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THE EXTENT OF REGIONAL ACIDIFICATION IN NORTH-WEST SCOTLAND: PALAEOECOLOGICAL EVIDENCE

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1 INTRODUCTION

By examining a series of sensitive lakes on a gradient from high to low acid deposition it is possible to show that the extent of acidification varies according to the level of sulphur deposition in a way that can be predicted from an empirical dose-response model (Battarbee 1989). In the project described below three sensitive sites from areas of low sulphur deposition were examined to determine whether acid deposition has affected these remote lakes and if so whether it has been sufficient to exceed a critical load above which ecological change occurs.

Loch Coire nan Arr lies on the Torridonian sandstones of the Applecross area (Figure 1) where sulphur deposition is estimated to be 0.71 g S m^{-2} yr^{-1}. This site is included in the DoE UK Acid Waters Monitoring Network (Patrick *et al.* 1991). Loch Uisge is situated to the south on granodiorite geology in the Morvern Area (Figure 1), where estimated sulphur deposition is 0.76 g S m^{-2} yr^{-1}. Both are clear water sites with a mean pH >6 (Table 1), their Ca^{2+} levels are <70 μeq l^{-1} which suggests that they are sensitive to acidification (Battarbee *et al* 1988). Their relatively high Na^{+} and Cl^{-} concentrations reflect a marine influence which is a consequence of proximity to the coast. Loch Teanga lies on South Uist in the Outer Hebrides (Figure 1), an area which falls between the 0.8 and 0.4 g S m^{-2} yr^{-1} isolines for annual non-marine sulphur deposition over the British Isles. Loch Teanga is more acid than the other sites in this sub-project and also has a water chemistry which clearly reflects its exposure to marine influence (Table 1).

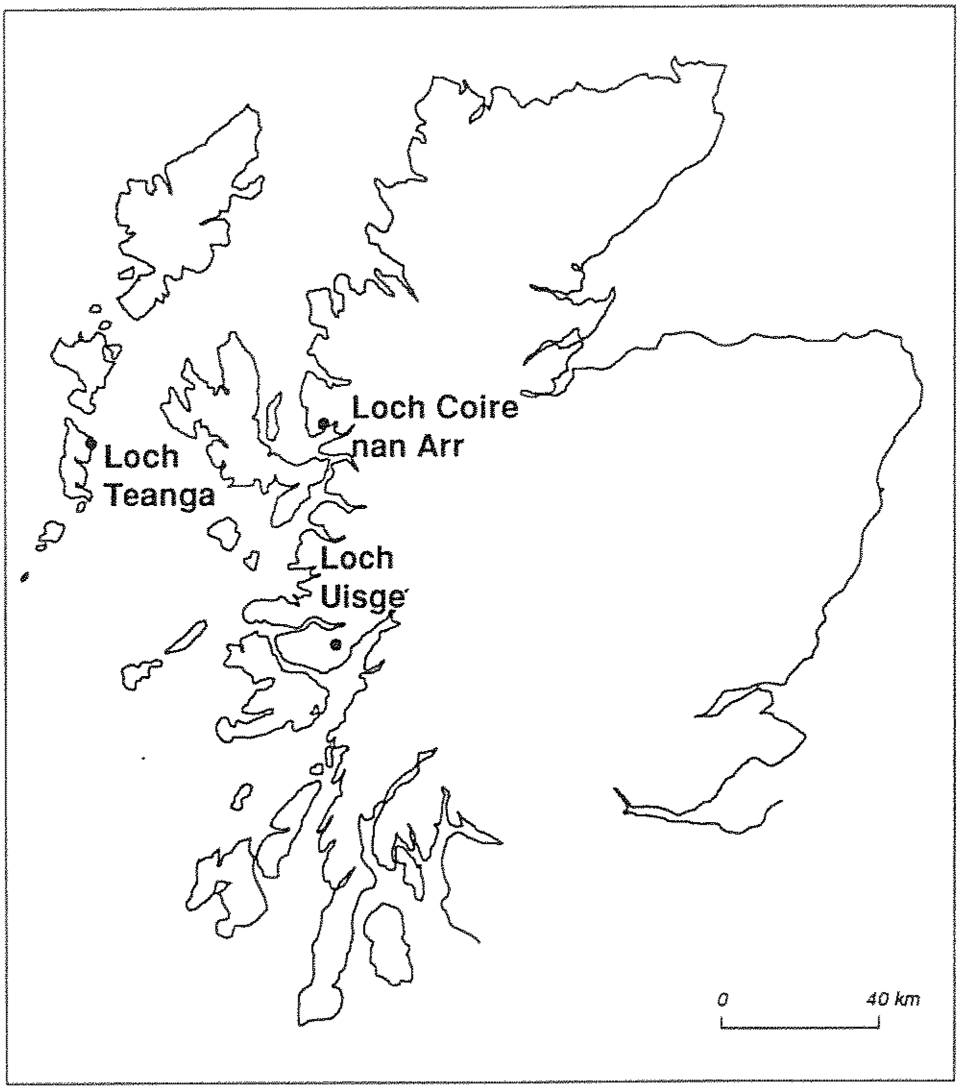
The sites were cored in June 1986 (Loch Coire nan Arr and Loch Uisge) and September 1987 (Loch Teanga). Methods for lithostratigraphic, biostratigraphic, radiometric, analysis follow the Royal Society Surface Water Acidification Project (SWAP) protocol (Stevenson *et al* 1987). Methods for carbonaceous particle and fly-ash analyses follow Rose (1990a, 1990b). The pH history of the lakes is reconstructed using two numerical methods: multiple regression (MR) of the pH preference groups (Flower 1986); and the more statistically robust weighted averaging (WA) method (Birks *et al.* 1990).

Table 1 **Lake water quality**

		L. Coire nan Arr	L. Uisge	L. Teanga
pH		6.47	6.39	5.7
TOC	mg l^{-1}	2.2	4.8	*
Conductivity	µS cm^{-1}	39.0	38.0	163.0
Alkalinity	µeq l^{-1}	27.9	*	12.04
Na^{+}	µeq l^{-1}	216.0	213.0	981.0
Ca^{+}	µeq l^{-1}	43.0	67.0	110.0
Mg^{2+}	µeq l^{-1}	59.0	57.0	255.0
K^{+}	µeq l^{-1}	13.0	15.0	23.0
SO_{42-}	µeq l^{-1}	45.0	50.0	233.0
Cl^{-}	µeq l^{-1}	263.0	220.0	1160.0
NO_{3-}	µeq l^{-1}	3.6	2.2	*
Total Al	µg l^{-1}	24.0	136.0	*
Non-labile Al	µg l^{-1}	22.0	*	*
Labile Al	µg l^{-1}	2.0	*	*

Determinations: Loch Coire nan Arr and Loch Uisge = 1986-1987 mean based on 6 measurements; Loch Teanga = 1987 single sample; * indicates determination not made.

Figure 1 Site location map



2 RESULTS

2.1 Loch Coire nan Arr

Bathymetry

The bathymetry of Loch Coire nan Arr is shown in Figure 2. The loch has a very simple profile with a single basin falling to 12 m at the deepest point. This is quite typical of glacial corrie lakes throughout the British Isles.

Lithostratigraphy

Lithostratigraphic results are presented in Figure 3. Percentage loss-on-ignition (LOI) values are relatively low throughout the core, never rising above 40%. This is in contrast with cores obtained from brown water lakes with very peaty catchments which can have %LOI values of >70%. The dry weight and wet density profiles mirror the %LOI profile with troughs in %LOI corresponding with peaks in dry weight and wet density. These features most probably represent inwash events of mineral material from the lake catchment.

Dating

Sediment samples from core ARR2 were analysed for ^{210}Pb, ^{226}Ra, ^{137}Cs and ^{241}Am by gamma spectrometry. Since the core post-dates the Chernobyl accident the gamma spectrum was also analysed for the short-lived isotope ^{134}Cs, characteristic of Chernobyl fallout. Although data on Chernobyl fallout (Clark and Smith 1988) indicate that there was very little deposition in the immediate area of Loch Coire nan Arr, traces of ^{134}Cs were observed in the topmost sediments of the core. The ^{210}Pb and ^{226}Ra results are given in Table 2, and ^{137}Cs, ^{134}Cs and ^{241}Am are given in Table 3.

Dates calculated using the CRS and CIC ^{210}Pb dating models (Appleby and Oldfield 1978) are shown in Figure 4. Results for the lower part of the core are fairly unambiguous. Below 13 cm, dated c. 1930, the unsupported ^{210}Pb activity (when plotted on a logarithmic scale) varies more or less linearly with depth and indicates a reasonably constant sediment accumulation rate of c. 0.0262 g cm^{-2} y^{-1}. Above this level however, there is a significant discrepancy between the two models. Both indicate an episode of accelerated sedimentation, the onset of which is dated to the period 1930-1940. The CRS model suggests that this period of high accumulation rates was sustained, with a decline to more normal accumulation rates only over the past 10-20 years. Conversely, the CIC model suggests that it was a relatively brief event, perhaps due to a localised slump, with near normal accumulation rates since then. Although a small area of the catchment of Coire nan Arr has been afforested it is unlikely that this would have caused a sustained episode of accelerated sedimentation. Moreover, the CIC model dates are consistent with the ^{137}Cs and ^{241}Am data. Although there is no ^{137}Cs peak to indicate the 1963 level directly, due possibly to the mobility of this isotope, 92% of the ^{137}Cs inventory lies above the 4 cm level and this would appear to exclude the possibility of rapid accumulation rates over the past 30 years. Traces of ^{241}Am at 1.75 cm suggest a date of c. 1963 for this level and Figure 4 shows that this is in good agreement with the CIC model date, but the CRS model date is significantly younger. In view of these results the dates given in Table 4 have been based on the CIC model.

Table 2 Loch Coire nan Arr: ^{210}Pb and ^{226}Ra data

Depth	Dry mass	^{210}Pb Conc.				^{226}Ra Conc.	
		Total		Unsupp.			
cm	g cm^{-2}	pCi g^{-1}	±	pCi g^{-1}	±	pCi g^{-1}	±
0.25	0.037	16.82	0.79	15.84	0.81	0.98	0.17
1.75	0.437	9.67	0.61	8.76	0.64	0.91	0.18
3.75	0.927	5.96	0.56	5.29	0.57	0.67	0.09
5.75	1.426	5.39	0.47	4.54	0.48	0.85	0.08
7.75	1.875	4.38	0.35	3.52	0.37	0.86	0.11
10.75	2.518	5.01	0.33	3.77	0.34	1.24	0.09
12.75	2.908	3.80	0.32	3.16	0.34	0.64	0.11
14.25	3.307	3.26	0.25	2.38	0.26	0.88	0.06
15.50	3.668	1.81	0.19	1.17	0.20	0.64	0.06
17.50	4.627	1.29	0.17	0.61	0.18	0.68	0.06
19.50	5.401	0.99	0.15	0.16	0.16	0.83	0.06
22.50	6.552	0.77	0.16	0.01	0.17	0.76	0.05

Table 3 Loch Coire nan Arr: ^{137}Cs, ^{134}Cs and ^{241}Am data

Depth	^{137}Cs Conc.		^{134}Cs Conc.		^{214}Am Conc.	
cm	pCi g^{-1}	±	pCi g^{-1}	±	pCi g^{-1}	±
0.25	12.35	0.24	0.60	0.18	0.00	0.00
1.75	7.44	0.22	0.00	0.00	0.04	0.03
3.75	1.39	0.10	0.00	0.00	0.00	0.00
5.75	0.29	0.06	0.00	0.00	0.00	0.00
7.75	0.11	0.07	0.00	0.00	0.00	0.00
10.75	0.09	0.05	0.00	0.00	0.00	0.00
12.75	0.10	0.09	0.00	0.00	0.00	0.00
14.25	0.00	0.04	0.00	0.00	0.00	0.00
15.50	0.00	0.00	0.00	0.00	0.00	0.00
17.50	0.00	0.00	0.00	0.00	0.00	0.00
19.50	0.03	0.04	0.00	0.00	0.00	0.00
22.50	0.00	0.00	0.00	0.00	0.00	0.00

Table 4 Loch Coire nan Arr: ^{210}Pb chronology

Depth	Cum. dry mass	Chronology			Sedimentation rate		
		Date	Age				
cm	g cm^{-2}	AD	yr	±	g cm^{-2}yr^{-1}	cm yr^{-1}	± (%)
0.00	0.000	1986	0				
0.50	0.104	1982	4	2			
1.00	0.237	1977	9	2	0.025	0.103	
1.50	0.370	1971	15	3			
2.00	0.498	1966	20	3			
2.50	0.621	1962	24	4			
3.00	0.743	1957	29	4			
3.50	0.866	1952	34	4			
4.00	0.989	1949	37	4			
6.00	1.482	1944	42	4			
8.00	1.929	1940	46	4	0.108	0.480	
10.00	2.357	1936	50	4			
12.00	2.762	1933	53	4			
14.00	3.240	1928	58	7			
14.50	3.379	1925	61	8			
15.00	3.523	1919	67	10			
15.50	3.668	1914	72	12			
16.00	3.908	1905	81	13			
16.50	4.147	1896	90	15	0.026	0.065	
17.00	4.387	1887	99	17			
17.50	4.627	1877	109	18			
18.00	4.821	1870	116	20			
18.50	5.014	1863	123	21			
19.00	5.208	1855	131	23			

Diatom analysis and pH reconstruction

A summary diatom diagram is shown in Figure 5. The diatom profile is remarkably uniform with no major changes in species abundance over the time period represented by the profile. The assemblage is dominated by the circumneutral species *Achnanthes minutissima*, *Fragilaria virescens* v. *exigua* and *Brachysira vitrea*; the alkaliphilous *Fragilaria vaucheriae* is also present at abundances >5%, as are a number of acidophilous species (eg. *Eunotia incisa* and *Frustulia rhomboides* v. *saxonica*).

pH was reconstructed using both the multiple regression and weighted averaging methods (Figure 5). The results of both reconstructions suggest that pH in the loch has been >6.0 throughout the time period represented by the core. pH appears to have been stable and there is no evidence of any recent acidification at this site. The surface sediment has a reconstructed pH of 6.5 (multiple regression) and 6.1 (weighted averaging) which is in good agreement with the current mean measured pH (6.47).

Diatom concentration results (Figure 6) show a period of relatively low concentration between 50-20 cm which is probably due to dilution by inwashed material. Concentrations subsequently rise to the top of the core.

Pollen analysis

A summary pollen diagram is shown in Figure 7. The pollen assemblage is dominated by peatland indicator taxa; in particular *Calluna vulgaris*, with Cyperaceae, *Sphagnum* and *Potentilla* also being important. Tree pollen is low, and is dominated by *Pinus*, which probably has a substantial long distance component. *Isoetes* spores are only present at a low abundance from 40-30 cm, this corresponds with diatom and lithostratigraphic evidence for an inwash event and it is likely that the inwash caused a decrease in transparency leading to a decrease in *Isoetes*. Similar events have been described elsewhere in the British Isles (Stevenson *et al.* 1990).

Carbonaceous particle analysis

Low concentration of particles was found in the sediments dating from the late-nineteenth and early-twentieth centuries (Figure 8). The concentration then starts to rise in the mid-1940s and reaches a peak at the top of the core. Overall, the profile has extremely low concentrations of particles compared to other sites situated in areas of high atmospheric deposition, although the timing and pattern of contamination is very similar.

Sediment chemistry

Dry weight (Figure 3) and major cation concentrations (Figure 9) in the sediment vary and indicate changes in the constitution of the sedimentary material, a conclusion supported by the changing sediment accumulation rates (Table 4).

These changes in sediment constitution and accumulation rate make establishing any contamination by trace metal more difficult. The trace metal results do show that the lead and zinc concentrations increase above 20 cm depth (Figure 10). However, a closer evaluation of the results reveals that the results do not support the conclusion that there is contamination by these metals. The nickel-depth profile is generally similar to those of sodium and magnesium and Figure 11 shows that there are no departures in the upper part of the core from the trace metal-sodium and trace metal-dry weight relationships established lower down. Further, the increases in lead and zinc concentration in the upper part of the core are not large compared to those observed in cores where contamination has been established.

This analysis suggests that the variation in trace metal concentration observed is due to changes in sediment constitution, possibly sediment particle size. As it is commonly found that trace metal concentrations increase as particle size decreases, the increase in lead and zinc concentration above 20 cm is probably due to a lowering of sediment particle size (lower dry weights) as a result of decreasing sediment accumulation rate.

Figure 2 L. Coire nan Arr: bathymetry (contour intervals in metres)

