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PALAEOECOLOGICAL EVALUATION OF THE RECENT ACIDIFICATION OF LOCHNAGAR, SCOTLAND

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Palaeoecological evaluation of the recent acidification of Lochnagar, Scotland.

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Summary

Lochnagar, a high altitude, relatively deep, corrie lake, lies on the Royal Deeside Estate of Balmoral, in an area which experiences moderate levels of acid deposition. The loch catchment comprises granite bedrock and is dominated by bare rock but overlain in places with blanket peats. Lochnagar may thus be considered potentially susceptible to acidification. The contemporary pH of the loch water is c. 5.0.

To investigate the history and potential causes of acidification at Lochnagar sediment cores were obtained in June 1986. Sediment samples were subjected to lithostratigraphic, radiometric dating, diatom, geochemical, carbonaceous particle, magnetic, and palynological analyses.

A large variation in gross sediment composition down the core produces, in particular, an irregular 'spikey' loss-on-ignition profile. Variations in the lithostratigraphic profiles are attributed to influxes of terrestrially-derived debris from the catchment.

^{210}Pb dating was utilised to provide a chronology of sediment accumulation. A reliable chronology is available back to c. 1886 (6.75 cm), near the ^{210}Pb equilibrium depth. Below 7 cm a layer of sediment with high ^{226}Ra activity makes it difficult to calculate accurate ^{210}Pb activities in the lower part of the core.

Diatom analysis shows a clear acidification sequence. The first sign of acidification is indicated by a decline in *Fragilaria virescens* and an increase in *Achnanthes marginulata* above 10 cm. A more pronounced change occurs after 7 cm (c. 1880) as several circumneutral species decrease and acidophilous *Achnanthes* and acidobiontic *Melosira* species increase. The acidophilous diatom flora at Lochnagar has some differences from floras at similar pH but lower altitude. Acidobiontic *Tabellaria* species are absent and the dominant species are *Achnanthes*, especially *Achnanthes marginulata* and associated varieties.

The pH history of the loch is reconstructed from diatom data. Prior to acidification the loch had a pH c. 5.7. The onset of acidification is dated to the mid-nineteenth century with reconstructed pH values falling to 4.8 at the core top (compared to the modern measured pH of 5.0).

Geochemical analysis indicates a progressive contamination of the upper sediments by trace-metals, notably zinc and lead. Zinc contamination commenced around 11 cm depth (early/mid-nineteenth century) which corresponds to the first evidence of acidification from the diatom record. Lead contamination started earlier at around 19 cm. Wastewater effluents are not present in the catchment and trace-metal contamination is therefore of of atmospheric origin.

Magnetic accumulation in the sediment increased only slowly between 1900 and the 1940s, since when a steady increase is apparent to the core top suggesting contamination by fly-ash material. Concentrations of spherical carbonaceous particles have also progressively increased since the 1890s with a major increase occurring between c. 1950-1973.

The recent local pollen record is dominated by a trend from *Calluna* to Gramineae over the last c. 200 years. This trend is the antithesis of that proposed by the 'land-use hypothesis' of surface-water acidification.

The remote and rugged catchment has not been subjected to land-use or land-management practices that might affect the water quality of the loch.

The results of this study reinforce the conclusion from work elsewhere in the United Kingdom, that the acidification of surface waters since the early/mid-nineteenth century has been the result of acid deposition. All the evidence from Lochnagar is consistent with the acid deposition hypothesis and the pattern and timing of observed changes can not be accounted for by alternative hypotheses.

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1.0 Introduction

Acid deposition has caused the strong acidification of several lochs in the Galloway area of south-west Scotland (eg. Battarbee *et al* 1985, Battarbee *et al* in press, Flower and Battarbee 1983, Flower *et al* 1987a), and at Loch Tanna on the Island of Arran (Flower *et al.* 1988a). A less strong, but still significant acidification has been documented at Loch Laidon on Rannoch Moor in central Scotland (Flower *et al* 1987b, 1988b). Palaeoecological methods are being employed to examine the distribution of recently acidified lochs elsewhere in Scotland (Battarbee *et al* 1988) and to investigate the cause of acidification. This report investigates the acidification status of Lochnagar, a high altitude corrie loch on the Balmoral Estate in the Grampian Mountains of east-central Scotland (Figure 1).

Lochnagar is the northern-most site in the United Kingdom for which the results of palaeoecological investigation are fully available so far. However, it lies on base-poor granites that are susceptible to the effects of acid deposition, as do the acidified Galloway lochs, Loch Tanna and Loch Laidon. In recent years the region has experienced hydrogen ion and non-marine sulphate deposition rates that, while not as severe as the Galloway region are still moderately high.

2.0 Lochnagar - Lake and Catchment

2.1 Lake

Lochnagar lies at an altitude of 785 m in the centre of the granitic massif which comprises much of Balmoral Forest in Aberdeenshire. This massif is separated from the granitic area of the main Cairngorm range by the valley of the River Dee (Figure 1). Lochnagar is a corrie loch and lies below a north-east facing steep back wall which rises to the summit of the same name. The loch is elliptical in shape and occupies an area of 9.8 ha. No distinguishable inflow feeds the loch, instead drainage is primarily from small seepage channels. The Loch drains to the north-east through a series of small pools to the Lochnagar Burn (Figure 2) which feeds the Gelder Burn, a south bank tributary of the River Dee. Snow generally occupies the catchment to a varying extent between November and May and a significant snow field accumulates in the main winter period. Snow-melt therefore comprises an important input to the loch. Unlike any of the other sites so far investigated in this project Lochnagar freezes each winter. Partial ice cover may last from November through June in many years with a complete ice cover between January and April which can approach 1 m thickness by early March.

A bathymetrical survey in June 1986 showed that the loch floor slopes quite sharply to a deep basin. The deepest point (24 m) (Table 1) is offset from the centre of the loch towards the back wall (Figure 3). The loch is deep for its size with a mean depth of 8.4 m (Table 1).

Loch water chemistry was monitored regularly between 1986 - 1987 with analyses being performed by the Department of Agriculture and Fisheries for Scotland (DAFS) laboratory at Pitlochry. Mean values for these samples are presented in Table 2. The loch is acid (mean pH 5.02). Conductivity is low (mean 21.4 $\mu S\ cm^{-1}$), bicarbonate alkalinity is zero and labile aluminium concentrations are relatively high (mean = 57 $\mu g\ l^{-1}$) (Table 2). Calcium levels, considered to be a good indication of the susceptibility of surface waters to acidification (cf. Battarbee *et al.* 1988), are low (mean 30.2 $\mu g\ l^{-1)}$ (Table 2). Despite the existence of some localised peat erosion in the catchment the TOC concentration in the loch is relatively low (mean 0.8 $mg\ l^{-1}$) (Table 2). Therefore there is little suggestion that the acidity of the loch results from humic acids. The loch water is exceptionally clear and on the day of survey in June 1986 the secchi disc depth was c. 6 m.

Aquatic macrophytes were sampled in August 1988 by trawling a double-headed rake from a boat along and across the loch. In addition, Ekman grabs were taken at 10 m intervals along 50 m transects perpendicular to the shore in north-west, north-east and southerly orientations. Vegetation was sparse in the steeply shelving sandy littoral zone, (in contrast to the bryophyte-covered boulders fringing the loch) and confined to scattered stands of *Juncus bulbosus* var. *fluitans* (*Juncus fluitans*), and *Isoetes lacustris*. *Fontinalis antipyretica* and filamentous green algae also occurred sporadically. *Isoetes*, *Sphagnum auriculatum* and the liverworts *Jungermannia exsertifolia*, *Scapania undulata* and *Jungermannia obovata* were occasionally present in deeper water, particularly the northern bay of the loch. The apparent maximum depth for macrophyte growth was c. 5 m.

A previous macrophyte survey of the loch by SCUBA divers in 1969 (Light 1975) yielded just two species, with *Isoetes* and *Juncus fluitans* both occurring in water 1-6 m deep.

The loch is remote and relatively inaccessible. Consequently very little is known of the fishery history of the loch. In the early-twentieth century fishing in the loch was considered "not worth speaking of" (Lyall 1910), but trout were reported in the loch in 1940 (Hardie 1940). A thorough gill net survey of the contemporary fishery status in 1983 yielded only 13 trout, all mature specimens (Morrison pers. comm.).

2.2 Catchment

The loch drains a catchment of 91.9 ha which reaches a maximum altitude of 1155 m at the summit of Lochnagar to the west of the loch (Figure 2). The geology is composed of biotite granite (Harrison 1987) overlain in places by blanket peat. However, the catchment is dominated by bare rock, both of the steep back wall and the extensive fields of large boulders and coarse screes that have developed between the corrie ridge and the loch. In terms of the classification of Kinniburgh and Edmunds (1986) the catchment constitutes an area of 'high acid susceptibility'.

The chemical composition of rainfall is measured at an ITE station located above Allt-na-giubhsaich, just 4.5 km east of the loch. Annual average data from this station for the period 1978 - 1987 is presented in Appendix 5. The loch and its catchment lie in an area of moderate acid deposition, with wet deposited acidity in the range 0.03 - 0.04 g H^+ m^{-2} yr^{-1} and wet deposited non-marine sulphate in the range 0.5 - 1.0 g S m^{-2} yr^{-1} (Barrett *et al* 1987) (Table 1).

The catchment is unafforested and the sparse vegetation is dominated by a community of stunted *Calluna* and *Vaccinium*, interspersed in places with *Scirpus*. *Molinia*, common at most sites studied so far in Scotland, is virtually absent. Lichens and mosses are abundant on the boulders and screes that characterise the catchment. Of the localised areas of peat in the catchment, certain areas, notably along the eastern shore are severely eroded. Pine stumps are revealed in peat exposures adjacent to the outflow and further down the Lochnagar Burn.

This area represents some of the most extreme environmental conditions to be found in the British Isles and there is no evidence for, nor rational expectation of, any land-use change or active land-management within the catchment. At over 700 m the catchment lies above the limit of summer sheep grazing in the region (Scottish Development Dept. 1967). Red deer range across the catchment when food is available, but stalking in the area, once popular (Clark 1981), is now rare and strictly controlled. The catchment comprises part of a nature reserve administered by the Scottish Wildlife Trust.

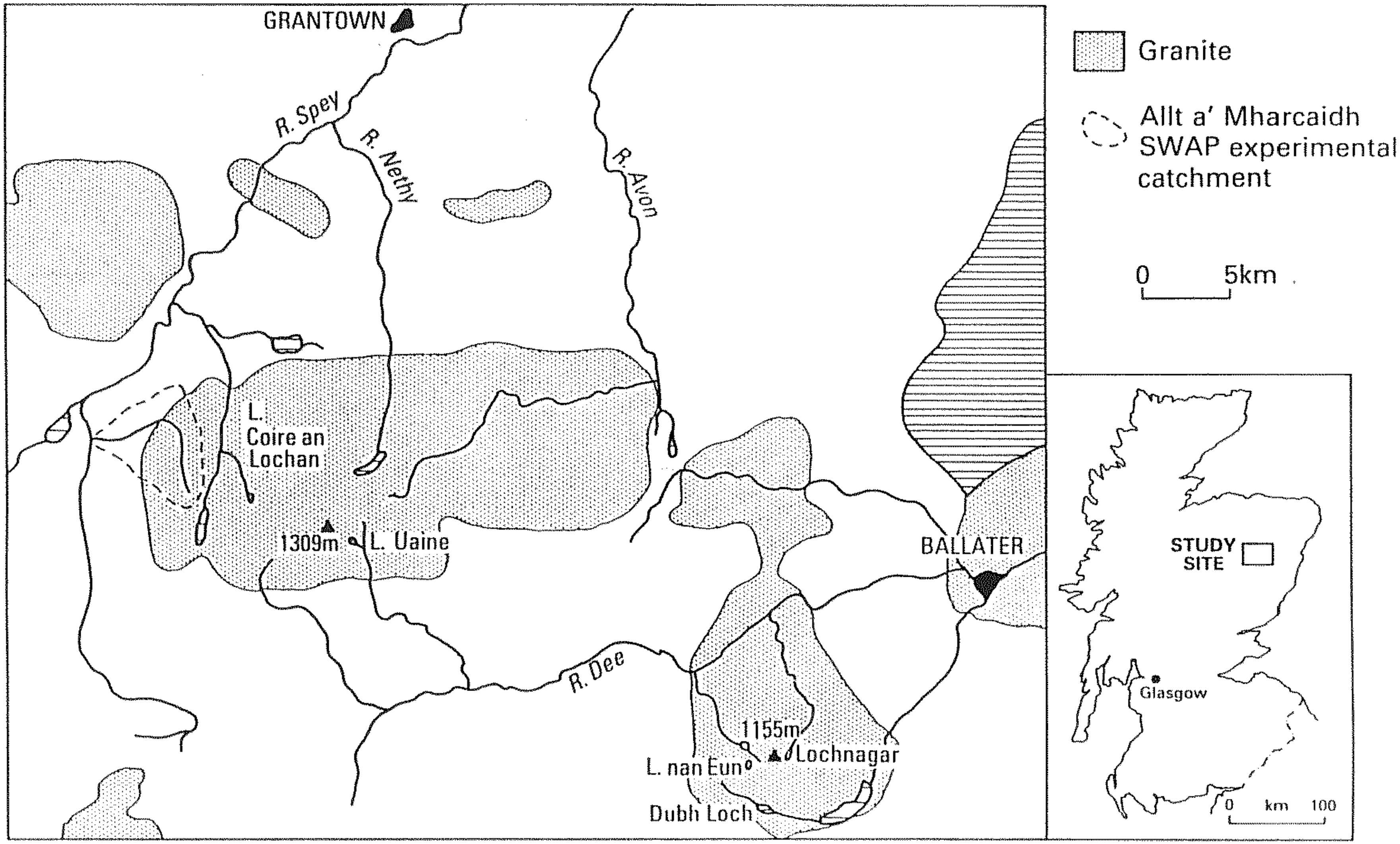

Figure 1. The location of Lochnagar

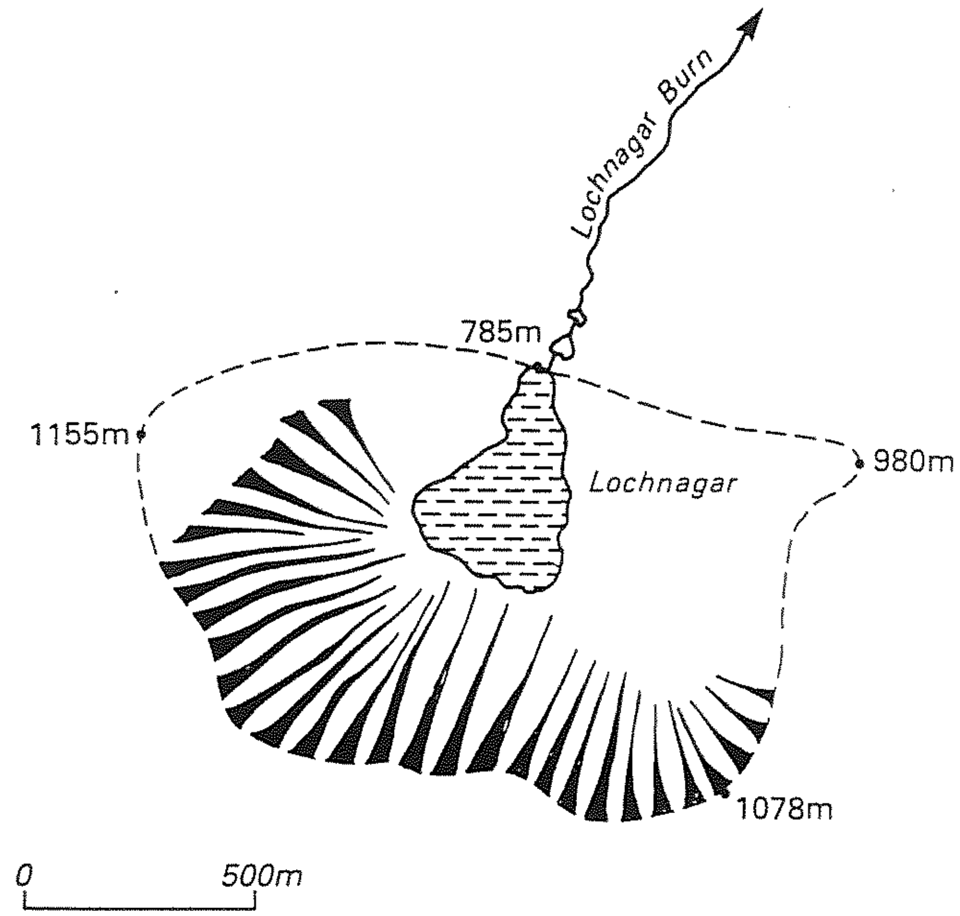

Figure 2. Lochnagar: Catchment.

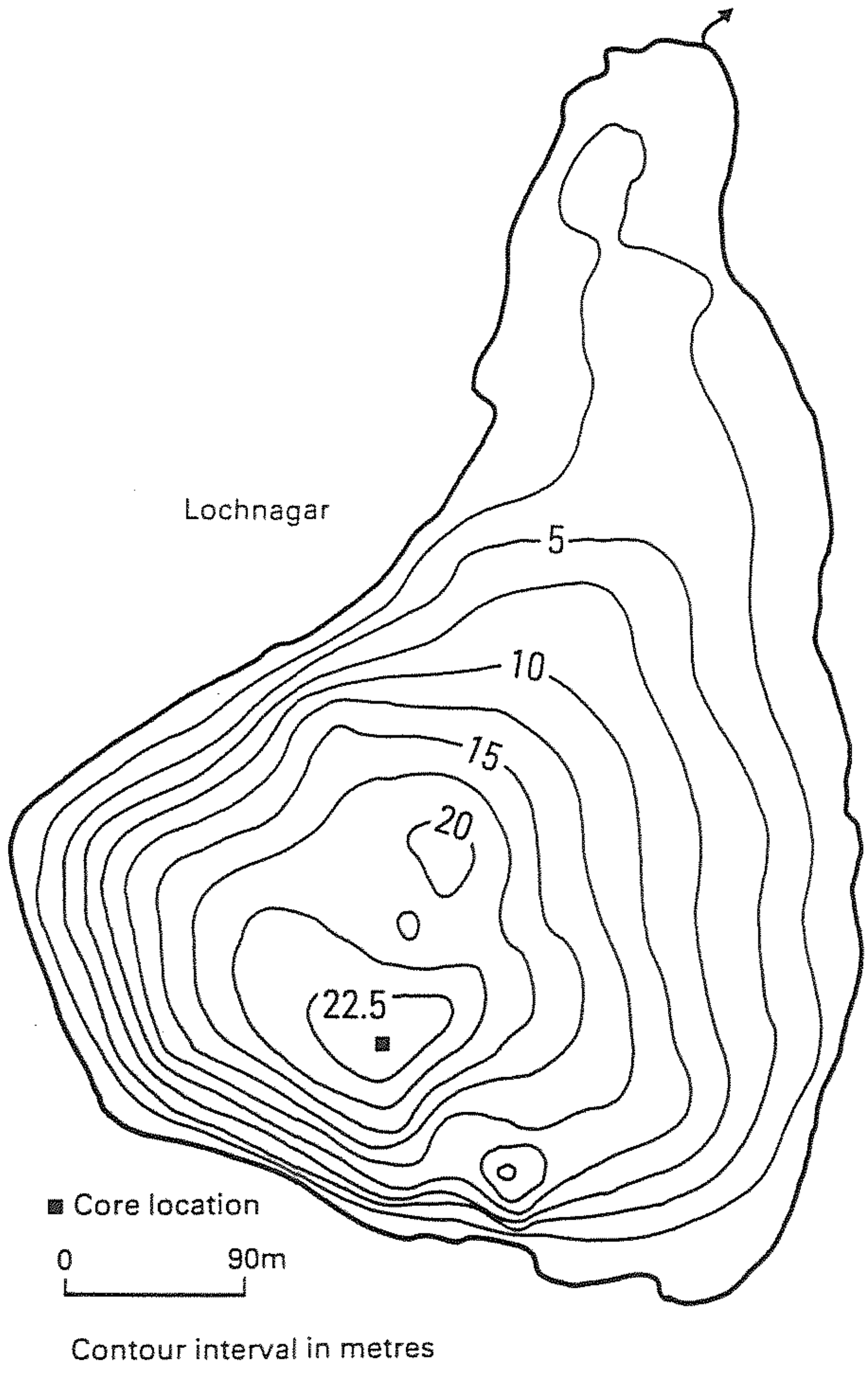

Figure 3. Lochnagar: Bathymetry.

Table 1 Lochnagar - site characteristics

Grid reference	NO 252859
Catchment geology	granite
Catchment type	moorland
Lake altitude	785 m
Maximum depth	24 m
Mean depth	8.4 m
Volume	0.82×10^{6} m^3
Lake area	9.8 ha
Catchment area	91.9 ha (excluding lake)
Catchment:lake ratio	9.37
Net relief	370 m
wet deposited acidity	0.03 - 0.04 g H^+ m^{-2} yr^{-1}
wet deposited non-marine sulphate	0.5 - 1.0 g S m^{-2} yr^{-1}

Table 2 Lochnagar - water chemistry (mean values 1986 - 1987)

Number of samples	6
pH	5.02
Conductivity µS cm^{-1}	21.4
Ca^{++} µeq l^{-1}	30.2
Mg^{++} µeq l^{-1}	33.7
K^+ µeq l^{-1}	7.5
Na^+ µeq l^{-1}	89.0
Cl^- µeq l^{-1}	76.2
SO_4^{--} µeq l^{-1}	66.0
Alkalinity µeq l^{-1}	0.0
TOC mg l^{-1}	0.8
Labile Al. µg l^{-1}	57.0

3.0 Methods

The loch was cored in June 1986 using a mini-Mackereth corer (Mackereth 1969) from an inflatable boat. Core NAG3, taken from the main basin at 23 m depth (Figure 3), yielded a sediment recovery of 76 cm and was used for the analyses presented below. The core was extruded at 0.5 cm (0 - 20 cm) and 1 cm (20 - base) intervals and subjected to lithostratigraphic, radiometric dating, diatom, geochemical, carbonaceous particle, magnetic, and palynological analyses according to the methods presented in Stevenson *et al.* (1987).

4.0 Sediment description

The sediment of core NAG3 was fairly homogeneous in texture and showed small variations in colour. Except for gritty and slightly lighter coloured layers at c. 9 - 13 cm and 29 - 30 cm depth, and for a gritty fibrous layer at c. 40 - 43 cm, the top 50 cm of sediment was dark brown (Munsel Colour 10YR/2/2) and fine grained. Between 50 - 60 cm depth the sediment was more sandy and lighter in colour being greyish brown (Munsel Colour 10YR/5/2). Below 60 cm depth the colour (Munsel Colour 10YR/3/3) and consistency of the sediment was very similar to that in the 13 - 50 cm section.

Profiles of sediment wet density, percentage dry weight and loss-on-ignition (LOI) show considerable down-core variation (Figure 4). Major changes in all three parameters occur at around 9 cm and particularly so at 40 cm depth as sharp peaks in dry weight and wet density are mirrored by low LOI values. Smaller but similar changes in these parameters also occur at 18 and 26 cm depth. The LOI curve is particularly 'spikey' showing the organic composition of the sediment varying between 10% and almost 50%. In some sections of the core there are considerable changes in the LOI profile while dry weight and wet density remain fairly constant (eg. below 50 cm depth). This is probably caused by differential changes in particle size in both organic and inorganic material, as well as by overall change in sediment composition.

