653	1979	6	2	0.221	2.03	7.1
11.50	1.1786	1978	7	2	0.286	2.65	7.9
13.50	1.3913	1977	8	2	0.352	3.27	8.7
15.50	1.6058	1977	8	2	0.423	3.97	9.3
17.50	1.8220	1976	9	2	0.500	4.75	9.8
19.50	2.0382	1976	9	2	0.577	5.53	10.3
21.50	2.2429	1976	9	2	0.647	6.22	11.0
25.50	2.6524	1975	10	2	0.796	7.59	12.4
33.50	3.4786	1974	11	2	0.888	8.38	13.4
41.50	4.3310	1973	12	2	0.893	8.00	14.4
49.50	5.2402	1972	13	2	1.141	9.92	20.9
57.50	6.1495	1971	14	2	1.389	11.84	27.4
65.50	7.0992	1971	14	2	1.417	11.98	27.1
73.50	8.0623	1970	15	2	1.371	11.51	24.5
81.50	9.0255	1969	16	2	1.326	11.05	21.8
89.50	9.9886	1968	17	2	1.225	10.08	19.2
97.50	10.9713	1967	18	2	0.712	5.40	12.7
99.50	11.2170	1967	18	2	0.621	4.45	11.1
101.50	11.5268	1967	18	2	0.733	4.88	10.9

Table 2 / cont'd

103.50	11.8367	1967	18	2	0.895	5.67	10.7
105.50	12.1465	1966	19	2	1.058	6.45	10.6
107.50	12.4564	1966	19	2	1.221	7.23	10.4
109.50	12.7662	1966	19	2	1.328	7.71	10.2
111.50	13.1472	1965	20	2	1.214	6.99	12.3
115.50	13.9093	1965	20	2	0.874	4.94	16.3
119.50	14.6713	1964	21	2	0.585	3.20	20.4
123.50	15.3535	1963	22	2	0.711	3.91	29.2
127.50	16.1031	1962	23	2	0.607	3.31	22.5
129.50	16.4779	1961	24	2	0.555	3.01	19.1
133.50	17.2150	1955	30	3	0.113	0.62	15.6
137.50	17.9479	1949	36	3	0.113	0.62	13.3
141.50	18.6937	1942	43	3	0.113	0.62	19.9
145.50	19.4667	1937	48	4	0.215	1.08	32.1
151.50	20.7044	1932	53	4	0.336	1.70	38.1
153.50	21.0997	1930	55	4	0.331	1.68	37.2
157.50	21.8570	1927	58	4	0.231	1.20	29.7
161.50	22.6052	1924	61	4	0.296	1.60	24.5
165.50	23.3363	1922	63	4	0.527	2.83	22.9
169.50	24.0775	1921	64	4	0.428	2.22	17.7
173.50	24.8879	1913	72	5	0.086	0.40	25.0
177.50	25.7411	1903	82	6	0.086	0.40	25.0
181.50	26.6144	1893	92		0.086	0.40	
185.50	27.4820	1883	102		0.086	0.40	
189.50	28.3132	1873	112		0.086	0.40	
193.50	29.1335	1863	122		0.086	0.40	
197.50	29.9986	1853	132		0.086	0.40	
201.50	30.8803	1843	142		0.086	0.40	

fairly uniform value of about 1-2 pCig-1 right up to a depth of 19.5 cm, and it is clear that most of this sediment is derived from the 1961 ploughing. The unsupported 210Pb concentration indicates a mean sedimentation rate for the lake during this period of about 0.40 g cm-2 yr-1, i.e., a ten-fold increase over the current value. The enhanced values at LF3 may again be related to sediment focussing. Calculations indicate acumulation rates at L3 up to 1.4 g cm-2 yr-1 in the period 1961-72, followed by a steady decline until current values are reached in the late 1970's. The reduction in accumulation rate is acompanied by an increase in the 137Cs concentration (Fig. 10). This increase is very pronounced above 14.5 cm, which has been dated to 1977.

Sediments immediately below 108 cm are characterised by high 226Ra concentrations, but have the same low unsupported 210Pb concentrations as sediments above this level. Sediment at 119.5 cm is dated by the CRS model to 1958 but it may well be that this entire section of the core, down to 130.5 cm, is inorganic inwash from the 1961 ploughing. The very low unsupported 210Pb concentration of 0.45 pCig-1 at 109.5 cm indicates that some of this material may have come in at very high accumulation rates of 1-2 g cm-2yr. The unsupported 210Pb peak of 5.7 pCig-1 at 139.5 cm indicates that this material is pre-inwash, and this is supported by the relatively low accumulation rates calculated for this level. Both the CRS model and CIC model (which should be applicable to this point) date 139.5 cm to the early 1940's. By extrapolation upwards 1960 should then be assigned to just below 130 cm. Below 139.5 cm the chronology indicates a disturbance with accelerated accumulation rates during the period 1920-30, spanning the depths 150-170 cm. A feature of this part of the core is a layer of sediment at 163.5 cm with an unusually high 226Ra concentration of 11.4 pCig-1, and an associated high 238U concentration. This material has no unsupported 210 Pb. Below 170 cm, dated by both the CRS and CIC models to ca. 1920, accumulation rates appear to be typical of present day values. A best estimate based on both the CRS and CIC models is 0.086 g cm-2 yr-1. At this accumulation rate 1850 would correspond to 200 cm, and 1800 would correspond to 220 cm. Further extrapolation would be unwarranted since other pollen evidence (see 4 below) shows that a major hiatus occurs in this region of the core.

3.3 Chronology for LF L1

It is immediately apparent that the 210Pb record for LF1 is incomplete. In this core the transition to highly organic material occurs at 34.5 cm. (Unlike L3 there is not however a sudden reduction to very low 226Ra values). Above this horizon L1 contains 25.5 pCi cm-2 of unsupported 210Pb, compared with 34.1 pCi cm-2 in L3. Below this level there are only 3.7 pCi cm-2 of unsupported 210Pb in L1, compared with 29.6 pCi cm-2 in L3. The 137Cs profile for L1 (Fig. 9) indicates measurable 137Cs concentrations down to 29.5 cm, with a further trace at 50.5 cm. The sediment at 50.5 cm is unusual, in the context of L1, in that it has a low 226Ra concentration relative to adjacent samples, and an abnormally low 238U concentration. At the same time this layer also has a high bulk density and low organic content. It is also the lowest point of the core at which there is definite evidence of unsupported 210Pb. It would thus appear reasonable to conclude that L1 contains no recent (i.e. post 1800) sediment prior to the mid 1950's, and that the bulk of the sediment down to at least 50 cm is associated with the 1961-63 ploughing and afforestation. The unsupported 210Pb concentration between 29.5 cm and 50.5 cm has a mean value of 1.3 pCig -1, and indicates sediment accumulation rates in the range 0.5-1.0 g cm-2 yr-1, so that the bulk of this material would date from the early 1960's. A reduction to moderate sediment accumulation rates is indicated by the sudden rise in 137Cs concentrations above 10 cm, and is dated to the early 1970's. A feature of the very recent sediments is the layer at 5.25 cm characterised by an abnormally high 226Ra concentration of 11.2 pCi g-1. The associated high unsupported 210Pb concentration and 137Cs concentration places this material above the inwash zone.

3.4 Chronology for LFV

The data for the earlier core LFV, though sparse, indicates a similar pattern to that seen in L1. The core contains 16.0 pCi cm-2 (or 18.7 pCi g-1 if account is taken for radio-active decay since collection) of unsupported 210Pb above the organic inwash horizon, and only 2.3 pCi cm-2 below this horizon. There is no clear evidence of unsupported 210Pb below 30 cm, and the variations in total 210Pb concentration beneath this level now appear to be largely due to 226Ra concentrations. Consequently the core lacks sediment of many decades prior to 1961-3 and is of little value in the context of the present study.

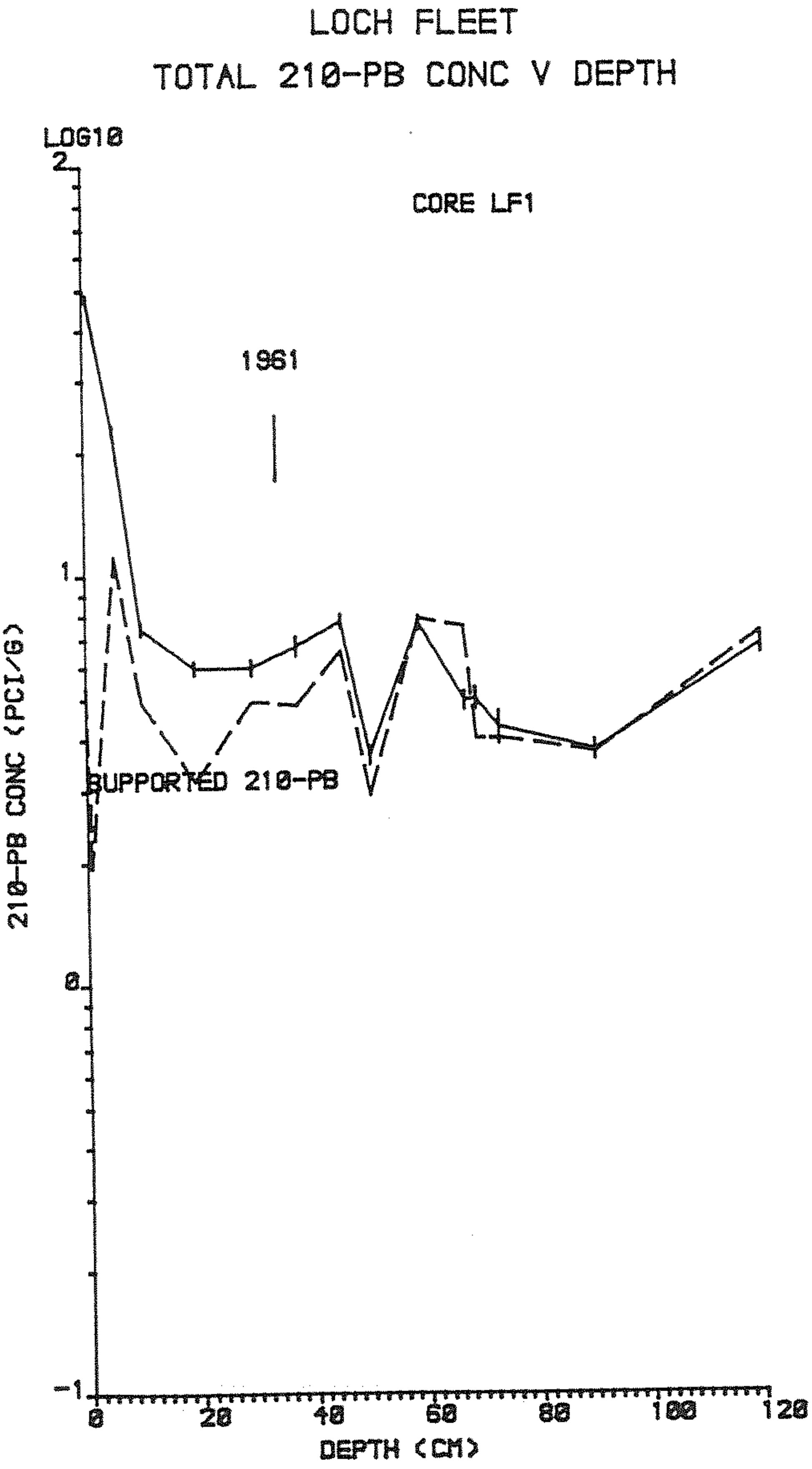


Fig. 4 Total 210-Pb for LF L1.

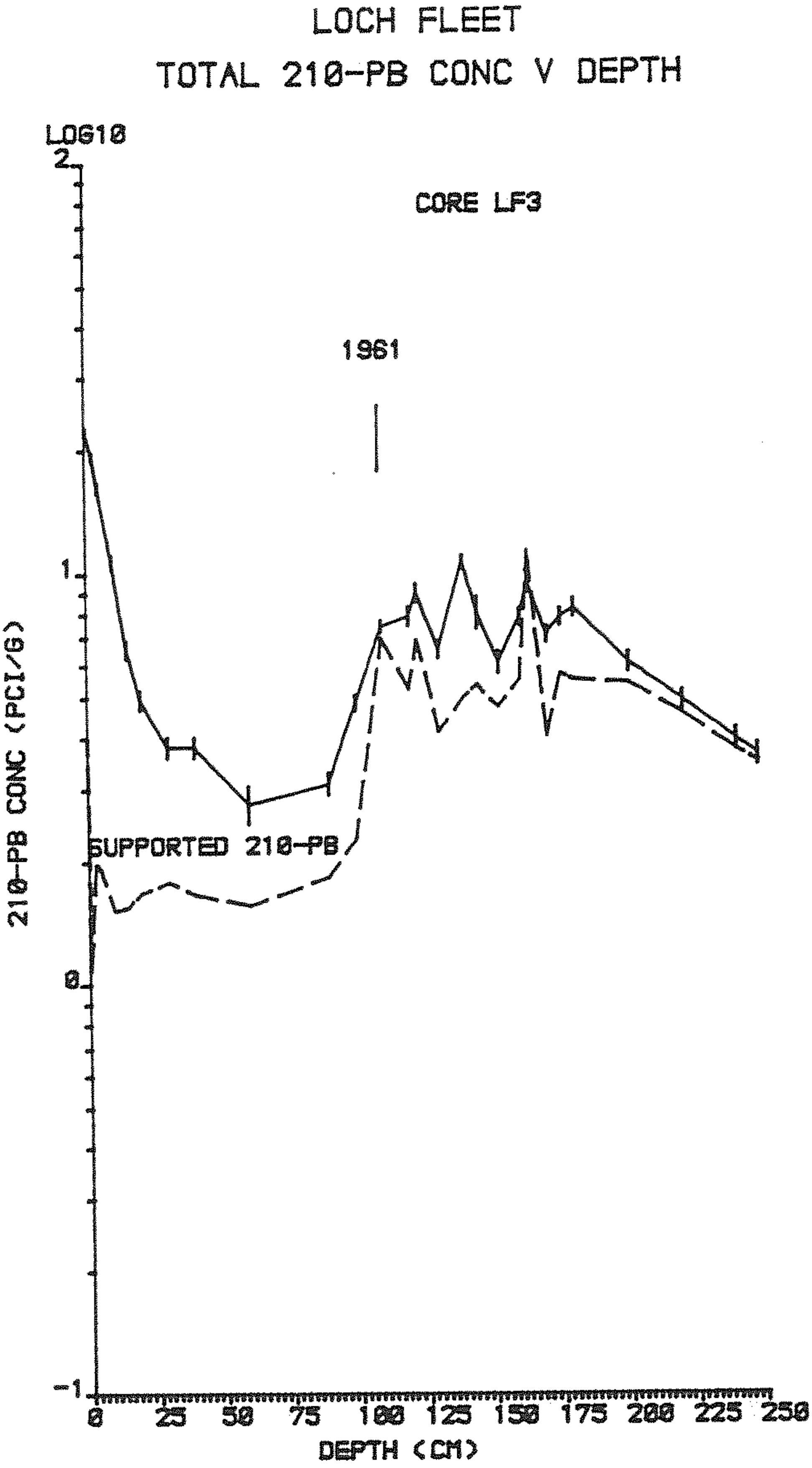


Fig. 5 Total 210-Pb for LF L3.

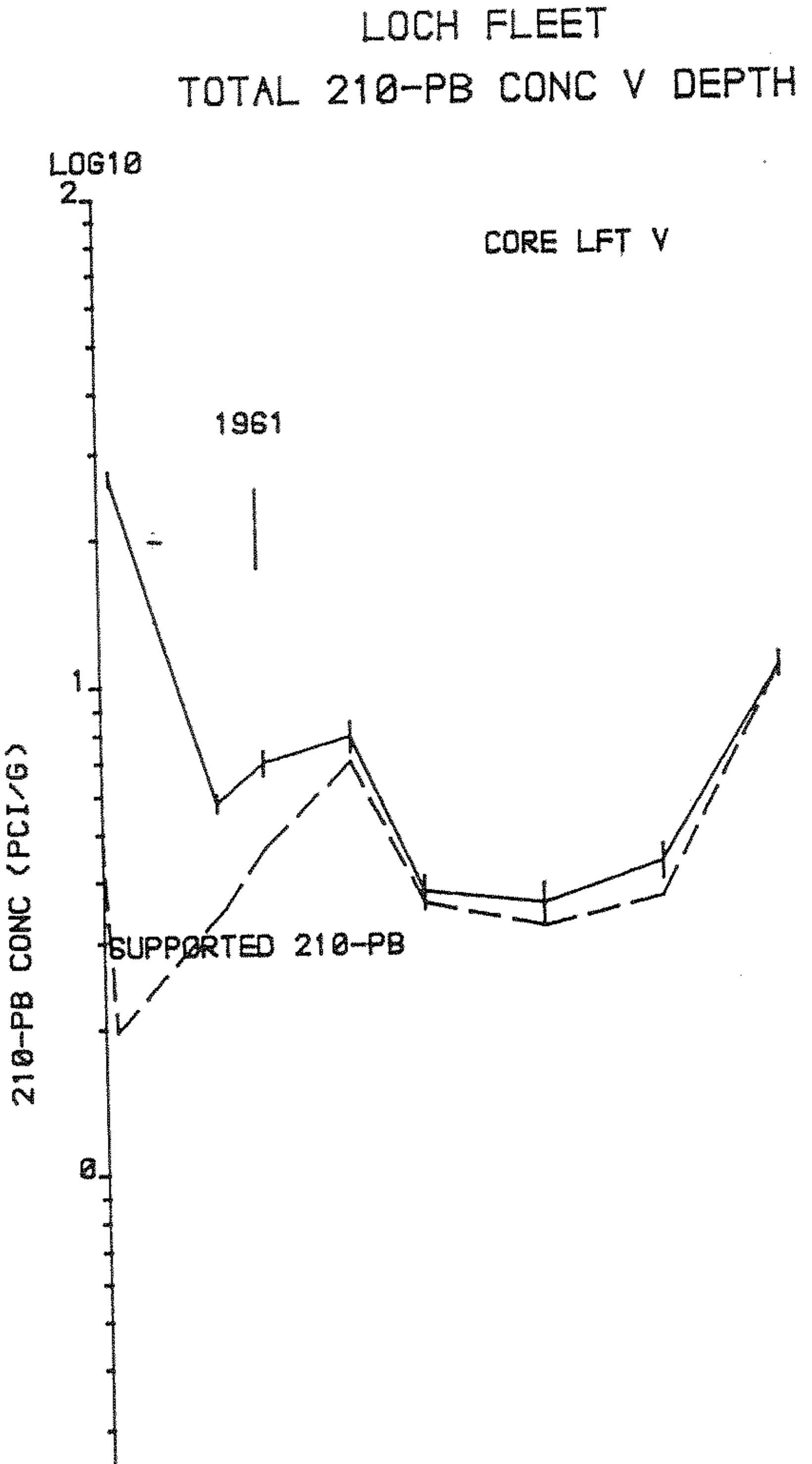


Fig. 6 Total 210-Pb for LFV.

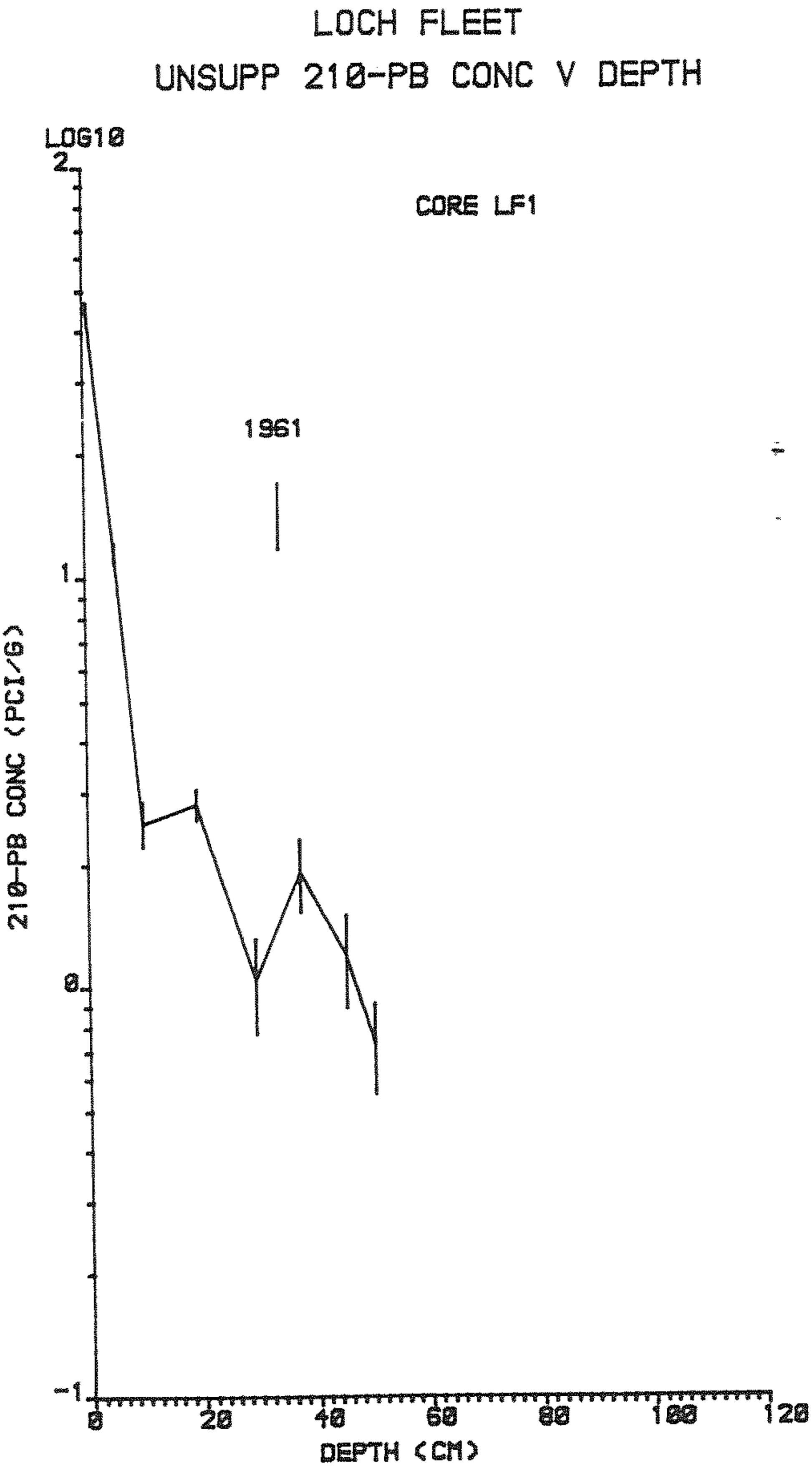


Fig. 7 Unsupported 210-Pb for LF L1.

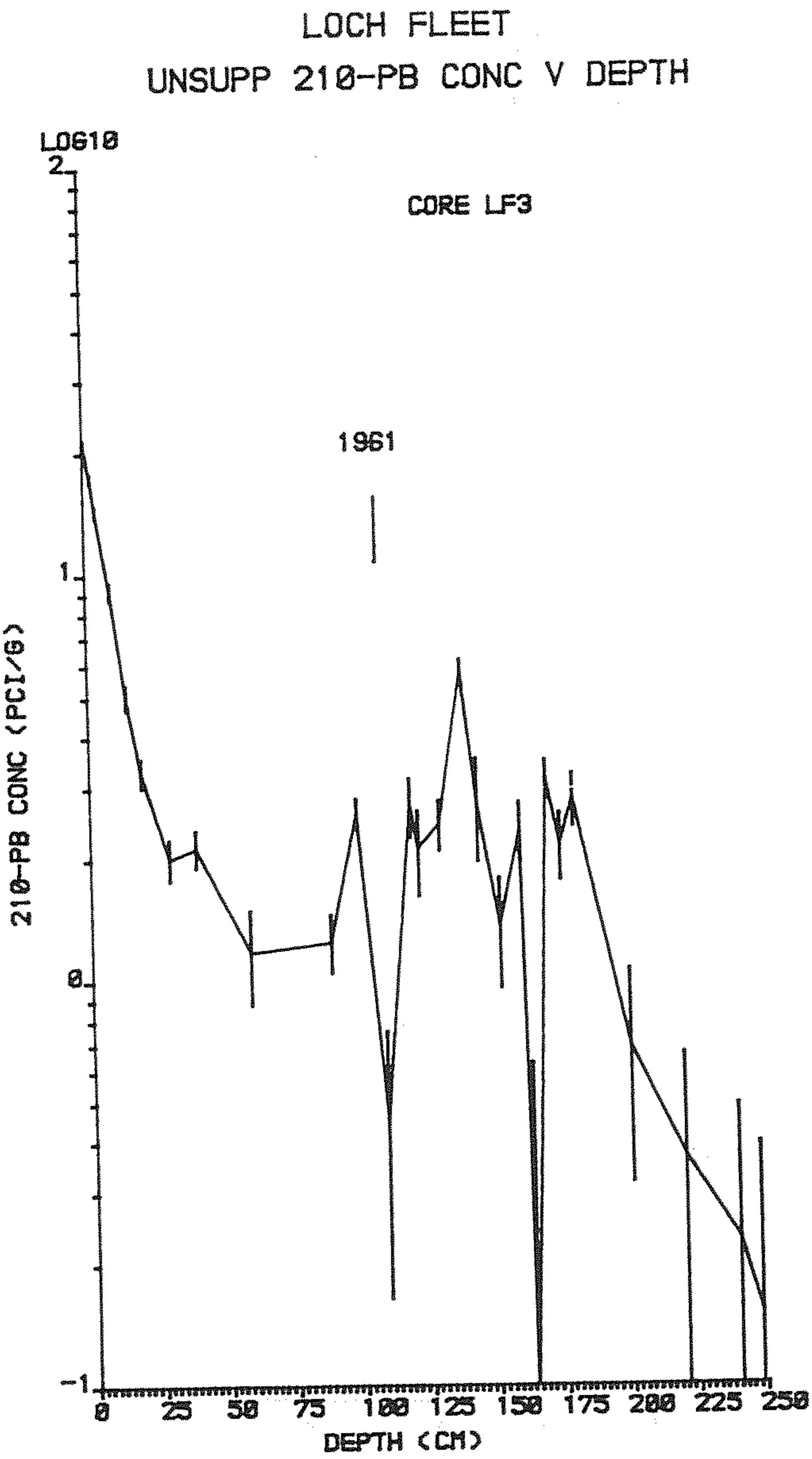


Fig. 8 Unsupported 210-Pb for LF L3.

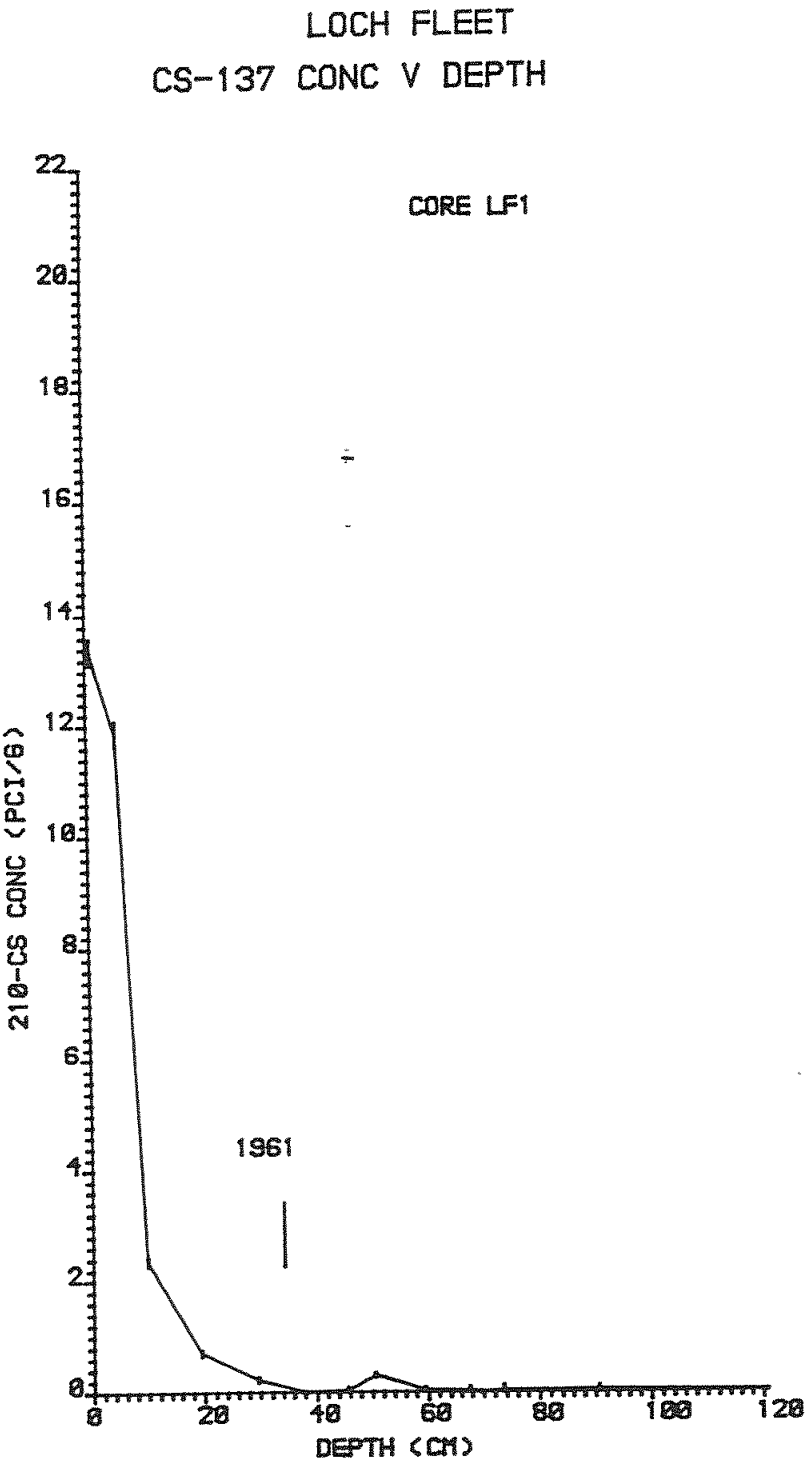


Fig. 9 137-Cs distribution for LF L1.

