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PALAEOECOLOGICAL EVALUATION OF THE RECENT ACIDIFICATION OF LOCH TANNA, SCOTLAND

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Palaeoecological evaluation of the recent acidification of Loch Tanna, Arran, Scotland.

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Summary

Loch Tanna, an elongated shallow lake, lies in an elevated location on the island of Arran, in an area which experiences relatively high levels of acid deposition (0.6 - 0.8 g S m^{-2} yr^{-1}). The loch catchment comprises granite bedrock predominantly overlain with blanket peats. Loch Tanna may thus be considered potentially susceptible to acidification. The contemporary pH of the loch water is around 5.0.

To investigate the history and potential causes of acidification at Loch Tanna sediment cores were obtained in June 1986. Sediment samples were subjected to lithostratigraphic analysis, radiometric dating, diatom, geochemical, carbonaceous particle, magnetic, and palynological analyses. Documentary sources were utilised to provide details of catchment land-use and management history.

The organic content of the sediment varies down the sediment core, producing an irregular 'spikey' loss-on-ignition profile. It is suggested that LOI peaks represent periods of inwash of peat eroded from the catchment.

^{210}Pb dating was utilised to provide a chronology of sediment accumulation. Levels of unsupported ^{210}Pb approach zero at 7.75 cm down the core and this level is dated to c. 1874. The period c. 1875-1934 is marked by a significant increase in sediment accumulation rate. ^{137}Cs data from the core were of little chronological value owing to a significant downward diffusion of this isotope.

Diatom analysis indicates an increase in acidobiontic and acidophilous species at around 10 cm depth associated with a decline in species less tolerant of acid conditions. Further shifts towards a more acidic flora were observed at 5 cm (c. 1938) and 2 cm (c. 1970).

The recent pH history of the loch is reconstructed from diatom data. Prior to acidification the loch was already fairly acid at pH c. 5.1. Unequivocal evidence of acidification is first apparent in the mid-nineteenth century. Thereafte pH values fall to 4.6 in the 1950s and 1960s.

Geochemical analysis indicates a progressive contamination of the upper sediments by trace-metals, notably zinc lead, copper and nickel. Zinc contamination commence around 10 cm depth (early-mid-nineteenth century) whic corresponds to the first evidence of acidification from th diatom record. Lead contamination started earlier at aroun 20 cm. Wastewater effluents are not present in the catchment and trace-metal contamination has therefore been o atmospheric origin.

Magnetic accumulation in the sediment has increase steadily from the late-nineteenth century, with the stronges increase occurring since c. 1940, suggesting contaminatio by fly-ash material. Concentrations of spherical carbonaceous particles have also progressively increased since th 1890s with a major increase occuring between c. 1950-1973.

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.

Utilisation of the catchment moorland vegetation fo grazing has always been of low intensity and no attempt has been made to improve the land by drainage, enclosure o liming. There has been a long history of grouse shooting and strips of vegetation have been and are still burnt for the benefit of grouse.

The results of this study reinforce the conclusion from work elsewhere in southern and central Scotland that the acidifcation of surface waters since the mid-nineteenth century has been the result of acid deposition. All the evidence from Loch Tanna is consistent with the acid deposition hypothesis and the pattern and timing of observed changes can not be accounted for by alternative hypotheses.

1.0 Introduction

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

Loch Tanna lies on base-poor granites that are susceptible to the effects of acid deposition, as do the acidified Galloway lochs and Loch Laidon, and experiences hydrogen ion and non-marine sulphate deposition rates that are similar to these two areas. However, Loch Tanna is much closer to the coast (Figure 1) than the acidified Galloway Lochs and Rannoch Moor and thus represents a different category of site for palaeoecological investigation, being coastal and in an area of high acid deposition.

2.0 Loch Tanna - Lake and Catchment

2.1 Lake

Loch Tanna lies at an altitude of 315 m in the centre of a granitic intrusion in north-west Arran. It is an elongated, narrow body of water 1.7 km long and comprises the largest loch on the island, covering 32.87 ha (Table 1). The loch is fed by only one distinguishable inflow, which drains from Dubh Loch to the west (Figure 2), and numerous small seepage channels. The outflow drains to the south via the Alt Tigh an Shiorraim stream which flows to Glen Iorsa.

Table 1 Loch Tanna - site characteristics

Grid reference	NR 921428
Catchment geology	granite
Catchment type	moorland
Lake altitude	315 m
Maximum depth	3.5 m
Lake area	32.9 ha
Catchment area (excluding lake)	300.43 ha
Catchment:lake ratio	9.14
Net relief	406 m

The loch is shallow for it's size. A partial bathymetrical survey in June 1986 showed the main body of the loch to comprise a gently sloping basin with a maximum depth of 3.5 m (Figure 3).

Loch water chemistry was monitored regularly between 1986 - 1987. Mean values for these samples are presented in Table 2. The loch is acid (pH 5.01). Conductivity is moderate, alkalinity is zero and labile aluminium concentrations are relatively high (mean = 87 $\mu g\ l^{-1}$) (Table 2). Levels of sodium and chloride are quite high and probably reflect the proximity of the site to the sea (4.5 km). Despite the existence of eroding peats in the catchment the TOC concentration in the loch is relatively low (mean = 1.8 mg l^{-1}). Therefore there is little suggestion that the acidity of the loch results from humic acids. The loch water is not noticeably coloured and the secchi disc depth was c. 3 m on the day of suvey.

Table 2 Loch Tanna - water chemistry (mean 1986-87)

Number of samples	7
pH	5.01
Conductivity $\mu S\ cm^{-1}$	47.00
Ca^{++} $\mu eq\ l^{-1}$	36.70
Mg^{++} $\mu eq\ l^{-1}$	67.60
K^{+} $\mu eq\ l^{-1}$	12.10
Na^{+} $\mu eq\ l^{-1}$	238.60
Cl^{-} $\mu eq\ l^{-1}$	218.30
SO_4^{--} $\mu eq\ l^{-1}$	91.00
Alkalinity $\mu eq\ l^{-1}$	0.00
TOC mg l^{-1}	1.80
Labile Al $\mu g\ l^{-1}$	87.00

A survey of benthic invertebrate fauna was carried out by the Clyde River Purification Board (CRPB 1986) in June 1986. The results of this survey are summarised in Appendix 1. Samples from the loch itself exhibited a low species diversity and were dominated by the acid tolerant mayfly *Leptophlebia vespertina*. A more diverse fauna was found in the loch outflow (Appendix 1).

The fishery history of the loch is not well documented. A late eighteenth century account (Anon 1799) does not specifically mention Loch Tanna, but records that the mountain lochs of mid-Arran abounded with salmon. In the mid-nineteenth century Loch Tanna was 'celebrated' for its large population of trout (Macmillan 1845, Lewis 1846). Lyall (1910) reported that although the trout in the loch were numerous and the fishing was preserved, they were small in size. By 1950 the brown trout stock of the loch were described as 'poor, stunted cannibals' which reached a maximum length of four inches (Firsoff 1951). The loch is still fished, albeit infrequently and still supports a fish population. However, the status of that population is unknown.

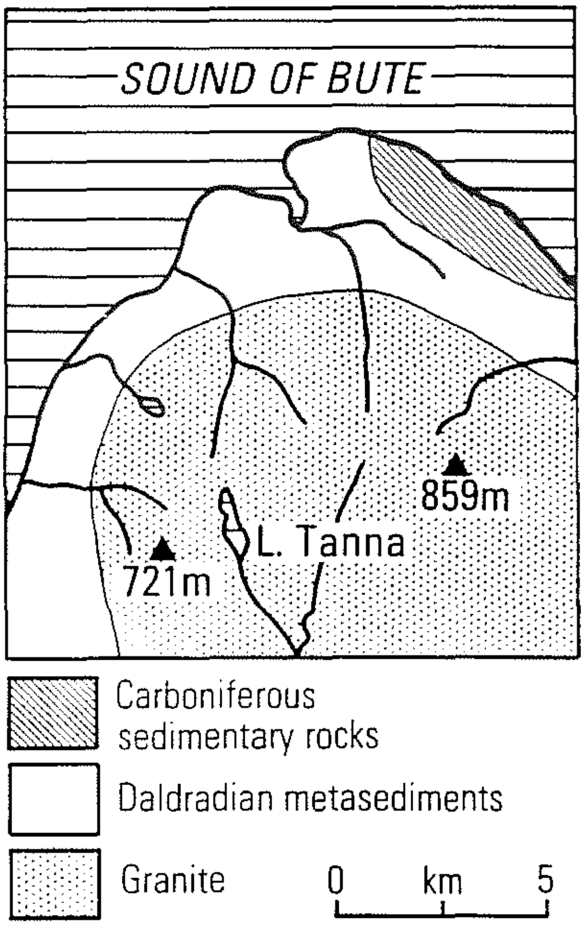

Figure 1 Location of Loch Tanna

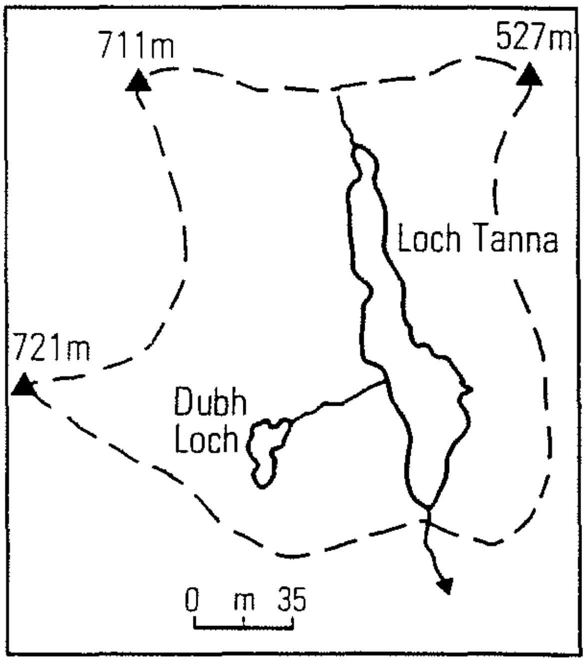

Figure 2 Loch Tanna: Catchment

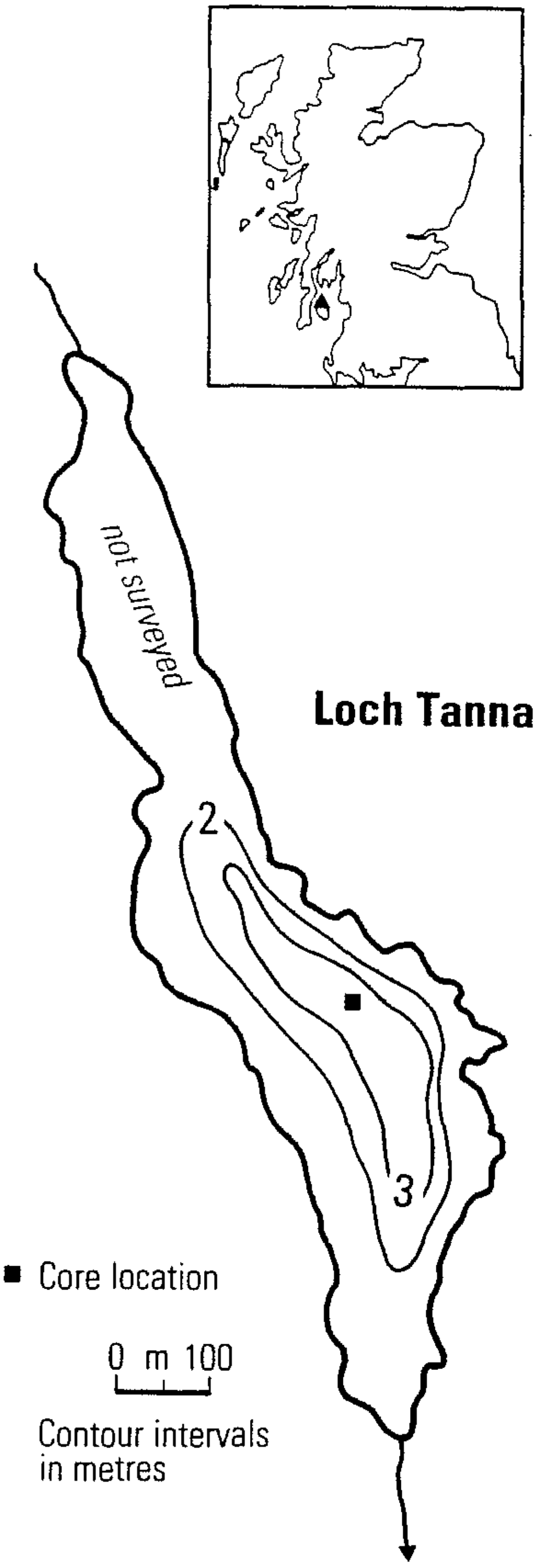

Figure 3 Loch Tanna: bathymetry

2.2 Catchment

The loch drains a catchment of 300.43 ha which reaches a maximum altitude of 721 m (Mullach Buidhe) in the west (Table 1). The geology is entirely composed of fine-grained granite (MacDonald and Herriot 1965) overlain by glacial moraine on which extensive blanket peats have developed and constitutes an area of 'high acid susceptibility' (Kinniburgh and Edmunds 1986).

The catchment is unafforested and the peats are dominated by a community of *Calluna* and *Molinia* with *Eriophorum* and *Sphagnum* on the wetter ground. In certain areas the peat is severely eroded, especially on the western and north-western slopes. Throughout these eroding areas and occupying a prominent position in the catchment vegetation, is *Racomitrium lanuginosum*, a moss whose presence has been linked to overburning of peatlands (McVean and Ratcliffe 1962). The arctic/alpine club moss *Huperzia selago* is also common throughout the catchment. To the west of the catchment the hill rises steeply and consists largely of bare rock on the upper reaches. *Juniperus communis* is occasionally present in this area

The catchment is exploited, and to a certain extent managed, for grouse shooting (Section 11.0).

The loch and its catchment lie in an area of moderately high acid deposition, with wet deposited acidity in the range 0.02 - 0.03 g H$^+$ m^{-2} yr^{-1} and wet deposited non-marine sulphate in the range 0.6 - 0.8 g S m^{-2} yr^{-1} (Barrett *et al.* 1987 (Table 1).

3.0 Methods

The loch was cored in June 1986 using a mini-Mackereth corer (Mackereth 1969) from an inflatible boat. Core TAN1, taken from the main basin at 3.5 m depth (Figure 3), yielded a sediment recovery of 80 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 palynoligical analysis according to the methods presented in Stevenson *et al.* (1987). The land-use and management history of the lake catchment was further detailed from documentary sources.

4.0 Sediment description

The Loch Tanna sediment core TAN1 consisted of black organic sediment of fairly homogeneous consistency. The percentage dry weight and wet density profiles (Figure 4) show minor down core variations and both decline in the top few centimetres, indicating increased water content in the surficial sediment. The loss-on-ignition (LOI) profile (Figure 4) shows considerably more variation. Below 45 cm the proportion of organic matter is fairly uniform at around 25% but above this depth it increases to a peak of over 40% at 30 cm. Between 30 and 15 cm the profile exhibits little variation with organic content remaining at about 35%. There are several spikes in the LOI profile between 15 and 8 cm and above this level the proportion of organic material declines irregularly to 24% at the sediment surface.

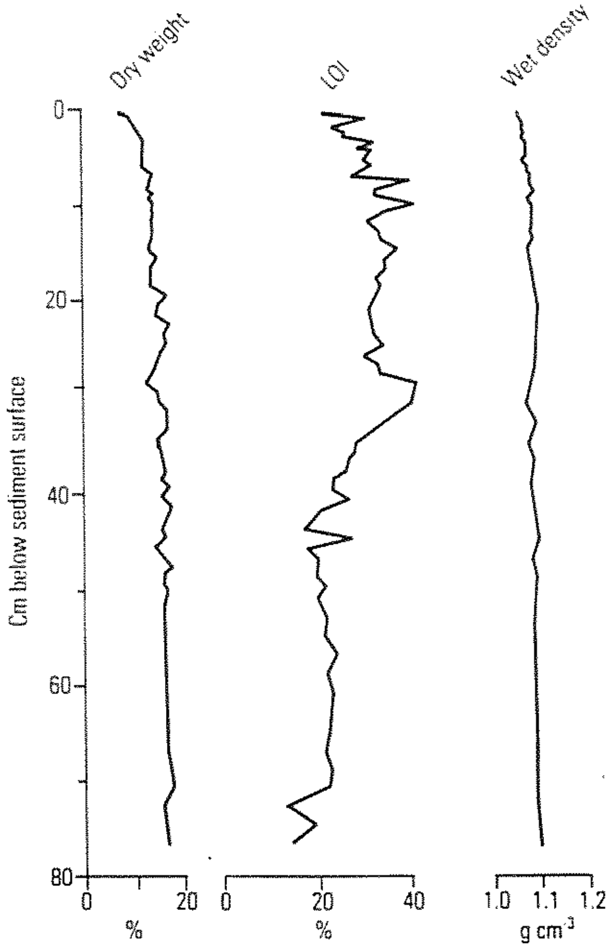

Figure 4 Lithostratigraphic data: Core TAN1

The organic material in the core is fairly fibrous and is clearly derived mainly from the erosion of catchment peats. Eroded peat probably accounts for the LOI increase at 45 cm and the subsequent spikes in LOI no doubt reflect further pulses of eroded peat washing in to the lake.