The large changes in gross sediment composition that occur in this core are unusual for lake sediment cores in general. Here, the variation is attributed to major fluxes of terrestrially-derived debris, mainly of sand but also of terrestrial plant remains, that have occurred as a result of past phases of accelerated catchment erosion.

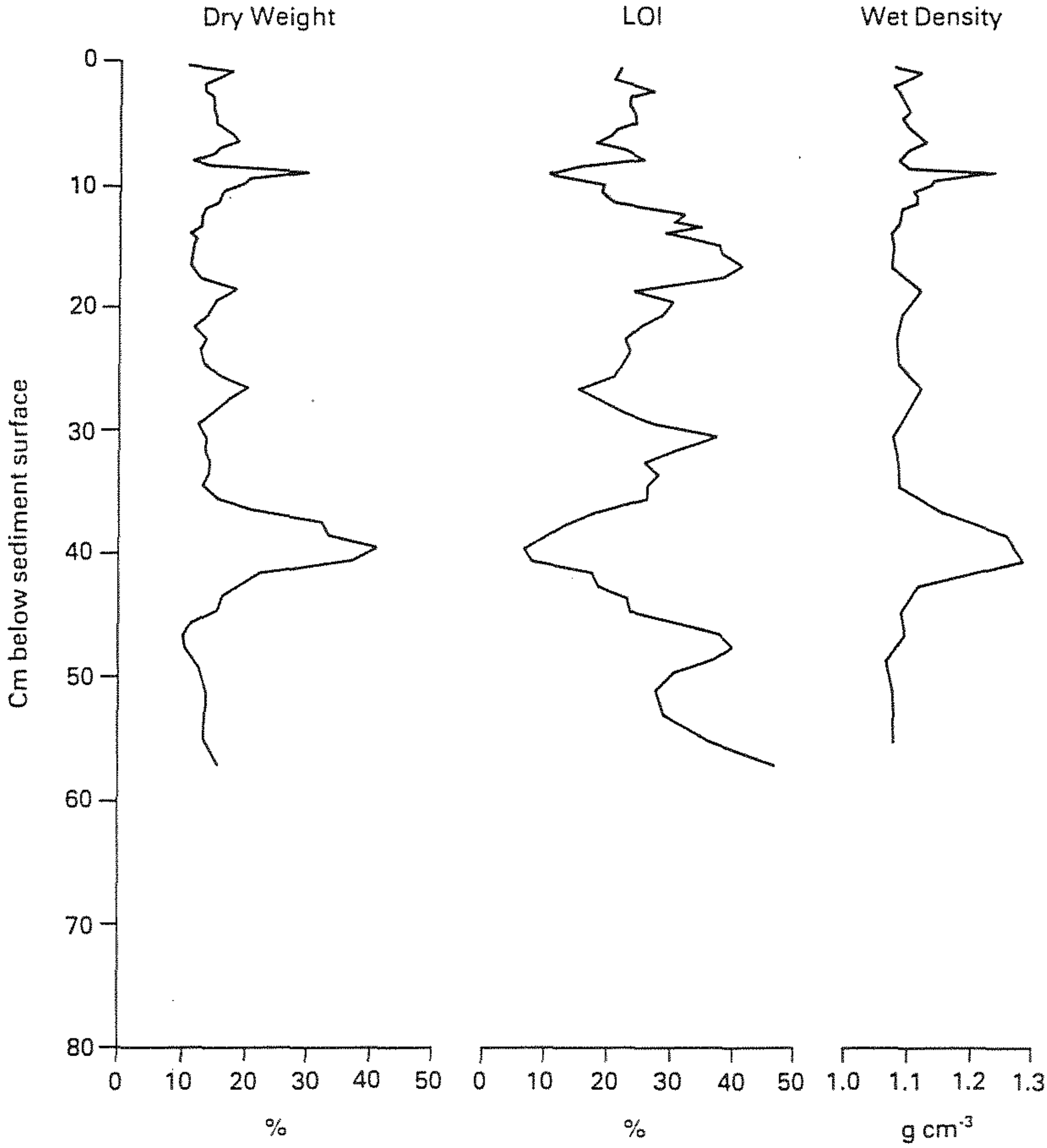

Figure 4. Lithostratigraphic data: Core NAG 3.

5.0 ^{210}Pb Dating

Sediment samples from core NAG3 were analysed for ^{210}Pb, ^{226}Ra, ^{137}Cs and ^{241}Am by gamma spectrometry (Appleby *et al.* 1986). The ^{210}Pb and ^{226}Ra results are given in Table 3 and shown graphically in Figure 5. The ^{137}Cs and ^{241}Am results are given in Table 4 and Figure 6. Table 5 gives values of a range of other radioisotopes determined by the gamma spectra.

The unsupported ^{210}Pb inventory of the core was calculated to be 17.6 pCi cm^{-2}, representing a constant ^{210}Pb supply of 0.55 pCi cm^{-2} yr^{-1}. This figure is only 18% of the value for nearby Lochan Uaine in the Cairngorms. In contrast to this the ^{137}Cs inventory of the core deriving from weapons testing fallout, of 8.35 pCi cm^{-2} is 64% of that at Lochan Uaine. The mean ^{226}Ra concentration in the Lochnagar sediments is 7.0 pCi g^{-1}, compared to 23.1 pCi g^{-1} at Lochan Uaine, and these results suggest that the enhanced ^{210}Pb supply at Lochan Uaine, associated presumably with the high ^{226}Ra activity, is quite localised.

^{210}Pb chronologies have been calculated using both the CRS and CIC ^{210}Pb dating models (Appleby and Oldfield 1978). The results are given in Figure 7. The decline in ^{210}Pb activity above 2.25 cm (dated 1967) appears to indicate a recent acceleration in sediment accumulation rate (paralleling that observed at Lochan Uaine - Appleby pers. comm.). Since the CIC model can not date non-monotonic features the CIC chronology has utilised the CRS model assumptions to date the level of peak ^{210}Pb activity. Below 3.75 cm (dated c. 1950) the CIC model indicates a constant sediment accumulation rate of 0.0082 g cm^{-2} yr^{-1}, whereas the CRS model suggests a steady acceleration since c. 1850. For this part of the core it is the CRS model dates that are unlikely to be reliable. Figure 5(a) shows that at 8 - 11 cm, near the ^{210}Pb equilibrium depth, there is an unusual layer of sediment with a very high ^{226}Ra activity. The sediment in this layer is also characterised by a high dry weight : wet density ratio (Figure 4), and by enhanced values of a number of natural radioisotopes (Table 5). The characteristics of this section of sediment may probably be best explained by a sediment inwash event, and although the minerogenic material of this section probably accumulated much more quickly than the sediment above, thus representing a short period of time in the core, this inwash layer makes it difficult to calculate accurate ^{210}Pb activities in the lower part of the core. The linearity of the unsupported ^{210}Pb profile between 3.75 and 6.75 cm (Figure 5b) provides good evidence for a constant accumulation rate above the anomalous layer. Using the methods outlined in Oldfield and Appleby (1984) a corrected CRS model chronology can be determined by using this accumulation rate to estimate the unsupported ^{210}Pb activity below 6.75 cm. This chronology, given in Table 6, shows a more or less constant sediment accumulation rate during the period 1886 - 1950. The recent increase in accumulation rates is dated to the early 1960s, with the most significant increases occurring during the past ten years.

The maximum ^{137}Cs activity in the core occurs in the top-most sample and is presumably the result of fallout from the Chernobyl accident. No ^{134}Cs was detected, presumably because fallout in this region was slight. Below the top-most layer the ^{137}Cs activity in the core has a well defined peak at 2.25 cm. The ^{241}Am concentration has a peak at about the same level, although the activities are very low and difficult to measure accurately. The ^{137}Cs and ^{241}Am profiles (Figure 6) show that the peaks are dated by ^{210}Pb to 1963 and 1954, and apparently confirms the association of these peaks with the 1963 fallout maximum. The presence of significant ^{137}Cs activities down to the ^{210}Pb equilibrium depth does however indicate significant downward diffusion (cf. Davis *et al.* 1984).

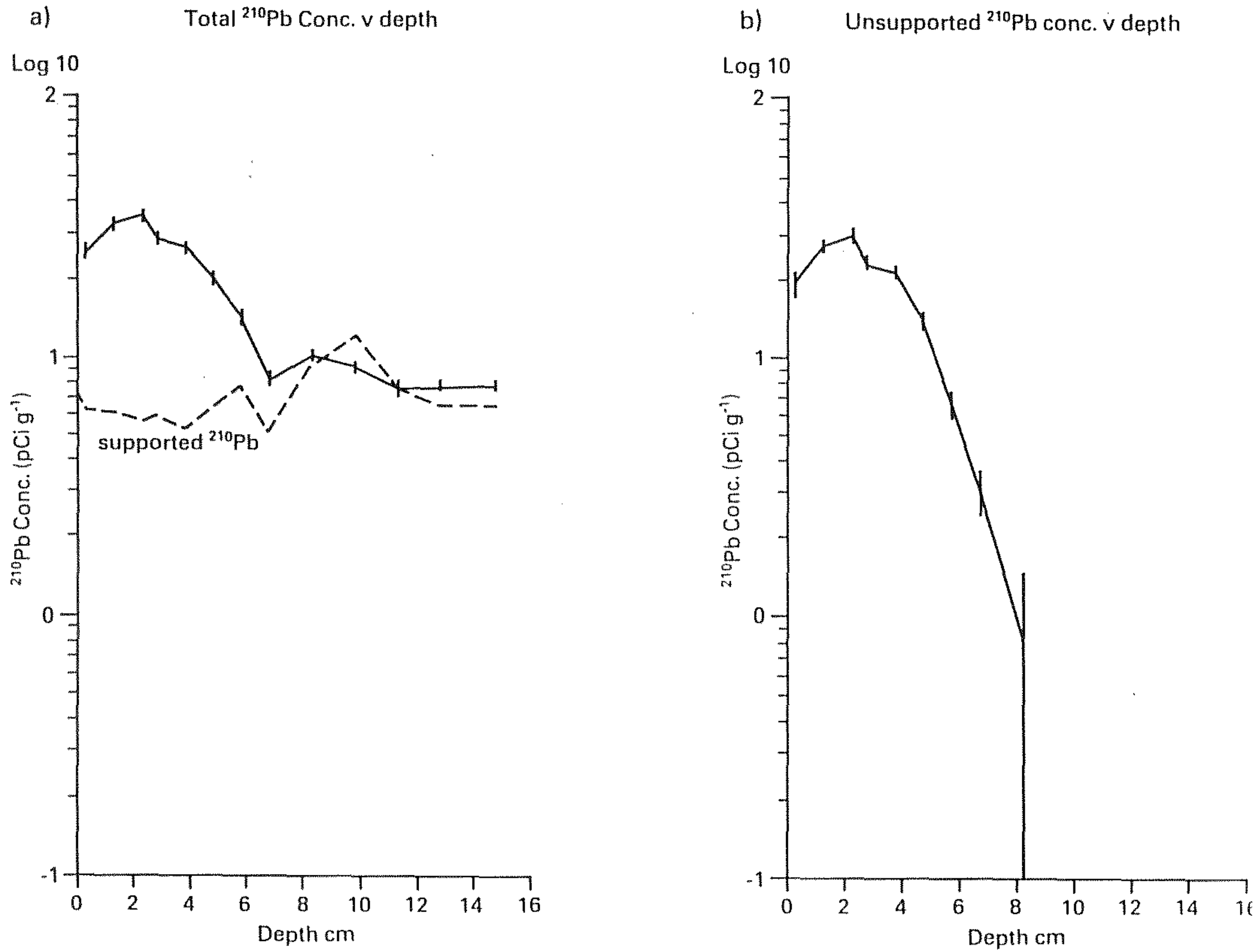

Figure 5. ^{210}Pb data: Core NAG 3.

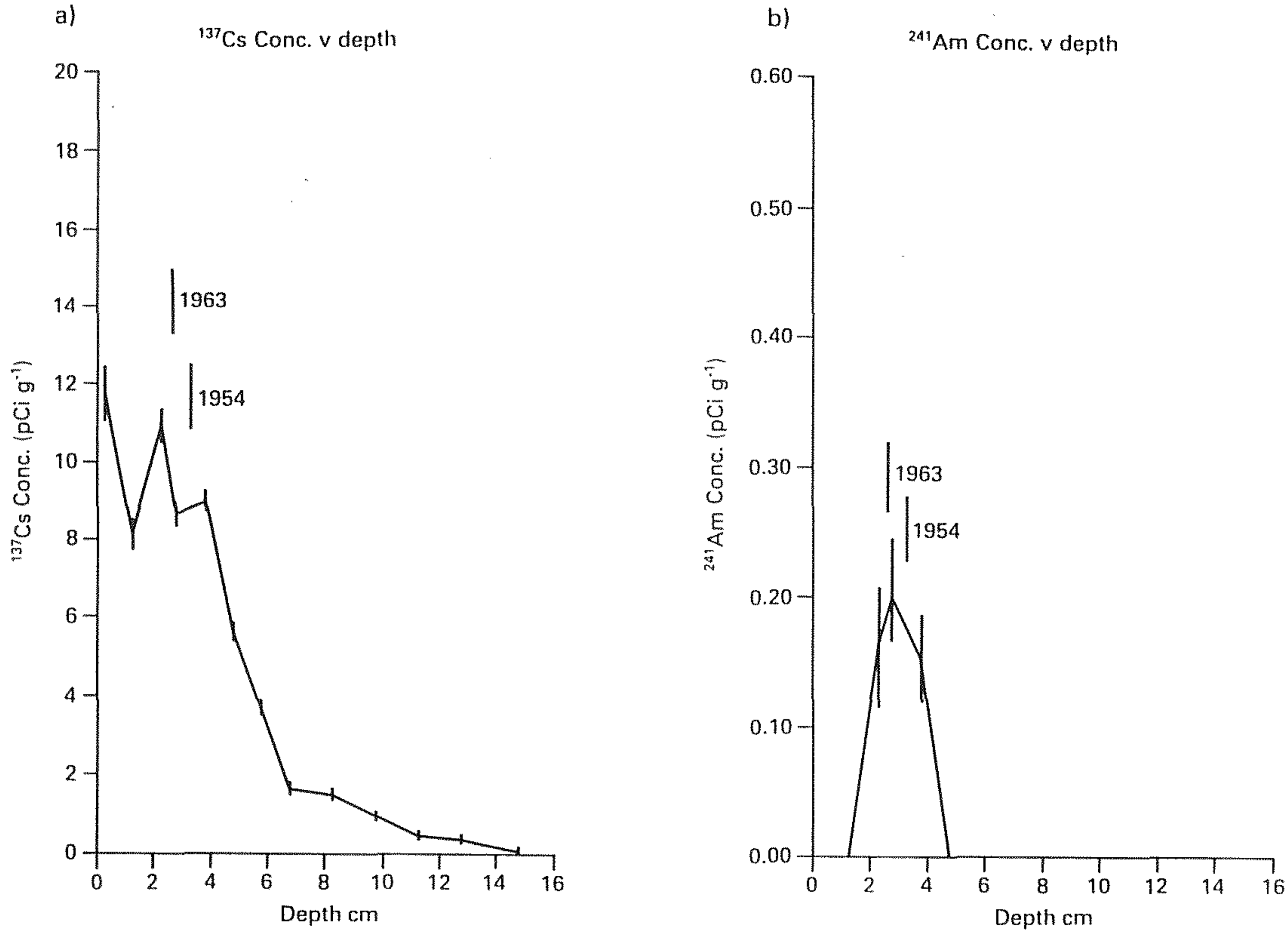

Figure 6. ^{137}Cs and ^{241}Am data: Core NAG 3.

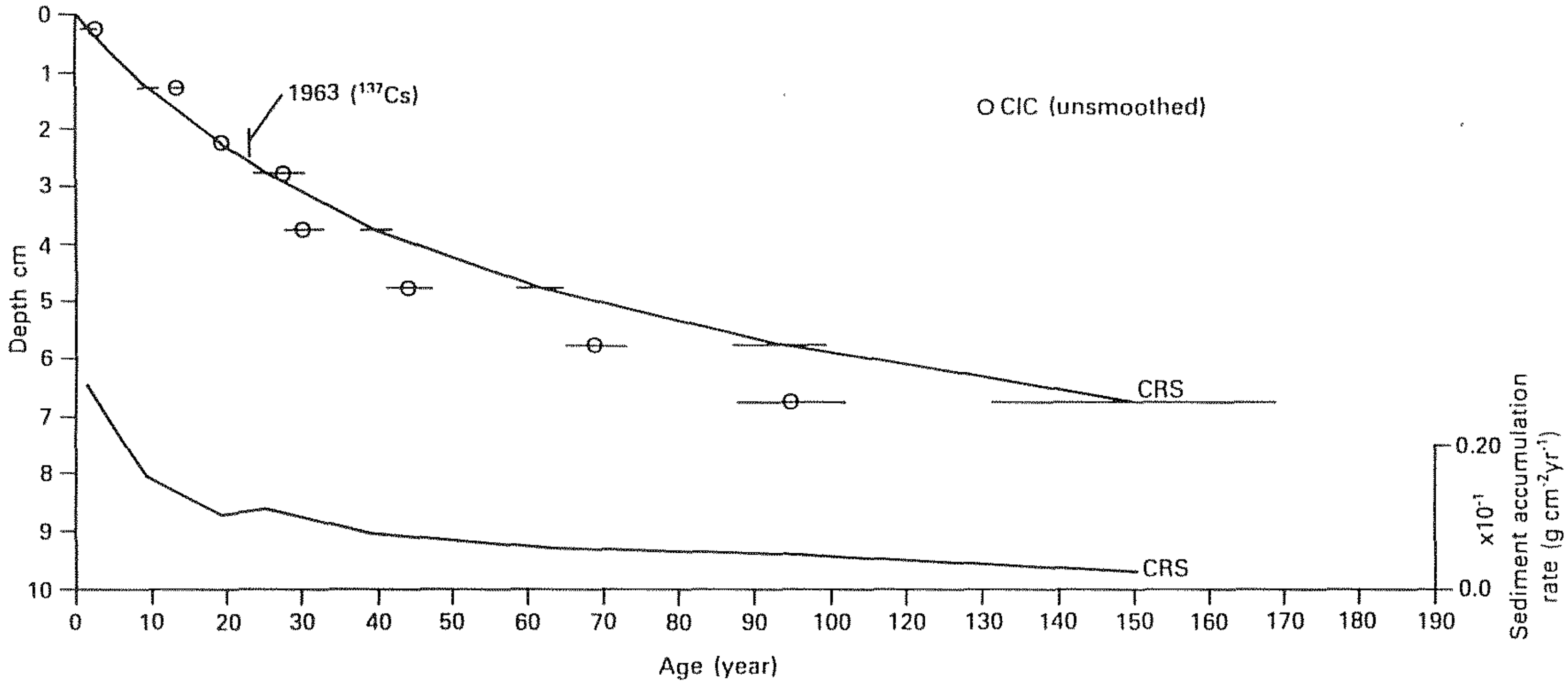

Figure 7. ^{210}Pb Chronology for Lochnagar.

Table 3 ^{210}Pb data for core NAG3

Depth	Dry mass	^{210}Pb Concentration				^{226}Ra Conc.	
		Total		Unsupp.			
cm	g cm^{-2}	pCi g^{-1}	±	pCi g^{-1}	±	pCi g^{-1}	±
0.25	0.0368	25.58	2.28	19.29	2.50	6.29	1.02
1.25	0.1987	33.08	1.51	27.00	1.56	6.08	0.39
2.25	0.3271	35.56	1.62	29.92	1.67	5.64	0.40
2.75	0.3903	29.09	1.19	23.23	1.23	5.86	0.30
3.75	0.5209	26.72	1.10	21.46	1.13	5.26	0.27
4.75	0.6730	20.47	0.90	13.94	0.95	6.53	0.31
5.75	0.8395	14.27	0.67	6.55	0.74	7.72	0.32
6.75	1.0128	8.11	0.54	2.98	0.60	5.13	0.26
8.25	1.3176	10.13	0.63	0.79	0.75	9.34	0.40
9.75	1.6879	9.18	0.53	-2.95	0.69	12.13	0.44
11.25	2.2167	7.53	0.57	0.06	0.66	7.47	0.34
12.75	2.4883	7.61	0.38	1.12	0.45	6.49	0.24
14.75	2.8245	7.73	0.38	1.25	0.45	6.48	0.24
16.75	3.1605	7.93	0.49	0.95	0.57	6.98	0.29

Table 4 ^{137}Cs and ^{241}Am data for core NAG3

Depth	^{137}Cs Conc.		^{241}Am conc.	
cm	pCi g^{-1}	±	pCi g^{-1}	±
0.25	11.79	0.78	0.00	0.00
1.25	8.08	0.36	0.00	0.00
2.25	10.96	0.41	0.16	0.05
2.75	8.65	0.26	0.20	0.04
3.75	8.96	0.25	0.15	0.03
4.75	5.64	0.20	0.00	0.00
5.75	3.66	0.16	0.00	0.00
6.75	1.59	0.13	0.00	0.00
8.25	1.45	0.14	0.00	0.00
9.75	0.89	0.10	0.00	0.00
11.25	0.40	0.11	0.00	0.00
12.75	0.31	0.06	0.00	0.00
14.75	0.05	0.05	0.00	0.00
16.75	0.00	0.00	0.00	0.00
Inventories	8.78±0.21 pCi cm^{-2}		0.06±0.01 pCi cm^{-2}	

Table 5 Miscellaneous radioisotopes for core NAG3

Depth cm	^{226}Ra	^{238}U	^{235}U pCi g^{-1}	^{228}Ac	^{228}Th	^{40}K
0.25	6.29	9.88	0.91	0.00	5.23	20.16
1.25	6.08	10.13	1.89	5.16	7.21	17.56
2.25	5.64	9.82	1.91	4.08	7.02	12.04
2.75	5.86	9.04	1.82	2.69	4.37	19.24
3.75	5.26	9.05	1.46	3.98	5.47	20.55
4.75	6.53	9.70	1.59	3.31	4.45	24.04
5.75	7.72	11.02	1.94	4.21	5.06	31.38
6.75	5.13	7.68	1.44	2.84	4.26	23.58
8.25	9.34	11.65	2.26	5.43	8.28	33.15
9.75	12.13	10.79	1.94	5.35	9.10	40.88
11.25	7.47	11.35	1.69	3.51	5.77	30.86
12.75	6.49	12.03	2.05	3.24	4.31	26.04
14.75	6.48	11.71	2.05	3.05	4.27	25.49
16.75	6.98	10.52	2.01	3.76	6.77	26.20

Table 6 ^{210}Pb chronology for core NAG3

Depth cm	Dry Mass g cm^{-2}	Date AD	Age yr	±	Sedimentation Rate g cm^{-2} yr^{-1}	cm yr^{-1}	±(%)
0.00	0.0000	1986	0				
0.25	0.0368	1985	1	2	0.0289	0.182	12.7
0.50	0.0773	1983	3	2	0.0257	0.164	11.2
0.75	0.1177	1981	5	2	0.0226	0.147	9.7
1.00	0.1582	1979	7	2	0.0195	0.130	8.2
1.25	0.1987	1977	9	2	0.0163	0.112	6.7
1.50	0.2308	1975	11	2	0.0150	0.106	6.9
1.75	0.2629	1972	14	2	0.0136	0.099	7.1
2.00	0.2950	1970	16	2	0.0123	0.092	7.2
2.25	0.3271	1968	18	2	0.0109	0.085	7.4
2.50	0.3587	1965	21	2	0.0114	0.088	7.5
2.75	0.3903	1962	24	2	0.0118	0.091	7.6
3.00	0.4229	1959	27	2	0.0110	0.084	8.0
3.25	0.4556	1956	30	2	0.0102	0.076	8.4
3.50	0.4882	1952	34	2	0.0094	0.068	8.8
3.75	0.5209	1949	37	3	0.0086	0.061	9.2
4.00	0.5589	1944	42	3	0.0082	0.057	10.5
4.25	0.5969	1939	47	3	0.0079	0.053	11.8
4.50	0.6350	1935	51	4	0.0076	0.049	13.2
4.75	0.6730	1930	56	4	0.0073	0.046	14.5
5.00	0.7146	1924	62	5	0.0074	0.046	17.8
5.25	0.7562	1918	68	6	0.0075	0.045	21.0
5.50	0.7979	1913	73	7	0.0076	0.045	24.3
5.75	0.8395	1907	79	8	0.0077	0.045	27.6
6.00	0.8828	1902	84	10	0.0080	0.046	29.5
6.25	0.9261	1896	90	12	0.0083	0.046	31.4
6.50	0.9695	1891	95	13	0.0086	0.046	33.4
6.75	1.0128	1886	100	15	0.0090	0.047	35.3

6.0 Diatoms and pH reconstruction

6.1 Diatom analysis

Figure 8 presents a summary diatom diagram for core NAG3. The full diagram is to be found in Appendix 1 and the full species list in Appendix 2.