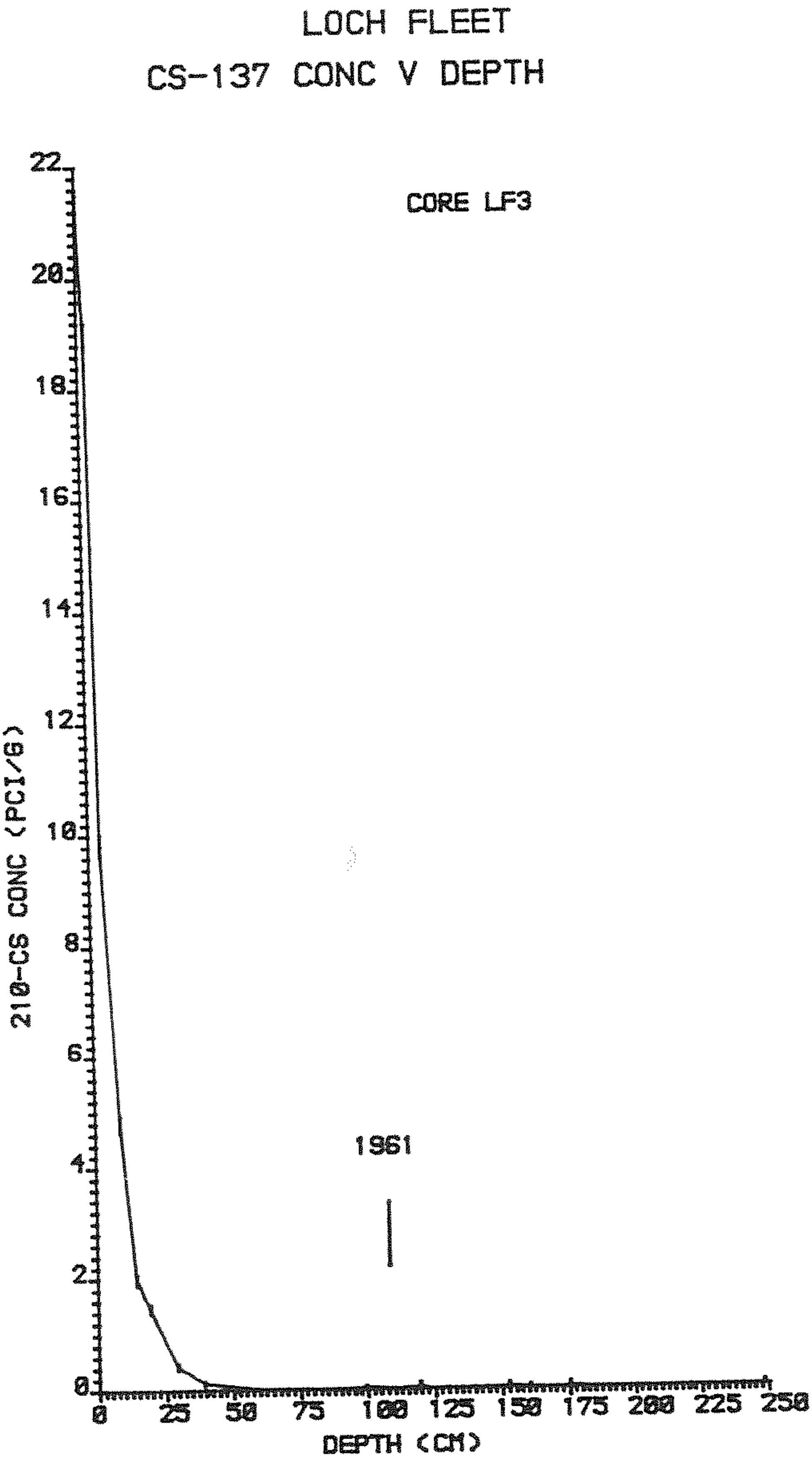


Fig. 10 137-Cs distribution for LF L3.

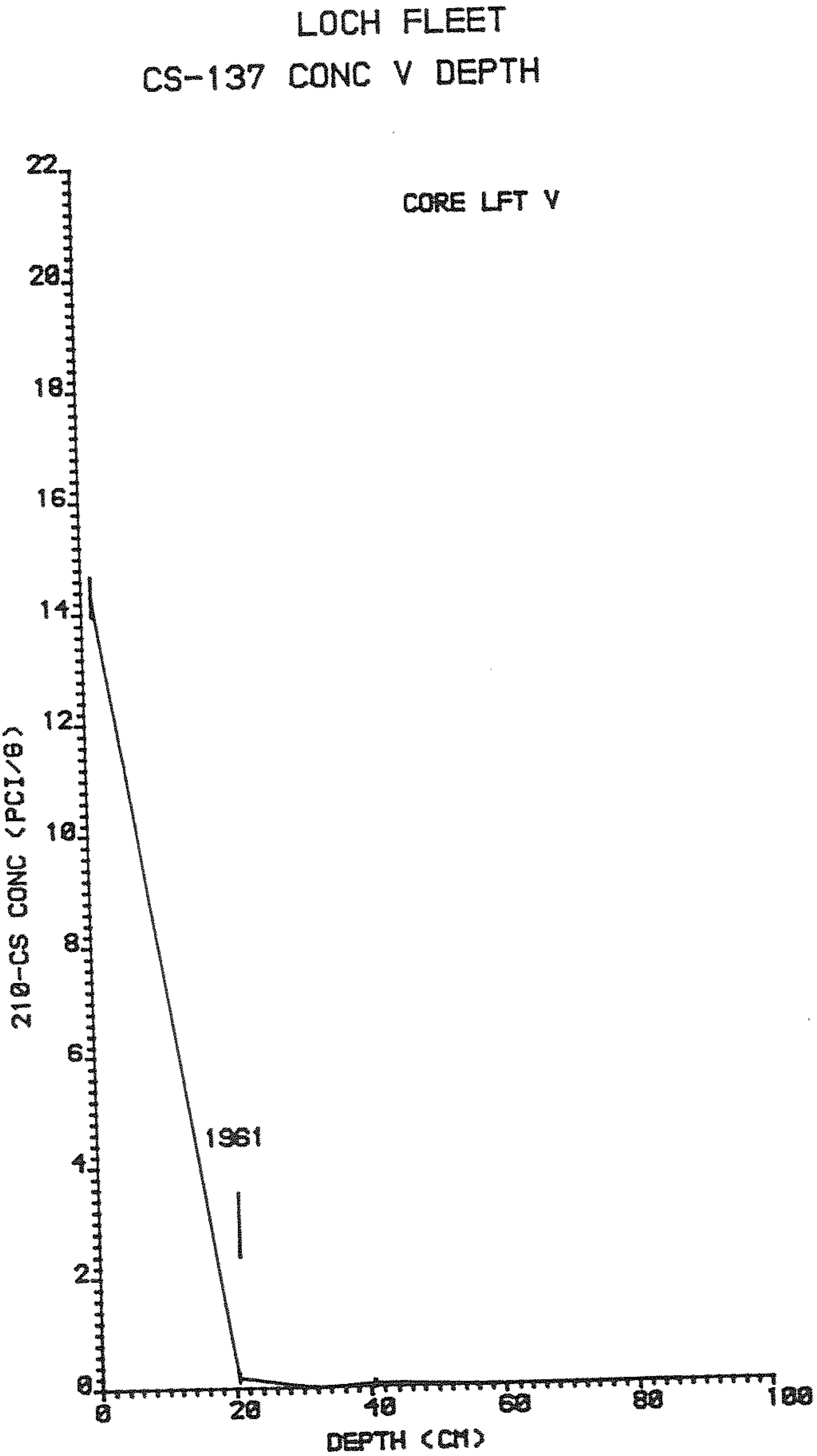


Fig. 11 137-Cs distribution for LFV.

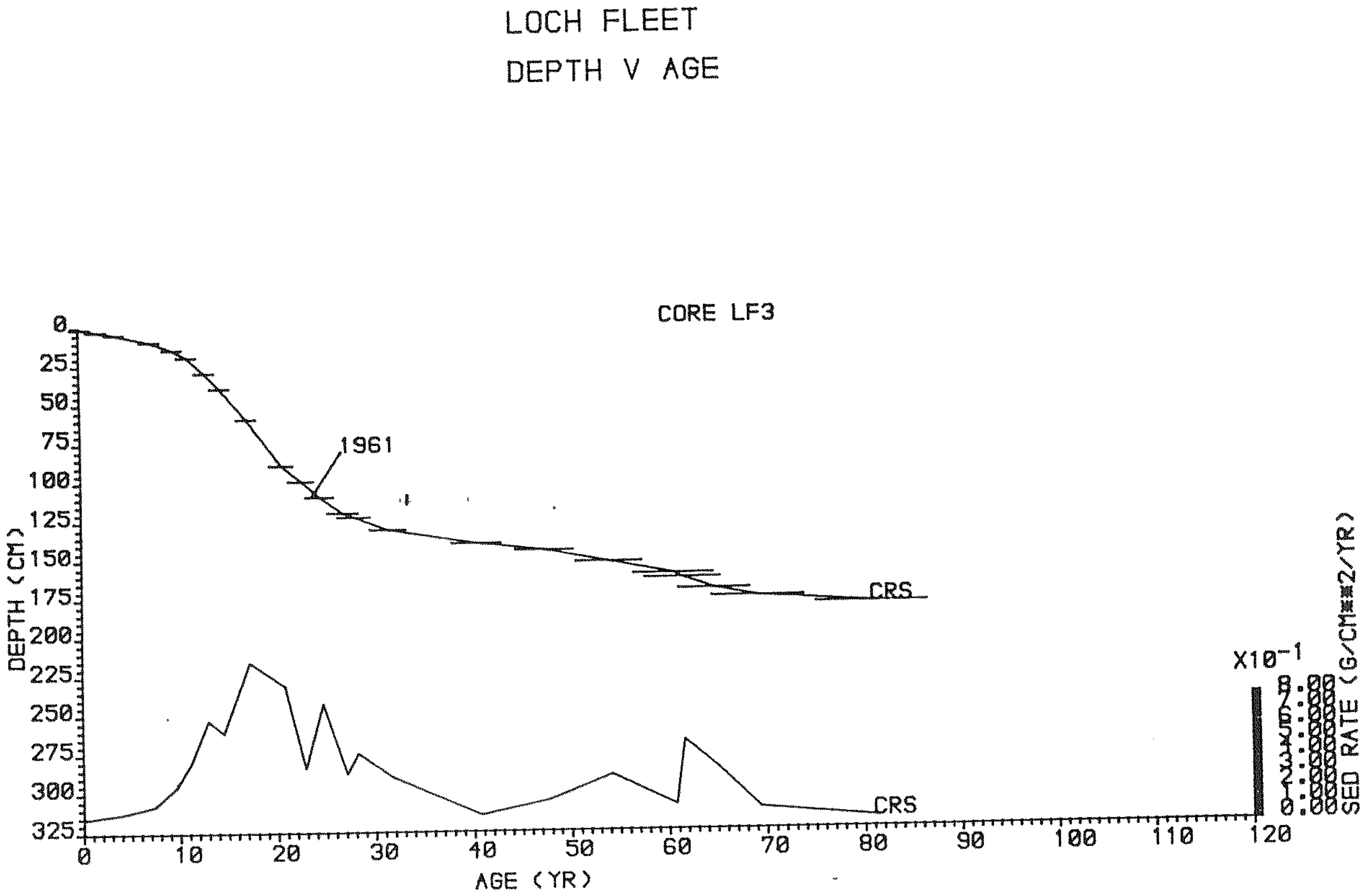


Fig. 12   Depth v. Age and dry mass accumulation rate for LF L3.

4. POLLEN ANALYSIS

Pollen analysis of cores L1 and L3 was carried out primarily as a chronological and stratigraphic aid, and, in association with the lithostratigraphy and 210Pb measurements, as a means of assessing the presence and extent of stratigraphic hiatuses. Full diagrams for both cores are included in Appendix A; Figs. 13 and 14 show summary diagrams for L3 and L1 respectively.

4.1 Core LF L3

For L3 five zones were defined according to standard statistical procedures (Birks 1986):

4.1.1 L3-1 Pinus/Corylus PAZ; 308-292 cm

The initial levels of the zone reflect an early postglacial habitat with arboreal values still rising as forest trees reinvade the area. The high values of pine and already high values of Coryloid pollen suggest a 8-9000 BP date. Remaining open habitats disappear as values of grass (Gramineae) pollen decline and full forest cover is achieved in the region. A change from a forest dominated by pine (*Pinus*) and hazel (*Corylus*) occurs as oak (*Quercus*) and elm (*Ulmus*) pollen values rise representing the immigration of mixed deciduous woodland into the area. At the very end of the zone the first indication of alder (*Alnus*) appears. In the nearby site of Round Loch of Glenhead the rational limit of this alder rise is dated to approximately 8500 BP (Jones *et al.* 1986). High values of *Isoetes* spores occur throughout the diagram indicating an extensive development of this aquatic macrophyte within the lake.

4.1.2 L3-2 Quercus/Alnus PAZ; 292-216 cm

Alder and oak values reach their highest levels in this zone as in most other pollen diagrams for this time period in north-west Europe. Pine becomes less important and pollen values decline to extremely low levels. This early and relatively brief pine phase is a characteristic feature of other diagrams from south-west Scotland (cf. Birks 1972, 1975,1984, Jones *et al.* 1986).

The first signs of anthropogenic disturbance are recorded above 256 cm as values of elm pollen decline and peaks occur in the major disturbance indicators *Plantago lanceolata*, Gramineae, *Anthemis* type and *Pteridium*.

4.1.3 L3-3 Calluna/Gramineae PAZ; 216-112 cm

Large increases in heather (*Calluna*) pollen and bog moss (*Sphagnum*) spores indicate the conversion of the acid oak forest to domination by blanket peat vegetation. Such changes are recorded for many sites in other areas of upland Britain dating from approximately 5000 BP onwards. However, at this site the presence of unsupported 210Pb at this level in the sediment (see above) indicates that these pollen spectra are of nineteenth century provenance and that a major hiatus occurs below 216 cm. Depressions in the *Isoetes* curve occur in this zone coincidentally with peaks in *Calluna*, *Sphagnum*, LOI values, and SIRM (see below) suggesting the inwash of peat as a result of catchment disturbances.

4.1.4 L3-4 Calluna PAZ: 110-22 cm, and L3-5 Pinus PAZ: 22-0 cm

Much of the sediment in these zones consists of peat eroded from the catchment following the 1963 pre-afforestation ploughing. Consequently the pollen content of the sediment consists of old reworked material as well as contemporary material from local vegetation. The impact of the peat erosion is demonstrated by the extremely low *Isoetes* values in the zone at levels where *Calluna* and Cyperaceae are high. This could be due to a dilution of *Isoetes* in the pollen count and to a temporary reduction in spore production related to an increase in turbidity in the water column. Despite these disturbances the recent afforestation of the Galloway region is indicated from about 60 cm upwards by the increasing pine values and by the occasional occurrence of spruce pollen, a species that dominates the catchment but produces only small quantities of pollen compared to pine.

4.2 Core LF L1

The pollen diagram for L1 (Fig. 14) was divided into only two zones. The lower zone is very similar to the bottom two zones of L3 (L3-1 and L3-2) and includes an expected conformable sequence of postglacial forest changes. A major hiatus occurs at 60 cm and is overlain by very recent reworked peat equivalent to zones L3-4 and L3-5.

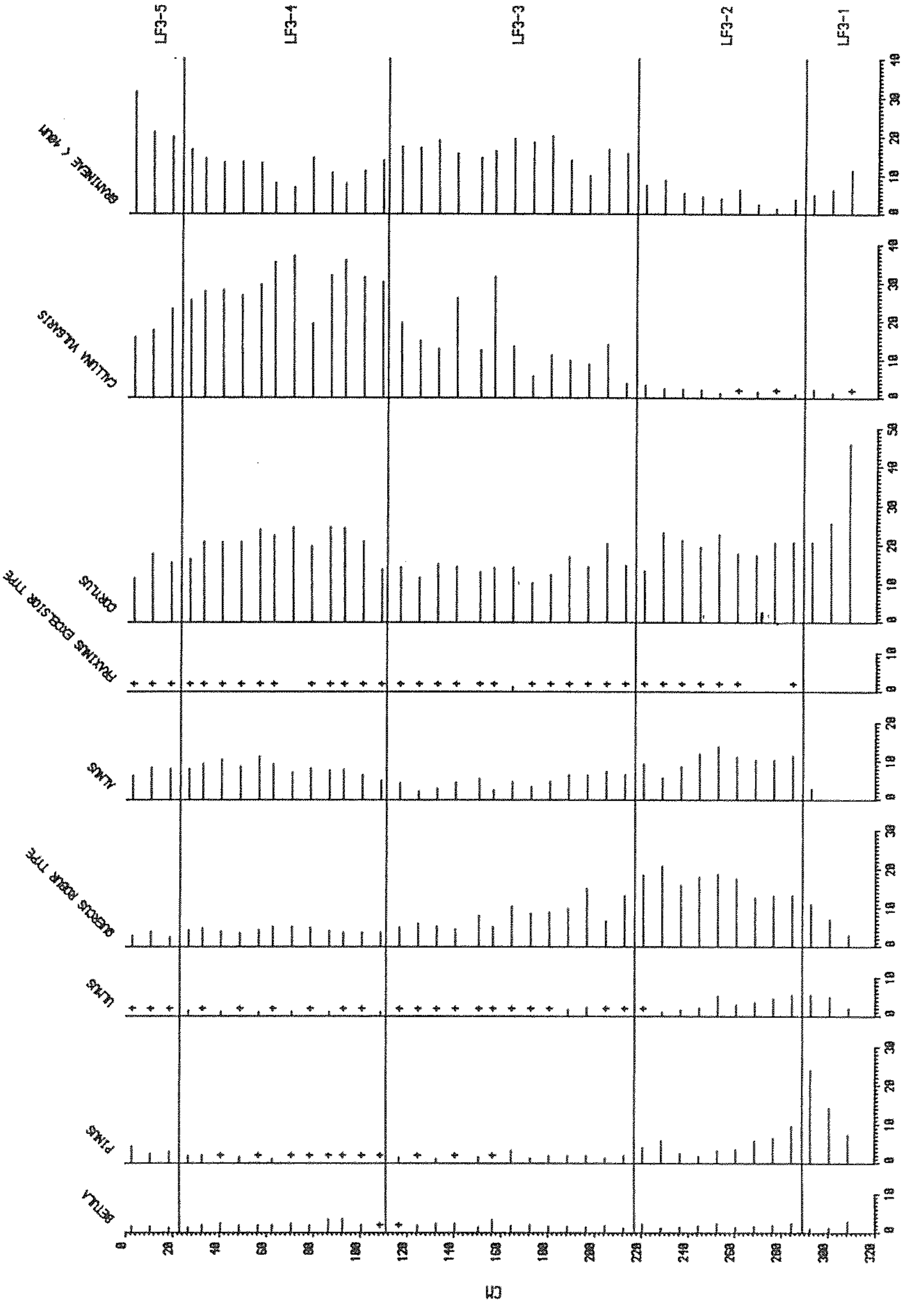


Fig. 13 Summary pollen diagram LF L3.

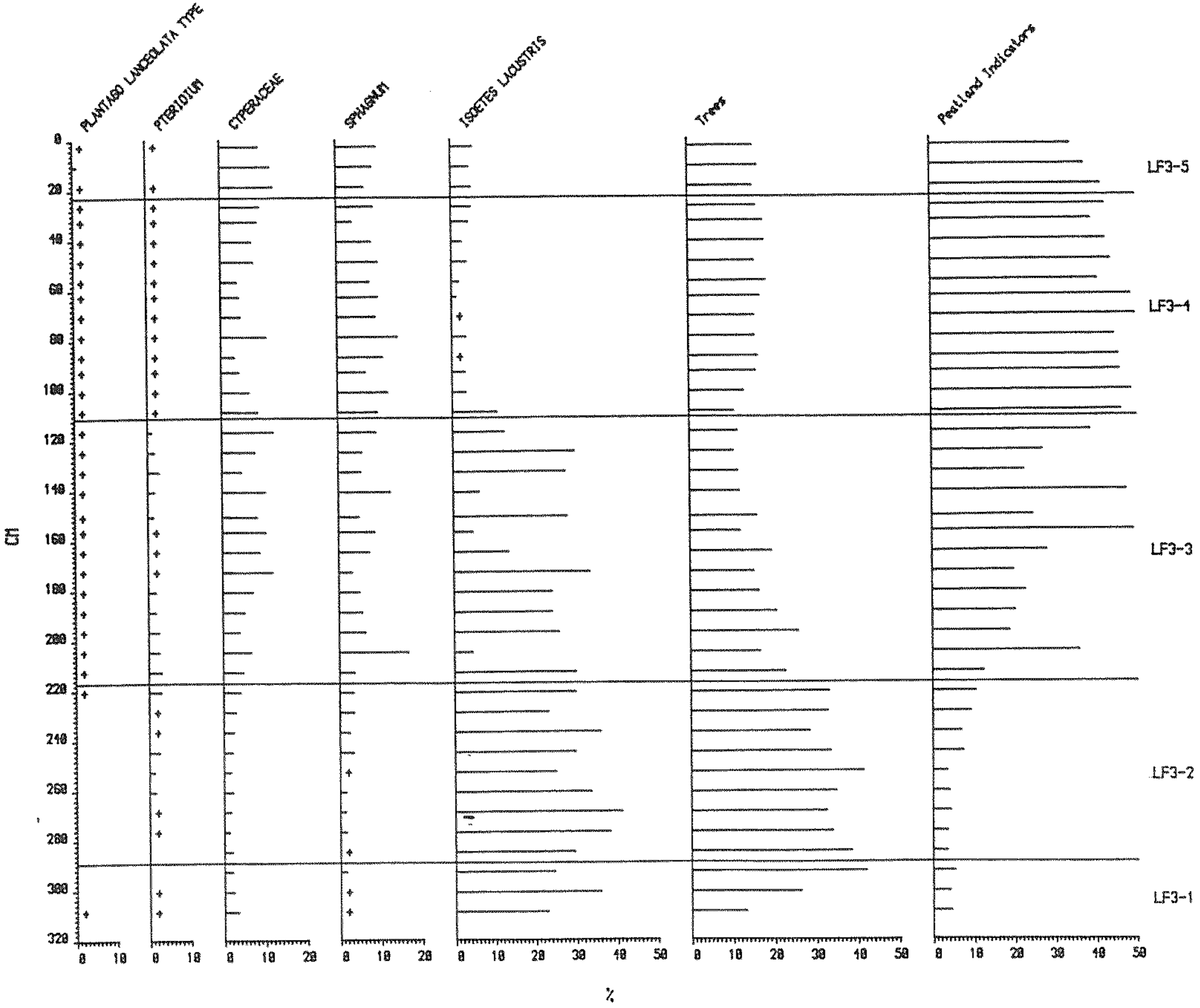

PLANTAGO LANCEOLATA TYPE
PTERIDIUM
CYPERACEAE
SPHAGNUM
ISOETES LACUSTRIS
Trees
Peatland Indicators
LF3-5
LF3-4
LF3-3
LF3-2
LF3-1
CM
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
0
10
20
30
40
50
%

Fig. 13 (cont'd)

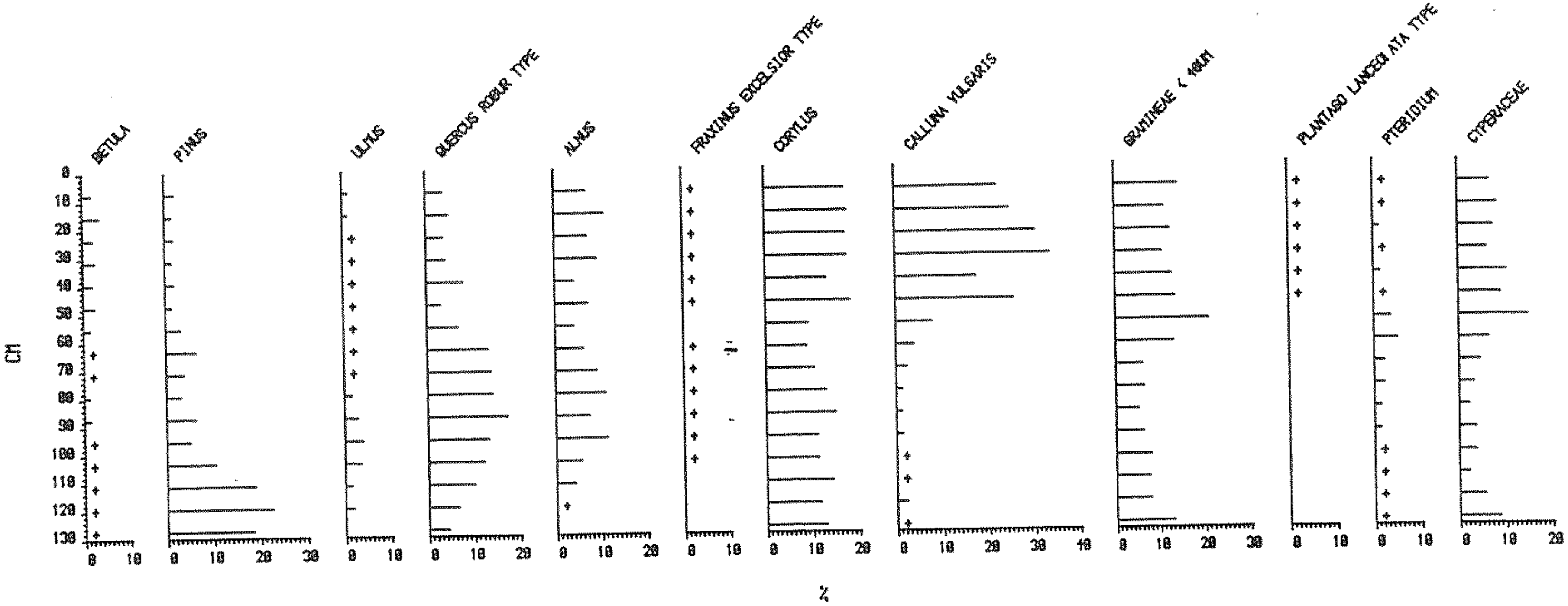


Fig. 14 Summary pollen diagram LF L1.

5. MINERAL MAGNETIC DATA.

5.1 Core LF L3

Figure 15 shows the results of a range of magnetic measurements on subsamples from Core L3. They help to characterize the nature of the sediment and to establish its source (cf. Oldfield, 1983) The diagram can be divided into 6 zones.

5.1.1 Zone A. Base to 264 cm

Samples from the deepest sections are characterized by very low susceptibility (x), isothermal remanence (SIRM) and anhysteretic remanence (ARM). SIRM/ARM is rather high and irregular; ARM/x and SIRM/x are lower. The reverse field ratios ('S') are initially 'hard'. From the base upwards, the high reverse field ratios especially tend to 'soften' dramatically. The values indicate low ferrimagnetic concentrations throughout. The basal samples, which also have very low loss-on-ignition and high bulk density, are rich in haematite - a primary component of the granite bedrocks. the low remanence/susceptibility quotients probably indicate relatively high paramagnetic iron concentrations whether as a result of the precipitation of Fe from solution or the detrital input of iron-rich primary materials cannot be determined.

5.1.2 Zone B. 264 cm to 230 cm

Within this zone, SIRM and ARM increase as do the remanence/susceptibility quotients. SIRM/ARM declines and the reverse field ratios remain soft though variable especially in the low reverse fields. Low though not minimal concentrations of ferrimagnetic grains are indicated as well as a decline in the relative importance of haematite. The low-backfield ratios and relatively low SIRM/ARM suggest the presence of fine grained secondary oxides in low concentrations.

5.1.3 Zone C. 230 cm to 150 cm

SIRM, ARM and x rise irregularly throughout this zone. Remanence/susceptibility quotients are rather low and SIRM/ARM also remains low. Reverse-field ratios are relatively low with a tendency for IRM 100mT/SIRM to decline irregularly through the zone. Rising ferrimagnetic concentrations are indicated; these are interpreted as including (and probably dominated by) the type of fine grained secondary 'magnetite-type' oxides formed in surface soil by fire and pedogenesis. There are distinctive 'spikes' of magnetic inwash. Below 180 cm they are associated with low SIRM/ARM and very 'soft' reverse-field values especially in the higher fields. These are most easily explicable as episodes of inwashed magnetically enhanced soil and they are probably related to episodes of burning in the catchment.