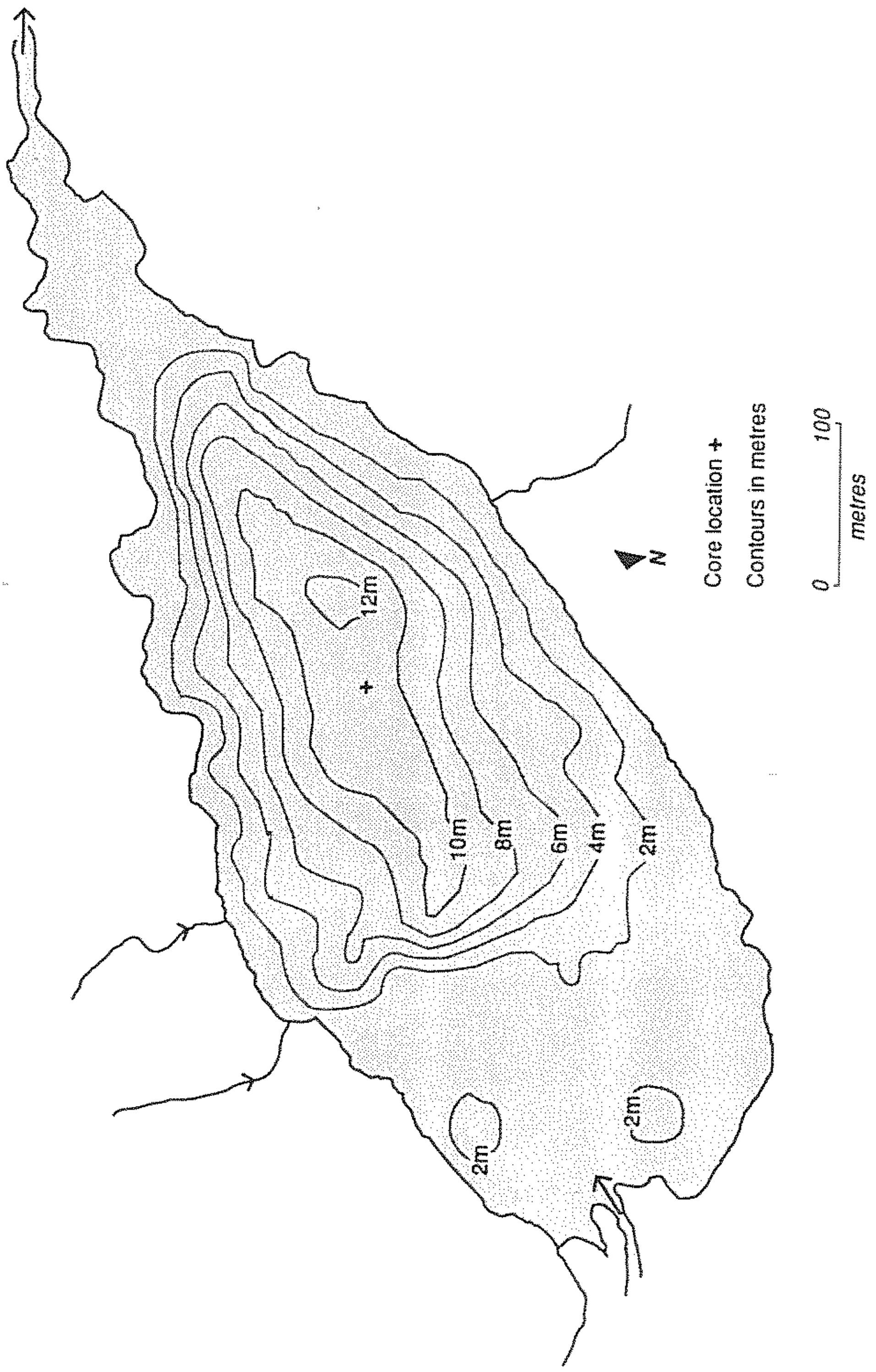


Figure 3 L. Coire nan Arr: lithostratigraphy

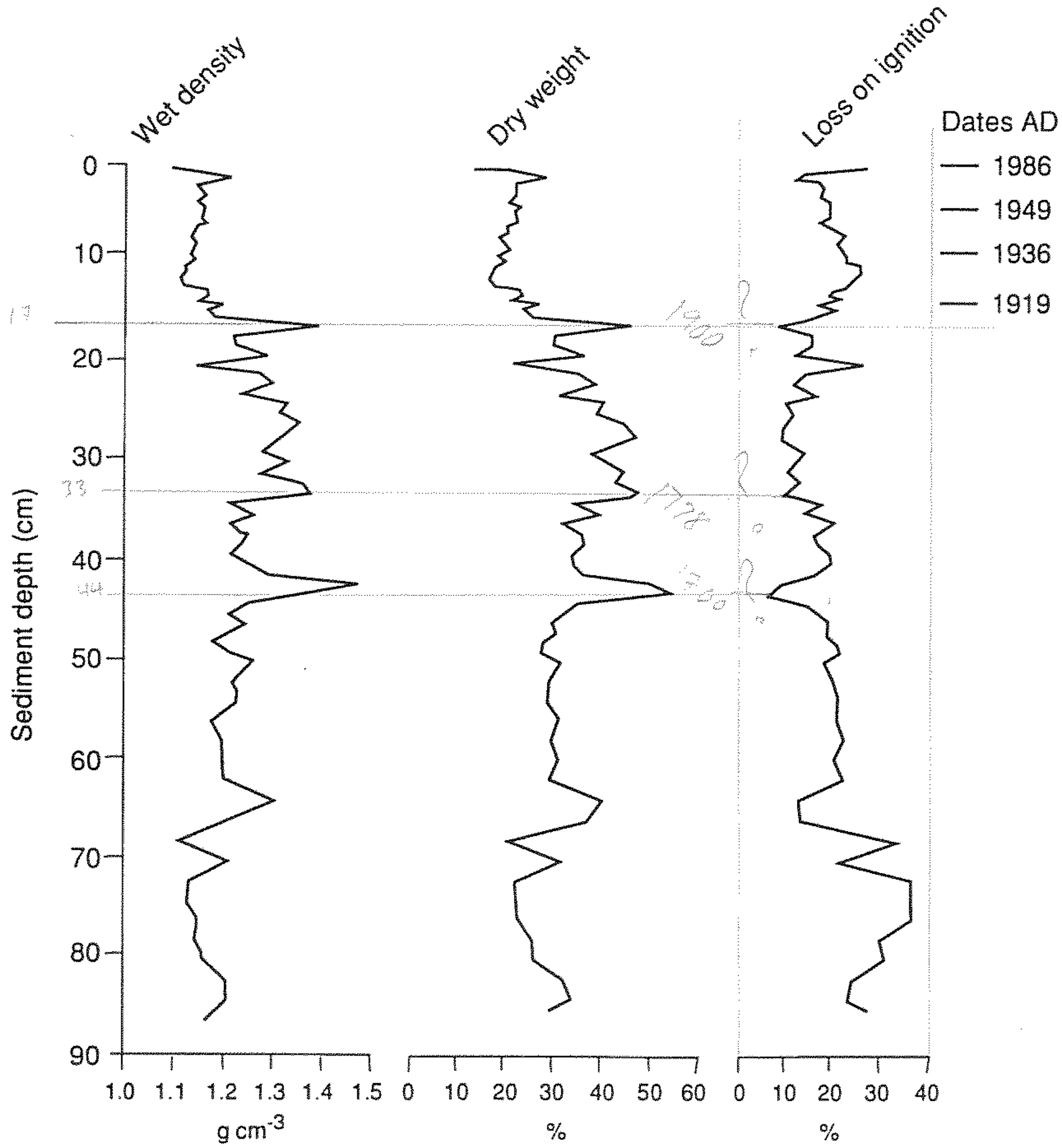


Figure 4 L. Coire nan Arr: ^{210}Pb Chronology

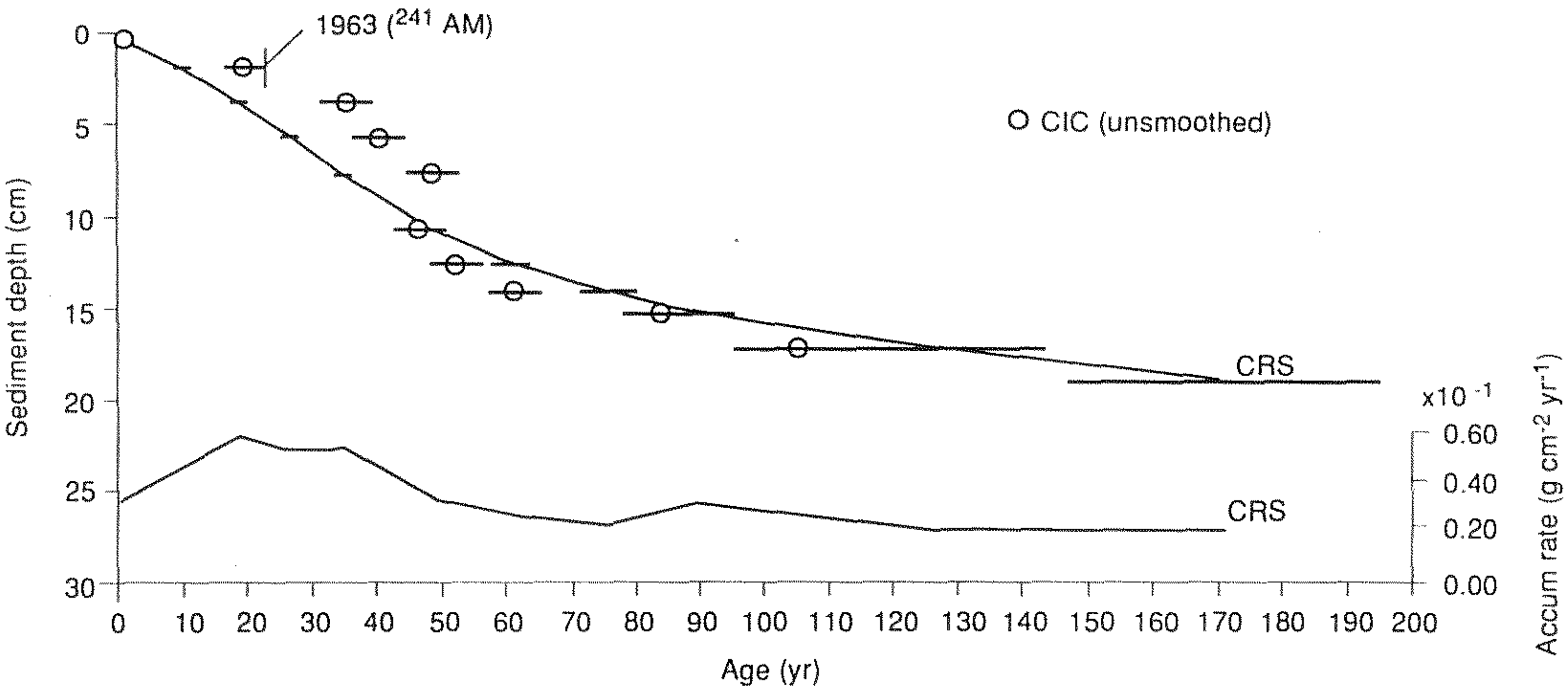


Figure 5 **L. Coire nan Arr: diatom summary diagram and pH reconstruction (WA = weighted averaging, MR = multiple regression)**

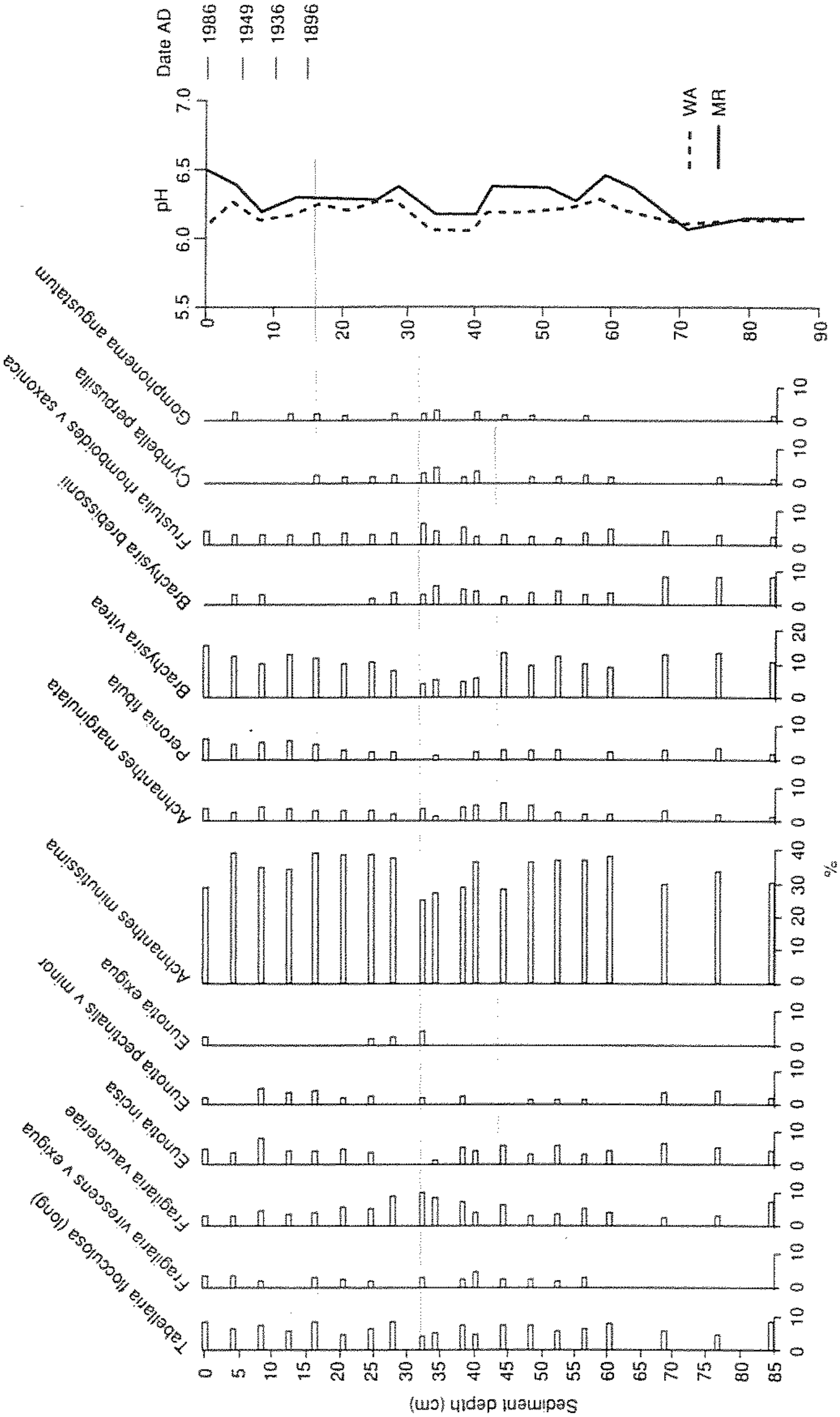


Figure 6 L. Coire nan Arr: diatom concentration (x 10^7 g^{-1}), showing 95% confidence limits

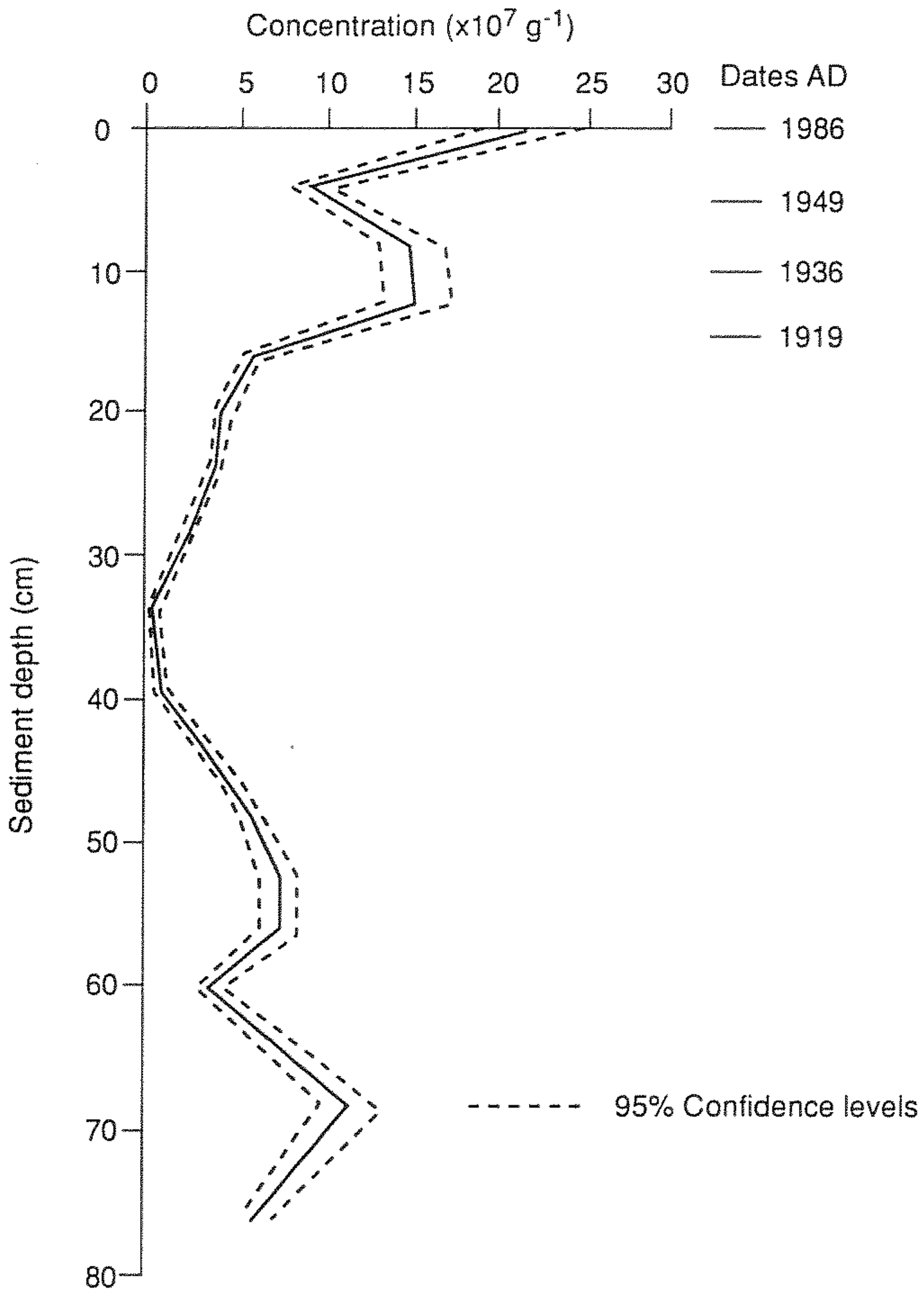


Figure 7 L. Coire nan Arr: summary pollen diagram

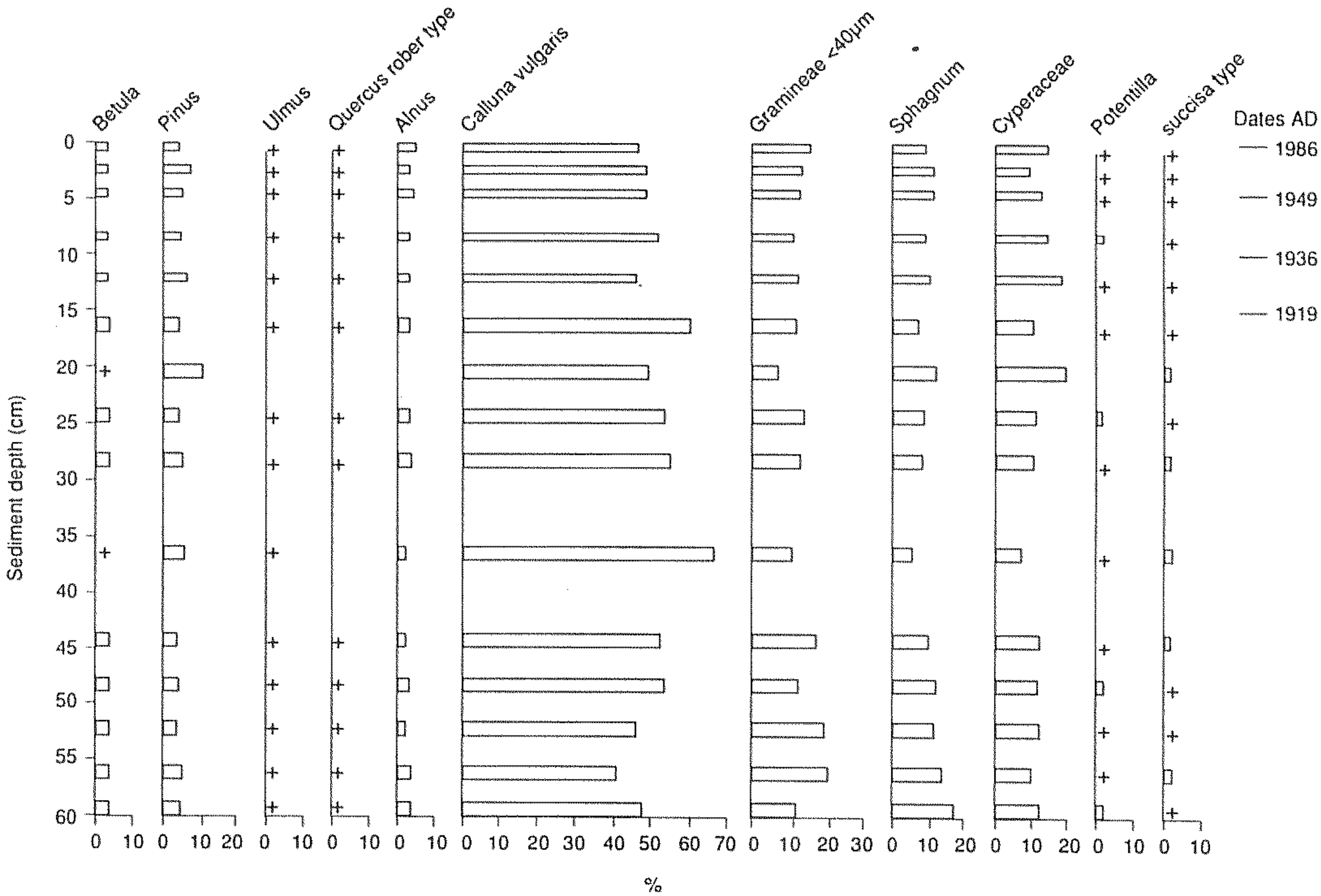


Figure 8 L. Coire nan Arr: carbonaceous particle profile (x 10^3 gDM^{-1})