5.0 ^{210}Pb Dating

Sediment samples from core TAN1 were analysed for ^{210}Pb, ^{226}Ra, ^{137}Cs and ^{241}Am by gamma spectrometry (Appleby *et al.* 1986). Loch Tanna is in a region subject to the fallout from the Chernobyl accident and the gamma spectra confirmed the presence of very high ^{137}Cs activities in the topmost sediments, together with significant concentrations of the short-lived isotopes ^{134}Cs and ^{103}Ru. The ^{210}Pb and ^{226}Ra results are given in Table 3 and shown graphically in Figure 5. The ^{137}Cs, ^{134}Cs and ^{103}Ru results

Table 3 ^{210}Pb data for core TAN1

Depth	Dry mass	^{210}Pb Conc.				^{226}Ra Conc.	
		Total		Unsupported			
cm	g cm^{-2}	pCi g^{-1}	±	pCi g^{-1}	±	pCi g^{-1}	±
0.25	0.0210	16.84	0.64	15.31	0.67	1.53	0.21
0.75	0.0684	14.82	1.07	12.30	1.15	2.52	0.42
1.25	0.1228	15.21	1.25	13.43	1.33	1.78	0.45
1.75	0.1794	12.85	0.82	10.84	0.88	2.01	0.32
2.25	0.2386	11.19	0.96	8.70	1.04	2.49	0.39
3.75	0.4403	8.12	0.58	5.92	0.62	2.20	0.21
4.75	0.5784	7.44	0.43	5.35	0.46	2.09	0.15
5.25	0.6469	5.33	0.46	3.44	0.49	1.89	0.16
6.25	0.7854	5.73	0.43	3.31	0.46	2.42	0.17
7.75	1.0175	4.62	0.25	2.35	0.27	2.27	0.10
8.75	1.1728	2.50	0.21	0.17	0.23	2.33	0.10
10.50	1.4496	2.53	0.24	-0.55	0.27	3.08	0.12
15.50	2.2355	1.98	0.19	-0.19	0.21	2.17	0.08

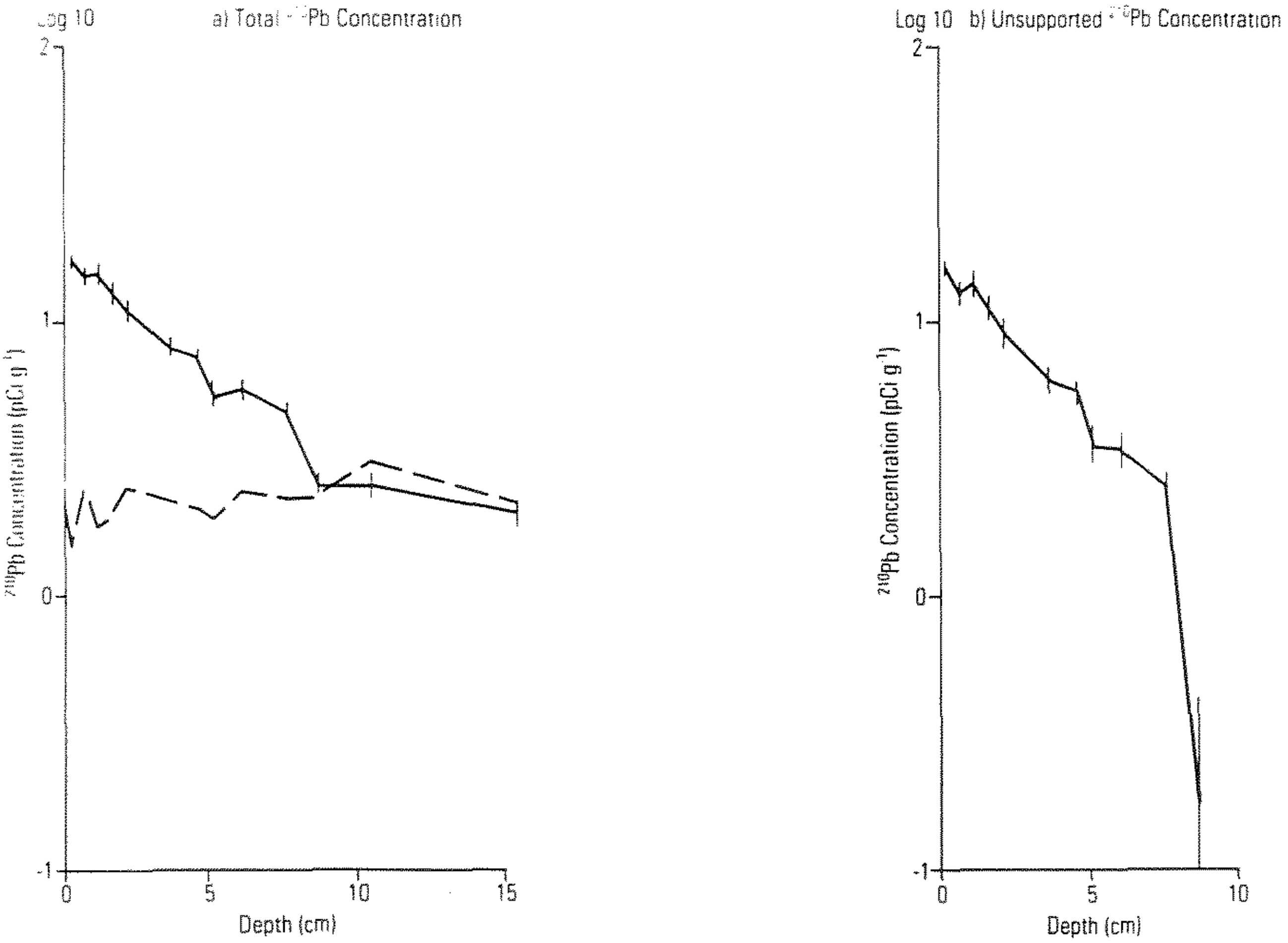

Figure 5 ^{210}Pb data, core TAN1

Table 4 ^{137}Cs, ^{134}Cs and ^{103}Ru data, core TAN1

Depth cm	^{137}Cs Conc. pCi g^{-1}	±	^{134}Cs Conc. pCi g^{-1}	±	^{103}Ru Conc pCi g^{-1}	±
0.25	51.89	0.52	25.72	0.92	44.54	1.64
0.75	19.36	0.54	4.71	0.47	0.00	0.00
1.25	15.49	0.57	2.11	0.41	0.00	0.00
1.75	13.51	0.39	0.85	0.30	0.00	0.00
2.25	12.01	0.43	0.00	0.00	0.00	0.00
3.75	5.99	0.00	0.00	0.00	0.00	0.00
4.75	3.30	0.16	0.00	0.00	0.00	0.00
5.25	3.28	0.17	0.00	0.00	0.00	0.00
6.25	1.78	0.15	0.00	0.00	0.00	0.00
7.75	2.08	0.09	0.00	0.00	0.00	0.00
8.75	1.63	0.08	0.00	0.00	0.00	0.00
10.50	1.20	0.08	0.00	0.00	0.00	0.00
15.50	0.41	0.05	0.00	0.00	0.00	0.00

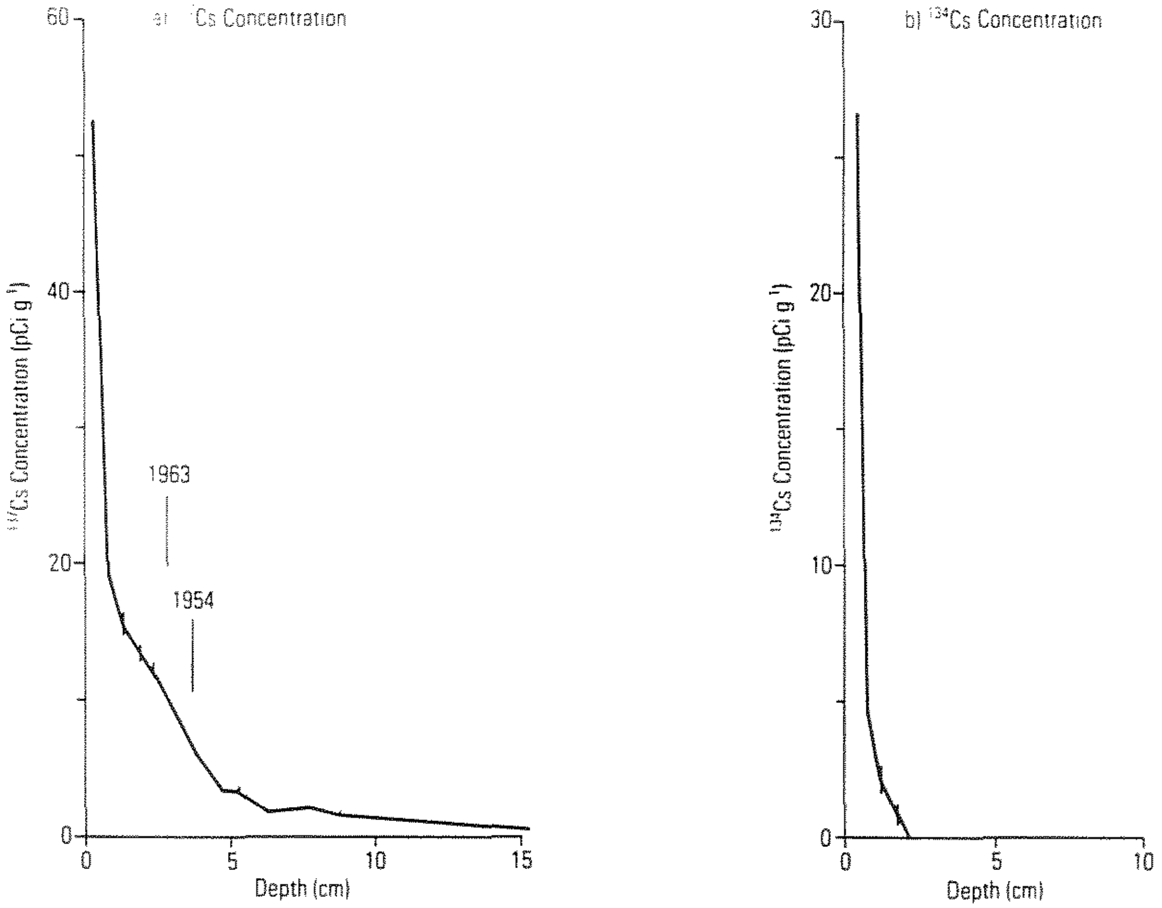

Figure 6 ^{137}Cs and ^{134}Cs data, core TAN1

Table 5 Miscellaneous radiosotopes for core TAN1

Depth cm	^{226}Ra	^{238}U	^{235}U pCi g^{-1}	^{228}Ac	^{228}Th	^{40}K
0.25	1.53	1.62	0.27	2.19	2.65	14.51
0.75	2.52	2.03	0.19	0.00	3.61	19.67
1.25	1.78	3.64	0.29	1.96	3.11	16.99
1.75	2.01	2.19	0.46	2.17	4.40	18.57
2.25	2.49	1.78	0.32	2.19	3.18	17.93
3.75	2.20	2.63	0.18	2.77	2.55	15.22
4.75	2.09	3.96	0.41	1.87	3.56	18.03
5.25	1.89	4.69	0.69	2.09	3.67	22.14
6.25	2.42	5.25	0.57	2.34	4.35	23.89
7.75	2.27	4.18	0.51	2.37	3.85	19.52
8.75	2.33	4.31	0.62	2.40	4.18	22.60
10.50	3.08	4.60	0.55	3.01	4.69	27.83
15.50	2.17	3.97	0.58	2.81	4.62	20.08

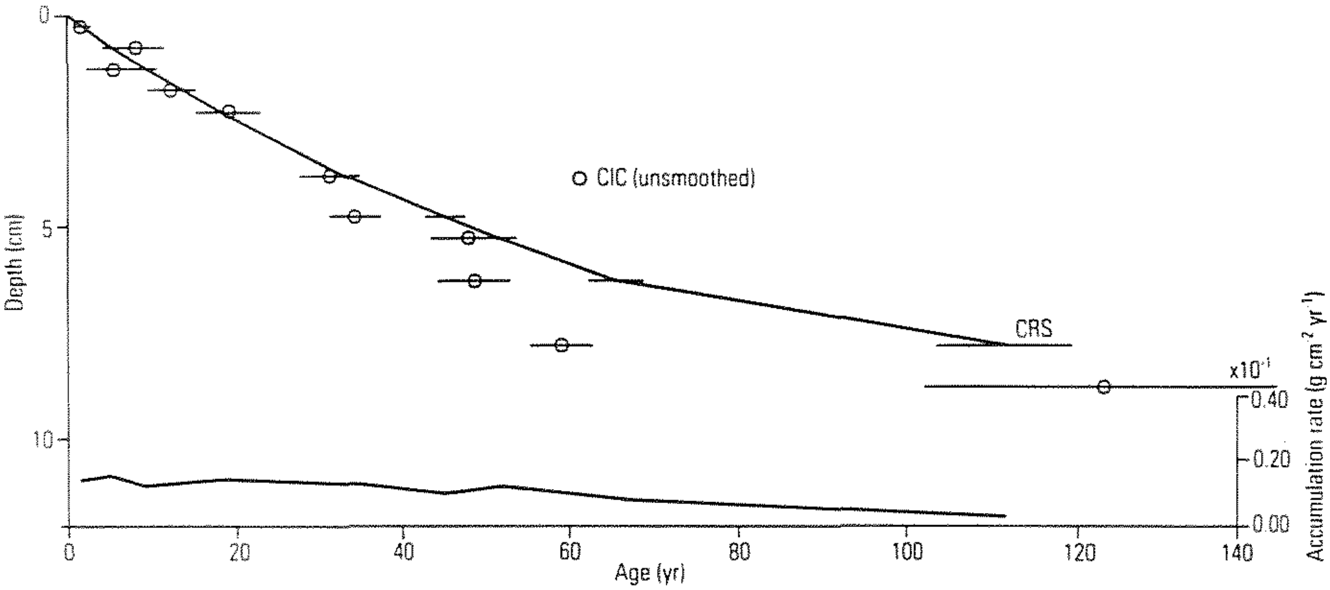

Figure 7 ^{210}Pb chronology, core TAN1

(corrected for decay) are given in Table 4 and Figure 6. There was no significant ^{241}Am activity. 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 7.3 pCi cm^{-2}, representing a constant ^{210}Pb flux of 0.23 pCi cm^{-2} yr^{-1}. This is significantly lower than the values obtained from other Scottish sites, but may reflect the westerly location of Arran and its separation from the mainland. The total ^{137}Cs inventory of the core was calculated to be 10.0 pCi cm^{-2}. Using the estimated ^{134}Cs:^{137}Cs ratio in the Chernobyl fallout of 0.64, the component of the ^{137}Cs inventory derived from Chernobyl fallout was determined to be 2.35 pCi cm^{-2}, leaving a balance of 7.65 pCi cm^{-2} accounted for by nuclear weapons testing fallout. The ratio of the ^{210}Pb and weapons fallout ^{137}Cs inventories is comparable to the mean of the values obtained from other UK sites and is perhaps an indication that the lower core inventories do indeed reflect lower atmospheric fallout.

^{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. Both models indicate a significant acceleration in recent sediment accumulation rates, the transition to higher accumulation rates

Table 6 ^{210}Pb chronology (CRS model) for core TAN1

Depth	Dry mass	Cumul unsupp. ^{210}Pb	Chronology Date	Age		Sedimentation rate		
cm	g cm^{-2}	pCi cm^{-2}	AD	Yr	±	g cm^{-2} yr^{-1}	cm yr^{-1}	±(%)
0.00	0.0000	7.26	1986	0				
0.25	0.0210	6.92	1984	2	2	0.0134	0.147	5.6
0.50	0.0447	6.57	1983	3	2	0.0142	0.147	7.5
0.75	0.0684	6.23	1981	5	2	0.0149	0.147	9.3
1.00	0.0956	5.85	1979	7	2	0.0135	0.128	9.6
1.25	0.1228	5.50	1977	9	2	0.0121	0.109	9.8
1.50	0.1511	5.12	1975	11	2	0.0126	0.111	9.3
1.75	0.1794	4.77	1973	13	2	0.0130	0.112	8.8
2.00	0.2090	4.46	1970	16	2	0.0135	0.110	9.3
2.25	0.2386	4.16	1968	18	2	0.0140	0.107	9.9
2.50	0.2722	3.85	1966	20	2	0.0138	0.105	9.9
2.75	0.3058	3.56	1963	23	2	0.0136	0.103	9.9
3.00	0.3395	3.30	1961	25	2	0.0134	0.101	9.9
3.25	0.3731	3.05	1958	28	2	0.0132	0.099	9.9
3.50	0.4067	2.82	1956	30	2	0.0130	0.097	9.9
3.75	0.4403	2.61	1953	33	2	0.0128	0.094	9.9
4.00	0.4748	2.37	1950	36	2	0.0120	0.088	10.0
4.25	0.5093	2.15	1947	39	2	0.0112	0.082	10.1
4.50	0.5439	1.96	1944	42	2	0.0104	0.076	10.2
4.75	0.5784	1.78	1941	45	3	0.0096	0.070	10.3
5.00	0.6127	1.61	1938	48	3	0.0109	0.079	12.0
5.25	0.6469	1.46	1934	52	3	0.0122	0.088	13.6
5.50	0.6815	1.31	1931	55	3	0.0111	0.080	13.0
5.75	0.7161	1.17	1928	58	3	0.0101	0.071	12.4
6.00	0.7508	1.05	1924	62	3	0.0091	0.063	11.8
6.25	0.7854	0.95	1921	65	3	0.0081	0.055	11.2
6.50	0.8241	0.75	1913	73	4	0.0072	0.048	13.2
6.75	0.8628	0.59	1905	81	5	0.0063	0.042	15.2
7.00	0.9015	0.46	1898	88	6	0.0054	0.036	17.2
7.25	0.9401	0.36	1890	96	7	0.0045	0.030	19.3
7.50	0.9788	0.29	1882	104	8	0.0036	0.023	21.3
7.75	1.0175	0.22	1874	112	8	0.0027	0.017	23.3

^{210}Pb flux = 0.23 ± 0.01 pCi cm^{-2} yr^{-1}
90% equilibrium depth = 6.7 cm or 0.86 g cm^{-2}
99% equilibrium depth = 8.5 cm or 1.13 g cm^{-1}

being marked by the abrupt change in slope of the unsupported ^{210}Pb profile at 7.75 cm (Figure 5b). Beneath this depth the unsupported ^{210}Pb activity falls very quickly to zero. Above 4 cm, dated c. 1951, the two models are in good agreement, both indicating a mean accumulation rate above this level of 0.014 ±0.002 g cm^{-2} yr^{-1}. Further down the core there is a significant divergence. The CRS model indicates that the acceleration in accumulation rates occurred between 1875 and 1934, with little change since then. The CIC model indicates a very abrupt transition during the period 1930-1940. Under the assumptions of the CIC model such a sustained increase in accumulation rate would normally be associated with a corresponding increase in the rate of supply of ^{210}Pb to the sediments. In view of the relatively low ^{210}Pb inventory and the absence of any major shift in the values of the radioisotopes listed in Table 5, the more conservative interpretation indicated by the CRS model would appear preferable and this forms the basis of the chronology given in Table 6.