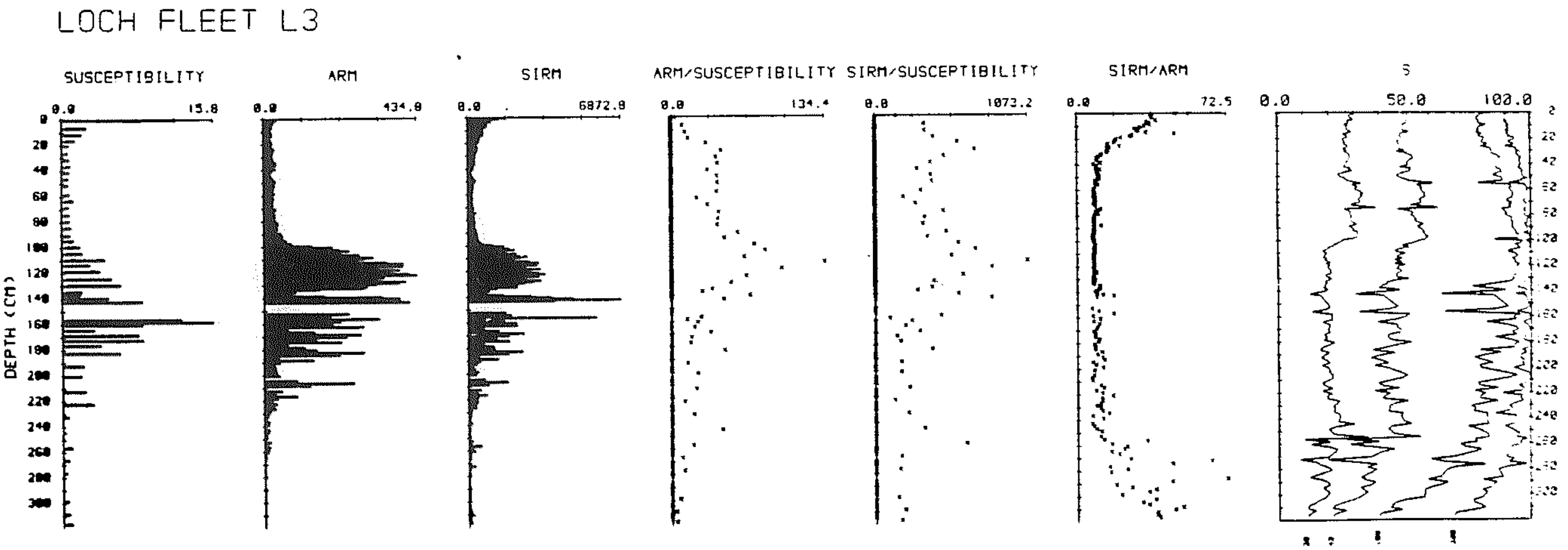


Fig. 15 Magnetic measurements from Loch Fleet Core LF L3.
Susceptibility values are $10^{-6}Gcm^3 \ Oe^{-1} \ g^{-1}$.
Remanence values are $10^{-6}Gcm^3g^{-1}$. 'S' ratios plot
IRM$_{-20mT}$/SIRM, IRM$_{-40mT}$/SIRM, IRM$_{-100mT}$SIRM and IRM$_{-300mT}$/SIRM measurements:-
100 = full reverse saturation; 50 = zero remanence.

Above 180 cm and up to the rather arbitrary zone boundary at the break between cores, peak magnetic concentrations often coincide with harder remanences and the inwash of subsoil or unweathered parent material into the lake may be inferred.

5.1.4 Zone D. 150 cm to 100 cm

This zone is marked by variable but mainly high SIRM and ARM values, but declining χ. Remanence/susceptibility quotients thus peak in this zone especially around 120 cm. The zone may be subdivided into a basal 'spike' of maximum remanence (especially SIRM) and susceptibility values (i), a narrow subzone of significantly reduced magnetic concentrations (ii) and a final subzone of higher concentrations (iii). The basal 'spike' has very hard remanence and high heamatite concentrations are indicated. These may be derived from unweathered parent material or from secondary iron-enriched subsoil (B' horizon) material rich in anti-ferrimagnetic minerals. The high SIRM/χ value suggests the former. By contrast the measurements for sub-zone (iii) are typical of fine grained secondary surface-soil derived magnetite.

Throughout Zones C and D the magnetic record indicates a highly unstable sedimentation regime with pulses of catchment derived material reaching the coring site from quite different source types including both enhanced and probably burnt surface soil and either unweathered parent material or subsoil.

5.1.5 Zone E. 100 cm to 35 cm

The sharp fall to low χ, SIRM and ARM values coincides with a change to very soft reverse field ratios. Coinciding as they do with a sharp increase in loss-on-ignition and a steep decline in 226Ra values, these changes denote the dominance of sedimentation by inwashed peats and/or the organic surface layers of podsolised and gleyed soils.

5.1.6 Zone F. 35 cm to surface

The increasing χ, SIRM and SIRM/ARM values are all characteristics typical of the postwar spherule dominated atmospheric deposition found in ombrotrophic peat sites.

5.2 Inferences

The magnetic record is compatible with an interpretation designating zones A & B as being respectively late-glacial and early post-glacial in age, Zones C & D as dating largely from a period of 19th and 20th century pre-afforestation catchment use which involved recurrent burning and quite rapid but irregular erosional loss, and zones E and F as reflecting the initially rapid then declining sedimentation resulting from ploughing and planting post-1960. Only in the final zone is the sedimentation rate and concomitant flux of catchment derived magnetic minerals low enough to allow recognition of a putative atmospheric component in the magnetic mineral assemblage within the sediments. Magnetic measurements from Cores L1 and L2 and several of the minicores indicate broad parallels. In every case there is evidence of a major hiatus below the recent sediments, a period of peat inwash post-afforestation and atmospheric deposition only in the most recent layers. Detailed correlations are not practical at present.

By combining the loss-on-ignition, magnetic and 226 Ra profiles, all of which provide clear evidence on sediment source type, it is clear that there are for at least parts of the period of 19th and 20th century sedimentation facies changes between sites within the lake at any given time. Thus, for example, the highly organic post-ploughing inwash in Core L3 is low in both magnetic and radium concentrations whereas in Core L1, magnetic and radium concentrations are high in similarly organic recent sediments. In the former case, pre-industrial peat is believed to be the main sediment source and in the latter, true soils with a rather higher inorganic mineral contentare thought to contribute to the sediments. To what extent this reflects differences in the parts of the catchment contributing sediment to different areas of the lake beds (cf. Dearing 1979) or selective sub-aqueous, post-depositional sediment transport associated with the strong focusing demonstrated at the site cannot be established from these data alone.

6. CHRONOSTRATIGRAPHY

In the absence of 14C dates it is difficult to put specific dates on the hiatuses in L1 and L3. However, the pollen and 210Pb data do allow general limits to be established and, if taken together with the magnetics, loi and diatom evidence the hiatus in L3 can be identified. In the case of L3 the pollen data show the presence of a conformable early post-glacial sequence from 9-8000 BP to some period after the elm decline (approx 5000 BP) at around 250 cm. The 210Pb data shows that samples above 180 cm must post-date 1800. Although there is evidence of unsupported 210Pb below 180 cm the concentrations are within the standard errors of the measurement. However, the pollen data suggests that catchment disturbance goes back to 208 cm with peaks recorded in *Sphagnum*, *Calluna* and Gramineae and a depression in the *Isoetes* values (Fig. 13). These features occur at the same time as loi and magnetic peaks (Figs 16 and 17) and the peak in *Cyclotella comensis* in the diatom diagram (Fig. 27). These peaks suggest that a brief period of peat erosion occurred, perhaps caused by catchment burning, at this time. Since other evidence from the Galloway region shows that significant peat erosion did not begin until recent centuries it can be postulated that the sediment from 208 to 180 cm post-dates the hiatus. Conversely it can be argued that the sediment below 216 cm must pre-date the main hiatus since the pollen spectra at this level and below are not characteristic of moorland but relate to the pre-moorland vegetation that occurred in this region more than 5000 years ago. Overall it is concluded that the hiatus in this core occurs somewhere between 216 and 208 cm and represents a gap in accumulation from about 5000 BP to about 1800 AD. 14C dating would be useful to test this deduction.

The L1 core is much shorter than L3 and appears to have a similar hiatus. The early pollen record from 1.30 to 60 cm is almost identical to L3 indicating the presence of a conformable sequence of early post-glacial sediments. The 210Pb data show that the upper 60 cm post-date 1800, and the pollen, magnetic, loi, and diatom evidence (cf. the *Cyclotella comensis* peak at 60 cm in Fig. 17) all correlate in a similar way to L3 and suggest that the hiatus must lie between 60 and 68 cm and cover approximately the same period of time. Again 14C dating would help to refine these estimates.

From these data we can conclude that a complete post-glacial sequence is unlikely to be found in the loch.

Using all chronostratigraphic information it is possible to reconstruct a cross sectional stratigraphy for Loch Fleet as shown in Fig 18.

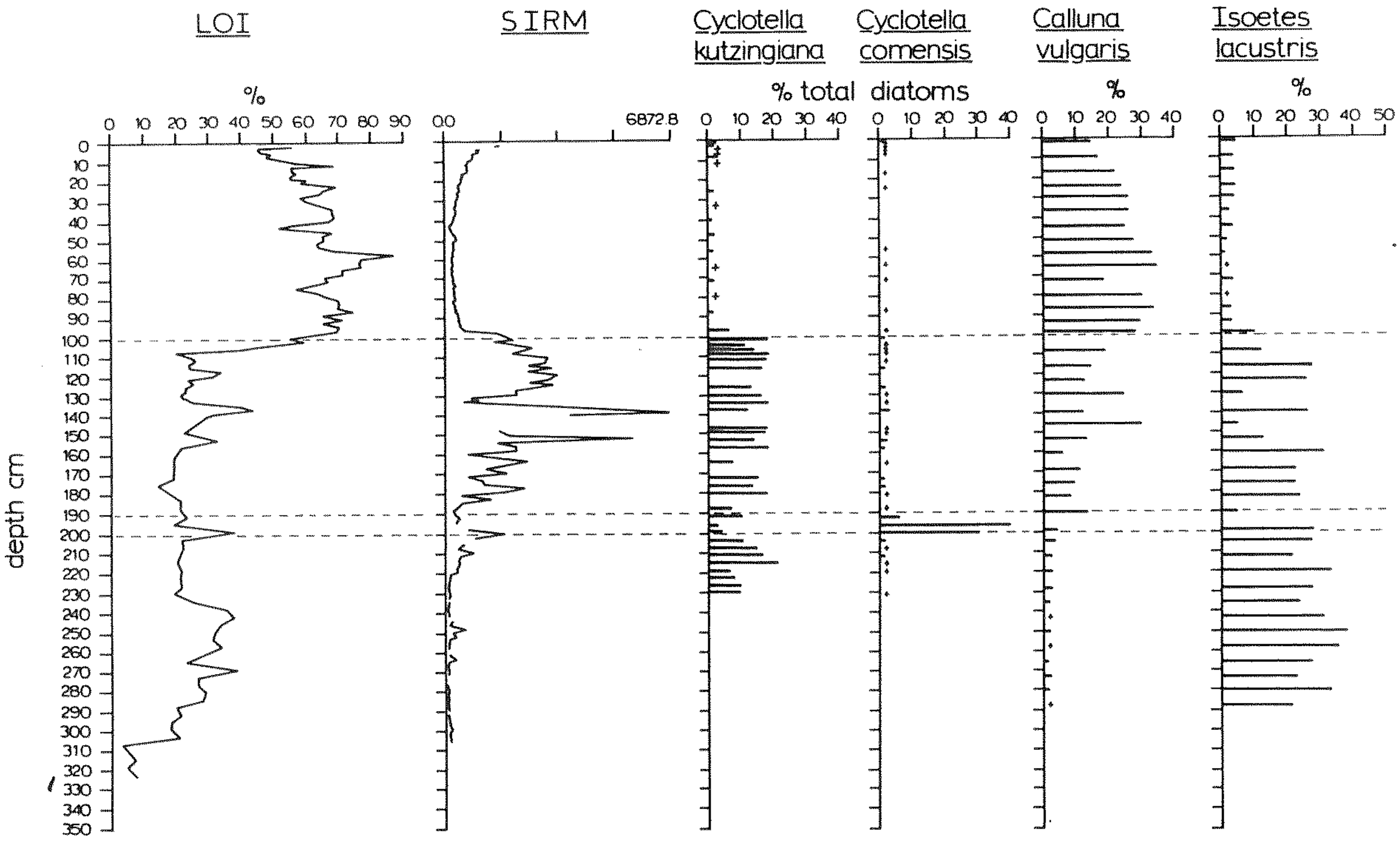


Fig. 16 Summary stratigraphic diagram for LF L3.

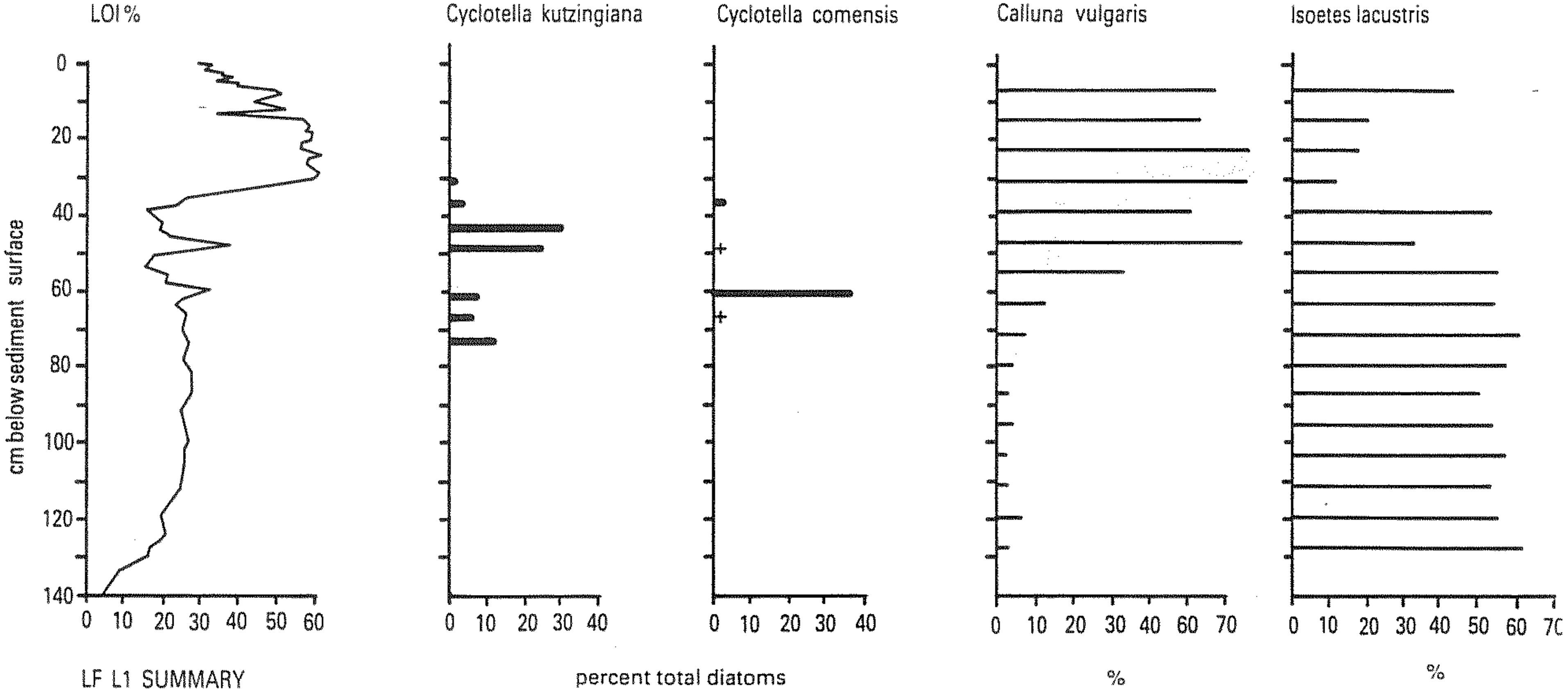


Fig. 17 Summary stratigraphic diagram for LF L1.

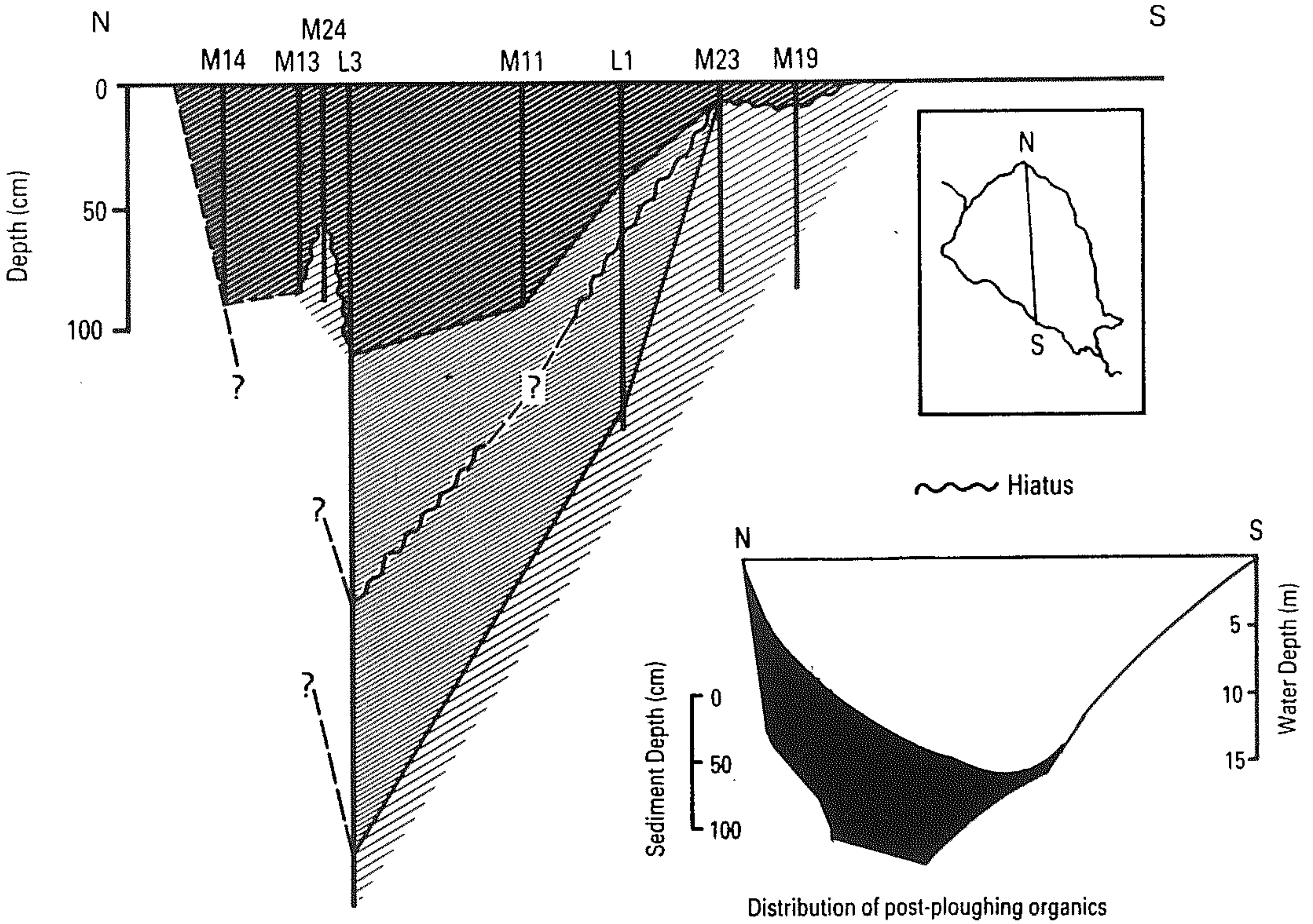


Fig. 18 N-S cross-sectional stratigraphy for L.Fleet, based on selected Minicores and Livingstone cores.

7. SEDIMENT RECORD OF ATMOSPHERIC CONTAMINATION

Lake sediments contain a record of atmospheric deposition, and where such deposition includes material associated with anthropogenic activity, the record can become a record of air pollution. In particular the stratigraphies of trace metals, magnetic mineralogy, and carbonaceous cenospheres ("soot") can be interpreted in this way. However, since the quantities of these variables in sediments are subject to the independent variation of sediment accumulation rate, concentration values must be transformed to flux values if they are to have historical meaning. This is especially so in the case of Loch Fleet where catchment ploughing has led to pronounced increases in sediment accumulation rates and the consequent dilution of most other constituents. In addition the atmospheric record in lakes with disturbed catchments, such as that of Loch Fleet, is often unclear since atmospheric pollutants stored in catchment soils are washed into the lake during erosive episodes and since erosion causes variations in the background flux of trace metals and magnetic minerals. Consequently, the results of the various analyses carried out are presented here but are not discussed in detail.

7.1 Trace metal data for cores LF L3 & LF L1

Figs. 19 and 20 show graphs of the concentration of Zn, Cu, and Pb against sediment depth for cores L3 and L1 respectively, whilst Fig. 21 shows the calculated fluxes for the three metals for L3 since about 1850.

The concentration data for both cores show similar trends. Prior to the hiatus the values for Pb are very low while those for Zn and Cu are somewhat higher. Without C14 dates it is not possible to make very accurate calculations of annual fluxes during this period but, from the pollen data, it can be establisehed that sediment accumulation rates were 50-100 times lower than in post-hiatus/pre-ploughing times. On this basis it can be estimated that trace metal fluxes during the early post-glacial period were very low indeed, perhaps less than 1 ug cm^{-2} yr^{-1}. The concentrations of trace metals after the hiatus (since about 1800 AD) show gradually then steeply rising values typical of profiles from other sites in the UK (cf Rippey et al. 1982) and indicating progressive contamination from industrial activity. However, some distortion of the atmospheric signal is apparent. The very large spike in flux values (Fig. 21) coincides with the period of maximum inwash and suggests that some of the Pb and Zn in particular is derived from the catchment. The subsurface decline in fluxes is consistent with both the stabilisation of the catchment soils and with the decline in the atmospheric flux of trace metals in recent years (Hilton et al. 1985).

7.2 Carbonaceous cenosphere data for LF L3

Because of the high and variable rate of sediment accumulation in the lake the concentration of carbonaceous particles is low, in some cases below the limit of detection (Fig. 22a). A somewhat clearer picture emerges when the data are expressed as fluxes (Fig.22b) although with the exception of the uppermost sediment these rates are also low in comparison to those for other nearby sites. Below 170 cm (approx. 1920) there are only sporadic occurrences of carbonaceous particles. Above this level there are particles in almost all samples and the fluxes rise significantly above 90 cm (from the late 1960's). There is a further rise above 30 cm (mid 1970's) both in concentration and flux. The concentration rise is accentuated because of the rapidly falling sediment accumulation rates over the top 20 cm. This post 1970 increase is not a feature of the non-afforested sites previously studied in Galloway (Battarbee et al. in prep.). It occurs as the lake rapidly acidifies and during the period of canopy closure of the catchment forest. It is not known at present whether and in what way these features might be related unless the growing forest causes greater air turbulence and enhanced dry deposition over the lake surface.

7.3 Mineral magnetic data for LF L3

The results of mineral magnetic analysis have been presented above (Section 5) and are shown in Fig. 15. Ferrimagnetic minerals in recent lake sediments are derived from both the catchment and the atmosphere. In the upper 35 cm of the L3 core the combination of values suggest the dominance of atmospheric over catchment derived sources. This is in agreement with the magnetic record of ombrotrophic peat bogs and closely follows the trend shown by the carbonaceous cenospheres (cf Fig. 22)

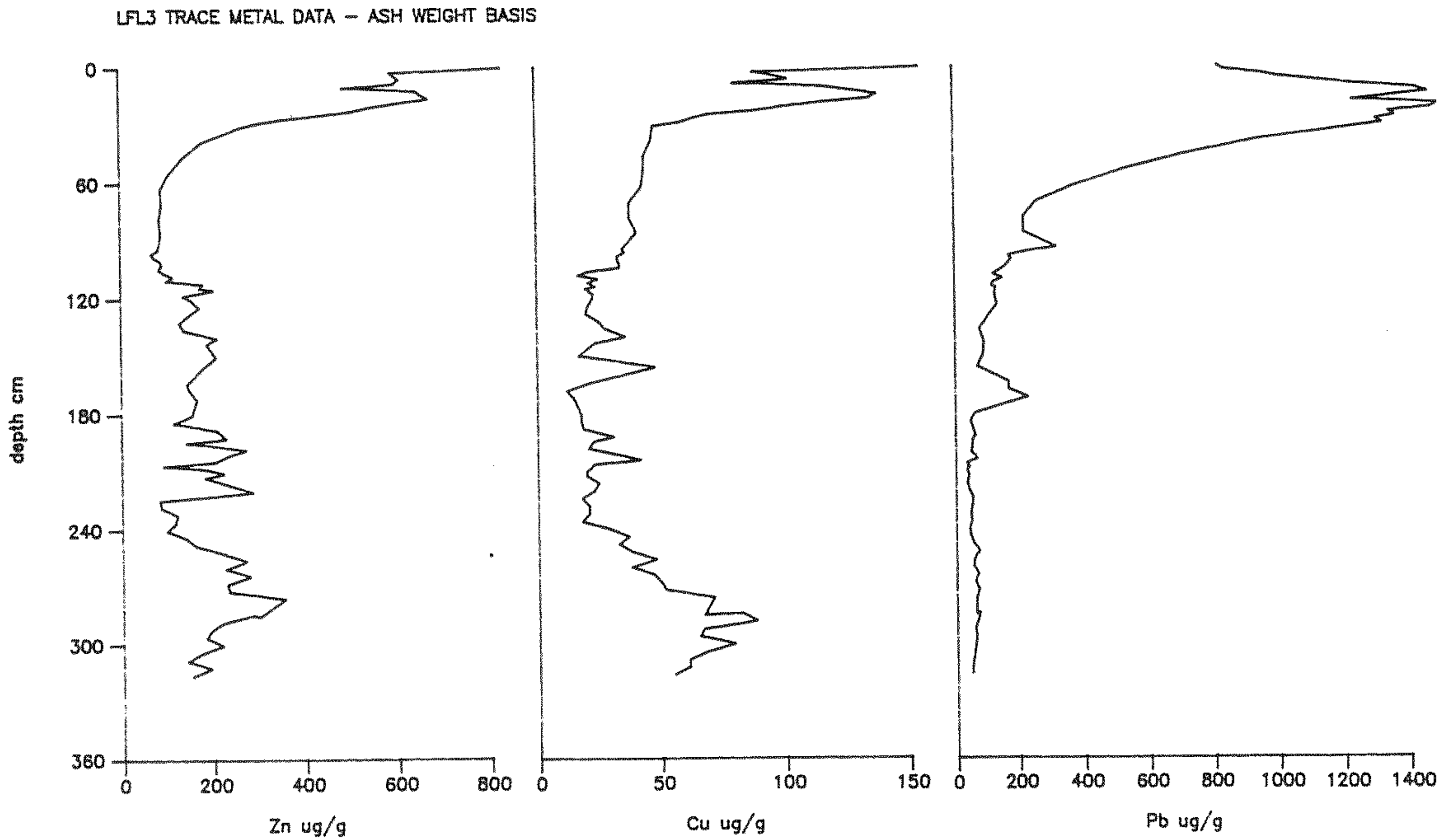


Fig. 19 Trace element (Zn, Cu, Pb) concentration data for LF L3.

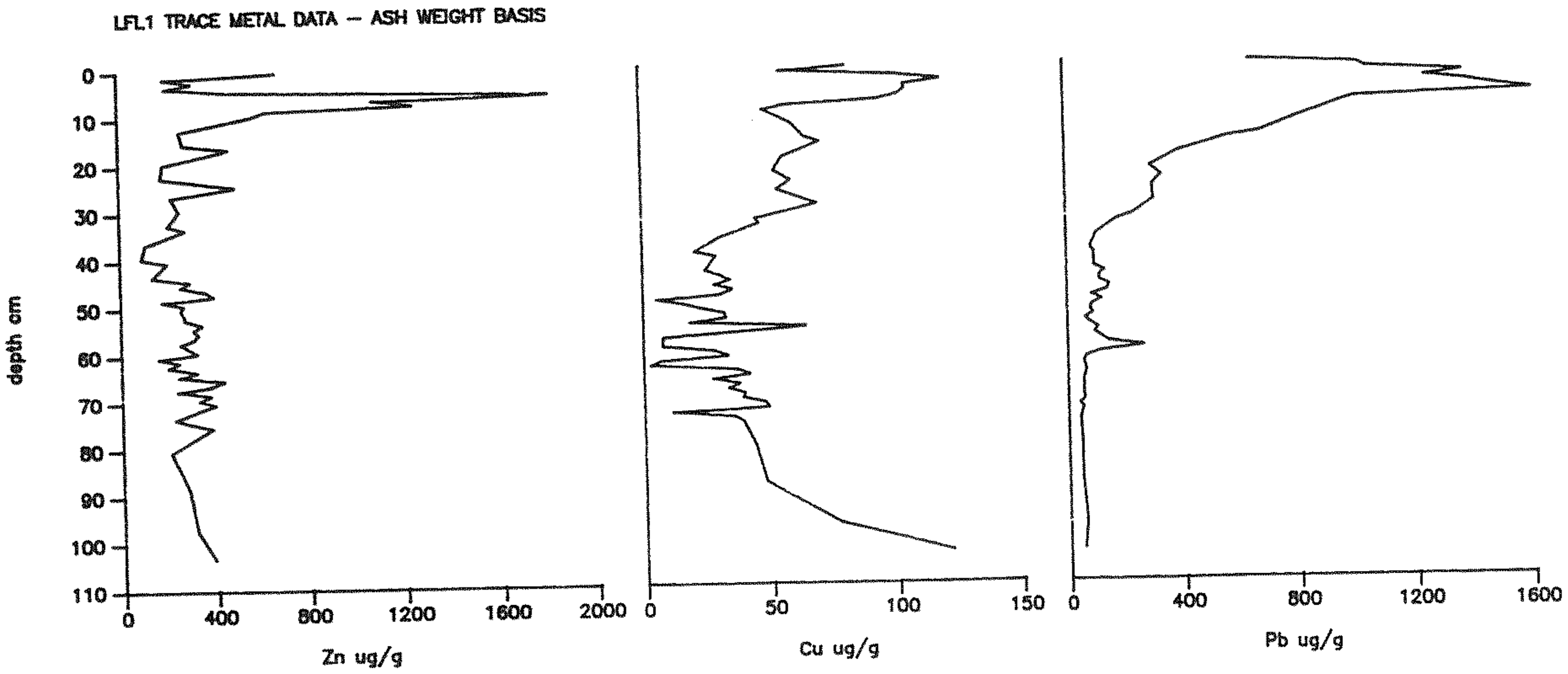


Fig. 20 Trace element (Zn, Cu, Pb) concentration data for LF L1.

