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Palaeoecological study of Linlithgow Loch, Scotland

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Palaeoecological study of Linlithgow Loch, Scotland

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PROJECT SPECIFICATION

1. Collect an open water and a littoral core from the loch
2. Extrude the cores in the field at 1 cm intervals
3. Describe the cores
4. Measure dry weight and organic matter content of selected levels of the two cores
5. Analyse spheroidal carbonaceous particles in 20 samples of the open water cores to establish sedimentation rates and approximate the chronology. Correlate the open water and littoral cores to provide an approximate chronology for the latter.
6. Analyse diatom assemblages in five samples from selected depths of the open water core
7. Analyse plant macrofossils in five samples from selected depths of the littoral core
8. Produce a summary report of the findings (August 2006).

1 METHODS

1.1 CORE COLLECTION

Two sediment cores were collected from Linlithgow Loch on 31 January 2006. A 121 cm core was taken from the open water in a depth of 13.75 m near to The Rickle using a Tapper coring device, and a 50 cm core was retrieved from the littoral zone in a water depth of 1.6 m towards the NE shore of the loch using a piston corer. Locations were recorded by GPS. A number of coring attempts were made in the marginal zone of the eastern end of the loch but very little depth of accumulated organic sediment could be found. A maximum sediment depth of ~50 cm was retrieved at the final coring location and therefore this sample was retained for analysis. However it was originally hoped that a longer littoral core could be collected.

Water depth, secchi depth, water colour, pH and conductivity were measured on site. Summary details of the cores are given in the results section in Table 1.

1.2 CORE EXTRUSION, DESCRIPTION AND LITHOSTRATHIGRAPHY

The cores were extruded in the field at 1 cm intervals and any visible stratigraphic changes were noted. The percentage dry weight (%DW) which gives a measure of the water content of the sediment, and percentage loss on ignition (%LOI) which gives a measure of the organic matter content, were determined in the laboratory on alternate samples by standard techniques (Dean 1974).

1.3 DATING

To provide an approximate chronology for LING1 (open water core), sediment samples from selected depths of the core were analysed for spheroidal carbonaceous particles (SCPs). Sample preparation and analysis followed the method described in Rose (1994). Dried sediment was subjected to sequential chemical attack by mineral acids to remove unwanted fractions leaving carbonaceous material and a few persistent minerals. SCPs are composed mostly of elemental carbon and are chemically robust. The use of concentrated nitric acid (to remove organic material), hydrofluoric acid (siliceous material) and hydrochloric acid (carbonates and bicarbonates) therefore does them no damage. A known fraction of the resulting suspension was evaporated onto a coverslip and mounted onto a microscope slide. The numbers of SCPs on the coverslip were counted using a light microscope at x400 magnification and the sediment concentration calculated in units of 'number of particles per gram dry mass of sediment' (gDM^{-1}). The detection limit for the technique is c. 100 gDM^{-1} and concentrations have an accuracy of c. ± 45 gDM^{-1}. A sediment reference standard was analysed along with the LING1 samples.

1.4 DIATOM AND MACROFOSSIL ANALYSIS

A small number of subsamples from LING1 (open water core) were prepared for diatom analysis following standard methods (Battarbee *et al*. 2001). The samples were initially screened to ensure sufficient preservation for analysis and to assess the degree of change in the core. The final selection of six samples for full analysis were chosen according to the approximate chronology established by SCP dating, to ensure inclusion of samples from key dates. The diatom species data are expressed as percentage relative abundances.

The littoral core (LING2) was analysed for plant macrofossils. Five sub-samples from LING2 were selected according to the lithostratigraphic profile of the core. Adjacent 1cm slices were combined to provide sufficient sediment for macrofossil analysis. Sediment sample sizes were determined both by mass and volume, with sediment volumes measured by water displacement and ranging from 30–50cm^3. Samples were divided into two size fractions by washing through 350µm and 125µm sieves. The entire retent of both sieves was examined using a stereomicroscope at 10-40x magnifications and identifiable plant, algal and some animal remains enumerated. The 350µm fraction contained the larger macrofossils including the majority of plant reproductive remains, molluscs, fish scales and the larger bryozoan statoblasts and cladoceran ephippia. The 125µm fraction contained smaller vegetative fossils including *Plumatella* spp. statoblasts and small *Chara* spp. oospores. Plant macrofossils were identified by comparison with herbarium documented reference material. It is not always possible to ascribe remains to species level, thus in some cases an aggregate group of species corresponding to the highest possible taxonomic resolution was used. The macrofossil remains have been retained for future reference and are stored under glycerol to prevent dessication and fungal infestations. Macrofossil data are expressed as number of macrofossils 100 cm^3 of wet sediment.