The ^{137}Cs data for this core appear to be of little chronological value. Figure 6a shows the depths dated by ^{210}Pb to 1963 and 1954. The presence of significant ^{137}Cs activities down to depths predating 1870 indicates significant downward diffusion of this isotope (cf. Davis *et al.* 1984). in the near-surface sediments ^{137}Cs activity is dominated by Chernobyl fallout, accounting for up to 80% of the total. The extent of the ^{137}Cs diffusion is indicated by the presence of ^{134}Cs down to 1.75 cm (dated 1973). Using the

^{134}Cs activity to partition the ^{137}Cs activity into its Chernobyl and weapons fallout components, the latter appears to attain a maximum value at about 2.5 cm, dated 1966, although there is no indication of any decline near the surface. There was slight evidence of ^{241}Am at 2.25 cm but the activity was too low to be of definite chronological value.

6.0 Diatoms and pH reconstruction

6.1 Diatom analysis

Figure 8 presents a summary diatom diagram for core TAN1. The full diagram is to be found in Appendix 2 and the full species list in Appendix 3.

Below about 10 cm depth in the sediment core the diatoms show relatively little change in species frequencies, with *Anomoeoneis (Brachysira) vitrea, Eunotia denticulata, Navicula heimansii* and *Frustulia rhomboides* var. *saxonica* dominating the flora. Only between 30 and 40 cm is there a slight change in species abundance as *A. vitrea* declines and *E. denticulata* and *E. veneris* increase. This change could be caused by catchment peat erosion at this time since LOI values increase in the core over this depth range (Figure 4). Above 10 cm (early nineteenth century by extrapolation) *A. vitrea* begins to decline sharply in abundance as does *Peronia fibula* and, at 9 cm, *E. denticulata.* At around 10 cm several acidobiontic species begin to increase, notably *Tabellaria binalis*, and *T. quadriseptata*, as do the acidophilous species *Semiorbis hemicyclus* and *Cymbella aequalis.* Around 5 cm (1940s) *E. denticulata* and *P. fibula* frequencies decline further and *E. veneris* declines in abundance. At 2 cm (1970) the acidobiontic species increase further in abundance as *C. aequalis* and *E. veneris* decline.

6.2 pH reconstruction

The recent pH history of Loch Tanna is reconstructed in Figure 9 according to the multiple regression method (Flower 1986). The large number of acidobiontic diatoms makes the use of the Index B method (Renberg and Hellberg 1982) inappropriate, since this group is given a high weighting. The multiple regression pH curve shows a decline from around 5.1 at the beginning of the nineteenth century to 4.6 in the 1950s and 1960s. A pH value of 4.7 in the most recent sediment compares well with a mean measured pH for the loch of 5.01. The precise date of the onset of acidification is difficult to determine since acidity increases consistently from 12 cm depth (c. 1780 AD by extrapolation) although it only exceeds earlier values above 9 cm (1840s by extrapolation).

The abundance decline of *A. vitrea*, a diatom known to be sensitive to pH change, can be a good guide to acidification. In Loch Tanna this indicates a date of about 1800 AD. However, the start of a clear response in the multiple

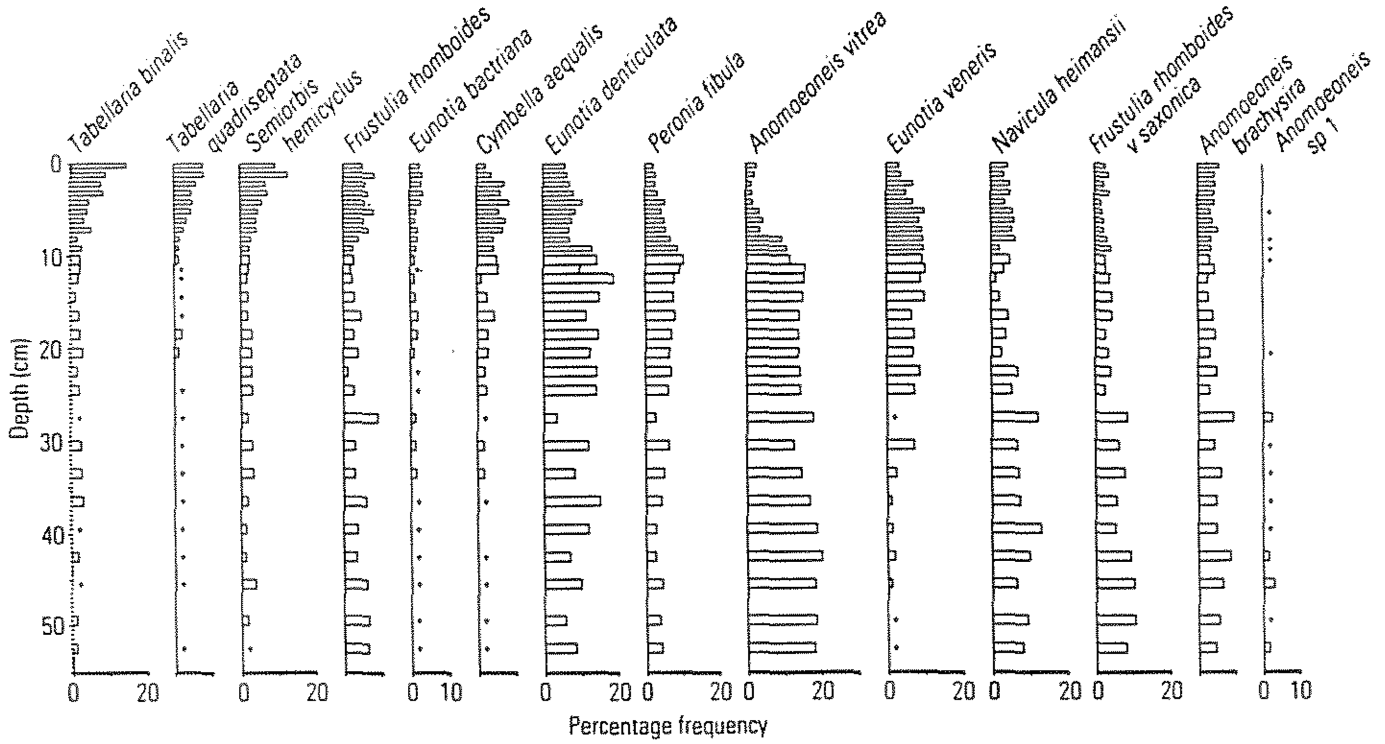

Figure 8 Summary diatom diagram, core TAN1

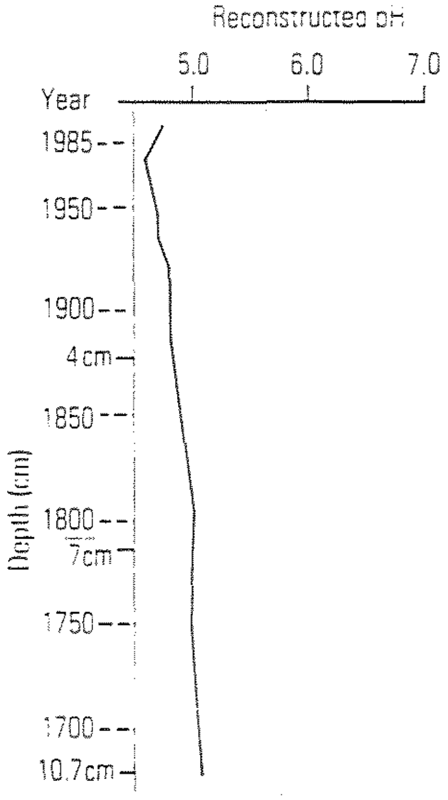

Figure 9 pH reconstruction, core TAN1

regression calculated pH curve does not begin until the 1840s (9 cm - by extrapolation). At pH c. 5.1 this site was unusually acidic in the pre-acidification state and in this respect may be considered similar to Loch Enoch in Galloway (eg. Flower *et al.* 1987a).

6.3 Diatom concentration

The concentration of diatom cells in the sediment of core TAN1 was determined using the latex microsphere method (Battarbee and Kneen 1982). The down-core variation in diatom concentration is shown in Figure 10.

Concentration values are relatively high (1.7×10^{-8} cells g^{-1} dry sediment) below 40 cm. However, the main feature of these data is the marked pre-nineteenth century decline in concentration between 39 and 21 cm, the section where a strong increase occurs in the sediment LOI profile (Figure 4). This change probably indicates that past inwash of catchment peat diluted the diatom component of the sediment at this time. Inwash effects appear to be reduced above 10 cm, although concentration values do not return to levels found at the core base. Since the loch is shallow and has clear water, the sharp diatom concentration increase at the core top probably reflects the presence of a living diatom community on the sediment surface.

7.0 Sediment geochemistry

7.1 Major cations

Both the basic sediment constitution (Figure 4) and major cation results (Figure 11, Appendix 4) indicate that there was a major change in the input of material from the catchment which started around 40 cm depth. The organic content doubles and all the major cations increase. The cation increases are more marked when the effects of changing organic content are removed by expressing the results per gramme minerals (Figure 12).

These results indicate that there has been an increase in the erosion rate of material from the catchment (Mackereth 1966, Engstrom and Wright 1984). However, this occurred well before the dated part of the sediment core. The cation fluxes (Figure 13) do, however, reflect the recent acceleration in sediment accumulation rate (Table 6).

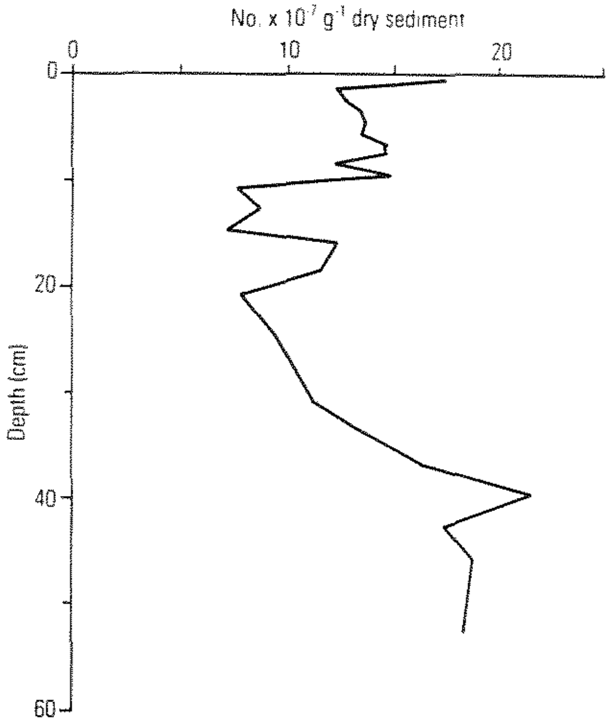

Figure 10 Diatom concentration data, core TAN1

7.2 Trace metals

The zinc and lead concentration-depth profiles indicate contamination of the sediments by these trace metals (Figure 14, Appendix 4). There also appears to have been copper and nickel contamination (Figure 15, Appendix 4). The degree of contamination is more pronounced when the effects of changing organic content are removed (Figure 16). However, because of the changes in sediment constitution, the depth at which contamination starts is difficult to identify precisely. Changes in sediment constitution can alter the trace metal concentrations in the absence of contamination.

Figure 17 shows two methods which allow the depth at which contamination starts to be estimated when there are large changes in the basic sediment constitution. The re-