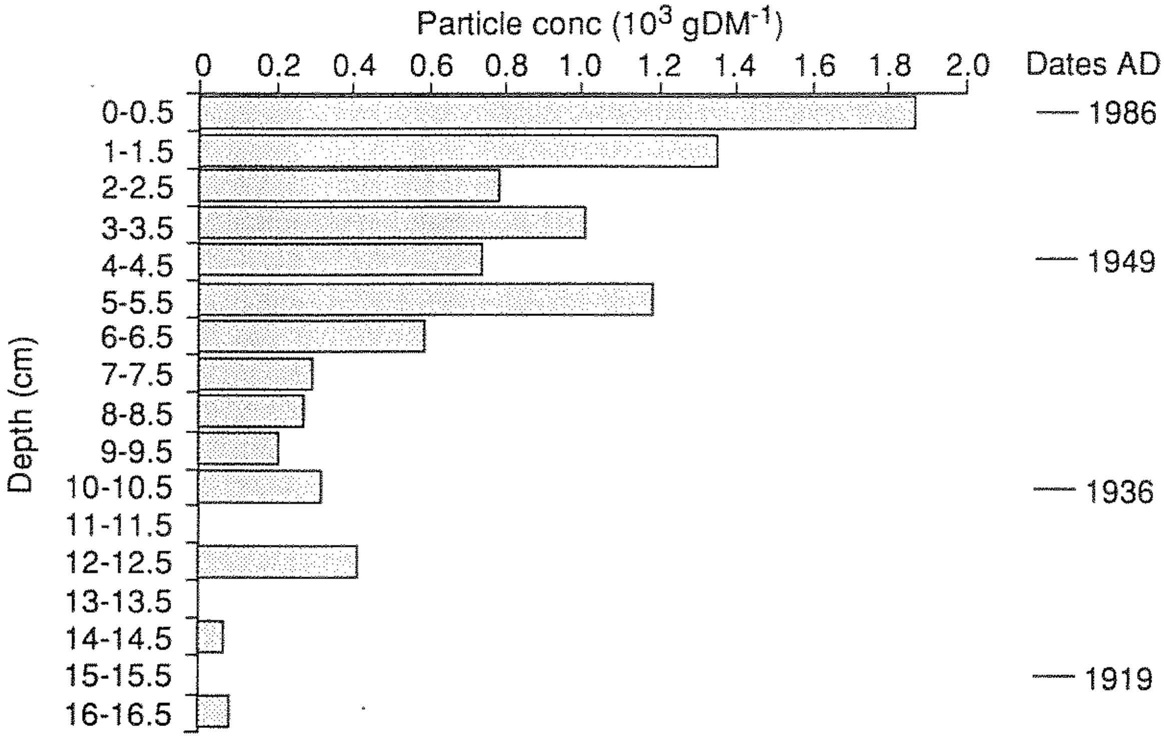


Figure 9 L. Coire nan Arr: the variation of major ion concentrations with sediment depth

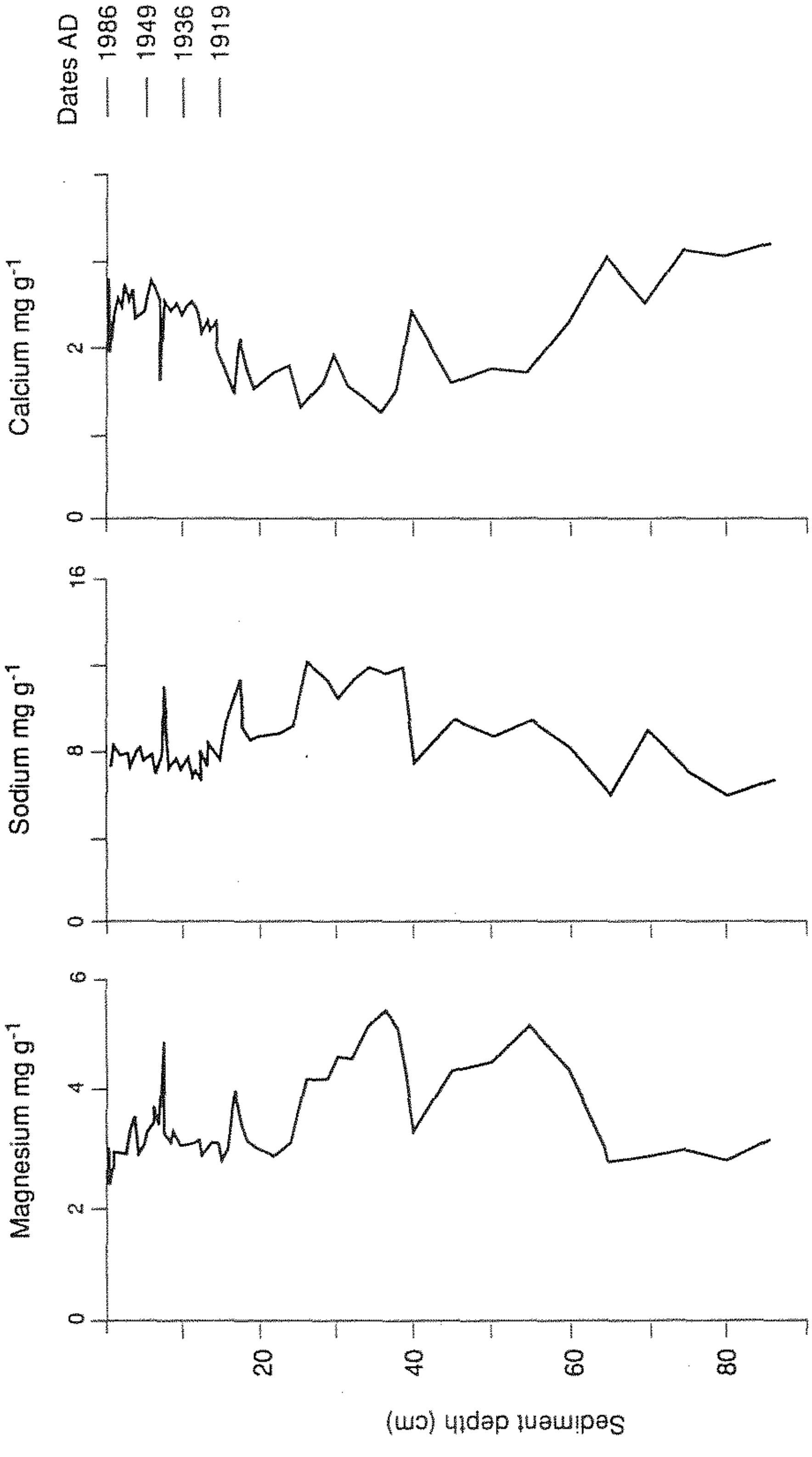


Figure 10 **L. Coire nan Arr: the variation of trace metal concentrations with sediment depth**

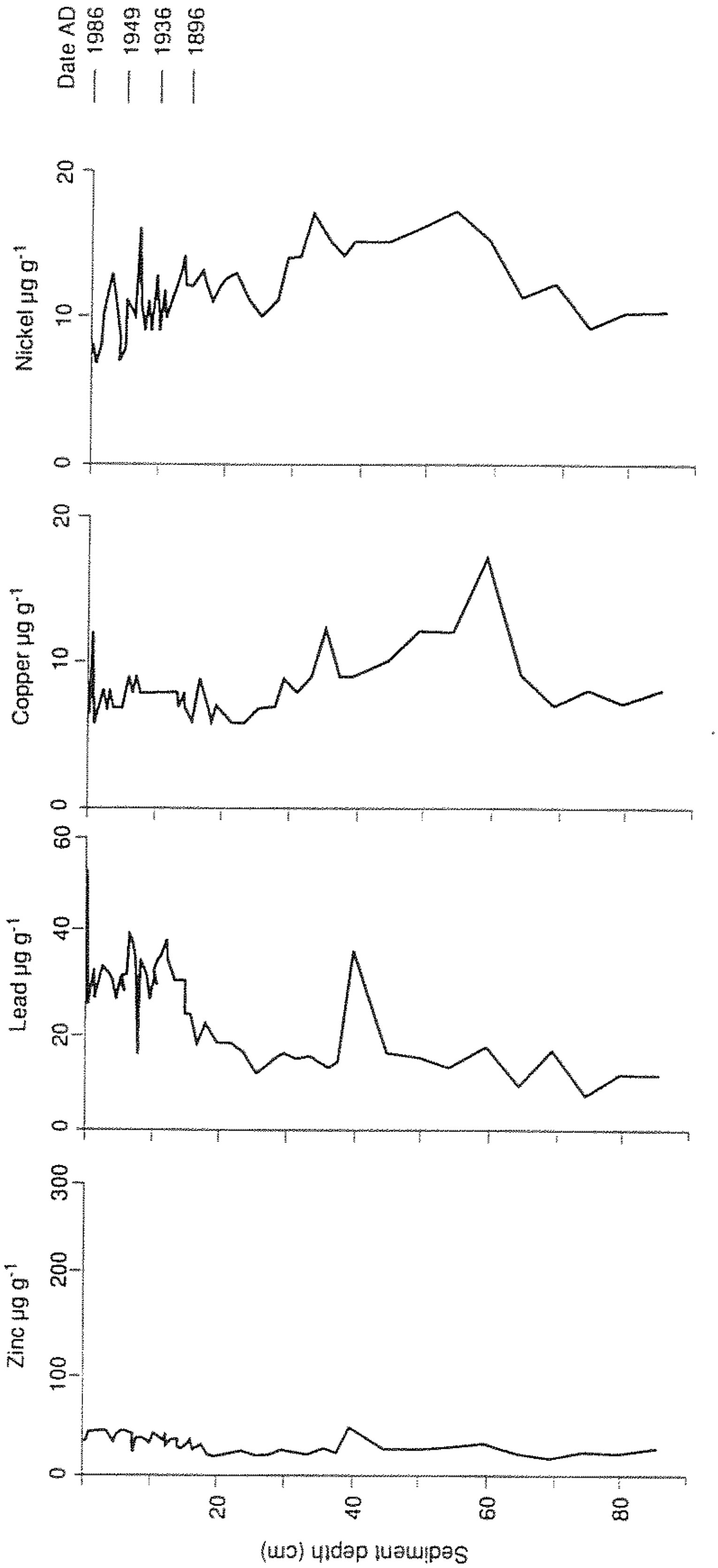
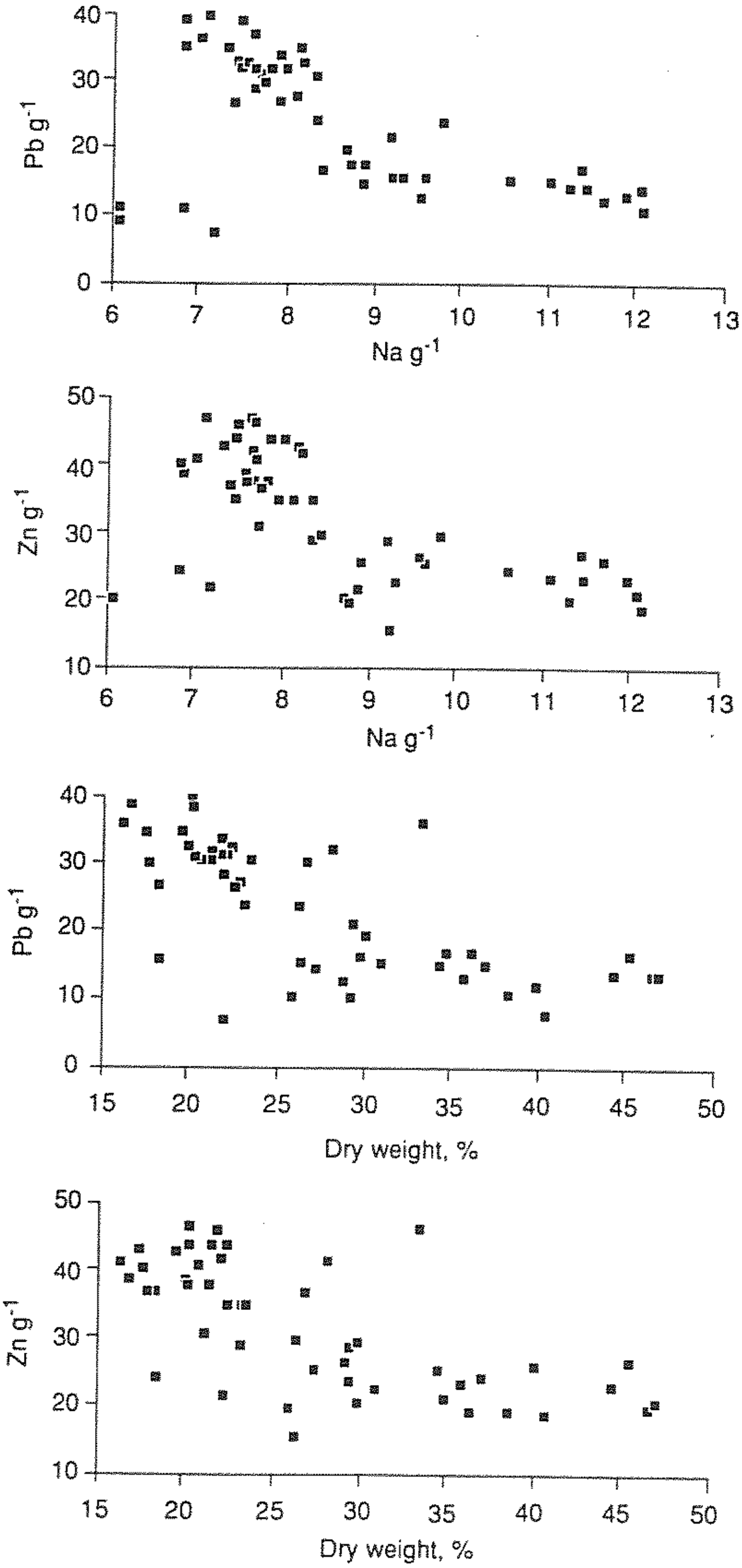


Figure 11 L. Coire nan Arr: the relationships between lead and sodium, zinc and sodium, lead and dry weight and zinc and dry weight in the sediments



2.2 Loch Uisge

Lithostratigraphy

Loch Uisge has higher %LOI values (Figure 12) than those observed at Loch Coire nan Arr (Figure 3). At the bottom of the profile %LOI values fluctuate at around 50%. There is a sharp drop in %LOI above 37 cm which is accompanied by a peak in both the wet density and dry weight. This probably represents a period of catchment erosion leading to the inwash of mineral material. The sediment between 31-36 cm was dark greyish brown, whilst that above and below this level was either black or dark brown in colour. Above 32 cm %LOI values rise to over 30% and fluctuate between about 30-40% to the top of the profile.

Dating

Sediment samples from core UIS1 were analysed for ^{210}Pb, ^{226}Ra, ^{137}Cs and ^{241}Am by gamma spectrometry. The ^{210}Pb and ^{226}Ra results are given in Table 5 and the ^{137}Cs and ^{241}Am results are given in Table 6, the isotope ^{134}Cs, indicative of Chernobyl fallout was not detected.

Dates calculated using the CRS and CIC ^{210}Pb dating models (Appleby and Oldfield 1978) are shown in Figure 13. The non-monotonic variation in unsupported ^{210}Pb between 2.75 and 8.75 cm (Table 5) is interpreted by the CRS model as an episode of accelerated sedimentation and is dated to the period 1950-1970. The sediments associated with this event have a higher bulk density, but the minerogenic radioisotopes do not indicate any significant change in the mineral character. Since non-monotonic features in the ^{210}Pb profile are indicative of the CRS model, this has been used to calculate dates in the upper part of the core. Sediments below 18 cm appear to be in radioactive equilibrium, but it is difficult to be certain whether the fairly abrupt decline in unsupported ^{210}Pb between 14.5 and 18.5 cm represents the passage of a significant period of time, or was the result of an earlier inwash episode. For this reason the use of the CRS model to calculate dates in the lower part of the core was considered inadvisable and dates below 8 cm have been based on calculations which make use of both dating models (Table 7).

The record of artificial radionuclides in this core is of little chronological value. The maximum ^{137}Cs activity occurs in the surficial sediments, and the absence of ^{134}Cs shows that this is not attributable to Chernobyl fallout. There is a small peak in ^{241}Am activity at the 2.75 cm level, but since the date of maximum fallout from nuclear weapons testing is coincident with the inwash event, this feature can not be regarded as a reliable indicator of the 1963 level.

The sediment density data points to an earlier inwash event at 30-35 cm. The present extrapolated chronology points to a mid-eighteenth century date for this feature.

Table 5 Loch Uisge: ^{210}Pb and ^{226}Ra data

Depth	Dry mass	^{210}Pb Conc.				^{226}Ra Conc.	
		Total		Unsupp.			
cm	g cm^{-2}	pCi g^{-1}	±	pCi g^{-1}	±	pCi g^{-1}	±
0.25	0.034	16.85	0.68	12.62	0.74	4.23	0.30
2.75	0.410	13.16	0.73	9.96	0.78	3.20	0.28
4.75	0.774	6.49	0.75	3.57	0.78	2.92	0.21
6.75	1.206	6.89	0.69	4.16	0.72	2.73	0.21
8.75	1.557	8.01	0.53	4.73	0.57	3.28	0.21
11.50	1.978	5.74	0.64	2.75	0.67	2.99	0.19
14.50	2.484	4.91	0.39	1.86	0.43	3.05	0.17
18.50	3.130	2.68	0.49	-0.96	0.55	3.64	0.25
22.50	3.900	3.37	0.41	0.19	0.44	3.18	0.17
45.50	9.067	2.41	0.38	-0.07	0.42	2.48	0.17

Table 6 Loch Uisge: ^{137}Cs and ^{241}Am data

Depth	^{137}Cs Conc.		^{214}Am Conc.	
cm	pCi g^{-1}	±	pCi g^{-1}	±
0.25	21.84	0.31	0.08	0.03
2.75	16.92	0.31	0.12	0.04
4.75	6.63	0.19	0.00	0.00
6.75	2.59	0.15	0.00	0.00
8.75	2.79	0.13	0.00	0.00
11.50	1.31	0.11	0.00	0.00
14.50	0.76	0.07	0.00	0.00
18.50	0.16	0.11	0.00	0.00
22.50	0.02	0.07	0.00	0.00
45.50	0.00	0.00	0.00	0.00

Table 7 Loch Uisge: ^{210}Pb chronology

Depth	Cum. dry mass	Date	Chronology Age		Sedimentation rate		
cm	g cm^{-2}	AD	yr	±	g cm^{-2}yr^{-1}	cm yr^{-1}	± (%)
0.00	0.000	1986	0				
0.50	0.071	1984	2	2	0.031	0.205	8.1
1.00	0.147	1981	5	2	0.030	0.195	8.6
1.50	0.222	1978	8	2	0.029	0.185	9.2
2.00	0.297	1976	10	2	0.028	0.175	9.7
2.50	0.373	1973	13	2	0.027	0.166	10.2
3.00	0.456	1971	15	2	0.030	0.174	11.8
3.50	0.547	1968	18	2	0.037	0.202	14.6
4.00	0.638	1966	20	2	0.043	0.230	17.5
4.50	0.729	1963	23	2	0.050	0.256	20.3
5.00	0.829	1960	26	3	0.051	0.257	21.4
5.50	0.936	1958	28	3	0.046	0.233	20.7
6.00	1.044	1955	31	3	0.041	0.208	20.1
6.50	1.152	1953	33	3	0.036	0.184	19.4
7.00	1.250	1950	36	4	0.032	0.165	19.1
7.50	1.337	1946	40	4	0.028	0.152	19.0
8.00	1.425	1943	43	4	0.025	0.138	19.0
8.50	1.513	1940	46	5	0.021	0.125	19.0
9.00	1.595	1936	50	5			
9.50	1.672	1932	54	6			
10.00	1.748	1929	57	7			
10.50	1.825	1925	61	9			
11.00	1.901	1922	64	10			
11.50	1.978	1918	68	13	0.021	0.131	
12.00	2.062	1914	72	14			
12.50	2.147	1910	76	14			
13.00	2.231	1906	80	16			
13.50	2.315	1902	84	18			
14.00	2.394	1898	88	20			
14.50	2.484	1896	92	24			

Diatom analysis and pH reconstruction

A summary diatom diagram is shown in Figure 14. Like Loch Coire nan Arr (Figure 5) the diatom profile is remarkably stable, with no major shifts in the dominance of species. Throughout the core the circumneutral species *Achnanthes minutissima* is dominant with abundances of around 30%. Other circumneutral taxa such as *Brachysira vitrea*, *Cymbella lunata*, *Cyclotella stelligera* and *Tabellaria flocculosa* are also common. *Cyclotella stelligera* is the only true planktonic form at this site and it is interesting that the abundance of this species falls above 35 cm, where there is lithostratigraphic evidence for an inwash event. It is possible that changes in water transparency associated with the inwash caused the decline of this species. Similar changes with other planktonic *Cyclotella* species have been observed elsewhere (Jones *et al.* 1989).

pH was reconstructed using the weighted averaging method (Figure 14). The reconstructed pH is very stable at pH >6 throughout the profile, with no evidence of recent acidification; in the last 150 years the pH has varied from 6.2 to 6.4. The reconstructed pH at the sediment surface is 6.2 which compares well with the mean measured current pH of the loch of 6.4. Reconstruction by multiple regression shows a very similar pH trend (Figure 14).