Since LING2 has not been independently dated and since it was not possible to correlate LING1 and LING2 using %DW and %LOI profiles, changes in the diatoms and plant macrofossils in the two cores cannot be correlated. Consequently, the diatom and aquatic macrophyte histories of Linlithgow Loch must be examined and interpreted independently.

2 RESULTS

2.1.1 CORE DESCRIPTIONS

Table 1 Details of the sediment cores collected from Linlithgow Loch

WBID	NGR	Coring date	Site code	Core code	Coring water depth (m)	Coring location	Core length (cm)	Core type	Secchi depth (m)	Water colour	pH	Cond ($uScm^{-1}$)
25687	NT002775	31.01.2006	LING	LING1	open: 13.75	NS 99990 77428	121	Tapper	1.2	clear	7.67	392
				LING2	littoral: 1.6	NT 00757 77801	59	Fat piston				

2.1.2 LITHOSTRATIGRAPHY

The %DW and %LOI measurements for LING1 are illustrated in Figure 1. Both %DW and %LOI are relatively stable throughout the upper 100 cm of LING1 with values of ~10-15% and ~30%, respectively. The lowermost part of the core has a higher clay content and is considerably less organic and more dense with %LOI as low as 5% and very high %DW values of ~70%.

The %DW and %LOI measurements for LING2 are illustrated in Figure 2. Between 0 and 35cm, %DW increases and then remains relatively high, fluctuating between ~25 and 40%. From 35cm %DW decreases and then remains stable at ~10% to the core bottom (59cm). %LOI steadily decreases from the core top to ~13cm, then between 13 and 35cm it increases gradually from ~15-30%. From 35cm, %LOI increases significantly and then remains relatively stable at around 80-90% to the core bottom.

The lithostratigraphy of LING2 is very different to that seen in LING1. In contrast to the open water core, LING2 (littoral core) has %DW values higher than %LOI towards the core top. From the middle of LING2, the organic matter content increases to very high values - %LOI as high as 90%, with correspondingly low %DW values of ~10%. There is no clay layer at the bottom of the littoral core.

Preliminary comparison of the the open water (LING1) and littoral (LING2) cores based on visual inspection of stratigraphic changes suggested that they did not contain enough common features to allow reliable core correlation. Following examination of the %DW and %LOI profiles, we conclude that the two cores are not sufficiently similar to enable correlation by lithostratigraphic means. Significant differences between the profiles suggest that independent dating of the littoral core (LING2) is required to afford a reliable chronology.

Figure 1: Percentage dry weight and organic matter profile of LING1

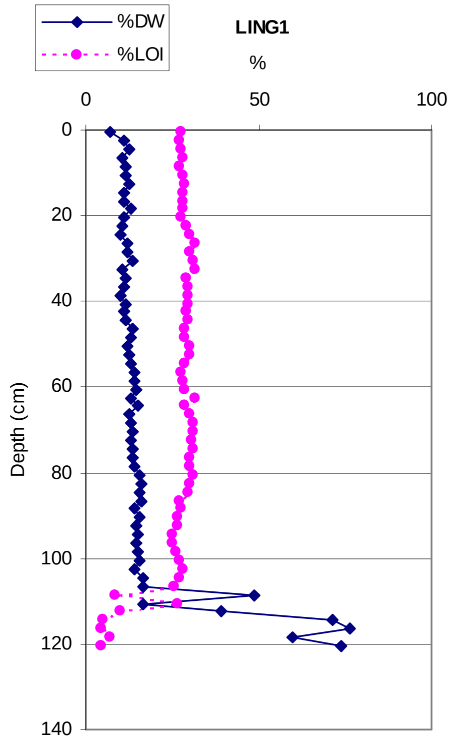
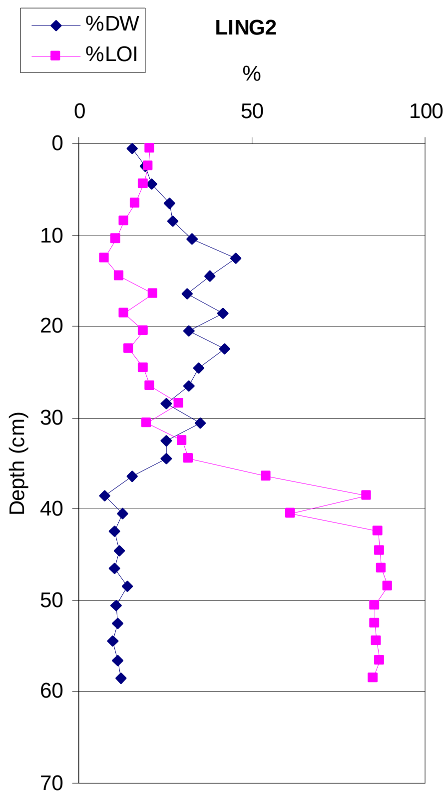