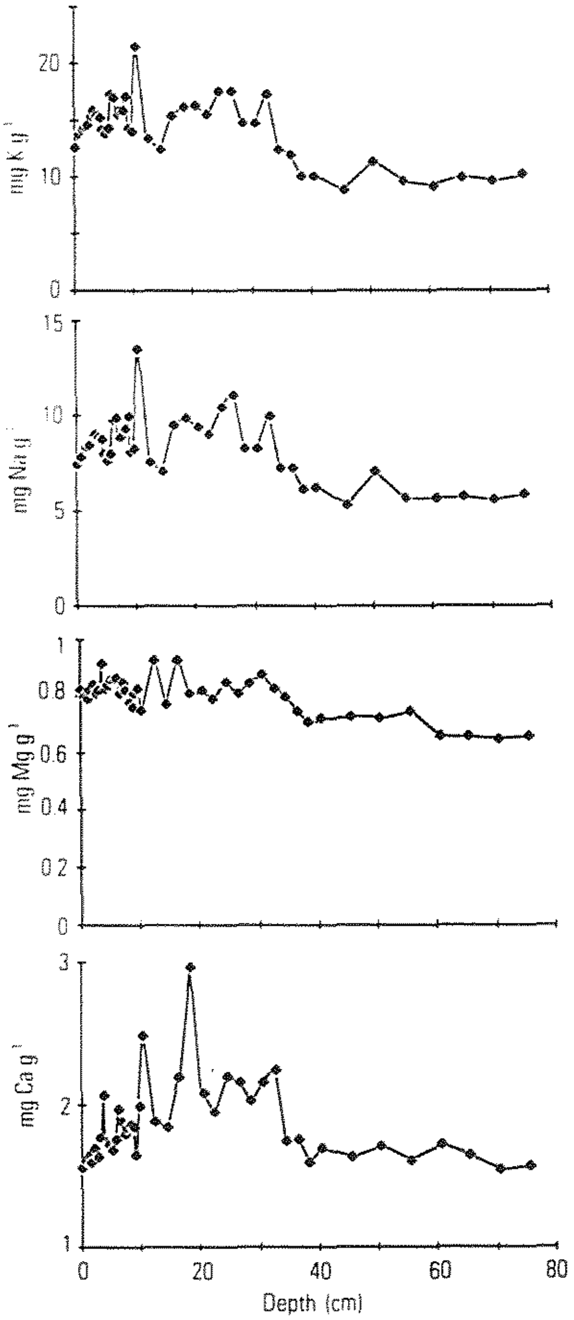

Figure 11 Major cation data, core TAN1

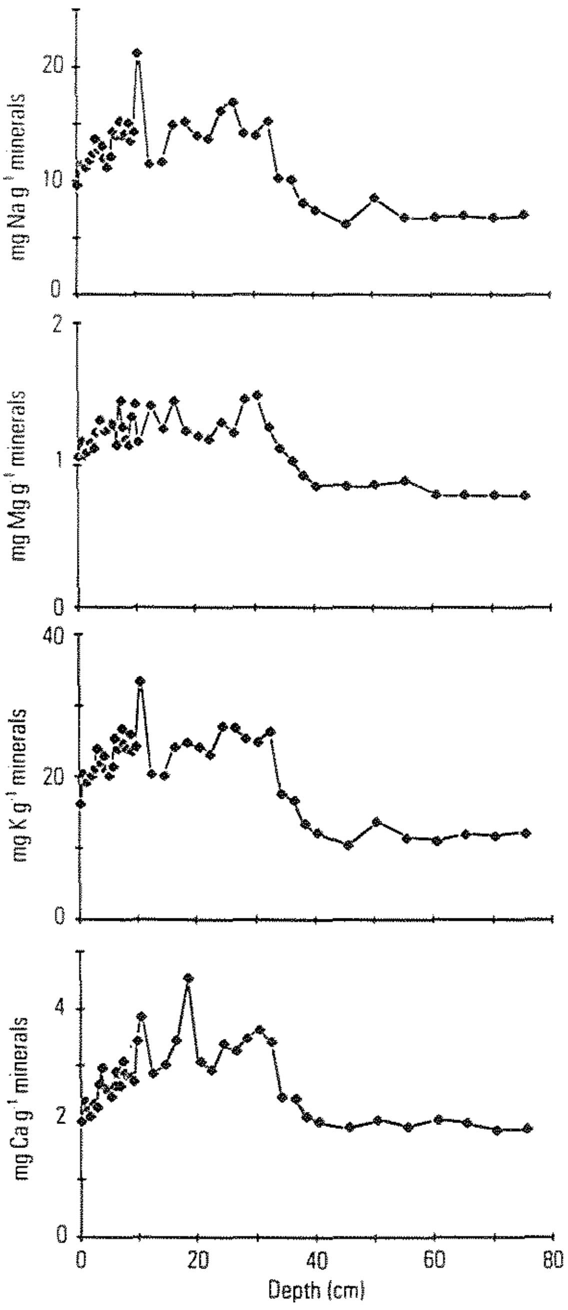

Figure 12 Major cation data, per gramme mineral, core TAN1

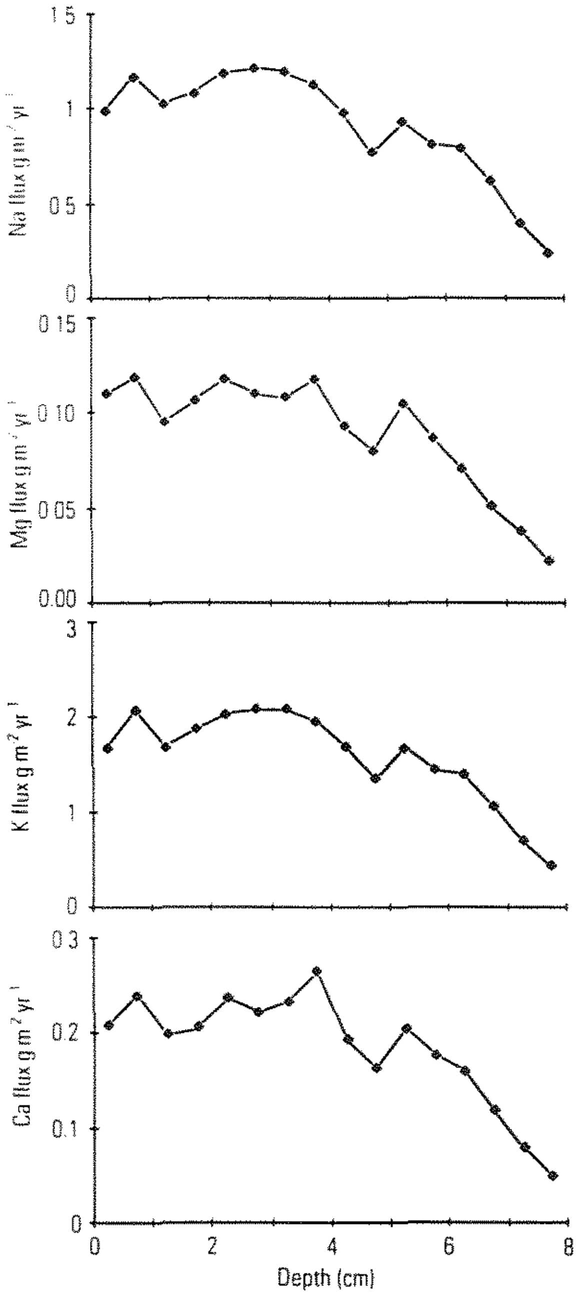

Figure 13 Major cations, flux data, core TAN1

gression method (Hilton *et al.* 1985) uses a statistical approach to establish the relationship between the trace metal and a major cation before contamination starts. This relationship allows the component of the total trace metal concentration resulting from changes in the sediment con-

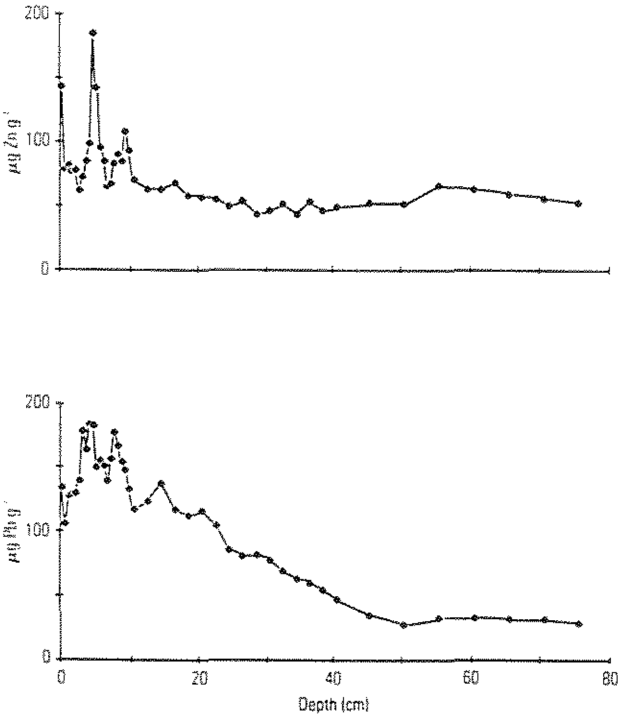

Figure 14 Zinc and lead data, core TAN1

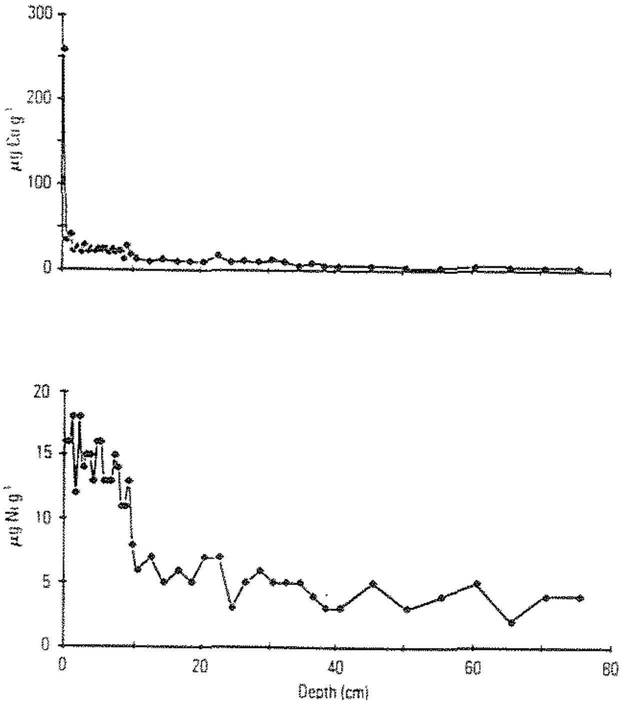

Figure 15 Copper and nickel data, core TAN1

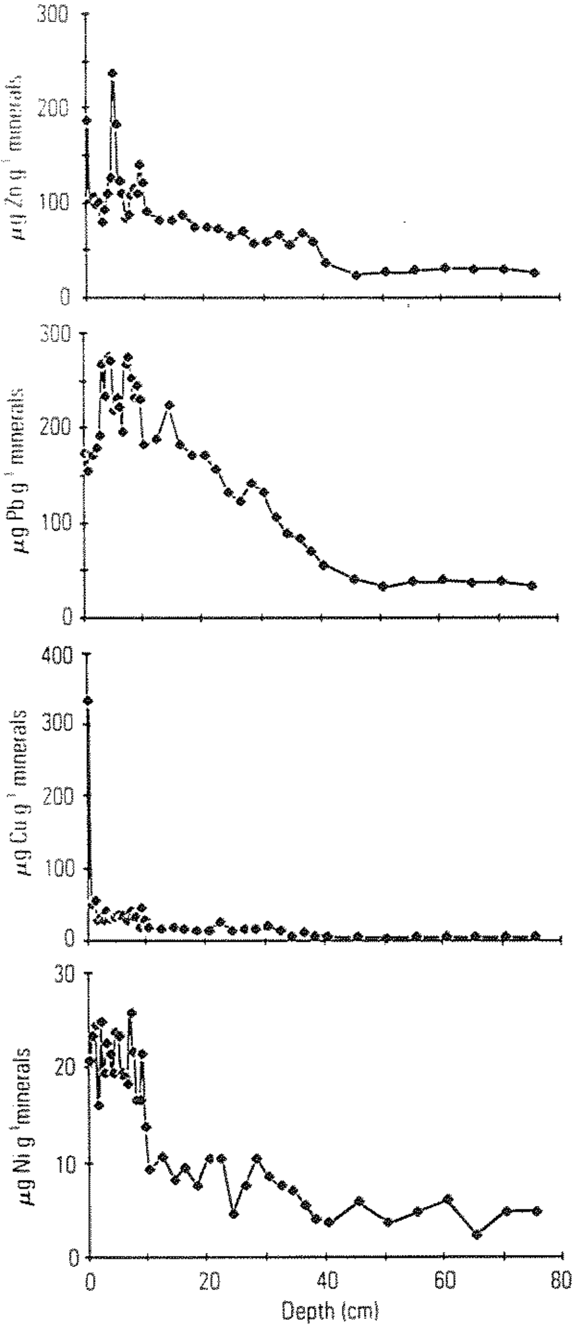

Figure 16 Trace metals, per gramme mineral, core TAN1

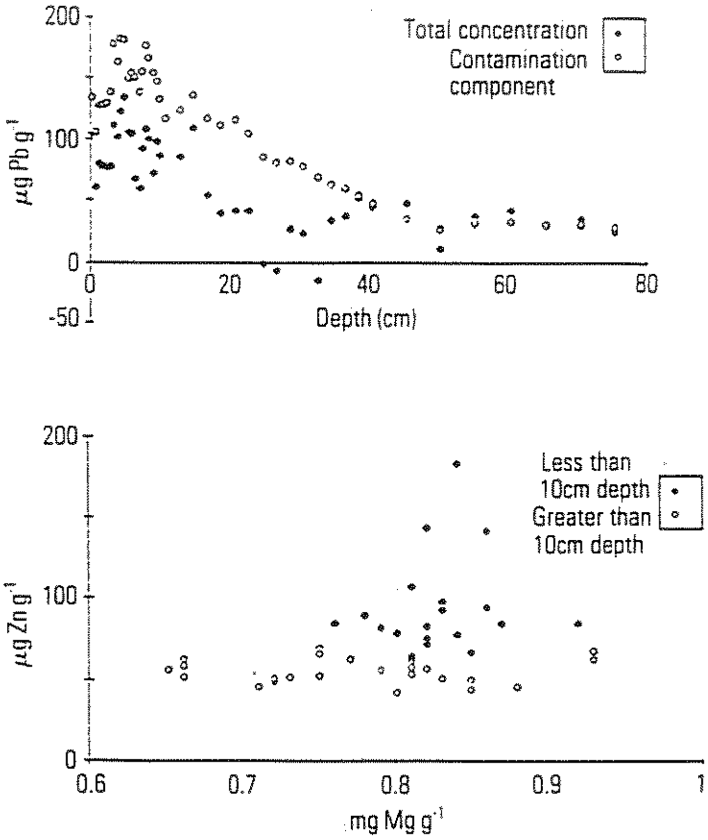

Figure 17 Estimate of depth of first contamination using a) regression method, b) visual method, core TAN1

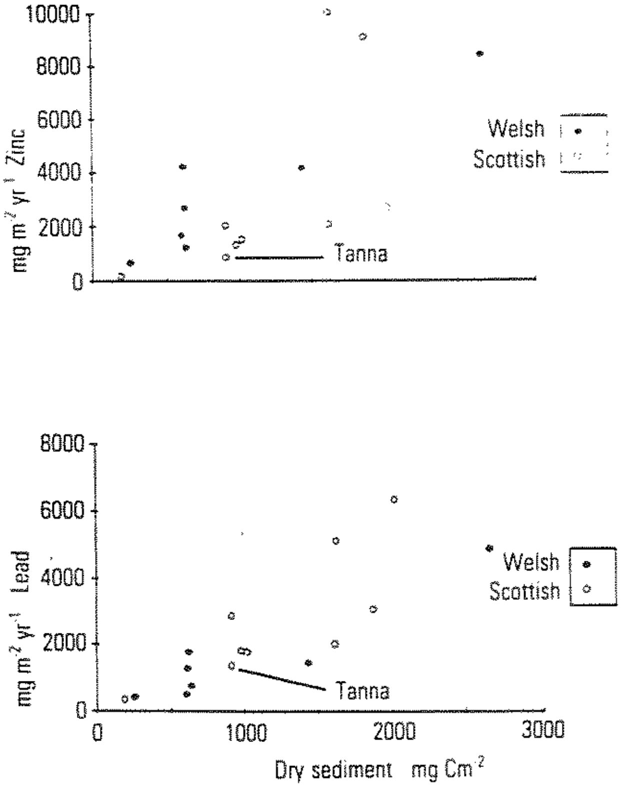

Figure 18 Zinc and lead burdens at selected sites in Wales and Scotland

stitution to be subtracted to give the contamination component. There needs to be a large change in the cation concentration in order to calculate the correct regression equation. The changes in Loch Tanna are not great enough for the method to work properly, as the contamination component should be zero, deeper in the core when there is no contamination. The lead contamination component, determined from the potassium concentration, does however, increase around 18 cm and this can be taken as the depth of first contamination.

A visual method is also shown in Figure 17 and this indicates that zinc contamination started later, around 10 cm. In the visual method a scattergram of the trace metal and major cation concentrations is produced and a judgement is made about the depth at which the trace metal concentration increases above the region of the diagram which contains all the points with no contamination. This approach is more suitable when the major cation concentrations are not large.

The scattergram method suggests that lead contamination in Loch Tanna started around 20 cm and zinc around 10 cm. As with all the other lakes in Wales and Scotland investigated in this project (Battarbee *et al.* 1988), there are no wastewater sources of trace metals in the catchment, so the most probable source of the contamination is from the atmosphere.

The amount of lead and zinc accumulated in the sediment of Loch Tanna since 1900 is compared with the other lakes investigated in this project in Figure 18. The zinc burden is particularly low. This may be due to the historically low pH (Section 6.0) which reduces the efficiency of zinc sedimentation and/or the site location. It has been found that the efficiency of recent zinc sedimentation has been reduced in lakes which have acidified as a result of atmospheric deposition (Kreiser *et al.* 1987). Alternatively the low zinc burden may derive from a lower deposition of trace metals in this coastal environment. The origin of these metals is primarily from the urban and industrial areas to the south and east of Arran. It was noted in Section 5.0 that the deposition of ^{137}Cs and ^{210}Pb were similarly lower. However, as the lead burden is not particularly low in Loch Tanna (Figure 18), the low pH may be the most important factor accounting for the low zinc burden.

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 Loch Tanna. 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 a steady increase in magnetic accumulation from the late-nineteenth century onwards. The steepest increases are post-1940 particularly over the last two decades. The pattern of increase is similar to that observed at the Welsh sites studied in this project (Battarbee *et al.* 1988). However, levels of peak deposition are higher at Loch Tanna.

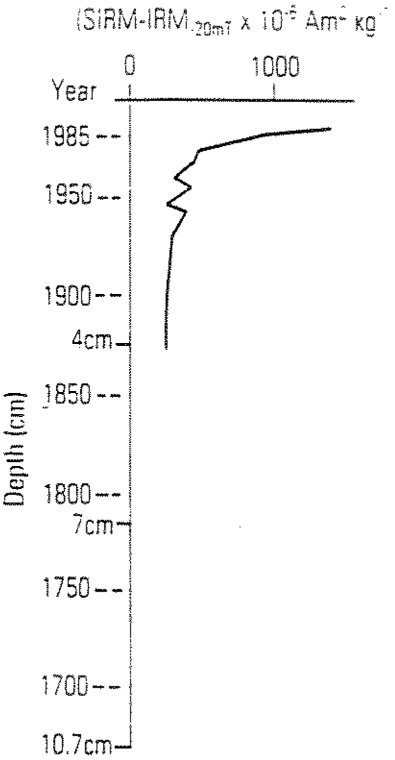

Figure 19 Magnetic deposition at Loch Tanna, core TAN1

9.0 Spherical carbonaceous particle (SCP) analysis

Core TAN1 was sub-sampled to a depth of 15 cm and analysed for concentrations of SCPs, the results are given in Figure 20.

Few SCPs are present in the sediment below 7 cm (c. 1898). Above this point the particles are observed at all levels. The concentrations increase progressively to the surface with the heaviest concentrations being in the most recent sediments. The peak concentration (16.8 x 10^{-3} g^{-1} dry sediment) occurs not at the sediment surface but at a depth of 1.75 cm (c. 1973). When expressed in terms of the organic fraction of dry sediment (determined by LOI), the concentrations give a similar pattern of distribution (Figure 20).