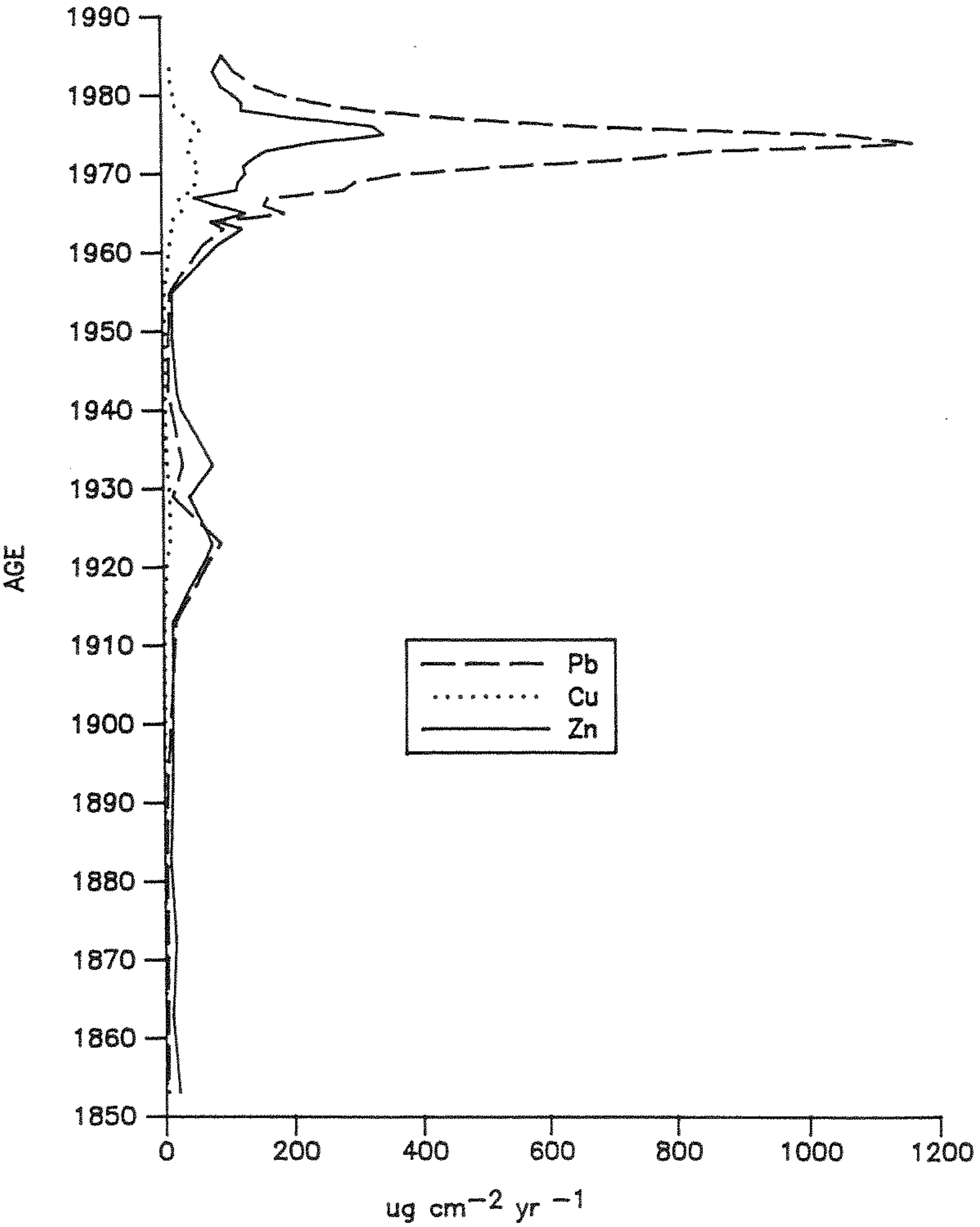


Fig. 21 Zn, Cu, Pb fluxes for LF L3 plotted against time.

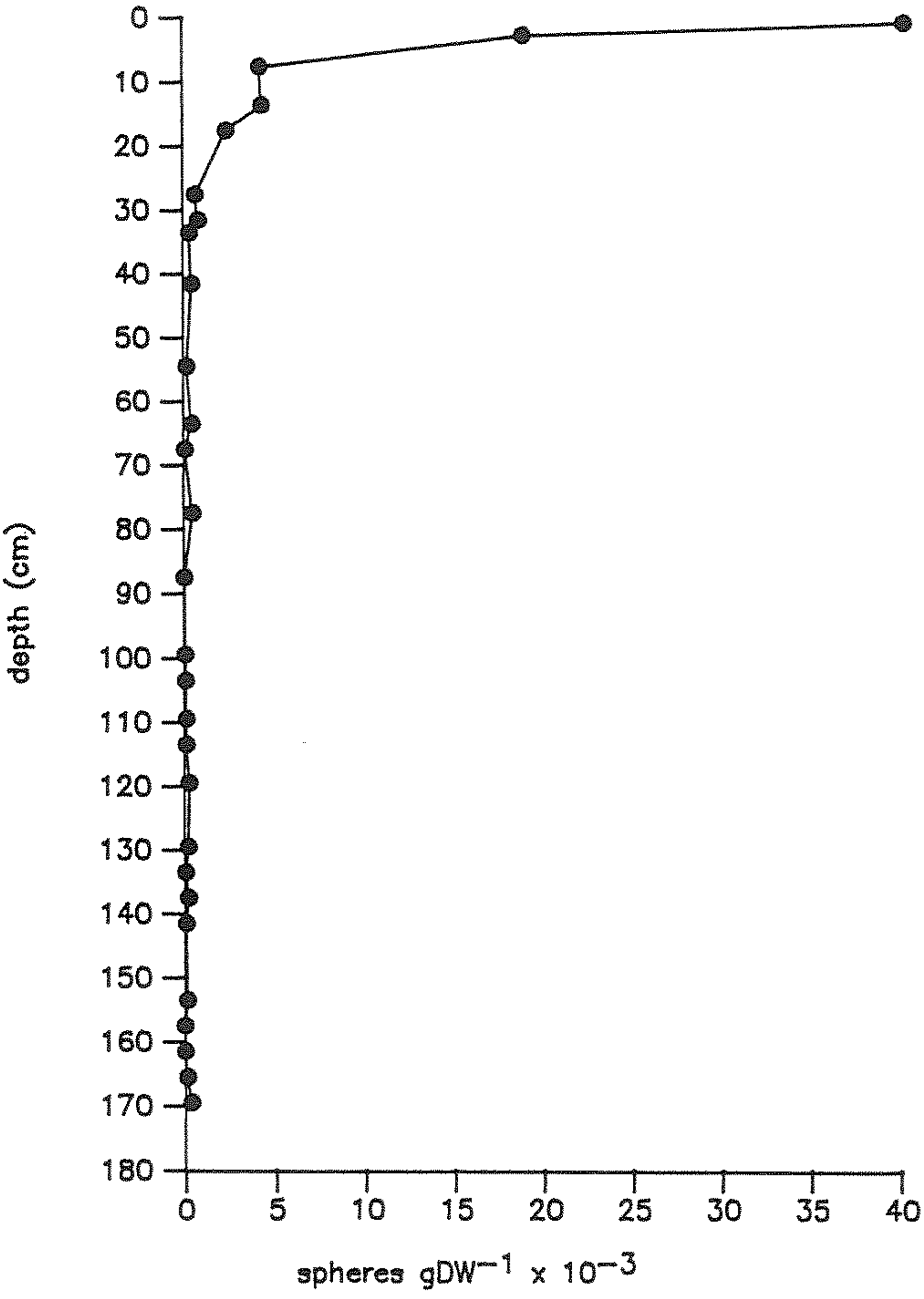


Fig. 22.a LF L3 carbonaceous cenosphere data: concentration.

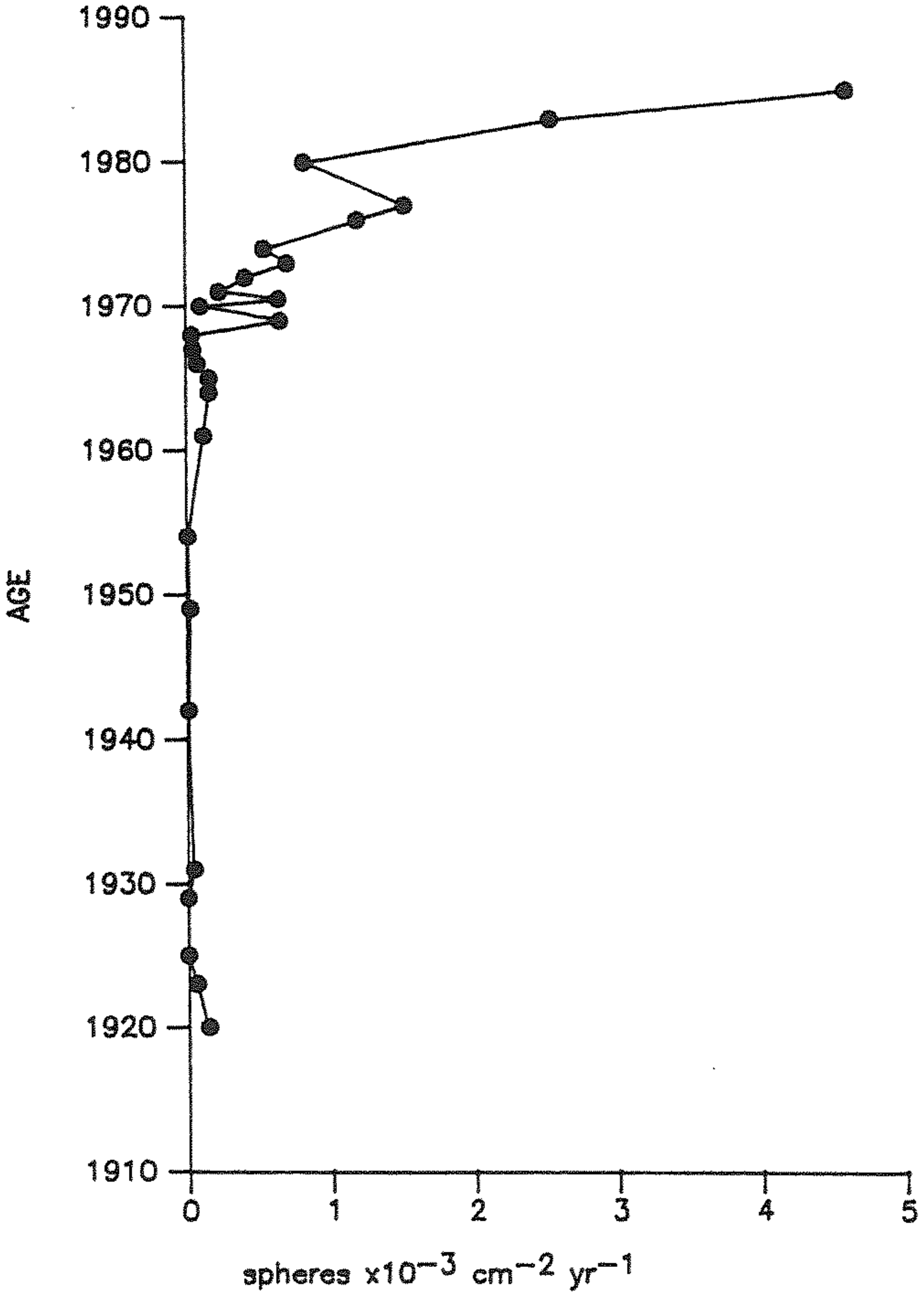


Fig. 22.b LF L3 carbonaceous cenosphere data: flux.

8. DIATOM ANALYSIS AND pH RECONSTRUCTION

8.1 Diatom flora

A full list of taxa occurring in the lake is given in Table 3. The table also indicates those taxa that occur in the uppermost sediment and thereby are approximately representative of the present (pre-liming) diatom flora of the lake.

8.2 Surface sediment diatom variability study.

To assess the variability of surface sediment diatom distributions, the surface 0-1 cm sample from 28 Kajak cores was analysed (Fig. 23). A summary diagram of the relative frequency distribution of selected taxa is presented in Fig. 24 and concentrations are shown in Fig. 25; more details are given in Appendix B. In general the data indicated substantial floristic uniformity between sites and very good repeatability of percentages for many taxa eg. Eunotia veneris, Frustulia rhomboides v. saxonica, Anomoeoneis brachysira v. thermalis. However some taxa show greater variation, especially Tabellaria quadriseptata, an important acidobiontic taxon and Cyclotella kutzingiana, a planktonic circumneutral species that no longer occurs in the lake in any abundance.

This variability results in a comparable variability in reconstructed pH (Fig. 26). Some samples have values around pH 5.5 as a result of the low frequency of acidobiontic taxa, and to some extent a rather high percentage of circumneutral taxa. A considerable number have values close to the measured pH of the lake although the median value is slightly on the high side.

The variability of the pH data is probably larger for this site than for others because of the more complex and highly focussed nature of sediment accumulation in the lake. A full explanation of the data requires the analysis of the uppermost few centimetres of a range of cores rather than the isolated analysis of surface sediments since the time represented by the 1 cm sediment surface sample could be substantially different within the lake. It is for example entirely likely that pre-1970 sediment containing Cyclotella kutzingiana and other circumneutral taxa occurs at or close to the sediment surface at certain places within the lake. The samples taken in this survey in areas of relatively slow sediment accumulation may include variable quantities of such earlier material. Equally the surface sediments from areas of very rapid accumulation may not contain less than a full annual cycle of material or may have been contaminated by the erosion and redistribution of older sediment within the system.

ACHNANTHES LINEARIS	W. SMITH
ACHNANTHES MICROCEPHALA	KUTZ.
ACHNANTHES PSEUDOSWAZI	CARTER
ACHNANTHES RECURVATA	HUST.
ACHNANTHES PERAGALLI	BRUN ET HERIBAUD
ACHNANTHES MINUTISSIMA	KUTZ.
ACHNANTHES AUSTRIACA	HUST.
ACHNANTHES NODOSA	A. CLEVE
ACHNANTHES MARGINULATA*	GRUN.
ACHNANTHES DEPRESSA	(CLEVE) HUST.
ACHNANTHES FLEXELLA	(KUTZ.) GRUN
ACHNANTHES FLEXELLA V ALPESTRIS	BRUN.
ACHNANTHES FRIGIDA	HUST.
ACHNANTHES SUBLAEVIS	HUST.
ACHNANTHES SUCHLANDTII	HUST.
ACHNANTHES DIDYMA	HUST.
ACHNANTHES PINNATA	HUST.
ACHNANTHES GIBBERULA	GRUN.
ACHNANTHES SP B	L. FLEET(NJA)
ACHNANTHES CF UMARA	L. FLEET(NJA)
ACHNANTHES CF LEVANDERI	
ACHNANTHES SP	
AMPHORA OVALIS	KUTZ.
AMPHORA OVALIS V LIBYCA	(EHR.) CLEVE
ANOMOEONEIS FOLLIS	(EHR.) CLEVE
ANOMOEONEIS SERIANS	(BREB.) CLEVE
ANOMOEONEIS VITREA*	(GRUN.) ROSS
ANOMOEONEIS STYRIACA	(GRUN.) HUST.
ANOMOEONEIS BRACHYSIRA	(BREB.) GRUN.
ANOMOEONEIS BRACHYSIRA V THERMALIS*	NOV. COMB.
ASTERIONELLA RALFSII	W. SMITH
ASTERIONELLA FORMOSA	L. FLEET(NJA)
CALONEIS BACILLUM	(GRUN.) MERESCHKOWSKY
CALONEIS BACILLARIS	(GREGORY) CLEVE
CYMBELLA VENTRICOSA	KUTZ.
CYMBELLA TURGIDA	GREGORY
CYMBELLA MICROCEPHALA	GRUN.
CYMBELLA CISTULA	(HEMPRICH) GRUN.
CYMBELLA CYMBIFORMIS	(AGARDH/ KUTZ.) V. HEURCK
CYMBELLA HYBRIDA	GRUN.
CYMBELLA NAVICULIFORMIS	AUERSWALD
CYMBELLA PERPUSILLA*	A. CLEVE
CYMBELLA AEGUALIS	SMITH
CYMBELLA CESATII	(RABH.) GRUN.
CYMBELLA HEBRIDICA*	(GREGURY) GRUN.
CYMBELLA GRACILIS	(RABH.) CLEVE
CYMBELLA GAEUMANNI	MEISTER
CYMBELLA ANGUSTATA	(W. SMITH) CLEVE
CYMBELLA OBTUSA	GREGORY
CYMBELLA CF CAESPITOSA	L. FLEET (NJA)
CYMBELLA CF OBTUSA	LOCH ENOCH (PJF)
CYMBELLA SP.	
COCCONEIS THUMENSIS	A. MAYER
CYCLOTELLA STELLIGERA	CLEVE ET GRUN.
CYCLOTELLA KUTZINGIANA*	THWAITES
CYCLOTELLA COMENSIS	GRUN.
CYCLOTELLA ARENTII	KOLBE
DIPLONEIS OVALIS	(HILSE) CLEVE
DIPLONEIS MARGINESTRIATA	HUST.
DIPLONEIS SP.	
EPITHEMIA ZEBRA	(EHR.) KUTZ.
EUNOTIA VENERIS*	(KUTZ.) O. MULLER
EUNOTIA PECTINALIS	(KUTZ.) RABH.
EUNOTIA PECTINALIS V MINOR*	(KUTZ.) RABH.
EUNOTIA PECTINALIS V VENTRALIS*	(EHR.) HUST.
EUNOTIA PECTINALIS V MINOR F IMPRESSA	(EHR.) HUST.
EUNOTIA PRAERUPTA	EHR.
EUNOTIA PRAERUPTA V BIDENS	GRUN.
EUNOTIA TENELLA*	(GRUN). HUST.
EUNOTIA ALPINA*	(NAEGELI) HUST.
EUNOTIA LUNARIS	(EHR.) GRUN.
EUNOTIA LUNARIS V SUBARCUATA	(NAEGELI) GRUN.
EUNOTIA BIDENTULA*	W.SMITH
EUNOTIA MONODON	EHR.
EUNOTIA MONODON V MAIOR F BIDENS	W. SMITH
EUNOTIA EXIGUA*	(BREB.) RABH.
EUNOTIA FABA	(EHR.) GRUN.
EUNOTIA RHOMBOIDEA*	HUST.
EUNOTIA ROBUSTA	RALFS
EUNOTIA ARCUS	EHR.
EUNOTIA BACTRIANA	EHR.
EUNOTIA DENTICULATA	(BREB.) RABH.
EUNOTIA DIODON	EHR.
EUNOTIA FLEXUOSA	KUTZ.
EUNOTIA FORMICA	EHR.
EUNOTIA IATRIAENSIS	FOGED
EUNOTIA MEISTERI	HUST.
EUNOTIA SUDETICA	(O. MULLER) HUST.
EUNOTIA BIGIBBA	KUTZ.
EUNOTIA POLYDENTULA	BRUN.
EUNOTIA GLACIALIS	MEIST.
EUNOTIA FALLAX	CLEVE
EUNOTIA FALLAX V GRACILLIMA	KRASSKE
EUNOTIA PRAERUPTA-NANA	BERG
EUNOTIA TRINACRIA	KRASSKE
EUNOTIA MICROCEPHALA	KRASSKE EX HUST.
EUNOTIA MICROCEPHALA V TRIDENTATA	(A. MAYER) HUST.
EUNOTIA VALIDA	HUST.
EUNOTIA GRACILIS	(EHR.) RABH.
EUNOTIA REPENS	BERG
EUNOTIA SP A	
EUNOTIA SP	
FRAGILARIA PINNATA	EHR.
FRAGILARIA PINNATA V LANCETTULA	(SCHUM.) HUST.
FRAGILARIA CONSTRUENS	(EHR.) GRUN.
FRAGIALRIA CONSTRUENS V VENTER	(EHR.) GRUN.
FRAGILARIA VIRESCENS*	RALFS
FRAGILARIA BREVISTRIATA	GRUN.
FRAGILARIA VAUCHERIAE	(KUTZ.) BOYE PETERSON
FRAGILARIA ELLIPTICA	SCHUM.
FRAGILARIA CF VIRESCENS*	L. FLEET (NJA)
FRAGILARIA SP	
FRUSTULIA RHOMBOIDES*	(EHR.) DE TONI
FRUSTULIA RHOMBOIDES V SAXONICA*	(RABH.) DE TONI
FRUSTULIA SP	
GOMPHONEMA ANGUSTATUM	(KUTZ.) RABH.
GOMPHONEMA ANGUSTATUM V PRODUCTA	GRUN.
GOMPHONEMA GRACILE	EHR.

Table 3: Species for LF L3 * Species >1% in surface sediment

GOMPHONEMA LAGERHEIMI	CLEVE.
GOMPHONEMA ACUMINATUM	EHR.
GOMPHONEMA ACUMINATUM V CORONATA	(EHR.) W. SMITH
GOMPHONEMA CONSTRICTUM	EHR.
GOMPHONEMA PARVULUM	KUTZ.
GOMPHONEMA INTRICATUM	KUTZ.
GOMPHONEMA LANCEOLATUM	EHR.
GOMPHONEMA SP	
KRASSKIELLA KRIEGERANA	(KRASSKE) ROSS & SIMS
MELOSIRA ITALICA	(EHR.) KUTZ.
MELOSIRA ITALICA V VALIDA	GRUN.
MELOSIRA LIRATA	(EHR.) KUTZ.
MELOSIRA LIRATA V PERGLABRA	(OSTRUP) N.-B. FLORIN
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 TENELLA	NYGAARD
MELOSIRA SP	
NAVICULA JARNEFELTII	HUST.
NAVICULA RADIOSA	KUTZ.
NAVICULA RADIOSA V TENELLA	(BREB.) GRUN.
NAVICULA SEMINULUM	GRUN.
NAVICULA SEMINULUM V INTERMEDIA	HUST.
NAVICULA MEDIOCRIS	KRASSKE
NAVICULA CRYPTOCEPHALA	KUTZ.
NAVICULA LANCEOLATA	(AGARDH) KUTZ.
NAVICULA PSEUDOSCUTIFORMIS	HUST.
NAVICULA PUPULA	KUTZ.
NAVICULA PUPULA V RECTANGULARIS	(GREGORY) GRUN.
NAVICULA HASSIACA	KRASSKE
NAVICULA COCCONEIFORMIS	GREGORY
NAVICULA SUBTILISSIMA*	CLEVE
NAVICULA ANGUSTA	GRUN.
NAVICULA FESTIVA	KRASSKE
NAVICULA HOFLERI*	CHOLNOKY
NAVICULA HEIMANSII	VAN DAM & KOOY.
NAVICULA MINIMA	GRUN.
NAVICULA SUBATOMOIDES	HUST.
NAVICULA KRASSKEI	HUST.
NAVICULA BRYOPHILA	PETERSEN
NAVICULA CONTENTA	GRUN.
NAVICULA PROTRACTA	GRUN.
NAVICULA SOHRENSIS	KRASSKE
NAVICULA CLEMENTIS	GRUN.
NAVICULA CARI	EHR.
NAVICULA IMPEXA	HUST.
NAVICULA MURALIS	GRUN.
NAVICULA TANTULA	HUST.
NAVICULA BREMENSIS	HUST.
NAVICULA JAAGII	MEISTER
NAVICULA SEMINULOIDES	HUST.
NAVICULA SCHASSMANNII	HUST.
NAVICULA RUPICOLA	HUST.
NAVICULA LAGERSTEDTII V PALUSTRIS	HUST.
NAVICULA PELLICULOSA	HUST.
NAVICULA SUBTILISSIMA VAR 1	L. FLEET (NJA)
NAVICULA CF SUBTILISSIMA	L. FLEET (NJA)
NAVICULA SP A	
NAVICULA SP	
NEIDIUM AFFINE	(EHR.) CLEVE
NEIDIUM AFFINE V AMPHIRHYNCHUS	(EHR.) CLEVE
NEIDIUM ALPINUM	HUST.
NEIDIUM SP	
NITZSCHIA PERMINUTA	GRUN.
NITZSCHIA HUNGARICA	GRUN.
NITZSCHIA FRUSTULUM	KUTZ.
NITZSCHIA PALEA	(KUTZ.) W. SMITH
NITZSCHIA GRACILIS	HANTZSCH
NITZSCHIA ANGUSTATA	(W. SMITH) GRUN.
NITZSCHIA ROMANA	GRUN.
NITZSCHIA MICROCEPHALA	GRUN.
NITZSCHIA SP	
PERONIA FIBULA*	(BREB. ex KUTZ.) ROSS
PINNULARIA HEMIPTERA	(KUTZ.) CLEVE
PINNULARIA MAIOR	KUTZ.
PINNULARIA MESOLEPTA	(EHR.) W. SMITH
PINNULARIA VIRIDIS	(NITZSCH) EHR.
PINNULARIA DIVERGENS	W. SMITH
PINNULARIA SUBLINEARIS	GRUN.
PINNULARIA MICROSTAURON	(EHR.) CLEVE
PINNULARIA BOREALIS	EHR.
PINNULARIA APPENDICULATA	(AGARDH) CLEVE
PINNULARIA ABAUJENSIS	(PANT.) ROSS
PINNULARIA DIVERGENTISSIMA	(GRUN.) CLEVE
PINNULARIA BICEPS	GREGORY
PINNULARIA UNDULATA	GREGORY
PINNULARIA HILSEANA	(JANISCH) MULL.
PINNULARIA SUBCAPITATA	GREGORY
PINNULARIA IRRORATA*	(GRUN.)HUST.
PINNULARIA STOMATOPHORA	GRUN.
PINNULARIA GRACILLIMA	GREGORY
PINNULARIA SUBSOLARIS	(GRUN.) CLEVE
PINNULARIA NODOSA	EHR.
PINNULARIA CF SUBSOLARIS	L. FLEET (NJA)
PINNULARIA SP	
RHOPALODIA GIBBERULA	(EHR.) O. MULLER
STAURONEIS ANCEPS	EHR.
STAURONEIS ANCEPS F GRACILIS	(EHR.) CLEVE
STAURONEIS LEGUMEN	EHR.
STAURONEIS PRODUCTA	GRUN.
STAURONEIS SP	
SEMIORBIS HEMICYCLUS	(EHR.) PATRICK
STENOPTEROBIA INTERMEDIA	LEWIS
SURIRELLA BISERIATA	BREB.
SURIRELLA DELICATISSIMA	LEWIS
SYNEDRA ULNA	(NITZSCH) EHR.
SYNEDRA RUMPENS	KUTZ.
SYNEDRA ACUS	KUTZ.
SYNEDRA PARASITICA V SUBCONSTRICTA	GRUN.
SYNEDRA MINUSCULA	GRUN.
SYNEDRA SP	
TABELLARIA FLOCCULOSA*	(ROTH) KUTZ.
TABELLARIA BINALIS*	(EHR.) GRUN.
TABELLARIA QUADRISEPTATA*	KNUDSON
TABELLARIA SP	

Table 3 (cont'd)