Figure 2: Percentage dry weight and organic matter profile of LING2



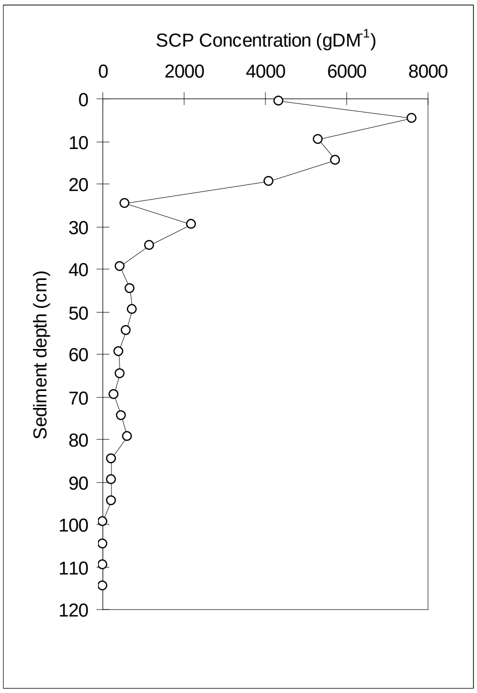
2.2 DATING

The results of the SCP analyses are presented in Table 2 and the SCP concentration profile is shown in Figure 3.

Table 2. LING1: SCP concentrations and 90% confidence limits.

Sediment depth (cm)	SCP concentration (gDM^{-1})	90% Confidence limits (gDM^{-1})
0 - 1	4342	5210 – 3473
4 – 5	7608	9192 – 6053
9 – 10	5295	6198 – 4392
14 – 15	5718	6694 – 4743
19 – 20	4103	5002 – 3204
24 – 25	541	847 – 235
29 – 30	2184	2898 – 1471
34 – 35	1148	1651 – 645
39 – 40	429	727 – 132
44 – 45	663	954 – 372
49 – 50	728	1085 – 371
54 – 55	566	886 – 246
59 – 60	409	692 – 126
64 – 65	418	707 – 128
69 – 70	272	538 – 5
74 – 75	467	791 – 143
79 – 80	620	970 – 269
84 – 85	226	448 – 5
89 – 90	225	446 – 5
94 - 95	198	392 – 4
99 – 100	0	0 – 0
104 – 105	0	0 – 0
109 – 110	0	0 – 0
114 - 115	0	0 – 0

Figure 3. LING 1: SCP concentration profile.



The SCP profile for LING 1 (Figure 3) clearly displays all the characteristic features seen in lake sediment cores throughout Europe (Rose et al., 1999). The first presence of SCPs occurs at 94 - 95 cm and a slow, but steady, increase in concentrations occurs from this depth to c. 25 cm when there is a decline in concentration followed by a rapid increase to a peak of over 7600 gDM^{-1} at 4 - 5 cm. SCP concentrations decline in the surface sediment sample.