The colour of the oxidised sediment prepared for analysis was very grey and noticeably darker than has generally been observed in similar analyses from other upland sites. The colouring may result from the presence of black irregular shaped particles in the sediment, reminiscent of char. A further unusual feature of the prepared sediment

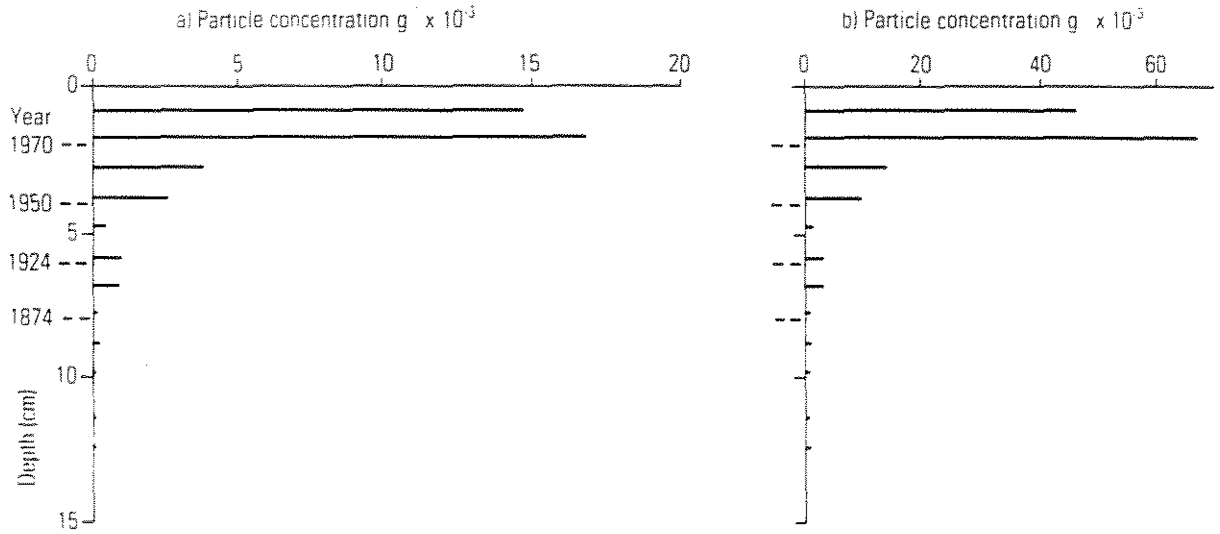

Figure 20 SCP data, a) concentration, b)concentration expressed in terms of organic fraction of dry sediment

was the presence of particles of a similar size range and shape to SCPs but distinguished from them by their shiny surface and their resistance to applied pressure at their surface. Unlike SCPs it is thought that these are solid particles and will be investigated further at a later date.

10.0 Pollen analysis

The summary pollen diagram derived from core TAN1 is presented in Figure 21, the full diagram may be found in Appendix 5.

Within the regional pollen rain very little change occurs through the diagram, although there is some decline in values of *Betula* and *Quercus*. This probably reflects the continuing removal of these trees from the lower wooded stream valleys. There is no indication of a distinct *Pinus* rise which would represent the recent afforestation of the uplands. Two distinct disturbance periods can be identified within the diagram as shown by peaks in the disturbance indicators *Plantago lanceolata*, *Rumex crispus* and *Pteridium* at 55 - 30 cm and 4 - 0 cm.

Within the catchment pollen record the major change is an increase in *Calluna* pollen throughout most of the diagram until 12 cm when the values collapse. This collapse is associated with a rise in Gramineae values. This trend from *Calluna* to Gramineae (Figure 22) over the last c. 200 years 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.

Values of *Huperzia selago* spores are high throughout the diagram and increase to 10% of the non-arboreal pollen at 45 cm. This reflects the prominent role that the plant plays within the catchment vegetation (Section 2.2).

Although the LOI values (Figure 4) suggest periods of blanket peat erosion, this is not apparently recorded by any changes in the loch flora since the normally responsive *Isoetes lacustris* appears to be absent throughout the core.

11.0 Land-use and management

Although a plan of 1799[1] indicates the presence of trees on the mid-western and mid-eastern shores of Loch Tanna, the catchment was by that date dominated by unwooded moorland.

There is no evidence from cartographic, air photograph or documentary sources that the remote, exposed moorland of the Loch Tanna catchment has ever been improved by drainage, enclosure or liming.

It is unlikely that the catchment ever supported a significant sheep population. The area comprised remote undivided common until the 1820s when it was apportioned as common land to Catacol Farm which lay some 6 km distant. In the past 50 - 70 years the catchment has never supported a sheep population in excess of 100 ewes and has not been grazed at all by sheep in recent years (Gibbs pers. comm.).

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[1] Scottish Record Office plan RHP46256: Plan of the County of Argyll engraved for Dr Smith's agricultural survey 1799

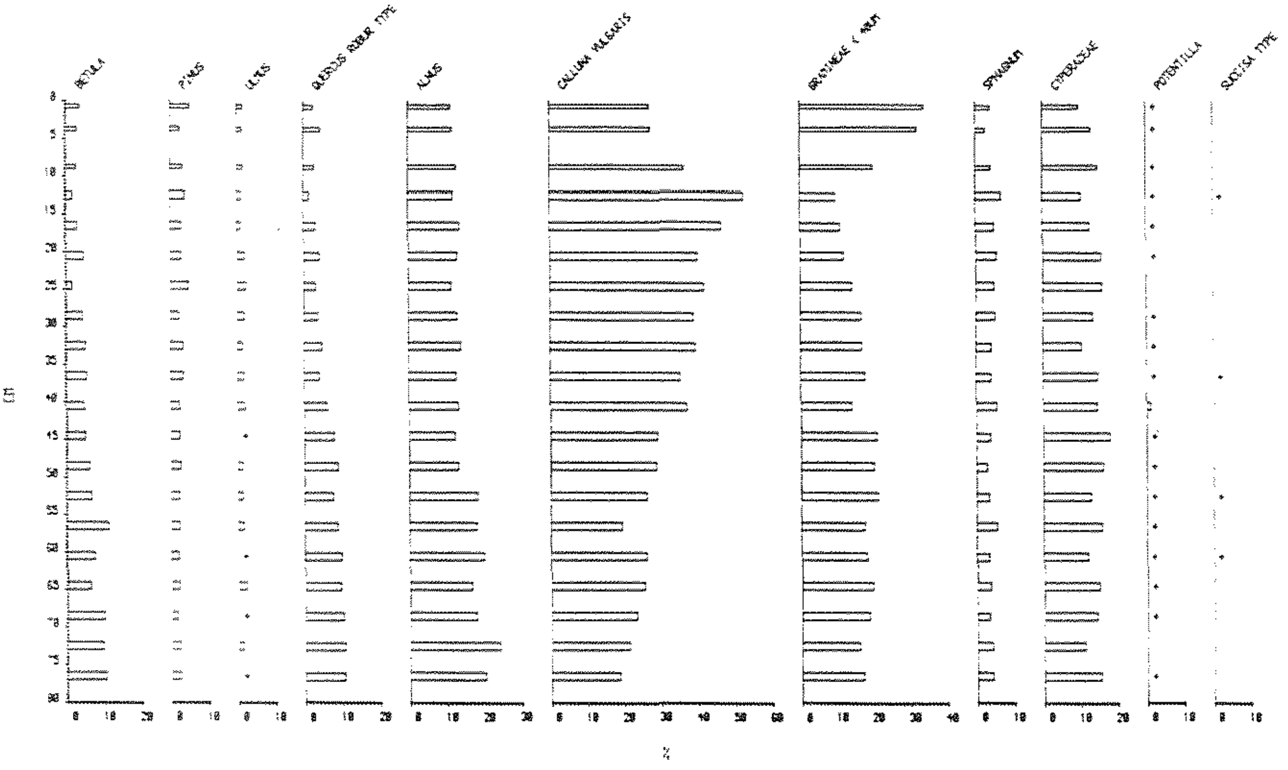

Figure 21 Summary pollen diagram (percentage frequency of pollen types on diagram)

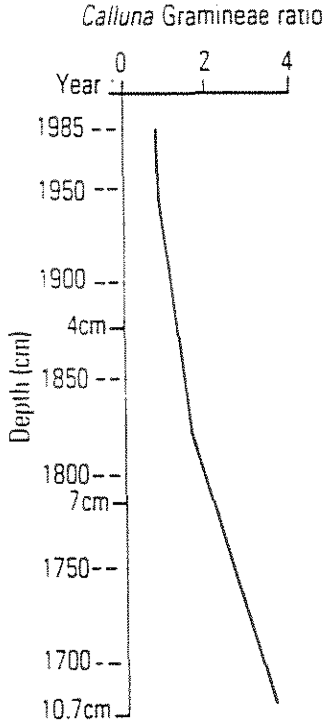

Figure 22 *Calluna*: Gramineae ratio, core TAN1

However, this area of moorland has a long history of exploitation for grouse. Although the Loch Tanna catchment was last intensively shot for grouse in 1977 (Gibbs pers. comm.) it is still regularly burnt in patches for the benefit of the birds. Burning of moorland vegetation for this purpose in central Arran dates from the late nineteenth century and evidence for the practice in the Loch Tanna catchment is provided by air photographs flown in 1946 and 1952[2].

Deer are infrequent visitors to the catchment. Royal Deer Commission deer counts in 1967, 1979 and 1982 failed to record any deer in the catchment during winter (Gibbs pers. comm.).

12.0 Summary of conclusions

1. Loch Tanna, an elongated shallow lake, lies in an elevated coastal location on the island of Arran, in an area which experiences relatively high levels of acid deposition. The loch catchment comprises granite bedrock predominantly overlain with blanket peats. Loch Tanna may thus be considered potentially susceptible to acidification. The mean contemporary pH of the loch water is 5.01.
2. To investigate the history and potential causes of acidification at Loch Tanna a sediment core was obtained in June 1986. Sediment samples were subjected to lithostratigraphic, radiometric dating, diatom, geochemical, carbona-

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[2] Air Photographs Unit, Scottish Development Department Edinburgh: 1) series 106G/Scot/UK 4Y 1:10,000, plates 3293-3296 and 4276-4279, flown May 4th 1946. 2) series 58/980 1:10,000, plates 3066-3069 and 4066-4069, flown 17th November 1952.

ceous particle, magnetic, and palynological analyses. Documentary sources were utilised to provide details of catchment land-use and management history.

3. The organic content of the sediment varies down the sediment core, producing an irregular 'spikey' loss-on-ignition profile. It is suggested that LOI peaks represent periods of inwash of peat eroded from the catchment.
4. ^{210}Pb dating was utilised to provide a chronology of sediment accumulation. Levels of unsupported ^{210}Pb approach zero at 7.75 cm down the core and this level is dated to c. 1874. The period c. 1875-1934 is marked by a significant increase in sediment accumulation rate. ^{137}Cs data from the core were of little chronological value owing to a significant downward diffusion of this isotope.
5. Diatom analysis indicates an increase in acidobiontic and acidophilous species at around 10 cm depth associated with a decline in species less tolerant of acid conditions. Further shifts towards a more acidic flora were observed at 5 cm (c. 1938) and 2 cm (c. 1970).
6. The pH history of the loch is reconstructed from diatom data. Prior to acidification the loch was already very acid at pH c. 5.1. Unequivocal evidence of acidification is first apparent in the mid-nineteenth century with pH values falling to 4.6 in the 1950s and 1960s.
7. Geochemical analysis indicates a progressive contamination of the upper sediments by trace-metals, notably zinc, lead, copper and nickel. Zinc contamination commenced around 10 cm depth (early-mid-nineteenth century) which corresponds to the first evidence of acidification from the diatom record. Lead contamination started earlier at around 20 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 has increased steadily from the late-nineteenth century, with the strongest increase occurring since c. 1940, suggesting contamination by fly-ash material. Concentrations of spherical carbonaceous particles have also progressively increased since the 1890s with a major increase occuring 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. Utilisation of the catchment moorland vegetation for grazing has always been of low intensity and no attempt has been made to improve the land by drainage, enclosure or liming. There has been a long history of grouse shooting and strips of vegetation have been and are still burnt for the benefit of grouse.
11. The results of this study reinforce the conclusion from work elsewhere in southern and central Scotland that acidifcation of surface waters since the mid-nineteenth century has been the result of acid deposition. All the evidence from Loch Tanna 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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34 Galloway lakes: bathymetries, water quality and diatoms.

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

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

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

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

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

No. 24 Patrick, S.T., Fritz, S.C., Stevenson, A.C., Appleby, P.G., Rippey, B., Oldfield, F., Darley, J., Battarbee, R.W., Higgitt, S.R. & Raven P.J. 1987
Palaeoecological evaluation of the recent acidification of Welsh lakes. VIII, Llyn Eiddew Bach, Gwynedd.

No. 25 Patrick, S.T., Stevenson, A.C., Fritz, S.C., Appleby, P.G., Rippey, B., Oldfield, F., Darley, J., Battarbee, R.W., Higgitt, S.R. & Raven P.J. 1987
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No. 26 Stevenson, A.C., Patrick, S.T., Kreiser, A. & Battarbee, R.W. 1987
Palaeoecological evaluation of the recent acidification of susceptible lakes: methods utilised under DoE contract PECD 7/7/139 and the Royal Society SWAP project.

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Palaeoecological evaluation of the recent acidification of Welsh lakes. X, Llyn Cwm Mynach, Gwynedd.

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

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

No. 30 Anderson, N.J., Patrick, S.T., Appleby, P.G., Oldfield, F., Rippey, B., Richardson, N., Darley, J. & Battarbee, R.W. 1988
An assessment of the use of reservoir sediments in the southern Pennines for reconstructing the history and effects of atmospheric pollution.

No. 31 Patrick, S.T., Flower, R.J., Appleby, P.G., Rippey, B., Stevenson, A.C., Cameron, N., Darley, J. and Battarbee, R.W. 1988
Palaeoecological evaluation of water quality change in Loch Urr, Galloway, Scotland.

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(Tel. 01 387 7050 ext. 5547)

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Appendix 1 Summary of CRPB invertebrate survey data 1986

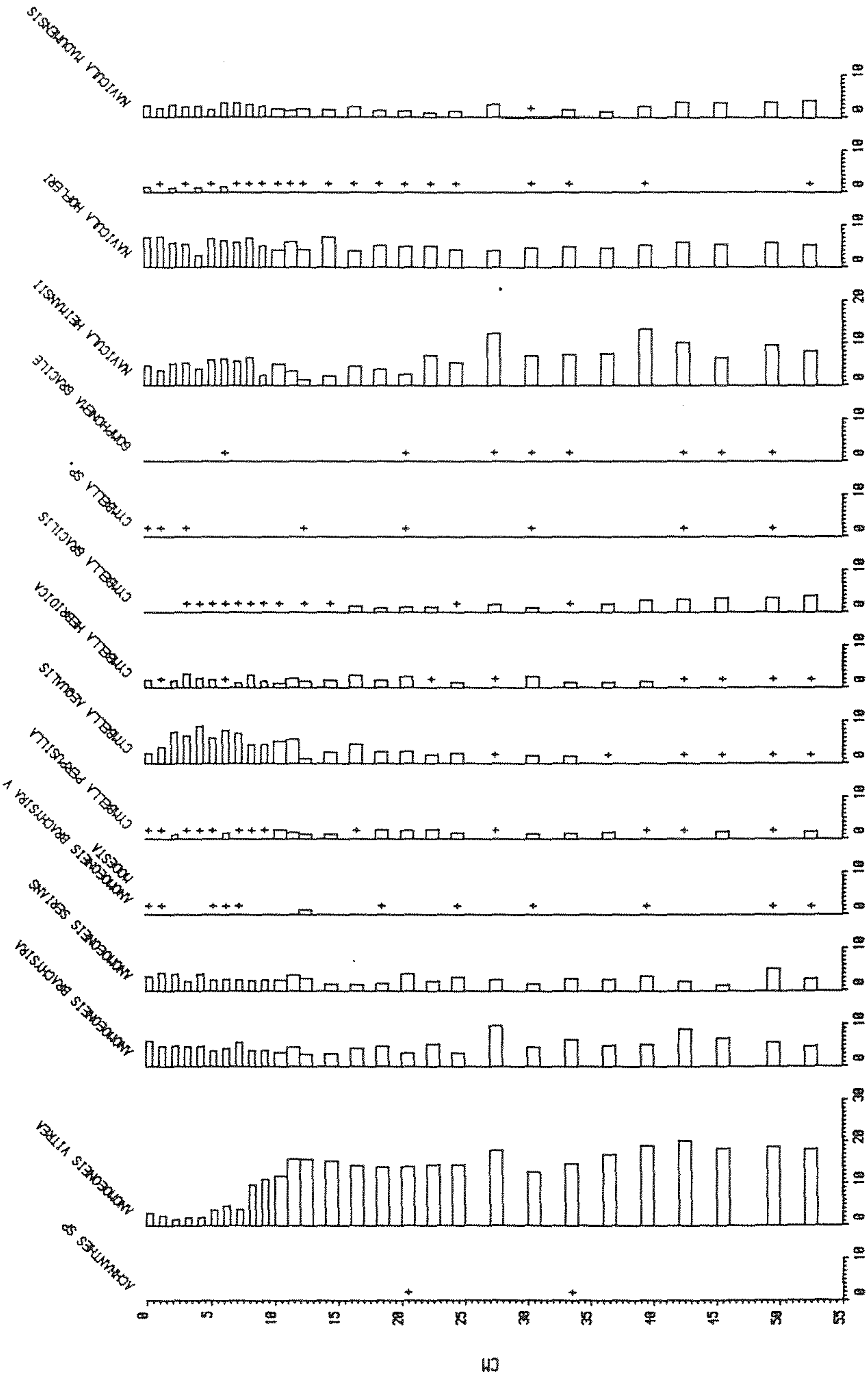
		Site	
	1	2	3
No. of Taxa	10	9	17
No. of families	8	7	15
Worms (%)	1	3	6
Mites (%)	1	0	0
Mayflies (%)	59	81	11
Stoneflies (%)	0	<1	18
Beetles (%)	22	<1	<1
Caddis flies (%)	4	6	19
Diptera (%)	13	9	46

