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Reconstructing the past submerged macrophyte flora of Martham South, Burntfen, Sotshole and Nortons Broads, Fritton Lake and Mautby Decoy

Final Report to the Broads Authority

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Photo – Burntfen Broad

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Introduction and project objectives

Study Rationale

The anthropogenically induced decline in the ecological quality and conservation value of European fresh waters is arguably ubiquitous. In lowland Britain the main impact on aquatic systems is that associated with elevated nutrient loading. The Norfolk and Suffolk Broads are internationally important wetlands spanning a number of river basins in East Anglia. The Broads have suffered, along with other wetlands, from the effects of eutrophication, which has had a deleterious effect on the system (Mason & Bryant 1975; Moss 1977). There has been a general decline in the ecological quality and conservation value of the Broads, with one of the main symptoms being elevated algal productivity. One of the changes in the ecological structure and functioning of shallow lakes in response to enrichment is an alteration in their macrophyte flora (Sayer et al. 1999; Ris & Sand-Jensen 2001; Davidson et al. 2005) and in extreme cases there may be the complete loss of submerged plants (Scheffer et al. 1993). The loss of the diversity of the macrophyte flora in the Broads is one of the contributing factors to the decline in their conservation value.

The six lakes, both Broads and non-Broads selected for study here have been selected either because they are being considered for restoration, Nortons Broad, Sotshole Broad, Burntfen and Mautby Decoy, or to gain some information on their past macrophyte flora, Martham South Broad and Fritton Lake. These sites are situated along a gradient of eutrophication impact with Martham South having been minimally impacted and sites such as Nortons Broad having been impacted to a large degree.

Study Aim

The main aim of the study is to investigate the former macrophyte flora of six lakes within the Broads area. In the absence of long term monitoring data palaeolimnological techniques have proved useful in determining the past submerged flora of a site. Specifically the sedimentary remains of plant macrofossils provide a means of determining the ancestral submerged macrophyte communities of the sites (Davidson et al. 2005).

Methods

Coring and lithostratigraphic analysis

Six sediment cores were extracted using an adapted Livingstone type fat piston corer (Livingstone 1955) on June 30th Nortons Broad and on 21st to 24th of October for 2008 for the remaining sites. The exact location of each core was recorded using a hand-held GPS. A single core was taken from each sites and extruded in the field. Summary details of the cores are given in Table 1. Selection of the optimal sampling location was subject to conflicting pressures as dating techniques have been developed on cores taken from the deepest point of a lake, where accumulation rate is assumed to be greatest and bio-turbation minimal, whereas macrofossil analysis is best carried out on cores located more in the littoral zone (Davidson et al. 2005). Site selection was based on a compromise between these two opposing influences. The cores were extruded in the field at 1 cm or 2 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 from each core by standard techniques (Dean 1974). The carbonate content was calculated by returning the crucible to the furnace for two hours at 925 ^{o}C and then reweighing.

Dating

Sediment samples from four of the six lake sediment cores: MARS1, BURF1, SOTS1 & MAUT1 were analysed for spheroidal carbonaceous particles (SCPs) following the method described in Rose

(1994). Dried sediment was subjected to sequential chemical attack by mineral acids to remove unwanted fractions leaving a suspension of mainly carbonaceous material and a few persistent minerals in water. 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 number 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 criteria for SCP identification under the light microscope followed Rose (submitted). Analytical blanks and SCP reference material (Rose, submitted) were included in each batch of sample digestions. Reference concentrations agreed with the expected values while no SCPs were observed in the blanks. The detection limit for the technique is c. 100 gDM^{-1} and concentrations have an accuracy of c. ± 45 gDM^{-1}

Spheroidal carbonaceous particles are produced exclusively by high temperature burning of fossil fuels. SCP concentration profiles have been used to date lake sediment cores for circa 20 years (Renberg & Wik, 1984; Rose et al., 1995) and the method is based on the allocation of dates to unambiguous features in the SCP concentration profile by means calibration to independently derived dates from techniques such as varve counting or radiometric analyses. SCP profiles across a region have been found to be reliable and repeatable and, once calibrated, dates using SCP profiles can be ascribed with confidence (Rose et al., 1995).

Rationale for SCP analysis of sediment cores in the Broads.

Background

The use of spheroidal carbonaceous particle (SCP) analysis to date sediment cores is well-established for the UK. The premise for this is that lake sediment record of SCPs across the UK is consistent, robust and attributable to known historical trends in fossil-fuel combustion and emission to the atmosphere (Rose 2001). Due to the consistent historical patterns of SCPs, key features of SCP concentration profiles may be attributed dates at which they occurred. For the UK this has been based on SCP profiles of over 80 radiometrically dated sediment cores (Rose and Appleby 2005). The SCP record is thus 'calibrated' to independent radiometric dates but also known to agree with historical emission and combustion data. SCP dating is applicable anywhere there is a replicable SCP sediment profile. However, in any new region this record needs to be calibrated before the SCP profile can be used to provide a chronology for undated cores.

SCP dating in the Broads

The use of SCPs to provide dates in the Broads area is based on the generally poor performance of the usually reliable radiometric approach (i.e. ^{210}Pb, ^{137}Cs, ^{241}Am) in these systems. It is currently unknown why radiometric dating is less satisfactory in shallow eutrophic waters but isotopic concentrations often appear to be low, profiles truncated and the resulting chronologies are thus short and have high errors. SCP records, while also frequently truncated (see below) still show the same temporal features and hence are able to provide dates in lakes of all types. Having established this, SCP dating has been widely used in the Broads area sometimes in preference to the radiometric approach. It is beyond the scope of this short note to discuss SCP and radiometric dating on a site-by-site basis, but this was done in a report to the Broads Authority in 2005 (Rose et al 2005). This report showed that the use of SCP dating in combination with radiometric dates provided both independent confirmation for the short radiometric record and was also able to extend sediment chronologies further back in time.

Limitations

While SCP dating in Broads cores is useful it is not a 'magic bullet' and is subject to the same sedimentological problems and depositional processes as any stratigraphic marker. Where sediments are disturbed the SCP record is such that dates can often not be attributed. Similarly, cores from sediments deposited in more dynamic environments such as littoral areas, are also problematic and sometimes SCPs are only present in the uppermost layers indicating a veneer of recently deposited material (possibly prior to transport) over an older sediment base. Such problems do not only affect SCPs of course, any dating approach suffers similarly in these areas.

Finally, as with any analytical procedure, SCP analysis has detection limits. While we can adjust the technique to reduce these, in rapidly accumulating lakes, the SCP concentration can be diluted by sediment inputs to a level below the analytical limit of detection resulting in a 'less than' value and an incomplete depositional record. In the Broads this most often happens in the 1940s just prior to the post-War rapid increase in SCP concentration (due to a boom in electricity generation). While this dilution truncates the SCP chronology, this feature can itself be a useful chronological marker.

New developments

Although SCP sediment concentration profiles have been used for 25 years for core dating purposes (Renberg and Wik 1984) until recently there has been little development of quality control procedures. Now the approach is becoming more widely used, a SCP reference standard has been produced and is available to analysts (Rose 2008). Similarly, for the first time, SCP identification criteria for the light microscope have been recorded so that analysts can use the same set of rules (Rose 2008). It is hoped that this will increase analytical rigour and lead to greater inter-laboratory comparison between studies.

Conclusions

SCP dating has become widely used in palaeolimnological studies from shallow, eutrophic waters principally due to a reduced performance of radiometric dating in these systems. However, while SCP dating performs reasonably well in these lake-types the SCP record is subject to the same depositional processes as any stratigraphic marker and is unable to date sediments where they are disturbed or non-conformable. Recent developments have placed SCP analysis on a stronger analytical footing and there is no reason why this approach cannot continue to provide sediment chronologies in the Broads area for many years to come.

Macrofossil analysis

In the absence of reliable historical information on past aquatic macrophyte communities, analysis of sedimentary macro-remains of plants (the seeds, fruits and remains of stems, leaves and rhizomes) may provide a technique for determining changes in the aquatic flora of a site (Birks 1980). Recent work has indicated that plant macrofossils provide a reliable means for tracking shifts in the dominant components of the submerged aquatic flora in shallow lakes (Davidson et al. 2005).

In this study 10 levels from each of the cores were analysed for plant and some animal macrofossils with at least 30 cm^3 of sediment was analysed in each sample. Samples were sieved at 350 and 125 microns, the exact sample volume being measured by water displacement. The entire residue on the 350 micron sieve was examined under a stereo-microscope at magnifications of X10-40 and plant and animal macrofossils were enumerated. A quantitative sub-sample, approximately one tenth of the sample, from the 125 micron sieve was analysed for smaller remains, such as leaf spines. All material was identified by comparison to reference material. It is not always possible to describe remains to species level, thus in some cases an aggregate groups of species corresponding to the highest possible taxonomic resolution was used. For example, *Potamogeton* leaf remains were grouped as *Potamogeton pusillus* agg. which will include *P. pusillus*, *P. berchtoldii* and perhaps *P. trichoides*. Distinct morphotypes of *Chara* oospores were also separated into groups but could not be identified to species so were termed species a, species b and so on. The data are presented as numbers of remains per 100 cm^3 of wet sediment.

Table 1. Broads core location, water depth and core length

NAME	NGR	CORING DATE	CORE CODE	WATER DEPTH AT CORE SITE (CM)	CORING LOCATION	CORE LENGTH (CM)
Martham South Broad	TG459201	21/10/08	MARS1	100	TG45950 20206	120
Burntfen Broad	TG338188	22/10/08	BURF1	131	TG33835 18774	135
Sotshole Broad	TG359137	22/10/08	ORML1	55	TG35945 13770	195
Nortons Broad	TG290168	30/06/08	NORT1	20	TG29093 16892	230
Mautby Decoy	TG483113	23/10/08	MAUT1	80	TG48197 11315	210
Fritton Lake	TG482003	23/10/08	FRIT1	210	TG48252 00853	125

Results

A summary of the location of sampling sites, water depth of coring location and core length are given in table 1.

Martham South Broad

Located in the Thurne Basin the Martham Broads are thought to be minimally impacted by eutrophication and as such have high conservation value. They have good water clarity and diverse populations of submerged plants.

Figure 1. Map of the Martham South Broad with coring location

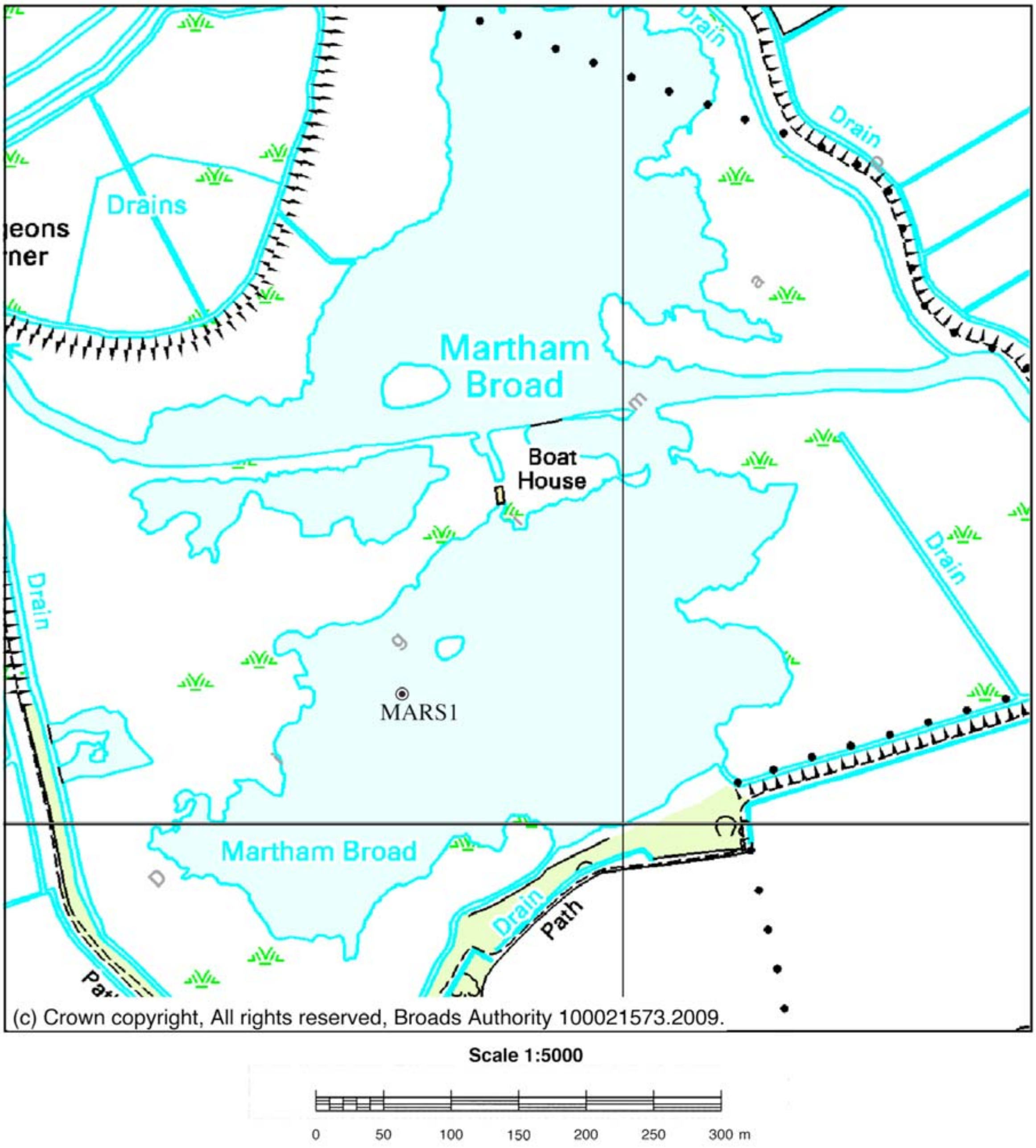
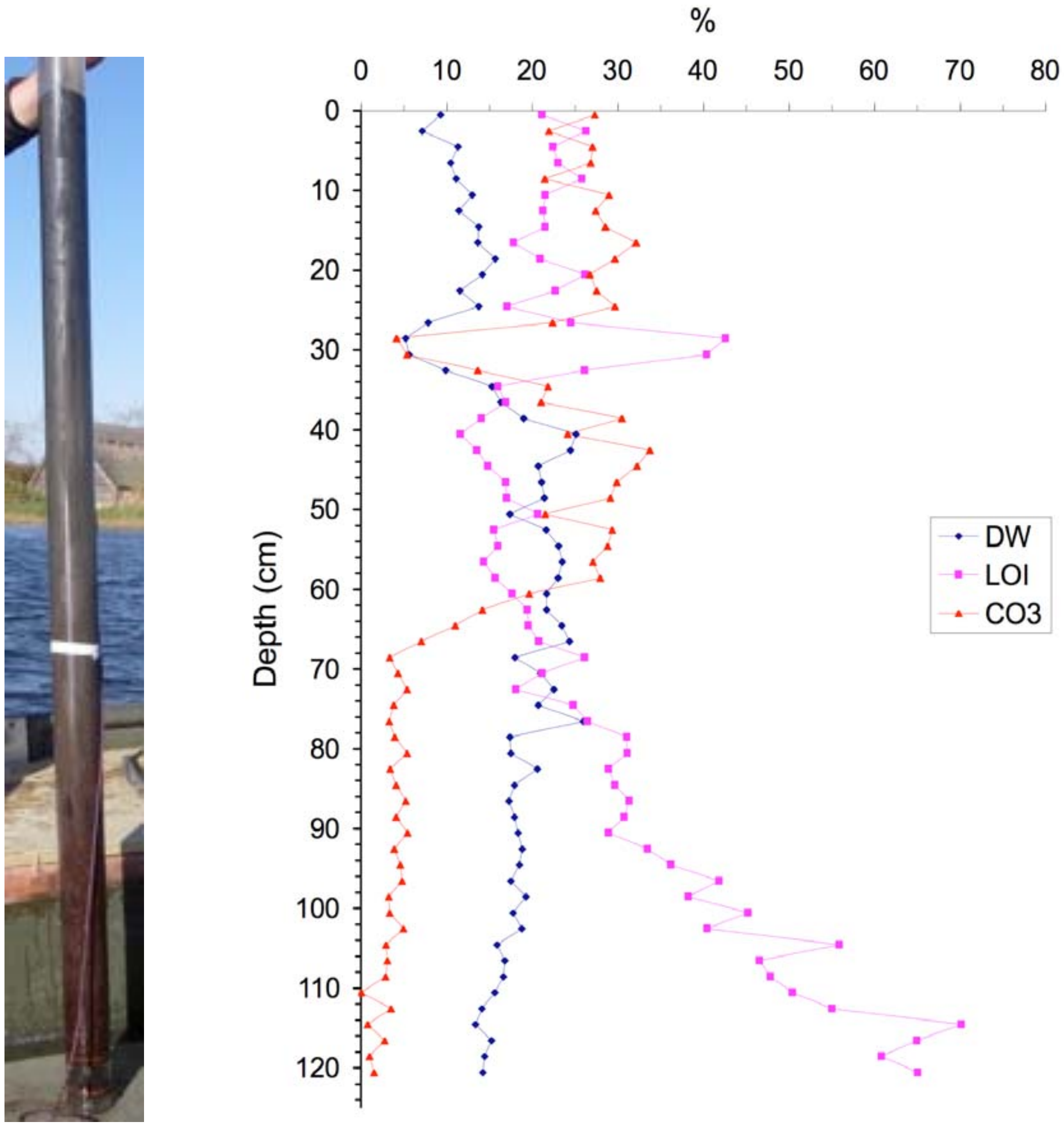


Figure 2 Lithostratigraphy of MARS1, Martham South Broad



Depth (cm)	Sediment colour
0-40	dark grey
40-80	grey marl
90-80	light brown/marl
125-90	Peat

MARS1 Core stratigraphy

MARS1 had a number of distinguishing features, which can be seen in Figure 2. The base of the core was peat, reflecting the origin of the Broads, characterised by very high organic content (LOI) (>60%) and the absence of carbonate. Organic content declined gradually from 120 cm to around 20% at 80 cm, dry weight (DW), above 80 cm the values for both DW and LOI remained relatively constant to 40 cm. The carbonate profile was remarkable, after a slow increase from complete absence in the peat to around 5% at 70 cm there was a dramatic increase to 35% at 60 cm. Carbonate levels then stayed high to 40 cm where there was a sharp drop to 5% at 30 cm then a sharp return to higher levels around 30%. The LOI values were the obverse of the carbonate values as values from 70 to 40 cm with a sharp rise to at 30 cm followed by a sharp decline to around 20% from 25 cm to the surface of the core. The visible colour changes in the cores (Fig. 2) match the measured lithostratigraphy closely, with a peat base indicating that the entire lacustrine period of the Broad was covered by the core. The high carbonate/marl layer between 80 and 40 cm is recognisable the light marl coloured sediments above which the sediment was darker, despite the high carbonate content.