The SCP record in European lake sediments has been found to be so consistent and reliable (there are no problems of re-mobilisation or dissolution etc.) that one of the main uses of the SCP record has been for dating purposes (e.g. Rose et al., 1995). In a given region, once a reliable SCP chronology has been established (using independent dating such as varve counting or ^{210}Pb dating etc.) then the SCP profile can be used with confidence to ascribe dates to the last c. 150 years of the sediment record. Traditionally, dates are attributed to the start of the record, the rapid increase in SCP concentration and the SCP concentration peak. Although there are regional variations, in Scotland the date of the start of the SCP record is usually given as the mid-nineteenth century as a result of developments in the Industrial Revolution whilst the start of the rapid increase in SCP concentration is usually ascribed to c.1950 due to the boom in electricity generation after the Second World War. Usually the most replicable and identifiable feature within a region is the peak in SCP concentration. It is also the feature that is most likely to vary between one region and another, as the “post-peak” decrease is due to many factors such as implementation of air quality legislation, introduction of particle arresting equipment and trends in industrial output, fuel use and economic development. In addition to these factors, the situation may be further complicated by the trans-boundary nature of the depositing particles. For example, most lakes receive deposition from the emissions of more than one country and the combination of national air quality legislation may result in a unique depositional regime for the region. For Scotland, the situation is simpler as most deposition is from the UK. However, variability in SCP concentration peak dates does occur across Scotland and for the southeastern Scotland region the date is considered to be 1994 ± 2 (Rose & Appleby, 2005). The SCP peak for LING 1, and hence 1994, can therefore be allocated to 4 – 5cm although it should be noted that the coarse analytical interval (5cm) is such that in reality this peak could occur anywhere between 1cm and 9cm (i.e. between the samples either side of that with maximum SCP concentration).

For Linlithgow Loch the sample at 24 – 25cm shows an unusually low SCP concentration and the reason for this is unclear. More detailed analysis would be required to resolve this. Further, the early ‘tail’ also appears to be longer than might be expected if the peak and ‘rapid increase’ features occur at 4 – 5cm and c. 25 - 30cm respectively and sediment accumulation rate has been constant through time. Therefore, this inconsistency may be due to an early SCP record in this heavily industrialised area of Scotland, or it may signal a period of higher sedimentation rate. For this current work, it is not possible to be certain of the cause for this, but in order to use SCPs for dating, we must assume the latter is correct.

More recently, the technique of dating sediment cores using SCPs has been developed (Rose & Appleby, 2005) such that dates are ascribed on the basis of cumulative percentage inventories calibrated using a number of independently dated profiles from across a number of defined regions in the UK. Southeastern Scotland forms one of these regions and the inventory dates for this region are based on a number of independently (^{210}Pb) dated sediment cores. Being based on inventory data these profiles are not susceptible to many of the processes that may affect SCP concentrations (e.g. in-wash events causing dilution of SCP concentrations) and hence the technique is more robust than ‘traditional’ SCP dating, which uses concentration data only. The inventory technique uses the SCP peak depth as 100% and all other percentiles are calculated relative to it. The advantages of this approach are that all future cores can have dates allocated to them and that dates can be allocated to each 10-percentile resulting in 11 dates for each core rather than the previous three. The disadvantage is that only dates between 1850 and the peak date (here, 1994) can be allocated to a core. For Linlithgow Loch, depths can be allocated to each of the 10-percentiles resulting in the chronology shown in Figure 2. These data can then be interpolated to provide dates for each 5cm level as shown in Table 3. Errors given in this table are based on the variability between the independently dated sediment cores from the region, and the errors from the original radiometric dating.

The SCP derived chronology (Figure 4) suggests that the sediment accumulation rate has varied over the last 150 years. A more rapid phase of accumulation (c. 0.70 cm yr^{-1}) from the start of the record is followed by a reduced rate after the middle of the 20th century (c. 0.41 cm yr^{-1}). Alternatively it is possible to fit a smooth curve through these data which would suggest a steady change over the period rather than a larger change in sediment accumulation rate at any one period of time.

In summary:

- The SCP concentration profile for the Linlithgow Loch core LING 1 shows a typical record with all the usual features. However, there is a long 'tail' to the record which suggests either an early SCP record (as a result of pre-1850 industrialisation) or a period of more rapid sediment accumulation rate.

- Dates ascribed using both SCP approaches are reasonably consistent. Dates have been allocated to each 10-percentile using those typical for the south-eastern Scotland region.

- The resulting chronology suggests that sediment accumulation rate was previously more rapid (c. 0.70 cm yr^{-1}) but that this has been reduced (c. 0.41 cm yr^{-1}) since the middle of the 20th century. Alternatively it is possible to fit a smooth curve through these data, which would suggest a steady change over the period rather than a change in sediment accumulation rate at any one period of time.