The major changes in diatom abundance occur above 10 cm depth. Below 10 cm the diatom assemblage is dominated by *Fragilaria virescens*, *Achnanthes marginulata* var. 2 and *Melosira distans* var. *nivalis*. One notable shift in species abundance below 10 cm is the increase in *Fragilaria vaucheriae* above 25 cm as *Melosira distans* declines. Above 10 cm *Fragilaria virescens* declines as *Achnanthes marginulata* increases. At between 7 cm (c. 1880) and 8 cm several species, including *Achnanthes marginulata* var. 2, *Frustulia rhomboides* var. *viridula*, *Fragilaria vaucheriae* and *Anomoeoneis vitrea* decline, as *Achnanthes marginulata* increases sharply. *Achnanthes austriaca* var. *minor* and *Melosira distans* var. *nivalis* also increase above 7 cm. At 5 cm (1924) *Achnanthes marginulata* achieves a frequency of almost 50% and this is maintained to the core top (1986).

6.2 pH reconstruction

The recent pH history of Lochnagar is reconstructed using the multiple regression method (Flower 1986) (Figure 9). However, in addition to the limitations imposed by core dating (Section 5.0), there are problems associated with unknown taxa, particularly a range of *Achnanthes* species and *Achnanthes marginulata* varieties, and taxa for which the pH preference is unclear. In order to produce a best estimate pH reconstruction for the loch, unknown taxa (principally *Achnanthes marginulata* var. 2) were removed from the diatom count data, and *Melosira distans* var. *nivalis* was utilised in the pH equation with an acidobiontic preference. The resulting pH curve (Figure 9) indicates that loch water pH declined from about 5.7 in the early nineteenth century to 4.8 at the core top, slightly lower than the measured pH of 5.0 (Table 2).

It is difficult to be precise about the onset of acidification at Lochnagar. The inwash of sediment (see Section 5.0) makes dating uncertain before 1886 (6.75 cm) and renders dating by extrapolation unreliable. Although rapid acidification does not begin before this depth the diatoms do indicate that the process was initiated at around 10 cm depth. Even so, because the inwash event is likely to represent a short time period, it is considered that acidification at Lochnagar occurred in the mid-nineteenth century.

6.3 Diatom concentration

The concentration of diatom cells in the sediment of core NAG3 was determined using the latex microsphere method (Battarbee and Kneen 1982). The down-core variation in diatom concentration is shown in Figure 10.

The diatom concentration curve shows marked variation, but in general concentrations are relatively high (> 1.0 x 10^{-8} cells g^{-1} dry sediment) throughout most of the upper 62 cm of sediment. The main feature of these data is the marked declines between 56-61 cm and 23-10 cm depth. These sections correspond with well defined troughs in the sediment LOI profile (Figure 4) and indicate inwash of minerogenic catchment material. The smaller concentration decline at c. 35 cm depth corresponds with a peak in LOI, probably indicating the dilution effect of an inwash of peat. The peak concentrations at 2 and 25 cm depth probably indicate an absence of diluting effects rather than any significant change in diatom productivity.

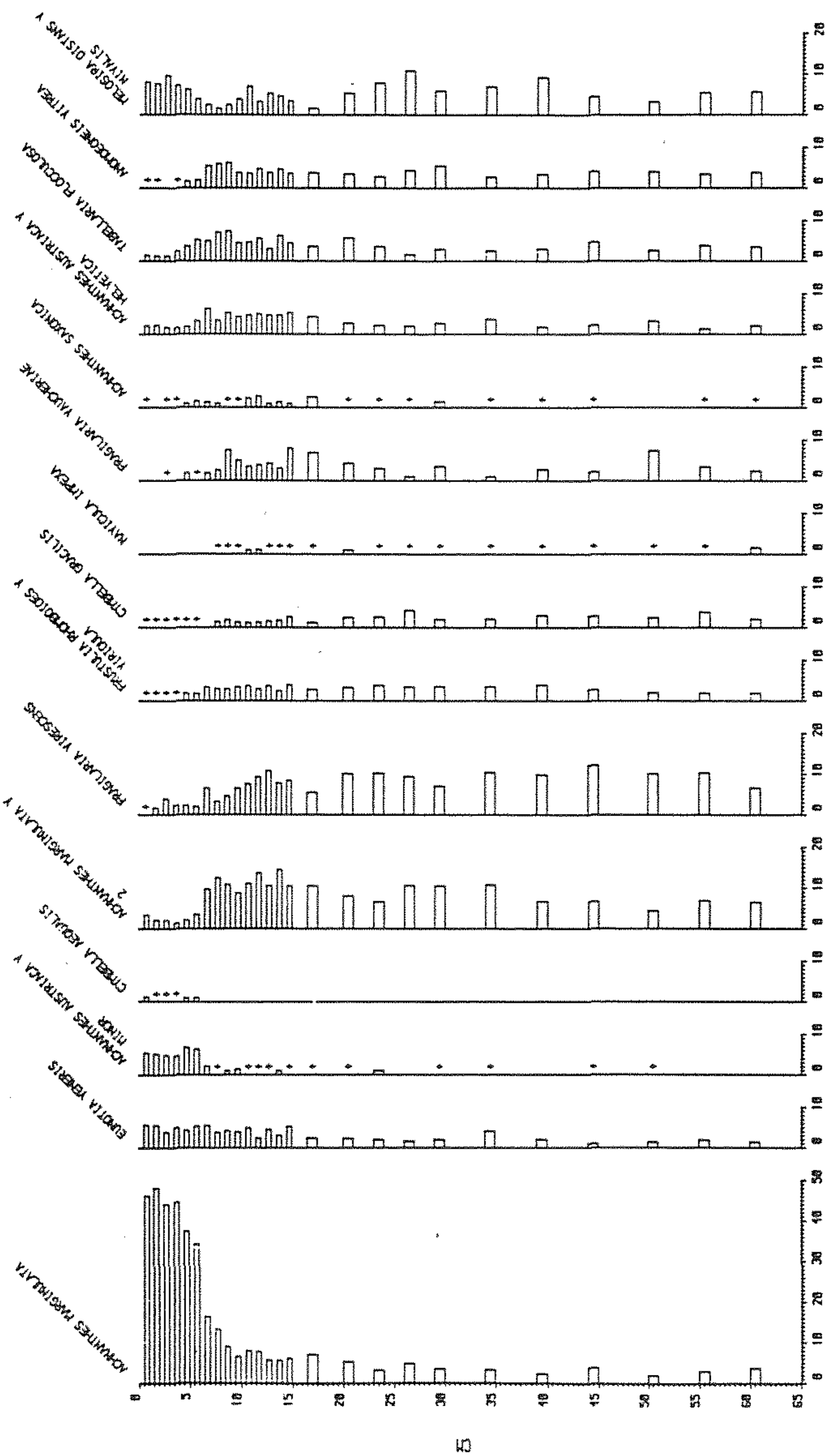

Figure 8. Lochnagar: Summary diatom diagram

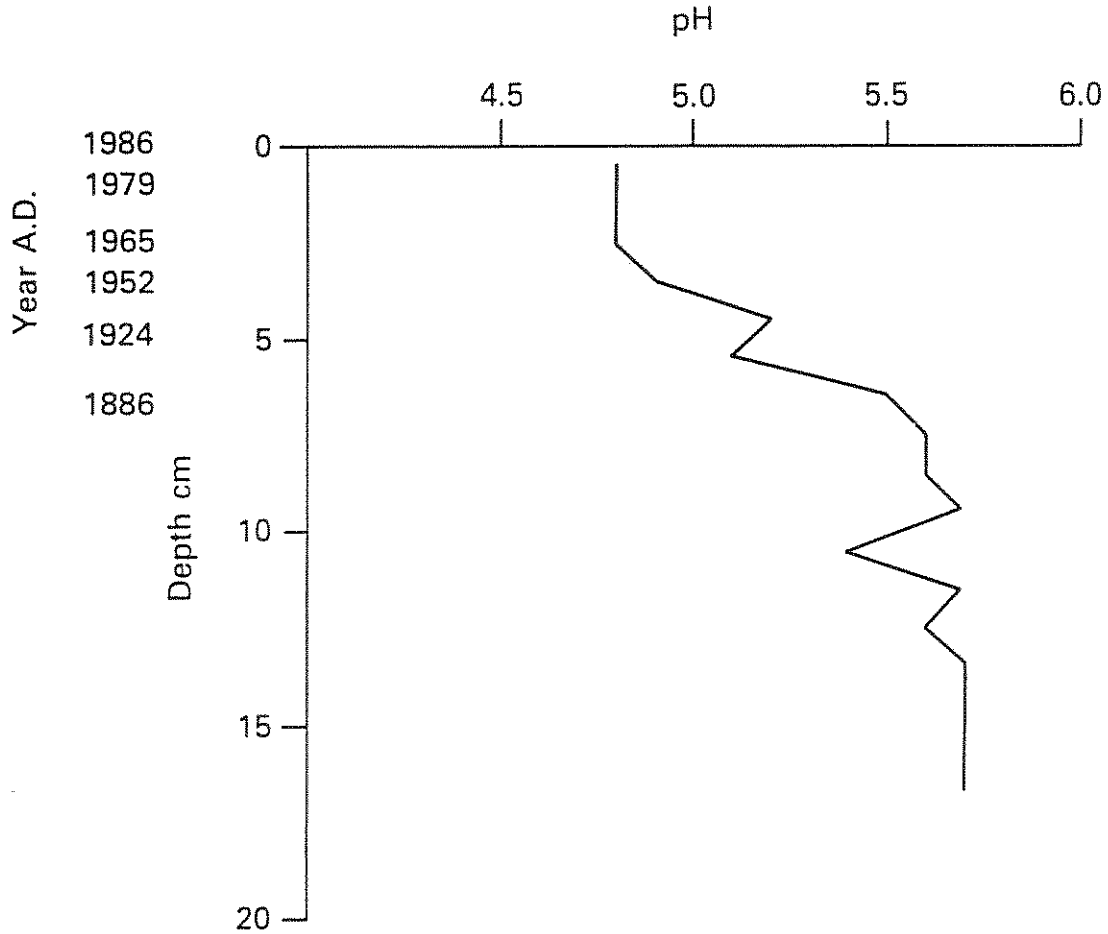

Figure 9. pH reconstruction (multiple regression) for Lochnagar.

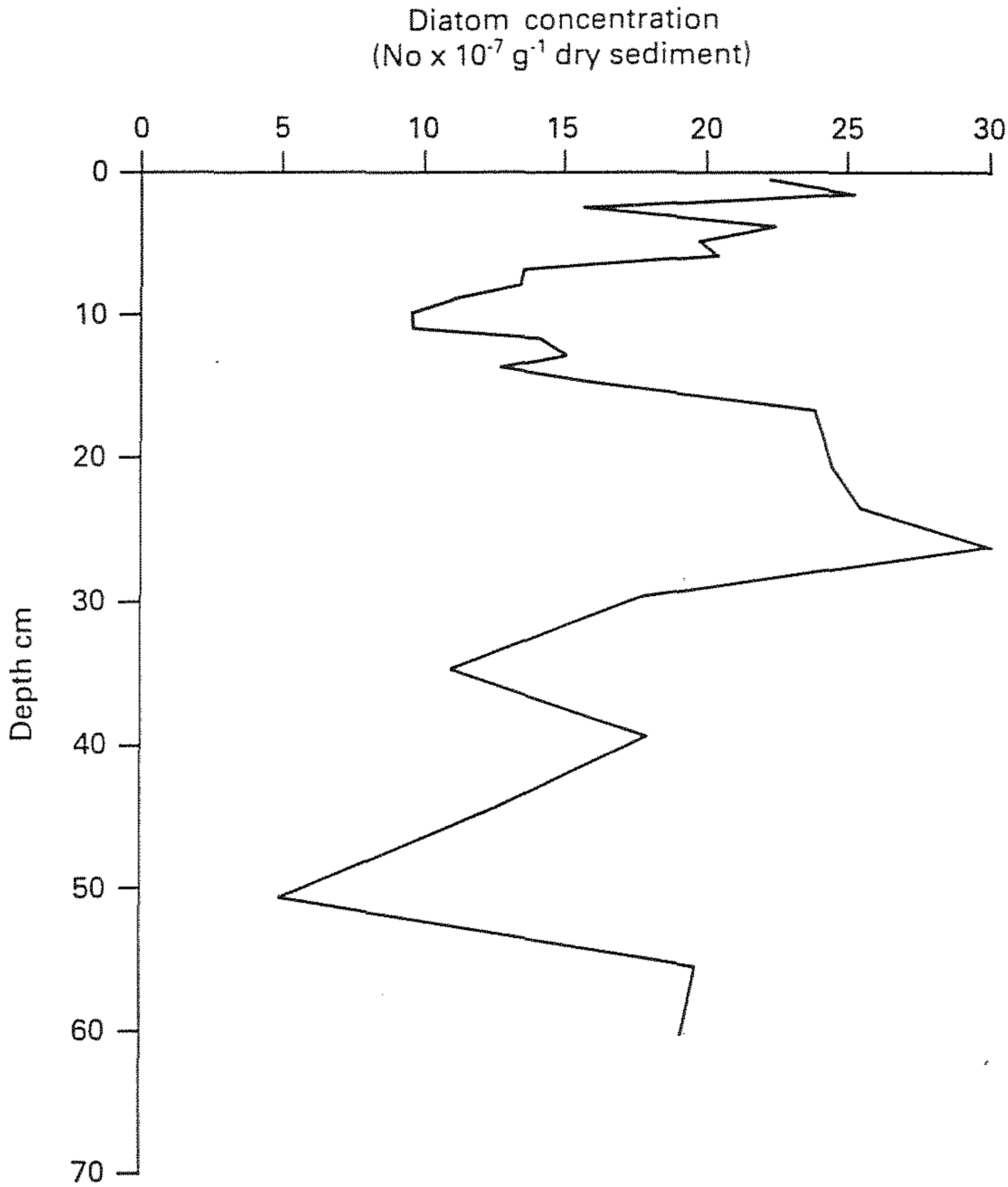

Figure 10. Diatom Concentration: Core NAG 3.

7.0 Sediment geochemistry

7.1 Major cations

Both the basic sediment constitution (Figure 4) and sediment dating (Section 5.0) show the 8-11 cm section to be coarser and more inorganic than the rest of the core. The major cation results (Figure 11, Appendix 3) all show peaks in this interval, but considering how marked the dry weight peak and LOI trough are at this depth, the cation peaks are more subdued. They are even less pronounced when the concentrations are expressed per gramme minerals (Figure 12). There are large concentration changes lower in the core (peaks around 50, 30 and 19 cm) and these further indicate that there have been changes in the erosion rate of material from the catchment. The cation fluxes (Figure 13) also record the recent increase in sediment accumulation rate that is shown by the dating results (Table 6).

7.2 Trace metals

The zinc, lead and copper concentration-depth profiles indicate that the sediments have become contaminated with these trace metals commencing at depths between 10 and 25 cm (Figures 14, 15, 16, Appendix 3). The Nickel profile is more like that of the major cations. Because there have been changes in the sediment constitution it is important to exercise care in identifying the depth at which contamination started. Changes in the basic sediment constitution can alter the trace metal concentrations in the absence of contamination from wastewater and from the atmosphere.

Figure 17 shows that lead contamination commenced around 19 cm, earlier than zinc which began around 11 cm. Below these depths the concentrations of the trace metals and the major cation potassium varied in a regular manner according to the constitution of the material delivered from the catchment. However, when contamination started the trace metal concentrations increased gradually without any change in the potassium concentration. As there are no wastewater sources of in the catchment of Lochnagar, the most probable source of the contamination is deposition from the atmosphere.

The amount of lead and zinc accumulated in the sediments of Lochnagar since 1900 is compared with the other lakes investigated in this project in Figure 18. The twelve lakes are a sufficient number to permit the division into sites with a sufficiently low pH to reduce zinc sedimentation efficiency (Patrick *et al.* 1988) and those which are not. A provisional line is indicated on Figure 18. More site investigations are required to test the validity of this division, but at Lochnagar it is apparent that pH has dropped sufficiently to lower the efficiency of zinc sedimentation.

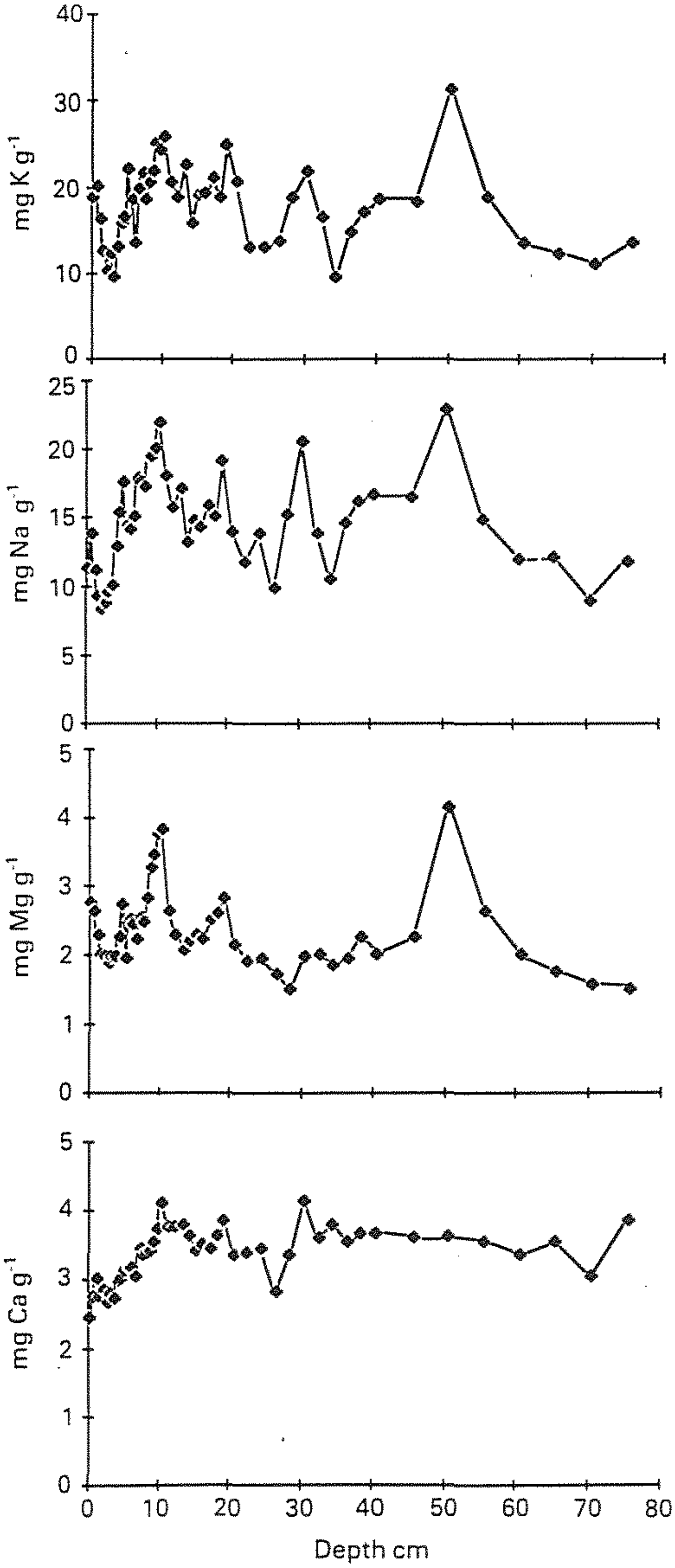

Figure 11. Variation of potassium, sodium, magnesium and calcium concentrations in Lochnagar.

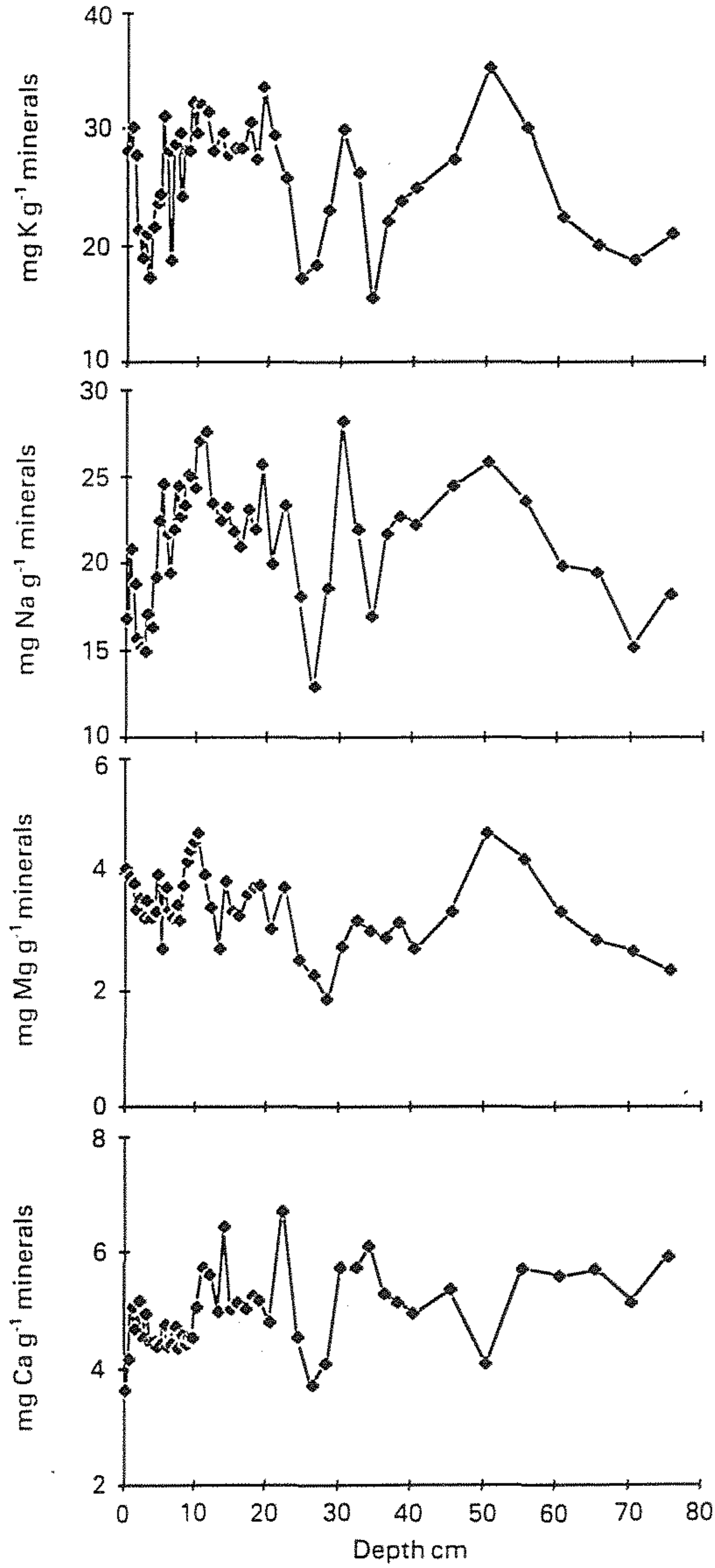

Figure 12. Variation of potassium, sodium, magnesium and calcium concentrations expressed per gramme minerals in Lochnagar.