The diatom concentrations (Figure 15) are relatively stable at this site but there is some evidence of dilution associated with the inwash event between 30-35 cm.

Pollen analysis

A summary pollen diagram is shown in Figure 16. The pollen assemblage is dominated by peatland indicator species particularly *Calluna vulgaris*, *Sphagnum*, Cyperaceae and *Potentilla*. Levels of tree pollen, especially *Betula* and *Alnus* are relatively high at this site. The ratio of *Calluna* to Gramineae pollen is relatively constant over the entire core suggesting that there has not been a major shift in the dominance of these two species.

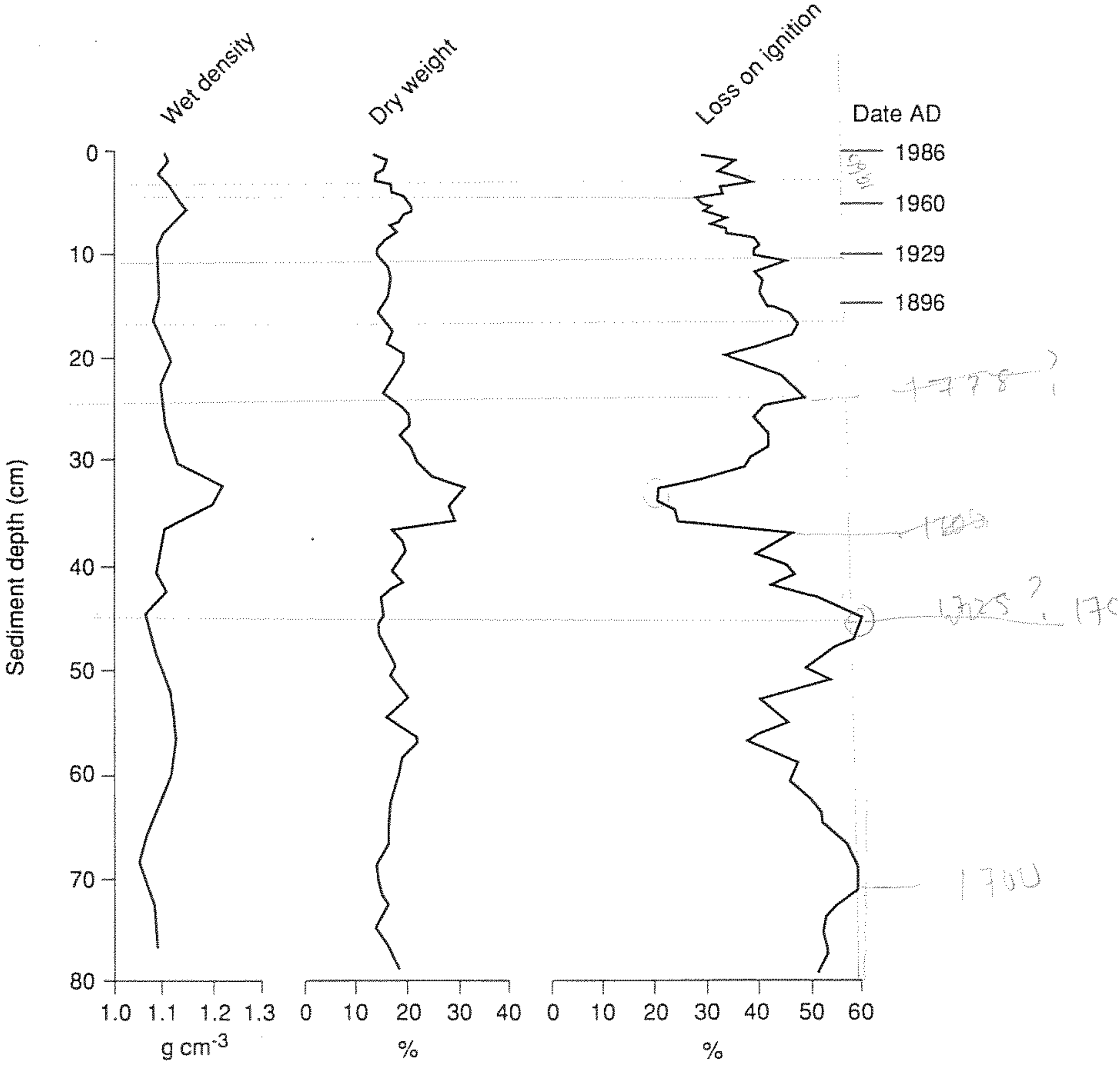
Carbonaceous particle analysis

Figure 17 shows an increase in carbonaceous particles, indicative of atmospheric contamination, from the late-nineteenth century (c. 1870) onwards, followed by a further increase at about 1940 and reaching a peak in the mid-1970s. The pattern and timing of these results is typical of other sites in the British Isles.

Sediment chemistry

The major cation concentrations in Loch Uisge generally increase up the core and indicate a non-stable sedimentation regime (Figure 18). Within the trace metal group, the nickel-depth profile is similar to that of the cations. Lead and zinc concentrations, on the other hand, increase in the upper part of the core, especially above 30 cm depth (Figure 19). Figure 20 shows that this increase is not due to changes in sediment constitution, but probably due to contamination. This depth is before the dated part of the core, but certainly corresponds to (the first half) of last century. In the case of this remote lake, the contamination is from material deposited from the atmosphere.

Figure 12 L. Uisge: lithostratigraphy



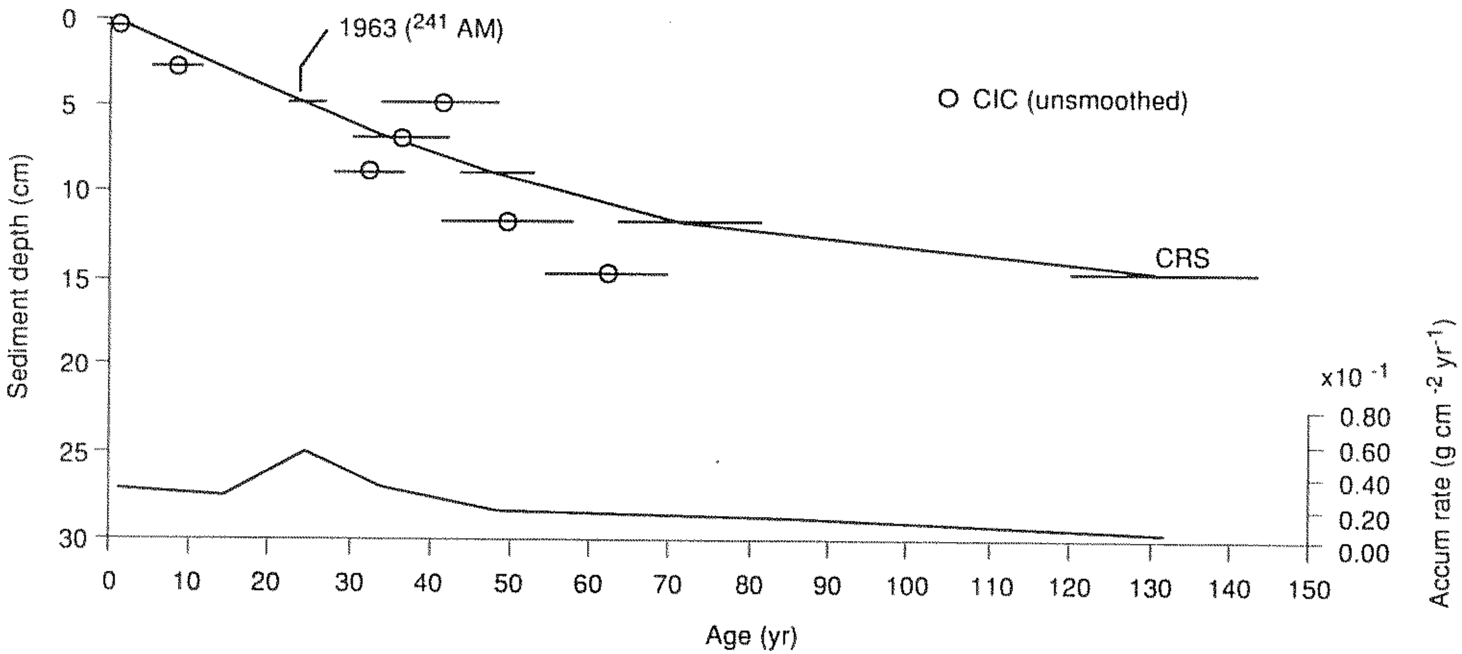


Figure 13 L. Uisge: ^{210}Pb chronology

Figure 14 **L. Uisge: diatom summary diagram and pH reconstruction (WA = weighted averaging, MR = multiple regression)**

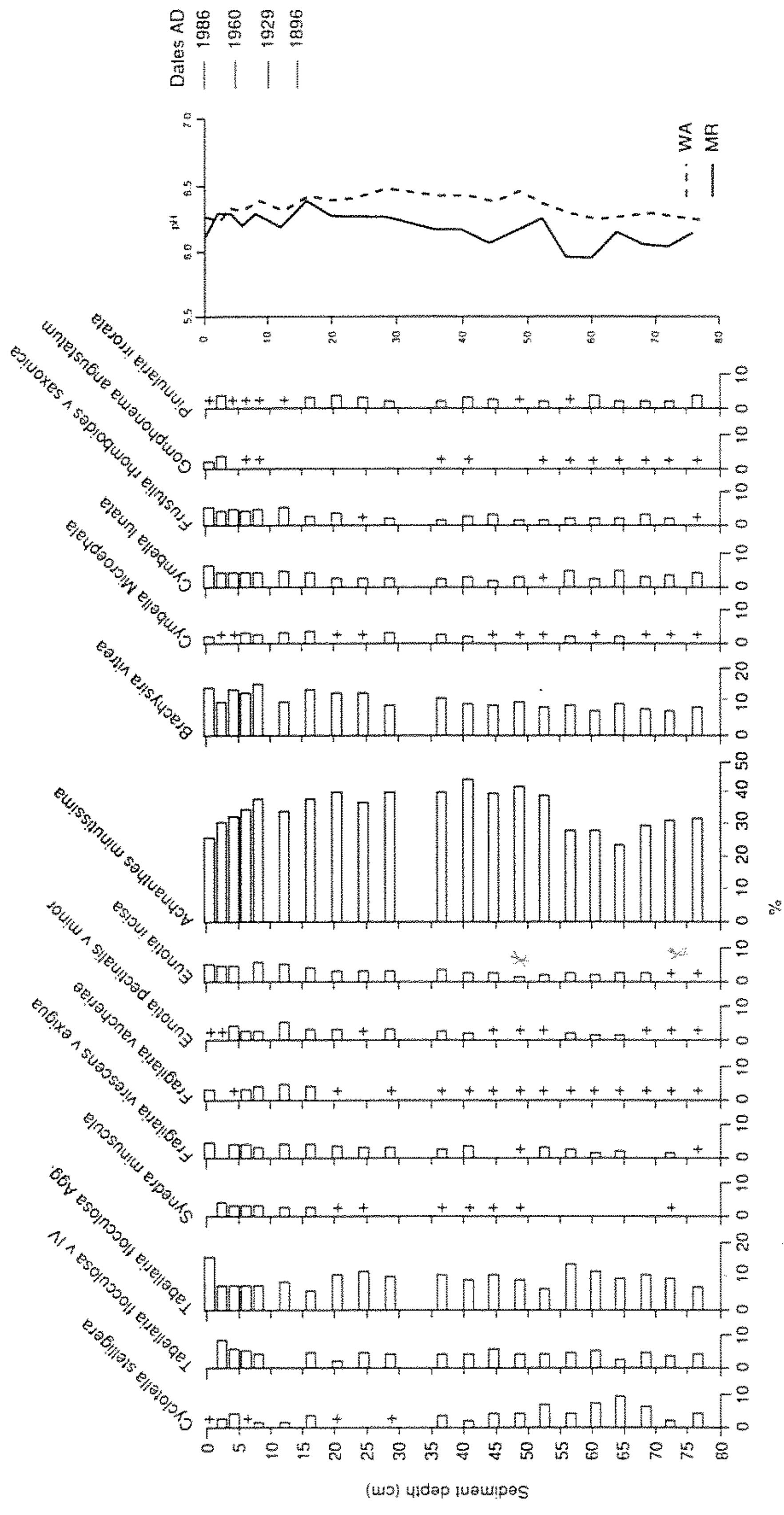


Figure 15 L. Uisge: diatom concentration (x 10^7 g^{-1}), showing 95% confidence limits