List of invertebrates recorded

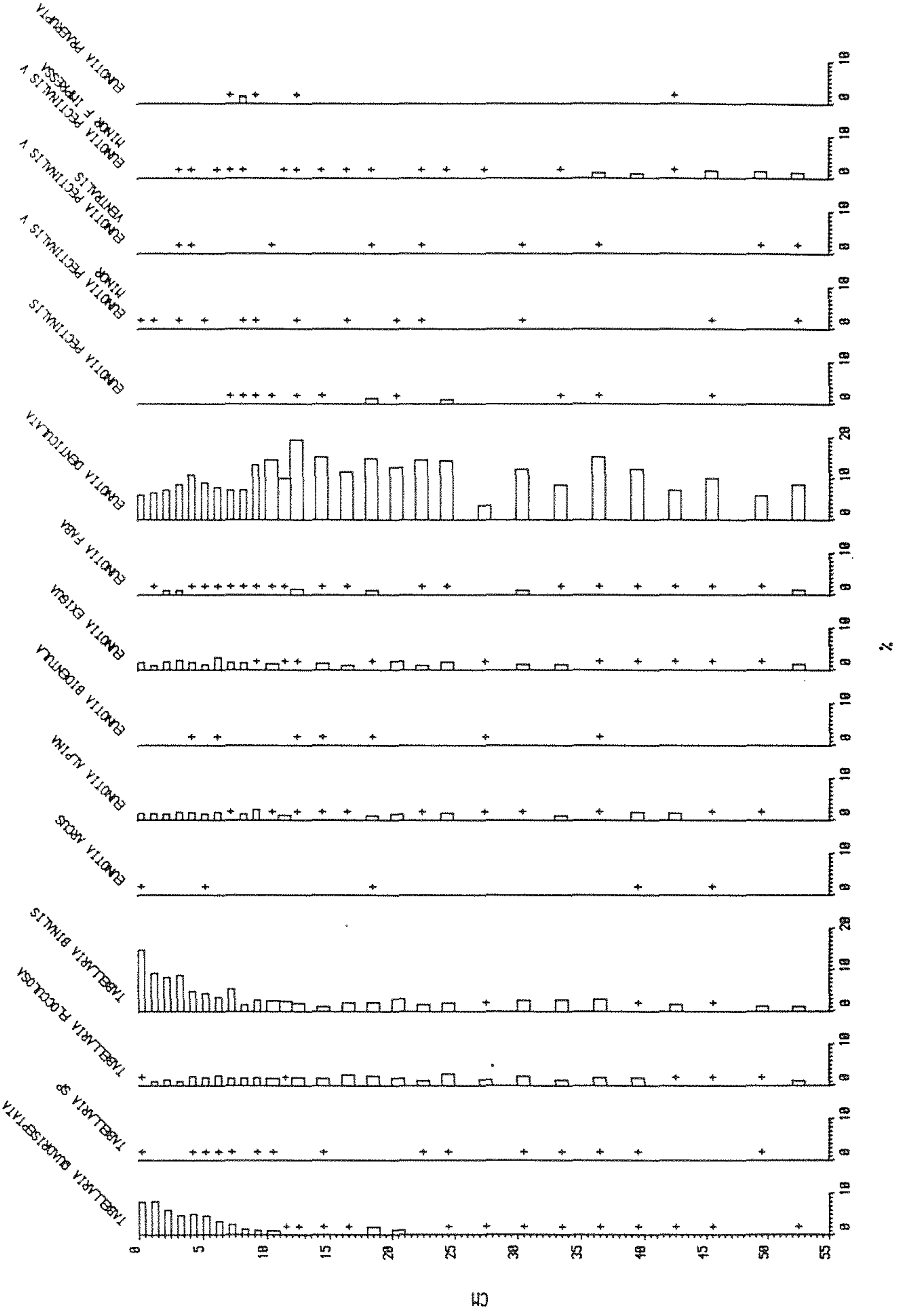
	1	2	3
Nais communis/variabilis			+
Stylodrilus heringianus			+
Enchytraeidae	+	+	+
Hydracarina	+		
Leptophlebia vespertina	+	+	+
Amphinemura sulcicollis			+
Leuctra moselyi			+
Isoperla grammatica			+
Chloroperla torrentium		+	+
Limnius volckmari	+		+
Dytiscidae	+	+	+
Plectrocnemia conspersa	+	+	+
Polycentropus flavomaculatus	+	+	+
Cyrnus flavidus		+	
Neureclipsis bimaculata			+
Phryganea varia		+	
Dicranota sp.			+
Eloeophila sp.	+		
Simuliidae		+	
Chironomidae	+	+	+
Empididae		+	

Sites 1 and 2 = lake margin, Site 3 = outflow

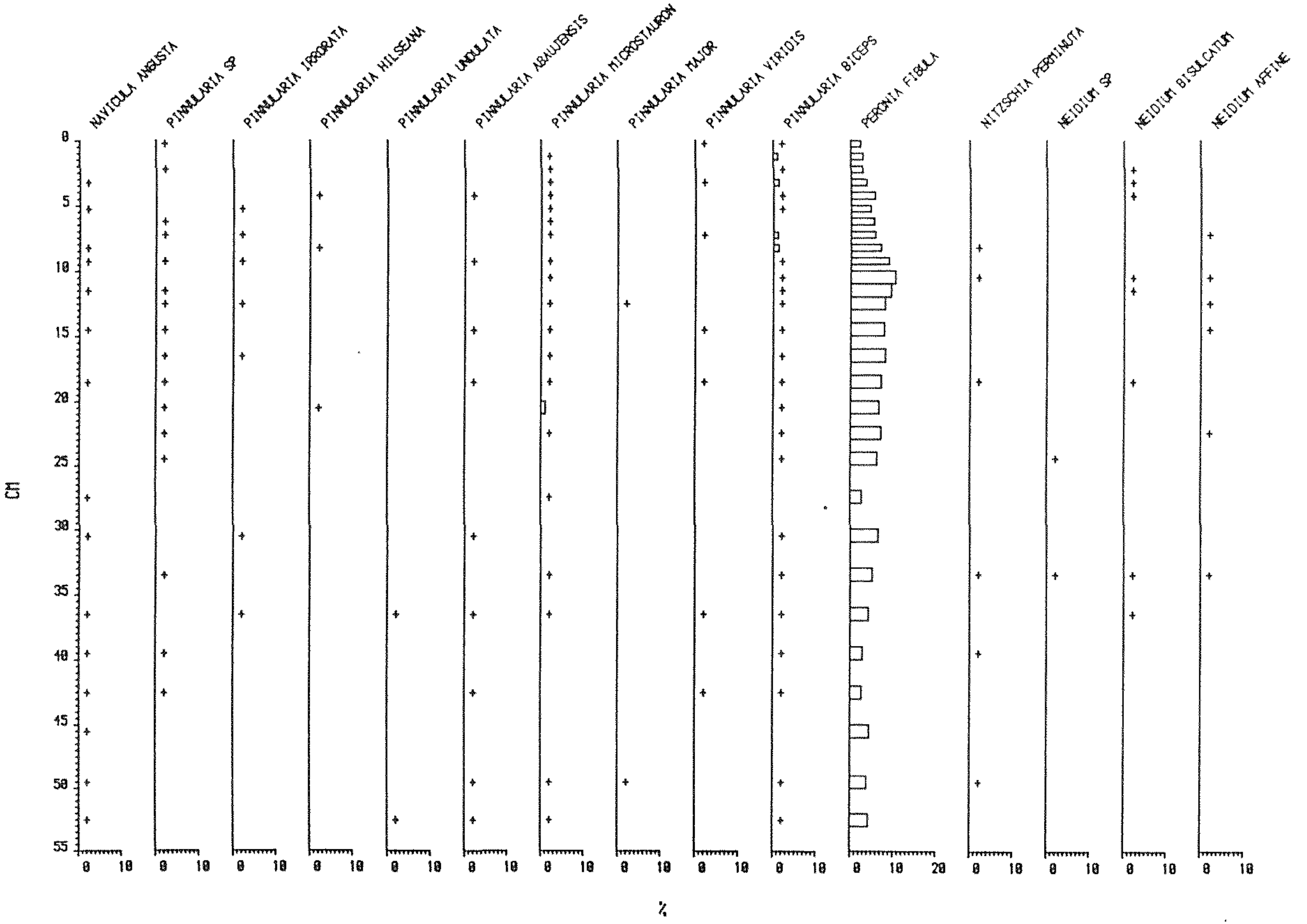
Appendix 2 Full diatom diagram, core TAN1