MARS1 Core chronology

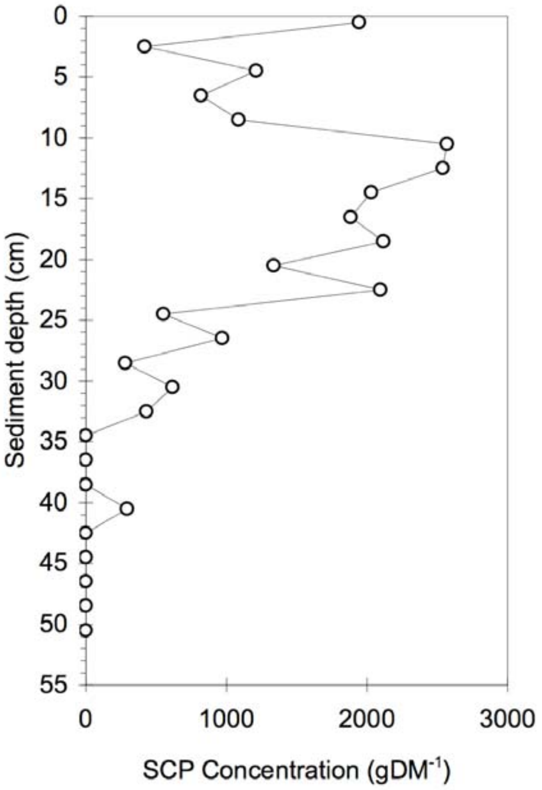
The SCP concentrations for MARS1 from Martham South Broad are shown in Table 2 and Figure 3 below. The first presence of SCPs occurred at 40 – 41cm and a continuous profile existed above 34 - 35cm. SCP concentrations increased irregularly from 34 – 35cm to a peak of over 2500 g DM^{-1} at 10 – 11 cm. With the exception of an elevated surface value, SCP concentrations decline from the peak to the sediment surface.

If it is assumed that the peak represents the period of maximum deposition then 10 - 11 cm may be ascribed the date 1978 (± 5) years. Given the sampling resolution this may lie between 9 and 12 cm. This produces a mean sediment accumulation rate for the most recent 30 years of 0.35 cm yr^{-1} (0.3 – 0.4 cm yr^{-1}). If this rate were extrapolated below 11 cm, then 1950, usually indicated by a rapid increase in SCP concentration, would be expected to occur at 20 – 21cm (17.5 – 23.5cm). However, this feature occurred below this range at 26 – 28cm suggesting that sediment accumulation rates were higher within this core between 1950 and 1978 with a mean sediment accumulation rate for this period of 0.589 cm yr^{-1} (0.553 – 0.625 cm yr^{-1}). Below this feature, SCP concentrations decrease rapidly to below the analytical detection limit. The presence of SCPs again at 40 – 41cm suggests that the end of the SCP record is due to concentrations falling below the detection limit, rather than being the start of the record in the mid-19th century. No dates can therefore be ascribed to MARS1 below 1950 except to say that sediments above 40 – 41cm are younger than 1850. The best available chronology is summarised in Table 2.

Table 2 Chronology for MARS1

Sediment depth (cm)	Age (Years)	Date
0	0	2008
5	14 ± 3	1994 ± 3
10	28 ± 5	1980 ± 5
15	38 ± 6	1970 ± 6
20	46 ± 8	1962± 8
25	55 ± 10	1953 ± 10
30	63 ± 12	1945 ± 12

Figure 3 MARS1 SCP concentration profile



MARS1 Macrofossil data

Summary macrofossil results for MARS1 comprising a selection of fossils of generally submerged species which summarise the major floristic changes along the length of the core are shown in Figure 4. Shifts in the animal macrofossil remains, in this case fish, macro-invertebrates, cladocerans, and molluscs can be seen in Figure 5.

Plant remains

The plant remains could be divided into three zones.

110-65 cm - The base of the sequence was characterised by a diverse flora containing *Myriophyllum spicatum*, *Potamogeton pectinatus*, *Potamogeton friesii* or *Potamogeton compressus*, *Hippuris vulgaris*, *Zannichellia palustris*, *Ranunculus* sect. *Batrachium* and notably *Ruppia maritma* and *Ruppia cirrhosa*. In the lowermost three samples the *Ruppia* seeds were numerous perhaps decreasing in number relative to *Potamogeton* taxa and *H. vulgaris* towards the top of the zone. *Chara* oospores of all three morphotypes identified here were present in very low numbers on the bottom zone.

65-20 cm - *(representing pre 1960)* In this section of the core the diverse assemblage of angiosperms was replaced by charophytes as the dominant component of the submerged flora at Martham Broad. *Potamogeton* species/species groups disappeared almost completely above the bottom most sample of this zone. *Chara* oospores numbers reached very high concentrations in this zone with all samples in this zone having >100 oospores per 100 cm^3. *Chara* type C was the most numerous with >1000 oospores per 100 cm^3 at the base of this zone.

20-0 cm - *(1960 to the present)* Remains of submerged and floating macrophytes were rare in the top section of the core. With only *H. vulgaris*, *Nymphaea alba*, *Z. palustris* and a very small number of *Chara* oospores present.

The plant macrofossil remains in MARS1 suggest that there have been profound changes to the submerged flora of the site since the Broad was formed. The current species rich macrophyte community is not well represented by the macrofossil record, though there are only two samples representing the last 40 years and analysis of other samples may provide a better reflection of the current site condition. There has been a shift from a diverse *Potamogeton-Myriophyllum-Ruppia* assemblage, through an assemblage dominated by *Chara* remains, which occurred at the same time as high carbonate content in the sediments. The final phase was relatively species poor, though in no way suggesting plants were absent.

Animal and cladoceran remains

The stratigraphy of selected animal remains from the macrofossil technique show a similar zonation to the plant macrofossil remains (Figure 5). The different zones in the animal stratigraphy were the mirrored those of the plant stratigraphy

110-65 cm - The bottom zone contained few animal remains with only foraminifera, which reflect a relatively high salinity and *Leydigia* and *Simocephalus* ephippia present in the bottom section of this zone. At the top of this section the currently rare bryozoan *Lophopus crystallinus* appeared briefly in the record.

65-20 cm - *(pre 1960)* This zone saw a increase in the diversity of remains, in particular many snail remains of both freshwater and more saline, such as *Theodoxus fluviatilis*. Chydorid taxa also became more numerous during this time as *Leydigia* spp. ephippia numbers fell.

20-0 cm - *(1960 to the present)* The fossil assemblage was sparse in this zone snail remains fell in number with only truly freshwater taxa present. *Leydigia* taxa re-appeared in the record and chydorid ephippia numbers disappeared. There were no pelagic taxa, or at least no significant numbers of pelagic taxa recorded in this core.

MARS1 interpretation

The macrofossil remains analysed in this core show that the site has undergone large shifts in the community composition since it was flooded in the medieval period. The initial phase strongly indicates a brackish system, with both freshwater and saline influences. The presence of foraminifera and *R. maritima* demonstrates that there were saline species present at that time. The permanence of brackish water and the degree of salinity is difficult to be sure of. There may have been relatively large inter-annual and decadal variation in the salinity of Martham Broad. The majority of the species present are tolerant of some level of salinity, such as *M. spicatum* and *P. pectinatus*. Towards the top of zone 1 there appears to have been a shift to a more freshwater system. The more saline tolerant species gave way to *Chara* species, which, with the exception of a couple of species, are mostly freshwater taxa. Without species level identification of the oospores it is difficult to be sure which species were present, the presence of *T. fluviatilis* in zone 2 does suggest some saline influence remained. Charophytes appear to have dominated the site for a long time, likely to be several hundred years. Indeed modern surveys show that *Chara* still dominate (Dan Hoare pers comm.). The palaeo record, however, suggests there has been some decline in the macrophyte abundance of the Broad. This may, however, be a function of the low resolution of the study, or patchiness of plant remains in more surface sediments. Analysis of cladoceran or perhaps ostracod remains at Martham South might be elucidate on more recent change as these two biological groups may more reliably identify significant changes in ecological function in shallow lakes. What is clear is that the Broad has undergone large changes in its submerged macrophyte flora, and that these changes appear to have been driven by changing salinity rather than eutrophication.

Figure 4 Summary stratigraphy for selected plant macrofossils for MARS1

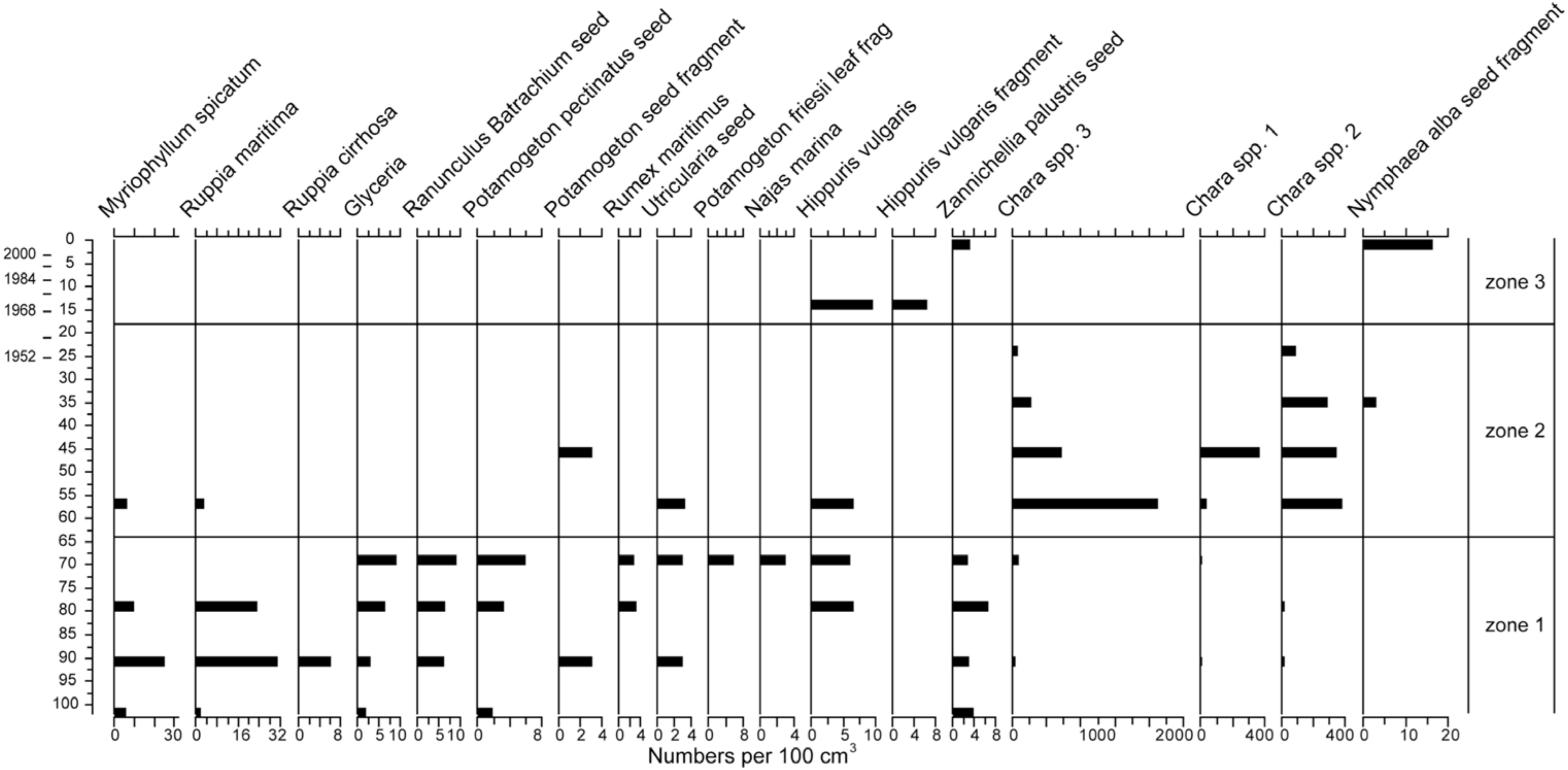
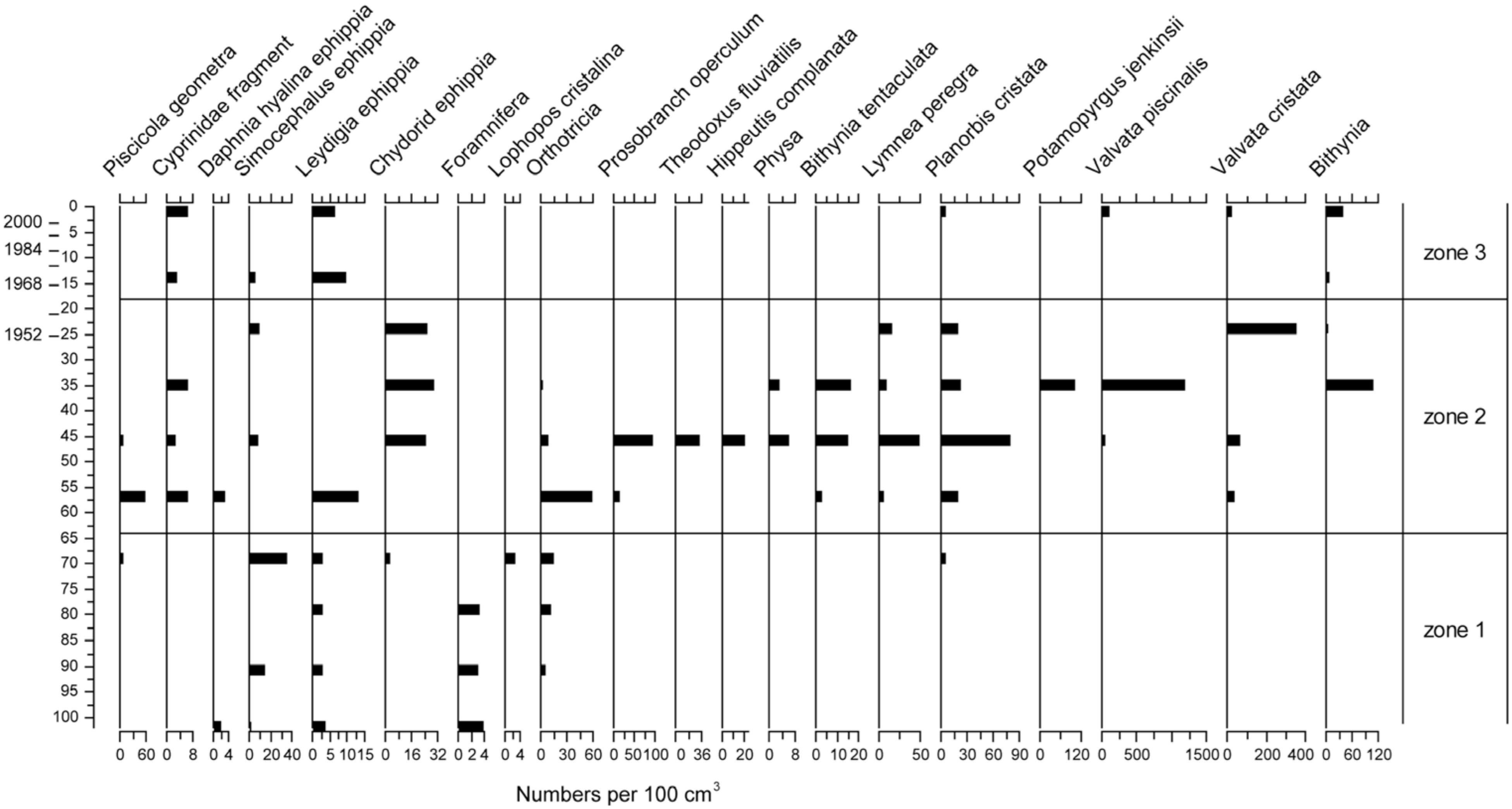


Figure 5 Summary stratigraphy of animal macrofossil for MARS1



Burntfen Broad

Burntfen Broad lies in the Bure catchment and is a relatively heavily impacted Broad having few macrophytes. It does, however, have extensive beds of *Nuphar lutea* along the western side of the Broad.. Figure 6 shows the Broad and the coring location and Table 1 provides details of the core and coring location.