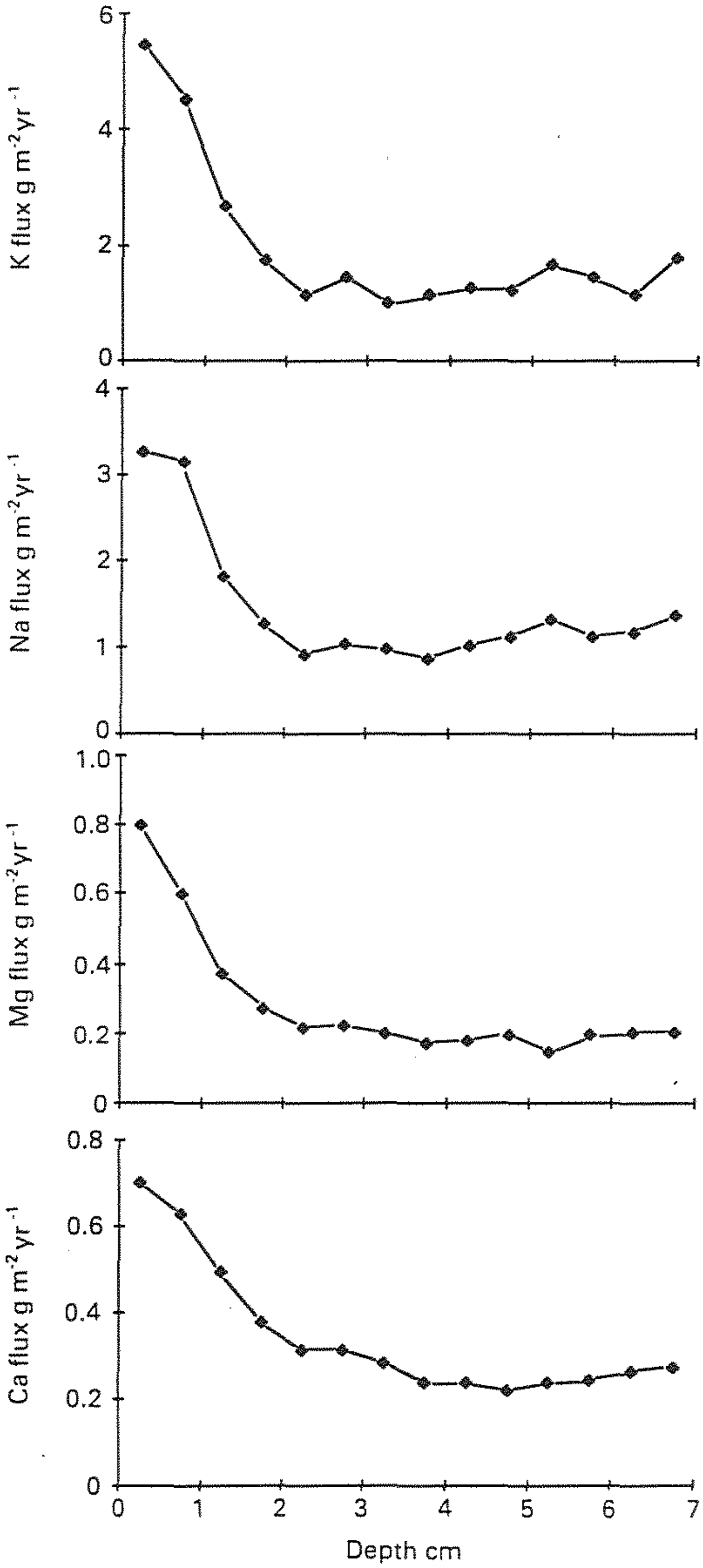

Figure 13. Variation of the potassium, sodium, magnesium and calcium fluxes in the sediments of Lochnagar.

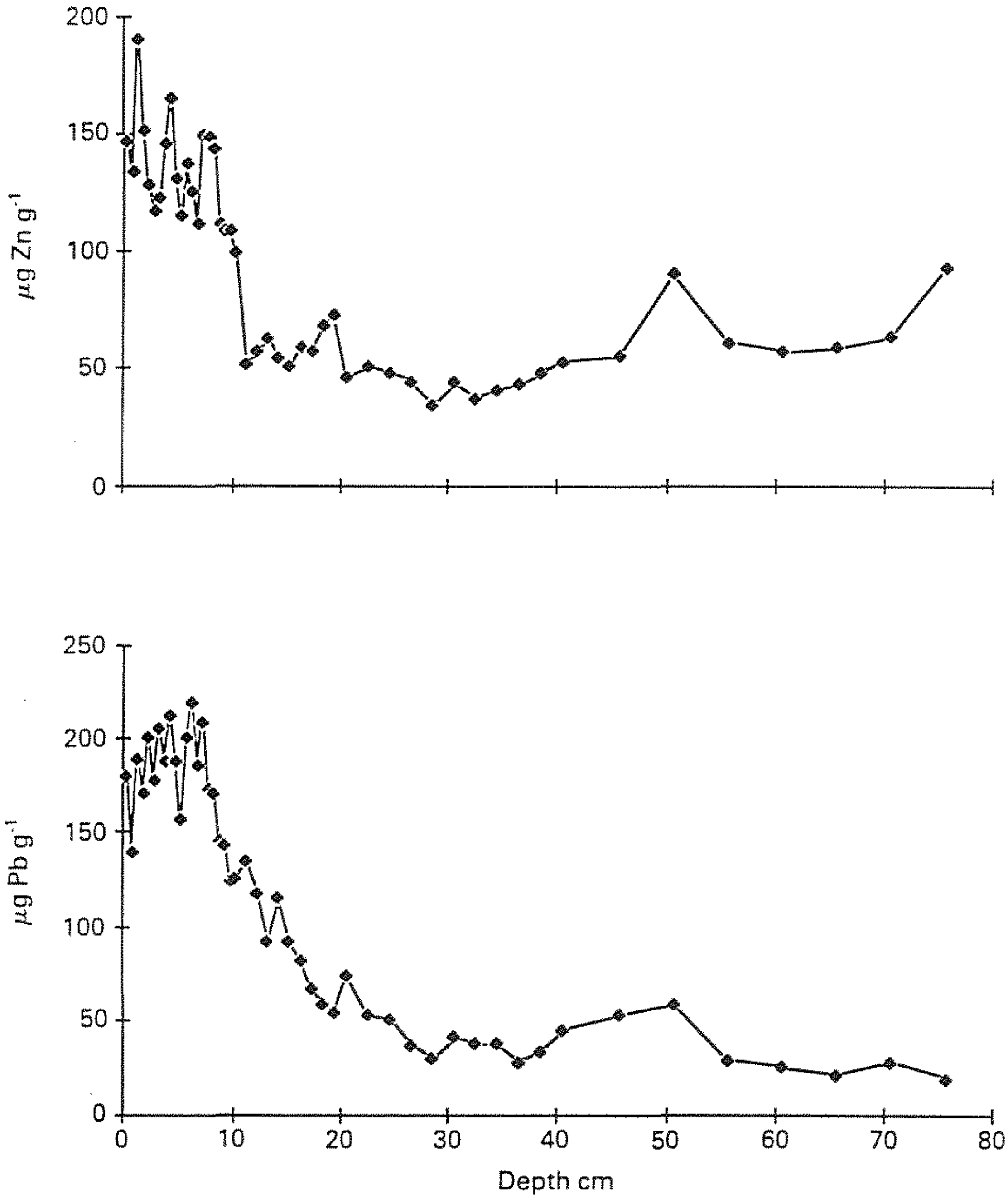

Figure 14. Variation of zinc and lead concentrations in Lochnagar.

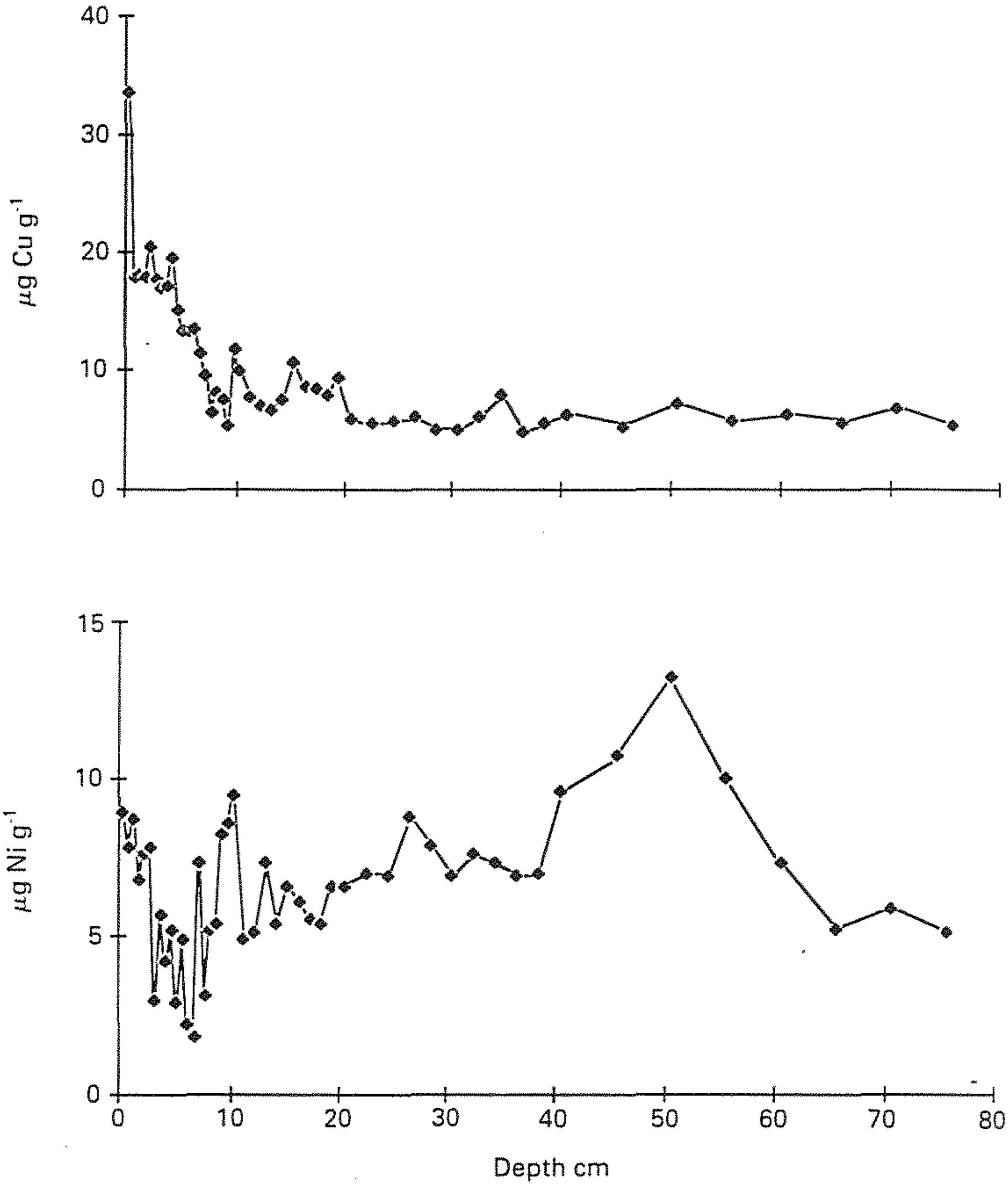

Figure 15. Variation of copper and nickel concentrations in Lochnagar.

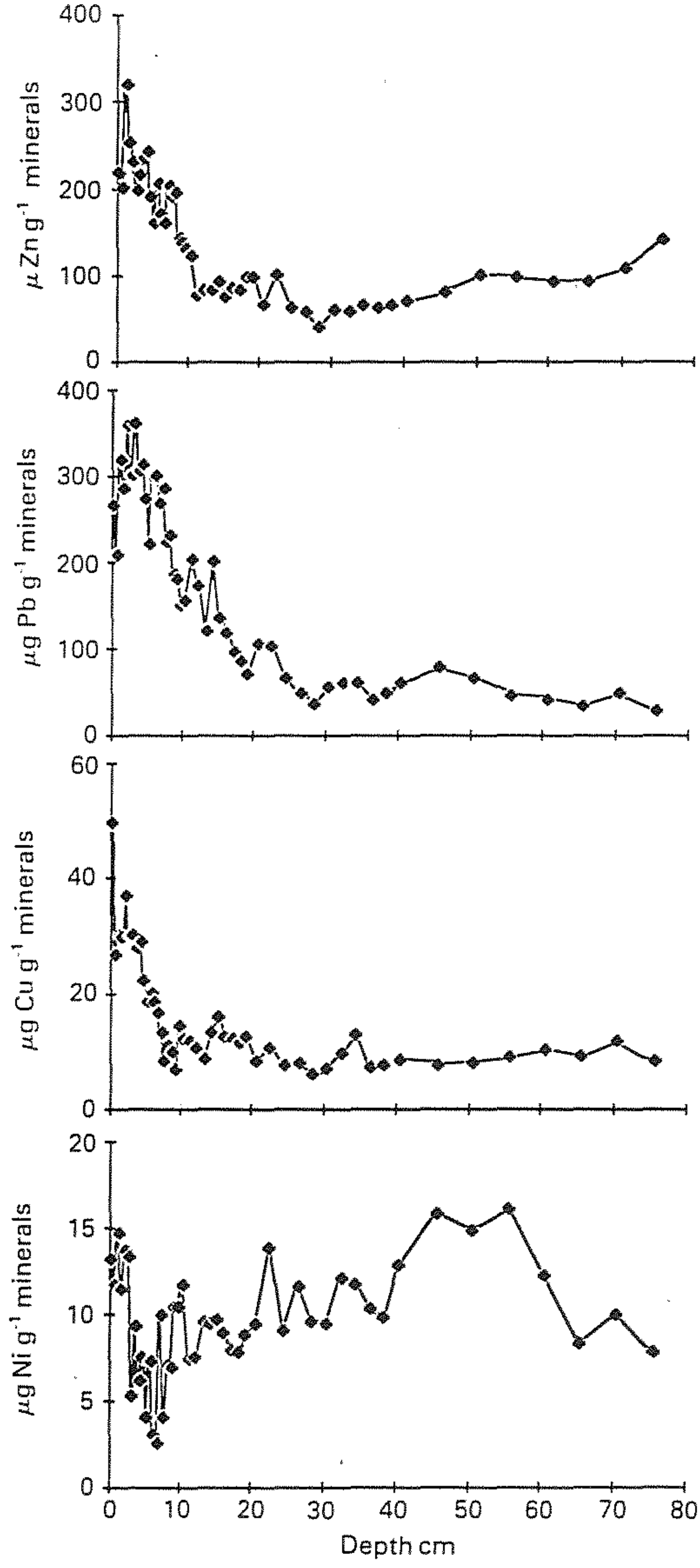

Figure 16. Variation of zinc, lead, copper and nickel concentrations expressed per gramme minerals in Lochnagar.

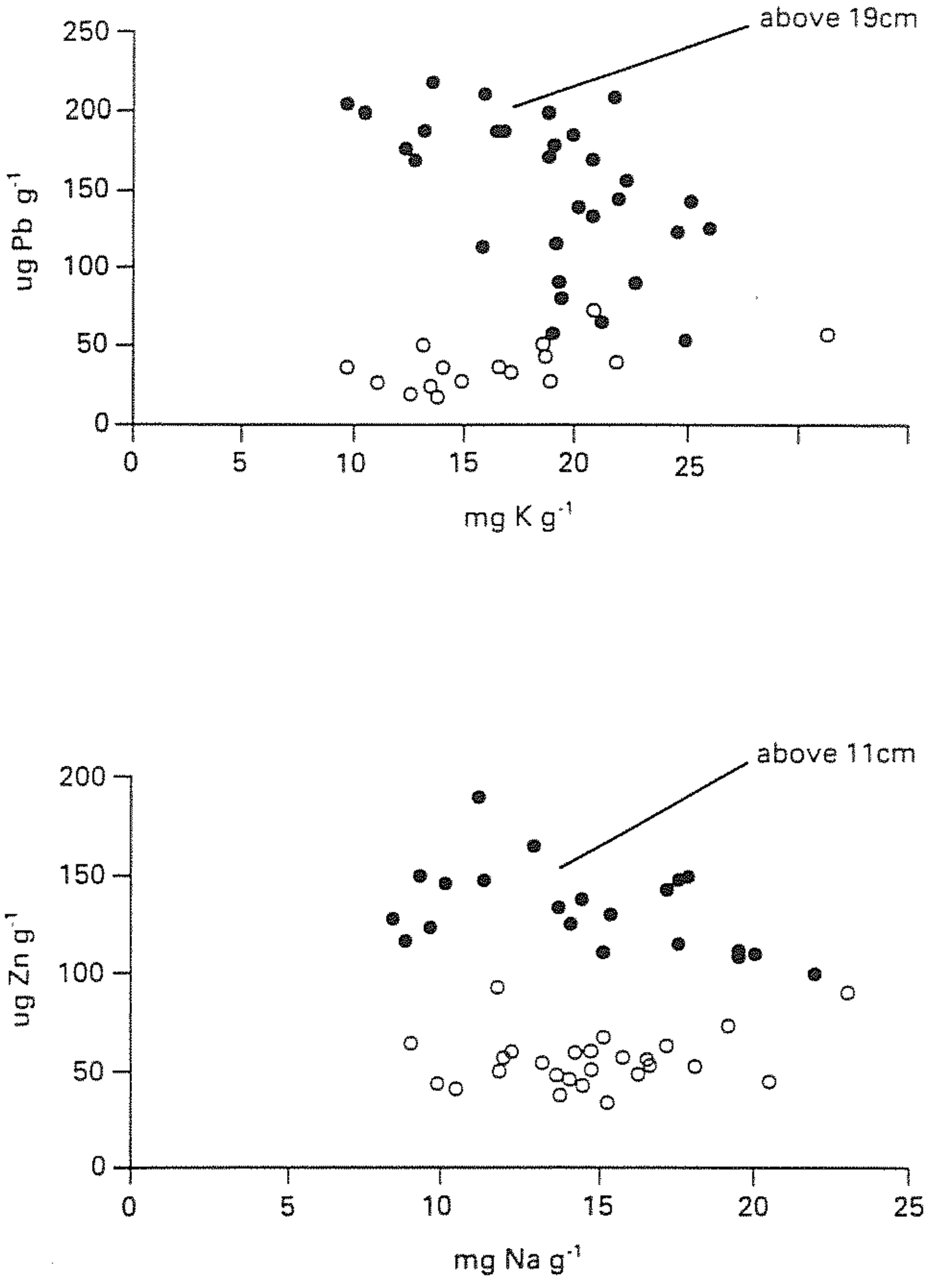

Figure 17. Visual method to estimate the depth when zinc and lead contamination starts in the sediments of Lochnagar.

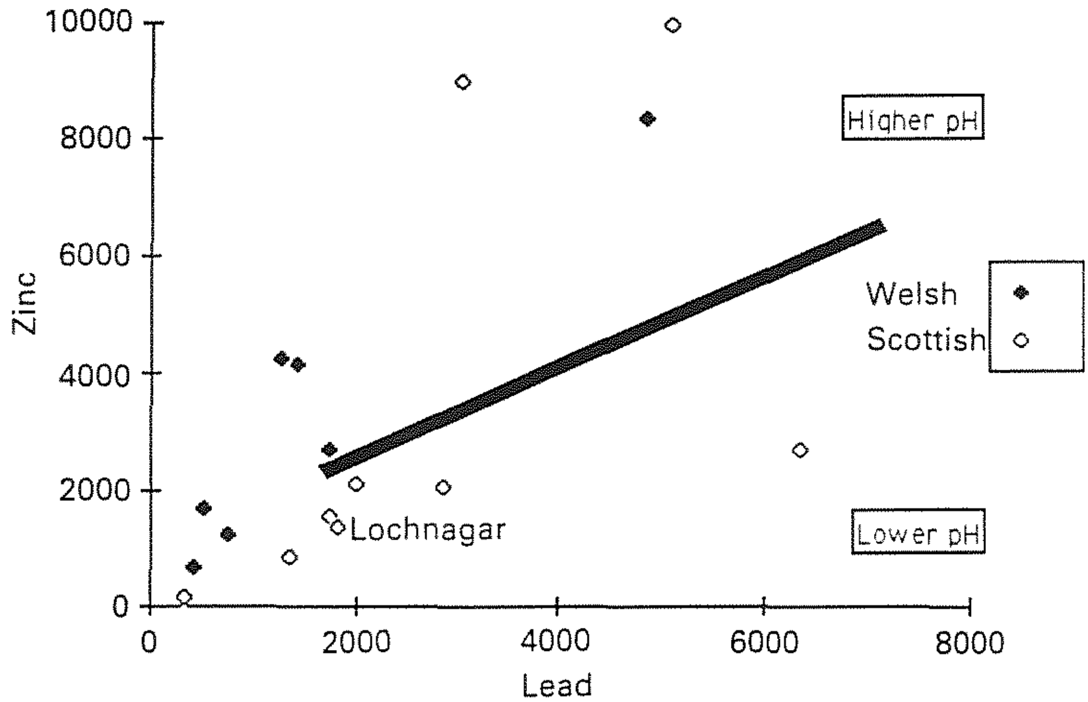

Figure 18. Comparison of the amounts of lead and zinc deposited (mg m^{-2}) in Welsh and Scottish lakes since 1900. When the pH of the lake falls below 4.5 - 5, the efficiency of zinc sedimentation drops, giving a lower zinc burden than expected. A provisional line which indicates the division between higher and lower pH lakes is suggested.

8.0 Magnetic susceptibility

The upper levels of lake sediment contain a record of particulate atmospheric pollution that can be detected by magnetic measurements providing the background input of magnetic minerals from the catchment is sufficiently low for the atmospheric component to be revealed. The magnetic particles that are extracted from such sediments are predominantly spherical and are identifiable as fly-ash from power stations.

Figure 19 plots the total (SIRM), 'soft' ($SIRM-IRM_{20mT}$) and 'hard' ($SIRM+IRM_{300mT}$) magnetic deposition for Lochnagar. Whereas the 'soft' component largely reflects magnetite deposition, the 'hard' component is related to the changing deposition of haematite-type (imperfect antiferromagnetic) oxides. Figure 19 shows only a slight increase in magnetic accumulation up to the 1940s, after which values increase dramatically, especially since 1960. The pattern of increase is similar to that observed at the Welsh sites studied in this project and at Loch Tanna (Battarbee *et al.* 1988). However, levels of peak deposition are much higher at Lochnagar.

9.0 Spherical carbonaceous particle (SCP) analysis

Core NAG3 was sub-sampled to a depth of 14.5 cm and analysed for concentrations of SCPs, the results are given in Figure 20. Second counts were made for three of the sediment levels to check accuracy. The limit of detection was determined to be 110 SCPs g^{-1}.