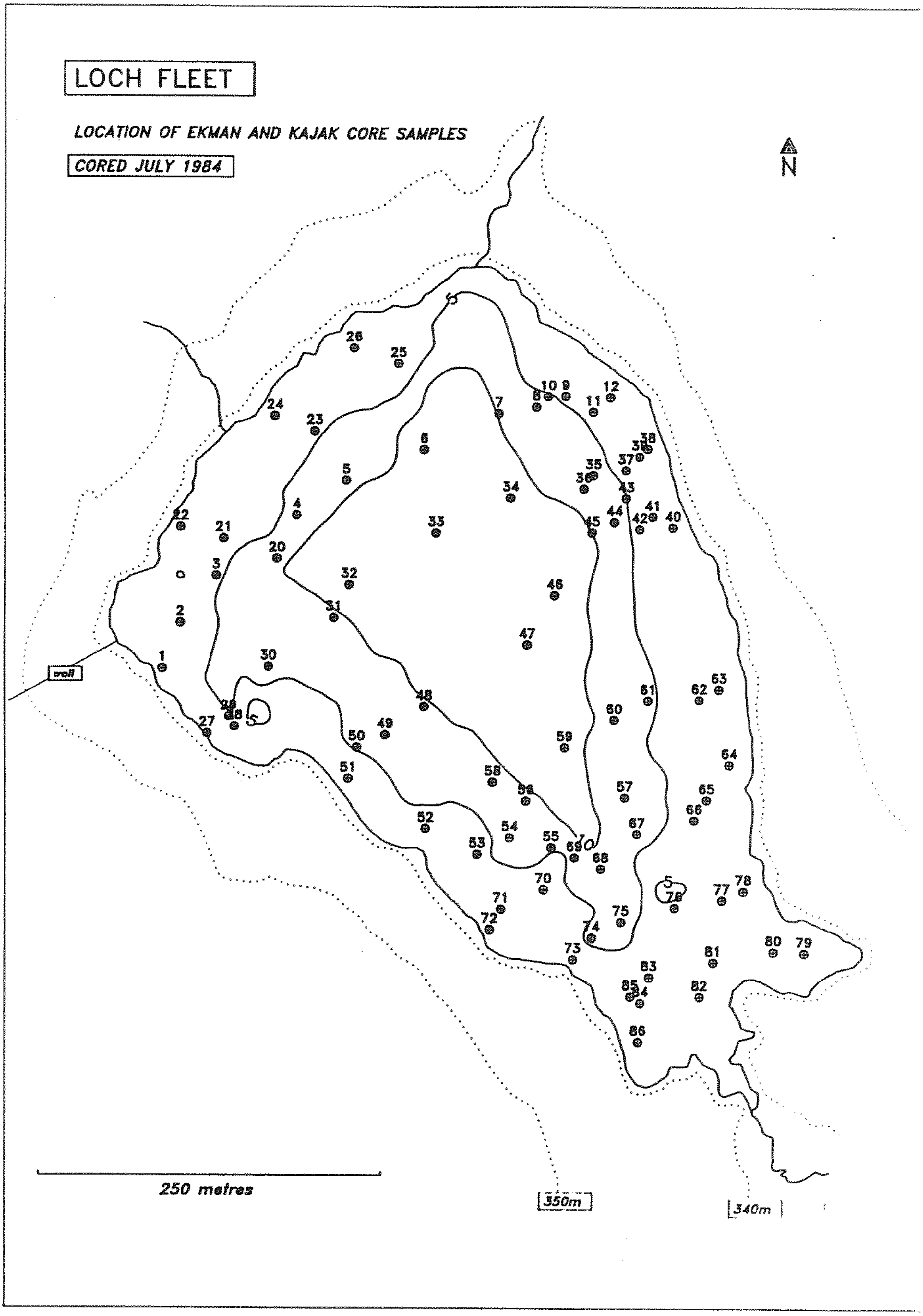
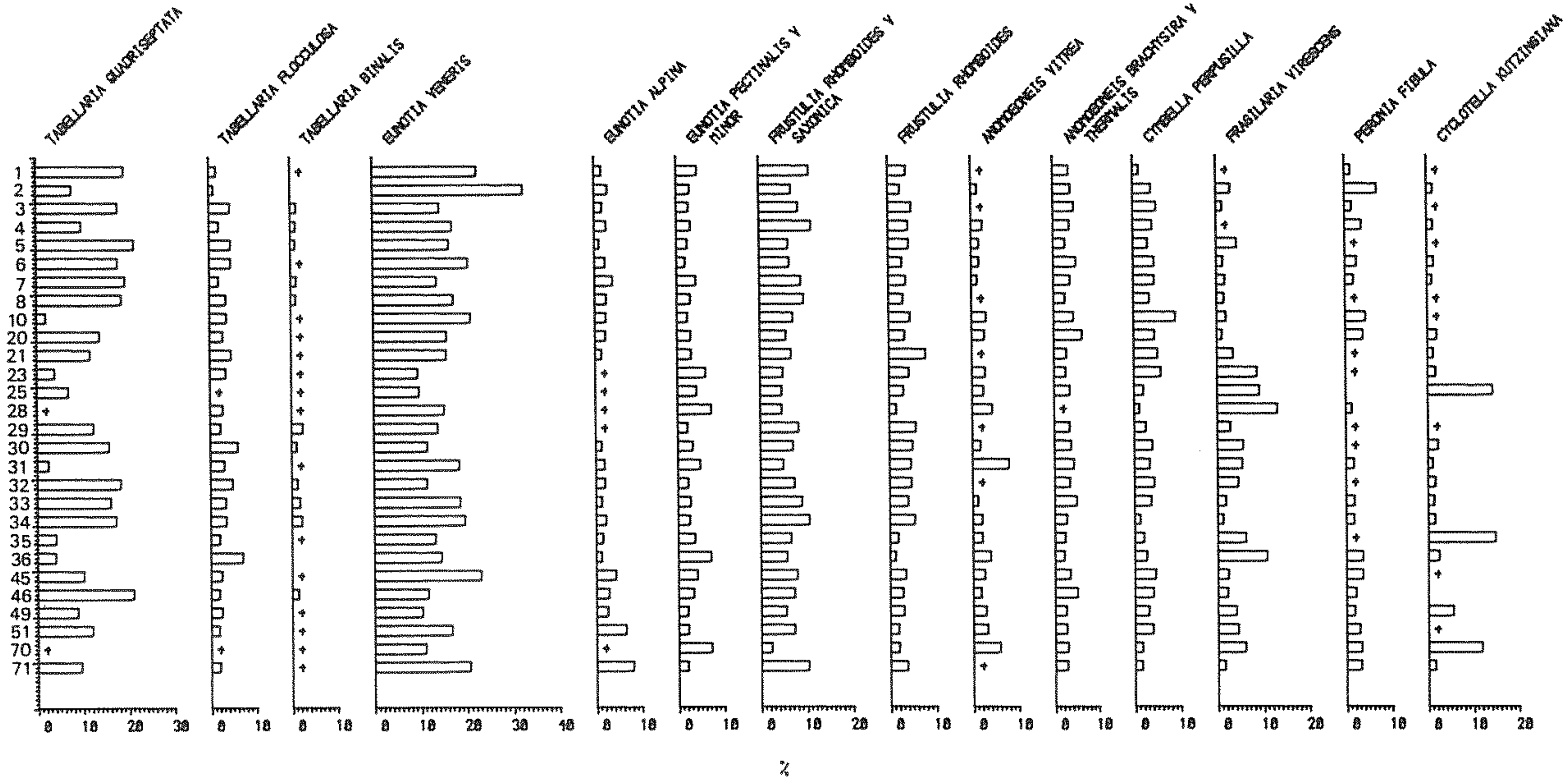


Fig. 23 Distribution of Kajak cores used in surface sediment variability study.



KAJAK CORE SURFACE SEDIMENT DIATOM ASSEMBLAGES : SUMMARY

Fig. 24 Summary diatom diagram for Kajak core surface samples.

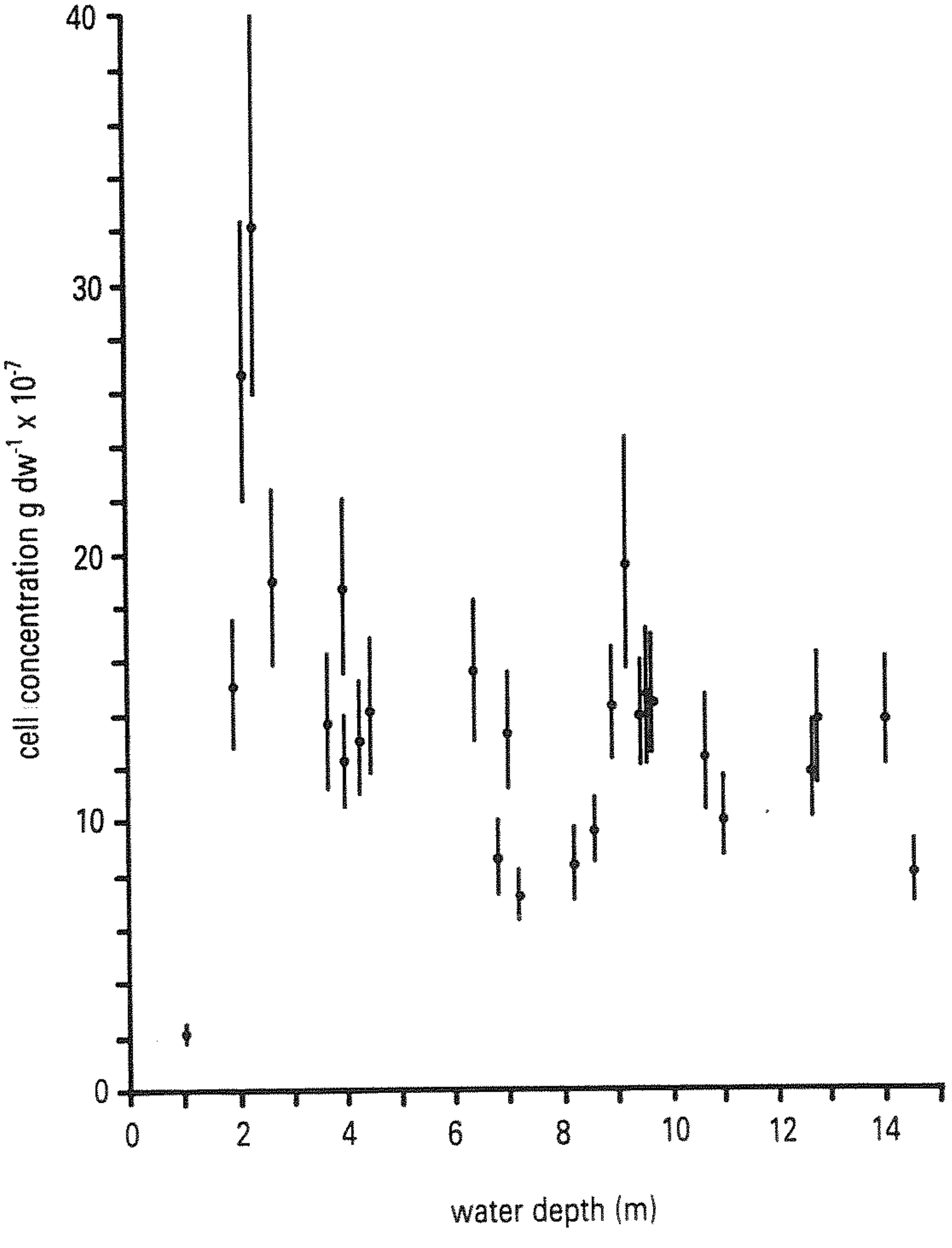


Fig. 25 Diatom concentrations v. water depth for Kajak core surface samples.

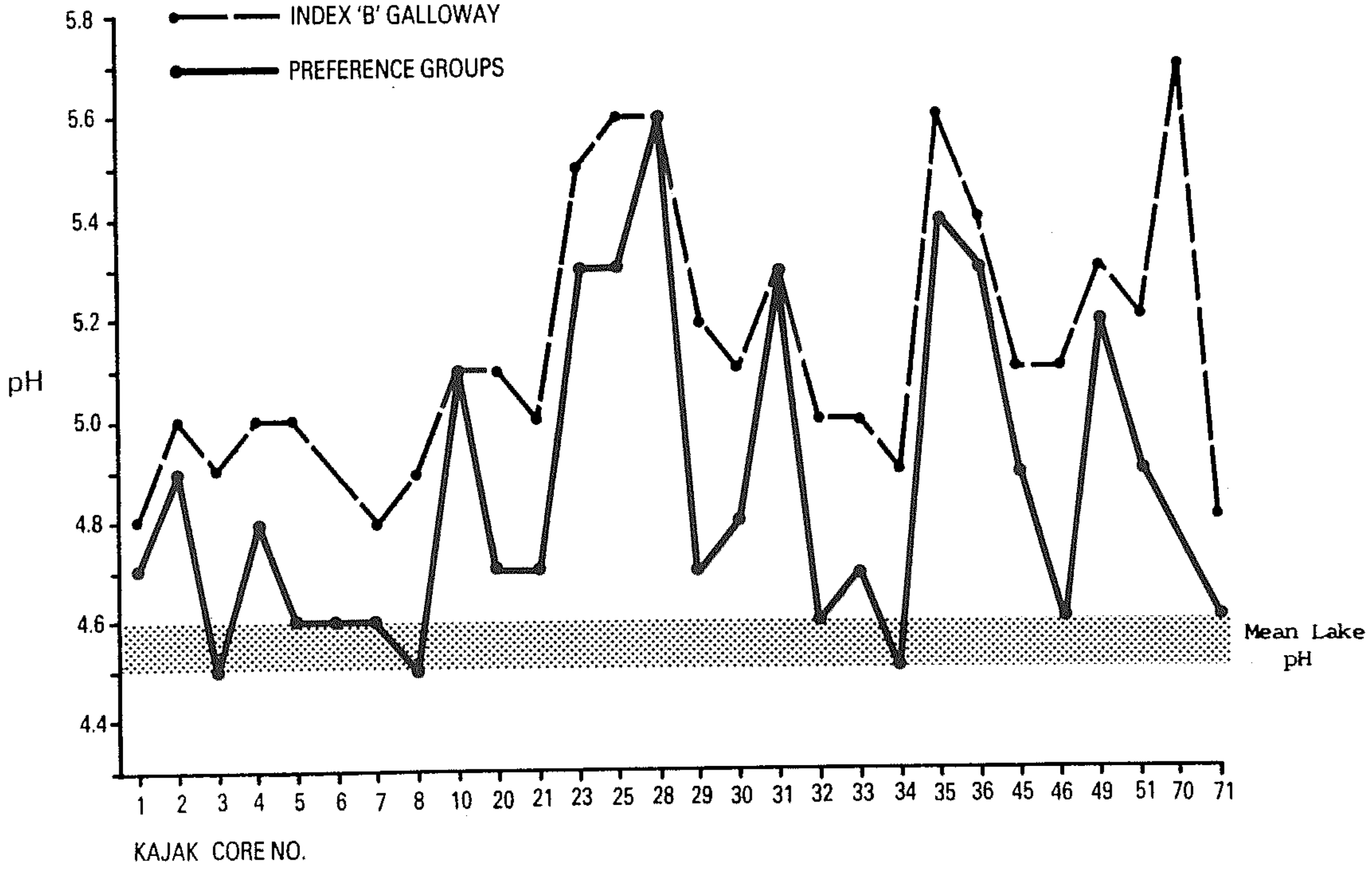


Fig. 26 pH reconstruction plot from surface samples.

8.3 Diatom biostratigraphy: LF L3

A complete diagram for core L3 is given in Appendix C. A summary diagram which includes the most commonly occurring taxa is shown in Fig. 27, and the concentration of diatoms at each level in core LF L3 is shown in Fig. 28.

The diagram was zoned using a statistical zonation package (Birks 1986) on the UCL VAX 11/750 computer. The various methods (SPLITINF; SPLITSQ; CONSLINK) used were in close agreement. 6 zones have been identified.

8.3.1 LF L3-D1 (<208 cm) **Cyclotella kutzingiana, Fragilaria virescens, Melosira perglabra**

The main taxa in this zone are *C. kutzingiana*, *F. virescens*, and *M. perglabra*. *Achnanthes minutissima* declines initially but recovers somewhat towards the end of the zone. Other important taxa are *Anomoeoneis vitrea*, *A. brachysira* v *thermalis*, *Cymbella gracilis* and *Frustulia rhomboides* v *saxonica*. All taxa are classed as either circumneutral or acidophilous species and *C. kutzingiana* is a circumneutral planktonic taxon.

8.3.2 LF L3-D2 (208-196) **Cyclotella comensis**

This zone is characterised by a very rapid expansion and decline of the small planktonic diatom *C. comensis*, and there is a small percentage increase in *A. minutissima*. *C. kutzingiana* declines briefly but begins to recover by the end of the zone. The other main taxa are the same as for zone D1.

8.3.3 LF L3-D3 (196-101) **Cyclotella kutzingiana, Fragilaria virescens, Achnanthes minutissima**

In this zone *C. kutzingiana* returns to maximum values, *F. virescens* has high but variable percentages, while *A. minutissima* reaches a peak in mid-zone and thereafter remains relatively constant to the upper zone boundary. *A. vitrea* has constant values of around 8% throughout the zone but *M. perglabra* declines steadily. *Navicula cocconeiformis*, *Eunotia veneris* and *E. pectinalis* v. *minor* make significant but low contributions. *F. rhomboides* v *saxonica* and *C. gracilis* remain constant. Despite this small change in the balance of the diatom spectrum the relative proportion of the circumneutral and acidophilous taxa is the same as for D1.

8.3.4 LF L3-D4 (101-20.5) **Anomoeoneis vitrea, Tabellaria flocculosa, Eunotia veneris**

C. kutzingiana declines abruptly to less than than 1% of the total and there are corresponding increases in *A. vitrea* and *T. flocculosa*, while *A. minutissima* declines steadily.

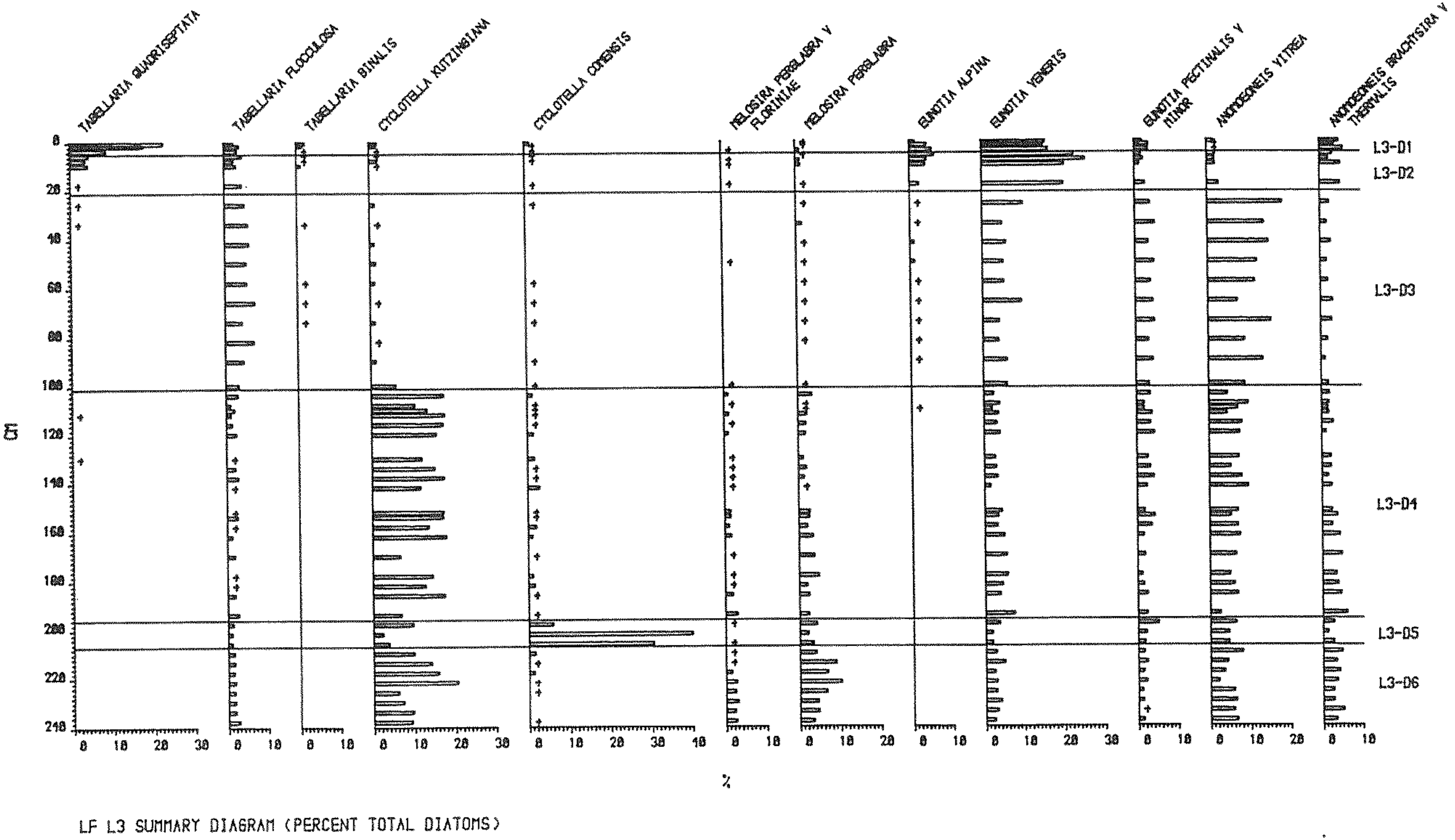
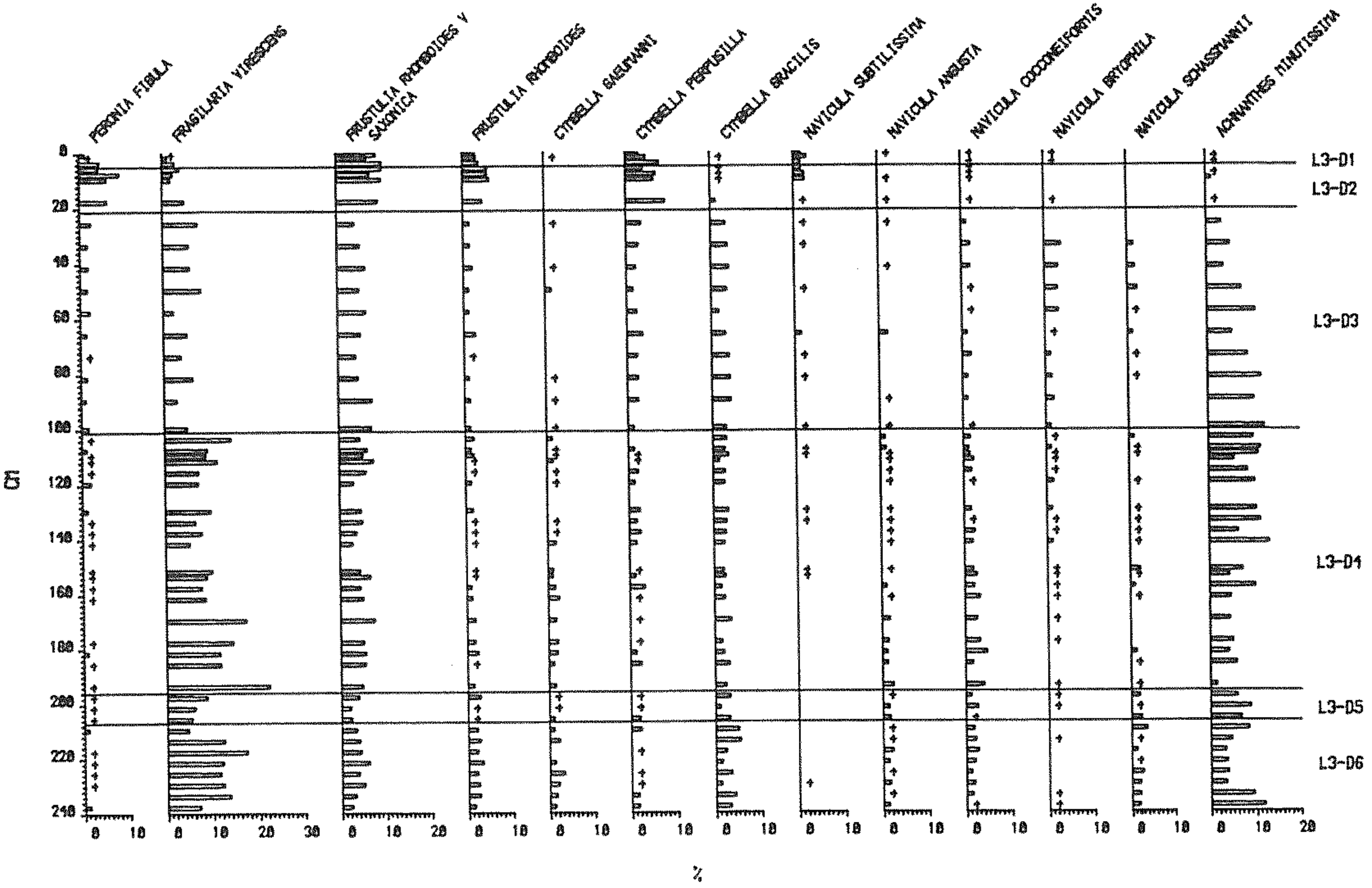


Fig. 27 LF L3 summary diatom diagram.



LF L3 SUMMARY DIAGRAM (PERCENT TOTAL DIATOMS)

Fig. 27 (cont'd)

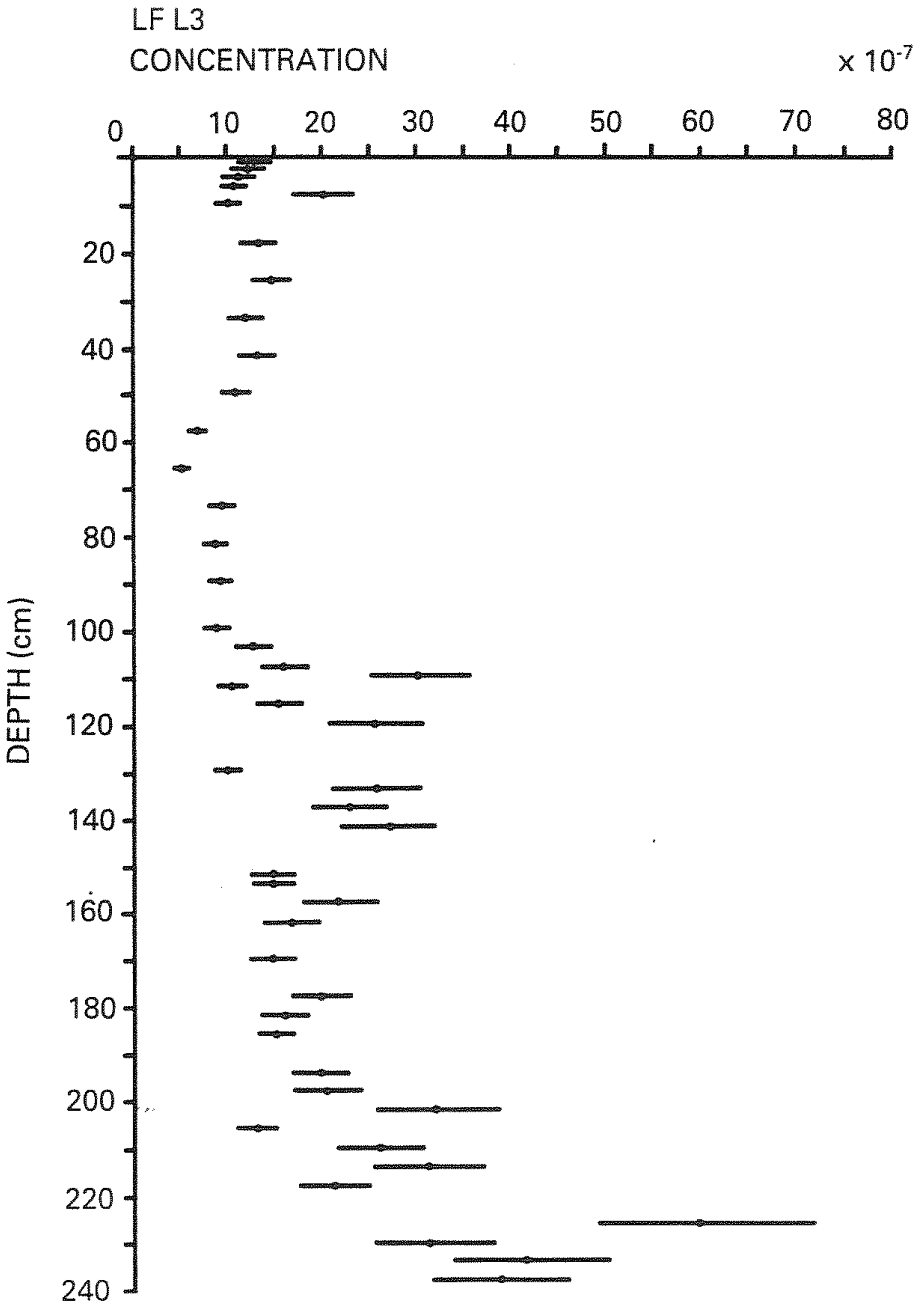


Fig. 28 Diatom concentration for LF L3.

F. virescens has lower values throughout and E. veneris begins to increase towards the end of the zone. E. pectinalis v minor increases and Navicula bryophila reaches maximum values. There are no acidobiontic diatoms present in this zone but the assemblage is somewhat more acidophilous in character than previously.

8.3.5 LF L3-D5 (20.5-4.5) **Eunotia veneris, Tabellaria quadriseptata**

The increase of the acidophilous E. veneris to maximum values corresponds to a rapid decline in the circumneutral A. vitrea and A. minutissima. Other taxa which increase in this zone are C. perpusilla, N. subtilissima and E. alpina, and the acidobiontic species Tabellaria quadriseptata becomes important for the first time.

8.3.6 LF L3-D6 (4.5-0) **Tabellaria quadriseptata Eunotia veneris, Tabellaria binalis**

The uppermost zone is characterised by a small decrease in E. veneris, an increase to a maximum of T. quadriseptata and a small but significant increase in T. binalis another acidobiontic taxon. The proportion of circumneutral taxa in the assemblage of this zone is very small.