Figure 6 Map of Burntfen Broad with location of BURF1

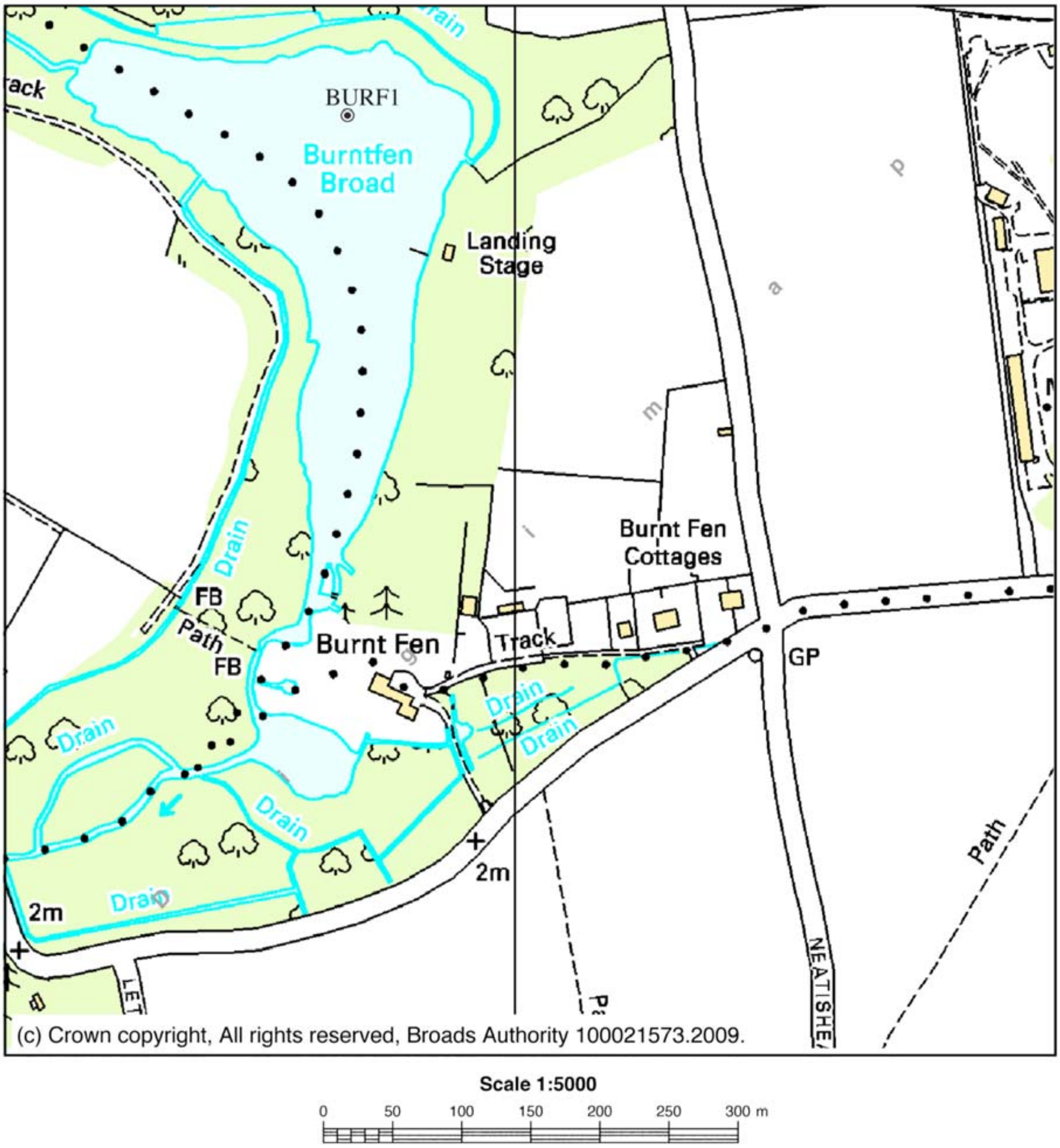


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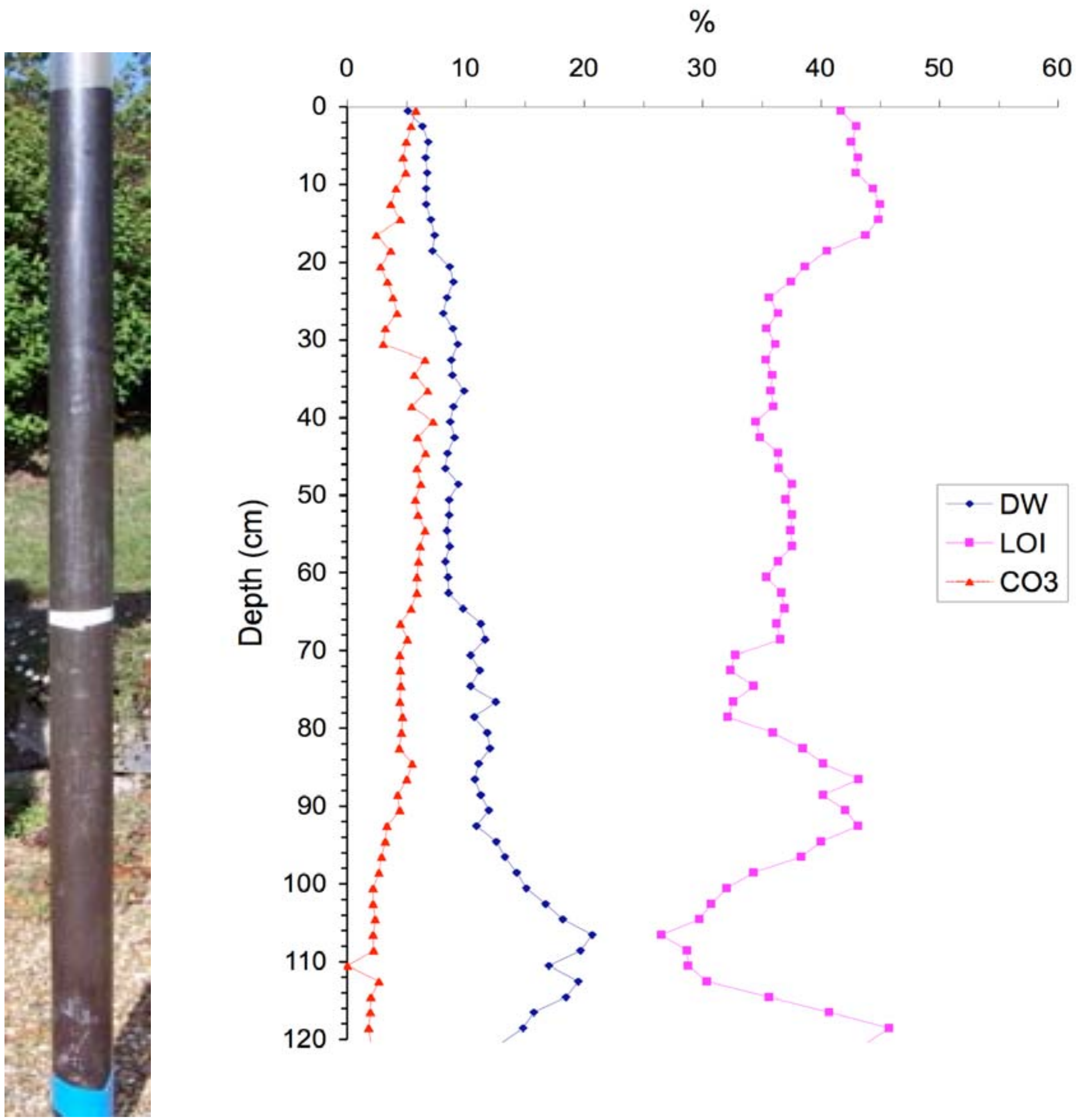
Figure 7 Lithostratigraphy of BURF1



Depth (cm)	Sediment colour
0-35	**dark-brown**
35-90	**mid-brown**
90-110	**light brown/marl**
110-120	**Peat**

BURF1 Core stratigraphy

The variability in the lithostratigraphy of BURF1 (Figure 7) was small. Organic content (LOI) was high, >40%, at the bottom of the core reflecting the peat at the base. There were several changes in the proportions of LOI and dry weight (DW) once the lake was formed above the peat. These changes were reflected by the alterations in the colour of the sediment (Figure 7). Above 30 cm there was a steady increase in LOI and decline in DW and carbonate.

BURF1 Core Chronology

The SCP concentrations for BURF1 from Burntfen Broad are shown in Figure 8 below. The first presence of SCPs occurs at 39 – 40cm and a continuous profile exists above this level. SCP concentrations increase slowly from 39 – 40cm until 27 – 28 cm when concentrations increase more rapidly. A peak SCP concentration of almost 5000 g DM^{-1} occurs at 9 – 10cm and then, with the exception of an elevated surface value, SCP concentrations decline again to the surface. The SCP concentration peak is usually the most easily definable feature of the SCP profile. If it is assumed that the peak represents the period of maximum deposition then 9 - 10 cm may be ascribed the date 1978 (± 5) years. Given the sampling resolution this may lie between 7 and 12 cm. This produces a mean sediment accumulation rate for the most recent 30 years of 0.317 cm yr^{-1} (0.233 – 0.400 cm yr^{-1}). If this rate is extrapolated below 10cm, then 1950, usually indicated by a rapid increase in SCP concentration, would be expected to occur at 18 – 19cm (13.5 – 23cm). However, this feature appears to occur below this range at 26 – 28cm suggesting that sediment accumulation rates were higher within this core between 1950 and 1978 with a mean sediment accumulation rate for this period of 0.625 cm yr^{-1} (0.461 – 0.972 cm yr^{-1}). Below this feature, SCP concentrations are low and the record probably stops as a result of SCP concentration falling below the analytical detection limit, rather than being the start of the record in the mid-19th century. No dates can therefore be ascribed to BURF1 below 1950. The best available chronology is summarised in Table 3.

Figure 8 BURF1 SCP concentration profile

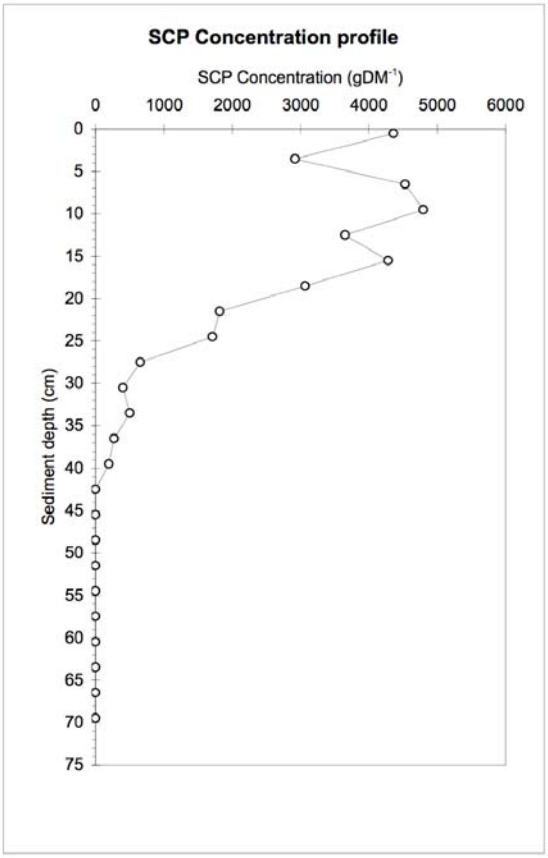


Table 3 Chronology for BURF1

Sediment depth (cm)	Age (Years)	Date
0	0	2008
5	16 ± 4	1992 ± 4
10	31 ± 5	1977 ± 5
15	39 ± 7	1969 ± 7
20	47 ± 8	1961± 8
25	55 ± 10	1953 ± 10
30	63 ± 12	1945 ± 12

BURF1 Macrofossil data

Plant remains

Zone 1 (120- 75cm) The abundance and diversity of macrofossil remains were both very high within zone 1 (Figure 9). *Callitriche* seeds and *Ceratophyllum* spines were present in the lower section of the zone but were absent from the top 2 samples of the zone. Oospores of *Chara* (oval) were present throughout the zone but increased at 80cm. Oospores of *Chara* (round) were also present in this 80cm sample. In contrast *Nitella* reached maximum abundance in the lowest sample (115cm) then decreased at 110cm and 100cm and then increased again towards the top of the zone. *Zannichellia* seeds also increased towards the top of the zone.

Potamogeton diversity was extremely high within zone 1 with remains of *P*. cf. *obtusifolius*, *P. pusillus* agg., *P. compressus*, *P. crispus* and *P. fressii*/ *compressus* agg. all found within zone 1. Remains from a broad leaf *Potamogeton* species were also present towards the top of the zone. *Ranunculus* sect. *Batrachium* remains first appeared at 110cm then increased markedly at 80cm. Remains of *Nymphaeaceae* trichosclereids appeared at the top of this zone but the numbers were low.

Zone 2 (75- 0cm) The diversity and abundance of macrofossils remains greatly reduced in this zone. *Potamogeton* species remains occurred in the lower section of zone 2 but were absent from the record above 55cm. *Callitriche* seeds, *Ceratophyllum* spines, *Zannichellia* seeds and *Chara* (oval) were present at 70cm but were absent from the rest of the zone. *Ranunculus* sect. *Batrachium* seed fragments were also absent above 40cm. *Stratiotes aloides* spines first appeared at 60cm and reached a maximum abundance of 83 at 40cm but decreased thereafter. *Nymphaeaceae* trichosclereids remains increased greatly within zone 2 and reach their maximum in the uppermost sample. *Lemna* spp. leaves were also present in this uppermost sample.

Animal remains

Zone 1 (130- 75cm)

The lower section of the core was dominated by *Cristatella* and *Plumatella* statoblasts, oribatid mite heads and *Orthotrichia* cases (Figure 10). *Piscicola geometra* and Frontoclypeal apotome remains of caddis fly were present throughout most of zone 1.

Remains of *Ceriodaphnia* spp., *Leydigia* spp. and *Daphnia hyalina* spp. increased towards the top of the zone. Whereas *Simocephalus* spp. remains were present, in low numbers, in the lower section of the core they were absent from the rest of the profile.