Figure 4. LING 1 Sediment chronology

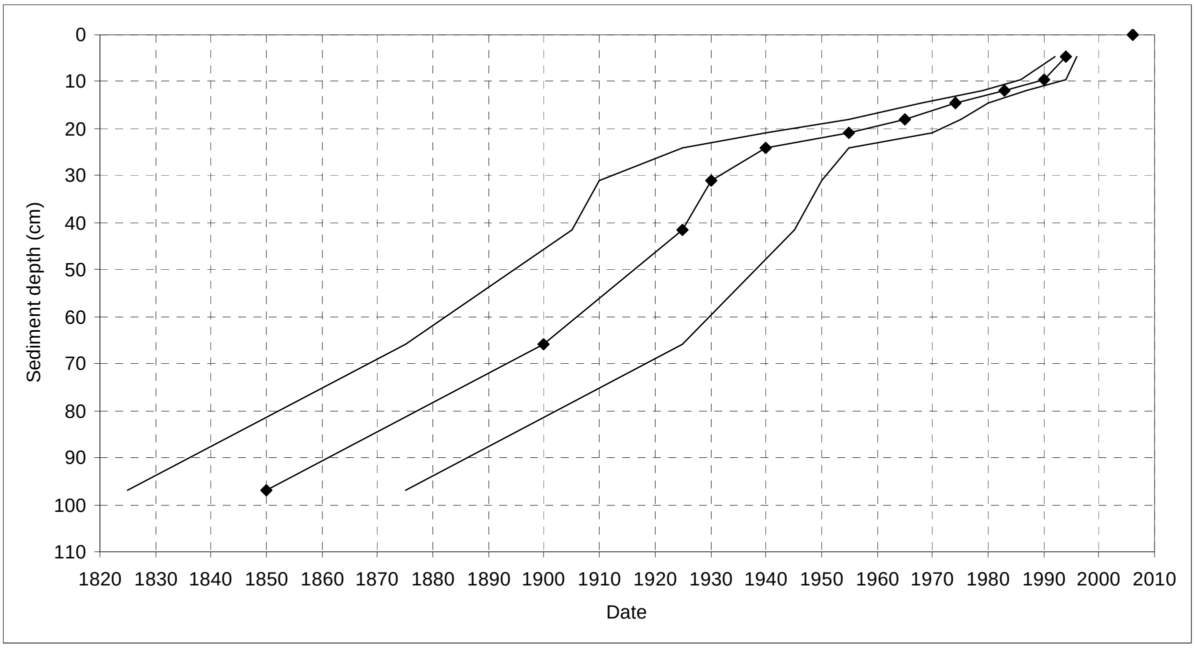


Table 3. Interpolated dates and sediment depths for LING 1

Sediment depth (cm)	Ascribed date	±
0 (sediment surface)	2006 (coring date)	0
5	1992	2
10	1989	4
15	1974	6
20	1960	10
25	1938	12
30	1932	20
35	1927	20
40	1925	20
45	1921	20
50	1916	20
55	1911	20
60	1906	20
65	1901	20
70	1893	25
75	1885	25
80	1877	25
85	1870	25
90	1862	25
95	1854	25

2.3 DIATOM AND MACROFOSSIL ANALYSIS

2.3.1 DIATOMS

Six samples were analysed for diatoms in LING1. The summary diatom diagram is illustrated in Figure 5. All samples showed good diatom preservation, with no evidence of frustule dissolution.

LING1 was dominated by diatom taxa typical of high alkalinity, eutrophic, relatively turbid lowland lakes (Bennion *et al*., 2004). The dominant diatom taxa throughout the core were centric planktonic species, including in particular those species usually measuring <10 µm in diameter - *Stephanodiscus parvus*, *Cyclostephanos tholiformis* and *Cyclotella pseudostelligera*. Slightly larger centric taxa of between 10 and 20 µm in diameter were also commonly encountered throughout the core, including species such as *Stephanodiscus hantzschii* and *Cyclotella meneghiniana*. Planktonic pennate diatom taxa (*Asterionella formosa* and *Fragilaria capucina* var. *mesolepta*) were also present throughout the core, but at much lower percentage relative abundances.

Although the planktonic centric diatom taxa dominate LING1, some periphytic (living on a substrate) taxa are also present. In particular, the epiphytic (living on plants) taxa, *Cocconeis placentula* and *Rhoicosphenia abbreviata* increase in relative abundance from approximately the 1960s. The increase in epiphyton may signify an increase in the availability of aquatic macrophytes as growth surfaces for diatom epiphyton. The increase could also indicate a reduction in the numbers of grazers e.g. molluscs. However, the most abundant epiphyte, *C. placentula* is an adnate diatom taxon that grows adpressed to its plant host and is therefore difficult for grazers to remove. This may indicate that the former explanation for the increasing relative abundance of epiphyton is more plausible.