Few SCPs are present in the sediment below 9 cm. Above this point the particles are observed at all levels. The concentrations increase progressively to the surface. However, the heaviest concentrations are not in the top-most sediments but at a depth of 2-2.5 cm (c. 1968). When expressed in terms of the organic fraction of dry sediment (determined by LOI), the concentrations give a similar pattern of distribution (Figure 20).

10.0 Pollen analysis

The summary pollen diagram derived from core NAG3 is presented in Figure 21, the full diagram may be found in Appendix 4.

Within the regional pollen spectra very little change occurs through the diagram. The pollen rain is dominated by *Betula*, *Pinus*, *Alnus* and *Quercus*. Despite the presence of nearby forestry plantations of *Picea* and *Pinus*, albeit at a lower altitude, the pollen diagram does not pick up this afforestation. Disturbances of the regional vegetation are identified by peaks in the major disturbance indicators *Plantago lanceolata* and *Rumex crispus* at 30 cm and 12 - 0 cm.

Within the catchment pollen record the major change is a fall in the *Calluna* : Gramineae ratio over the last 200 years. This trend from *Calluna* to *Gramineae* over this period has been recognised at many of the upland sites studied in this and associated projects (Battarbee *et al.* 1988). It is the reverse of what might be expected if the 'land-use hypothesis' (eg. Rosenqvist 1977, 1978, Krug and Frink 1983) was responsible for lake acidification.

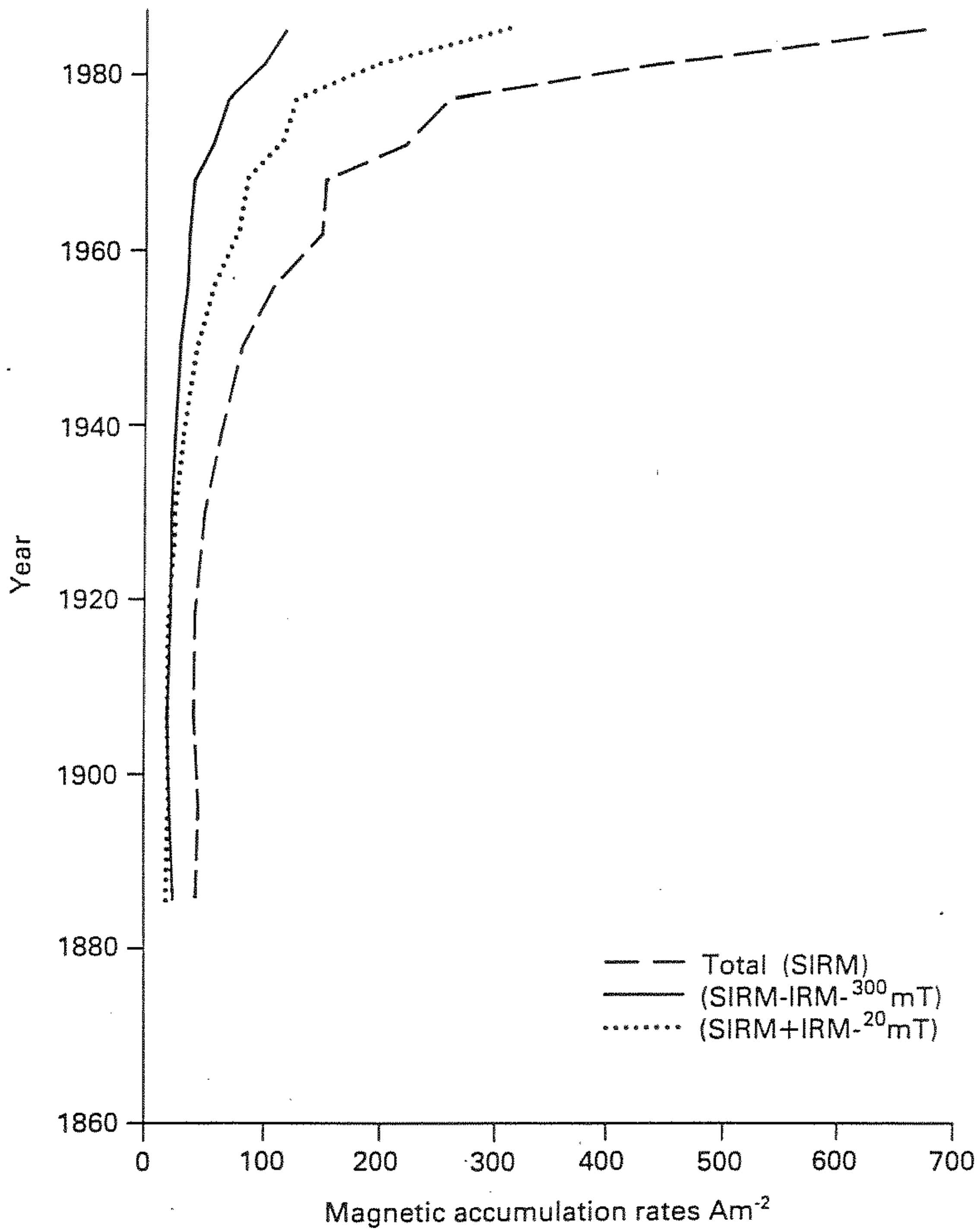

Figure 19. Magnetic deposition at Lochnagar.

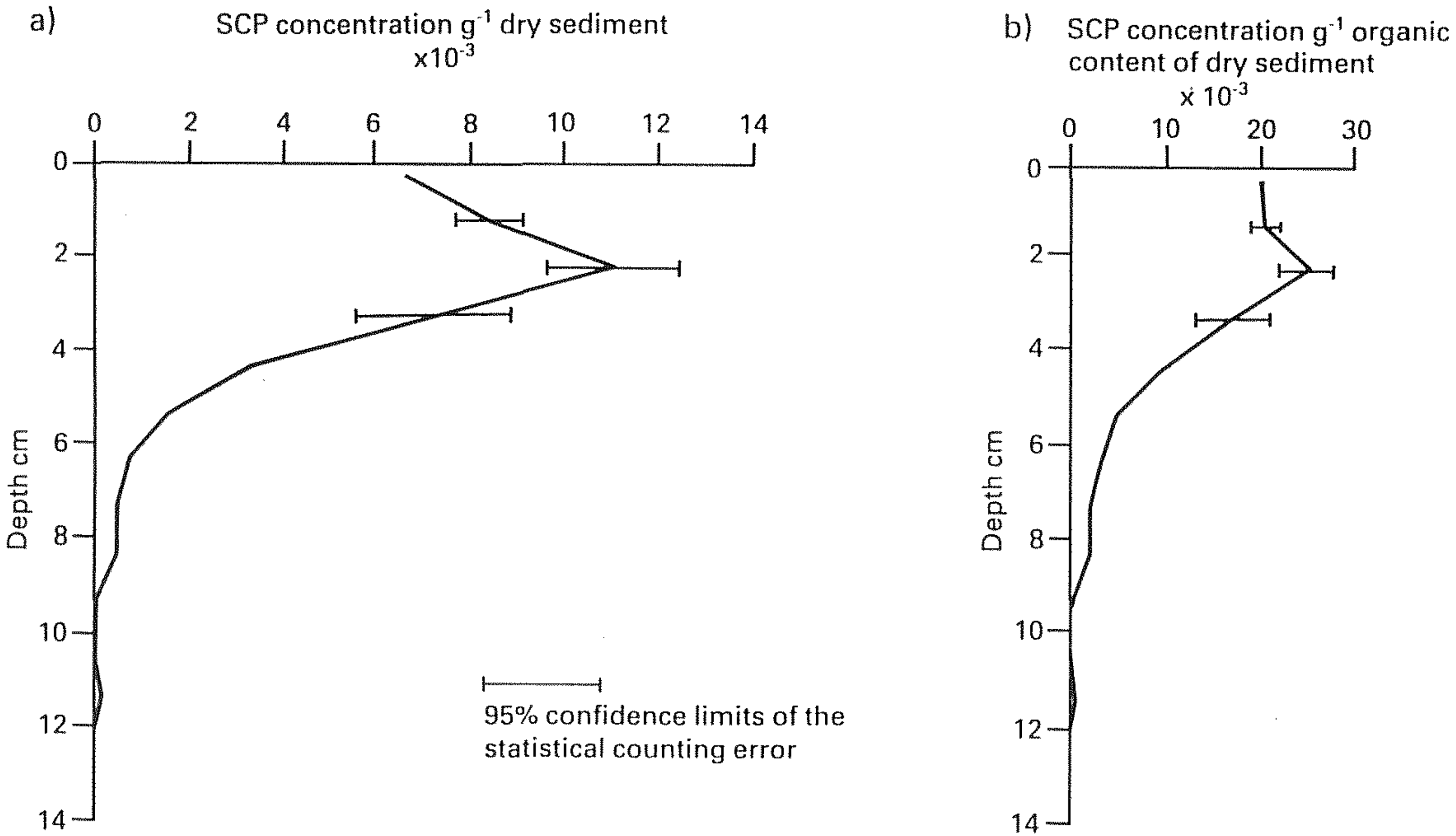

Figure 20. Carbonaceous Particle data: Core NAG 3.

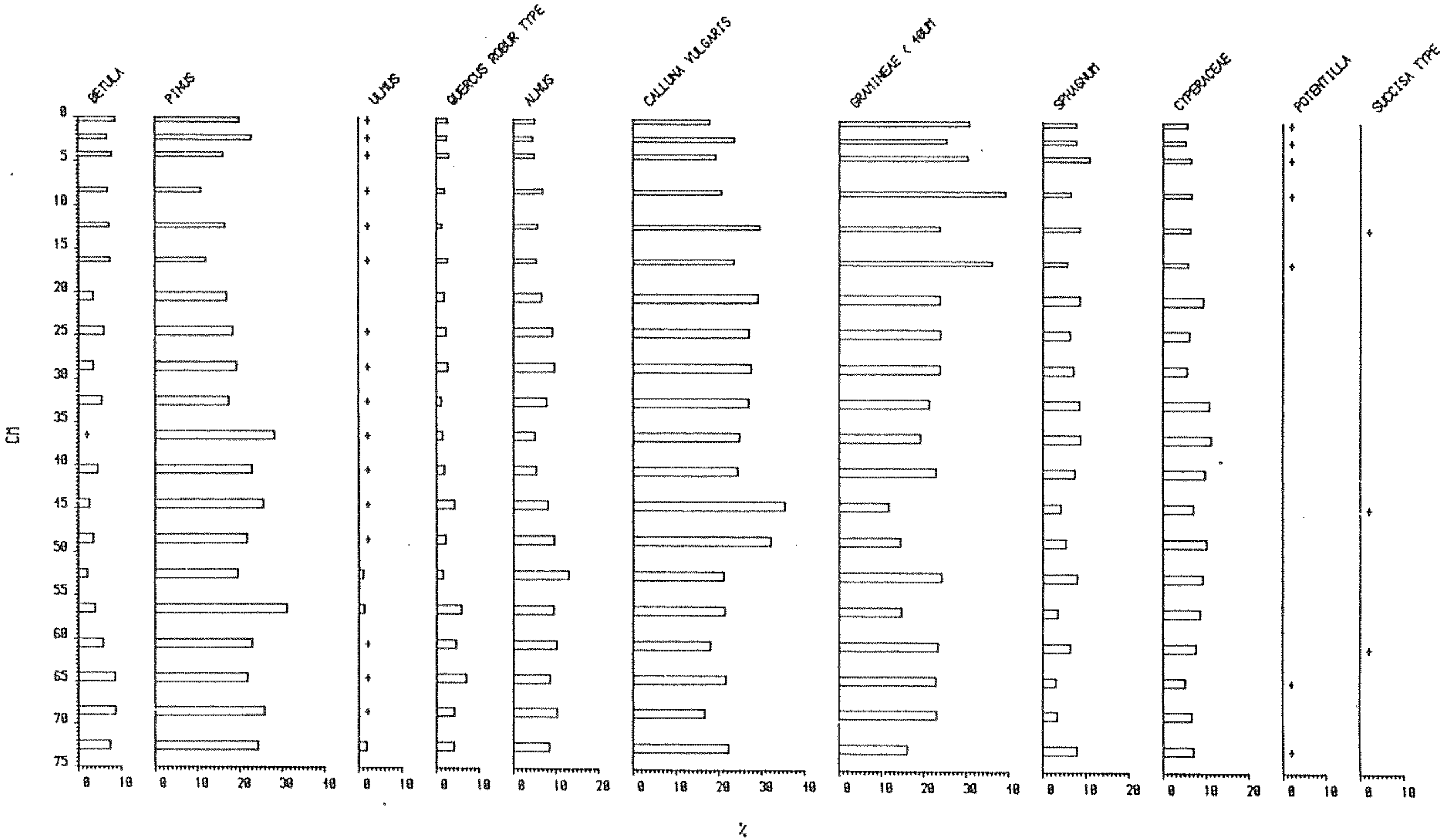

Figure 21. Lochnagar: Sumary pollen diagram (percentage frequency of pollen types on diagram)

11.0 Discussion

The acid diatom flora at Lochnagar has some differences from floras at similar pH but lower altitude sites. *Tabellaria* species are absent and the dominant species are *Achnanthes*, especially *Achnanthes marginulata* and associated varieties. Although Lochnagar is not as strongly acidified as many Galloway sites (eg. Battarbee *et al* 1985, Battarbee *et al* in press, Flower and Battarbee 1983, Flower *et al* 1987a), diatom analysis of the loch's sediments indicates that Lochnagar has experienced a marked 'recent' acidification of about 1 pH unit. Evidence from lithostratigraphic analysis, radiometric dating, diatom concentration data and geochemical analyses reveals a sediment inwash event in the core below 7 cm at a time when acidification was first occurring. This makes it difficult to be precise in dating the onset of acidification. A linear extrapolation of the rate of sediment accumulation back from 6.75 cm (c. 1886) to the first sign of acidification (10 cm) gives a date of 1800. However, since this minerogenic section of sediment probably accumulated much more rapidly than sediment above 7 cm a more recent date is probable and the best estimate suggests that acidification began in the mid-nineteenth century.

As at other sites (Battarbee *et al.* 1988) Lochnagar has been contaminated by trace metals and carbonaceous particles. Increases in the concentration of lead and zinc in the sediment date from the early-nineteenth century. The carbonaceous particle record shows some late-nineteenth and early-twentieth century contamination and a typically marked increase from the 1930s to about 1970. The magnetic mineral record also shows a clear increase in recent decades. Since the high, remote catchment has not been subjected to land-use or land-management practices that might affect the water quality of the loch, the only plausible cause for the acidification of Lochnagar is acid deposition.

The role of atmospheric deposition in surface water acidification is now well established and the results from Lochnagar confirm and reinforce this role. Still uncertain however, is the precise geographical extent of acidification. All three sites in Scotland, lying on sensitive geology in areas of moderate acid deposition, examined in this specific project - Loch Tanna (Arran) (Flower *et al.* 1988a), Loch Laidon (Rannoch Moor) (Flower *et al.* 1987b, 1988b) and Lochnagar, have experienced acidification. Loch Urr (Galloway), a less sensitive site lying in an area of high acid deposition has not been acidified (Patrick *et al.* 1988). The full extent of acidification in Scotland will only be revealed when palaeoecological investigations of sensitive sites lying further to the north and west, in areas of lower acid deposition, are completed.

12.0 Summary of conclusions

1. Lochnagar, a high altitude, relatively deep, corrie lake, lies on the Royal Deeside Estate of Balmoral, in an area which experiences moderate levels of acid deposition. The loch catchment comprises granite bedrock and is dominated by bare rock but overlain in places with blanket peats. Lochnagar may thus be considered potentially susceptible to acidification. The contemporary pH of the loch water is c. 5.0.

2. To investigate the history and potential causes of acidification at Lochnagar sediment cores were obtained in June 1986. Sediment samples were subjected to lithostratigraphic, radiometric dating, diatom, geochemical, carbonaceous particle, magnetic, and palynological analyses.

3. A large variation in gross sediment composition down the core produces, in particular, an irregular 'spikey' loss-on-ignition profile. Variations in the lithostratigraphic profiles are attributed to influxes of terrestrially-derived debris from the catchment.

4. ^{210}Pb dating was utilised to provide a chronology of sediment accumulation. A reliable chronology is available back to c. 1886 (6.75 cm), near the ^{210}Pb equilibrium depth. Below 7 cm a layer of sediment with high ^{226}Ra activity makes it difficult to calculate accurate ^{210}Pb activities in the lower part of the core.

5. Diatom analysis shows a clear acidification sequence. The first sign of acidification is indicated by a decline in *Fragilaria virescens* and an increase in *Achnanthes marginulata* above 10 cm. A more pronounced change occurs after 7 cm (c. 1880) as several circumneutral species decrease and acidophilous *Achnanthes* and acidobiontic *Melosira* species increase. The acid diatom flora at Lochnagar has some differences from floras at similar pH but lower altitude. *Tabellaria* species are absent and the dominant species are *Achnanthes*, especially *Achnanthes marginulata* and associated varieties.

6. The pH history of the loch is reconstructed from diatom data. Prior to acidification the loch had a pH c. 5.7. The onset of acidification is dated to the mid-nineteenth century with reconstructed pH values falling to 4.8 at the core top (compared to the modern measured pH of 5.0).

7. Geochemical analysis indicates a progressive contamination of the upper sediments by trace-metals, notably zinc and lead. Zinc contamination commenced around 11 cm depth (early/mid-nineteenth century) which corresponds to the first evidence of acidification from the diatom record. Lead contamination started earlier at around 19 cm. Wastewater effluents are not present in the catchment and trace-metal contamination has therefore been of atmospheric origin.

8. Magnetic accumulation in the sediment increased only slowly between 1900 and the 1940s, since when a steady increase is apparent to the core top suggesting contamination by fly-ash material. Concentrations of spherical carbonaceous particles have also progressively increased since the 1890s with a major increase occurring between c. 1950-1973.

9. The recent catchment pollen record is dominated by a trend from *Calluna* to Gramineae over the last c. 200 years. This trend is the antithesis of that proposed by the 'land-use hypothesis' of surface-water acidification.

10. The remote and rugged catchment has not been subjected to land-use or land-managementpractices that might affect the water quality of the loch.

11. The results of this study reinforce the conclusion from work elsewhere in the United Kingdom, that the acidification of surface waters since the early/mid-nineteenth century has been the result of acid deposition. All the evidence from Lochnagar is consistent with the acid deposition hypothesis and the pattern and timing of observed changes can not be accounted for by alternative hypotheses.

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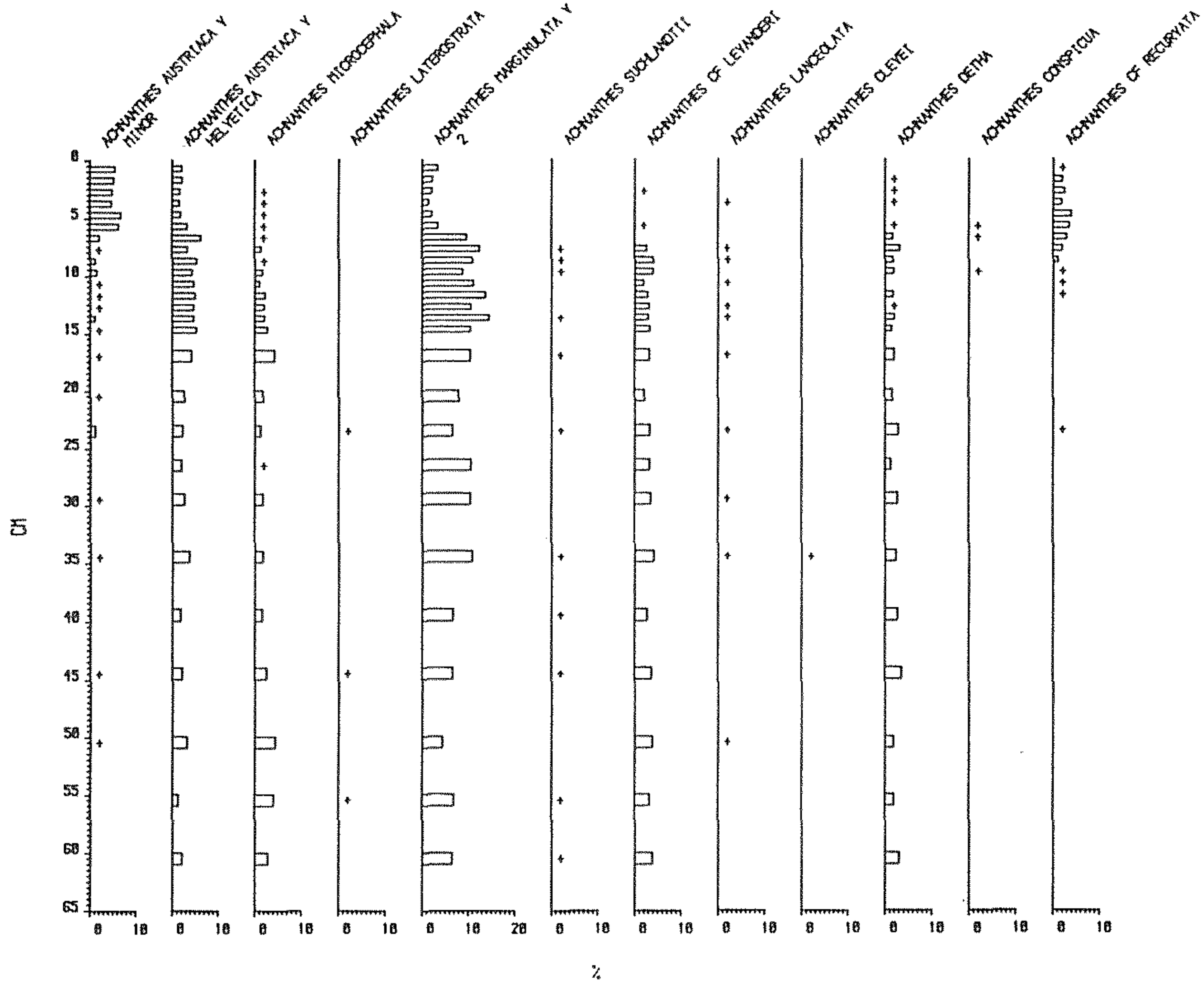
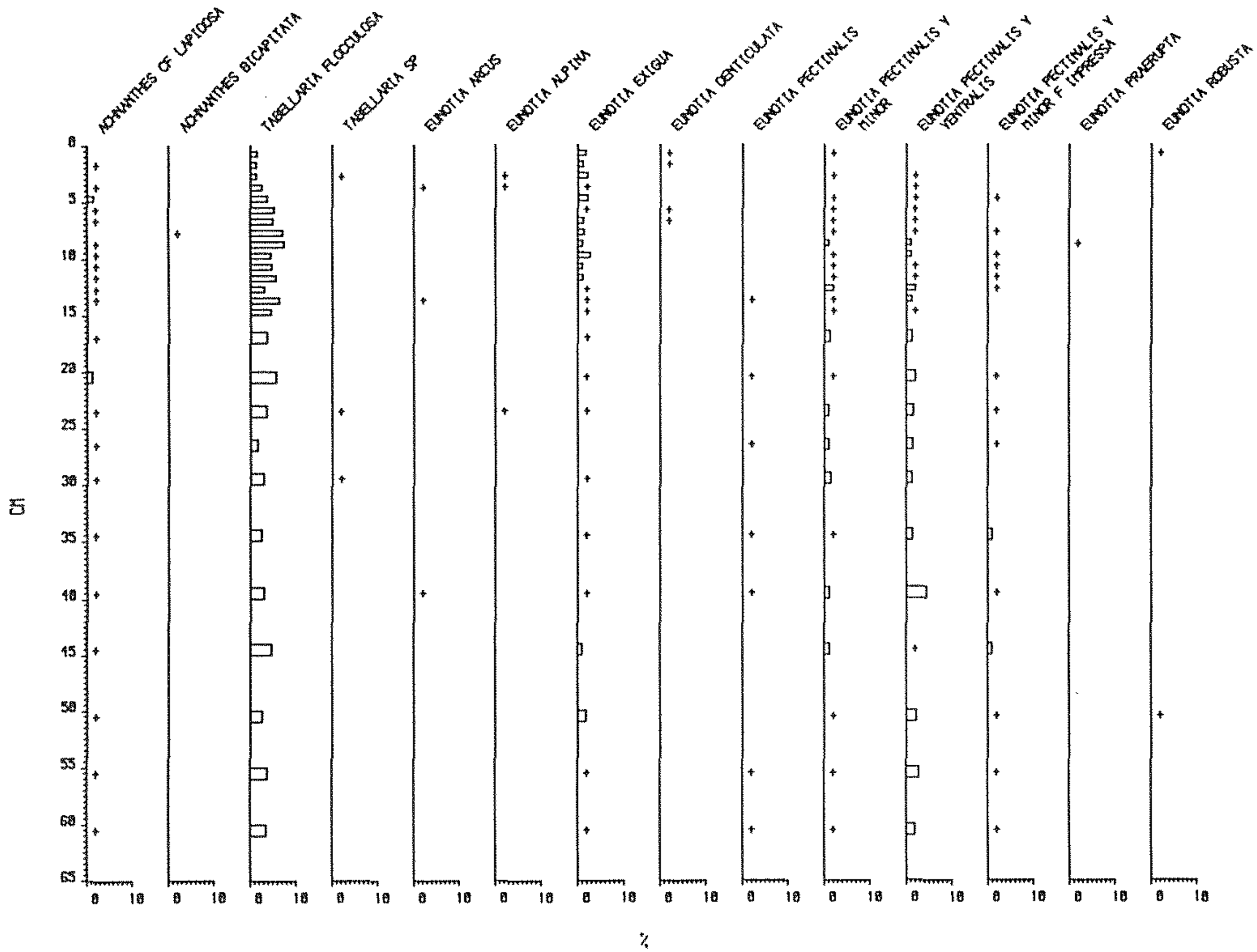


Appendix 1. Lochnagar: Full diatom diagram.