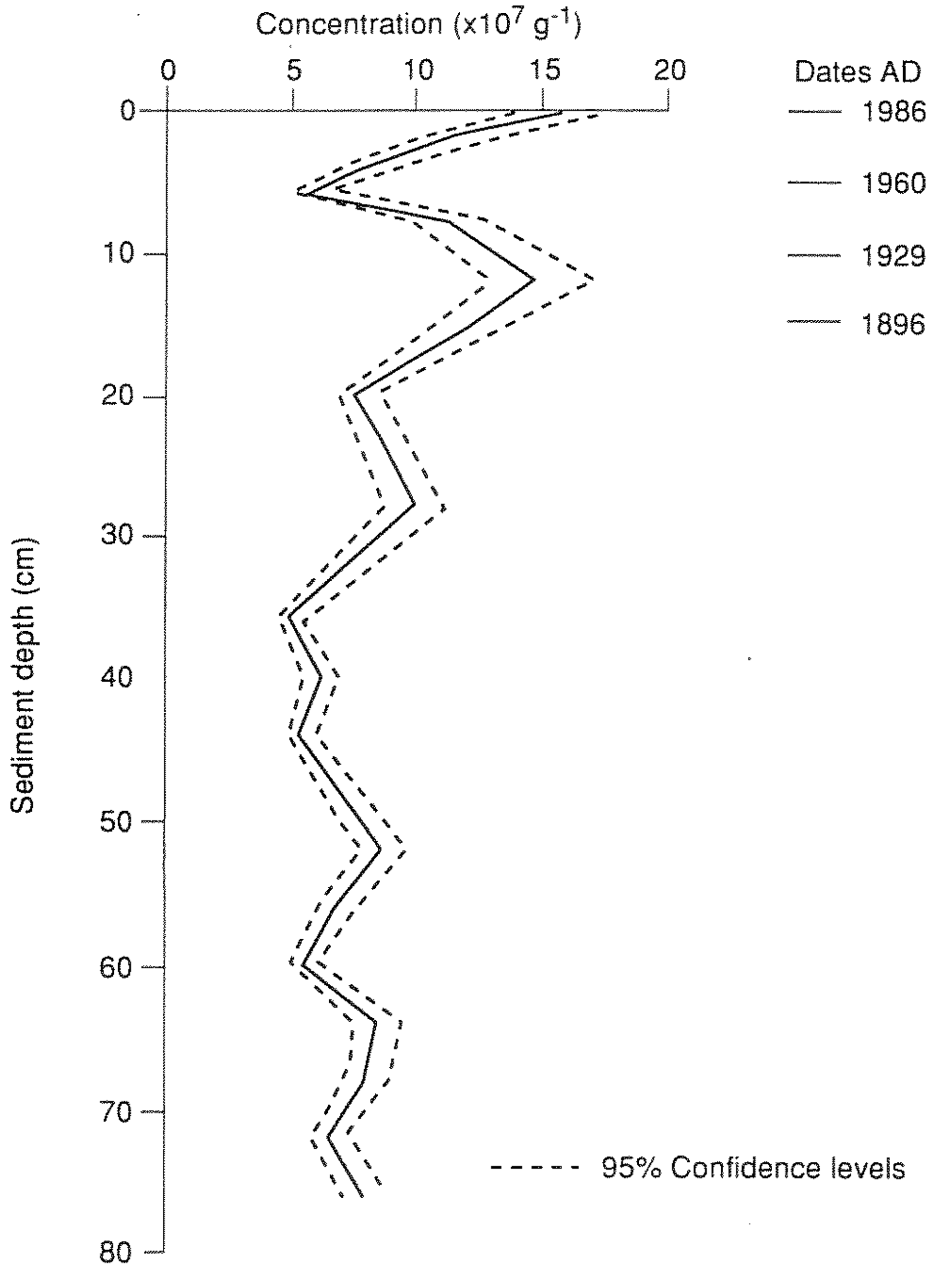


Figure 16 L. Uisge: pollen summary diagram

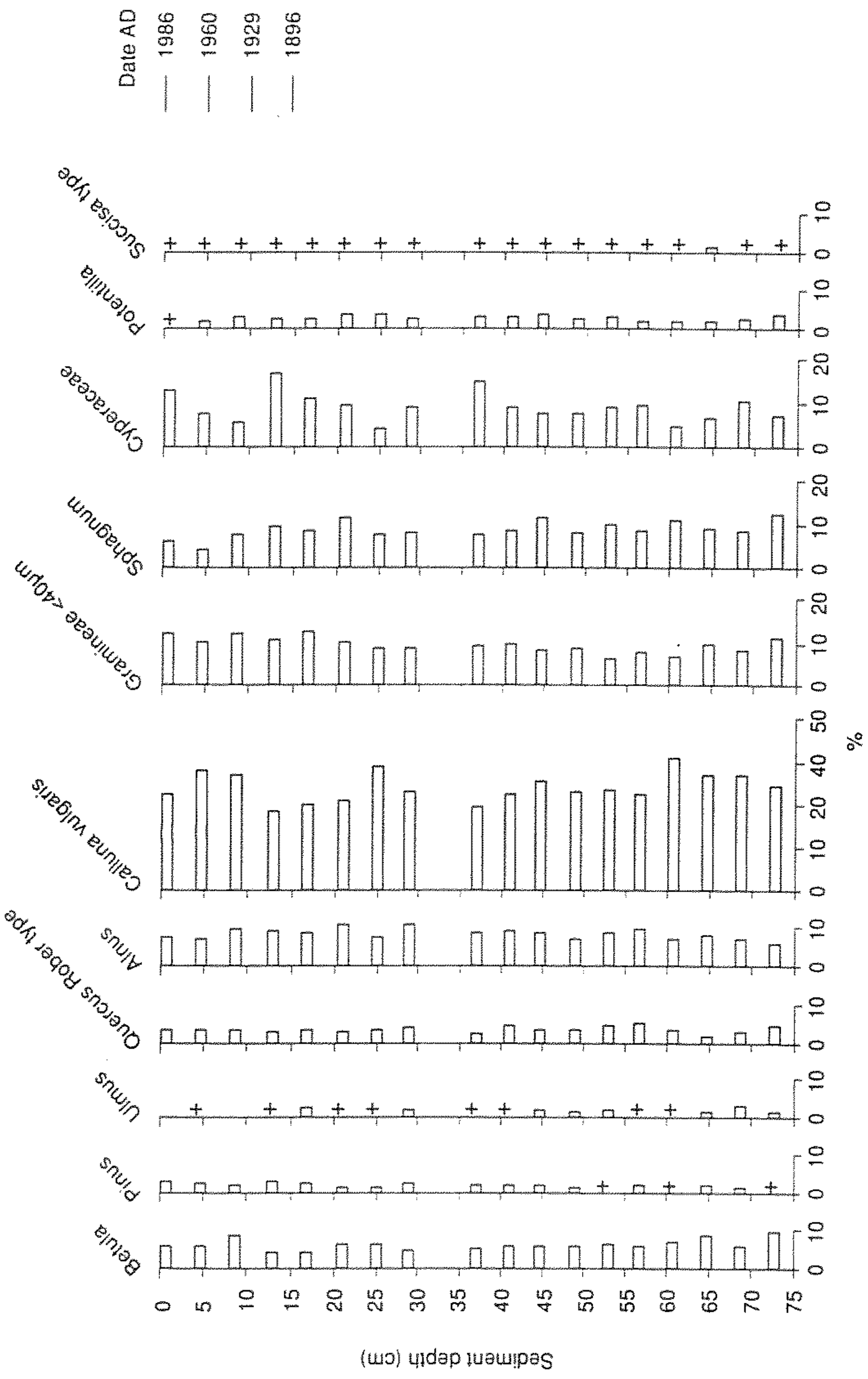


Figure 17 **L. Uisge: carbonaceous particle profile**

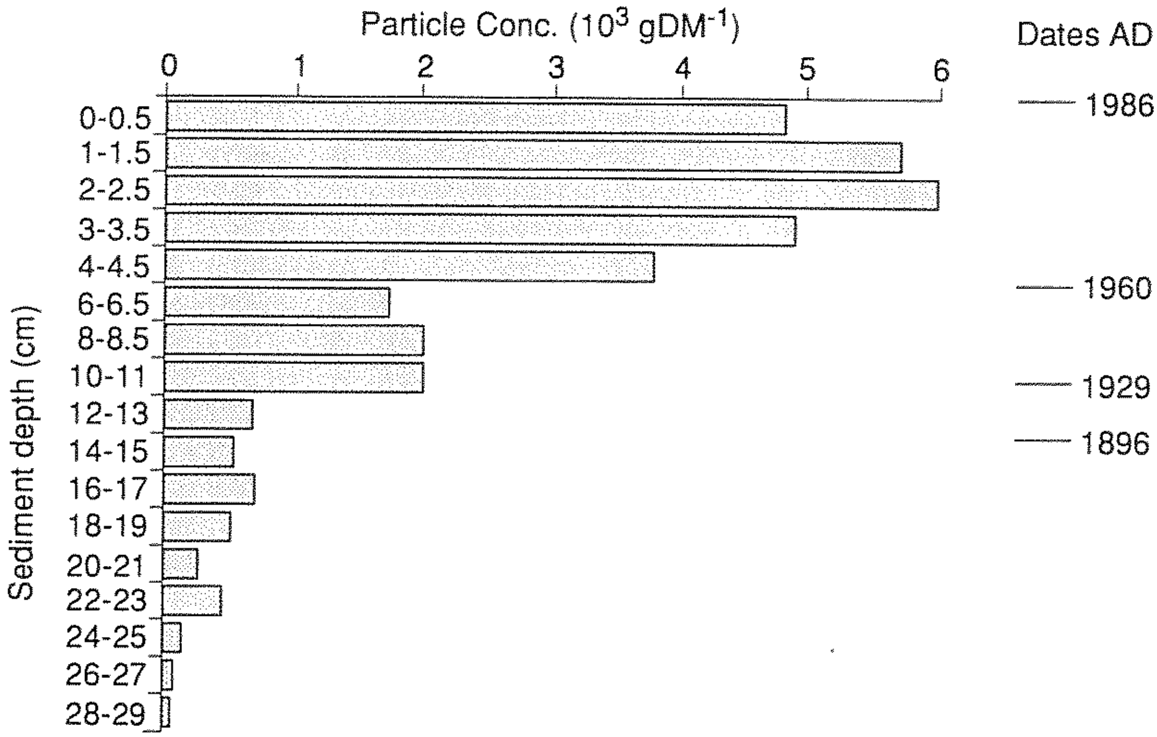


Figure 18 **L. Uisge: the variation of major ion concentrations with sediment depth**

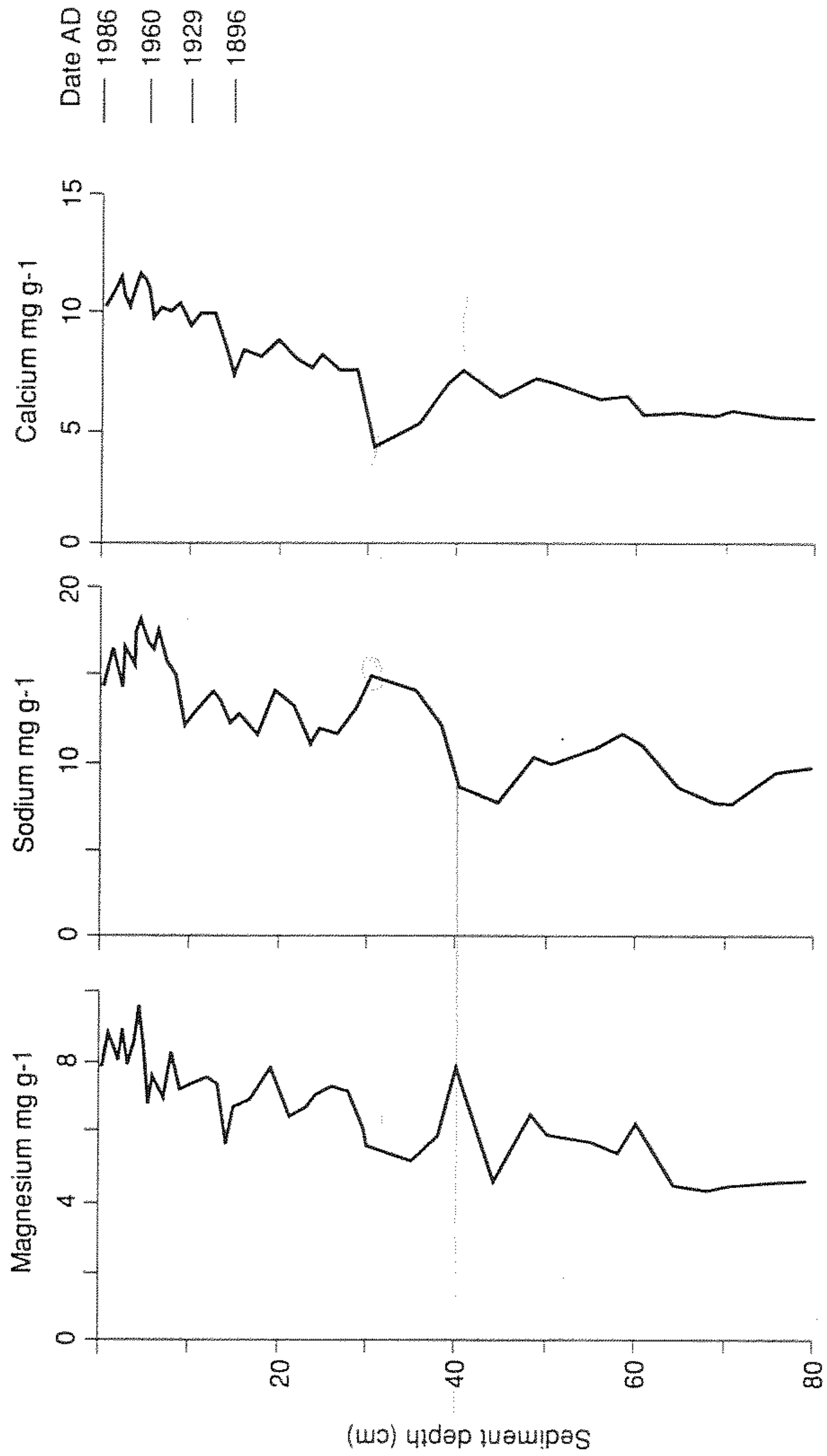


Figure 19 L. Uisge: the variation of trace metal concentrations with sediment depth

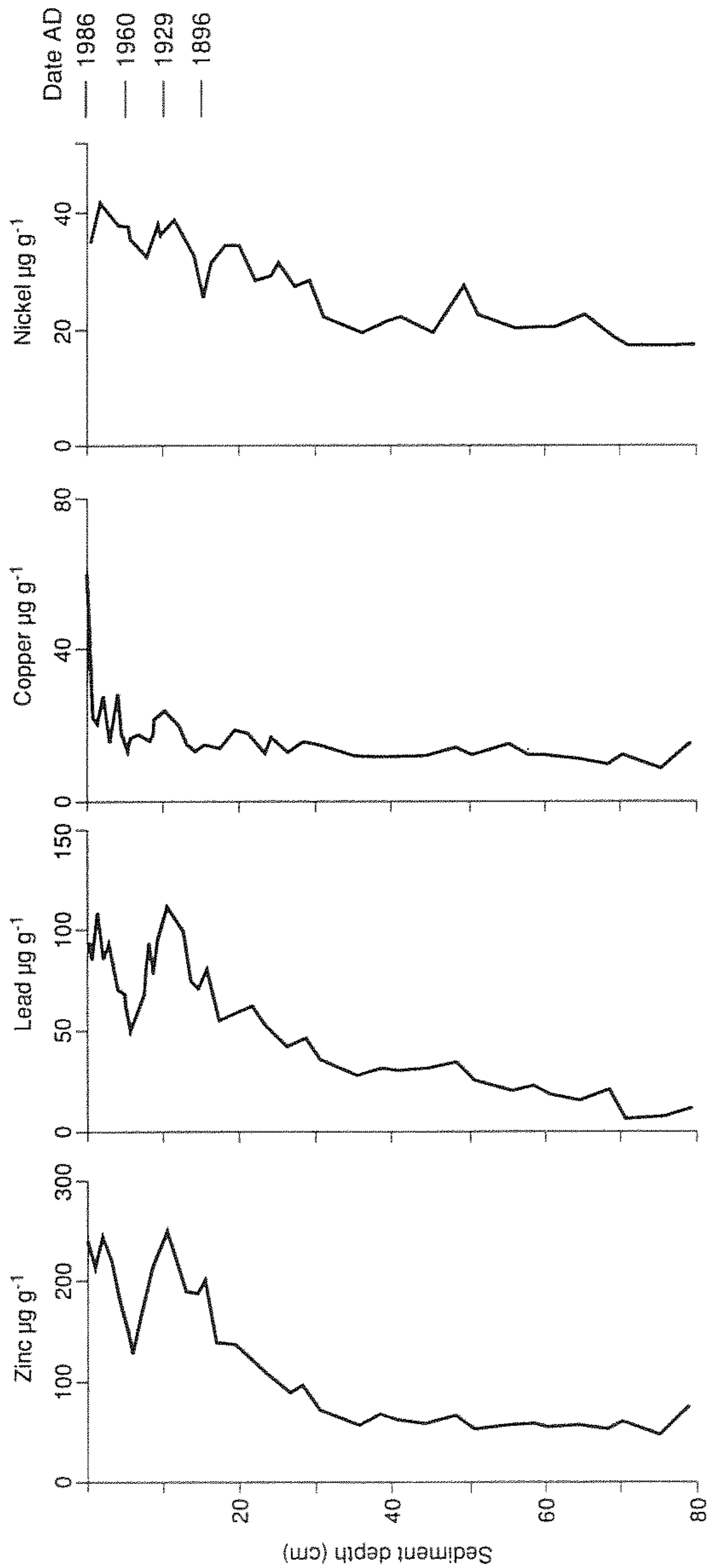
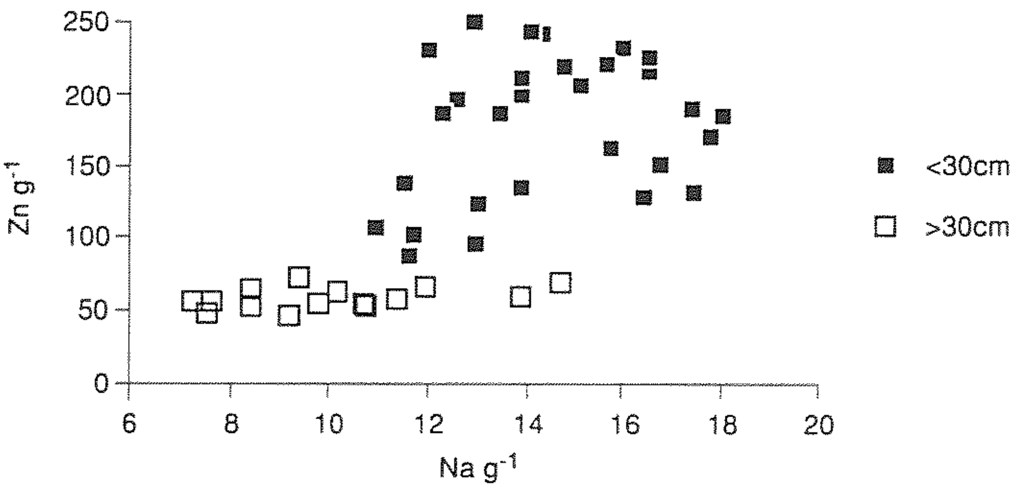
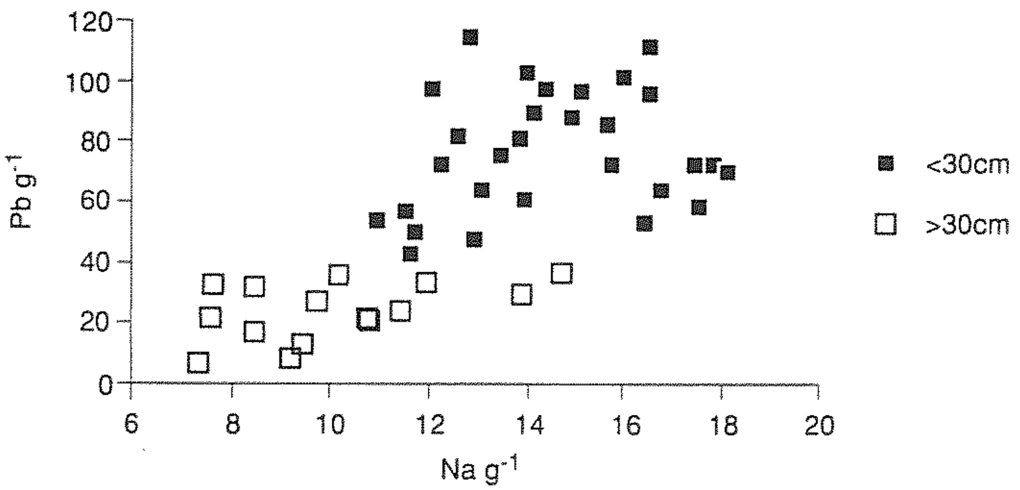


Figure 20 L. Uisge: the relationships between zinc and sodium and lead and sodium in the sediments





2.3 Loch Teanga

Loch Teanga lies in a coastal location on the Island of South Uist in the Outer Hebrides (Figure 1). Consequently it is exposed to strong marine influences, but measured atmospheric pollution in the area is low. Precipitation data for the locality is available from Gisla, a site on the Island of Lewis some 70 km north of the lake (Table 8) and show that the mean pH is around 4.8 and that sea salts (Na and Cl) are present in relatively high concentrations. Modelled annual deposited S for the 20 km grid square containing Loch Teanga is 0.38 g S m^{-2} yr^{-1} (R.G. Derwent pers. comm.) and compares well with measured values of 0.32 and 0.39 g S m^{-2} yr^{-1} at Gisla in 1987 and 1988 respectively.

Table 8 Precipitation weighted annual means values for Gisla, 1987-88. [Concentration values are all as μeq l^{-1}; sulphate refers to non-marine S; source - Warren Spring Laboratory]

	Rain (mm)	H^+	SO_{42-}	Na^+	Mg^{2+}	Ca^{2+}	Cl^-
1988	1318.0	15.0	16.0	237.0	55.0	13.0	289.0
1987	1206.0	17.0	17.5	229.0	54.0	14.0	274.0

The lake is located at 25 m altitude and its catchment lies on resistant metamorphic rocks (Lewisian gneiss) which possess little acid neutralizing capacity. The catchment is relatively small, of low relief, and has no significant drainage streams. Blanket peat is abundant within the catchment and the dominant vegetation type is *Calluna* heath which is extensively burnt for sheep grazing. The lake is oligotrophic, mildly acid and relatively deep with a maximum depth of 20 m (Figure 21 - Flower and Nicholson 1986). The water chemistry of this loch is not well known but two samples were collected for analysis in 1983 and 1987 (Table 9).

Table 9 Water chemistry data for Loch Teanga, 1987 and 1983. [Ionic concentrations are in μeq l^{-1}.]

	pH	**Cond. μS cm^{-1}**	**Alkal -inity**	**Ca^{2+}**	**Mg^+**	**Na^{2+}**	**SO_{42-} (tot.)**	**Cl^-**
1987	5.7	163.0	20.0	110.0	255.0	981.0	233.0	1160.0
1983	6.1	93.0	34.0	91.0	166.0	672.0	100.0	861.0

Lake sediment is not deposited symmetrically within the Loch Teanga basin and in the deepest area grey late-glacial clay predominates. The more recent organic sediments were subsequently found deposited mainly on the shallower slopes in the southern portion of the basin. The point finally selected for sediment coring is shown on Figure 21. Coring of this lake was carried out using Livingstone coring apparatus. A full post-glacial sediment sequence of 5.3 m was obtained. Results presented here will refer mainly to the most recent sediment (upper 70 cm).

Loch Teanga possesses steeply shelving rock margins and this combined with the peat stained water suppresses extensive macrophyte growth within the lake. However, in the shallower northern arms of the lake, *Juncus bulbosus* v. *fluitans* is common and elsewhere where gravels or mud extend into the photic zone *Isoetes lacustris* is fairly abundant. Nothing is known about the invertebrate or plankton communities of this lake but local reports that it supports a small population of undersized trout indicates that feeding potential is poor.