Aside from the slight increase in the relative abundance of epiphytic diatoms towards the core top, there are no clear stratigraphic changes in the diatom profile of LING1. Planktonic diatoms dominate throughout the core and the main changes that have occurred are simply shifts between different planktonic diatom taxa that cannot easily be attributed to changing environmental conditions in the loch. From the diatom record of LING1, it can be concluded that Linlithgow Loch is a eutrophic, plankton-dominated system and that this has been the case since at least 1850.

2.3.2 MACROFOSSILS

Five samples were analysed for macrofossils in LING2: 0-2cm, 10-12cm, 20-22cm, 30-32cm, 50-52cm. In the absence of dates, the levels selected for analysis were chosen using the core's lithostratigraphic profile for guidance. The summary macrofossil diagram is illustrated in Figure 6, where data are presented as the number of macrofossil remains per $100cm^3$ of sediment.

Only one level was selected for analysis from the highly organic section of LING2 (35-59cm depth). This section of the core recorded very low numbers and a low diversity of macrofossils, with only a few reproductive remains of marginal plants including *Urtica dioeca* and *Carex* spp. seeds. The only other macrofossil remains present in this section of the core were statoblasts of the bryozoan, *Plumatella* spp. The high organic content and low aquatic macrofossil content of the 50-52cm sediment sample suggest that the area of the loch from which LING2 was taken may have been a semi-terrestrial, moist, marshy marginal area in the past and may not have been permanently submerged. This suggests that the lake level may have been lower in the past and that the water table in the area has since risen.

In the upper section of LING1 (above 35cm), the macrofossil remains suggest a true aquatic environment. Species typically associated with open water and permanent submerged conditions are present in the macrofossil record from 0-31cm sediment depth. At 31cm, the number of remains of aquatic species is relatively low compared with higher up the core, which may indicate that water levels in the loch were gradually increasing to their present levels. At 31cm, there are relatively high numbers of marginal plant remains, including the seeds of *Urtica dioeca*, *Carex* spp., *Juncus* spp., *Caryophyllaceae* spp. and *Chenopodiaceae* spp. However, at this level in the core there are also seeds of aquatic plant species including *Ranunculus* sect. *Batrachium*, *Myriophyllum spicatum*, *Chara* sp., *Zannichellia palustris* and *Potamogeton* spp., along with fish and cladoceran remains, suggesting a true aquatic environment.

From 31cm to the core top, relatively large numbers of aquatic macrofossil remains were recovered. The numbers of *Chara* sp. oospores increase to approximately 400-500 oospores per $100cm^3$. Similarly, the numbers of *Z. palustris* seeds increase to approximately 100 seeds per $100cm^3$. Higher up the trophic cascade, cladoceran ephippia concentrations increase, in particular *Daphnia* sp. ephippia increase in abundance to 300-400 per $100cm^3$. The increasing presence of planktonic cladocerans suggests that the loch supports a high algal population to support the large zooplankton population. The presence of large numbers of cladocerans also suggests that planktivorous fish predation is relatively low. This is in agreement with the absence of fish scales / other remains from the 11 and 1cm sediment samples.

In both the 11cm and surface sediment samples there are considerably fewer remains of marginal and herbaceous plants than lower down the core. However, the species that are represented in the macrofossil record are in good agreement with a number of those species recorded in a vegetation survey of the loch in 2004 (Smith, 2004).

Elodea canadensis leaves are only found in the surface sediment sample. This may reflect the recent arrival of this submerged aquatic macrophyte in the loch, although since vegetative remains such as leaves are often poorly preserved in sediment cores, the presence of *E. canadensis* leaf fragments only in the surface sediment sample may equally reflect taphonomic processes. The vegetation survey of the loch in 2004 (Smith, 2004) noted that despite the presence of few aquatic macrophytes in the loch, *E. canadensis* was dominant alongside *Callitriche* sp., suggesting that the macrofossil record provides a reasonable representation of the aquatic flora of the loch. Although no remains of *Callitriche* sp. were found in LING2, this may simply reflect the absence of *Callitriche* sp. plants in the locality of the coring site. Since the core was taken in the winter (January 2006), the location, extent and species composition of macrophyte beds could not be assessed.