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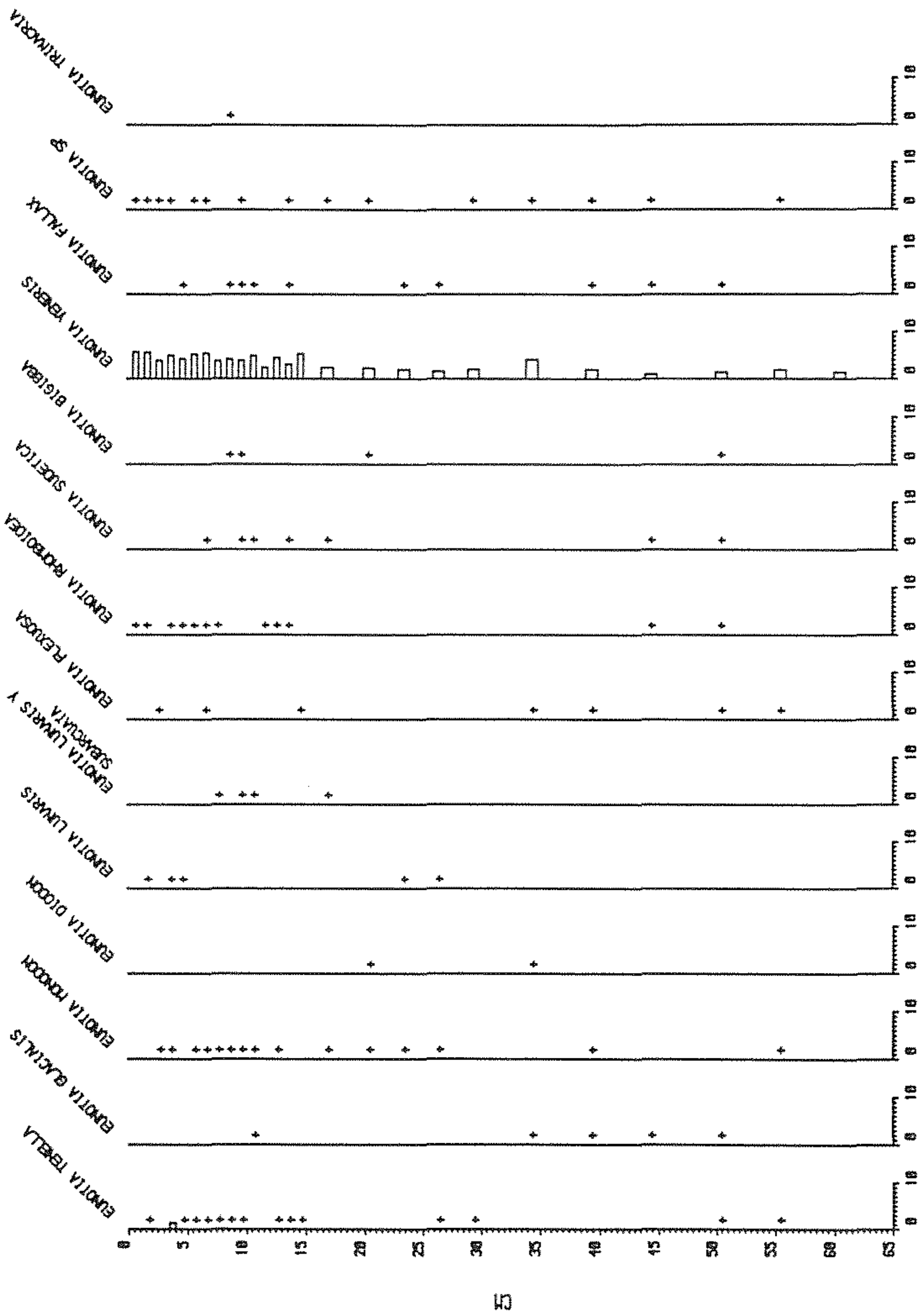

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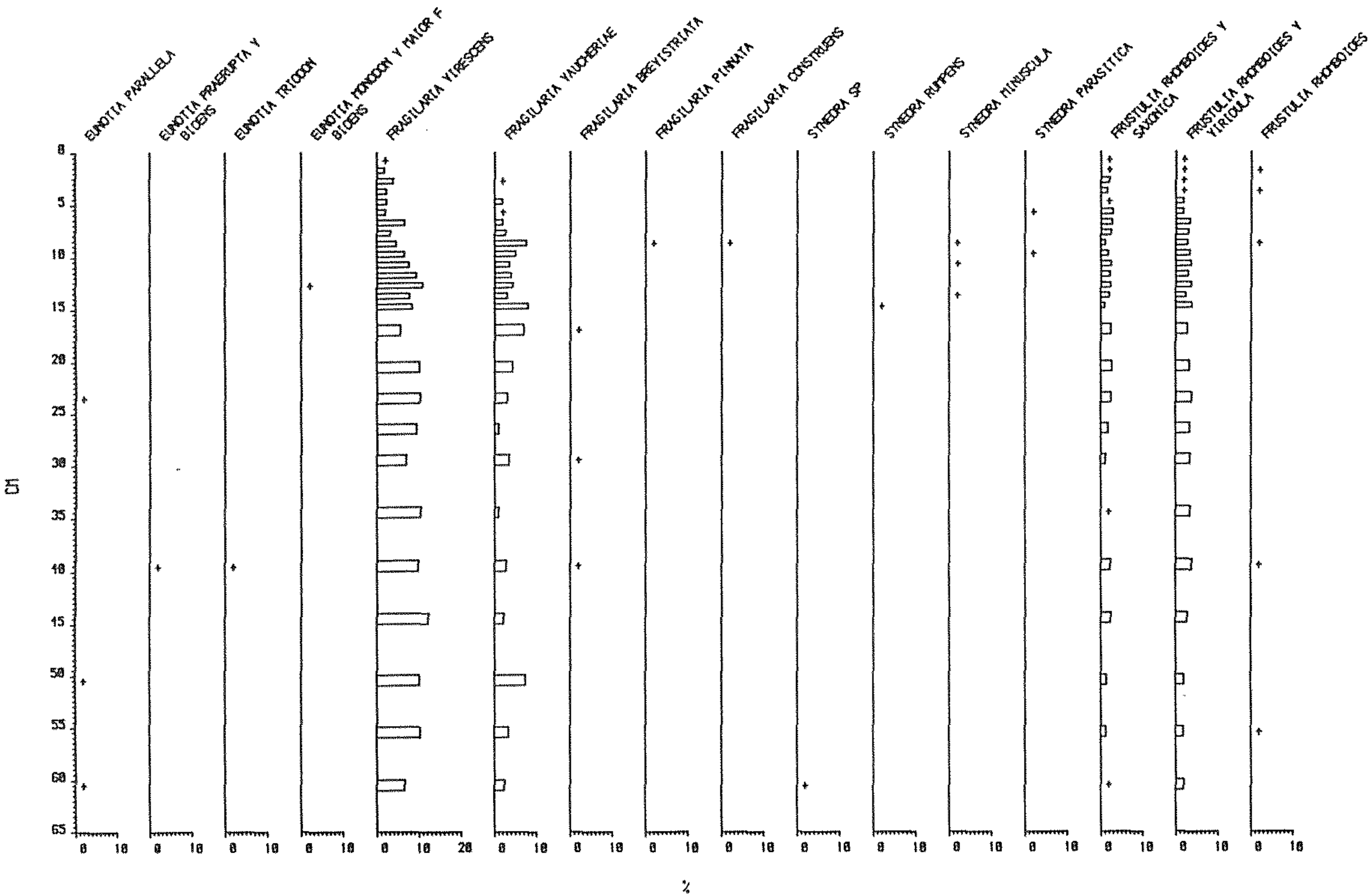

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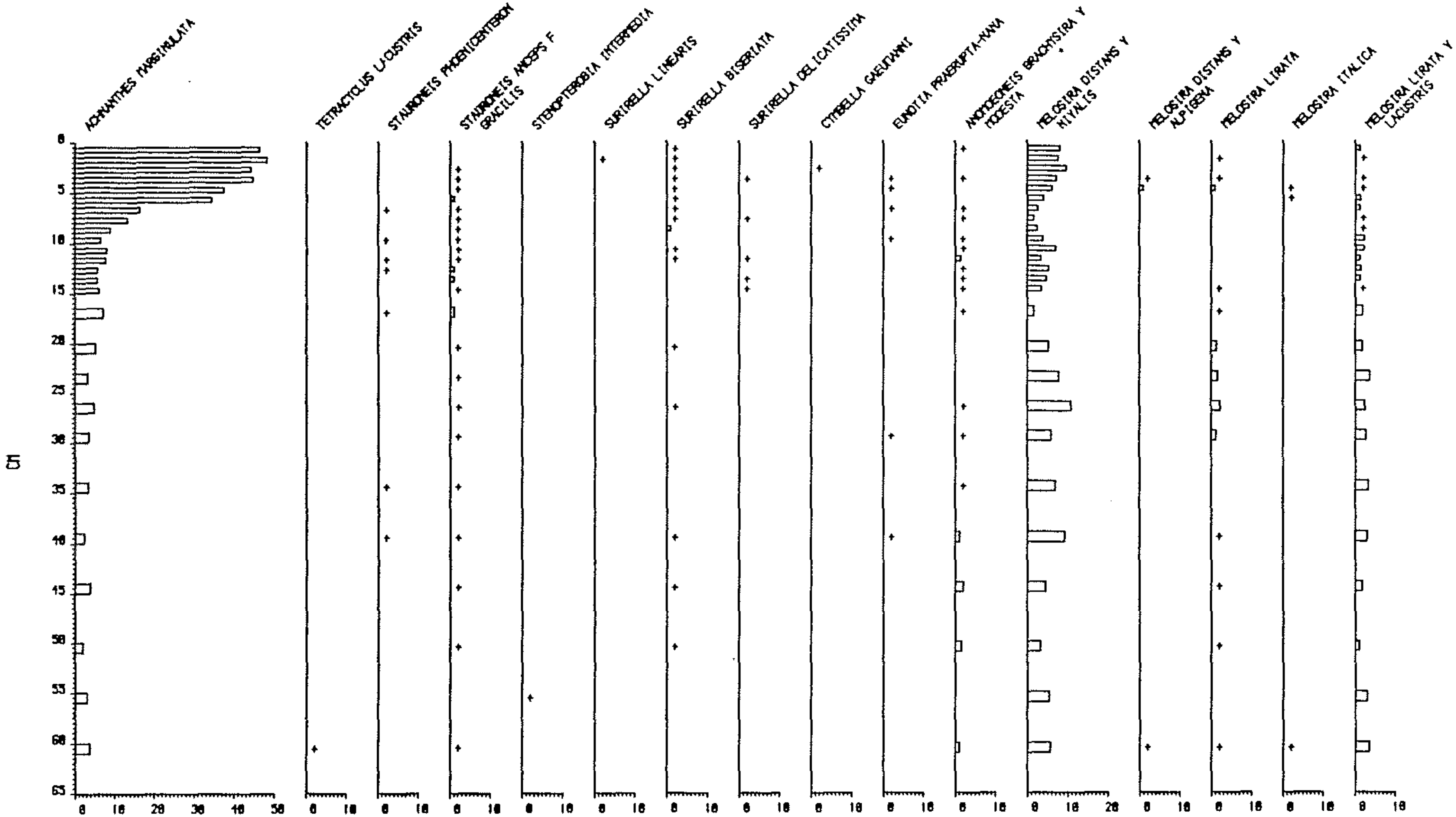

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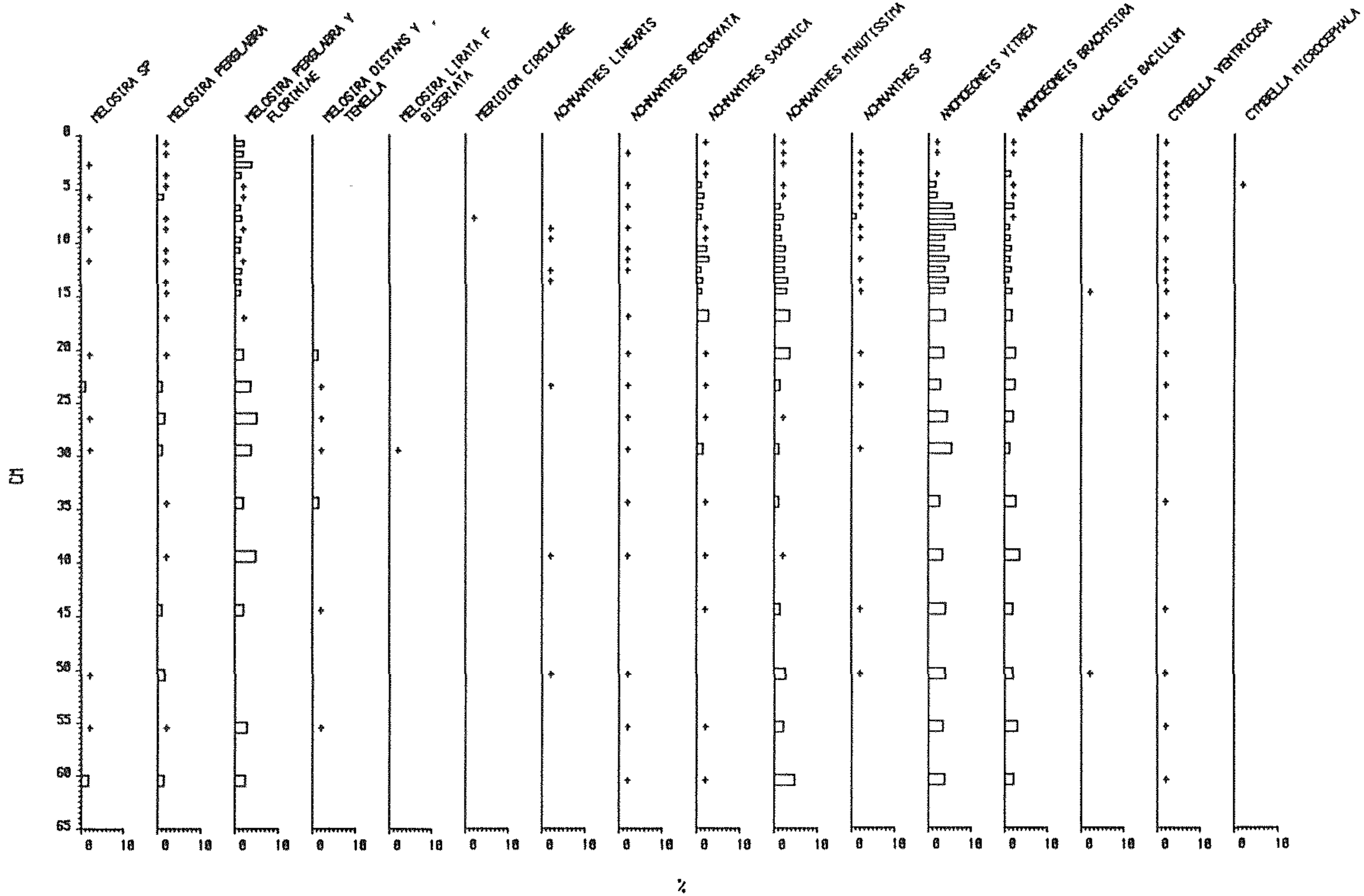

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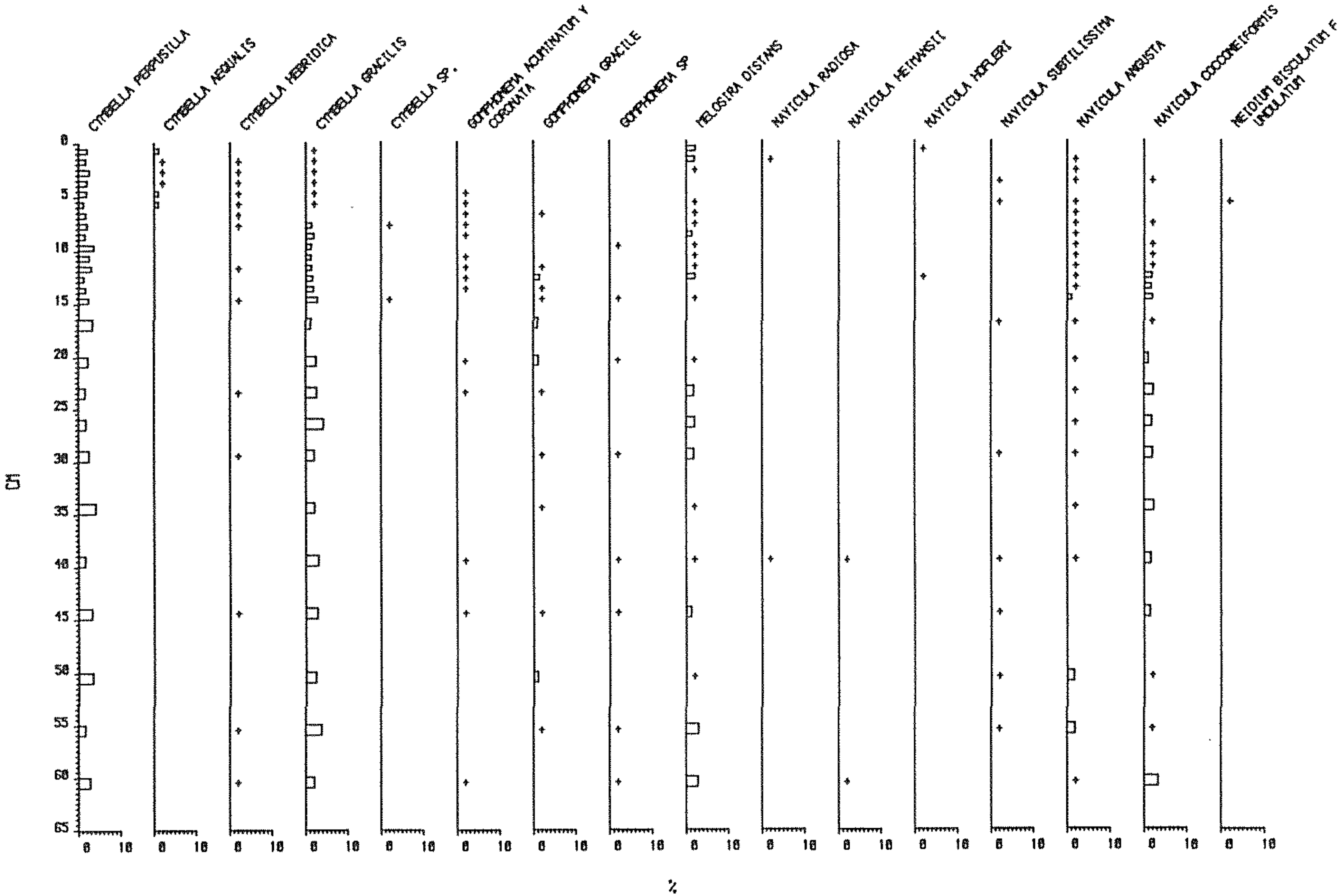

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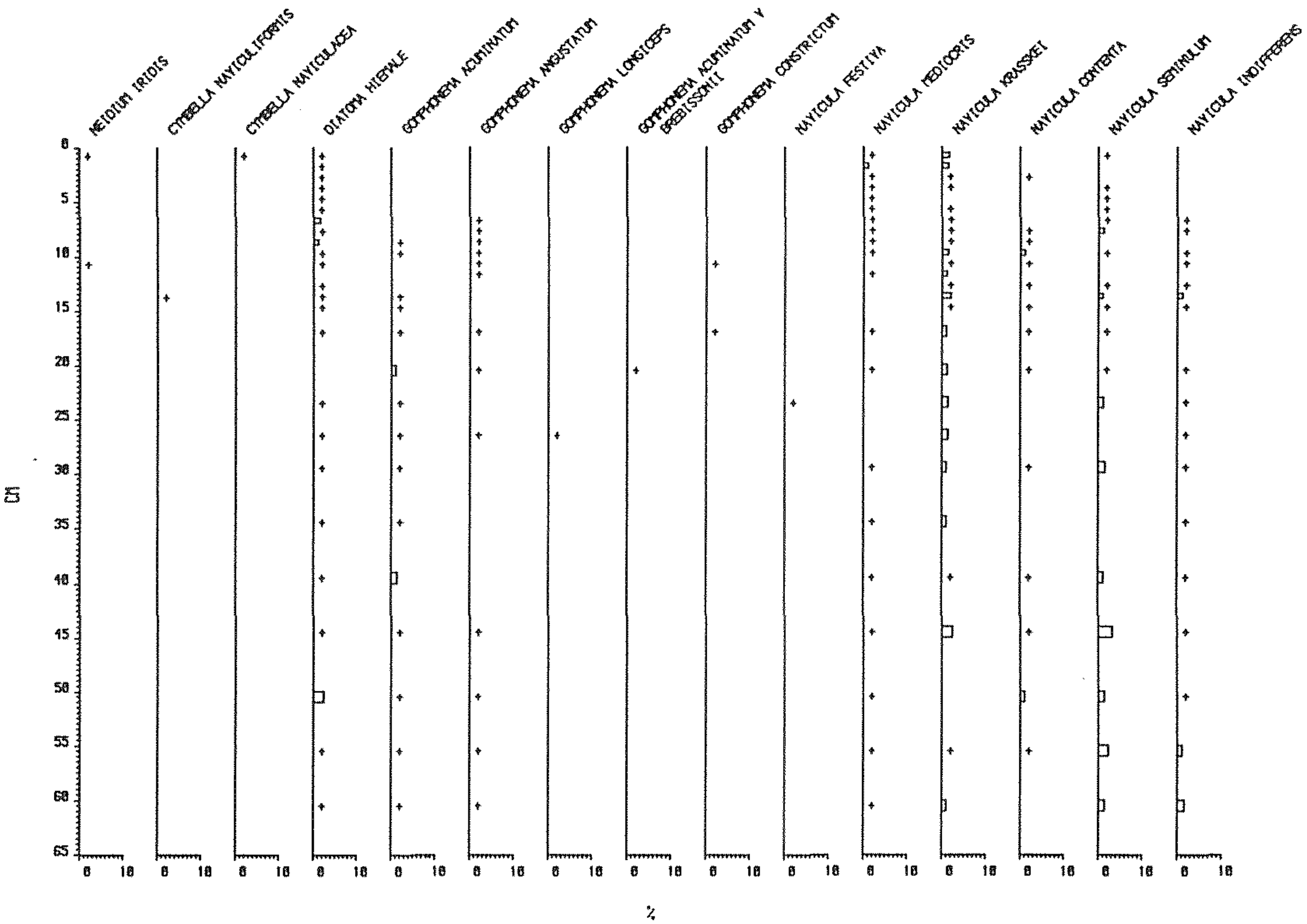