Figure 9 Plant Macrofossil stratigraphy of BURF1

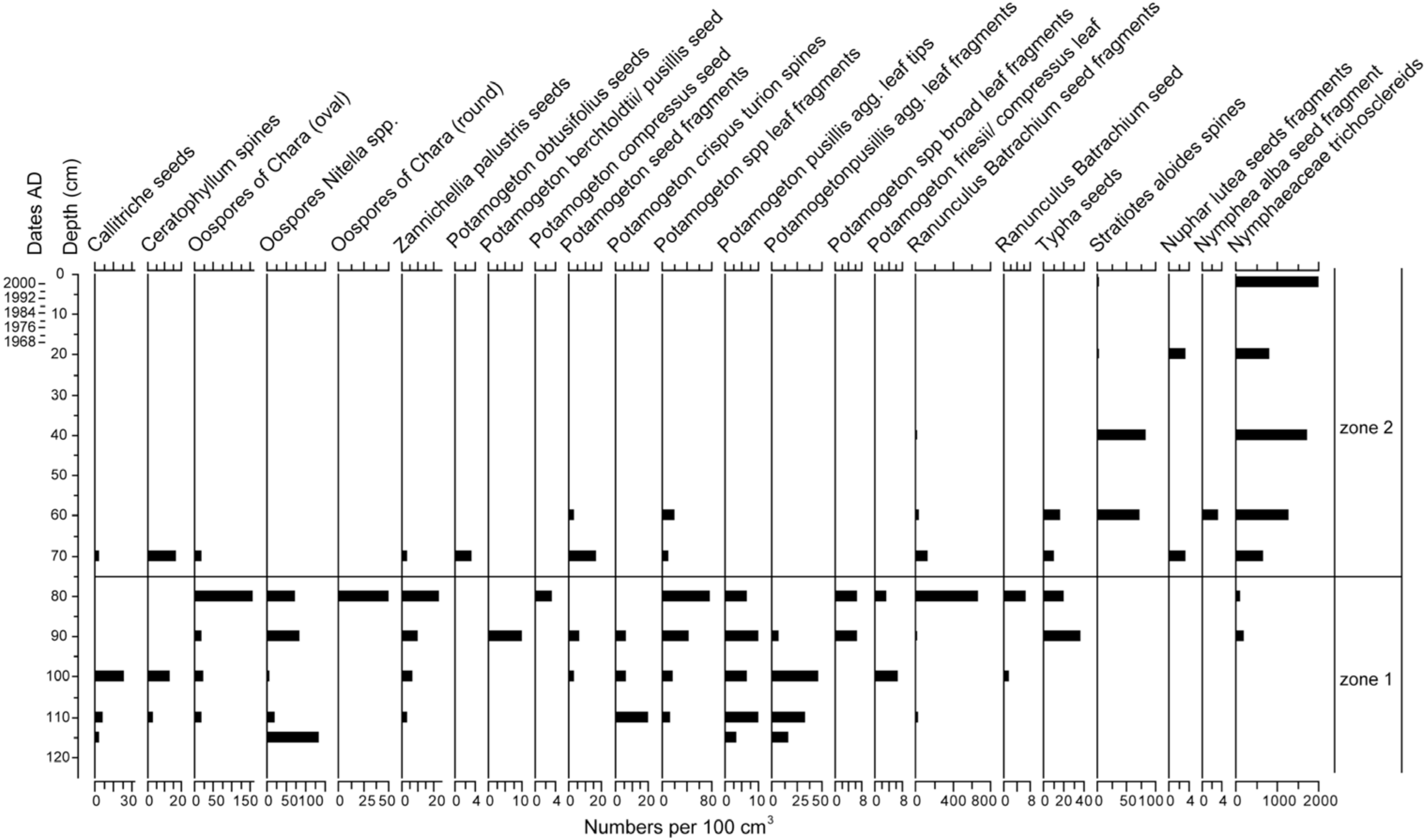
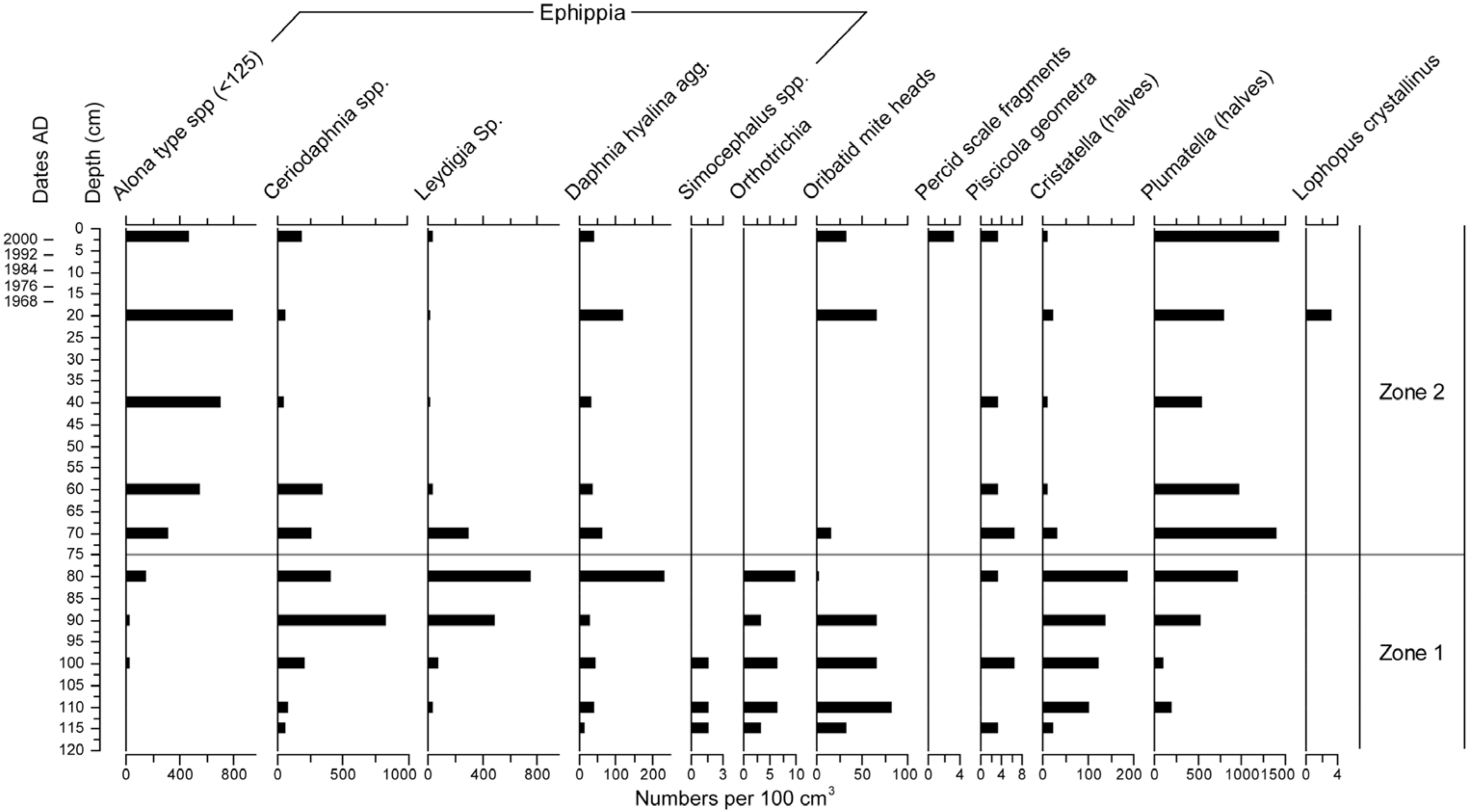


Figure 10 Animal macrofossil stratigraphy for BURF1



Zone 2 (75- 0cm)
Numbers of *Plumatella* statoblasts remained high in zone 2 decreasing slightly in the middle of the zone (20cm and 40cm samples). In contrast the numbers of *Cristatella* statoblasts were greatly reduced in zone 2. A few *Lophopus* remains were found in the 20cm sample. Oribatid mites decreased in number in the lower section of zone 2 and then increased again towards the top of the core. *Orthotrichia* cases were absent from zone 2 and the numbers of Frontoclypeal apotome remains are also reduced in the upper section of zone 2.

Remains of *Ceriodaphnia* spp., *Leydigia* spp. and *Daphnia hyalina* spp. were present throughout zone 2 in reduced numbers. In comparison *Alona* type ephippia numbers increased in zone 2.

BURF1 interpretation

The diversity and abundance of plant remains was very high at the base of the core, in zone 1, which can speculatively be said be from the initial flooding of the Broad to between 1700 and 1800 AD. *Potamogeton* species remains, a species group which is generally quite poorly represented in the sediment record (Davis 1985; Davidson *et al*. 2005), were particularly abundant and diverse. There were at least 5 species of *Potamogeton* recorded, including a broad-leaved species and the currently rare *P. compressus* in addition there were at least 2 species of *Chara*, one of *Nitella*, *Callitriche*, *Ceratophyllum* and *Ranunculus* sect. *Batrachium*. Thus, there were at least 11 species of submerged plant remains found in the first zone of the core from Burntfen Broad. Plant macrofossil analysis reflects the dynamics of the dominant components of the submerged flora (Davidson et al. 2005), thus it is likely that Burntfen Broad may have supported many more species, as relatively rare species are unlikely to be recorded in the sediments. The fauna represented by the core below 75cm was a mixture of benthic and pelagic taxa, with *Daphnia* and C*eriodaphnia* ephippia present in high numbers, in particular towards the top of zone 1 and *Simocephalus*, *Leydigia*, *Orthotricia* and *oribatid* mites below 75 cm, suggesting abundant benthic habitats, a corollary of abundant submerged plant cover. Above 75 cm and in particular above 60 cm there was a dramatic decline in the remains of submerged species with a shift to floating-leaved vegetation, represented by *S. aloides* and *Nymphaeaceae*. This occurred in concert with a change in animal remains with an increase in *Alona* type ephippia remains and a decrease in the larger bodied cladoceran remains. In the absence of data on the chitinous cladoceran remains it is difficult to isolate the cause of these observed shifts. They are, however, likely to have resulted from a decline in the abundance and diversity of submerged plants, which is strongly suggested by the macrofossil data. It is likely, however there has been both and shift in the balance from benthic to pelagic productivity (Vadeboncoeur et al. 2003) and an increase in the density of zooplanktivorous fish (Jeppesen et al. 2000) both of which will lead to a decrease in quality of the light climate required by submerged plants.

To summarise the data suggest a very large change in the flora of Burntfen over the last several 100 years with the loss and a diverse and abundant submerged flora and a shift to a large phytoplankton crop despite the presence of relatively large beds of white and yellow water lily.

Sotshole Broad

Sotshole Broad lies in the Southern Bure catchment (Figure 11), it is currently a very shallow Broad, which is reflected in the water depth from which the core was collected (Table 1).

SOTS1 Core stratigraphy

The lithostratigraphy of the core can be seen in Figure 12, the base of the core had high LOI and low carbonate which is characteristic of peat. From 210 to 155 cm high LOI and low carbonate persisted, thereafter there was a sharp decline in LOI from 80% to 30% at 140 cm, there was a concurrent increase in carbonate from 5% to 25% at the same time. These changes were reflected in the shift from peat to a more marl like sediment which was first brown then more grey. This persisted up the core to around 110 cm where there was a darkening of sediment colour an increase in LOI and a decrease in carbonate.

Figure 11 Map of Sotshole Broad with coring location

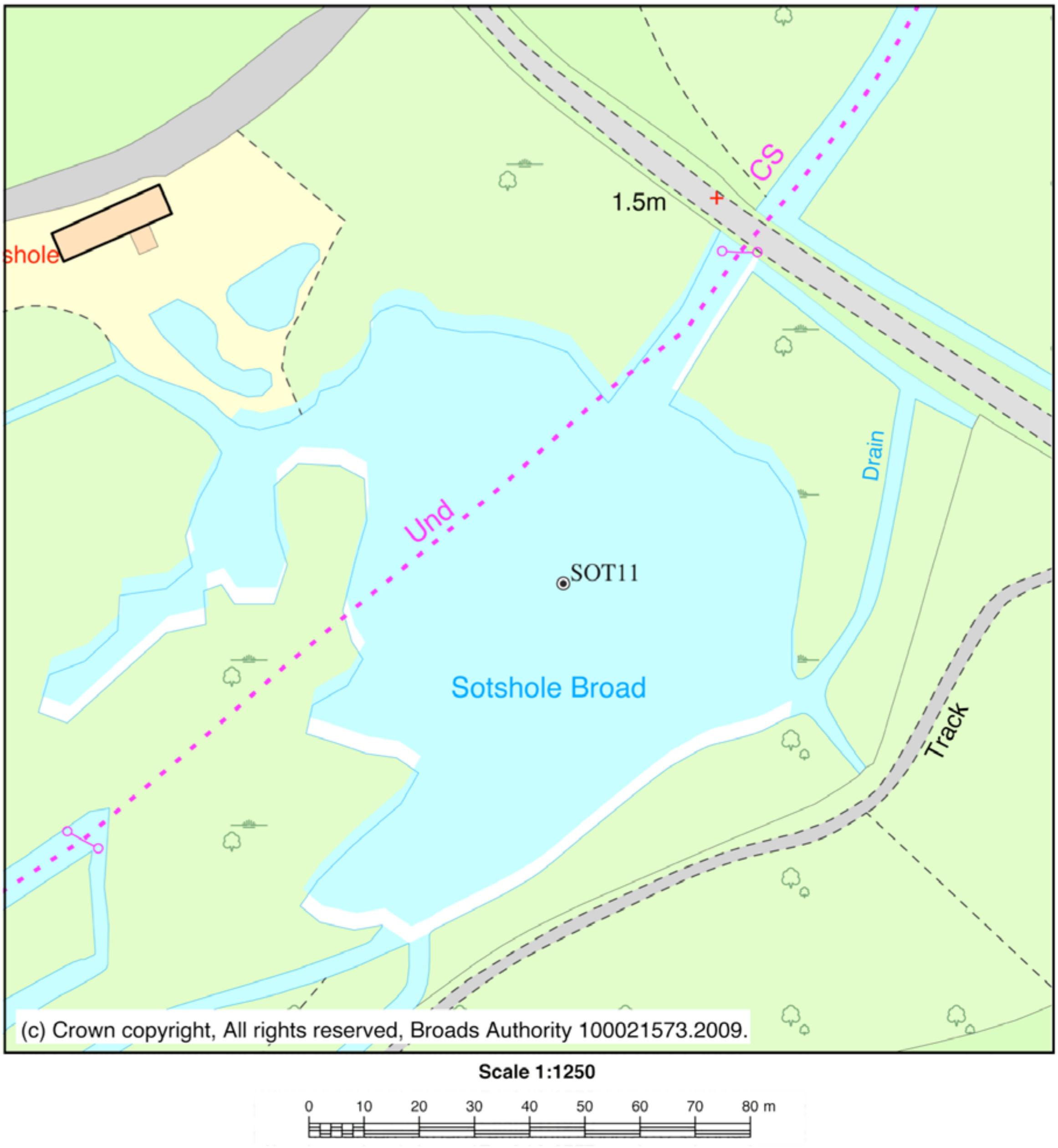
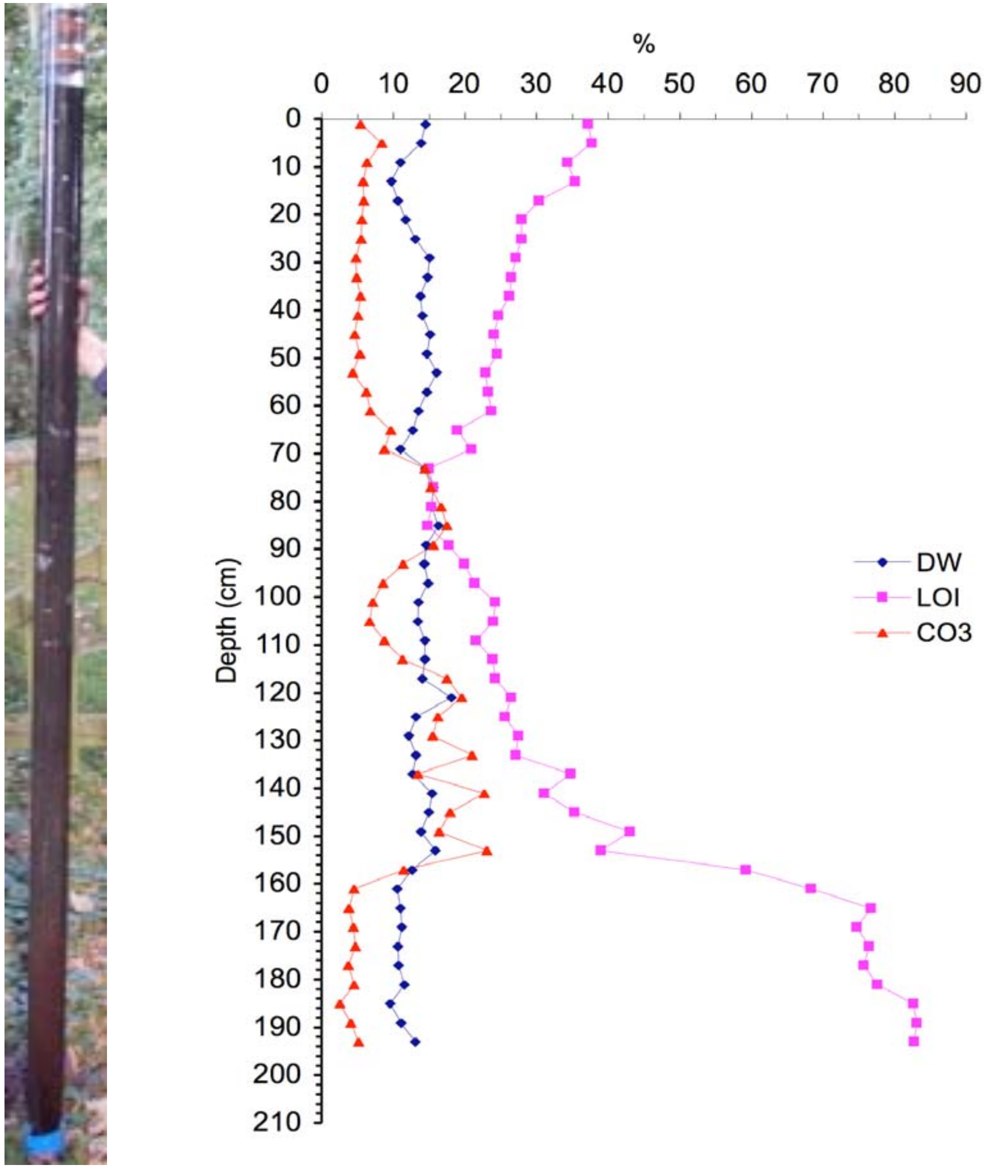