Lithostratigraphy

The percentage dry weight curve (Figure 22) shows no abrupt changes although there is a slight but sustained trend towards declining values from the core base to c. 12 cm depth. Furthermore, between 12 and 2 cm values are marginally but consistently higher than in the immediately preceding section. There are also two small and isolated dry weight peaks at 134 and 155 cm depth. These increases are associated with low values for organic content and indicate an accelerated supply of minerogenic material to the lake. Most variation occurs in the LOI profile (Figure 22) which shows a trend towards increasing values from c 30% at 145 cm to about 65% at 20 cm depth; but superimposed on this trend are three major peaks at 80, 46 and 20 cm. Minor peaks also occur at 138 and 110 cm depth. In the top 20 cm of sediment LOI values decline from c. 65% to about 35%, approaching those at the core base. At about 13 cm depth there is a small but distinct increase in sediment dry weight.

Because low values in the LOI profile do not coincide with peaks in dry weight the dominant process determining the LOI profile is considered to be inwash pulses of organic material (corresponding to the LOI peaks) rather than minerogenic inwash pulses causing depressed LOI values. Hence, the LOI profile is probably a record of peat erosion events within the catchment, most likely caused by catchment over-burning in the past. Of these peat erosion pulses the most recent seems to be the most intense and is followed by an increase in mineral soil erosion, as evidenced by the slight dry weight increase in the upper 13 cm of the core.

Dating

The unsupported ^{210}Pb inventory for the core is 11.6 pCi cm^{-2} which represents a constant flux of 0.36 pCi cm^{-2} yr^{-1}. The unsupported ^{210}Pb activity profile is fairly linear (Table 10) and consequently there is little discrepancy between the sets of dates generated by both the CRS and CIC dating models (Appleby and Oldfield 1978). Both models indicate a mean sediment accumulation rate of 0.012 g cm^{-2} yr^{-1} since 1900. Figure 23 shows the dates for the core calculated using both the CRS and CIC models. For the lower depths in the core where uncertainties in the dating parameters become relatively large dates have been calculated using the mean accumulation rate calculated from both models. The lowest dated level in the core is 21.5 cm (1863) from which the accumulation rate declines from 0.19 cm yr^{-1} to 0.139 cm yr^{-1} by 4.5 cm depth (1963); above this level the accumulation rate increases. In terms of dry matter accumulated per year there is relatively little change, the lowest rate occurs at 12 cm which increases to a minor peak at 9.5 cm and a larger peak at 1 cm depth.

Loch Teanga is a region subject to fallout from the Chernobyl accident and the gamma spectra confirmed the presence of high ^{137}Cs in the core top together with significant concentrations of the associated short-lived isotope ^{134}Cs (Table 11). Since the ^{134}Cs : ^{137}Cs ratio in Chernobyl fallout is about 0.6, the component of the ^{137}Cs inventory deriving from this fallout is estimated to be 1.7 pCi cm^{-2}, with the remainder (7.6 pCi cm^{-2}) resulting from weapons testing fallout. The ^{137}Cs profile extends down to 37 cm and offers further evidence of the mobility of this isotope in lake sediment. The ^{134}Cs profile reveals the presence of Chernobyl-derived ^{137}Cs down to at least 2 cm (dated to 1979).

The chronology for this sediment core is shown in Table 12.

Table 10 ***Loch Teanga: ^{210}Pb and ^{226}Ra data***

Depth	Dry mass	^{210}Pb Conc.				^{226}Ra Conc.	
		Total		Unsupp.			
cm	g cm^{-2}	pCi g^{-1}	±	pCi g^{-1}	±	pCi g^{-1}	±
0.25	0.006	34.22	1.94	34.09	2.01	0.13	0.52
0.75	0.026	19.94	2.20	19.15	2.24	0.79	0.44
1.75	0.094	26.05	1.19	25.72	1.23	0.33	0.30
2.75	0.166	19.73	1.65	19.73	1.65	0.00	0.00
4.25	0.273	18.16	1.39	17.76	1.45	0.40	0.43
5.25	0.350	12.65	0.79	12.65	0.79	0.00	0.00
7.25	0.506	8.83	0.57	8.31	0.59	0.52	0.17
9.75	0.698	4.77	0.38	4.58	0.40	0.19	0.11
12.25	0.876	3.64	0.34	3.38	0.36	0.26	0.12
15.25	1.050	2.48	0.50	2.31	0.52	0.17	0.13
21.50	1.427	1.07	0.31	0.92	0.33	0.15	0.12
27.50	1.798	0.00	0.00	-0.06	0.20	0.06	0.20
33.50	2.188	0.26	0.23	0.09	0.25	0.17	0.09
37.50	2.474	0.75	0.35	0.44	0.42	0.31	0.23

Table 11 ***Loch Teanga: ^{137}Cs and ^{134}Cs data***

Depth	^{137}Cs Conc.		^{134}Cs Conc.	
cm	pCi g^{-1}	±	pCi g^{-1}	±
0.25	45.05	0.96	13.39	1.01
0.75	23.36	0.69	7.01	0.78
1.75	18.24	0.47	4.57	0.50
2.75	8.82	0.50	0.00	0.00
4.25	8.99	0.44	0.00	0.00
5.25	8.02	0.32	0.00	0.00
7.25	7.31	0.22	1.26	0.38
9.75	3.05	0.13	0.00	0.00
12.25	4.29	0.15	0.00	0.00
15.25	3.22	0.14	0.00	0.00
21.50	0.31	0.08	0.00	0.00
27.50	0.28	0.15	0.00	0.00
33.50	0.00	0.00	0.00	0.00
37.50	0.62	0.27	0.00	0.00

Table 12 Loch Teanga: ^{210}Pb chronology

Depth	Cum. dry	Chronology			Sedimentation rate		
	mass	Date	Age				
cm	g cm^{-2}	AD	yr	±	g cm^{-2}yr^{-1}	cm yr^{-1}	± (%)
0.00	0.000	1987	0				
0.50	0.016	1986	1	2	0.014	0.302	9.2
1.00	0.043	1984	3	2	0.016	0.269	10.2
1.50	0.077	1981	6	2	0.013	0.198	7.3
2.00	0.112	1979	8	2	0.012	0.165	6.6
2.50	0.148	1976	11	2	0.012	0.169	7.8
3.00	0.183	1973	14	2	0.012	0.165	8.5
3.50	0.219	1969	18	2	0.011	0.154	8.7
4.00	0.255	1966	21	2	0.011	0.143	8.8
4.50	0.292	1963	24	2	0.010	0.139	8.6
5.00	0.331	1959	28	2	0.011	0.143	8.1
5.50	0.370	1956	31	2	0.011	0.146	8.0
6.00	0.409	1952	35	2	0.011	0.145	8.5
6.50	0.448	1949	38	2	0.011	0.145	9.0
7.00	0.487	1945	42	3	0.011	0.145	9.5
8.00	0.564	1938	49	3	0.012	0.150	11.1
9.00	0.641	1932	55	4	0.012	0.158	13.0
10.00	0.716	1925	62	4	0.112	0.164	15.1
11.00	0.787	1919	68	5	0.011	0.160	17.8
12.00	0.859	1912	75	6	0.010	0.157	20.6
13.00	0.920	1906	81	7			
14.00	0.978	1902	85	9			
15.00	1.036	1897	90	10			
16.00	1.100	1891	96	10			
17.00	1.156	1886	101	10			
17.50	1.187	1884	103	10	0.011	0.194	
18.50	1.246	1878	109	10			
19.50	1.307	1873	114	11			
20.50	1.367	1868	119	11			
21.50	1.427	1863	114	12			

Diatom analysis and pH reconstruction

The summary diatom frequency diagram (Figure 24) shows that below 21 cm depth (1860s) the composition of the sedimentary diatom assemblage is very stable despite the variations in gross sediment stratigraphy. This lower section is characterised by approximately similar abundances of *Fragilaria virescens* v. *exigua*, *Brachysira vitrea* and the planktonic diatom *Cyclotella kutzingiana* v. *minor*. Above this depth at 18 cm, or the 1870s, the assemblage composition begins to change slightly as *C. kutzingiana* declines and *Peronia fibula* increases. *C. kutzingiana* v. *minor* declines further and drops to c. 5% abundance by 7 cm depth or the 1950s and after reaching a peak abundance of c. 15% *Achnanthes minutissima* follows a similar pattern of decline. Over this period *B. vitrea* increases irregularly to a peak abundance of almost 30%. After the 1950s *B. vitrea* frequencies decline somewhat and those of *A. minutissima* and *C. kutzingiana* v. *minor* remain low, but small increases in *Peronia fibula* and *Eunotia pectinalis* v. *minor* occur. The frequencies of *F. virescens* peak at 17 cm, 9 cm and 2 cm depths showing little consistent trend towards change. However, frequencies increase in the upper 5 cm as those of *B. vitrea* decline. The increase in minerogenic material around 12-10 cm depth may influence changes in abundance at this depth in the core.

Assessment of acidity change in the lake as recorded by the diatom assemblages is simplified by combining the diatoms into pH preference groups (Figure 25). Below about 20 cm depth in the core (pre 1860) group frequencies are fairly stable. Between 19 and 15 cm (late-nineteenth century) the circumneutral group frequency increases whilst that of the acidophils declines. Above 15 cm depth the circumnuetral group declines irregularly to the core top (1986); correspondingly, acidophils increase irregularly to achieve maximum abundance in the most recent sediment. Only minor shifts occur in the alkaliphilous group.

The pH reconstructions generated using both the WA and MR methods are shown in Figure 24. The latter method typically produces marginally lower pH values but both reconstructions produce similar results, with comparable values all agreeing within 0.2 pH units. Reconstructed pH values for the present (from the core top) are within the measured range of values for the lake (see Table 9). Within the ^{210}Pb chronology, inferred pH shows a slight decline to pH 6.1 at around 20 cm depth (1860s) before increasing to pH 6.3 by 15 cm depth (c. 1900). Above this depth pH declines irregularly to pH 5.8 (WA) or pH 6.0 (MR) at the core top. The estimated root mean squared error for the WA method is 0.32 pH units (Birks *et al.* 1990), so not all post-1860 reconstructed pH differences are statistically significant. However, the pH curves do suggest a small decline in lake pH since the 1900s, which is principally related to the decline of planktonic *Cyclotella* taxa towards the core top.

The influence of pulses of inwashed material can be clearly seen in the diatom concentration curve for this core (Figure 26). Low diatom concentrations at c. 20, 45 and below 65 cm depths coincide with increasing LOI values of the three major inwashed pulses of peat (cf. Figure 22). Immediately above 14 cm depth the diatom concentration declines further as minerogenic inwash causes further dilution (cf. dry weight increase in Figure 22).

Pollen analysis

Pollen analysis has been performed on the whole 5 m sediment sequence, however only the record of vegetation change over the upper metre, particularly the upper 20 cm, is relevant to this study. The pollen summary diagram (Figure 27) shows that from below 1 m depth to about 30 cm the proportion of *Calluna* pollen increases from around 30% to almost 90% and totally dominates the pollen sum at this upper section. Tree pollen declines over the lower section of the core as *Calluna* increases, *Quercus* declines from c. 30% to insignificant levels by 70 cm depth and although *Pinus* pollen similarly declines it retains a significant presence and shows an increase in the surface sediment. These changes indicate that trees were formerly common around Loch Teanga, but it is unclear whether the pollen peaks around 175 cm depth are from direct supply by a then extant woodland or from reworking of then already fossil deposits. Since this peak coincides with a major decline in *Isoetes* spores (Figure 27) the latter may be correct. Disturbance indicators such as *Plantago lanceolata* are present throughout the upper 2 m of sediment and indicate human impacts on the catchment vegetation. Consequently, the increase in *Calluna* pollen in the upper part of the core is thought to derive both from an increased abundance in the catchment and from increased peat erosion. The latter is suspected since *Calluna* pollen achieves peak abundances as the organic content of the core increases (cf. Figure 22).

The increase in *Pinus* pollen at the core top probably results from long-distance transport of pollens. The grass pollen (Figure 27) shows a similar increase to that of *Calluna* but continues to increase in the nineteenth and early-twentieth century period as *Calluna* declines. This is attributable to anthropogenic interference in the catchment, probably burning for sheep grazing.

Carbonaceous particle and ash sphere analysis

These analyses were performed following the methods of Rose (1989a,b,). The carbonaceous particle profile (Figure 28) shows a characteristic trend with concentrations showing a sustained increase beginning in the 1940s and accelerating up to the 1960s. The concentrations increase during the 1970s but level off in the 1980s. The ash sphere concentration profile (Figure 29) shows similar timing in increased concentrations, but levels-off earlier, in the mid-1970s.

The similarity of the carbonaceous particle and ash profiles suggests a predominantly coal burning origin for the former. However, there is an order of magnitude difference in concentration between the two sedimentary components. Much amorphous particulate carbon was present in upper section of the core. This material is not formed by high temperature fuel combustion and its presence probably results from domestic fires or, most likely, from catchment peat burning.

Sediment chemistry

The sediments of this lake are quite peaty and this is shown by the relatively high LOIs. LOI decreases strongly above 25 cm depth (mid-nineteenth century) and this is accompanied by an increase in the major cation concentrations (Figure 30). There is evidence here of major changes in the sedimentation regime in the lake.

The changes in sediment constitution are responsible for much of the variation in trace metal concentrations (Figure 31). While nickel behaves like a major cation, the zinc and lead concentrations increase strongly above 40 cm with marked fluctuation in concentration between 40 and 50 cm depth. However, Figure 32 shows that much of this variation is due to changes in sediment constitution reflecting changes in sediment sources within the catchment and only above 8 cm do zinc and lead from non-catchment sources contaminate the sediment. This depth dates to the mid-1930s. The choice of 8 cm as the point where contamination starts is not altered even if the effect of the major changes in LOI on the trace metal and major cation concentrations are excluded by expressing the concentrations per gramme minerals. As wastewater sources are absent contamination in this remote lake must come from the atmosphere.

Discussion

The reconstructed pH history of Loch Teanga shows that no significant acidification has occurred during the past c. 150 years. The small fluctuations in reconstructed pH since the mid-nineteenth century between pH 6.0 and 6.4 reflect changes in the diatom assemblages in the upper core section. There is no consistent pH change over this period which suggests that influences other than those of acid deposition have affected the diatom record. The marked decline in *Cyclotella* taxa beginning around the turn of the century is important in producing the small post-1900 decline in inferred lake pH. This change preceded contamination of the sediment by zinc from atmospheric sources and probably resulted from major changes in catchment land-management since around the turn of the twentieth century. This process has been observed elsewhere (Jones *et al.* 1989), as *Cyclotella* are sensitive both to acidification and soil inwash effects.

Another way of looking at possible lake acidification effects is to examine the relationship between non-marine common cations and alkalinity in the lake water using the equation of Henriksen (1982). This follows conversion of pH 5 end-point alkalinity to equivalence alkalinity and use of non-sea salt cation concentrations:

where, acidification = 0.93 (Ca + Mg) -14 - alk

at Loch Teanga = 0.93 (60 + 8) - 44 = 19

This acidification index value suggests that the lake is moderately acidified (cf. Harriman and Wells 1985). However, the large difference in chloride concentration measured on the two sampling dates (Table 9) indicates that the lake is subject to major sea salt incursions. These episodes disturb catchment cation exchange processes and result in increase proton release and the alteration of base cation equilibria. This, together with organic acidity contributed from the peatland catchment, makes application of the Henriksen equation unreliable. If the equation is computed using chemistry data for the low sea salt period 1987 then the acidification index is lower at 14.8. Compared with other lakes the acidification index values for Loch Teanga are less than half those calculated for strongly acidified sites in south-west Scotland but are similar to the value calculated for moderately acidified Loch Laidon (Harriman and Wells 1985) in the central Scottish Highlands. Diatoms in the Loch Teanga core give little evidence of water acidification compared with the diatom record in Loch Laidon (Flower *et al.* 1988). Furthermore, significant acidification of Loch Teanga is incompatible with the carbonaceous particle and trace metal evidence, since contamination is much greater at Loch Laidon.

Despite the lack of recent marked acidification, the carbonaceous particle record of fossil fuel combustion in Loch Teanga is unequivocal evidence that the lake is impacted by atmospheric pollution. The level is however low and, despite any local contamination effects, surface sediment concentrations of carbonaceous particles in Loch Teanga are over an order of magnitude less than in strongly acidified Galloway lakes. On the other hand, the concentration is rather more than the 'background' concentration of around 1000 particles gDM^{-1}, or less, found in lake sediments in the far north of Scotland (Jones *et al.* 1992), or in mid-Norway (eg. Rose 1991). The higher than background concentrations in Loch Teanga (and at sites in the far west of Ireland - see Flower *et al.* 1992) could arise from local point sources. Certainly for Loch Teanga a small oil fired power utility lying only a few kilometres to the north could account for some of the carbonaceous particle contamination of sediment at this site.