8.4 Diatom biostratigraphy LF L1

A small number of samples from core L1 was analysed in order to assist with core correlation. A summary diagram is shown in Fig.29. Despite the wide sampling interval it is possible to identify a number of the features described above for LF L3 especially the C. comensis peak, the C. kutzingiana decline, and the high M. perglabra percentages below 65 cm.

8.5 pH reconstruction

Both Index B (Renberg & Hellberg 1982) and multiple regression models (Flower 1986) were used to reconstruct pH from the diatom assemblages in the core. The results are very similar (Fig. 30) although the multiple regression of pH preference groups gives slightly higher (0.2 pH unit) values than Index B. The inferred value for the surface sample using Index B is 4.5, close to the measured mean annual value of the contemporary lake water.

Below 110 cm (before about 1965) the reconstructed pH is relatively constant at 5.9-6.0. Between ca. 110 and 30 cm (1965-1974) there is a slight decrease to pH 5.7-5.8 reflecting the loss of the planktonic taxon C. kutzingiana and the decrease of F. virescens. These changes coincide with the abrupt increase in loss on ignition values caused by peat inwash following ploughing. If the decline in C. kutzingiana was caused by the inwash then the slight decrease in pH indicated by the model may be an artefact. Above 30 cm (after about 1974) there is a rapid decline in pH

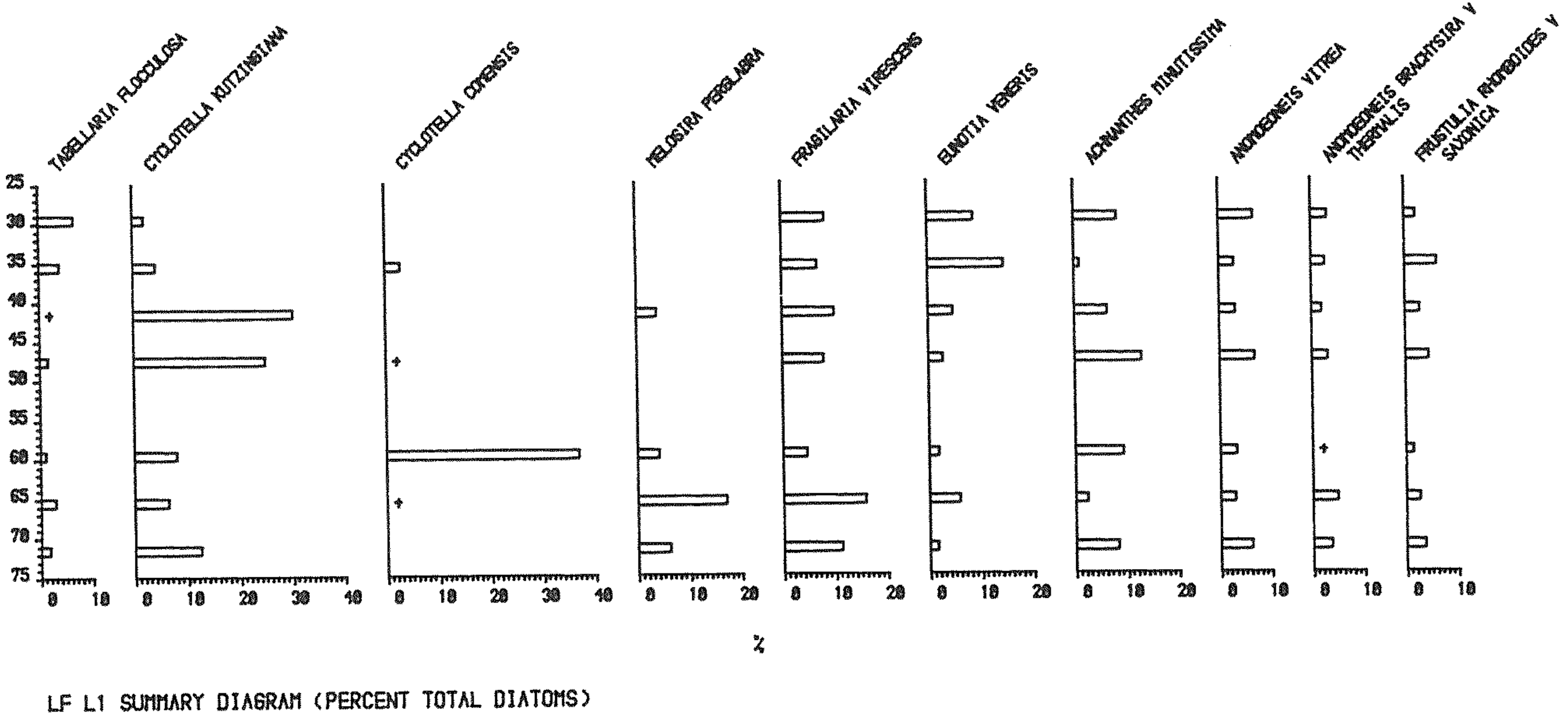


Fig. 29 LF L1 summary diatom diagram.

from about 5.6 to 4.6. Overall the data suggest that there has been a decrease in pH of between 1.0 and 1.5 pH units between about 1960 and the present.

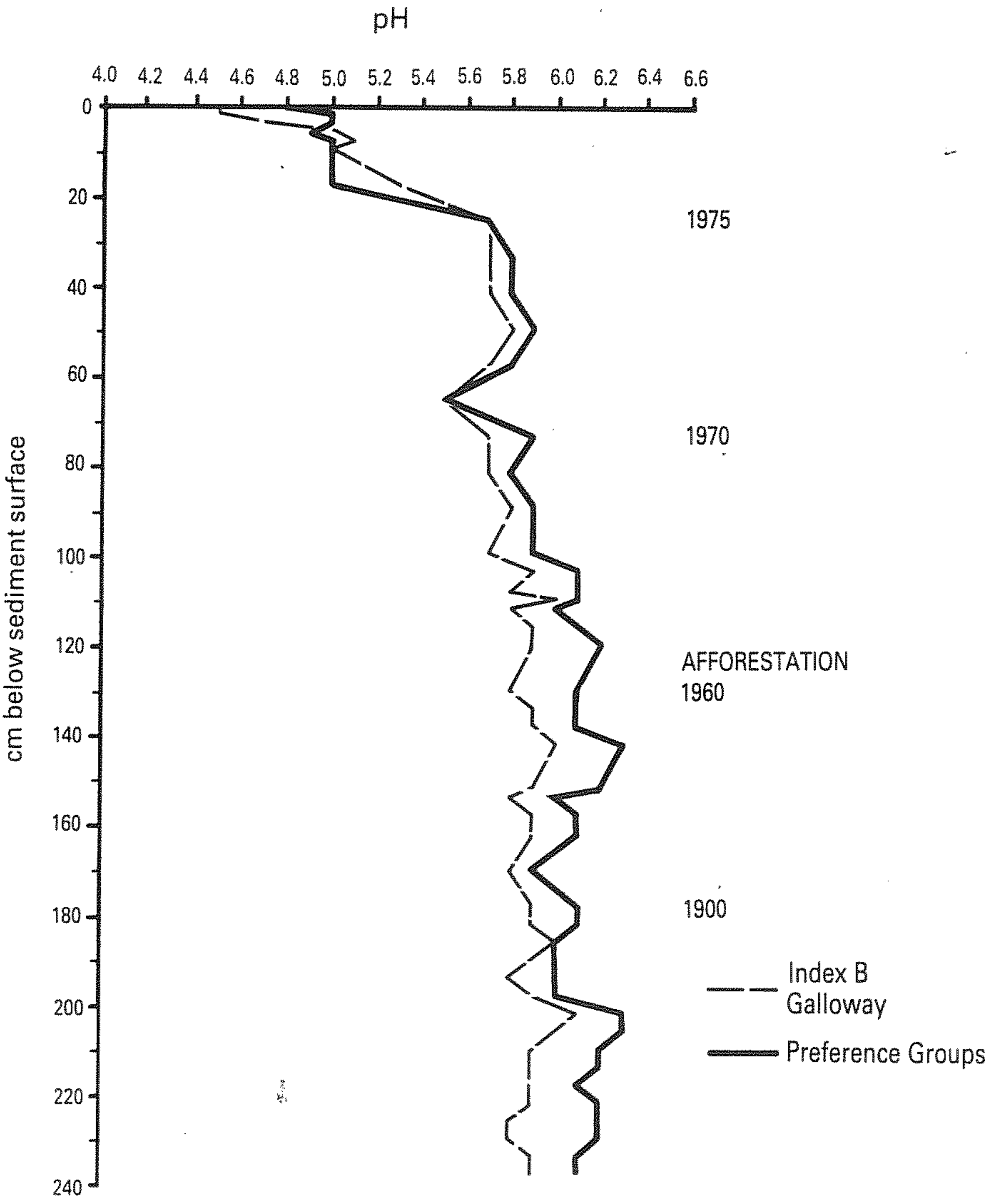


Fig. 30 LF L3 pH reconstruction: Index B and MR Preference groups.

9. DISCUSSION AND CONCLUSIONS

9.1 Sediment distribution

It is clear from the foregoing that **sediment distribution in space and time in L. Fleet is complex and this is manifested by both the asymmetry of sediment accumulation within the basin and the occurrence of substantial hiatuses,** some of which are not apparent from visual inspection of the cores. Loch Fleet is not unusual in this respect; it can be regarded as an extreme example of sediment distribution in wind-stressed upland lakes in the UK where basin shape and orientation in relation to dominant wind directions influence the patterns and limits of organic sediment accumulation.

9.2 Sediment hiatuses - the beginning

The occurrence of hiatuses is a logical consequence of the above. Hiatuses are likely to occur in any lake at any time as the preferred foci for sediment accumulation shift through time. This is true for L. Fleet and accounts for the variation in time for the beginning of hiatuses at different places within the lake.

However, it is also our belief that the main hiatus in L. Fleet (c 5000 BP - 1800 AD) occurs throughout the basin. This implies either that sediment was not being produced in the loch and its catchment or that the material produced did not accumulate but passed instead down the outflow. The former implication is clearly inappropriate; the latter is highly probable. Since organic sediment does not accumulate in the deepest water it is clear that there is sufficient energy within the system to maintain sediment in suspension within the water column. This not only allows sediment to be deposited on the northern slopes of the basin but also allows some of it to be lost down the outflow. In the early post-glacial period the balance between seston production and outflow loss must have been positive allowing sediment accumulation to take place in the basin. A change in this balance would then have occurred allowing no net storage of seston. Indeed such a change may have led to the resuspension and loss of sediment deposited from an earlier period.

Precisely when and why such change occurred has not been established. 14C dating can be used to fix a lower limit. The cause of the change is conjecture although establishing its timing would allow some of the possibilities to be evaluated. So far it appears that the hiatus occurs at or somewhat after the elm decline, about 5000 BP, when animal husbandry was first introduced in Britain and when Neolithic man began to clear the forests. Most workers would agree that these developments would lead to an increase in erosion and sediment yield to the lake and conditions should be in favour of sediment accumulation rather than the opposite. However, it is also known that thermal stratification is sensitive to changes in shelter and it could be argued that the loss of native forests in the catchment at this time led to an increase in exposure, greater seston suspension and a net loss of sediment from the lake. A change in wind pattern and strength could have produced similar results. It is interesting to note that sediment is now accumulating in many new areas of the lake following afforestation. Whilst this is likely to be related to the major peat inwashes caused by catchment ploughing, the pattern of accumulation might also owe something to the renewed shelter offered by the coniferous plantation, especially since this is sited on the upwind shore.

9.3 Sediment hiatuses - the end

In cores L1 and in 8 of the mini-cores the renewal of accumulation is related to the major increase in sediment supply to the lake from post-ploughing catchment erosion. In core L3, however, it seems beyond doubt from the 210Pb data that the renewal of accumulation in that part of the lake began in the early nineteenth century. Whilst this is very convenient for our lake acidification study it is difficult to explain. In the absence of increased shelter it can only be argued that thischange reflects an increase in sediment supply to the lake 200 or more years ago. In the core from Round Loch of Glenhead we observed a very distinct increase in organic matter content in the sediment that we equated with the beginning of blanket peat erosion a few hundred years ago, perhaps as a result of climatic change (Little Ice Age) in conjunction with the introduction of sheep grazing and moorland burning. It is possible that we are seeing the same record in the sediments of Loch Fleet. The high Pteridium values and the temporary depressions in Isoetes percentages in the pollen record are consistent with burning and erosion respectively (Fig. 13) and the sudden increase in plankton in the diatom diagram at 208 cm (Fig. 27) suggests a nutrient input perhaps as a result of a significant catchment fire. In addition, and quite independently the magnetic data also suggest an increase in catchment derived material during the nineteenth and early 20th century. From these observations we can argue, whatever the cause, that a renewal of sediment accumulation in a limited region of the lake at the centre of the preferred accumulation zone is not necessarily unexpected.

9.4 Chronology and sediment accumulation rates.

9.4.1 Early post-glacial sediments

Both cores L1 and L3 contain early post-glacial sediments, the extents of which can be approximately assessed from the pollen data (Figs. 13 & 14). In L1 the sediment spans 9000-5000 BP at an approximate accumulation rate of 0.18 mm yr-1, whereas L3 spans the same time interval but with a mean accumulation rate of approximately 0.28 mm yr-1. 14C dates are required for more accurate dating and accumulation rate estimates.

9.4.2 c.1800 - 1963 AD sediments

Only core L3 contains an appreciable thickness of sediments of this age. The 210Pb data show that the accumulation rate of sediment over this period varied from 0.4-2.8 cm yr-1. This is a very high accumulation rate compared with rates of c 0.2cm yr-1 at Round Loch at this time. In addition it should be realised that this rate is core specific and not a mean rate estimated for the basin as a whole and inter-basin comparisons cannot be made on a single core basis. In the case of L. Fleet the whole-basin rate is likely to be quite low if it is assumed that the focus of accumulation during this period was of small size.

9.4.3 post 1961-63 sediments.

The erosion and inwash caused by pre-afforestation ploughing in the catchment in 1963 is clearly marked in all cores although the precise record varies from core to core. In core L1 and L2 the first indication of catchment erosion is the LOI decrease and bulk density increase at 60 cm and 65 cm respectively. These levels are characterised by iron oxide bands presumably the result of oxidation of reduced iron species in the sub-peat horizons of the catchment following ploughing and their subsequent transfer to the lake. Above this LOI values increase rapidly to over 50% as newly exposed catchment peats in the banks of drainage ditches are eroded. In L3 the iron oxide bands are absent but the sudden increase in organic content is clear. Shortly after this major change in sediment structure the accumulation rate data from the 210Pb dating (Fig 12) shows the major inwash to have occurred perhaps 3-4 years after afforestation when accumulation rates for 4 years after reached 10 cm yr-1 at this site. These rates decline rapidly from the peak in 1970-71 in parallel with the loi values, suggesting the progressive stabilisation of the ploughed part of the catchment as drainage ditches become vegetated, as the canopy closes and as the growing forest intercepts and evapotranspires an increasing amount of incident precipitation. The present sediment accumulation rate for this part of the lake is 1.47 cm yr -1 (0.114 g cm-2 yr -1)

It is clear from the mini-core loi profiles (Fig. 3) that this enormous inwash not only caused a dramatic increase in sediment accumulation rates at the L1-L3 sites but that it caused sediment to accumulate over additional parts of the lake bottom, either areas where sediment had not accumulated since c 5000 BP (see above) or directly over late-glacial clays (eg. at M4, M8, M10, M15, and M24; Fig. 3). An estimate of the area of recently covered lake bottom could be made from our present data although more cores would be required to establish the precise amount and to estimate the total mass of catchment peats inwashed since 1963. The possible influence of this on the acidification of the lake would depend on the cation exchange capacity of the late-glacial clays and the area of clays covered by the inwashed material, and on any reduction of within-lake alkalinity generation caused by the abrupt change in sediment type in contact with the water.

9.5 Vegetation and land-use history

The size of the sediment hiatus limits the potential of the sediment sequence as a record of lake and catchment history to the early post-glacial period and to the post 1800 period. For the early period the pollen record shows a typical forest sequence for this part of Scotland with a pre-boreal and boreal pine-birch forest being replaced by mixed deciduous woodland as climate improved and woodland trees migrated from southern refugia. The precise correlation with other local profiles requires 14C dating.

The post 1800 pollen spectra are characteristic of upland blanket peat sites, dominated by *Calluna*, Cyperaceae, and Gramineae, although tree pollen from lower altitude sites are present. Throughout the period there is evidence of catchment disturbances possibly as a result of fires indicated by high *Calluna* values, low *Isoetes* values, peaks in LOI and SIRM, and, in the case of the 196-208 cm event (Fig. 16), a major increase in *Cyclotella comensis*, a planktonic diatom. Although the pollen record shows an increase in coniferous pollen in the uppermost sediment, the best evidence for the afforestation of the catchment in the 1960's is the very pronounced increase in the organic content of the sediment and the sudden increase in rate of sediment accumulation following the ploughing and subsequent erosion of peats in the catchment.

9.6 Air quality history

Almost all lake sediments in industrial areas are characterised by elevated concentrations and fluxes of heavy metals in recent sediments. Loch Fleet is no exception but the record is less easy to read because of the hiatus and because of the effect of the major inwash. The absence of sediments between 5000 BP and 1800 AD prevents the establishment of baseline trace metal values for the period immediately prior to the industrial revolution. Baseline values from the pre 5000 BP sediments at Loch Fleet and from more recent sediments at closeby sites eg Round Loch and Loch Enoch can be used as substitutes (Battarbee *et al.* in prep.). For Loch Fleet the early post-glacial flux for Pb was less than 1 ug cm-2 yr-1, derived from the catchment. The modern flux of about 100 ug cm-2 yr-1 is a measure of the enhanced flux from atmospheric sources. A clearer indication of the atmospheric component of these trace metal fluxes can be seen in the sediments of lakes with undisturbed catchments.

The carbonaceous particle record also reflects air pollution history but in a somewhat different way. It specifically represents the deposition of particles from fossil fuel combustion processes and much of the material is likely to be derived from power stations. The carbonaceous particle record in the L. Fleet sediment is strongly influenced by the inwash event and by the speed of accumulation of sediment prior to the inwash. As a result the record, when compared to less disturbed systems, is rather patchy and clear trends are only observed in the uppermost post-1970 sediment (Fig. 22). A very marked rise in concentration and flux of particles can be seen over this time interval. This is atypical for the non-afforested sites so far studied and suggests some relationship between the deposition of particles and the growing forest. A similar change is shown by the magnetic parameters over the same time interval (cf Fig. 15) and possibly suggests a common origin for these materials.

9.7 Lake history - evidence from the diatom record

The diatom diagram as yet only includes the upper 240 cm and is considered to represent the post hiatus (post about 1800 AD) sediment and the upper part of the pre-hiatus sediment (pre about 5000 BP). The hiatus is thought to occur at about the 210 cm level (Fig. 27).

The early nineteenth century sediments contain a diatom assemblage typical of pre-acidification Galloway lakes and is particularly similar to the pre-1900 flora of Loch Dee. The planktonic species Cyclotella kutzingiana is well represented and the pH reconstruction gives a value of pH 6.0. Except for a very pronounced peak of Cyclotella comensis at about 200-208 cm there is virtually no change in the flora until about 100-110 cm. There is also little difference between the assemblage at 240 cm, which we assume to relate to mid post-glacial times and the pre-afforestation flora suggesting either that conditions have remained the same for at least 5000 years prior to the post afforestation acidification or that conditions have returned to those of the mid Postglacial following a change that is not recorded due to the presence of the hiatus. It is possible that the C. comensis peak is a remnant of that assemblage. This latter interpretation, however, is far less likely than the former since stability over such long periods have been demonstrated from other Galloway sites (Jones et al. 1986).

The early C. comensis peak is particularly interesting in this context since it clearly represents a short lived disturbance in an otherwise stable system. Such a stimulus to the plankton is likely to be the result of a sudden nutrient inwash that could only be derived at that time from a severe burning of the catchment. This event is recorded independently in the pollen diagram, in the magnetic record, and in the LOI record (Figs 16 & 17) and taken together suggests there was a peat inwash at that time. In the pollen record there is a very pronounced decrease in Isoetes, a species well known to be sensitive to turbidity and light penetration, and a significant peak in Calluna and Sphagnum spores that could be caused by a soil inwash. SIRM and ARM values also peak at this time and there is a spike in the LOI profile (Fig. 16) indicating an inwash of organic material. A small increase in the Pb concentration at this point (Fig. 19) also seems to be related to this event.

Despite this event the stability of the flora up to the point of afforestation in 1963 is remarkable since at all other sites on granitic rocks so far examined in Galloway acidification has occurred in the nineteenth century or shortly thereafter. Even Loch Dee that has a substantial part of its catchment on non-granitic rocks shows a clear acidifiction from about 1890 onwards; Loch Skerrow, similarly situated lost its Cyclotella plankton in the nineteenth century, and Lochs Grannoch, Enoch, Valley, and the Round Loch of Glenhead, sites wholly on granite completely lost their alkalinity during this period. For L. Fleet there is no tendency towards acidification despite the increased acid loading that is likely to have taken place especially in the period from 1930-1970. **The implication of all this is that there must be one or a number of sources of alkalinity in the Loch Fleet catchment that do not occur or are not as important at other sites,** even the neighbouring Loch Grannoch. In fact the pH reconstruction, as well as the presence of a well developed plankton in L. Fleet show that L. Fleet has probably had a significantly higher alkalinity than L. Grannoch throughout the recent two centuries.

The effect of the ploughing and afforestation at 110 cm (1963) is dramatic for the plankton and for the meroplanktonic Melosira taxa all of which decline to almost zero values, but has little effect on the attached flora, especially the circumneutral Anomoeoneis vitrea and Achnanthes minutissima. The difference in response between the two habitats suggests that the inwash of catchment peats is not an important acidifying event. Its influence on the plankton is more likely caused by increasing water turbidity and decreasing light penetration (a sharp drop in Isoetes spores also occurs at this time). The small drop in the reconstructed pH values may be partly real, partly an artefact of this habitat loss. An almost identical change occurred in the Round Loch at 40 cm, when the plankton decreased, and Isoetes decreased in response to peat erosion some 3-400 years ago or more.

The contrast with Loch Grannoch at this time is striking. Like Loch Fleet the catchment was afforested in the early 1960's but the pH of the lake has declined to about 4.5 prior to afforestation. Following afforestation there was a small increase in reconstructed pH which we argued was not related to a change in water quality but to the input of acidophilous diatoms with the eroding peats (Battarbee & Flower 1985). We expected a similar story at Loch Fleet but the situation here is clearly different. There is no pre-afforestation acidification, and although there is a tremendous peat inwash it cannot have contained many diatoms, since the post-afforestation diatom assemblage is dominated by circumneutral taxa that would not be found in peats and the diatom concentration is proportionately diluted by the increased sediment accumulation (cf Fig. 28). We can be confident therefore that the water pH in the lake for the period shortly after afforestation was close to the reconstructed pH of 5.7-5.8 suggested by the diatom model. In fact the data indicate that these conditions continued until very recently and after the period of maximum inwash.

A very sudden and acute acidification of the lake is registered in the uppermost 25 cm of sediment. The 210Pb dates suggest that this is equivalent to about 1975-6. The diatom changes that take place are identical to those observed at other sites over much longer time periods. Typically Anomoeoneis vitrea and Achnanthes minutissima decline and Eunotia veneris increases, and then as the lake permanently loses its alkalinity Tabellaria quadriseptata, Tabellaria binalis and other acidobiontic taxa take over. In Loch Fleet this sequence is compressed into a 10-15 year period and is more reminiscent of the rapid changes that have taken place in Sweden and Finland than in Galloway. It is even more remarkable that it occurs at a time when acid deposition has been decreasing.

9.8 Causes of acidification

If it is assumed, as seems reasonable, that the major inwash is caused by the 1961-3 deep ploughing of the catchment, a feature that is independently dated to about 1964 by 210Pb analysis, the following conclusions can be made:

1. No acidification of the lake occurred until at least 1960

2. Initial catchment ploughing and planting did not cause acidification although it did cause an abrupt elimination of the diatom phytoplankton, probably because of a sudden deterioration in light climate associated with inwashed material.

3. Acute acidification of approximately 1 pH unit from about 5.6 to 4.6 occurred starting in the mid 1970's.

It has been argued above that the lack of early acidification compared to other sites in the region must be related to unknown sources of alkalinity in the catchment, and that these sources were able to neutralise the effects of acid deposition and any additional acidity caused by peat drainage and erosion even at the peak of these influences in the 1960's. The main acidification occurs at a time when acid emissions (and deposition) have been declining. Acid deposition cannot therefore be the direct cause of the acidification.

Two main catchment changes have taken place during the last 20 years, the afforestation and the halting of catchment burning and grazing in the non-afforested part of the catchment. Although periodic burning may have produced temporary nutrient and alkalinity pulses (see above for example) there is no evidence that a halting of this process can cause the kind of acidification recorded here (Jones et al. 1986). Indeed the process is so rapid that if it were the cause acidification trends between burnings would be expected in pre-afforestation times, and this is not the case.

The effect of afforestation, on the other hand can be more dramatic. The data suggest that acidification began when the forest was about 10-12 years old. It has been established that throughfall and particularly stemflow is much more acid than incident precipitation in maturing Sitka spruce stands in the Loch Fleet catchment and that further acidification can occur in the litter layer (Nesbit & Leach pers. comm.). In places where the underlying soils have little neutralising capacity this acidity is likely to be passed on to surface waters.

9.9 Implications

9.9.1 Mechanisms of acidification involving afforestation

It seems beyond doubt that the acute acidification of Loch Fleet is associated with afforestation but our observations suggest that initial ploughing and planting are not the cause. The acidification occurs well after the establishment of the forest. Either the trees themselves are the source of considerable acidity through cation exchange by the needles or, despite the recent fall in acid deposition, they become very effective scavengers of acid aerosols when they are 10+ years old.

Other factors may also be involved. It is interesting to note that the acidification is coincident with steeply rising fluxes of carbonaceous cenospheres and magnetic minerals of atmospheric origin in the sediments. This pattern is unlike non-afforested sites and suggests that the forest may enhance dry deposition over the lake surface. And a further factor might be the loss of lake neutralising capacity caused by the covering of mineral sediment in the lake by eroded peats following the catchment ploughing.

Some of these putative mechanisms are related only to afforestation processes but others point to an interaction between the forest and a polluted atmosphere. A comparison of Loch Fleet with a similarly afforested site in an area of low acid deposition would allow some of these inferences to be evaluated.

9.9.2 Sources of alkalinity.

Since the main inflows to the loch outside the planted area are highly acidic the sources of alkalinity in the catchment are not obvious, which suggests they must be associated with groundwater flow and are not readily apparent. If they are associated with the afforested side of the catchment or are derived through the lake sediments the sudden collapse of neutralising capacity would be easier to explain.

9.9.3 Fish history.

Loch Fleet had a good brown trout fishery up until the 1950's. Our data on loch acidity is consistent with this, and the situation contrasts markedly with the situation on the Loch Doon granite where marked declines in fish stocks at Loch Enoch, Round Loch (?), and Loch Dee, all followed evidence from the diatom record of earlier acidification. In Loch Fleet the fish decline can be divided into three stages, the initial decline in the mid 1950's, the drop to residual levels in 1965, and the elimination of fish in 1975. (Fig. 31).

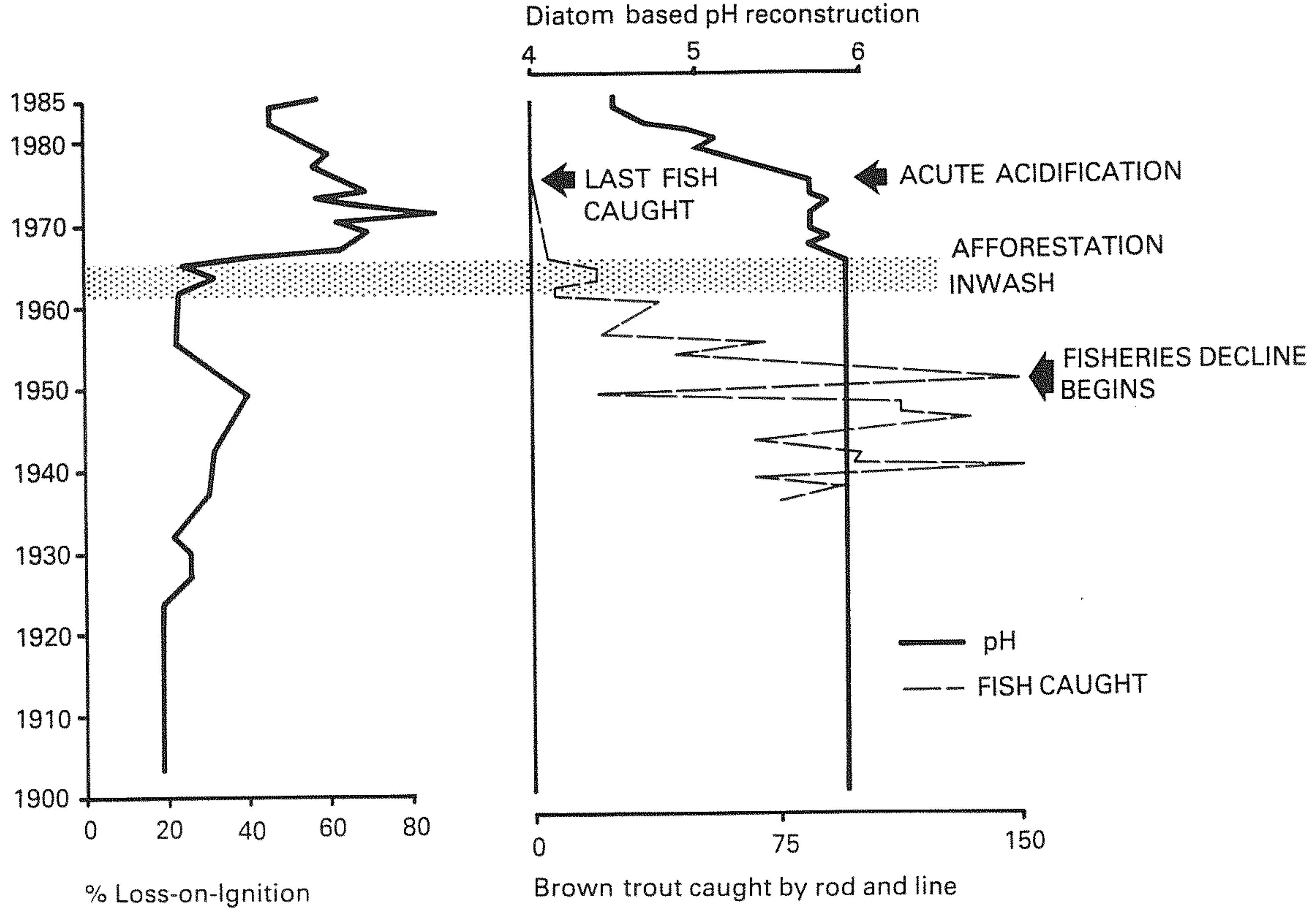


Fig. 31 LF L3: LOI and pH reconstruction compared with fish history.