Figure 12 SOTS1 lithostratigraphy



Depth (cm)	Sediment colour
0-50	Very dark brown
51-110	Gradual change from black to grey
110-155	Grey with mollusc shells
155-180	Brown with mollusc shells
180-210	dark brown/peat

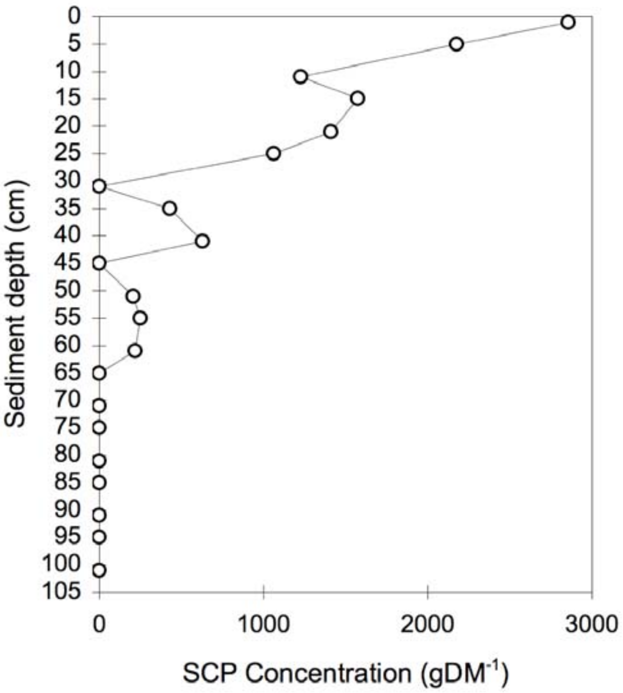
SOTS1 Core chronology

The SCP concentrations for SOTS1 from Sotshole Broad are shown in the Table 4 and Figure 13 below. Low SCP numbers were observed throughout the core above 60 – 62 cm resulting in low concentrations and large confidence intervals. However, a continuous profile was interrupted at 44 – 46cm and at 30 – 32cm where no SCPs were found. It is unclear why the record was interrupted at these points. There are no clues in the lithostratigraphic data which may indicate a reason.

Table 4 Chronology for SOTS1

Mean depth (cm)	SCP conc (gDM^{-1})	90% C.L. (gDM^{-1})
1	2856	1143
5	2176	870
11	1226	454
15	1575	690
21	1412	523
25	1063	521
31	0	0
35	430	298
41	629	356
45	0	0
51	206	202
55	251	246
61	218	214
65	0	0
71	0	0
75	0	0
81	0	0
85	0	0
91	0	0
95	0	0
101	0	0

Figure 13 SOTS1 SCP concentration profile



A first presence of SCPs occurs at 60 – 62 cm and, with the exceptions of the two levels mentioned above for which concentrations were 0 gDM^{-1}, SCP concentrations generally increase from this first presence to the sediment surface. Concentrations increase more rapidly above 30cm and a maximum concentration of almost 3000 gDM^{-1} is observed in the surface sediment sample. This is unusual, as a decline in SCP concentration is usually observed in the uppermost levels of UK sediment cores. It is unclear why there is no sub-surface SCP concentration peak, but this may be due to sediment disturbance or a missing section of sediment accumulation at the top of the core. If the latter is true then at least the most recent 30 years is absent from this core.

As a result of this unusual profile, it is not possible to date the SOTS1 core using SCPs. It maybe that the depth of around 30cm corresponds to the 1950s, the start of a period of rapidly increasing SCP concentration following the Second World War, but there is a great deal of uncertainty about this. The only chronological information that can be stated with any certainty for SOTS1 is that the sediments above 60 – 62cm are more recent than 1850, as they contain SCPs.

SOTS1 Biological data

Plant remains

Zone 1 (160-60 cm) had a diverse species assemblage, with 7 aquatic macrophyte species and 4 types of *Chara* present (Figure 14). The basal part of zone 1, below 120 was the richest section, with both fine-leaved and broad-leave *Potamogeton* found along with *Zannichellia palustris* seeds, *Ceratophyllum* spp., above 120 cm *Stratiotes aloides* leaf spines, and *Nymphaeaceae* trichosclereids became more numerous.

Zone 2 (60cm to surface) saw all plant remains, with the exception of *Stratiotes aloides* leaf spines, and *Nymphaeaceae* trichosclereids, disappear.

Animal remains

Zone 1, in particular below 110 cm, had an abundant and diverse faunal assemblage, with a number of mollusc species recorded (Figure 15). *Ceriodaphnia* spp. was the dominant component of the cladocera fauna, with *Daphnia* also present in the lower section of the core. Above 110 cm there was a decline in the mollusc fauna, with all species declining, this occurred at the same time as the decline in the number and abundance of plant remains.

In zone 2 above 60 cm cladoceran ephippia, in particular pelagic species *Daphnia hyalina* was present at relatively stable abundances, other taxa including *Leydigia*, *Simocephalus*, *Alona* and *Daphnia magna* increasing towards the top of the core.

SOTS1 interpretation

The lack of a good chronology for SOTS1 means that it is difficult to identify the timing of any of the observed changes in the sediment core. The base of the sequence was peat, which suggests the core goes back to the medieval formation on the water body.

The plant macrofossil analysis indicates that Sotshole Broad has undergone a series of profound changes in the flora and fauna. The study suggests that these changes either happened a relatively long time ago, or that the sediment accumulation rate has been very high since the change occurred. At this time a relatively specie rich *Potamogeton* and *Chara* spp. dominated community was lost and replaced by a floating leaved species. The likely increase in accumulation rate may also contribute to the decline in the abundance of remains.

Figure 14 Plant macrofossil stratigraphy of SOTS1

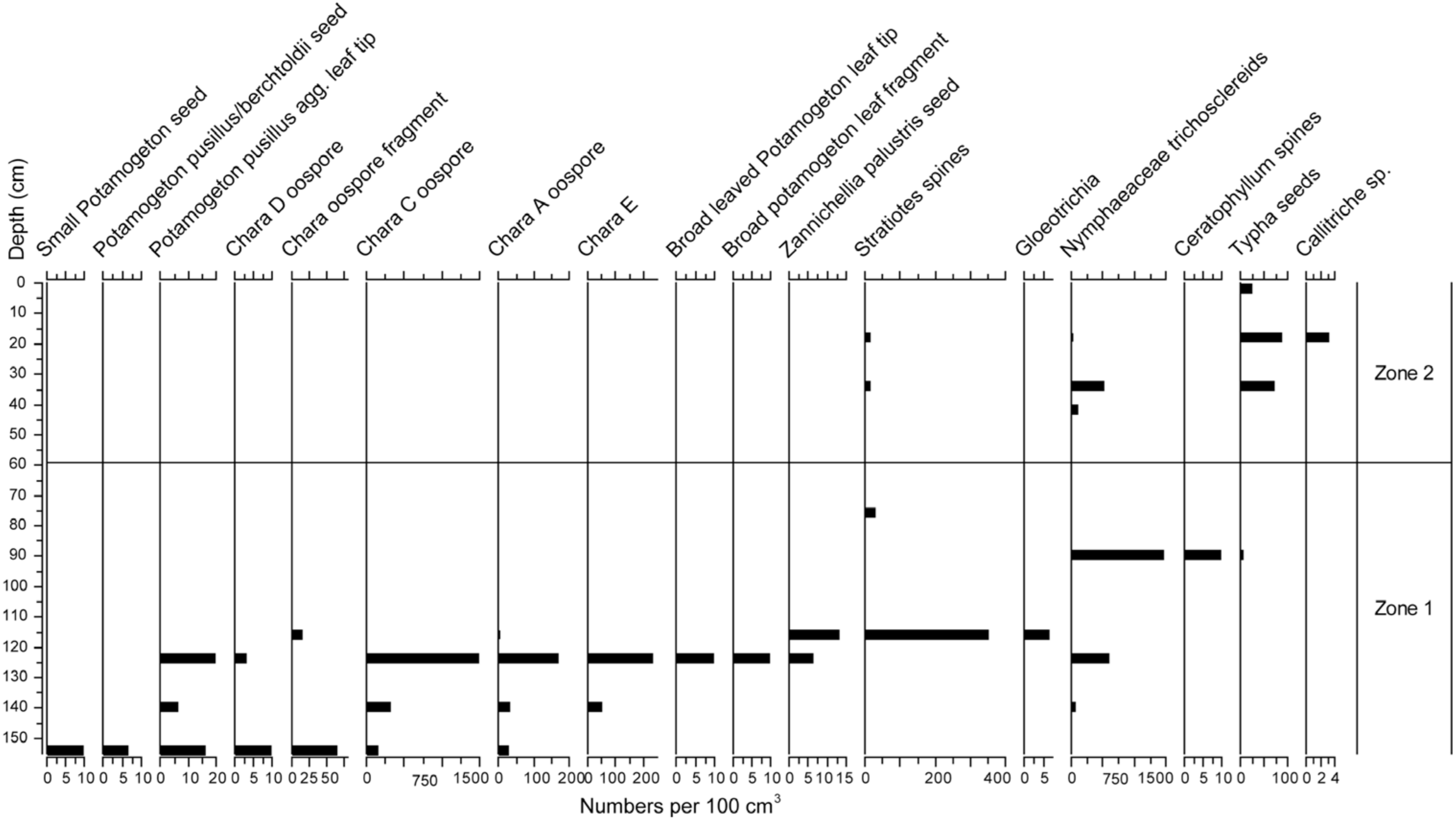
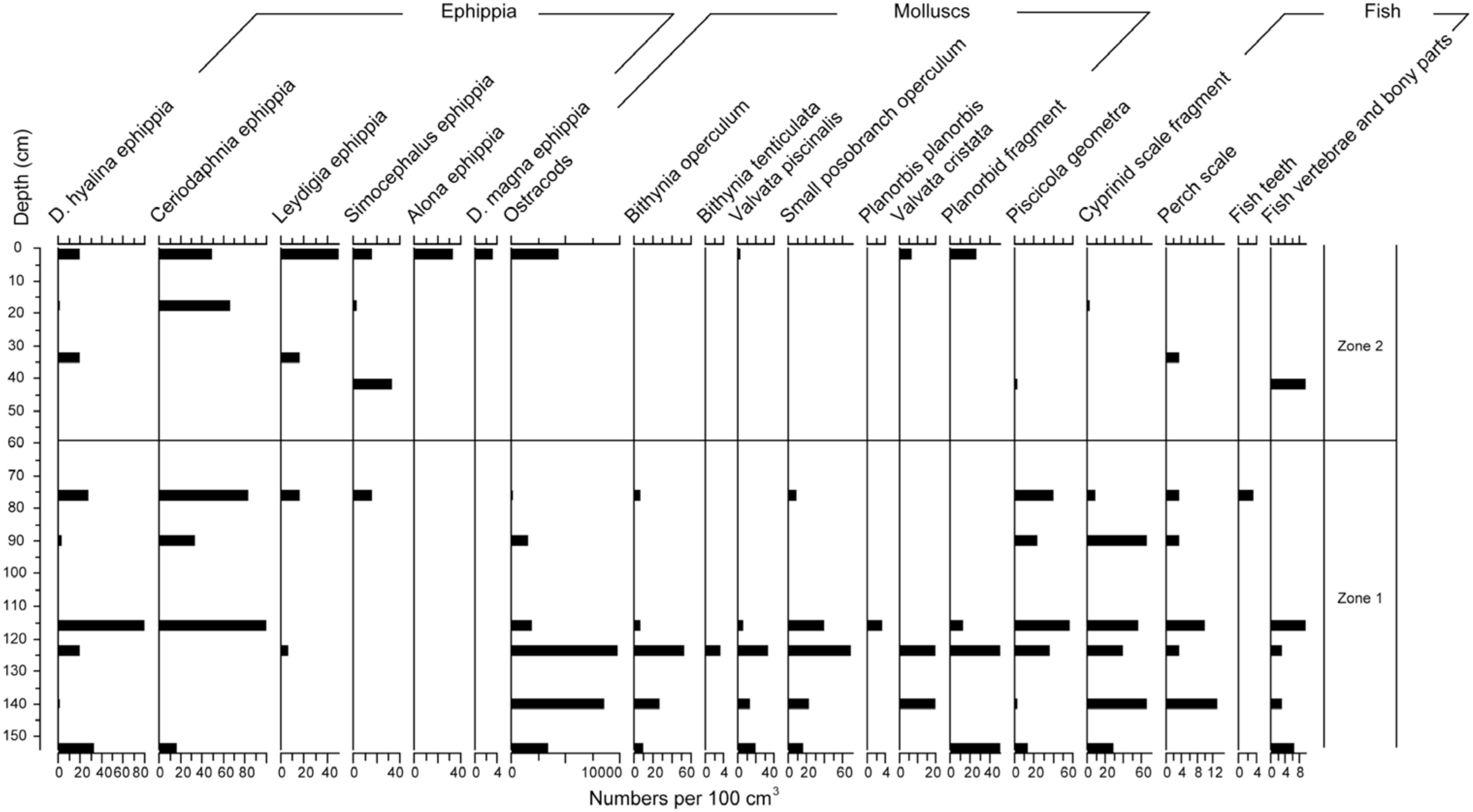


Figure 15 Animal macrofossil stratigraphy from SOTS1

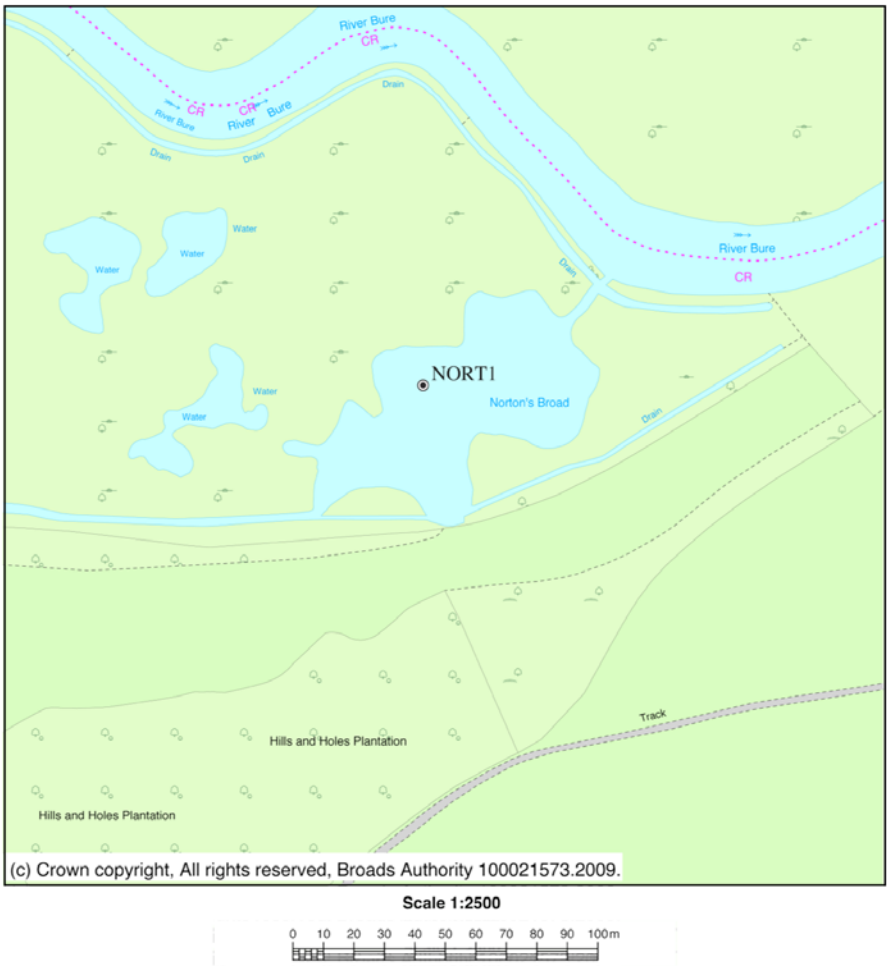


The changes in invertebrate fauna mirror those of the plants with the loss of plant associated mollusc species, replaced by more pelagic cladoceran taxa and a general decline in the number of remains.