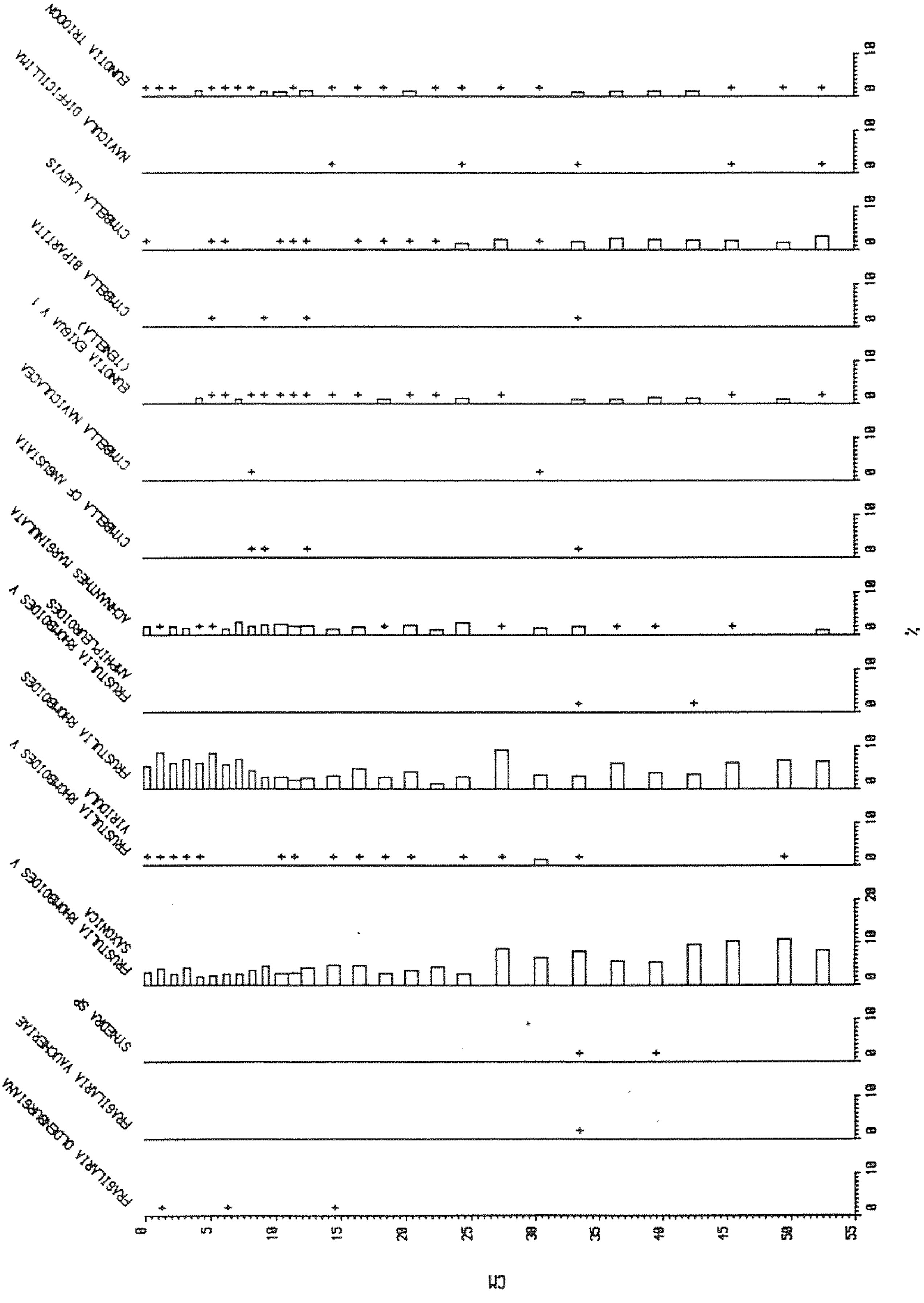
Appendix 2 continued



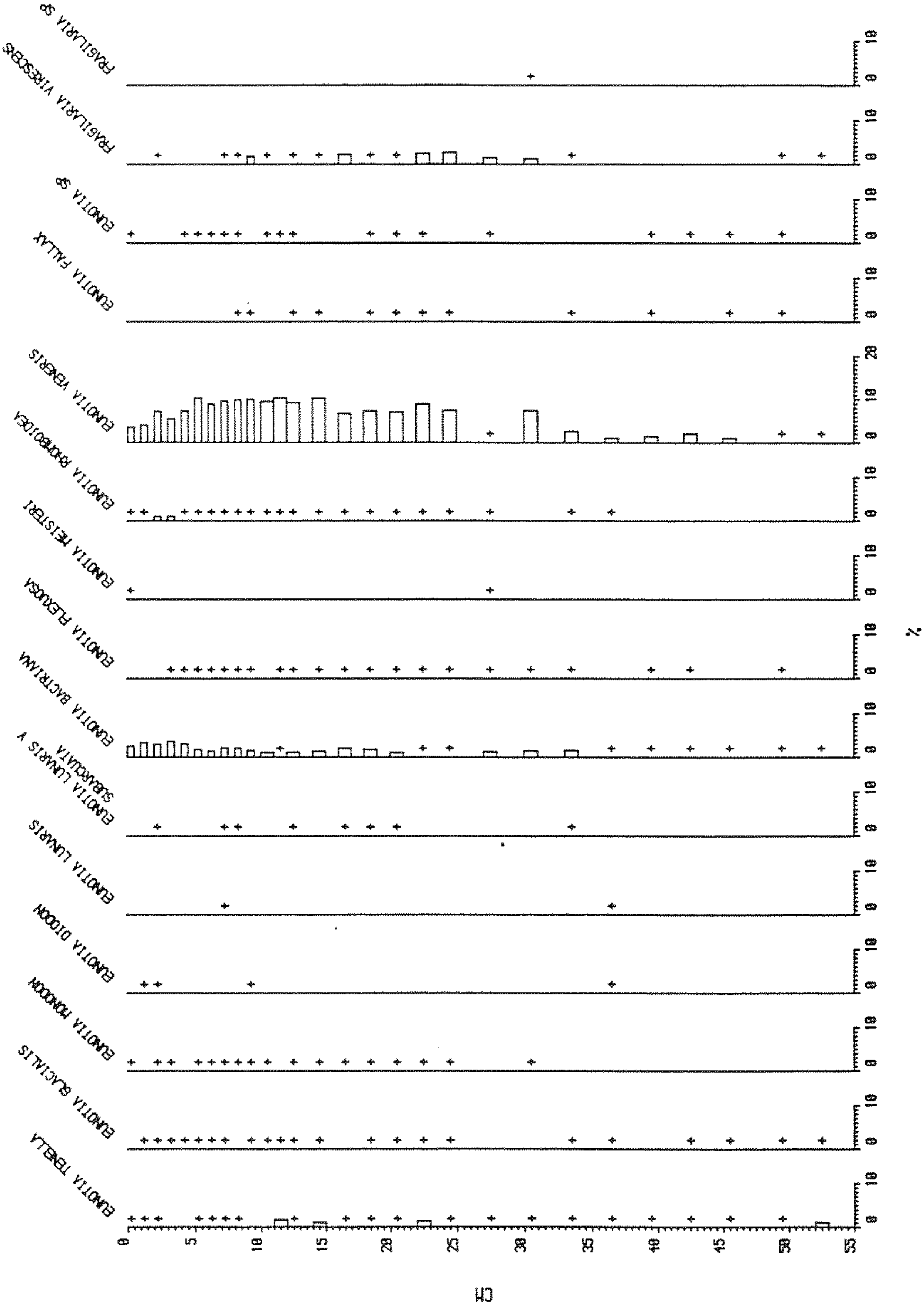
Appendix 2 continued

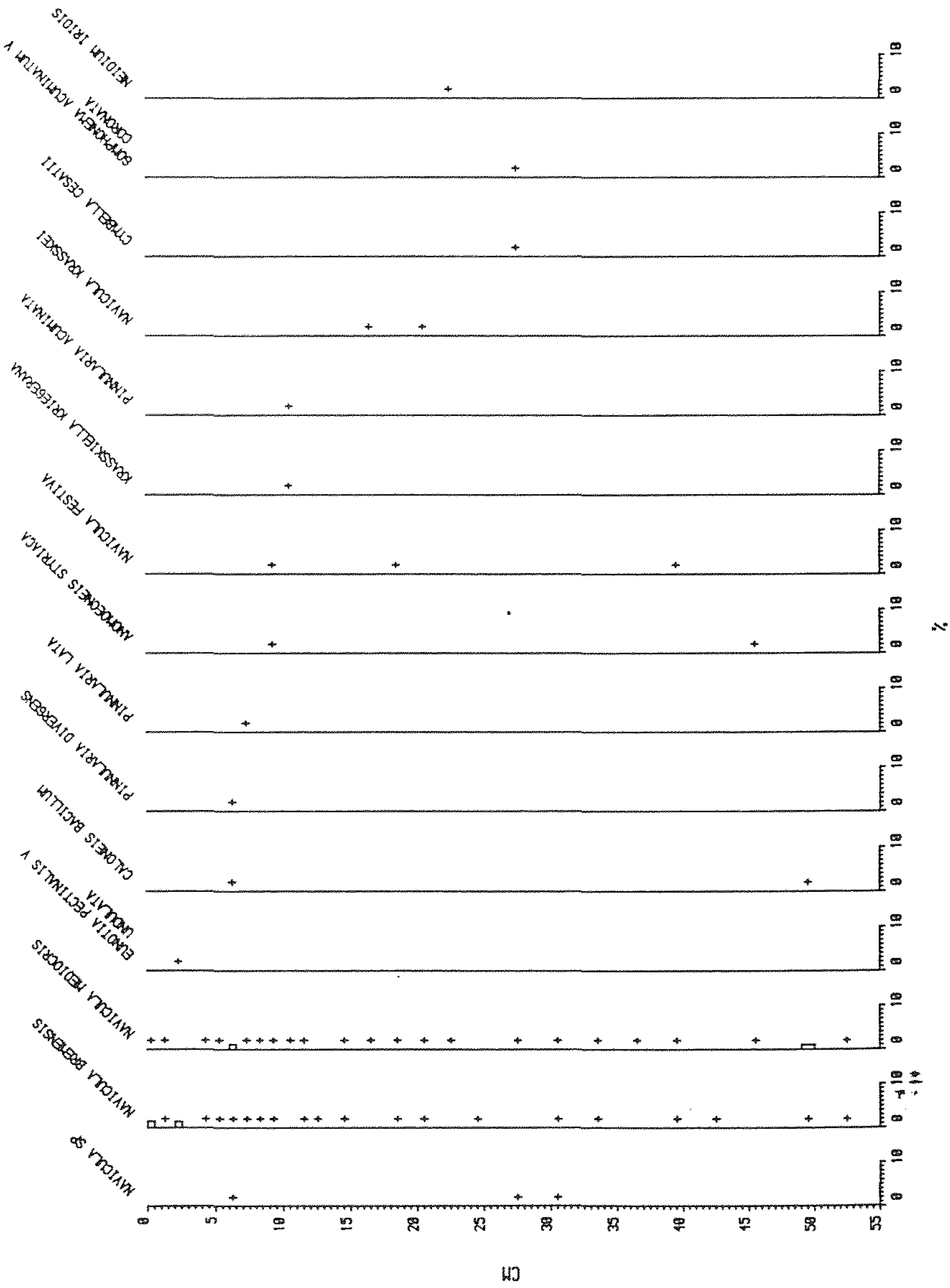


Appendix 2 continued

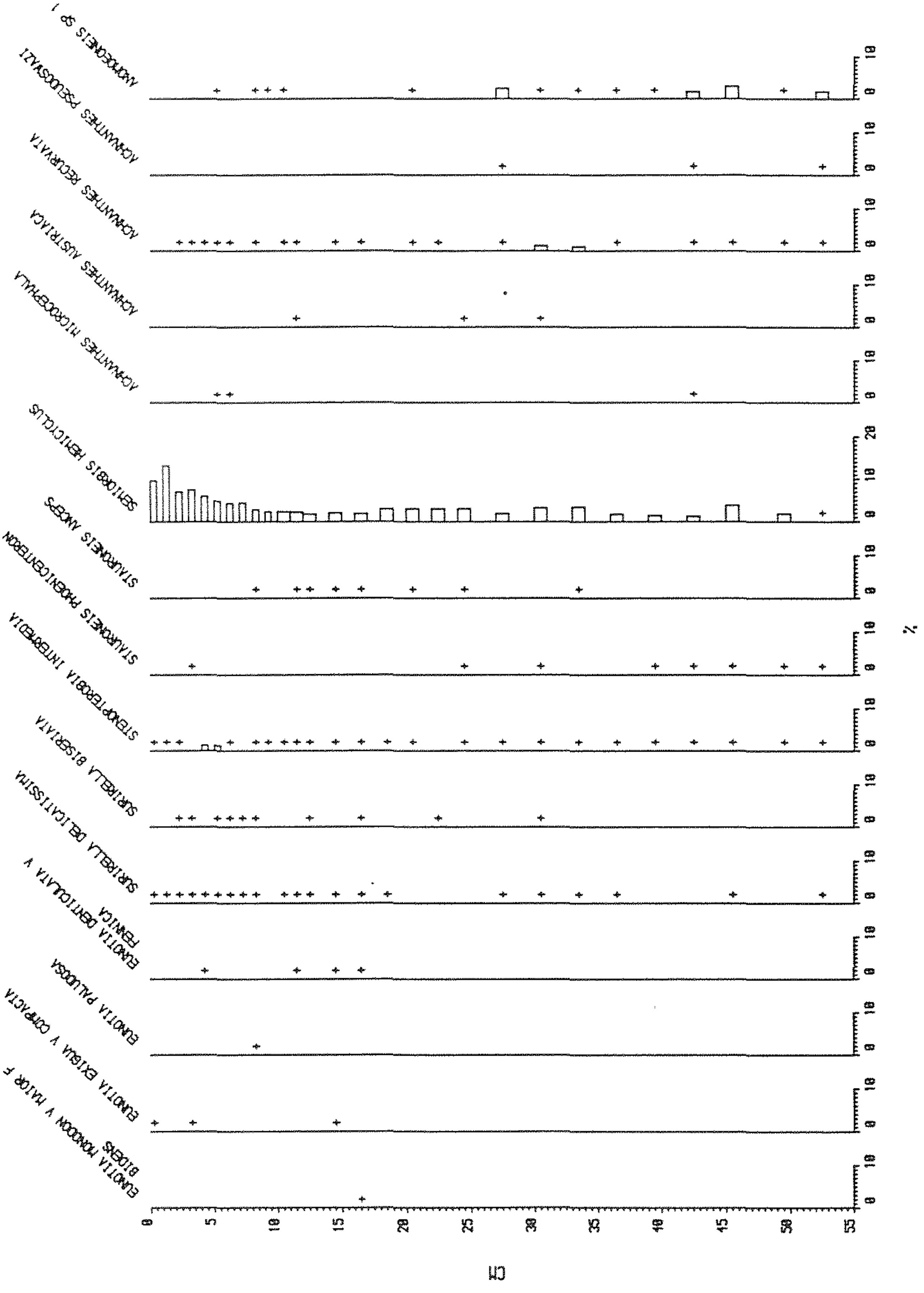


Appendix 2 continued




NEIDIUM IRIDIS
GOMPHONEMA ACUMINATUM V CORONATA
CYMBELLA CESATII
NAVICULA KRASSKEI
PINNULARIA ACUMINATA
KRASSKELLA KRIEGERANA
NAVICULA FESTIVA
ANOMOEONEIS STYRIACA
PINNULARIA LATA
PINNULARIA DIVERGENS
CALONEIS BACILLUM
EUNOTIA PECTINALIS V UNDULATA
NAVICULA MEDIOCRIS
NAVICULA BREMENSIS
NAVICULA SP
0
10
%
0
5
10
15
20
25
30
35
40
45
50
55
CM

Appendix 2 continued



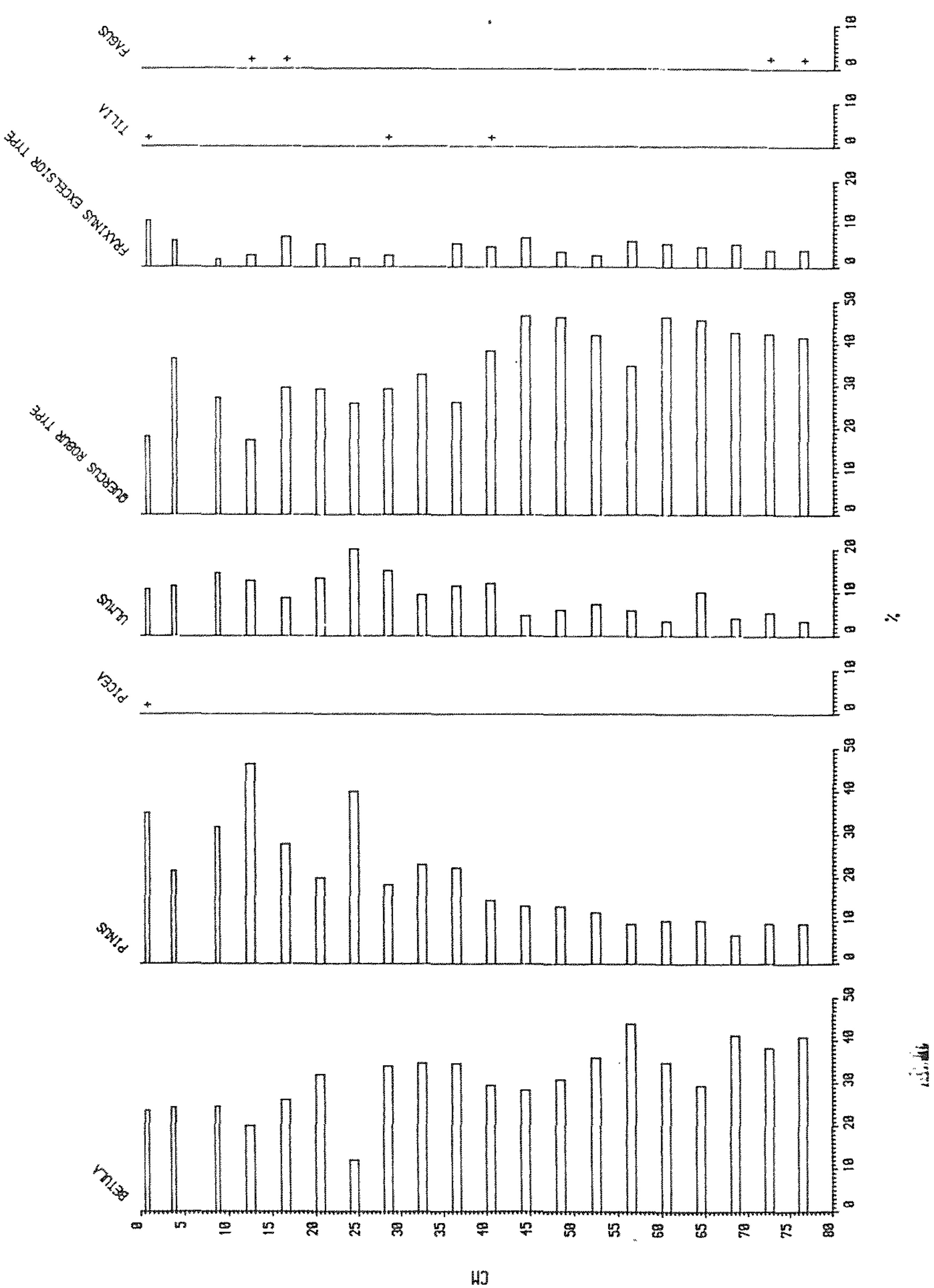
Appendix 3 Full diatom species list, core TAN1

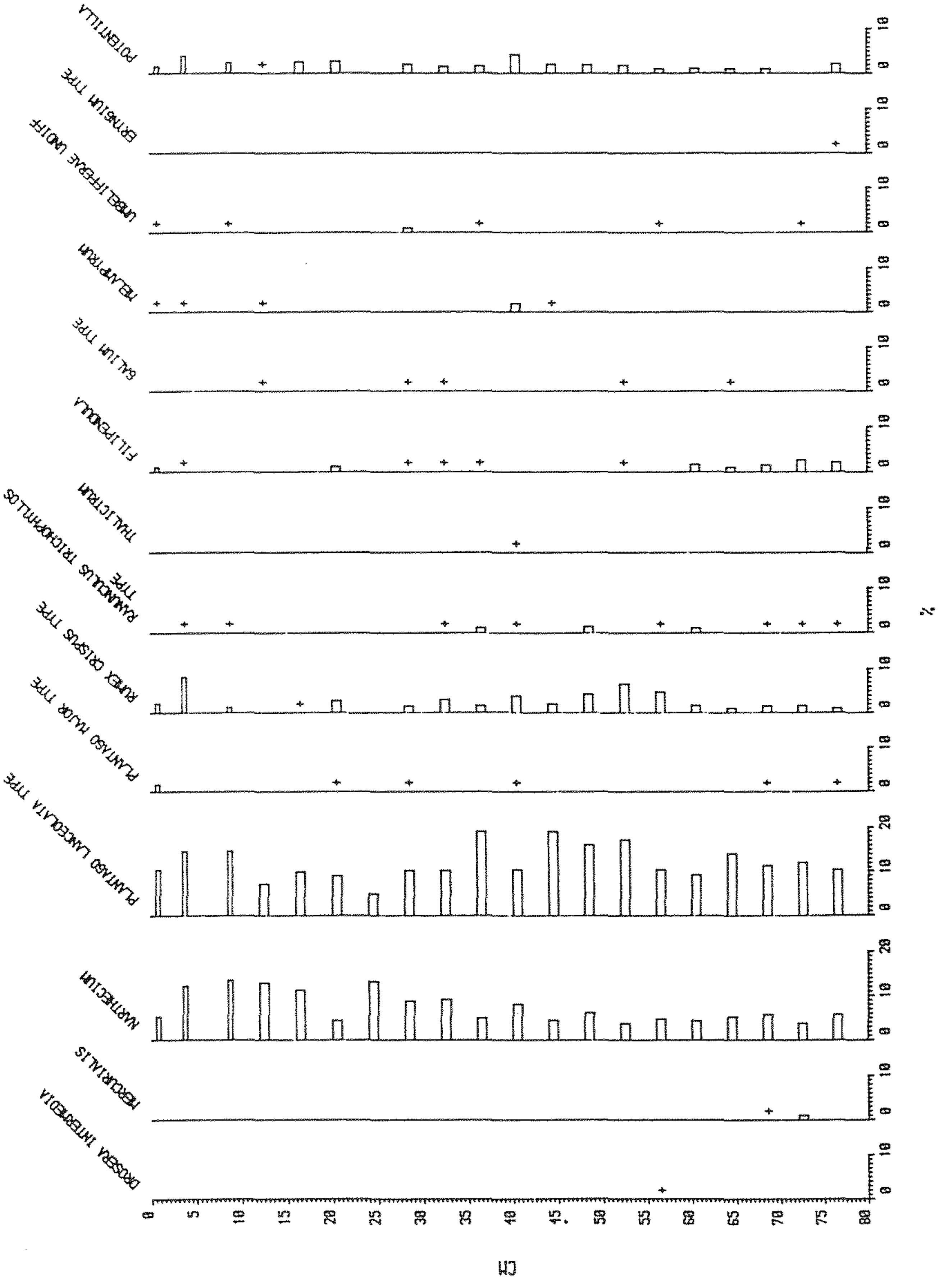
Achnanthes microcephala KUTZ.
Achnanthes pseudoswazi CARTER
Achnanthes recurvata HUST.
Achnanthes austriaca HUST.
Achnanthes marginulata GRUN.
Achnanthes sp
Anomoeoneis serians (BREB.) CLEVE
Anomoeoneis vitrea (GRUN.) ROSS
Anomoeoneis styriaca (GRUN.) HUST.
Anomoeoneis brachysira (BREB.) GRUN.
Anomoeoneis brachysira v modesta C.EULER
Anomoeoneis sp 1 ROUND LOCH (VJ)
Caloneis bacillum (GRUN.) MERESCHKOWSKY
Cymbella perpusilla A. CLEVE
Cymbella laevis NAEGELI
Cymbella aequalis SMITH
Cymbella cesatii (RABH.) GRUN.
Cymbella hebridica (GREGORY) GRUN.
Cymbella gracilis (RABH.) CLEVE
Cymbella bipartita MAYER
Cymbella naviculacea GRUN.
Cymbella cf angustata L. TANNA (RJF)
Cymbella sp.
Eunotia veneris (KUTZ.) MULLER
Eunotia pectinalis (KUTZ.) RABH.
Eunotia pectinalis v minor (KUTZ.) RABH.
Eunotia pectinalis v ventralis (EHR.) HUST.
Eunotia pectinalis v undulata (RALFS) RABH.
Eunotia pectinalis v minor f impressa (EHR.) HUST.
Eunotia praerupta EHR.
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 exigua v compacta HUST.
Eunotia faba (EHR.) GRUN.
Eunotia rhomboidea HUST.
Eunotia arcus EHR.
Eunotia bactriana EHR.
Eunotia denticulata (BREB.) RABH.
Eunotia denticulata v fennica HUST.
Eunotia diodon EHR.
Eunotia flexuosa KUTZ.
Eunotia meisteri HUST.
Eunotia glacialis MEIST.
Eunotia fallax CLEVE
Eunotia triodon EHR.
Eunotia paludosa GRUN.
Eunotia exigua v 1
Eunotia sp
Fragilaria virescens RALFS
Fragilaria vaucheriae (KUTZ.) BOYE PETERSON
Fragilaria oldenburgiana HUST.
Fragilaria sp
Frustulia rhomboides (EHR.) DE TONI
Frustulia rhomboides v saxonica (RABH.) DE TONI
Frustulia rhomboides v amphipleuroides GRUN.
Frustulia rhomboides v viridula BREB. EX (KUTZ.) CLEVE
Gomphonema gracile EHR.
Gomphonema acuminatum v coronata (EHR.) W. SMITH
Krasskiella kriegerana (KRASSKE) ROSS & SIMS
Navicula mediocris KRASSKE
Navicula angusta GRUN.
Navicula festiva KRASSKE
Navicula hofleri CHOLNOKY
Navicula heimansii VAN DAM & KOOY.
Navicula krasskei HUST.
Navicula bremensis HUST.
Navicula difficillima HUST.
Navicula madumensis JORGENSEN
Navicula sp
Neidium iridis (EHR.) CLEVE
Neidium affine (EHR.) CLEVE
Neidium bisulcatum (LAGERSTEDT) CLEVE
Neidium sp
Nitzschia perminuta GRUN.
Peronia fibula BREB. ex (KUTZ.) ROSS
Pinnularia acuminata SMITH
Pinnularia major (KUTZ.) W.SMITH
Pinnularia viridis (NITZSCH) EHR.
Pinnularia divergens W. SMITH
Pinnularia microstauron (EHR.) CLEVE
Pinnularia abaujensis (PANT.) ROSS
Pinnularia biceps GREGORY
Pinnularia undulata GREGORY
Pinnularia hilseana (JANISCH) MULL.
Pinnularia irrorata (GRUN.)HUST.
Pinnularia lata (BREB.) SMITH
Pinnularia sp
Stauroneis anceps EHR.
Stauroneis anceps f gracilis (EHR.) CLEVE
Stauroneis phoenicenteron (NITZSCH) EHR.
Stauroneis sp a
Semiorbis hemicyclus (EHR.) PATRICK
Stenopterobia intermedia LEWIS
Surirella biseriata BREB.
Surirella delicatissima LEWIS
Synedra sp
Tabellaria flocculosa (ROTH) KUTZ.
Tabellaria binalis (EHR.) GRUN.
Tabellaria quadriseptata KNUDSON
Tabellaria sp