3 SUMMARY POINTS

- The SCP concentration profile for core LING 1 shows a typical record with all the usual features. However, there is a long 'tail' to the record which suggests either an early SCP record (as a result of pre-1850 industrialisation) or a period of more rapid sediment accumulation rate.

- The %LOI and %DW profiles of LING1 (open water core) and LING2 (littoral core) are not sufficiently similar to enable correlation by lithostratigraphic means. Significant differences between the profiles suggest that independent dating of LING2 is required to afford a reliable chronology and to enable the dating of stratigraphic changes.

- The dominant diatom taxa in LING1 are planktonic centric species including small *Stephanodiscus*, *Cyclostephanos* and *Cyclotella* spp. These taxa are typical of high alkalinity, eutrophic, relatively turbid lowland lakes and their presence throughout the core from at least 1850 until the present day, suggests that Linlithgow Loch has been eutrophic for at least the past 150 years.

- From the 1960s to the present day, the increasing relative abundance of epiphytic diatom taxa suggests an increase in the cover of aquatic macrophytes and hence the increasing availability of aquatic macrophytes as growth surfaces for diatom epiphyton.

- In LING2, the high organic content and poor representation of aquatic macrofossils from 35-59cm suggests that lake levels were probably lower in the past and that the littoral area from which the core was taken may once have been semi-terrestrial.

- The macrofossil remains in the upper section of LING2 suggest that the lake has developed into a true aquatic ecosystem, supporting a submerged macrophyte community and relatively large numbers of zooplankton. The submerged macrophyte community appears to be of relatively low diversity and dominated by species typically found growing in high alkalinity, lowland and/or enriched waters e.g. *Chara* sp., *Z. palustris*, fine-leaved *Potamogeton* spp. and *E. canadensis*.

- The plant species represented in the macrofossil record are in reasonable agreement with the species recorded in a vegetation survey of the loch in 2004. Species that are poorly represented in the macrofossil record may be absent due to taphonomic processes.