Nortons Broad

Nortons Broad is an extremely shallow Broad located in the Bure catchment just south of Wroxham (Figure 16). The Broad's connection to the river has historically resulted in extremely high accumulation rates. This has resulted in a very thin skim of water overlying the mud surface, reflected in the very shallow water depth at the coring site (Table 1). Dating of the sediment core was not attempted due to limited resources and the greater likelihood of the dating techniques not working at site wit very high accumulation.

Figure 16 Map and coring location of Nortons Broad



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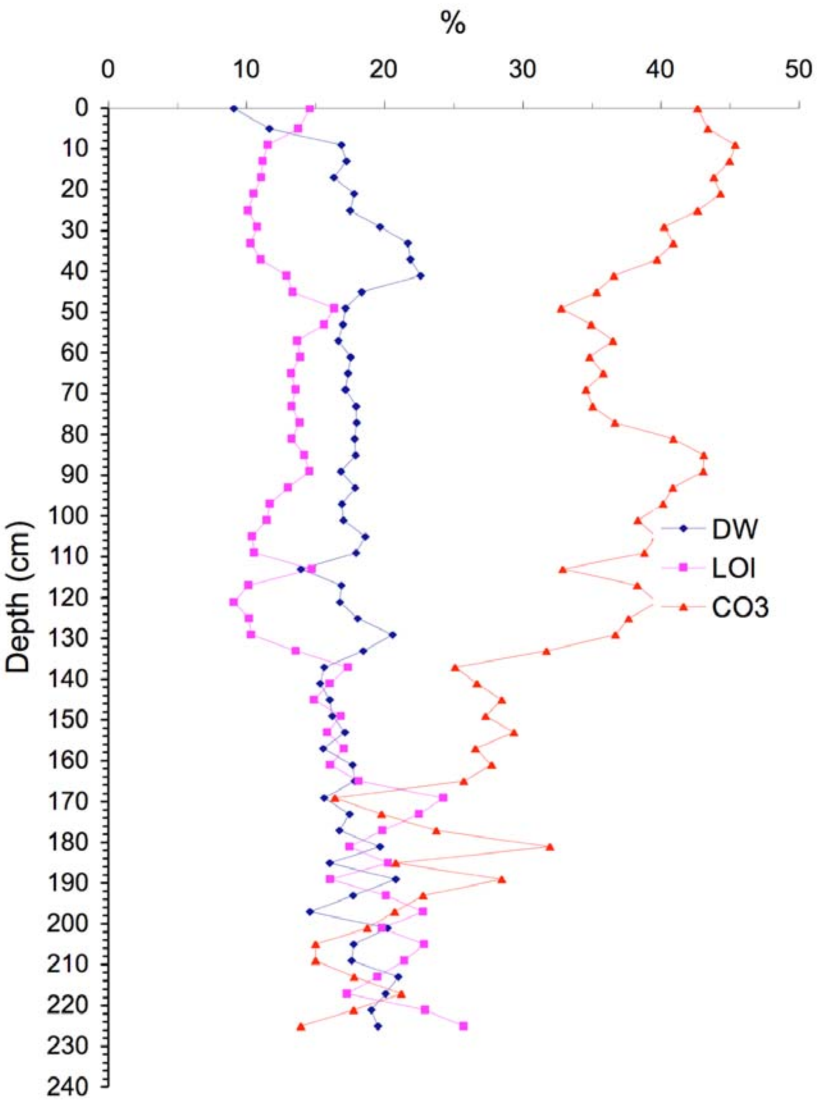
NORT1 core lithostratigraphy

The core NORT1 did not have very high LOI at any part of the core, and thus does not cover the entire life of the Broad (Figure 18). The LOI is in fact quite low for a Norfolk Broad, suggesting that the riverine influence on the lake has been very important to the sediment structure. LOI and dry weight did not vary greatly along the entire length of the core. In contrast carbonate increased at 140 cm to around 40% and continued at a relatively high level to the surface of the core.

Figure 17 Lithostratigraphy NORT1



Depth (cm)	Sediment colour
0-150	light-brown
150-190	black sediment

NORT1 Biological remains

Figures 18 and 19 are summaries of the stratigraphy of the plant and animal remains found in the core. The species plotted in the diagrams were selected on the grounds of abundance and relevance to the investigation. The absence of dating for the core means that, whilst it is safe to assume changed up the core are chronological, no date can be ascribed to any observed patterns.

Plant remains

There were relatively few remains in the core from Nortons Broad. The very high accumulation rates mean that any remains are diluted by the volume of, often riverine, sediments. There were, however, some remains found. The aquatic macrophyte assemblage in Zone 1 was dominated by the leaf spines of *Ceratophyllum* spp. and *Nymphaeaceae* trichosclereids. Aquatic and terrestrial moss leaves and *Juncus* seeds were also common in this zone. In, addition the remains of a broad-leaved *Potamogeton* (cf. *praelongus*) and fine-leaved *Potamogeton pusillus* agg. were found, though these *Potamogeton* remains only appeared in the record at a depth of 184cm.

In zone 2 *Nymphaeaceae* trichosclereids and *Ceratophyllum* spines were still present and even relatively abundant in the lower half of the zone, below 100 cm. Furthermore other aquatic species, in this case *Chara* oospores and the seeds of *Hippuris vulgaris* were also found in low numbers around 100 cm. Above 100 cm all remains fell in abundance, with only filamentous algae threads and very few *Ceratophyllum* spines present in the surface sediments.

Animal remains

Consistent with the patterns in the plant remains there were very low abundances and diversity of animal remains above 100 cm. Below 100 cm, in particular below 160 cm mollusc remains were abundant as were cladoceran ephippia both benthic, *Leydigia* spp. and pelagic, *Ceriodaphnia* spp., taxa. Above 100 cm there was a complete absence of pelagic cladoceran species and very occasional remains of mollusc, in particular *Valvata* species, which are more with mud surfaces rather than plant surfaces.

NORT1 interpretation

In the absence of a reliable chronology the timing of any changes revealed by the core cannot be identified. Furthermore, the large riverine input may have provided a large volume of sediment making remains rare and therefore more difficult to find. The input of large volumes of sediment would however, severely impact any plant species present. In addition the core does not appear to go back to a time period where the broad was minimally impacted. Given these caveats, the data from NORT1suggest that the macrophyte flora of Nortons Broad has changed over the time period represented by the core. The macrophyte abundance at the time represented by the bottom section of the core was probably high, dominated by *Ceratophyllum,* several species of *Potamogeton* and water lily. This community supporting a relatively diverse mollusc and cladoceran fauna, with both benthic and pelagic taxa present. Above 100 cm in the there appears to have been a profound change with the loss of abundant submerged plants. Whether this resulted from a high algal crop through nutrient enrichment, sediment input from the river, or a reduction in water depth to a point where submerged plants were not viable is difficult to say. The lack of any pelagic taxa in the cladoceran assemblage suggests that the there may have been insufficient water depth to support planktonic organisms. Despite this, it may have been a combination of all these factors contributed to the loss of an ecologically robust ecosystem. Any attempt to restore the site may need to address all these factors.

Figure 18 Plant macrofossil remains for the core NORT1

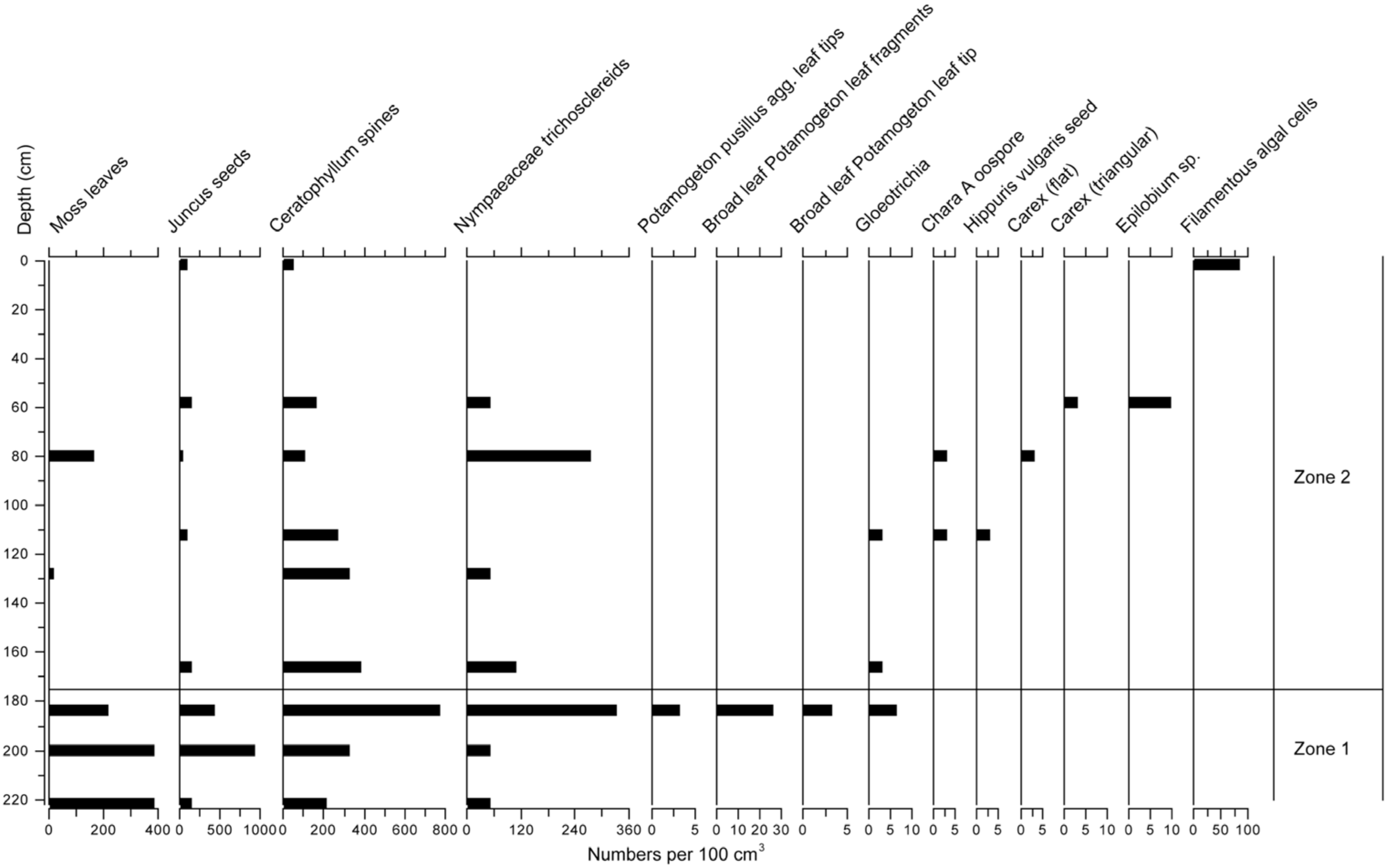
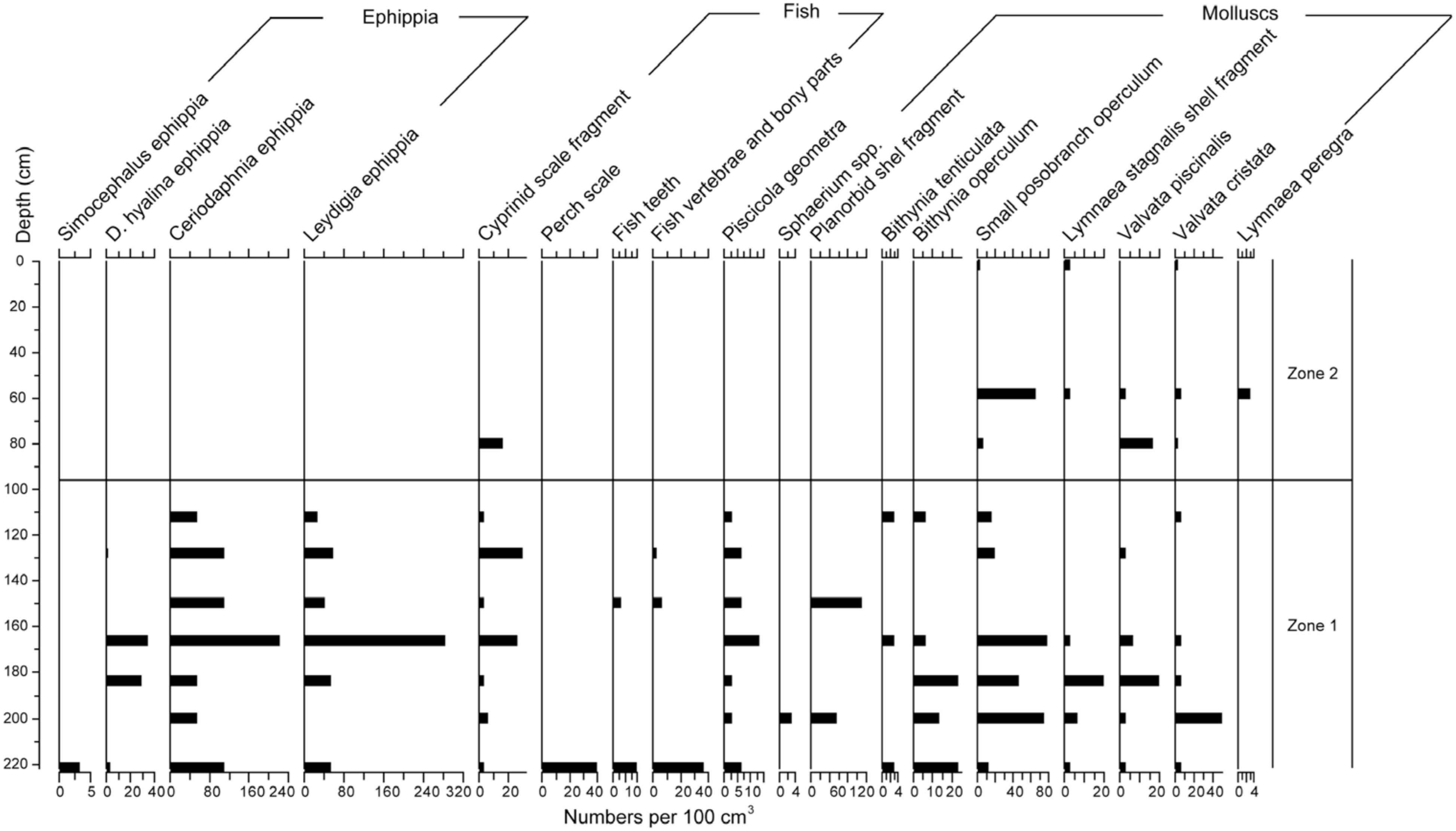


Figure 19 Animal macrofossil stratigraphy for the core NORT1



Mautby Decoy

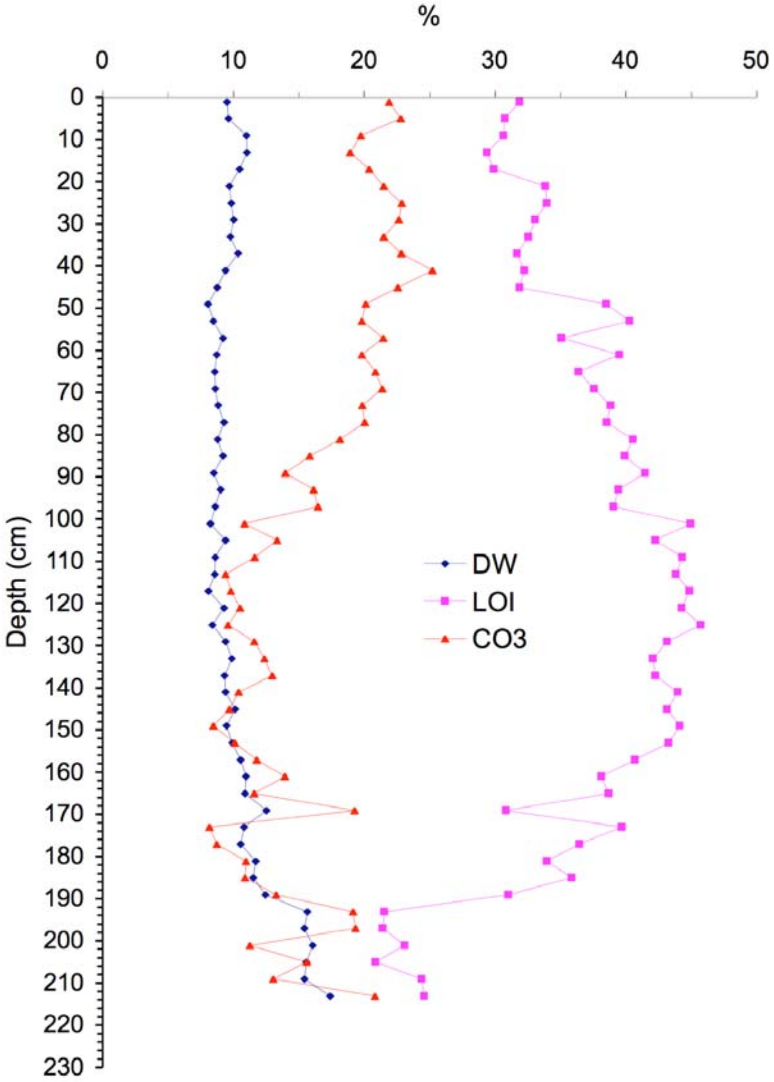
The map of the site and core location of MAUT1 is shown in Figure 20 and the details of location water depth and core length in Table 1.