Clearly the explanation for these changes is more complex than originally thought. The initial decline occurred at a time when general water quality for fish survival in the lake was good. However, following the above discussion on sources of alkalinity, it is likely that many of the catchment streams were strongly acidified as a result of acid deposition by this time and spawning in the main inflow would presumably have become very poor at a time when considerable fishing was taking place (Loch Fleet News 5). We would therefore attribute this early decline to poor recruitment, although this would be to some extent invalidated were the outflow stream an important spawning area or were there a higher alkalinity spawning stream in the afforested area. If this were the case then overfishing or unsuitable stocking (?) could have been the main cause of the decline. The most significant decline in fish stocks occurred between 1964 and 1965, the year after the catchment was planted. The dramatic erosion following the ploughing of the catchment has already been described. It led to the loss of the phytoplankton and to a major reduction in the growth of Isoetes, the dominant submerged macrophyte in the lake. It would not be surprising if this event also caused a sudden decline in the fish population to residual values. The inwash was short-lived but the fish population did not recover despite the reasonable quality of the lake water. If a spawning site had existed in the now-afforested area this would no longer be available, and the only spawning area with suitable water quality in the late 1960's and early 1970's would have been the outflow. However, any chance of a recovery from this base would have been eliminated when the lake water itself became acidified in the 1970's. The last fish was caught in 1975; perhaps a coincidence but at precisely the time the acute lake acidification took place.

We would argue therefore that the fish history is related to the forest history and acid deposition history, in a complex interrelated way.

9.9.4 Management policy.

If we are right then the natural way to restore a viable fish population to the loch is not to lime or burn, but to carefully clear the catchment of trees, and to locate the natural spawning areas of trout that undoubtedly occurred in the 1950's, when acid deposition was probably at similar levels to today. These must have been in the afforested area or in the outflow, since the non-afforested inflows are acidified and must have also been acidified in the 1950's.

The data presented here clearly indicate that Loch Fleet is not typical of the many lakes throughout the United Kingdom where acidification has occurred over the last century and has been primarily due to acid deposition. It may prove to be more representative of lakes that have only become acidified very recently either as a result of afforestation or as a result of a combination of forest growth and acid deposition.

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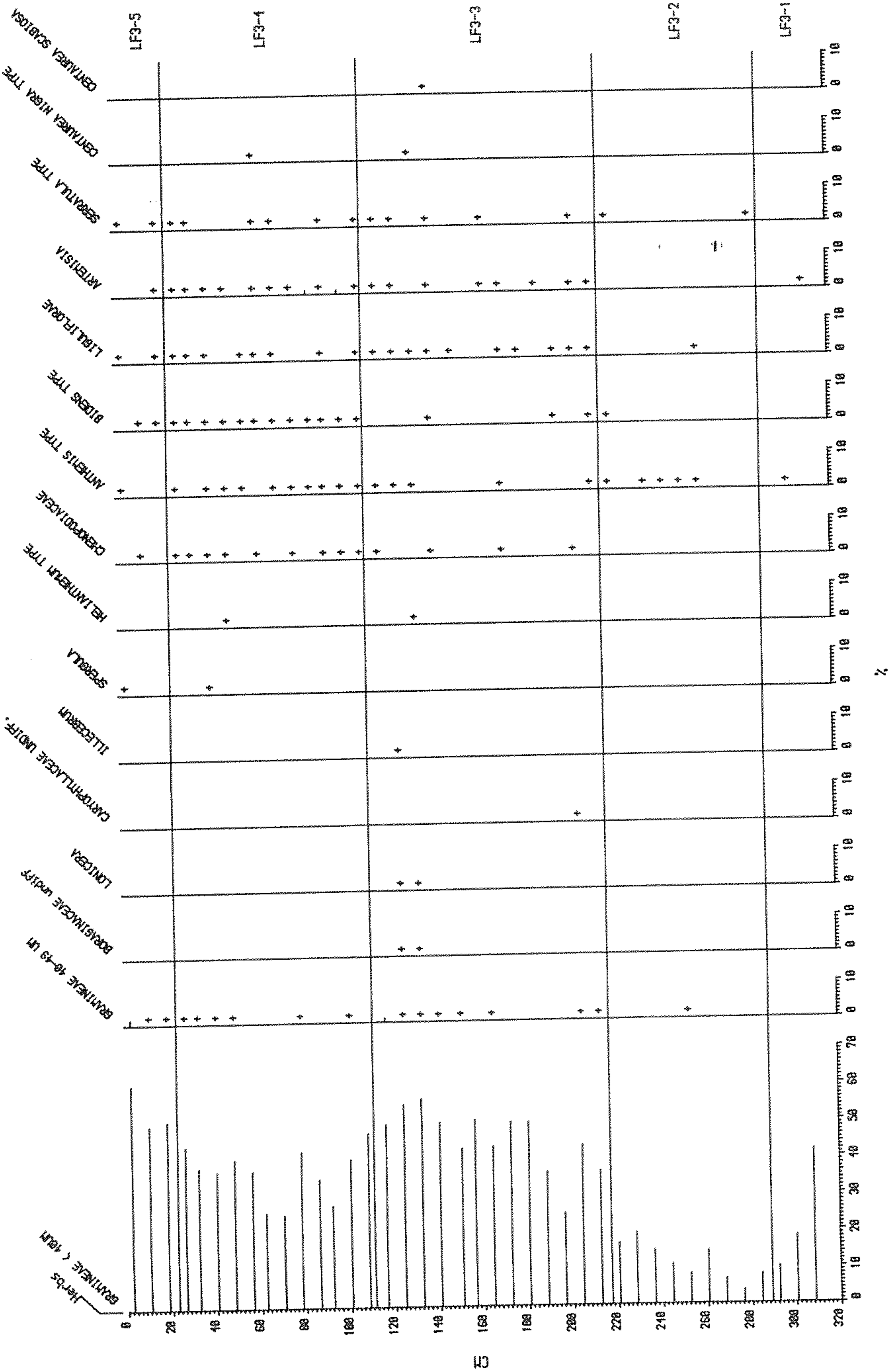
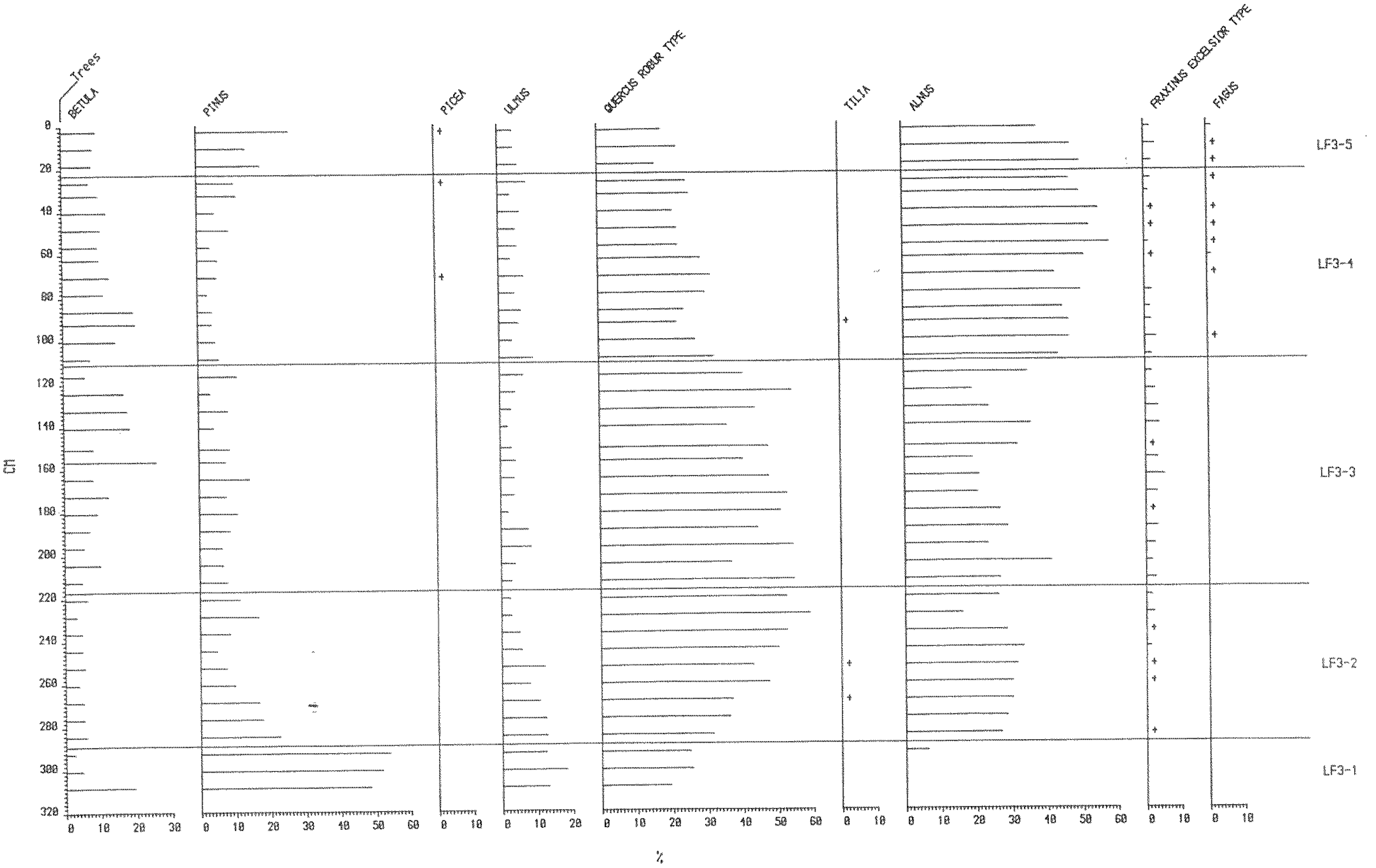
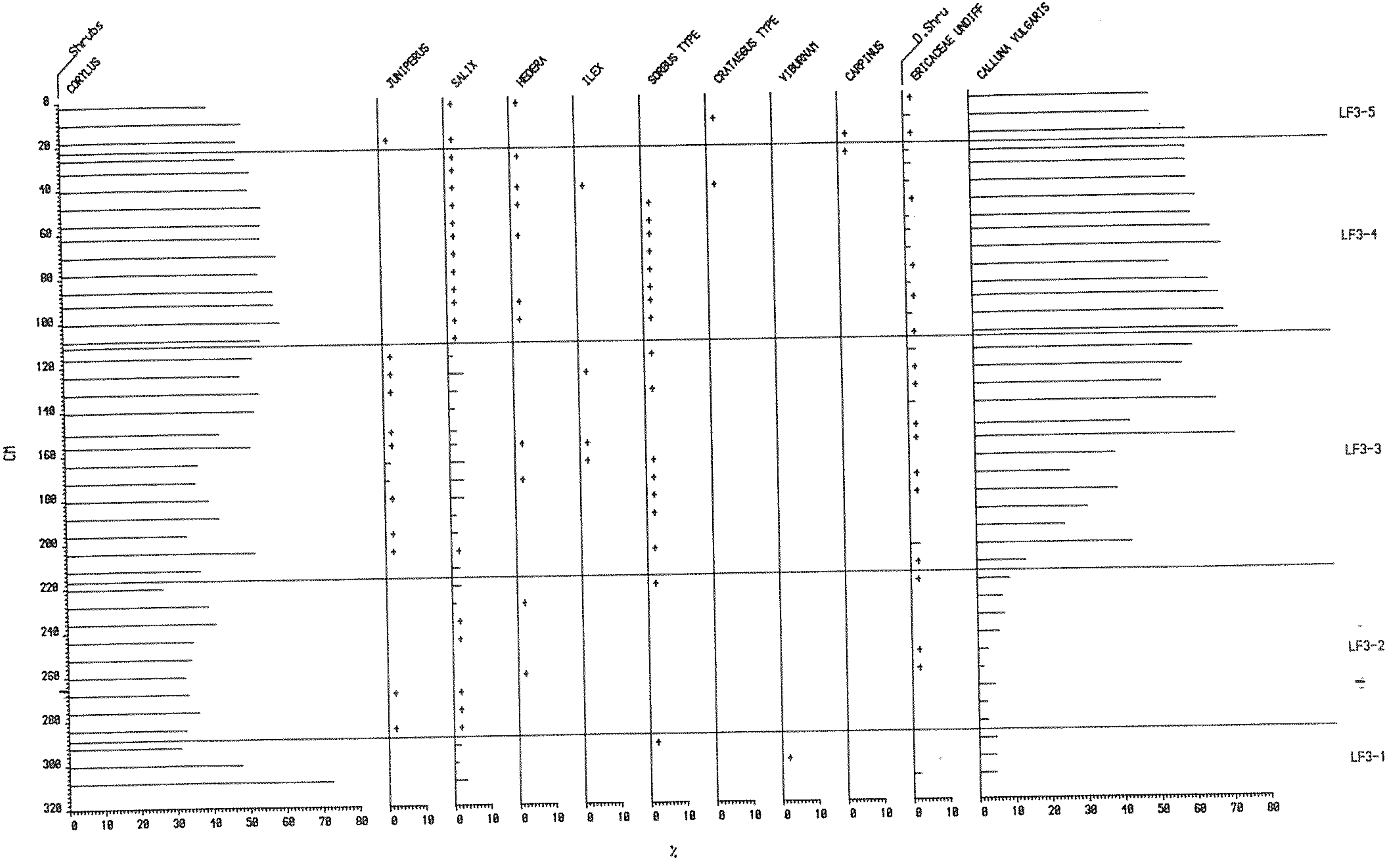


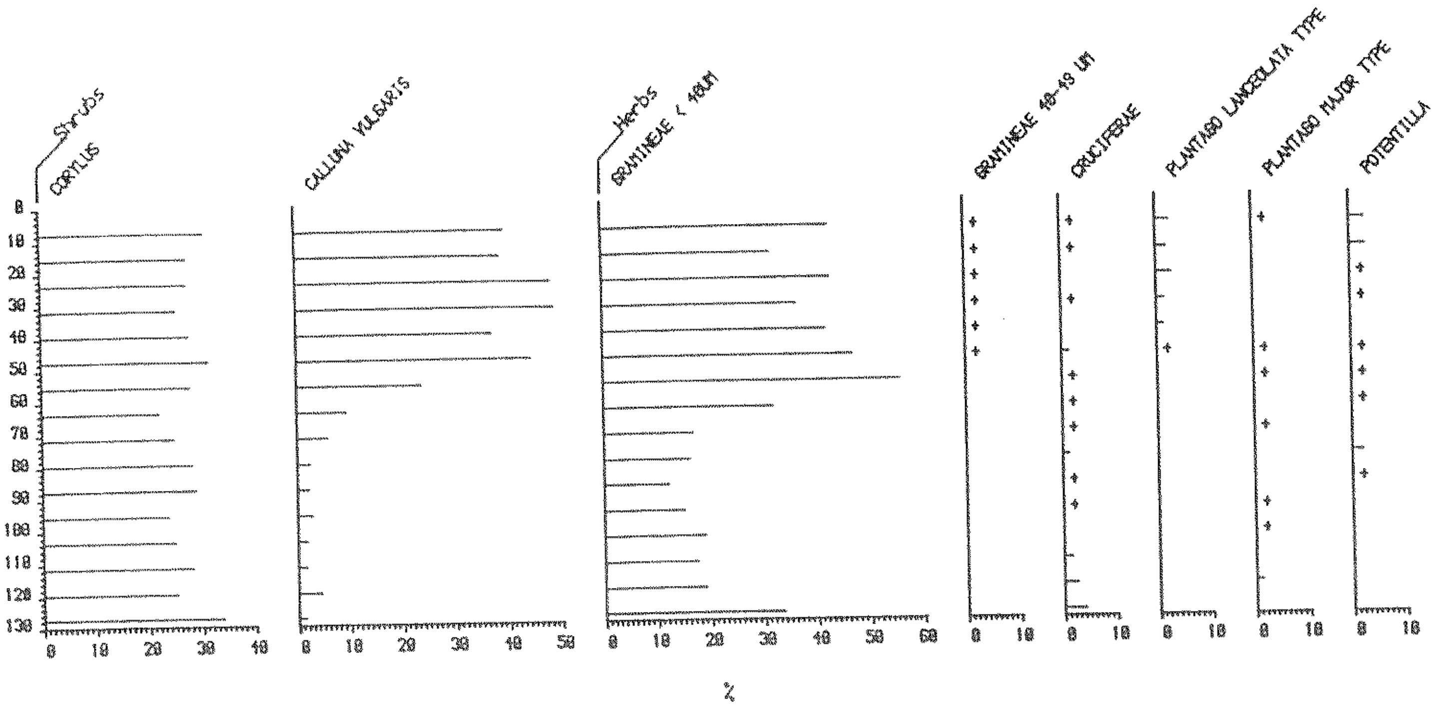
Loch Fleet %AP+Herbs



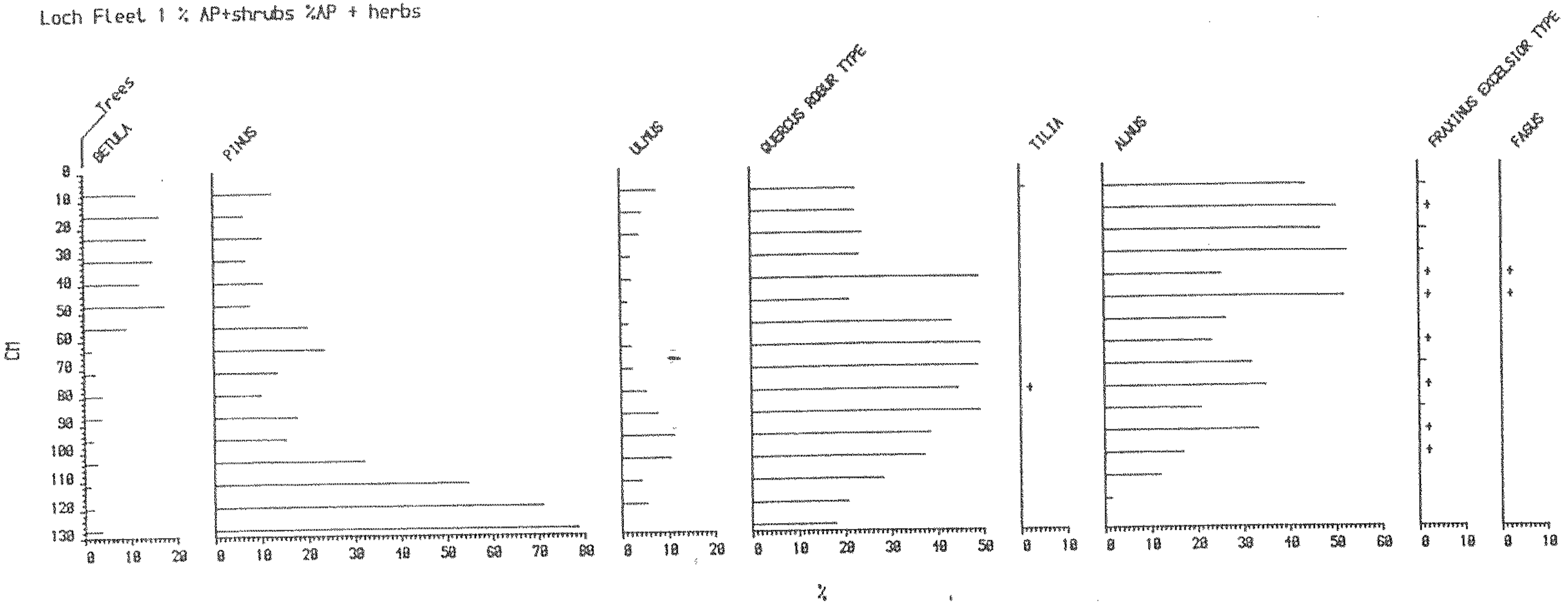
Loch Fleet 3 % AP



Loch Fleet   Shrubs %AP+Shrubs   DwF Shrubs %AP+DwF Shrubs



Loch Fleet 1 % AP+shrubs %AP + herbs



Loch Fleet 1 %AP

Appendix B: Summary Diatom Data
Kajak Surface Sediment Samples

Kajak	Depth	Tabellaria quadriseptata	Eunotia veneris	Frustulia rhomboides v. saxonica	Cyclotella kutzingiana	Eunotia pectinalis v. minor	Fragilaria virescens	Cymbella perpusilla	Eunotia alpina
1	1·00	19·3	22·5	10·9	0·6	4·5	0·6	1·3	1·6
2	2·71	7·8	32·5	7·0	1·3	2·9	3·1	3·9	2·9
3	4·47	17·9	14·4	8·5	0·7	2·6	1·3	5·0	1·7
4	8·60	9·9	17·1	11·3	1·3	3·0	0·9	4·1	2·6
5	10·70	21·4	16·4	6·3	0·5	2·3	4·4	3·1	1·0
6	14·10	17·8	20·5	6·5	1·4	1·8	1·4	4·5	2·3
7	9·50	19·4	13·7	9·0	1·0	4·1	1·8	4·5	3·9
8	7·20	18·6	17·3	9·6	0·9	2·9	1·6	3·4	2·5
10	6·60	2·0	21·0	7·2	0·7	2·2	2·0	9·0	2·4
20	8·95	13·8	15·8	5·7	2·0	2·9	1·1	4·5	2·3
21	3·70	11·7	15·7	6·8	1·2	3·0	3·5	5·1	1·4
23	4·00	3·9	9·5	5·0	1·7	6·1	8·7	5·8	0·6
25	4·00	6·9	9·8	4·7	14·3	4·1	9·2	2·0	0·4
28	2·20	0·4	15·2	4·7	0·0	7·3	13·1	1·1	0·6
29	4·35	12·4	13·8	8·3	0·5	2·1	2·8	2·5	0·7
30	6·94	15·8	11·5	7·1	2·2	3·2	5·6	3·9	1·3
31	9·50	2·5	18·4	5·0	1·0	4·8	5·4	3·3	1·9
32	12·70	18·3	11·4	7·4	1·6	2·2	4·5	4·3	2·0
33	14·60	16·1	18·6	9·0	1·3	2·7	1·8	3·6	1·3
34	11·00	17·3	19·6	10·6	1·5	2·5	1·2	1·2	2·2
35	6·80	4·1	13·2	6·6	14·8	3·6	6·1	2·0	1·5
36	8·20	4·0	14·5	5·7	2·4	7·1	10·7	2·6	1·2
45	9·60	10·2	23·0	7·9	0·7	4·1	2·3	4·5	2·8
46	12·70	21·1	11·6	7·3	0·0	3·3	2·1	4·0	2·8
49	6·40	8·8	10·3	5·5	5·5	2·0	4·0	3·0	2·5
51	1·30	12·0	16·7	7·3	0·5	2·1	4·4	3·9	6·5
70	2·40	0·8	11·0	2·3	11·8	7·2	6·0	1·6	0·8
71	2·00	9·6	20·6	10·3	1·5	2·0	1·5	1·5	8·1

Table App. B.1
Percentage Data

Appendix B: Summary Diatom Data
Kajak Surface Sediment Samples

Table App. B.2

Percentage Data

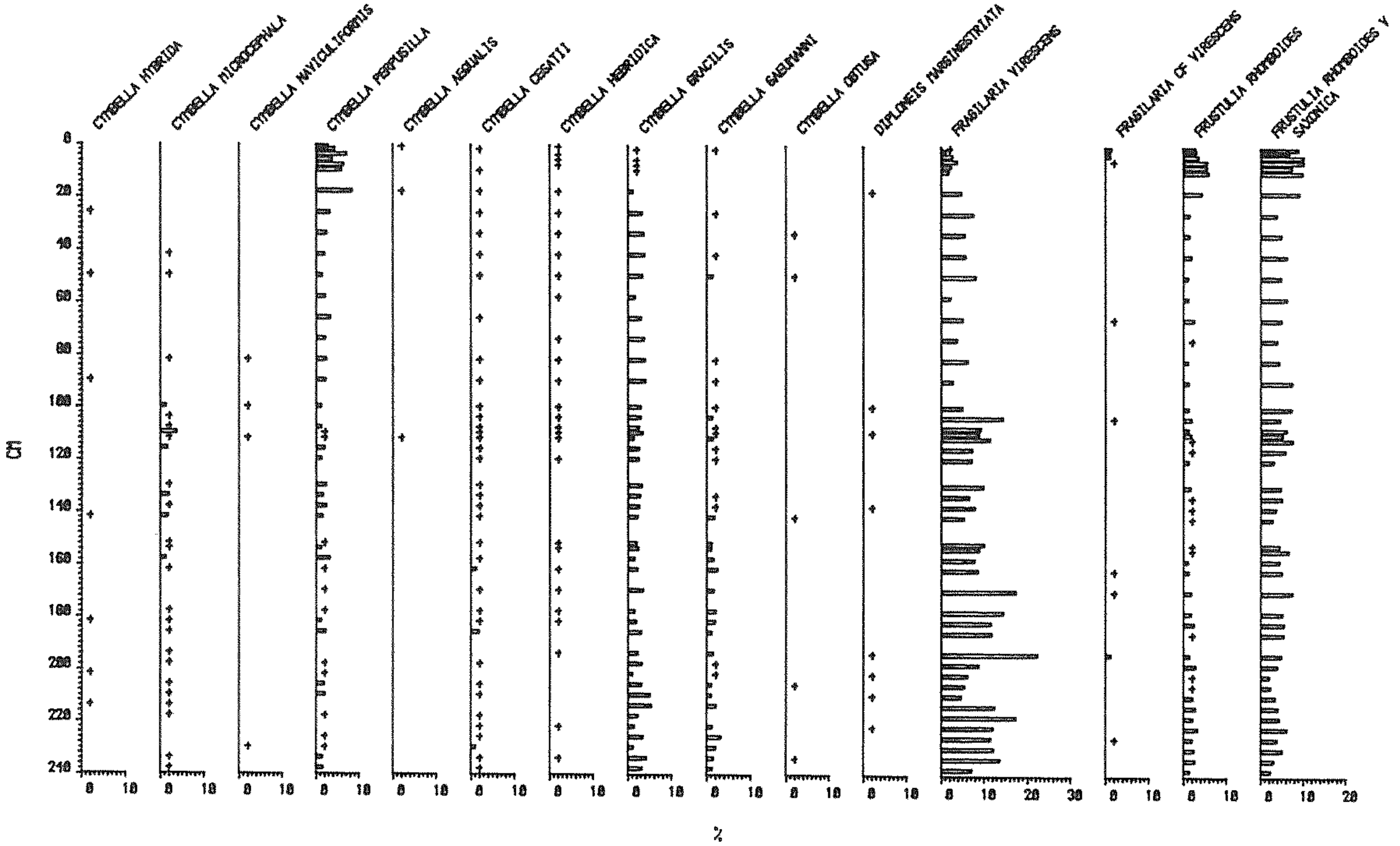
Kajak	Tabellaria quadriseptata	Eunotia veneris	Fragilaria saxonica	Cyclotella kutzingiana	Eunotia pectinalis v. minor	Fragilaria virescens	Cymbella perpusilla	Eunotia alpina
Mean	11·56	16·27	7·27	2·60	3·52	3·97	3·54	2·21
St. Dev	6·66	5·02	2·13	4·04	1·63	3·20	1·68	1·68
Max	21·40	32·50	11·30	14·80	7·30	13·10	9·00	8·10
Min	0·40	9·50	2·30	0·00	1·80	0·60	1·10	0·40

Table App. B.3

	Cell total Concen. x 10^7	Cell Concentration x 10^6							
Mean	13·76	14·49	21·7	9·16	4·01	5·28	6·30	4·58	3·13
St. Dev	5·84	8·32	11·5	2·98	7·82	5·00	7·26	2·37	8·01
Max	32·03	28·20	60·6	15·30	37·86	22·97	34·59	10·77	12·47
Min	2·16	1·13	4·9	2·37	0·0	0·97	0·14	0·28	0·35