Appendix 4 Geochemical analyses of core TAN1

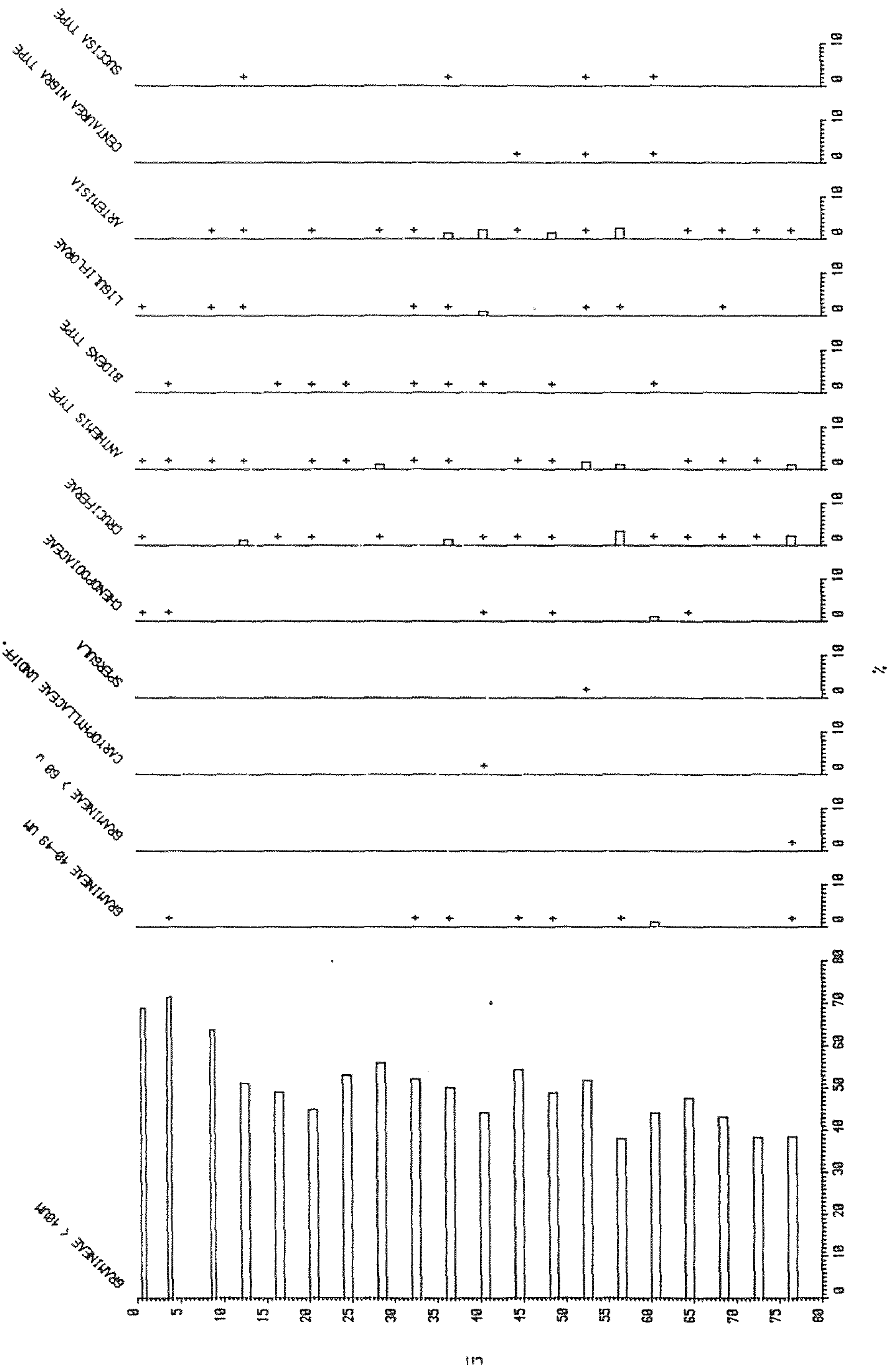
Depth	Zn	Pb	Cu	Ni	Ca	Mg	Na	K
cm		ug g^{-1}				mg g^{-1}		
0.25	144	134	259	16	1.56	0.82	7.42	12.55
0.75	79	106	35	16	1.61	0.80	7.87	13.87
1.25	82	128	41	18	1.65	0.79	8.50	14.11
1.75	76	129	22	12	1.59	0.82	8.37	14.46
2.25	78	130	25	18	1.69	0.84	8.51	14.61
2.75	62	139	21	14	1.63	0.81	8.95	15.34
3.25	72	178	28	15	1.77	0.82	9.06	15.81
3.75	85	163	22	15	2.07	0.92	8.87	15.36
4.25	98	183	23	13	1.73	0.83	8.75	15.20
4.75	184	182	22	16	1.72	0.84	8.03	14.13
5.25	142	150	24	16	1.68	0.86	7.62	13.78
5.75	95	155	23	13	1.76	0.86	8.06	14.33
6.25	85	151	24	13	1.97	0.87	9.77	17.23
6.75	65	139	21	13	1.88	0.81	9.91	16.93
7.25	67	156	24	15	1.79	0.85	8.87	15.56
7.75	83	177	21	14	1.84	0.82	9.00	15.94
8.25	90	167	22	11	1.86	0.78	9.36	15.83
8.75	85	154	12	11	1.85	0.76	9.97	17.11
9.25	108	148	28	13	1.65	0.81	8.15	14.29
9.75	93	133	17	8	2.00	0.83	8.28	14.04
10.50	70	117	12	6	2.48	0.75	13.55	21.50
12.50	63	124	10	7	1.88	0.93	7.51	13.34
14.50	63	137	12	5	1.85	0.77	7.11	12.37
16.50	68	117	10	6	2.20	0.93	9.53	15.46
18.50	58	112	9	5	2.97	0.81	9.94	16.26
20.50	57	116	10	7	2.08	0.82	9.47	16.42
22.50	56	105	17	7	1.95	0.79	9.08	15.52
24.50	50	86	9	3	2.19	0.85	10.48	17.58
30.50	46	78	12	5	2.16	0.88	8.26	14.72
32.50	51	69	9	5	2.25	0.83	9.97	17.30
34.50	43	63	5	5	1.74	0.80	7.30	12.49
36.50	53	60	8	4	1.76	0.75	7.27	12.00
38.50	46	54	5	3	1.60	0.71	6.17	10.11
40.50	49	47	5	3	1.69	0.72	6.28	10.11
45.50	52	35	5	5	1.63	0.73	5.26	8.85
50.50	51	27	3	3	1.71	0.72	7.04	11.35
55.50	66	32	4	4	1.61	0.75	5.63	9.56
60.50	63	33	5	5	1.72	0.66	5.69	9.16
65.50	59	31	4	2	1.64	0.66	5.75	9.96
70.50	56	31	4	4	1.54	0.65	5.54	9.61
75.50	52	28	4	4	1.57	0.66	5.88	10.21

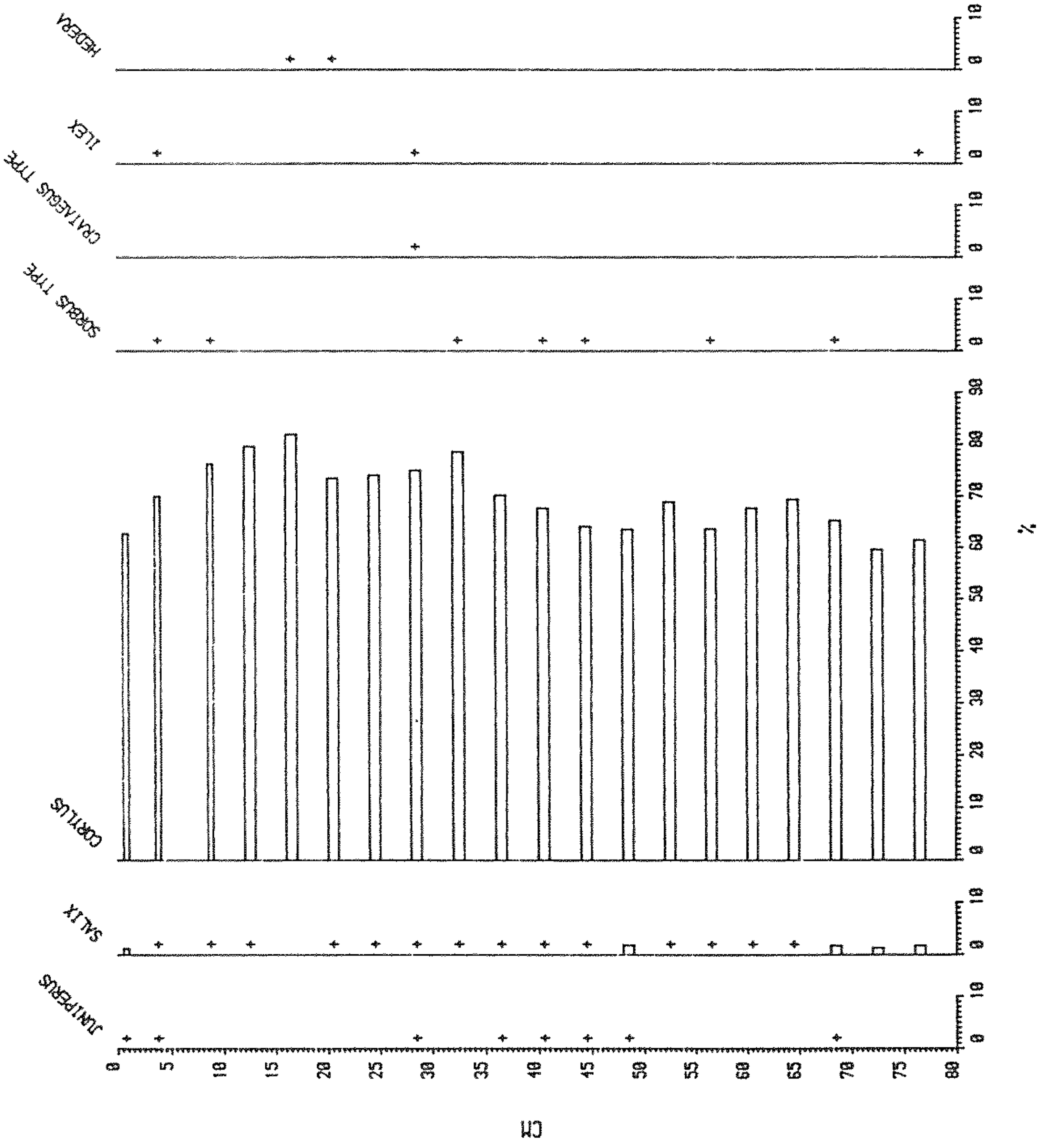
Appendix 5 Full pollen diagram, core TAN1.
(Trees = % tree pollen, shrubs = % trees + shrubs, herbs = % trees + herbs, aquatics = % total pollen)

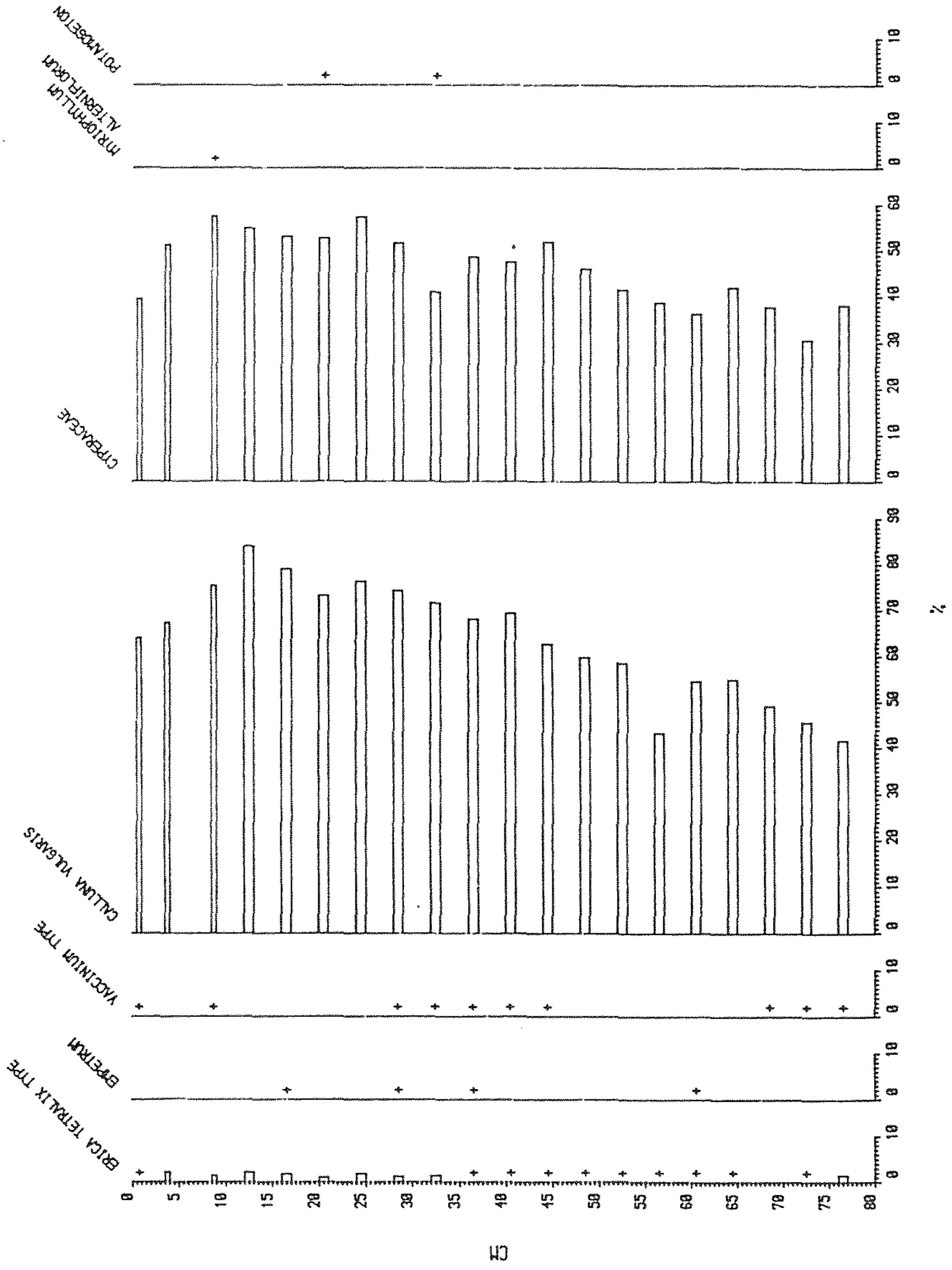



POTENTILLA
ERYNGIUM TYPE
UMBELLIFERAE UNDIFF
MELAMPYRUM
GALIUM TYPE
FILIPENDULA
THALICTRUM
RANUNCULUS TRICHOPHYLLOS TYPE
RUMEX CRISPUS TYPE
PLANTAGO MAJOR TYPE
PLANTAGO LANCEOLATA TYPE
NARTHECIUM
MERCURIALIS
DROSERA INTERMEDIA
0
10
20
%
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
CM

Appendix 5 continued




HEDERA
ILEX
CRATAEGUS TYPE
SORBUS TYPE
CORYLUS
SALIX
JUNIPERUS
0
10
20
30
40
50
60
70
80
90
%
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
CM


POTAMOGETON
MYRIOPHYLLUM ALTERNIFLORUM
CYPERACEAE
CALLUNA VULGARIS
VACCINIUM TYPE
EMPETRUM
ERICA TETRALIX TYPE
%
CM
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
90

Appendix 5 continued