Figure 20 Map of Mautby Decoy with the location of MAUT1

MAUT Core stratigraphy

The lithostratigraphy of MAUT1 showed considerable variation with the base of the core from 220 to 200 cm having low LOI and relatively high carbonate. Above 200 cm LOI rose sharply from 20% to 40% and carbonate fell to 10%. Between 180 and 50 cm LOI remained high and then fell gradually to 30% at the surface of the core. Carbonate stay low from 180 to 100 cm then started to rise gradually to 20%at 70 cm and stayed relatively stable until the surface. Dry weight of the sediment did not vary great along the length of the core.

Figure 21 Lithostratigraphy of MAUT1



Depth (cm)	Sediment colour
0-40	black
40-180	Pale grey
180-220	marl like

MAUT1 Core chronology

The SCP concentrations for MAUT1 from Mautby Decoy are shown in Figure 22 below. The first presence of SCPs occurs at 56 – 58cm and a continuous profile exists above 34 - 35cm. SCP concentrations increase slowly from 56 – 58cm up to 48 – 50cm when they increase more rapidly to a peak of just over 3000 g DM^{-1} at 24 – 26 cm. SCP concentrations then decline from the peak to the sediment surface. The SCP concentration profile from MAUT1 appears remarkably smooth but the coarse sampling and analytical interval undoubtedly conceal a degree of noise. These coarse intervals increase uncertainty in the dates that may be ascribed.

If it is assumed that the peak represents the period of maximum deposition then 26 - 28 cm may be ascribed the date 1978 (± 5) years. Given the sampling resolution this may lie between 18 and 32 cm. This produces a mean sediment accumulation rate for the most recent 30 years of 0.833 cm yr^{-1} (0.60 – 1.07 cm yr^{-1}). If this rate is extrapolated below 28 cm, then 1950, usually indicated by a rapid increase in SCP concentration, would be expected to occur at 48 – 49cm (35 – 62 cm). This appears to agree well with the observed profile where this feature would appear to lie between 45 and 50cm. Therefore, the data suggest that sediment accumulation rates in the MAUT1 core have remained largely unchanged over the last 50 – 60 years. Below this depth, SCP concentrations decrease to below the analytical detection limit between 56 - 58cm and 64 - 66cm. This is due to concentrations falling below the detection limit, rather than being the start of the record in the mid-19th century. No dates can therefore be ascribed to MAUT1 below 1950 except to say that sediments above 56- 58cm are younger than 1850. If the sediment accumulation rate of the last 50 – 60 years also remained unchanged in the past then 1850 might be expected to lie at around 130cm depth. However, any such extrapolations should be treated with utmost caution. The best available chronology is summarised in Table 5.

Figure 22 SCP Concentration profile for MAUT1 core from Mautby Decoy.

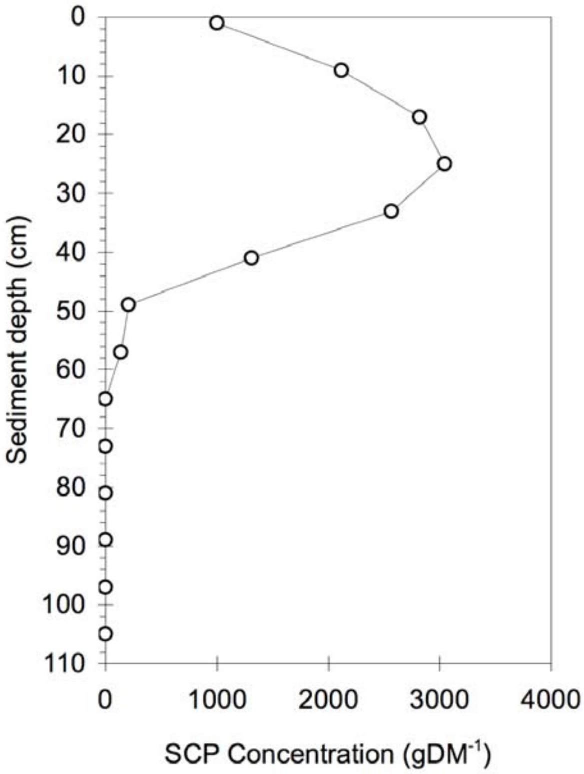


Table 5 Chronology for MAUT1. Dates in italics should be treated with more caution.

Sediment depth (cm)	Age (Years)	Date
0	0	2008
10	12 ± 4	1996 ± 4
20	24 ± 6	1984 ± 4
30	36 ± 8	1972 ± 8
40	48 ± 10	1960± 10
50	60 ± 12	1948 ± 12
60	*72 ± 15*	*1936 ± 15*

MAUT1 Biological remains

Plant remains

The lowest zone consisted of one sample at the base of the core which contained remains of *Hippuris vulgaris, Ranunculus* sect. *Batrachium* along with fine and broad-leaved *Potamogeton* species (Figure 23). In zone 2 there was a change in assemblage with *Chara*, *Myriophyllum* spp., *Nymphaea alba* and *Nuphar lutea,* and *Ceratophyllum* spp. all present. There was a slight difference between the bottom half of the zone and the top half with a shift from *Chara* dominance, through *Myriophyllum* and *Ranunculus* through to *Nymphaeaceae* and *Ceratophyllum* towards the top of zone 2. Zone 1 had just one sample, containing *Ceratophyllum* spp. and fine-leaved *Potamogeton* species were the only aquatic macrophyte remains found. Gloeotrichia and filamentous algae were also present at this level.

Animal remains

Animal remains were very abundant and diverse in this core. The zones were different from those for the plant remains (Figure 24). The division coming around 110cm, this was the point in the plant record where *chara* dominance gave way to elodeid plants such as *Myriophyllum* and *Ceratophyllum*. In the lowest section *Leydigia* and *Ceriodaphnia* ephippial remains were most abundant, there was evidence of fish in the form of scales, but very few other remains were evident. Ostracods were the other remain present in relatively similar abundances along the entire length of the core.

In zone 2 the remains of molluscs were more abundant and diverse. There was good evidence of abundant fish community. Towards the top to the core the numbers of all cladocera ephippia increase with the majority of those present being pelagic taxa, which may suggest an increase in planktonic primary productivity. The increase in *Leydigia*, *Simocephalus* and the molluscs in the surface sediments suggest either an increase in benthic productivity or an increase in habitat. The likely habitat of these benthic species are submerged macrophytes. Thus the animal remains data may indicate a recovery in the plant community.

Figure 23 Plant macrofossil stratigraphy from MAUT1

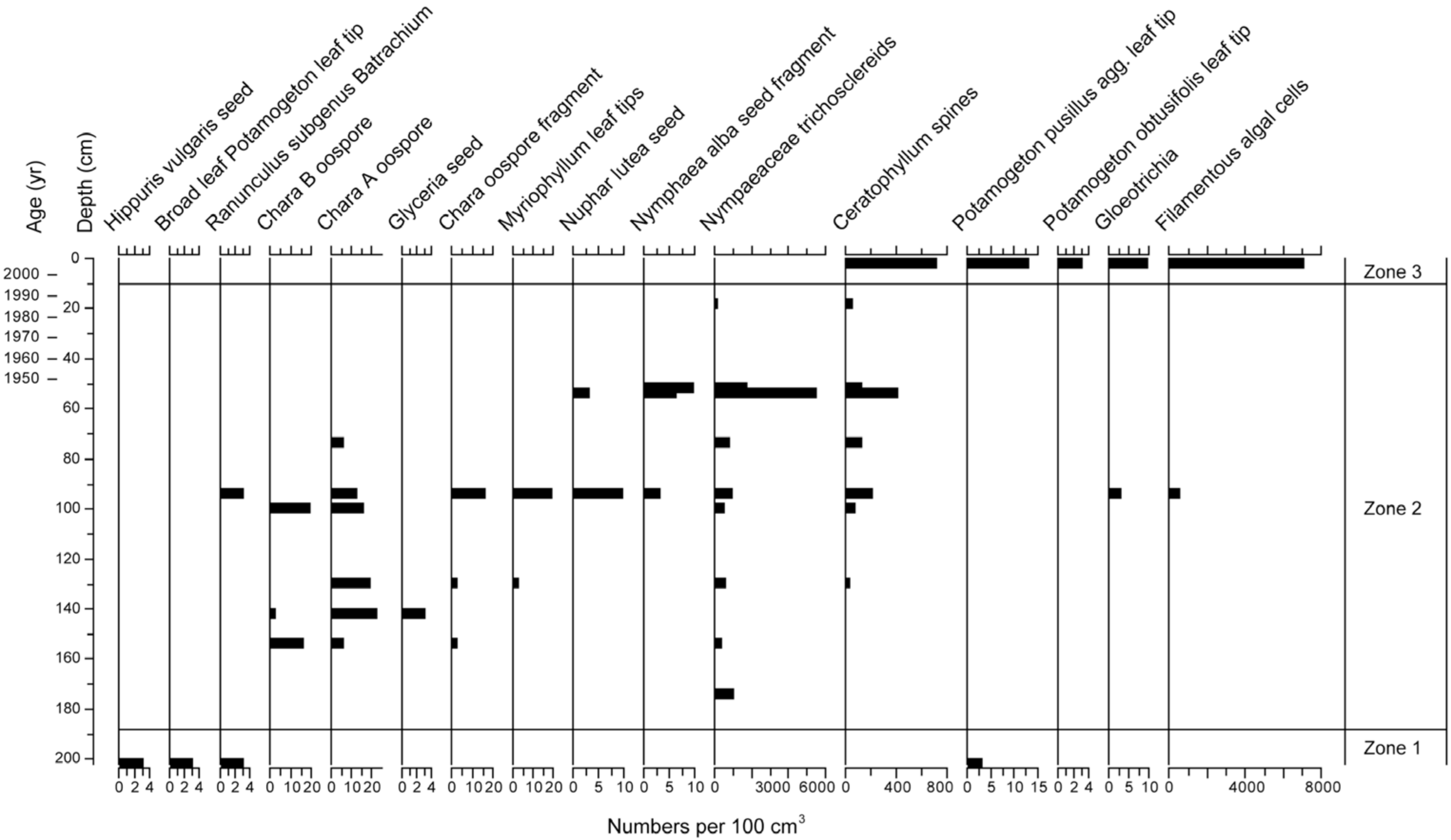
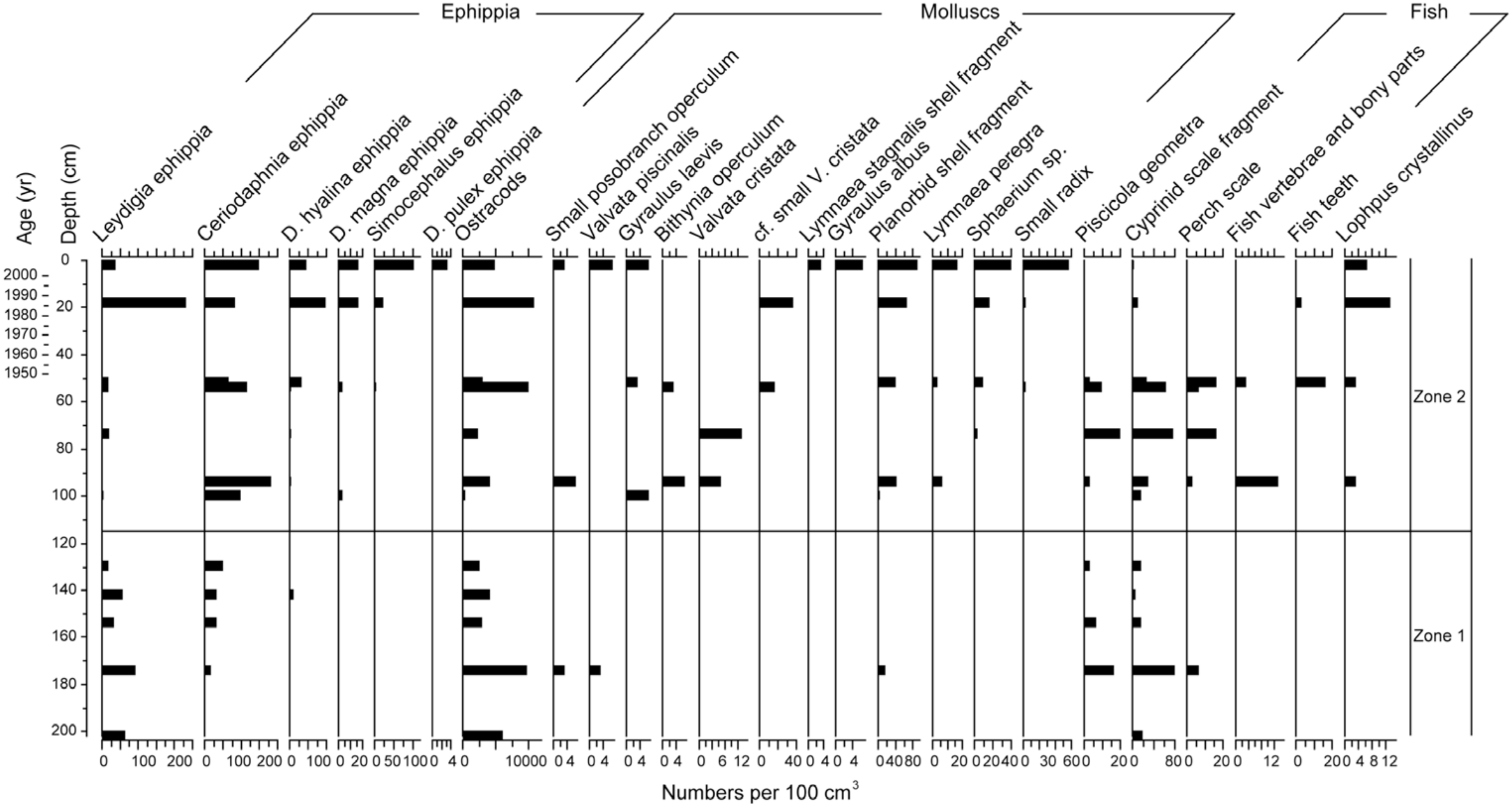


Figure 24 Animal macrofossil stratigraphy from MAUT1



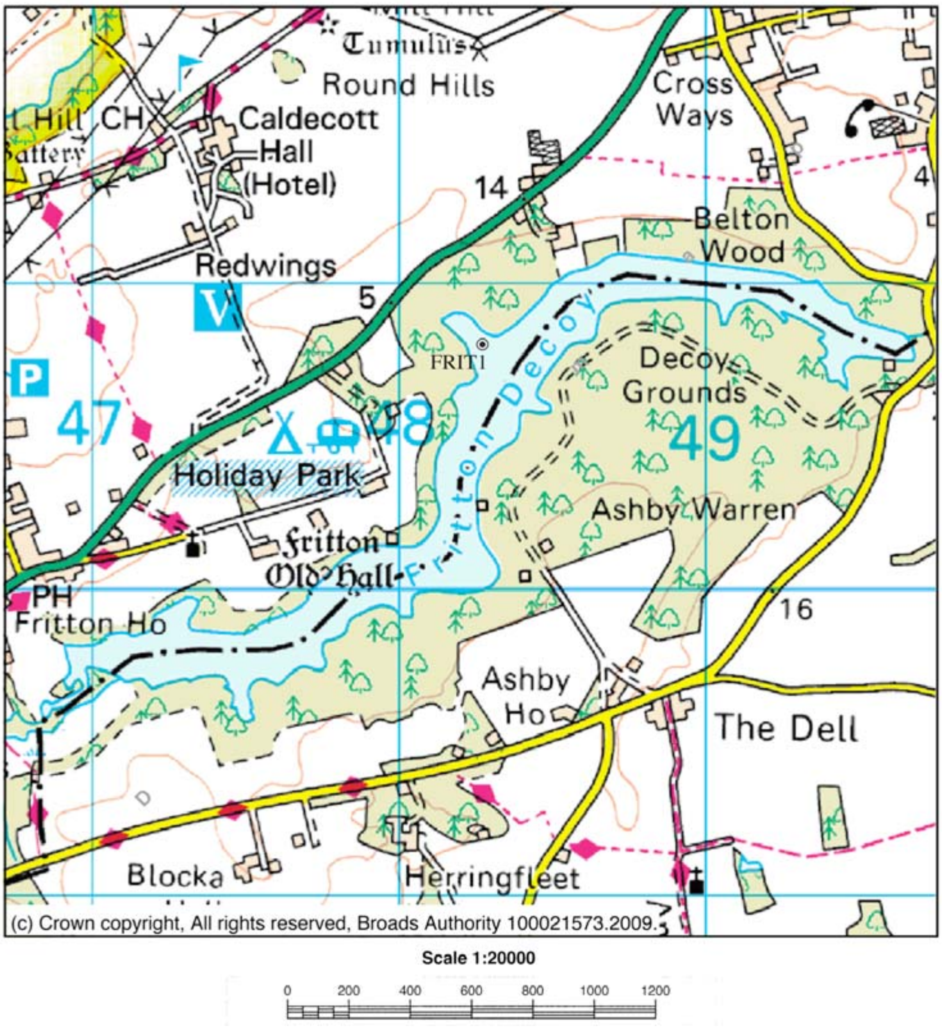
MAUT1 interpretation

The data presented here suggest that Mautby Decoy has undergone a series of profound changes in macrophyte flora. The macrofossil remains evidence a change from a *Chara* dominated community, though elodeids, to a floating leaved community consisting in *N. alba* and *N. lutea* with *Ceratophyllum* associated with it. At the top of the core there was perhaps a slight change indicated, but macrofossil remains in surface sediments tend to be sparse even in sites with quite abundant extant macrophyte populations. In contrast to the plant remains the animal remains suggest there may have been some recovery at the top of the core, as benthic cladocerans and a number of mollusc species are numerous in the top core. Mollusc shells may be dissolved in the sediments, thus their remains may be absent in lower levels either through actual absence or through a lack of preservation. The cladoceran remains on the other hand do not degrade so combined with the molluscs the slight recovery in plant abundance seems a good interpretation of the data. The other notable presence, was *Lophopus crystallinus*, a rare bryozoan, the statoblast of which suggest it may still occur at the site.