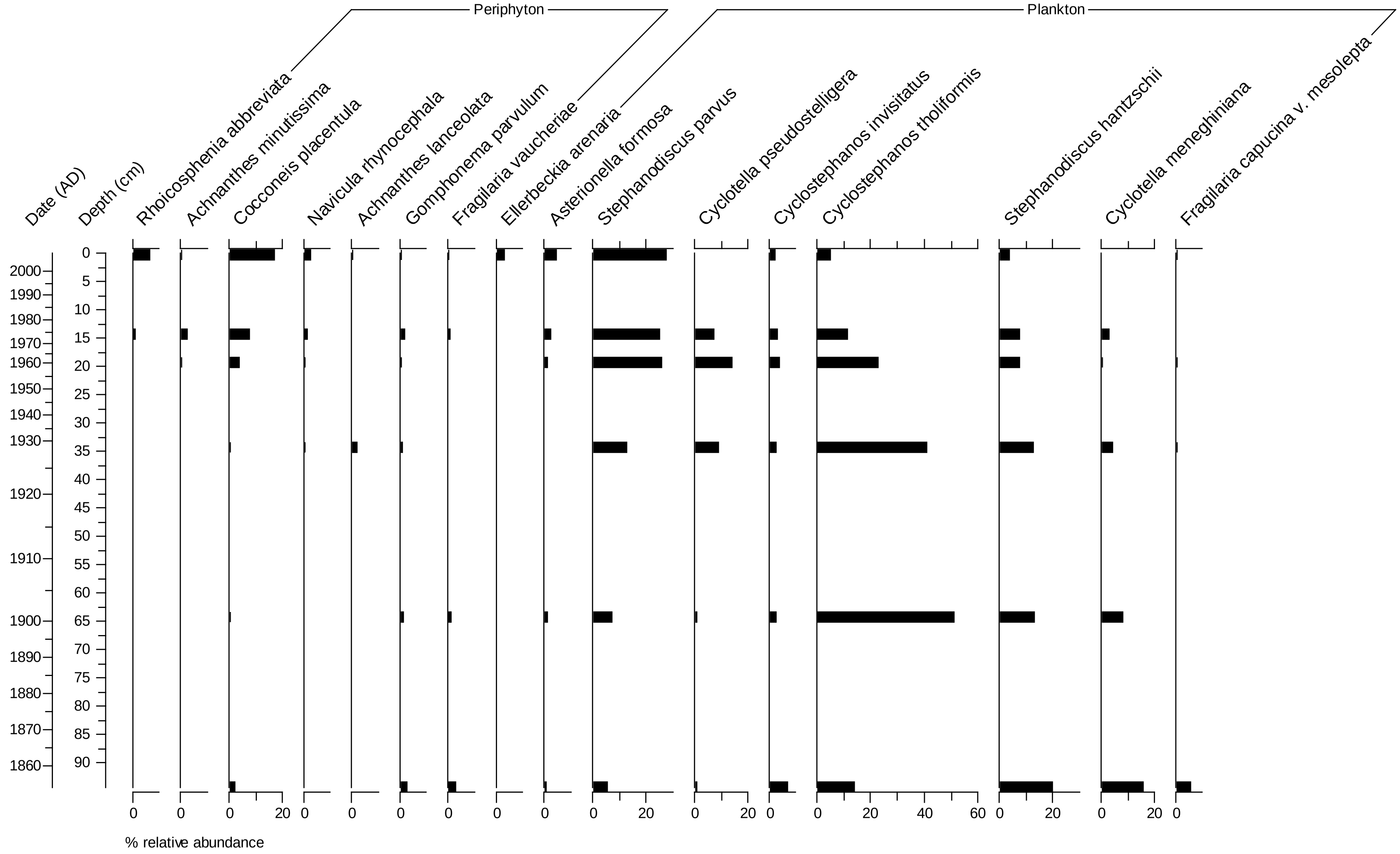


Figure 5: Stratigraphic diagram illustrating the percentage relative abundance of the dominant diatom taxa (>2%) in core LING1

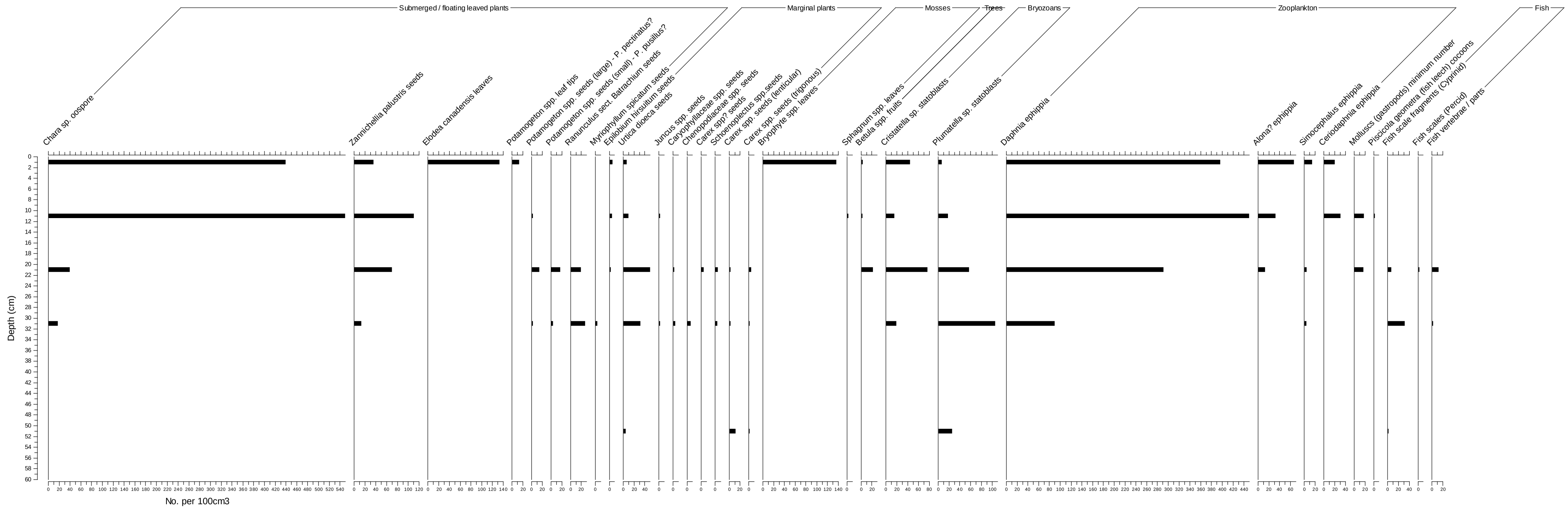


Figure 6: Stratigraphic diagram illustrating the macrofossil remains recovered from core LING2. Data are presented as the number of macrofossil remains per 100cm^3 of sediment.

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