1m
1m
5m
9m
13m
17m
3m
1m
17m
17m
19m
core location +
contours in metres
0
100
Metres

Figure 22 **Loch Teanga: lithostratigraphy**

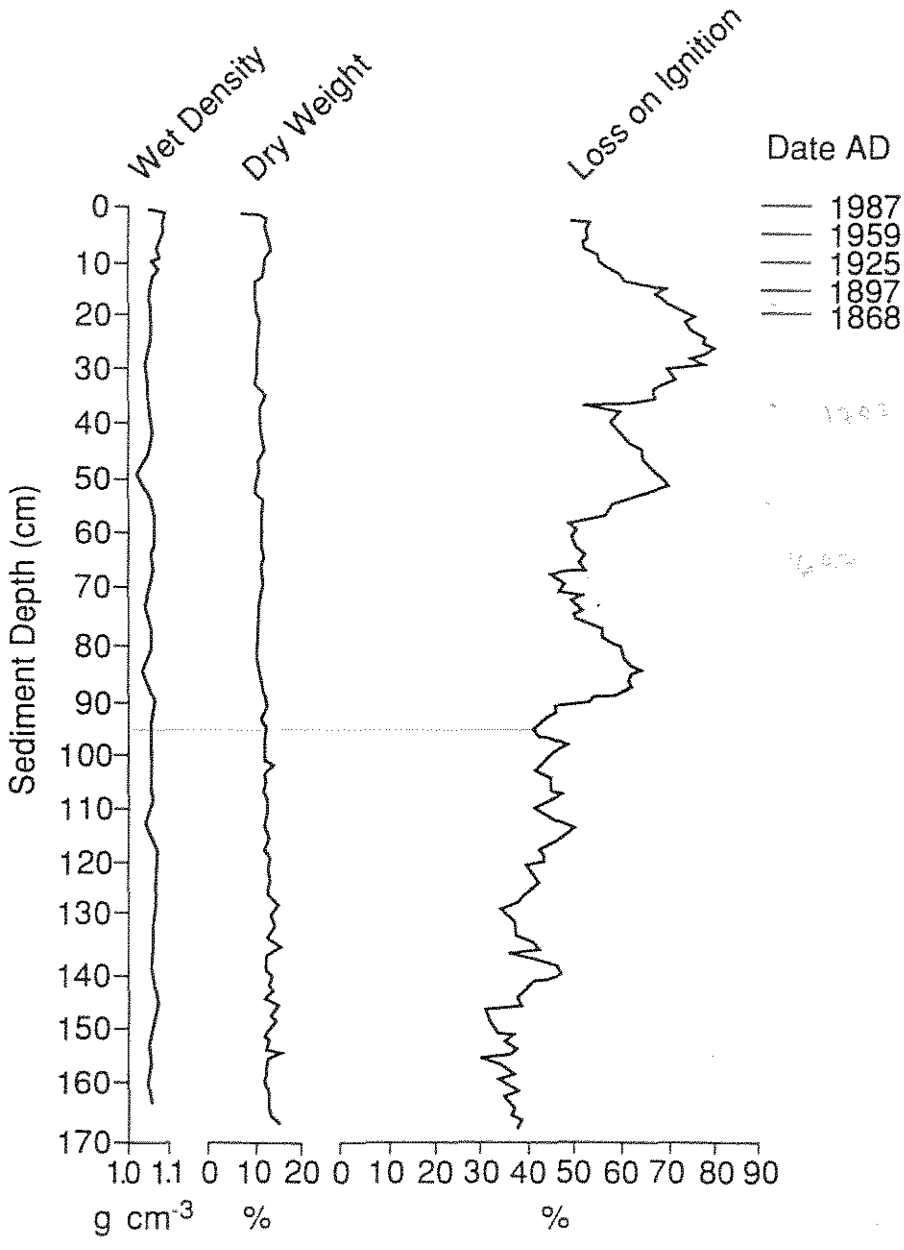


Figure 23 Loch Teanga: ^{210}Pb chronology

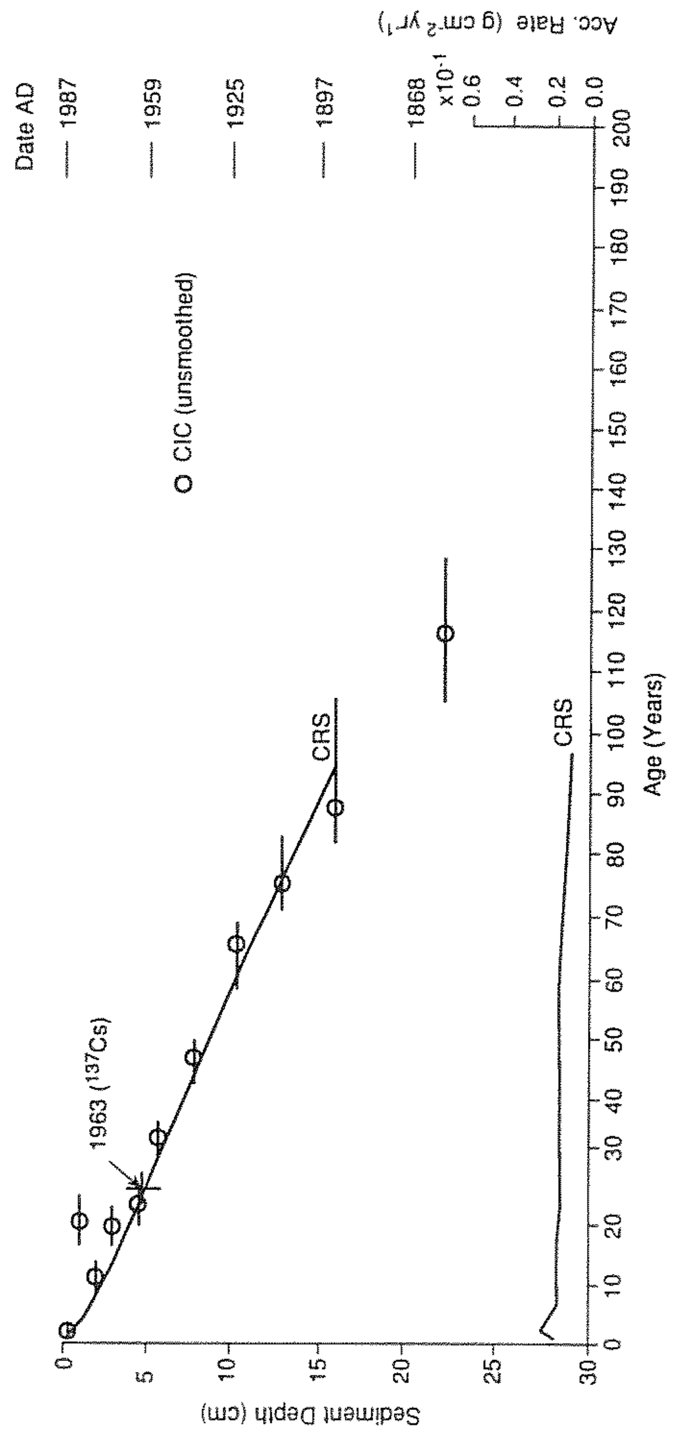
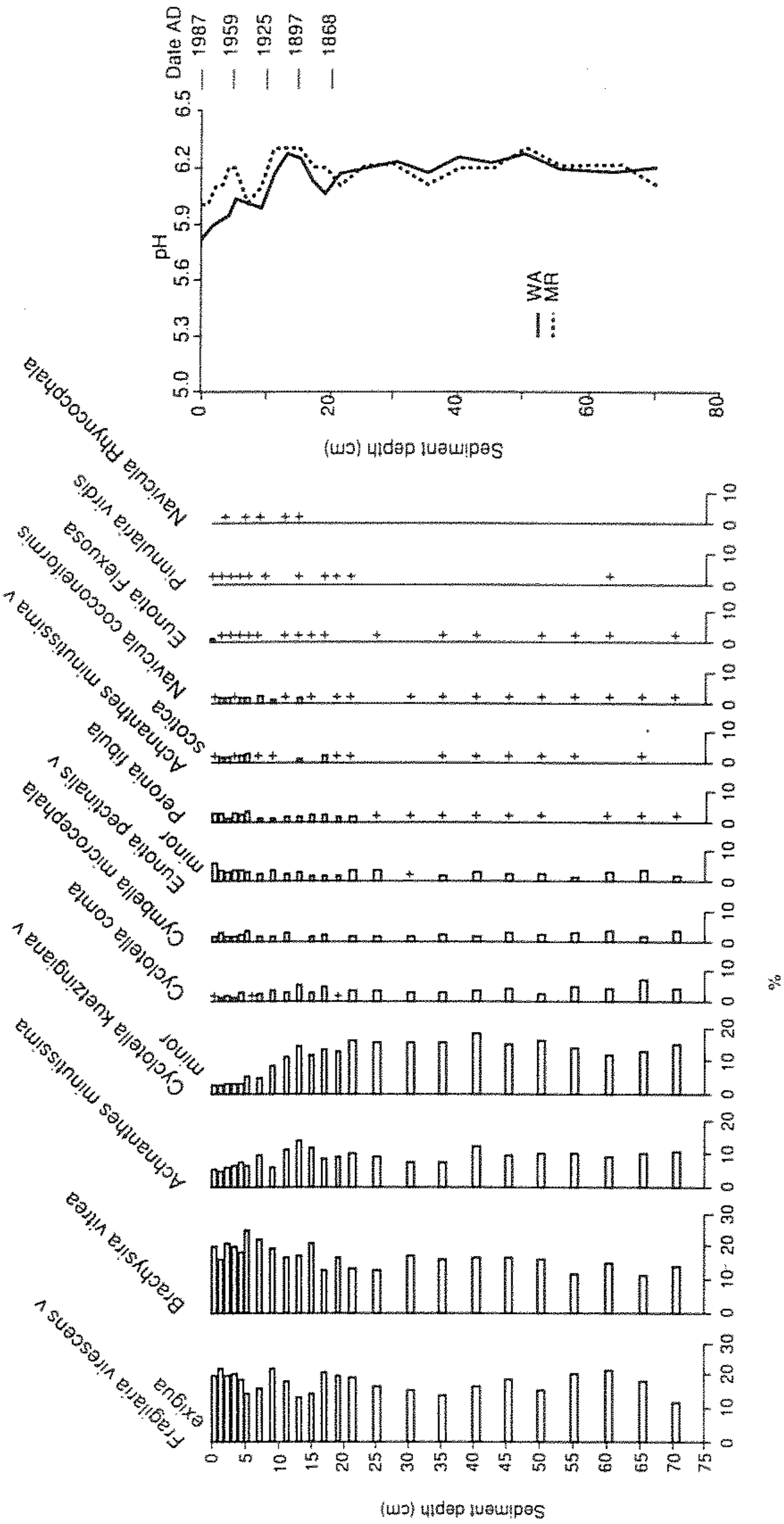


Figure 24 **Loch Teanga: summary diatom diagram and pH reconstruction (WA = weighted averaging, MR = multiple regression)**



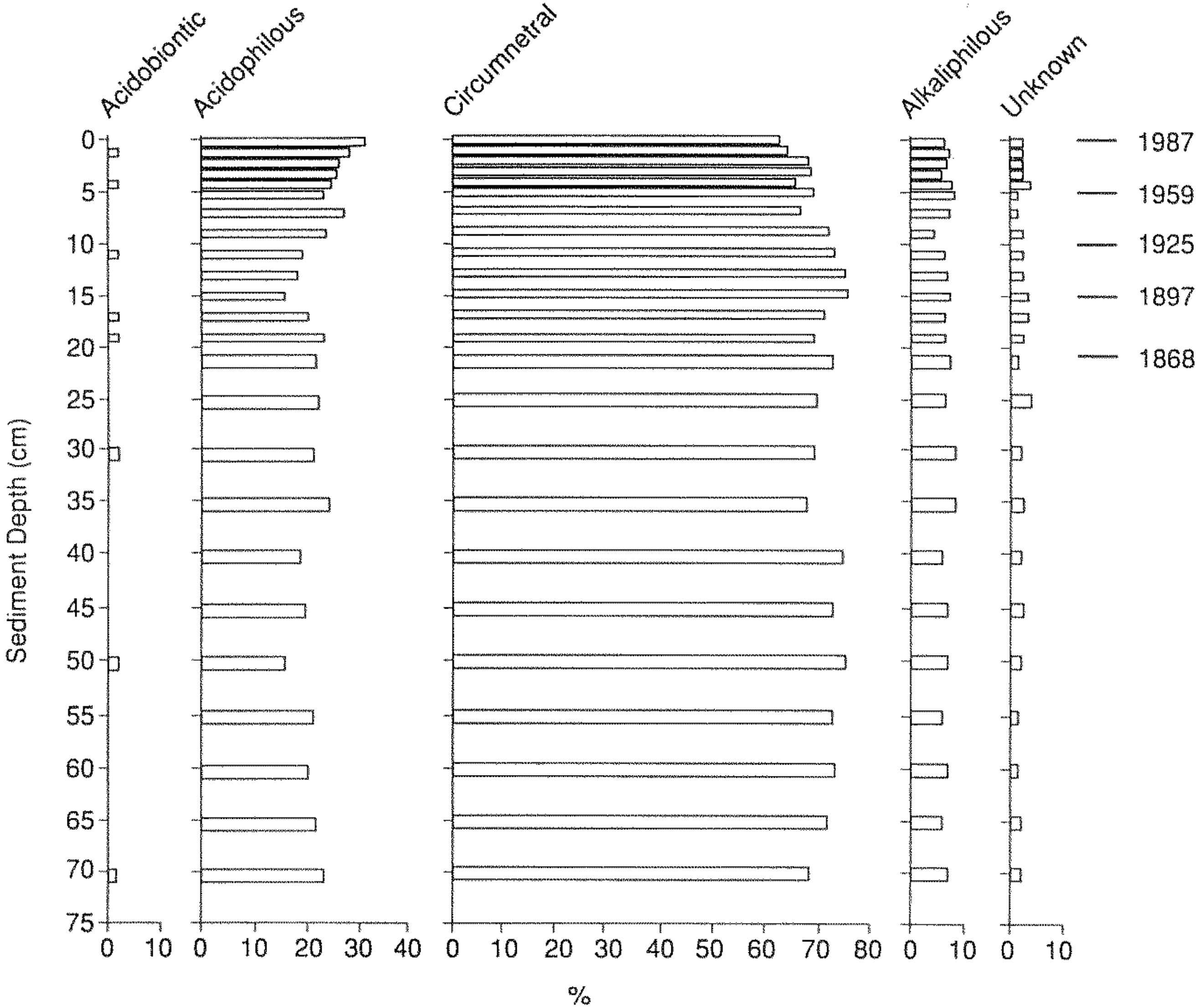


Figure 25 Loch Teanga: diatom pH preference groups

Figure 26 Loch Teanga: diatom concentration profile, indicating 95% confidence limits