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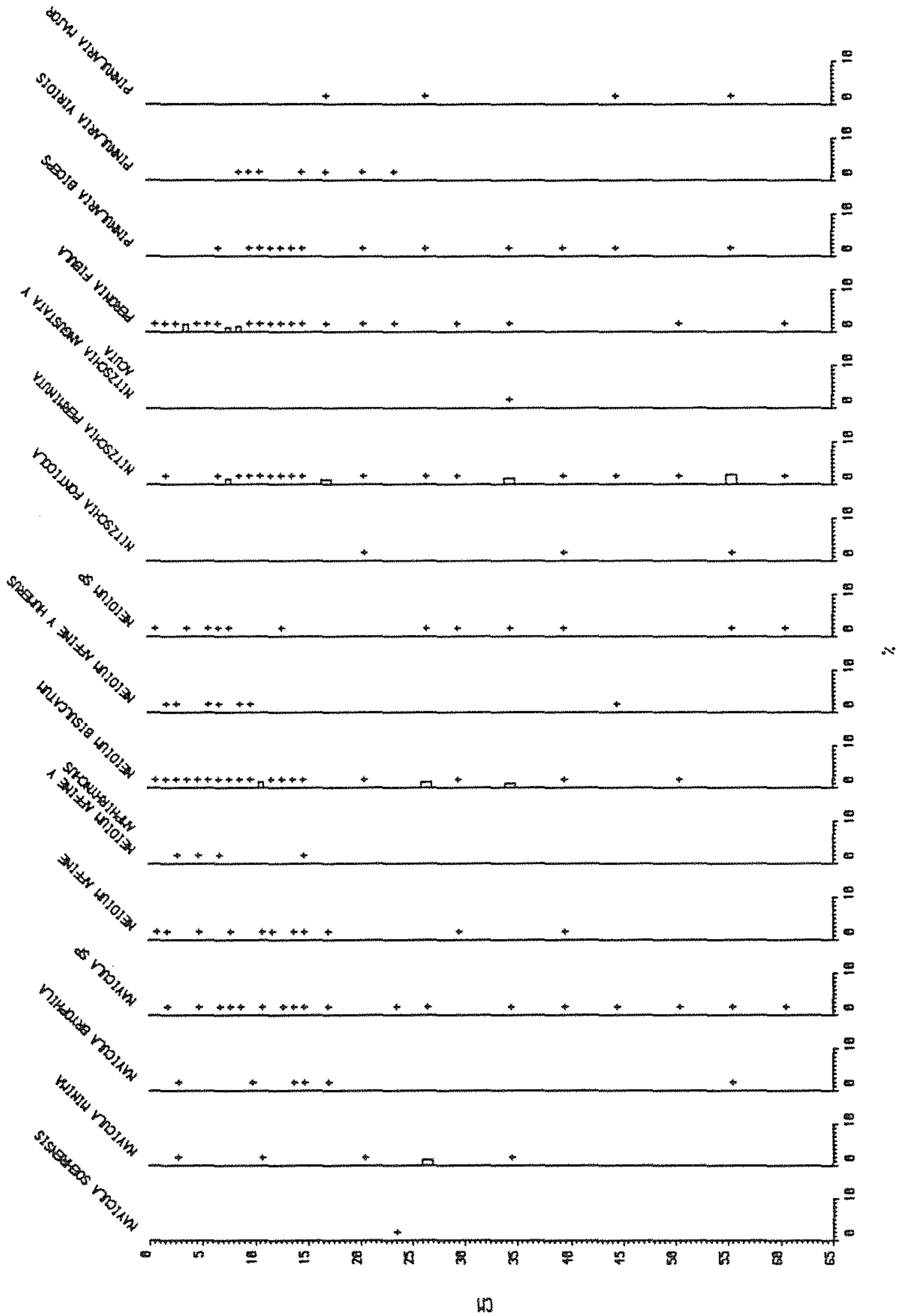
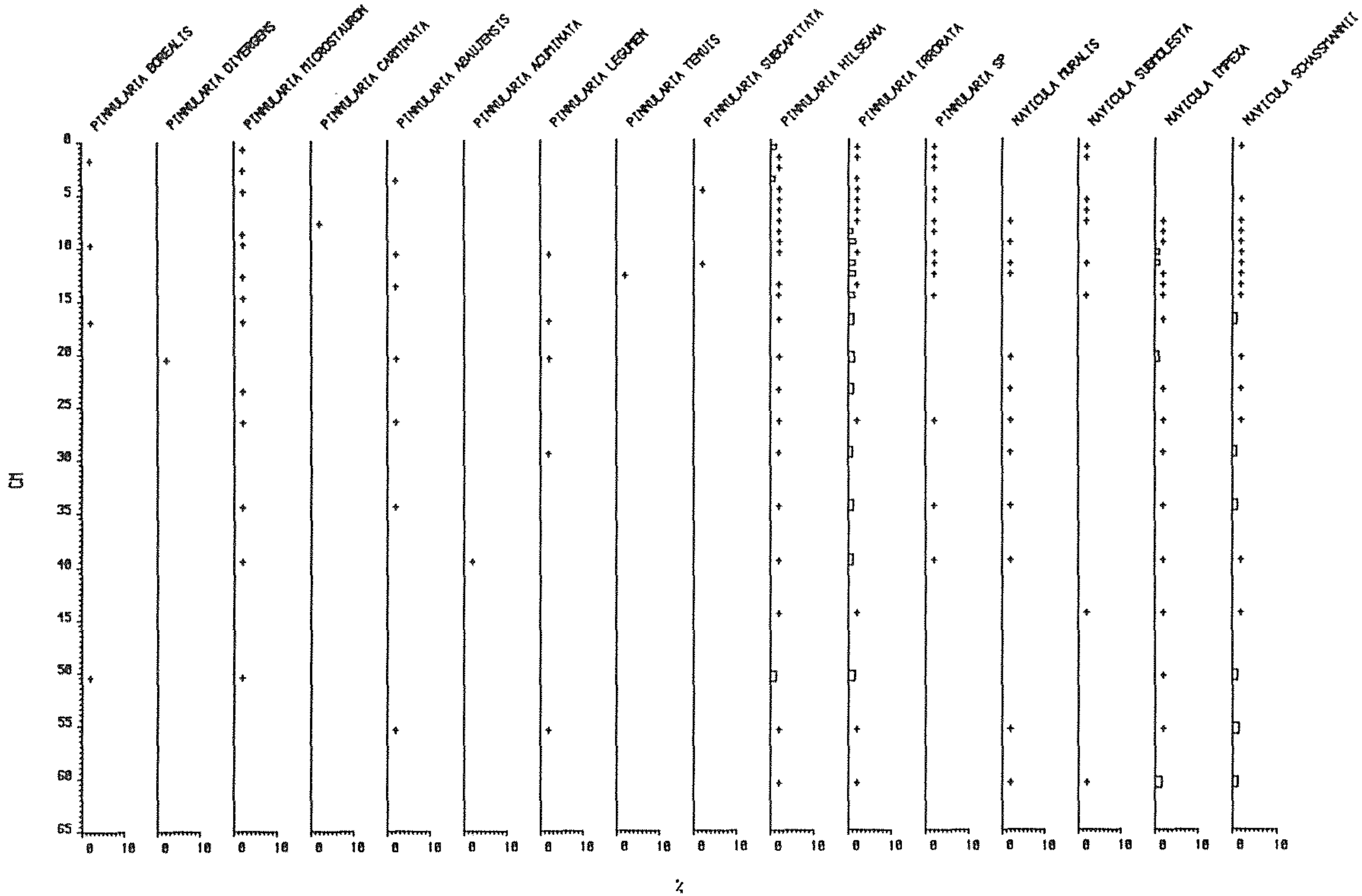
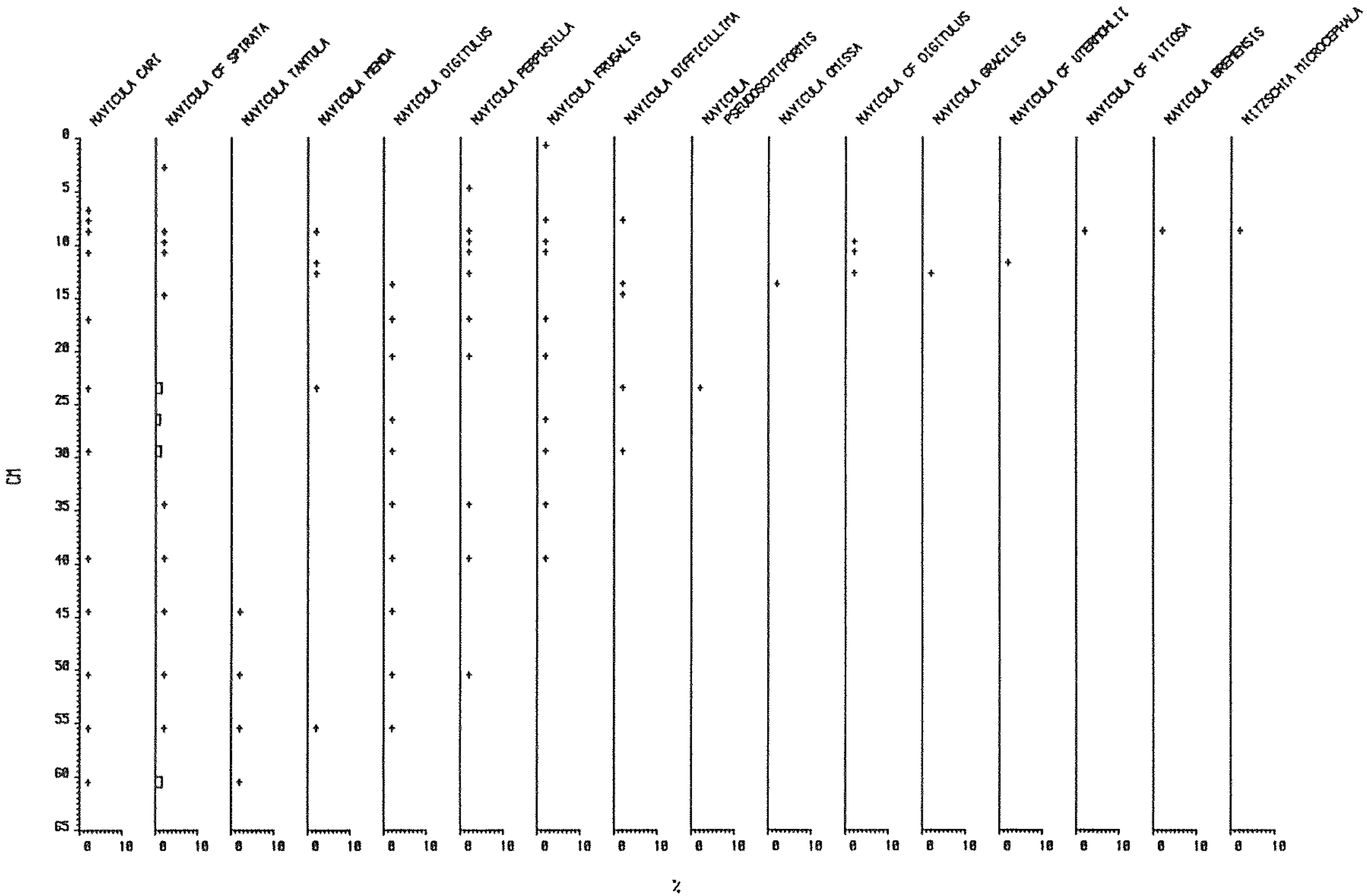


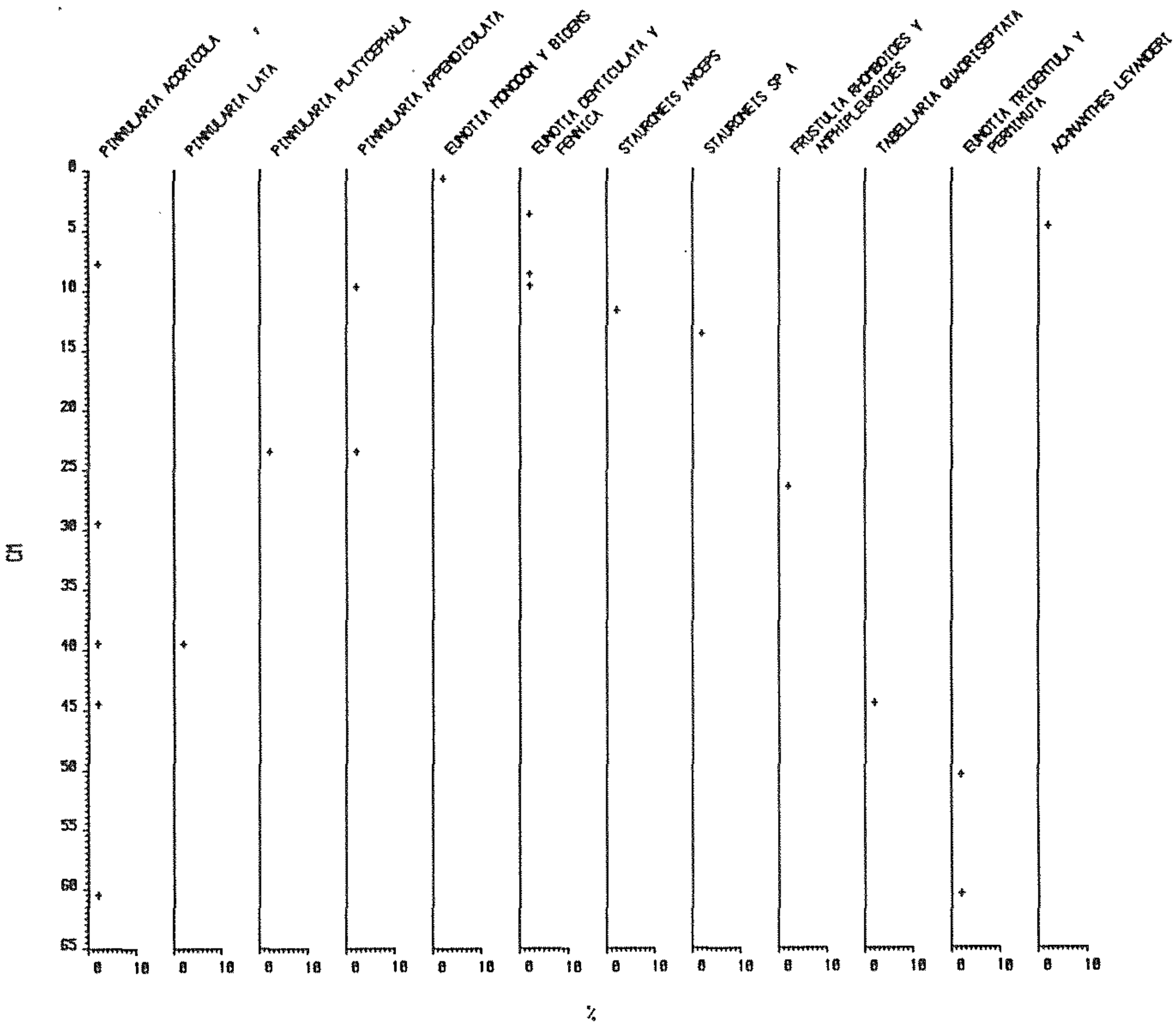
Appendix 1. cont.



Appendix 1. cont.



Appendix 1. cont.



Appendix 1. cont.

Appendix 3 Diatom species list: core NAG3

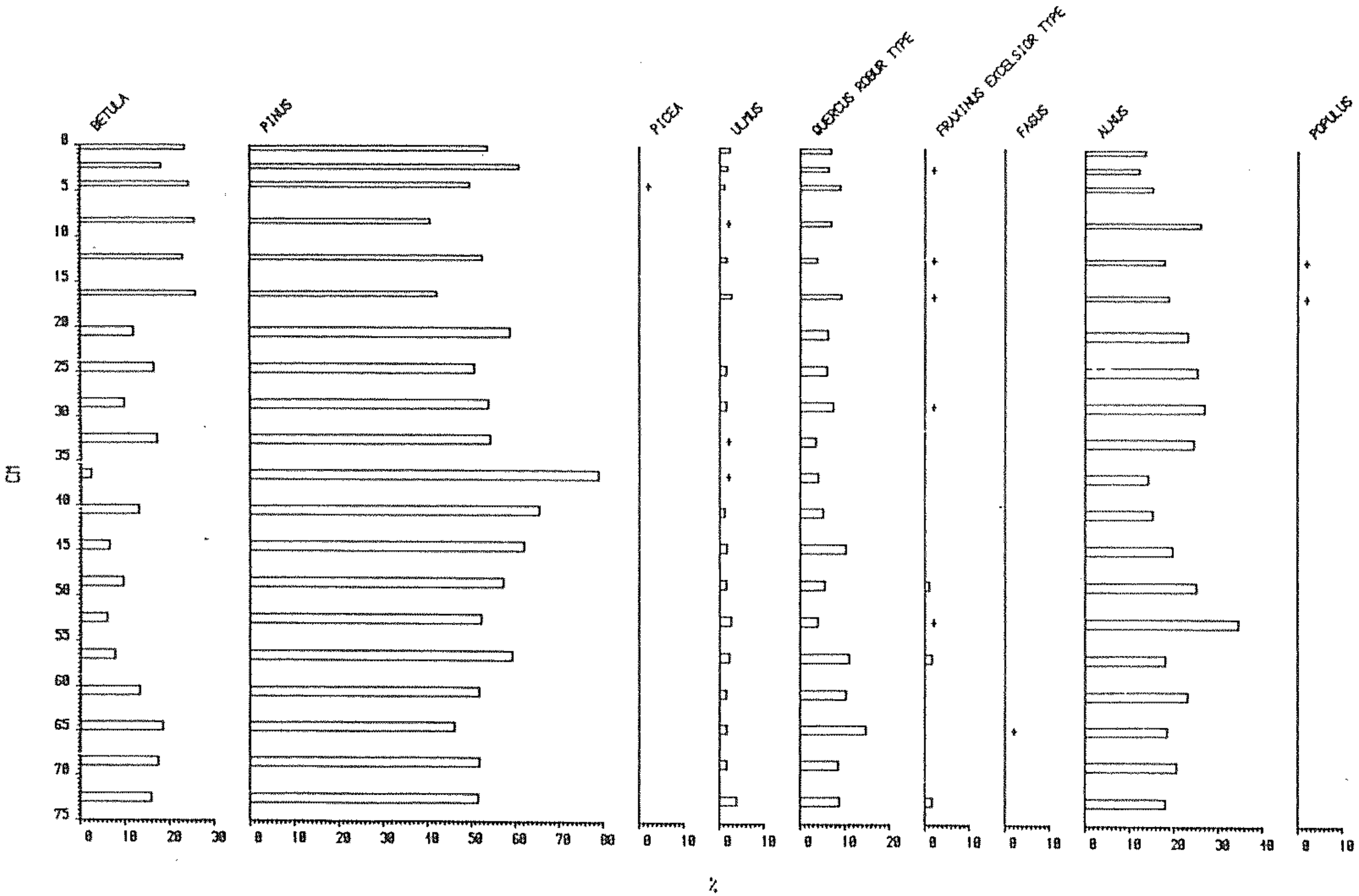
Achnanthes lanceolata BREB.
Achnanthes linearis W. SMITH
Achnanthes microcephala KUTZ.
Achnanthes clevei GRUN.
Achnanthes recurvata HUST.
Achnanthes minutissima KUTZ.
Achnanthes austriaca v minor L. GRANNOCH (RJF)
Achnanthes austriaca v helvetica HUST.
Achnanthes laterostrata HUST.
Achnanthes marginulata GRUN.
Achnanthes conspicua A. MAYER
Achnanthes saxonica KRASSKE
Achnanthes suchlandtii HUST.
Achnanthes detha
Achnanthes levanderi
Achnanthes bicapitata HUST.
Achnanthes [cf. recurvata] LOCHNAGAR (RJF)
Achnanthes [marginulata var. 2] L. UAINE (VJJ)
Achnanthes cf. levanderi
Achnanthes cf. lapidosa
Achnanthes sp.
Anomoeoneis vitrea (GRUN.) ROSS
Anomoeoneis brachysira (BREB.) GRUN.
Anomoeoneis brachysira v modesta C. EULER
Caloneis bacillum (GRUN.) MERESCHKOWS
Cymbella ventricosa KUTZ.
Cymbella microcephala GRUN.
Cymbella naviculiformis AUERSWALD
Cymbella perpusilla A. CLEVE
Cymbella aequalis SMITH
Cymbella hebridica (GREGORY) GRUN.
Cymbella gracilis (RABH.) CLEVE
Cymbella gaeumannii MEISTER
Cymbella naviculacea GRUN.
Cymbella sp.
Diatoma hiemale (LYNGBYE) HEIBERG
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 monodon EHR.
Eunotia monodon v major f bidens W. SMITH
Eunotia monodon v bidens (GREGORY) HUST.
Eunotia exigua (BREB.) RABH.
Eunotia rhomboidea HUST.
Eunotia robusta RALFS
Eunotia arcus EHR.
Eunotia denticulata (BREB.) RABH.
Eunotia denticulata v fennica HUST.
Eunotia diodon EHR.
Eunotia flexuosa KUTZ.
Eunotia sudetica (O. MULLER) HUST.
Eunotia bigibba KUTZ.
Eunotia glacialis MEIST.
Eunotia fallax CLEVE
Eunotia praerupta-nana BERG
Eunotia trinacria KRASSKE
Eunotia parallela EHR.
Eunotia triodon EHR.
Eunotia tridentula v perminuta GRUN.
Eunotia sp.
Fragilaria pinnata EHR.
Fragilaria construens (EHR.) GRUN.
Fragilaria virescens RALFS
Fragilaria brevistriata GRUN.
Fragilaria vaucheriae (KUTZ.) BOYE PETERS
Frustulia rhomboides (EHR.) DE TONI
Frustulia rhomboides v saxonica (RABH.) DE TONI
Frustulia rhomboides v amphipleuroides GRUN.
Frustulia rhomboides v viridula (BREB. EX KUTZ.) CL
Gomphonema angustatum (KUTZ.) RABH.
Gomphonema gracile EHR.
Gomphonema acuminatum EHR.
Gomphonema acuminatum v coronatum (EHR.) W. SMITH
Gomphonema acuminatum v brebissonii (KUTZ.) CLEVE
Gomphonema constrictum EHR.
Gomphonema longiceps EHR.
Gomphonema longiceps v subclavatum GRUN.
Gomphonema sp.
Melosira italica (EHR.) KUTZ.
Melosira lirata (EHR.) KUTZ.
Melosira lirata v lacustris GRUN.
Melosira lirata f biseriata (GRUN.) CAMBURN
Melosira distans (EHR.) KUTZ.
Melosira distans v tenella (NYGAARD) FLORIN
Melosira distans v nivalis (W. SM.) KIRCHNER
Melosira distans v alpigena GRUN.
Melosira perglabra OSTRUP
Melosira perglabra v floriniae CAMBURN
Melosira sp.
Meridion circulare AGARDH
Navicula radiosa KUTZ.
Navicula seminulum GRUN.
Navicula seminulum v intermedia HUST.
Navicula mediocris KRASSKE
Navicula pseudoscutiformis HUST.
Navicula indifferens HUST.
Navicula gracilis EHR.