Table App. B.4

	Cells cm^{-2} x 10^7	Cell Concentration cm^2 x 10^6							
Mean	1·32	1·11	1·99	0·83	0·72	0·55	0·70	0·40	0·25
St. Dev	1·36	0·80	1·82	0·78	2·04	0·71	1·10	0·35	0·26
Max	6·65	2·93	8·80	4·17	9·81	2·53	4·06	1·40	1·01
Min	0·10	0·12	0·20	0·10	0·00	0·03	0·01	0·01	0·02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CYMBELLA MICROCEPHALA
CYMBELLA NAVICULIFORMIS
CYMBELLA PERPUSILLA
CYMBELLA AEQUALIS
CYMBELLA CESATII
CYMBELLA HEBRIDICA
CYMBELLA GRACILIS
CYMBELLA GAEUMANNI
CYMBELLA OBTUSA
DIPLONEIS MARGINESTRIATA
FRAGILARIA VIRESCENS
FRAGILARIA CF VIRESCENS
FRUSTULIA RHOMBOIDES
FRUSTULIA RHOMBOIDES V SAXONICA
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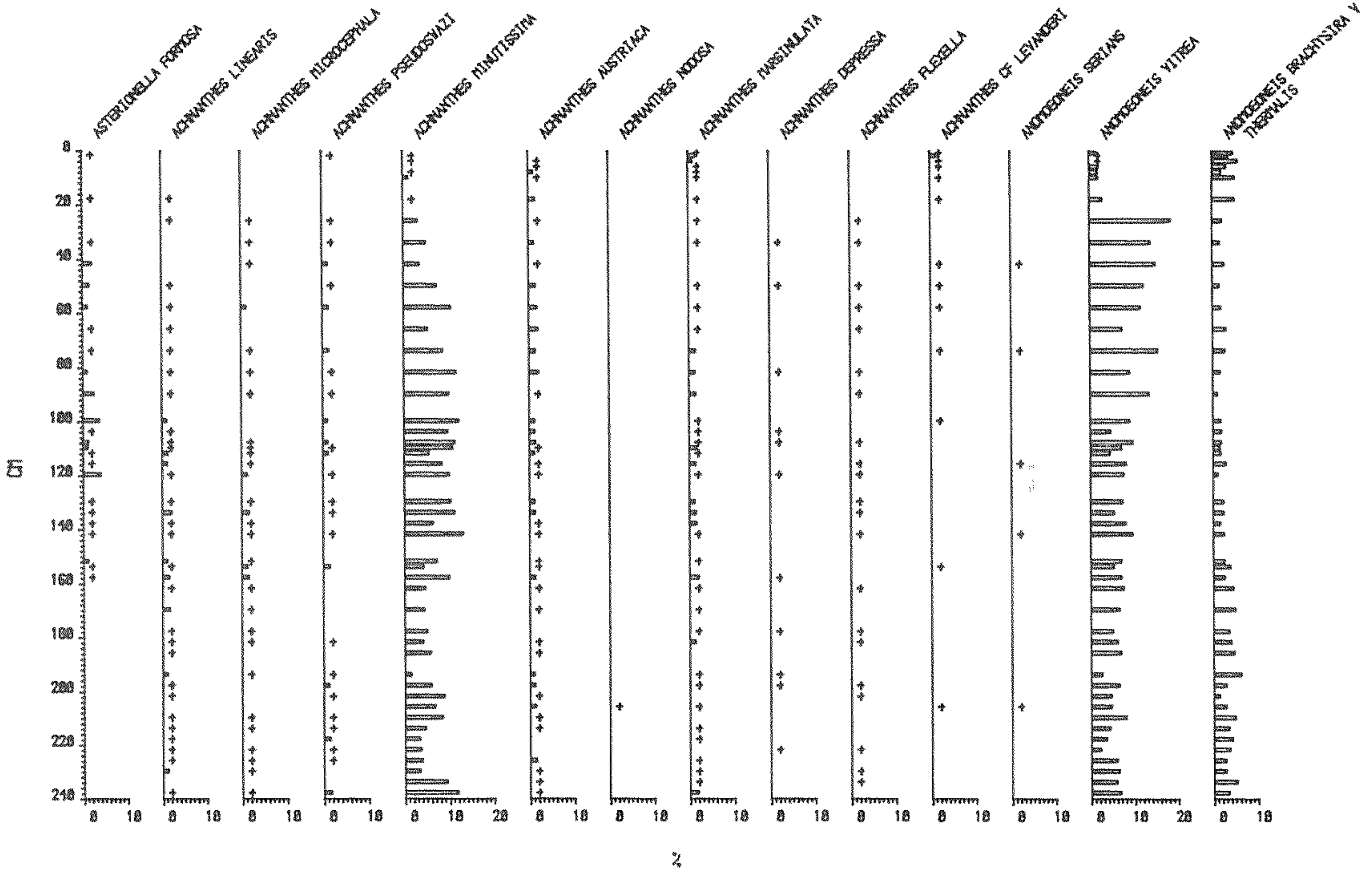
LF L3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ACHNANTHES LINEARIS
ACHNANTHES MICROCEPHALA
ACHNANTHES PSEUDOSWAZI
ACHNANTHES MINUTISSIMA
ACHNANTHES AUSTRIACA
ACHNANTHES NODOSA
ACHNANTHES MARGINULATA
ACHNANTHES DEPRESSA
ACHNANTHES FLEXELLA
ACHNANTHES CF LEVANDERI
ANOMOEONEIS SERIANS
ANOMOEONEIS VITREA
ANOMOEONEIS BRACHYSIRA V THERMALIS
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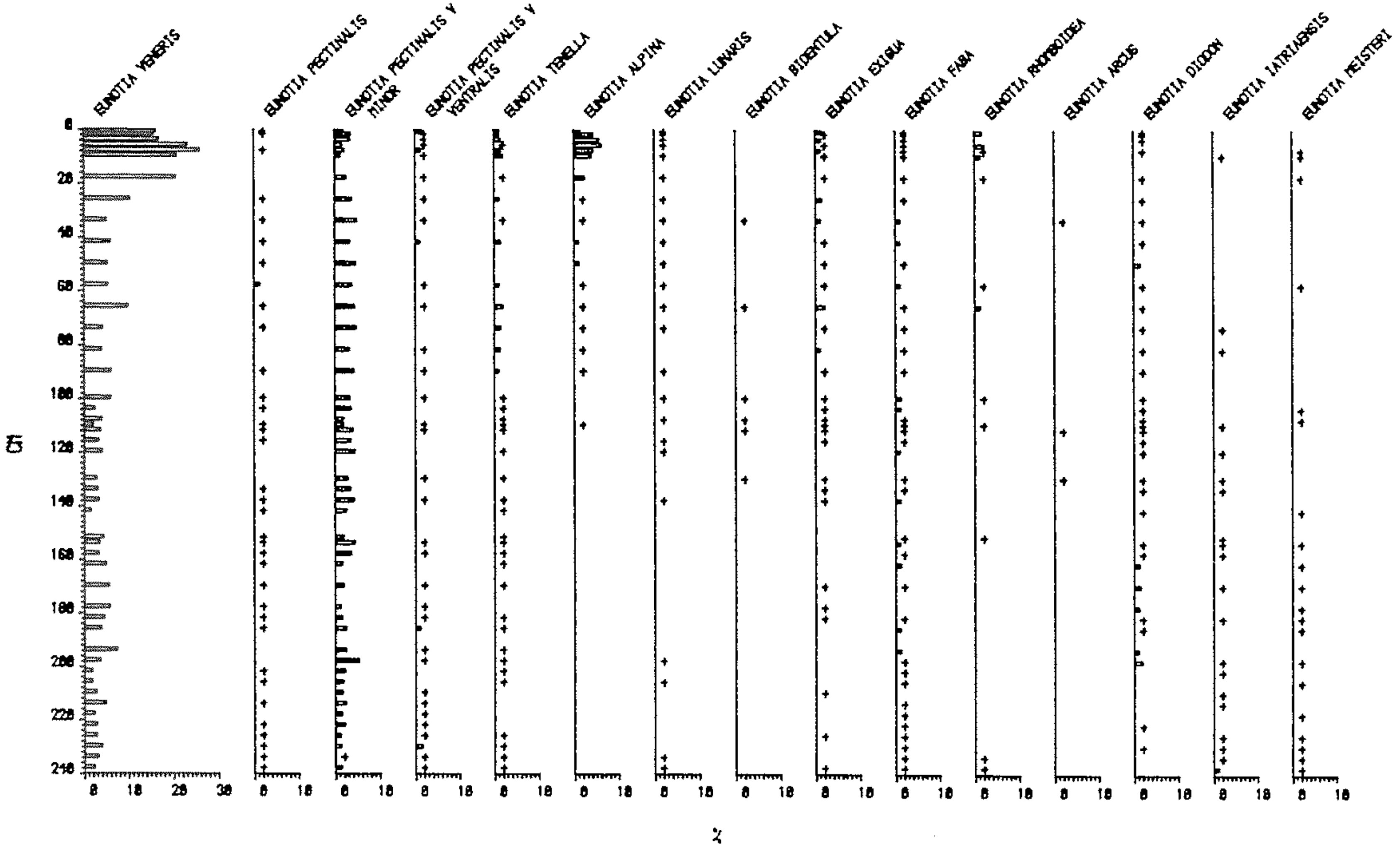
LF L3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EUNOTIA PECTINALIS
EUNOTIA PECTINALIS V MINOR
EUNOTIA PECTINALIS V VENTRALIS
EUNOTIA TENELLA
EUNOTIA ALPINA
EUNOTIA LUNARIS
EUNOTIA BIDENTULA
EUNOTIA EXIGUA
EUNOTIA FABA
EUNOTIA RHOMBOIDEA
EUNOTIA ARCUS
EUNOTIA DIODON
EUNOTIA IATRIAENSIS
EUNOTIA MEISTERI
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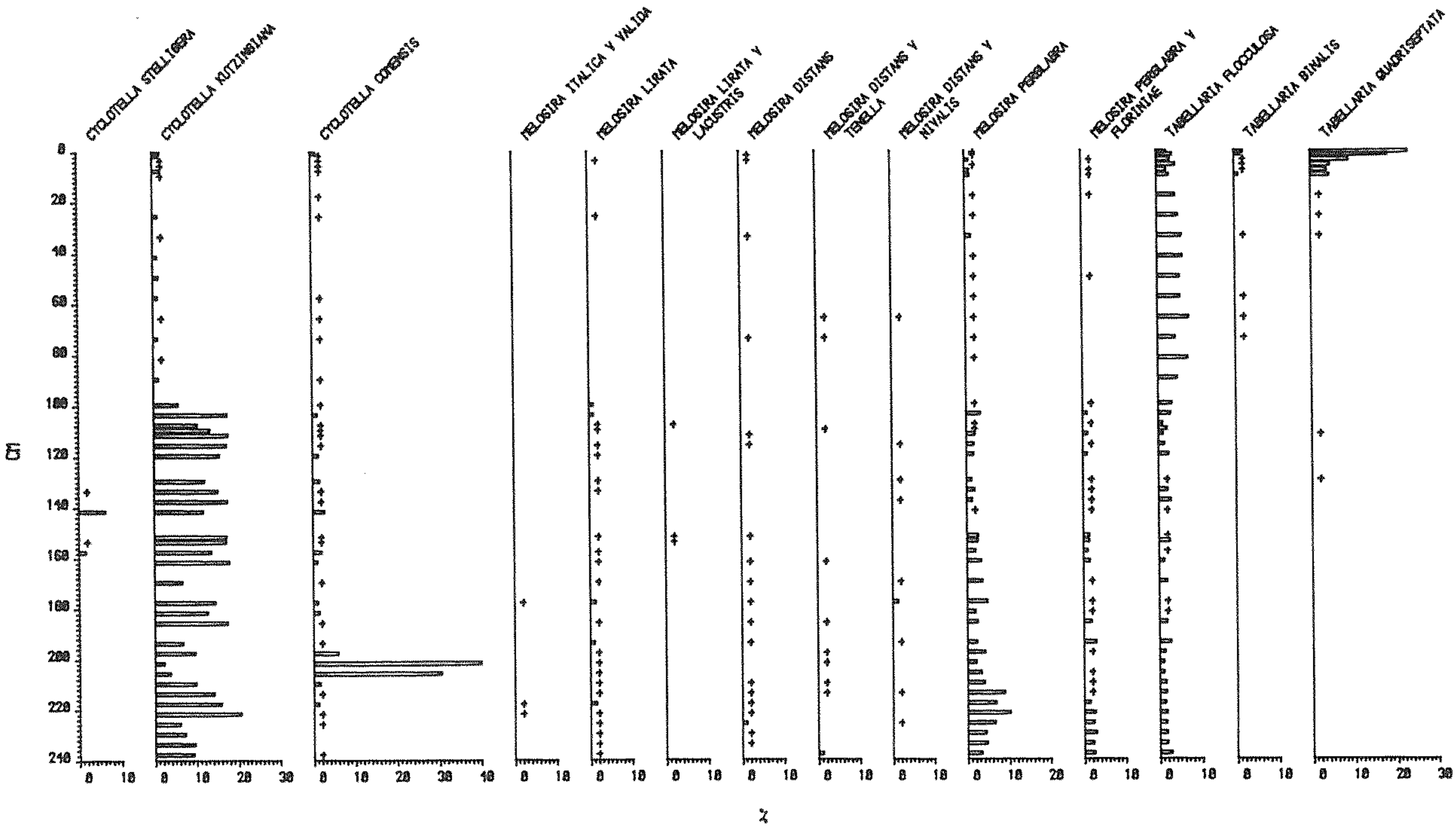
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MELOSIRA LIRATA
MELOSIRA LIRATA V LACUSTRIS
MELOSIRA DISTANS
MELOSIRA DISTANS V TENELLA
MELOSIRA DISTANS V NIVALIS
MELOSIRA PERGLABRA
MELOSIRA PERGLABRA V FLORINIAE
TABELLARIA FLOCCULOSA
TABELLARIA BINALIS
TABELLARIA QUADRISEPTATA
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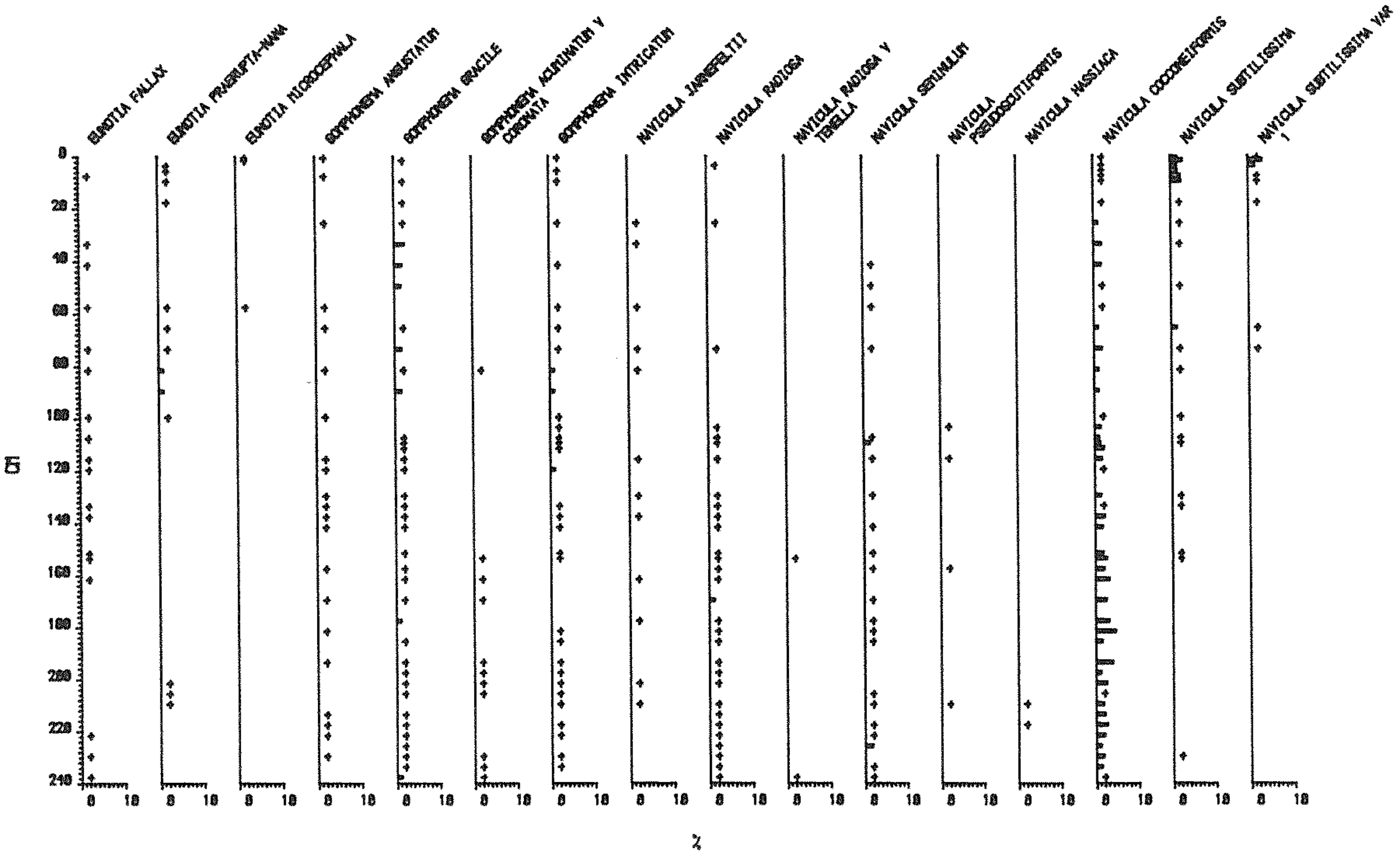
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GOMPHONEMA ACUMINATUM V CORONATA
GOMPHONEMA INTRICATUM
NAVICULA JARNEFELTII
NAVICULA RADIOSA
NAVICULA RADIOSA V TENELLA
NAVICULA SEMINULUM
NAVICULA PSEUDOSCUTIFORMIS
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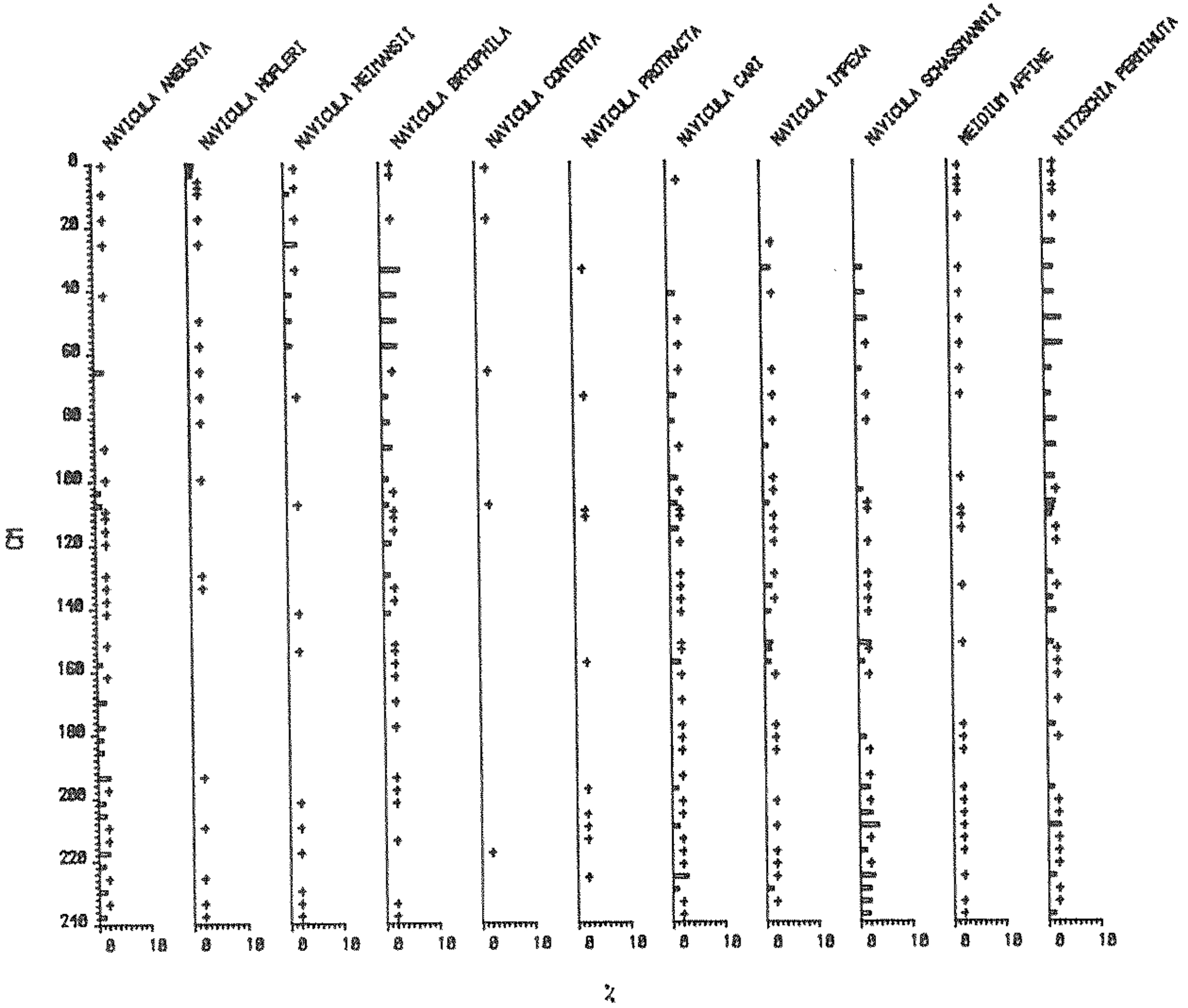
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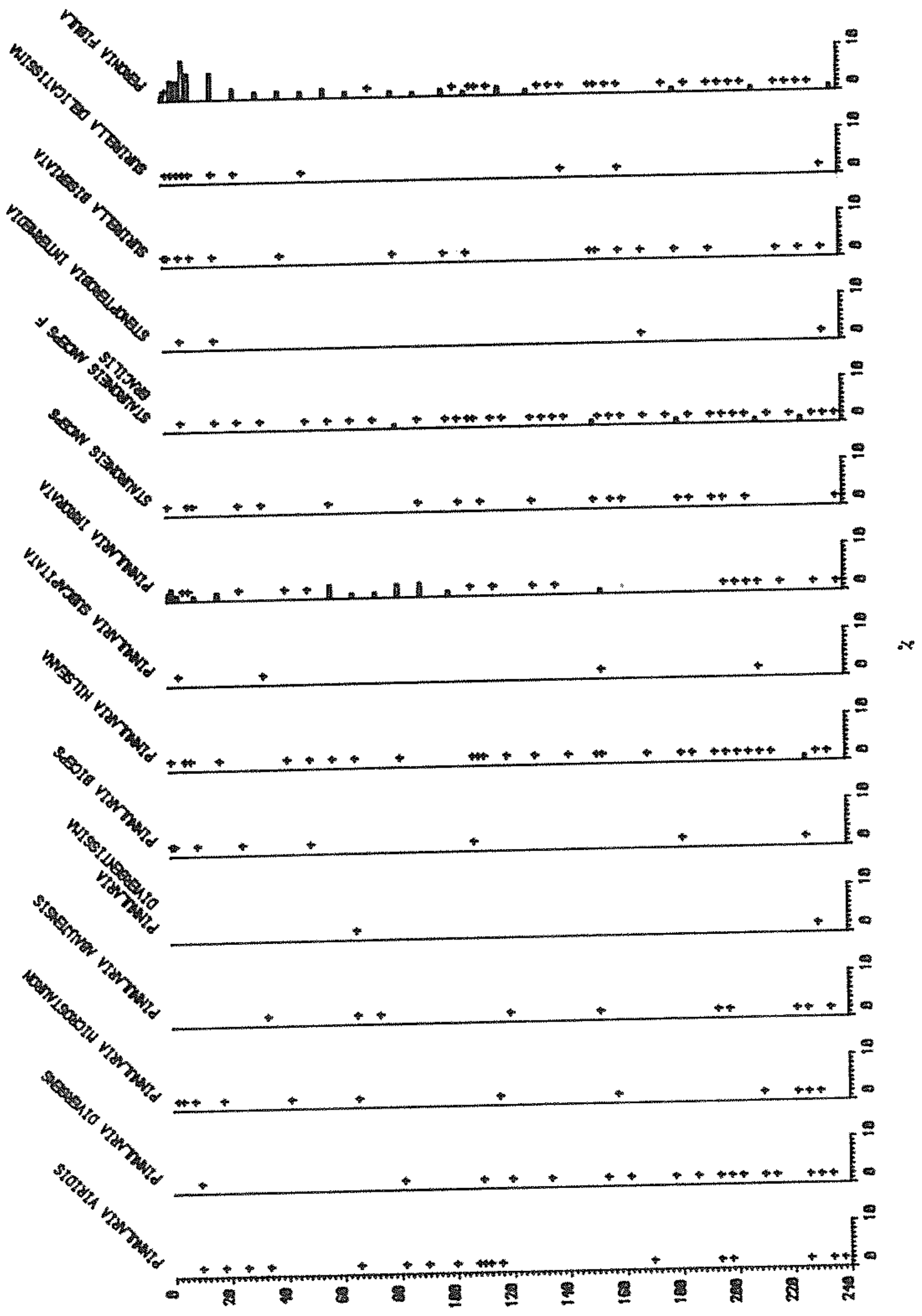
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PINNULARIA SUBCAPITATA
PINNULARIA HILSEANA
PINNULARIA BICEPS
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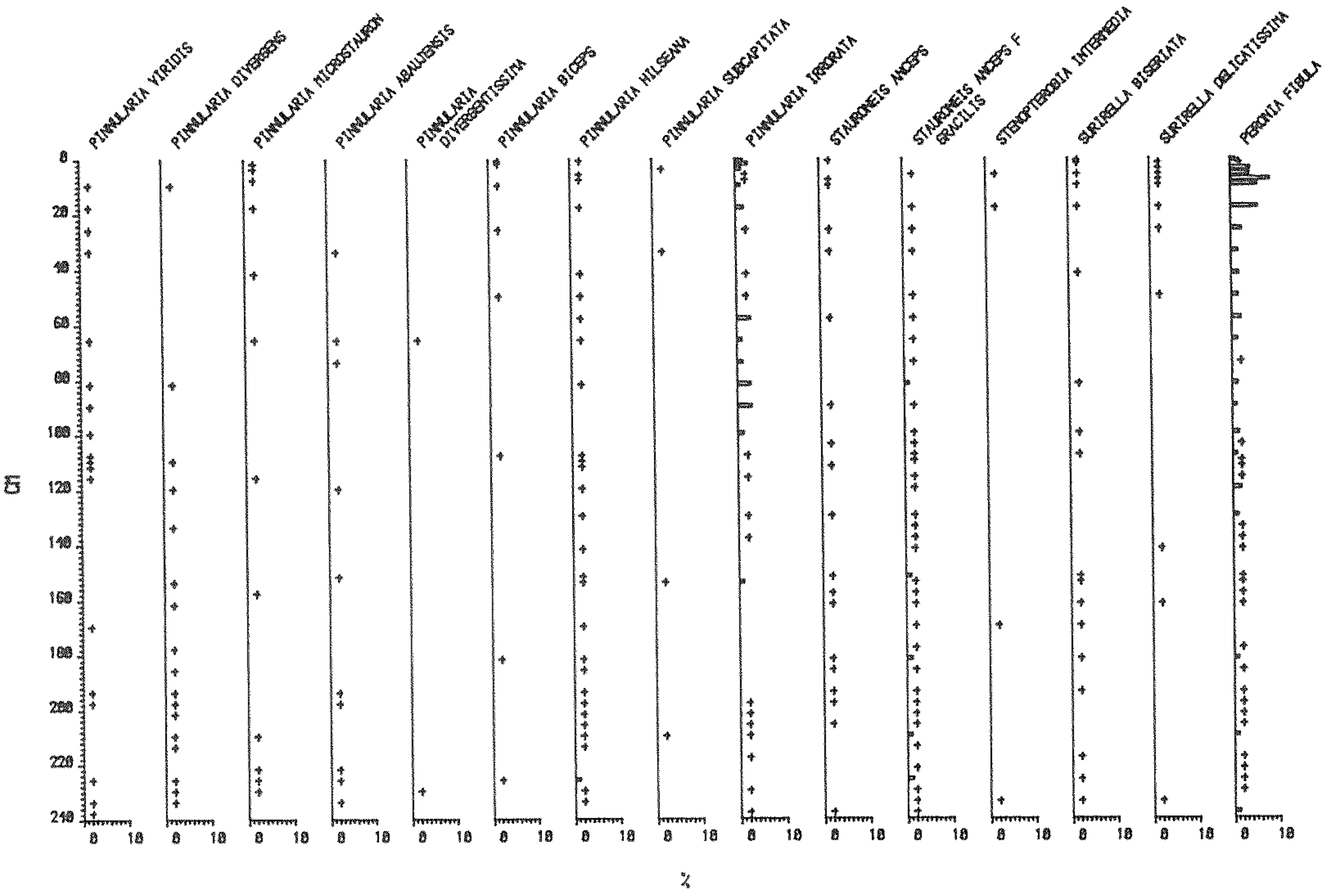
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