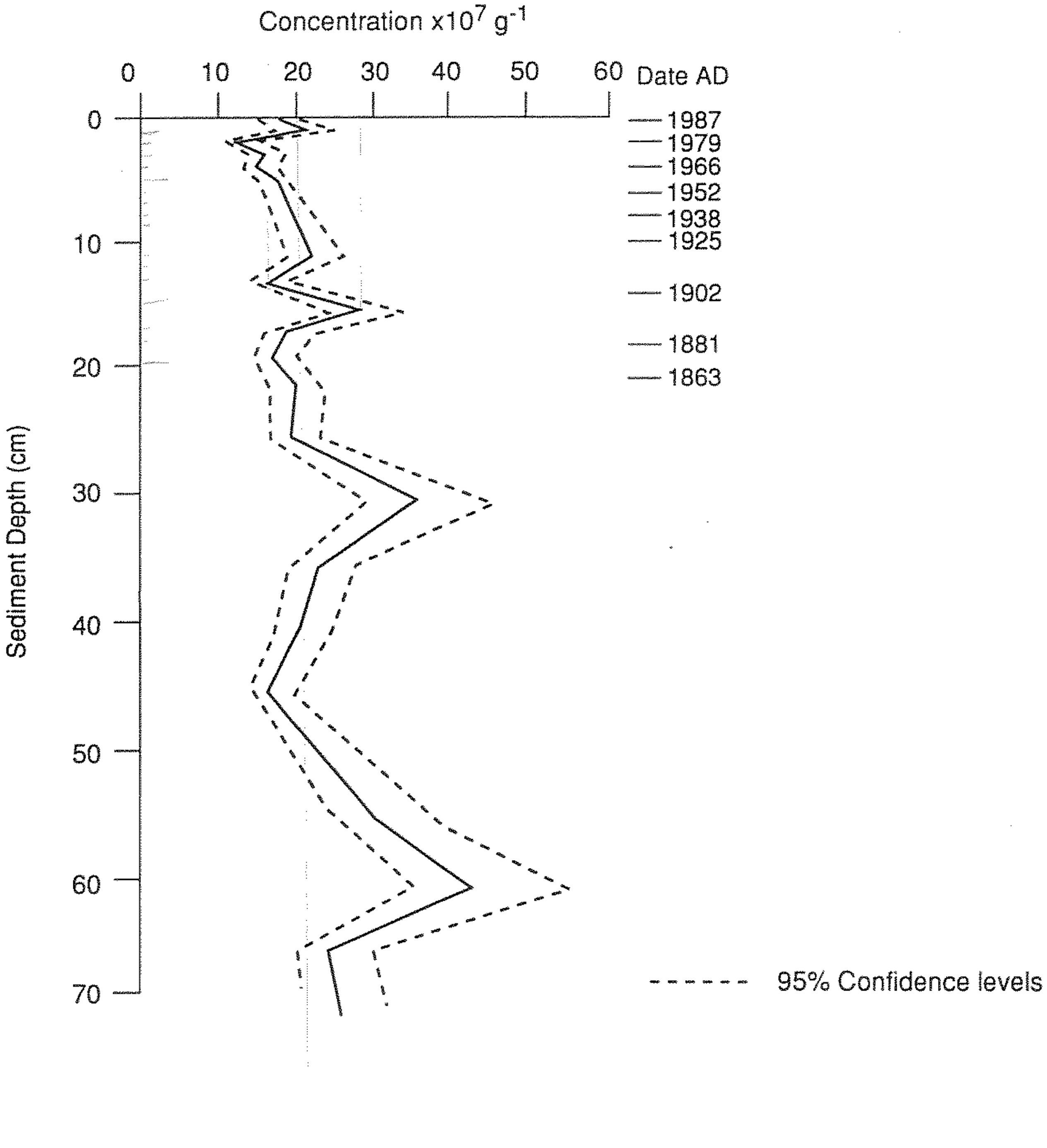


Figure 27 Loch Teanga: summary pollen diagram

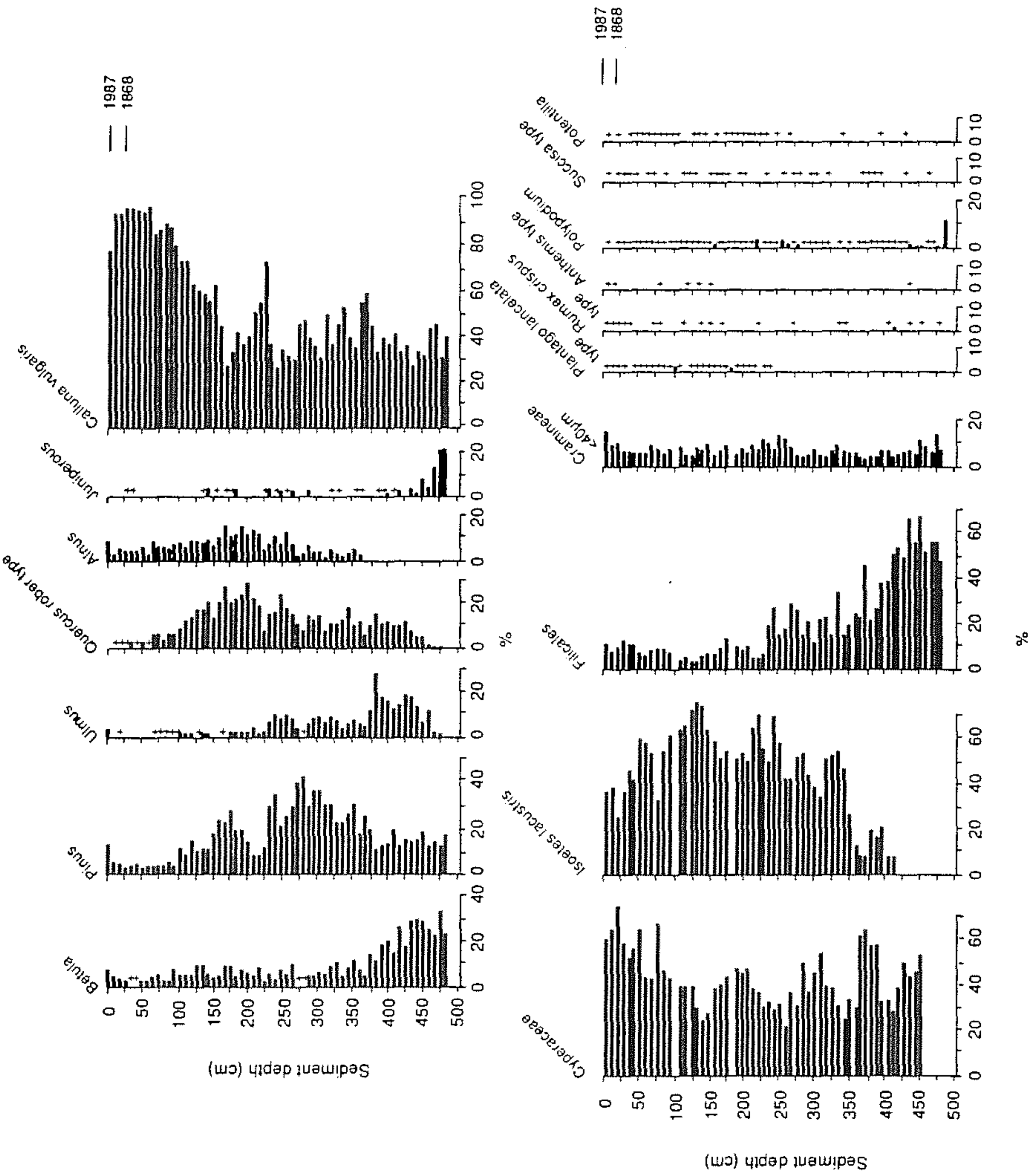


Figure 28 Loch Teanga: carbonaceous particle concentration profile

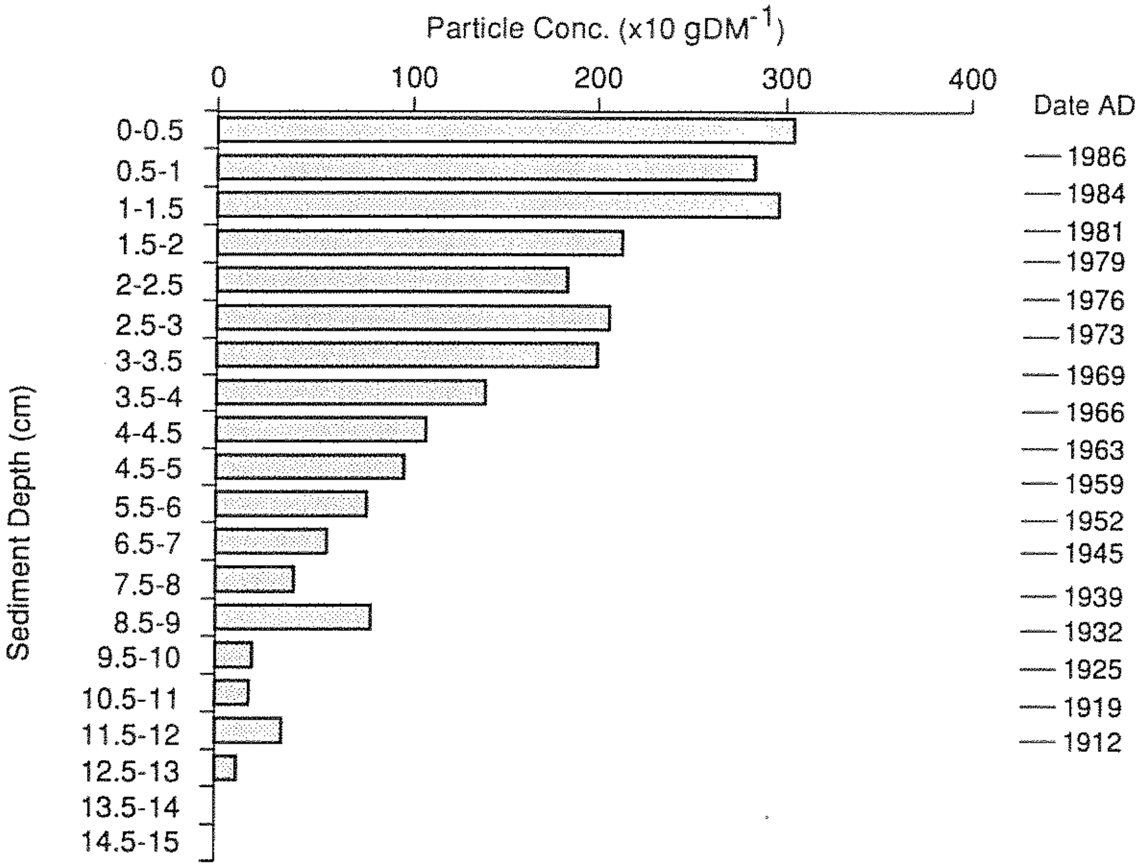


Figure 29 Loch Teanga: ash sphere concentration profile

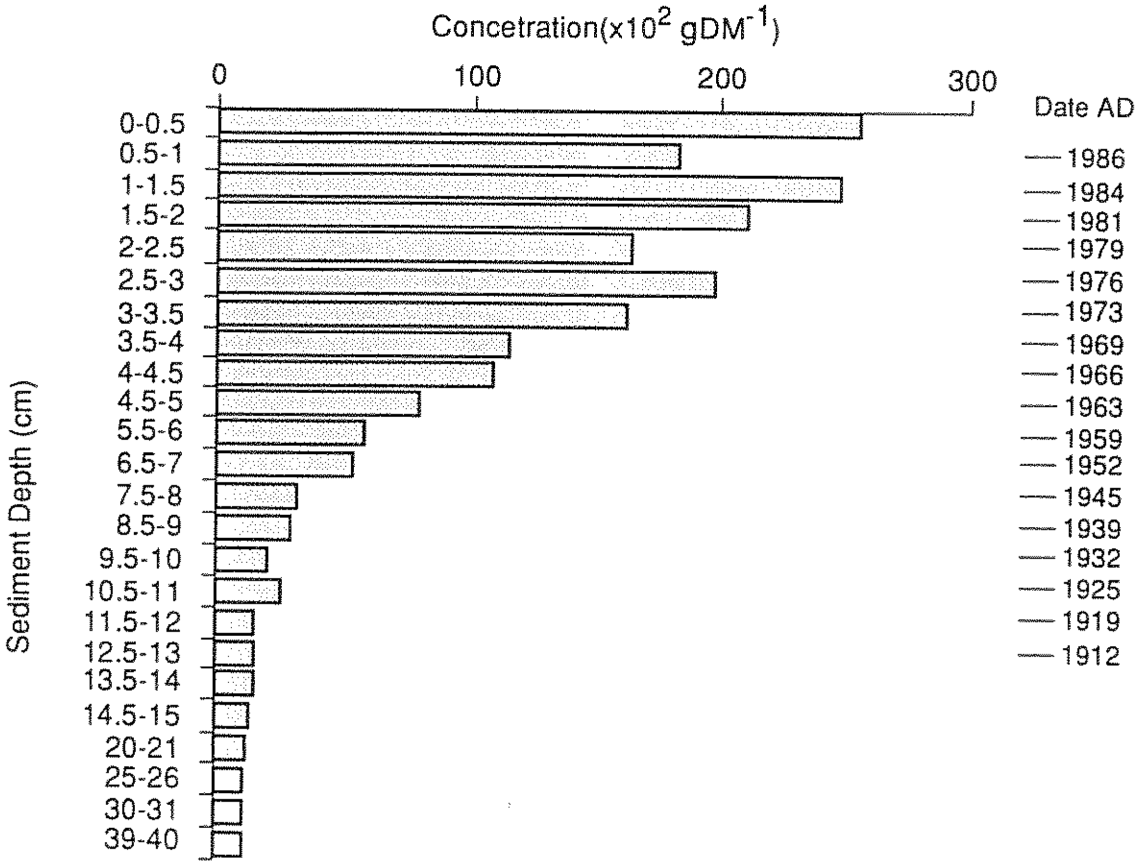


Figure 30 Loch Teanga: variation of major ion concentrations with sediment depth

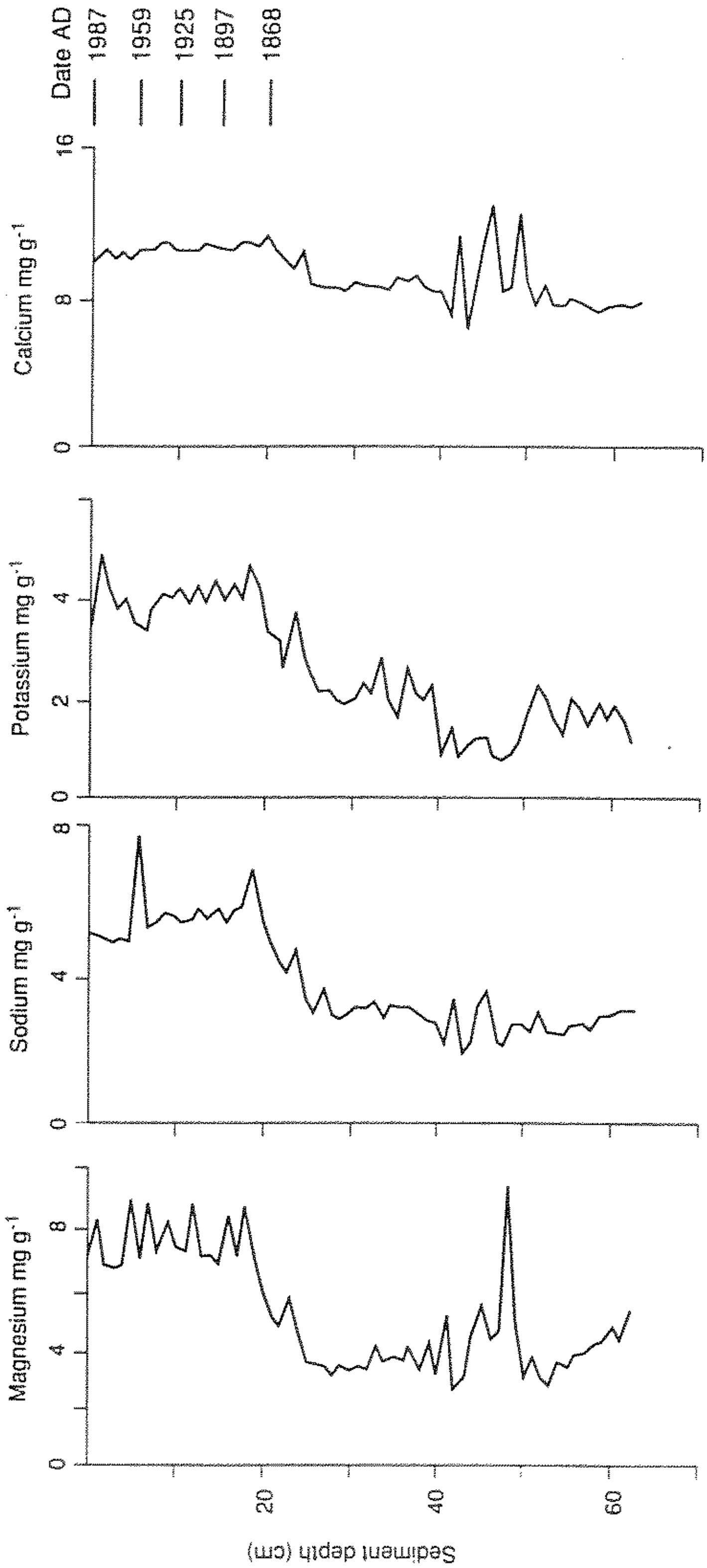


Figure 31 Loch Teanga: variation of trace metal concentration with sediment depth

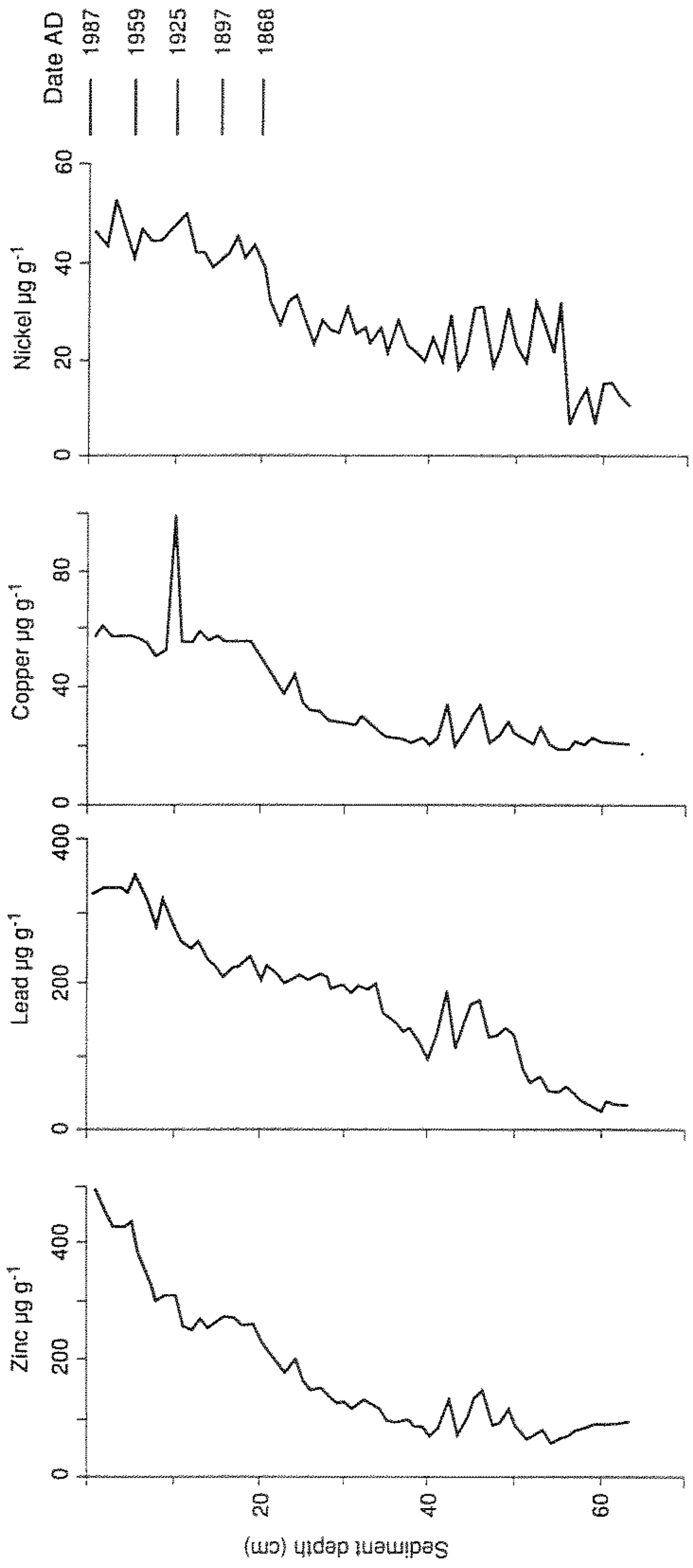
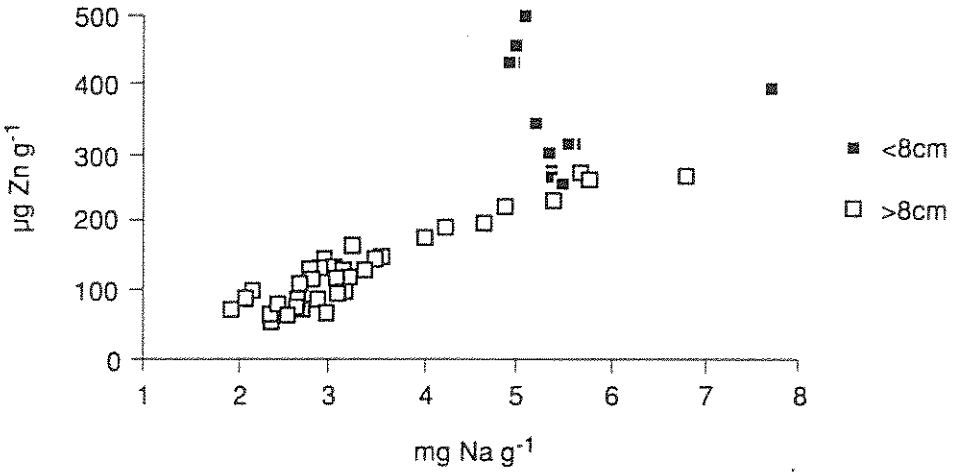
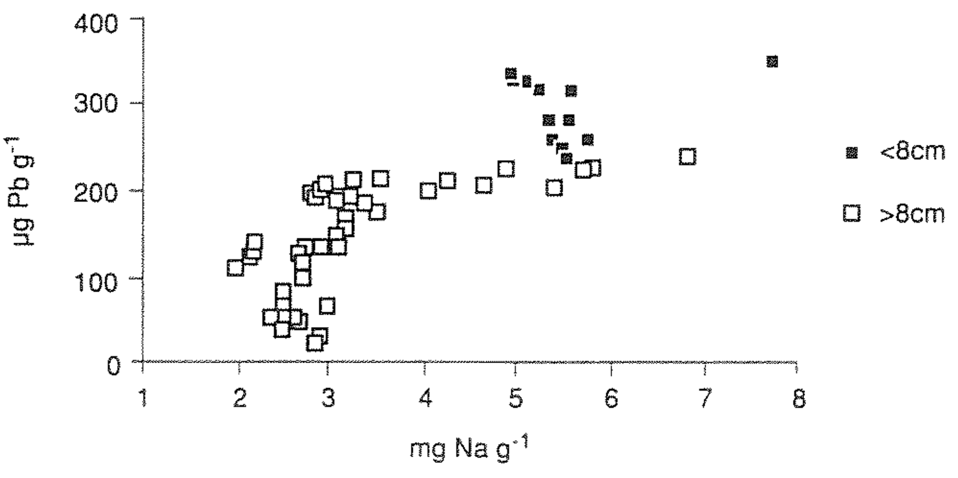


Figure 32 **Loch Teanga: relationships between zinc and sodium and lead and sodium concentrations in the sediments**





3 DISCUSSION AND SUMMARY OF CONCLUSIONS

The purpose of this project was to evaluate the recent palaeolimnology of three sensitive sites lying in areas of low sulphur deposition (<0.8 g S m^{-2} y^{-1}).

All the sites show a record of atmospheric contamination as indicated by the presence of carbonaceous particles. At both Loch Coire nan Arr and Loch Uisge there is evidence for slight atmospheric contamination from the late-nineteenth century onwards, whilst at Loch Teanga contamination begins in the early twentieth century. All the sites show a further increase in concentration from about 1940, with peak concentrations found in the mid-1970s at Loch Uisge, the mid-1980s at Loch Coire nan Arr, and the late-1980s at Loch Teanga. This pattern and chronology of the carbonaceous particle profiles is similar to many other sites in the United Kingdom (Battarbee *et al.* 1988) but the concentrations are much lower than those in areas of higher atmospheric deposition. For example, at the Round Loch of Glenhead, a site lying in an area of high sulphur deposition (1.24 g S m^{-2} yr^{-1}), peak concentrations of carbonaceous particles are over 10 times higher than those found at Loch Uisge (Jones *et al.* 1990). Loch Teanga shows a similar level of contamination to the mainland sites, Loch Coire nan Arr and Loch Uisge, and these sites in general have similar surface sediment concentrations of carbonaceous particles to sites in the west of Ireland, possibly indicating a similar degree of atmospheric pollution in these two regions.

The stable diatom assemblages found over the last 200 years at Loch Coire nan Arr and Loch Uisge together with the diatom-based pH reconstructions show no evidence for lake acidification in the recent past. At these two sites, the present day pH of around 6.5 has been maintained over the last 200 years. At Loch Teanga land-management practices in the recent past have affected the sedimentary record; however, diatom analysis provides no definite evidence of lake acidification from atmospheric pollution.

Although all sites show evidence of atmospheric contamination, from the carbonaceous particle record, this is not linked with lake acidification. This suggests that the sulphur deposition levels at these sites has been and is below the critical load for lake acidification to occur.

In conclusion, it is clear that atmospheric contamination of these sites is relatively small and insufficient to cause any significant change in diatom communities and lake water pH. The present non-marine sulphur deposition levels of <0.8 g S m^{-2} yr^{-1} are, and have been, insufficient to exceed the critical load values. This observation fits with results that would be predicted from the relationship between sulphur loading and lake water calcium concentration in UK lakes (Battarbee 1989).

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