Appendix 3 Cont.

Navicula cocconeiformis GREGORY
Navicula subtilissima CLEVE
Navicula perpusilla GRUN.
Navicula angusta GRUN.
Navicula festiva KRASSKE
Navicula hoefleri CHOLNOKY
Navicula heimansii VAN DAM & KOOY.
Navicula minima GRUN.
Navicula krasskei HUST.
Navicula bryophila PETERSEN
Navicula contenta GRUN.
Navicula soehrensis KRASSKE
Navicula cari EHR.
Navicula impexa HUST.
Navicula muralis GRUN.
Navicula frugalis HUST.
Navicula tantula HUST.
Navicula bremensis HUST.
Navicula difficillima HUST.
Navicula omissa HUST.
Navicula schassmannii HUST.
Navicula digitulus HUST.
Navicula menda CARTER
Navicula submolesta HUST.
Navicula [cf. utermohlii] L. LAIDON (RJF)
Navicula [cf. vitiosa] L. HIR (SF)
Navicula [cf. spirata] L. HIR (SF)
Navicula [cf. digitulus] L. URR (RJF)
Navicula sp.
Neidium iridis (EHR.) CLEVE
Neidium affine (EHR.) CLEVE
Neidium affine v amphirhynchus (EHR.) CLEVE
Neidium affine v humerus REIMER
Neidium bisulcatum (LAGERSTEDT) CLEVE
Neidium bisulcatum f undulatum O. MULL.
Neidium sp.
Nitzschia fonticola GRUN.
Nitzschia perminuta GRUN.
Nitzschia angustata v acuta GRUN.
Nitzschia microcephala GRUN.
Peronia fibula (BREB. EX KUTZ.) RO
Pinnularia acuminata SMITH
Pinnularia major (KUTZ.) W. SMITH
Pinnularia viridis (NITZSCH) EHR.
Pinnularia divergens W. SMITH
Pinnularia microstauron (EHR.) CLEVE
Pinnularia borealis EHR.
Pinnularia appendiculata (AGARDH) CLEVE
Pinnularia abaujensis (PANT.) ROSS
Pinnularia carminata BARBER & CARTER
Pinnularia biceps GREGORY
Pinnularia legumen EHR.
Pinnularia hilseana (JANISCH) MULL.
Pinnularia subcapitata GREGORY
Pinnularia irrorata (GRUN.)HUST.
Pinnularia tenuis GREGORY
Pinnularia acoricola HUST.
Pinnularia platycephala (EHR.) CLEVE
Pinnularia lata (BREB.) SMITH
Pinnularia sp.
Stauroneis anceps EHR.
Stauroneis anceps f gracilis (EHR.) CLEVE
Stauroneis phoenicenteron (NITZSCH) EHR.
Stauroneis sp. a
Stenopterobia intermedia LEWIS
Surirella biseriata BREB.
Surirella linearis W. SMITH
Surirella delicatissima LEWIS
Synedra rumpens KUTZ.
Synedra parasitica W. SMITH
Synedra minuscula GRUN.
Synedra sp.
Tabellaria flocculosa (ROTH) KUTZ.
Tabellaria quadriseptata KNUDSON
Tabellaria sp.
Tetracyclus lacustris RALFS

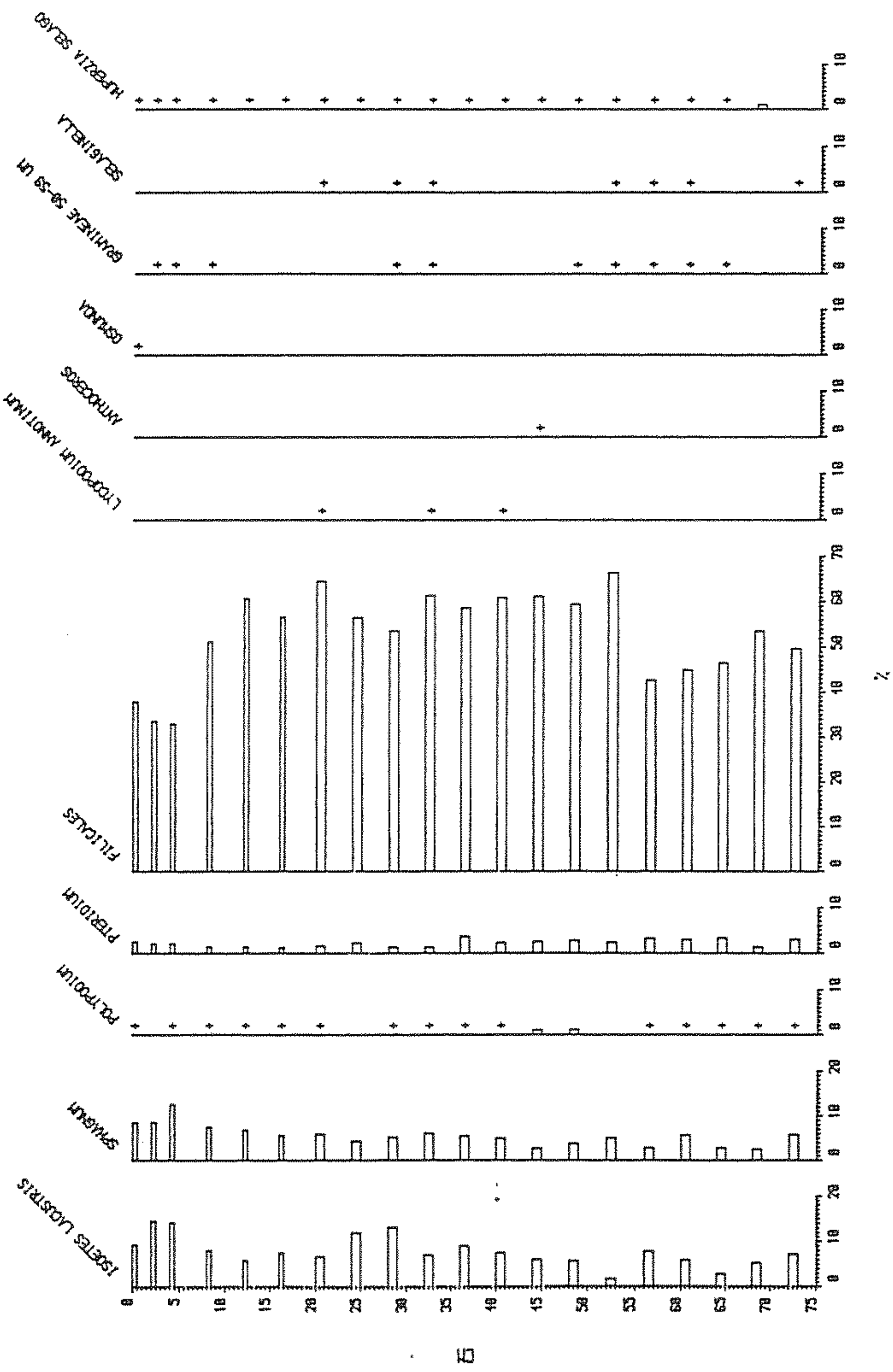
Appendix 3 Geochemical data for core NAG3

Depth cm	Zn	Pb µg g-1	Cu	Ni	Ca	Mg mg g-1	Na	K
0.25	147	180	33.5	8.9	2.44	2.77	11.33	18.94
0.75	134	140	17.8	7.8	2.77	2.65	13.85	20.08
1.25	190	189	18.0	8.7	3.01	2.29	11.18	16.45
1.75	151	170	17.8	6.8	2.77	2.01	9.28	12.71
2.25	128	200	20.5	7.6	2.87	1.99	8.41	10.47
2.75	117	177	17.7	7.8	2.67	1.90	8.79	12.28
3.25	123	205	17.0	3.0	2.79	2.00	9.65	9.70
3.75	146	188	17.1	5.7	2.75	2.00	10.03	13.19
4.25	165	212	19.6	4.2	3.00	2.27	12.95	15.87
4.75	131	188	15.2	5.2	3.01	2.73	15.41	16.71
5.25	115	157	13.3	2.9	3.14	1.95	17.53	22.15
5.75	137	200	13.3	4.9	3.18	2.52	14.46	18.71
6.25	125	219	13.4	2.2	3.17	2.46	14.13	13.59
6.75	112	186	11.5	1.8	3.04	2.23	15.12	19.77
7.25	149	209	9.6	7.3	3.45	2.54	17.84	21.61
7.75	148	173	6.4	3.1	3.35	2.49	17.60	18.69
8.25	144	170	8.1	5.2	3.38	2.82	17.23	20.71
8.75	112	145	7.6	5.4	3.43	3.27	19.49	21.89
9.25	109	143	5.3	8.2	3.54	3.45	19.50	25.22
9.75	109	125	11.8	8.6	3.75	3.77	20.03	24.46
10.25	100	126	10.0	9.5	4.11	3.83	22.04	26.00
11.25	52	135	7.8	4.9	3.78	2.64	18.13	20.67
12.25	57	117	7.1	5.1	3.78	2.31	15.77	19.01
13.25	63	92	6.7	7.3	3.80	2.08	17.19	22.62
14.25	54	115	7.5	5.4	3.66	2.22	13.2	15.76
15.25	51	92	10.7	6.6	3.42	2.29	14.79	19.23
16.25	59	82	8.6	6.1	3.52	2.25	14.34	19.37
17.25	57	67	8.4	5.5	3.46	2.51	15.84	21.05
18.25	68	59	7.9	5.4	3.64	2.62	15.17	18.98
19.25	73	54	9.5	6.6	3.85	2.83	19.18	24.98
20.50	46	74	5.9	6.6	3.37	2.15	14.06	20.63
22.50	51	53	5.5	7.0	3.40	1.92	11.83	13.14
24.50	48	51	5.7	6.9	3.45	1.94	13.79	13.05
26.50	44	37	6.0	8.8	2.83	1.73	9.86	13.91
28.50	34	30	5.0	7.9	3.35	1.52	15.29	18.98
30.50	44	41	4.9	6.9	4.16	2.00	20.54	21.79
32.50	37	38	6.0	7.6	3.61	2.03	13.83	16.54
34.50	41	38	8.0	7.3	3.80	1.87	10.51	9.63
36.50	43	28	4.8	6.9	3.55	1.96	14.57	14.89
38.50	48	34	5.6	7.0	3.67	2.27	16.22	17.04
40.50	53	45	6.3	9.6	3.69	2.03	16.63	18.65
45.50	55	53	5.2	10.7	3.61	2.27	16.49	18.50
50.50	90	59	7.2	13.2	3.63	4.19	23.00	31.32
55.50	61	29	5.7	10.0	3.56	2.65	14.71	18.87
60.50	57	25	6.3	7.3	3.35	2.01	11.95	13.52
65.50	59	21	5.6	5.2	3.55	1.78	12.12	12.48
70.50	64	28	6.9	5.9	3.04	1.58	9.00	11.04
75.50	93	19	5.4	5.1	3.87	1.53	11.84	13.66

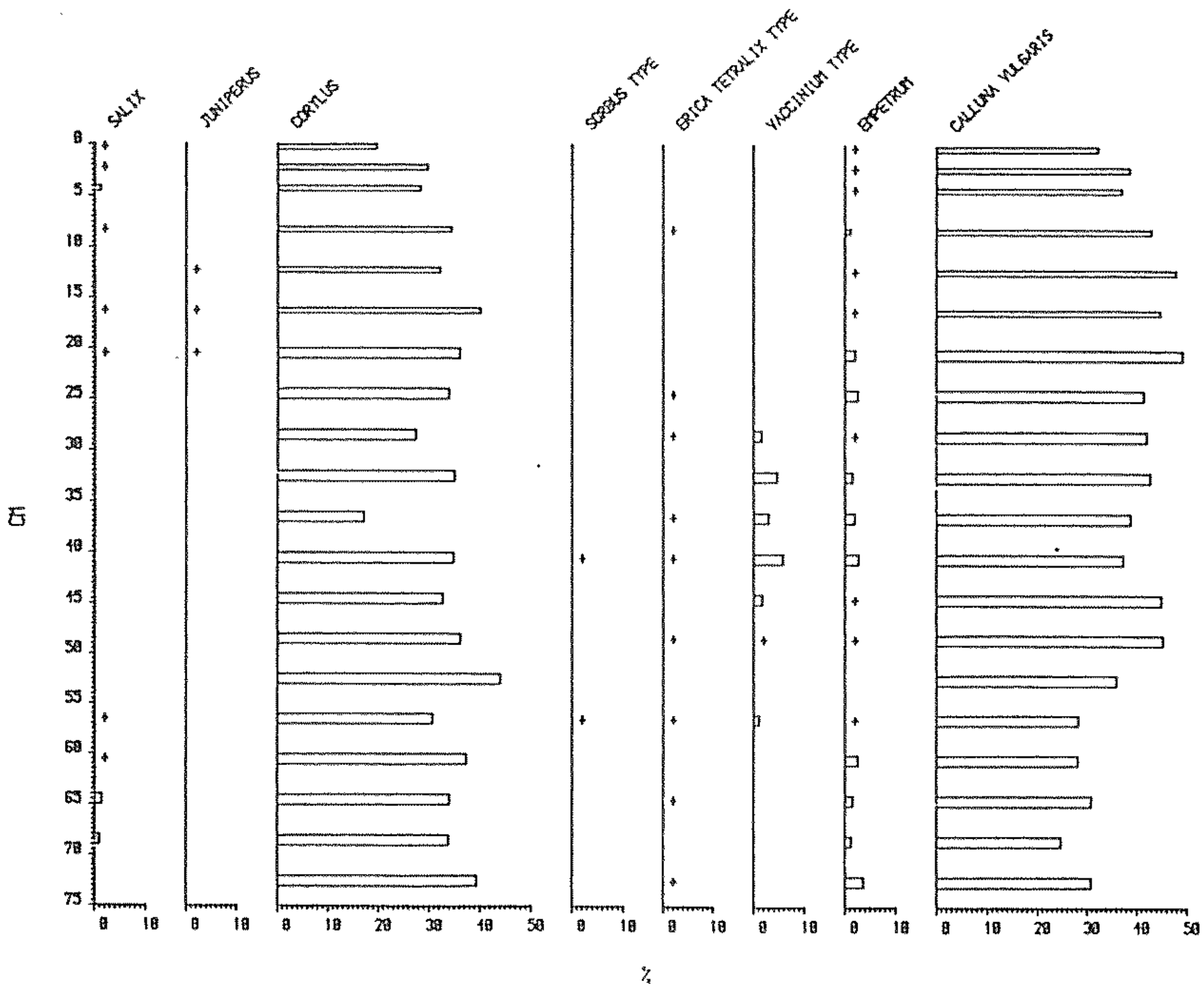


Appendix 4. Lochnagar full pollen diagram

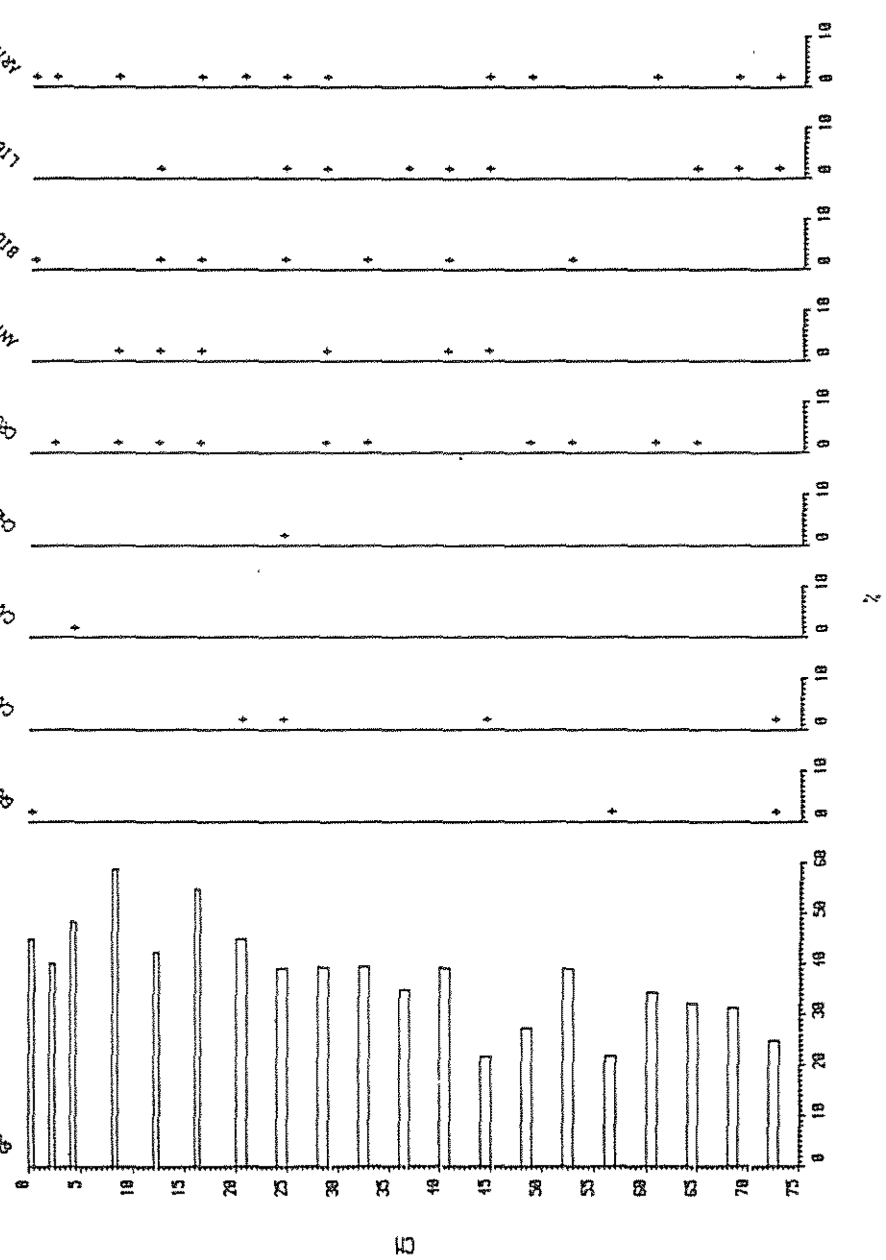
(Trees = % tree pollen,
shrubs = % trees + shrubs,
herbs = %trees + herbs,
aquatics = % total pollen)



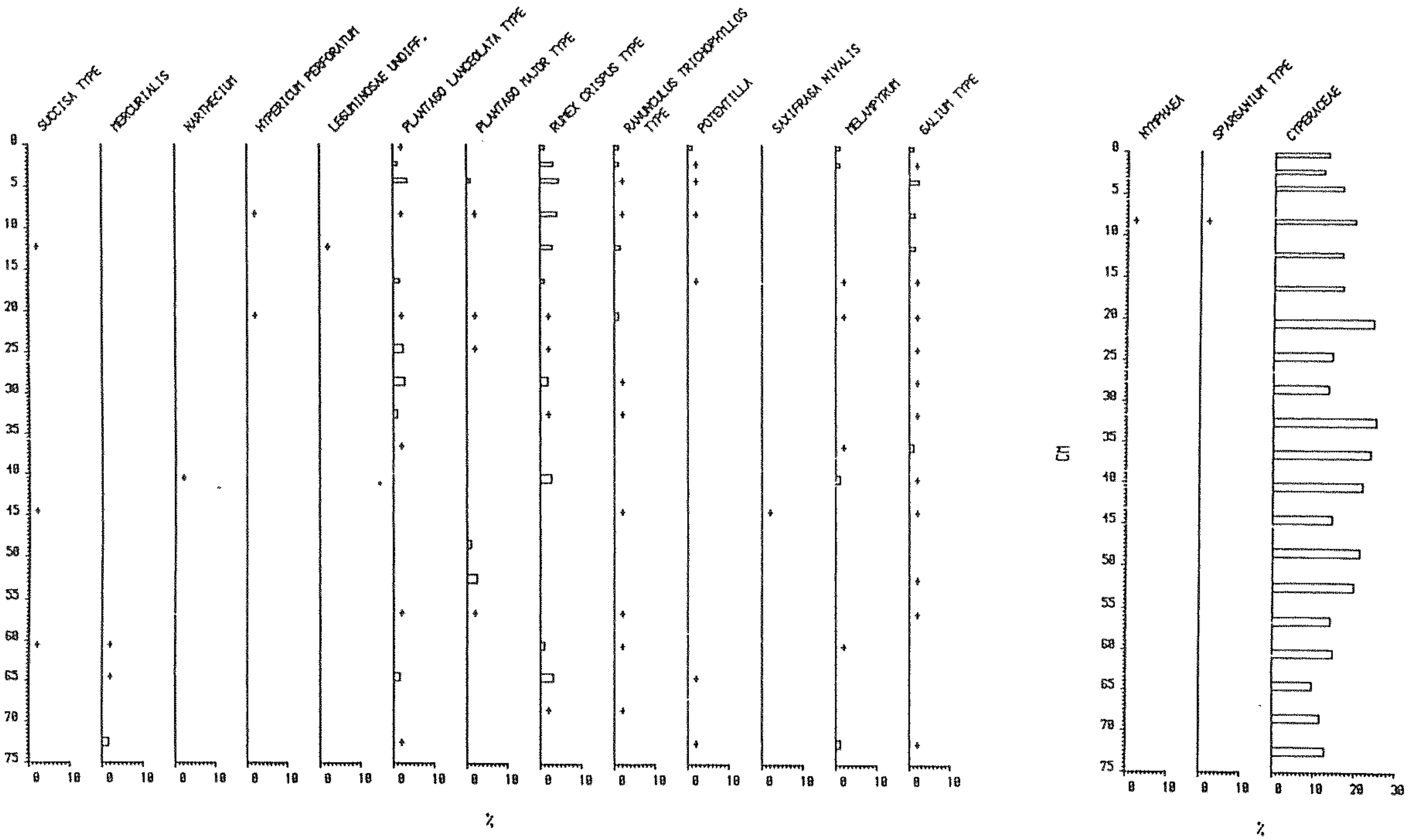
Appendix 4. cont.



Appendix 4 cont.



Appendix 4. cont.



Appendix 4. cont.

Appendix 5 Chemical composition of rainfall at Lochnagar 1978 - 1987. Annual average data from ITE bulk monthly collector. (Concentrations in $\mu g\ l^{-1}$)

Ion	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987
H^+	44	48	65	38	37	32	33	21	25	25
NH_4^+			20	22	26	14	21	11	18	15
Na^+			44	28	37	65	42	37	63	37
K^+			3	3	3	4	3	3	4	4
Ca^{++}				25	25	21	13	7	16	10
Mg^{++}	16	9	19	10	25	18	10	10	12	8
Cl^-			48	42	43	72	45	44	58	42
NO_3^-			19	18	19	25	22	14	19	19
SO_4^{--}	48	54	59	44	49	51	50	35	43	34

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