Fritton Decoy

Fritton Decoy is a relatively large and deep site (Figure 25), to the extent that the core was taken from a shallow, relatively sheltered bay where some sediment had accumulated. No dating was carried out on the core.

Figure 25 Map and coring site of Fritton Decoy



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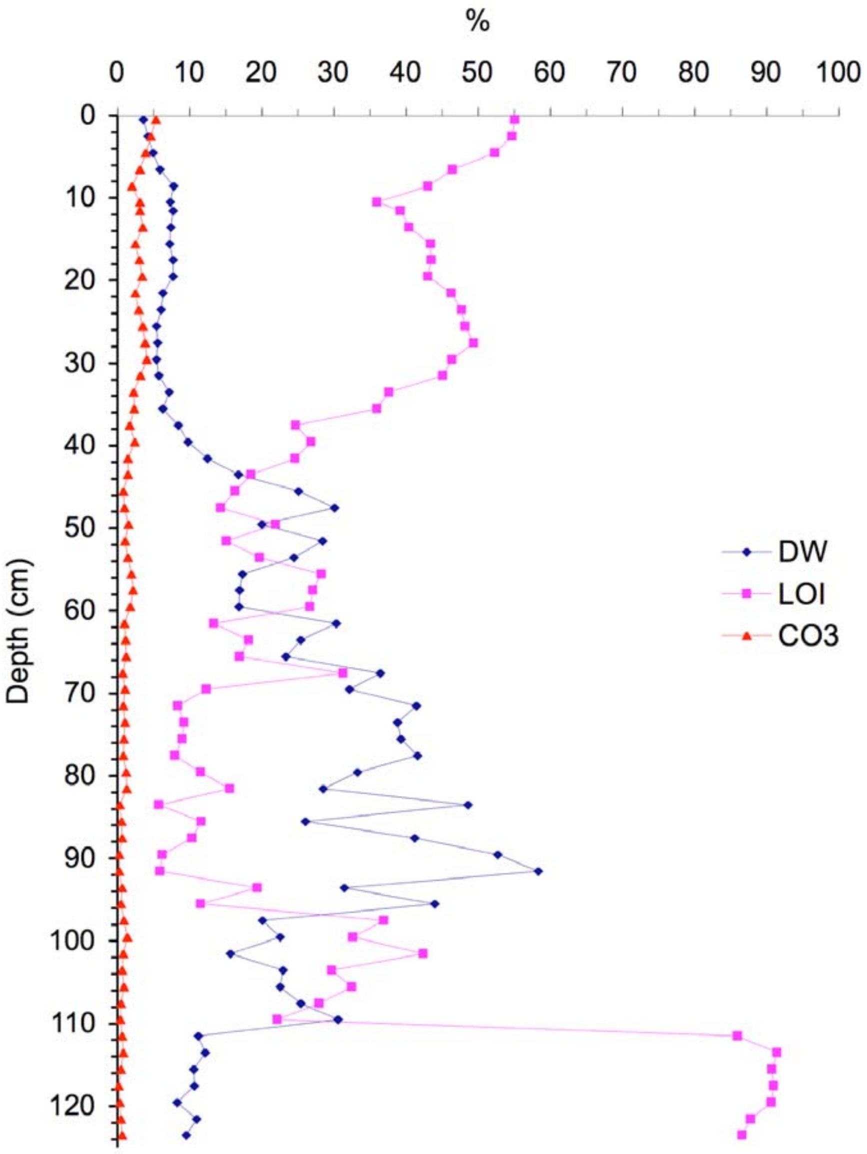
FRIT1 core stratigraphy

The core had peat at the base suggesting the core covers the full age of the lake, with very high organic content (LOI) of around 90%. The was then, at 110 cm a dramatic fall in LOI to a level more usual for a lake, around 30%. The dry weight of the sediment rose at this time. After a long period of low LOI and relatively high DW from 110 to 50 cm LOI increased steadily to from 20% to 55% at the surface and DW fell from 30% to around 5 % at the surface. Carbonate shoed very little variation along the length of the core. The three periods match very well with the obvious colour changes in the core.

Figure 26 FRIT1 lithostratigraphy



Depth (cm)	Sediment colour
0-50	Dark brown gytja
50-110	Light mid-brown
110-120	Peat

FRIT1 Biological remains

Plant remains

Zone 1 - *(110- 75cm)* Zone 1 was dominated by a number of *Chara* (oval) oospores reaching an abundance of 40 per 100cm^3 in the 100cm and 80cm samples. Numbers of *Nitella* oospores increase towards the top of the zone reaching a maximum abundance of 106 per 100cm^3 at 80cm. Numbers of *Gleotrichia* also increase towards the top of the zone. *Callitriche* seeds were present within the

110cm and 90cm samples in low numbers. The abundance and diversity of macrofossil remains increase towards the top of the zone, with the appearance of *Potamogeton pusillus* agg. leaves and seeds, *Zannichellia* seeds and *Stratiotes* spines.

Zone 2 - *(75- 0cm) Potamogeton* remains continued to dominate in the lower section of zone 1 with remains of both *Potamogeton pusillus* agg. leaves and seeds and *Potamogeton fresii/compressus* leaves. The number of *Potamogeton* remains decreased after 60cm and remained absent throughout the remainder of the core. *Myriophyllum c.f. alterniflorum* seeds also occur at 60cm. Remains of *Ranunculus* sect. *Batrachium* appeared at the bottom of zone 1 with a large increase in their abundance at 40cm, followed by a decrease towards the top of the core. Numbers of *Zannichellia seeds, Typha* seeds and *Stratiotes* spines were also high at 40cm. The diversity and abundance of macrofossil remains was reduced in the upper three core samples.

Animal remains

Zone 1 (110- 50cm)

Large numbers of caddis case remains, *Orthotrichia* cases, oribatid mite heads and *Cristatella* statoblasts were present in the lower half of the core. Numbers of *Piscicola geometra* increased in the upper section of the zone.

Ephippia remains were limited in the lower core samples with only a few *Leydigia* and *Daphnia hyalina* agg. remains present below 50cm.

Zone 2 (50- 0cm)

Remains of *Plumatella* statoblasts increased in zone 1 with corresponding decreases in *Cristatella* statoblasts. Numbers of *Ceriodaphnia, Daphnia hyalina* agg.*, Daphnia magma* and *Daphnia pulex* all increased towards the top of the core.

FRIT1 interpretation

The change in macrofossil assemblages, both plant and animal is a classic eutrophication driven succession of species. The community was initially *Chara* dominated, but perhaps forming part of a relatively rich community where benthic productivity was important. Thereafter there was a shift to more canopy forming plants including *Potamogeton* taxa and *Ranunculus* sect. *Batrachium*. Thereafter plants may have been absent or so rare that sedimentary remains were so rare as to be unlikely to be found. The animal remains suggest that the last section of the core represents a period with a relatively large phytoplankton crop as it supports a large abundance of *Daphnia* taxa. In the absence of analysis of cladoceran or diatom remains from the core it is more difficult to speculate on the processes involved in the change in plant remains observed in the core.

Figure 27 Plant macrofossil stratigraphy for FRIT1

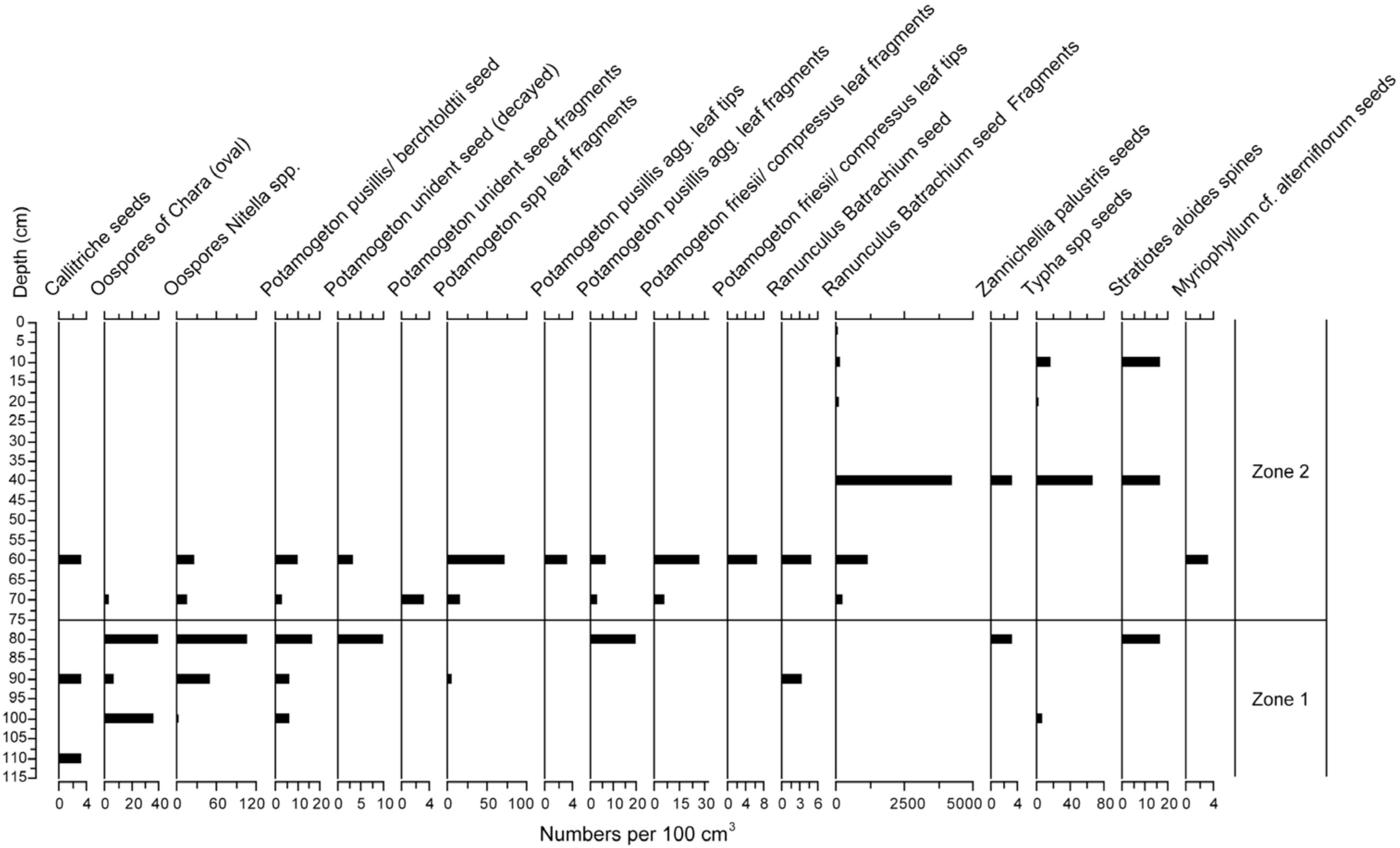
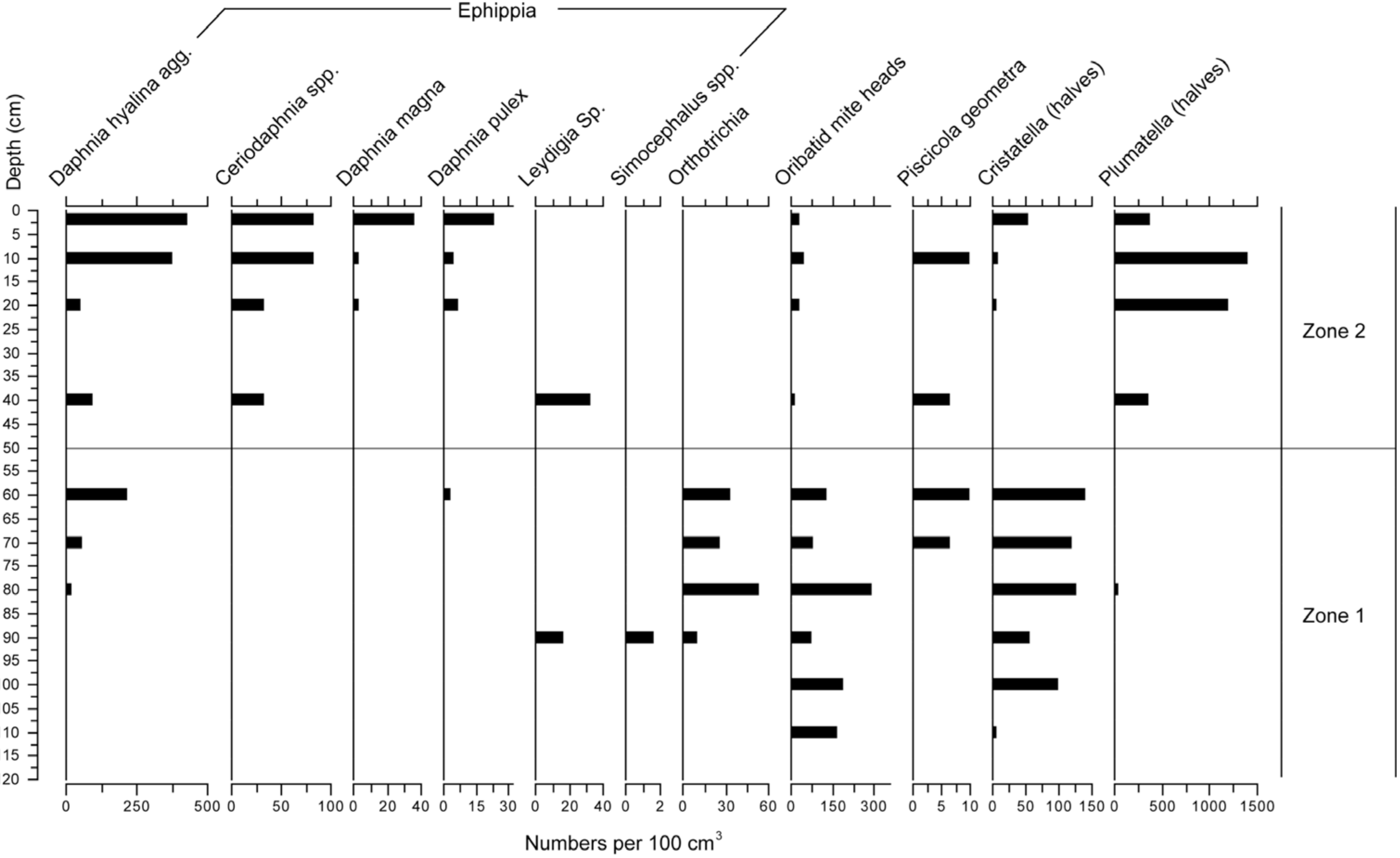


Figure 28 Animal macrofossil stratigraphy for FRIT1



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