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Palaeoecological investigation of the past biological structure and function of the Trinity Broads

Report to the Trinity Broads Partnership

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Executive Summary

This is the final report to the Trinity Broads Partnership on the 'Palaeoecological investigation of the past biological structure and function in the Trinity Broads'. The Trinity Broads are deeper and discrete from much of the rest of the Norfolk Broads and there has therefore been much speculation that their biology was different from the Broads in other river basins. The aim of the project was to employ palaeoecological techniques to investigate the past biological structure and function of the Broads, in particular the past aquatic flora.

Sediment cores were taken from semi-littoral areas of each of the Broads, two cores were taken from Ormesby Broad one at the Northern end and the other in the Eastern Arm, and a single core was taken from Rollesby, Lily, Ormesby Little and Filby Broads in March 2007. The cores were extruded in the field, stratigraphic changes were noted and the percentage dry weight and organic matter content of each core were subsequently determined in the laboratory. In order to date the cores sediment samples, with the exception of the Lily Broad core, were analysed for sphaeroidal carbonaceous particles (SCPs) and reasonable chronologies were established for all the cores, with all the cores, perhaps with the exception of the Ormesby Little Broad core, covering the entire history of the site.

Samples from each core were analysed for the plant and animal macrofossil and the cladoceran remains were also analysed. The results from the former provide a good indication of changes in the submerged flora of the Broads and the latter can provide insights into how the ecological functioning of a lake changes over time, providing an explanation of why the macrophytes flora changed.

The macrofossil and cladoceran profiles from each of the cores showed broadly similar patterns across the four Broads. At the base of each sequence there was a period with diverse, abundant macrofossil remains, characterised by a number of *Potamogeton* species and large numbers of stonewort (*Chara* & *Nitella*) remains, known as oospores. At this time the fauna of the sites, both cladoceran and molluscan, reflected a community dominated by benthic species. After this initial period, which is likely to have lasted many hundred years, species such as *Callitriche* and *Ranunculus* sect. *Batrachium* (Water crowfoots) appeared in the record and the number and diversity of *Chara* remains declined. This second phase in submerged flora was accompanied by a shift to more pelagic cladoceran species and a decline in mollusc diversity and abundance. The final stage in the sequence of changes, reflected by each core, was a shift to an assemblage dominated by fine leaved *Potamogeton* leaf fragment, *Nymphaeaceae* remains and *Zanichellia palustris* leaves and seeds. All the cores reflected a further shift to pelagic cladoceran species at this time, with large bodied *Daphnia* species dominant in the final phase. There were, however, some changes towards the surface of the core, in particular in the Ormesby cores, as some of the more plant associated species increased in relative abundance. This may reflect a recent (last 10 years) increase in macrophyte abundance. The changes, both in the submerged flora and the cladoceran fauna, that have occurred at all the Trinity Broads over the last 150 years or almost certainly a reflection of the progressive, chronic, eutrophication of the system.

The timing of the changes between the sites appeared to vary with a sequence of impact from North to South. Ormesby Broad being the first to be impacted and then the effects of eutrophication cascading down the system. Each Broad in turn having acted as a buffer to eutrophication to its downstream neighbour until some critical point at which the buffering capacity failed. Thus, Filby Broad maintained a macrophytes community dominated by *Chara* perhaps 80 years longer than Ormesby Broad.

This study has elucidated the former plants and animal communities and the degree of ecological change at the Trinity Broads, since their formation, but perhaps more importantly in the last 150 years. There have been very substantial changes in ecological function and community structure. The information provided here will hopefully assist in management of the site and also allow the success of any management to be placed within a historical context.

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Photo – Ormesby Little Broad

Table of contents

List of Figures

List of Tables

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; Sayer et al. in press-a) 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 Trinity Broads are thought to have been less impacted by eutrophication as they are isolated from the main river and a sluice has controlled tidal inputs since the late 1800s. A number of observations from earlier last century (Gurney 1929) highlighted differences between the Trinity Broads and those of the rest of Broadland. Other work, including the doctoral studies of Hameed (1989) which involved palaeolimnological studies of Ormesby and Lily Broads, indicated quite profound changes in the nutrient chemistry and diatom assemblages. In addition, Hameed carried out some work on plant macrofossils which suggested that Ormesby Broad contained significant cover of charophytes, the study was, however, limited to oospores of charophytes and the leaf spine cells (trichoschlereids) of the water lily both white (*Nymphaea alba*) and yellow (*Nuphar lutea*).With the notable exception of the Hameed (1989) study there is very little hard evidence on the former submerged plant communities of the Trinity Broads, this project set out to address this knowledge gap.

Study Aims

The main aim of the study is to investigate the former biological structure and function of the Trinity Broads system, which includes Ormesby, Rollesby, Lilly, Ormesby Little and Filby Broads. Specifically to:

1. Track changes in the composition of the submerged aquatic flora
2. To assess changes in the fish and macrophyte abundance

This will be determined by analysing sedimentary remains of plant macrofossils which provide a means of determining the ancestral submerged macrophyte communities of the sites (Davidson et al. 2005). In addition, analysis of sub-fossil cladoceran remains will provide an indication of changes in productivity, zooplanktivorous fish density and macrophyte abundance (Jeppesen et al. 2001).

Methods

Coring and lithostratigraphic analysis

Six sediment cores were extracted using an adapted Livingstone type fat piston corer (Livingstone 1955) on the 7th and 8th of March 2007. The exact location of each core was recorded using a hand-

held GPS. Two cores were taken from Ormesby Great Broad at the Northern end (ORMG1) and the other in the Eastern Arm (ORMG2). Single cores were taken from Rollesby (ROLL2), Lily (LYLI1), Ormesby Little (ORML1) and Filby (FILBY1) Broads. 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 and was greatly assisted by detailed maps of sediment and water depth provided by Randall Surveys. The coring sites were, in general, in deeper water than previous macrofossil studies carried out in the Broads (e.g. Davidson et al. 2006) as the Trinity Broads are deeper the was a lack of sediment of sufficient depth towards the edges of the Broads. 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 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 five lake sediment cores: FILB1, ORMG1, ORMG2, ORML1 & ROLL2 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).

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 15 levels from ORMG1, ORMG2, ORML1, FILB1 and 7 levels from ROLL2 were analysed for macrofossils. Around 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 identified, these likely reflect different species and the rudimentary nomenclature of A, B and C was kept constant across the different cores. The data are presented as numbers of remains per 100 cm^3 of wet sediment.

Cladoceran analysis

Cladocera are microscopic crustaceans (zooplankton) and are represented in lake sediments by a variety of body parts. The composition of both the contemporary communities and their sedimentary remains have been shown to reflect changes in habitat structure (i.e. macrophytes) and zooplanktivorous fish density in shallow lakes (Jeppesen et al. 2001; Davidson et al. 2007). Sediment samples from each of the cores were prepared using an adaptation of the standard sub-fossil cladocera preparation technique (Korhola & Rautio 2001). This adapted method is based on that currently employed by colleagues working on Danish lakes (Jeppesen et al. 1996; Jeppesen 1998). For each sample at least 5 cm^3 of sediment was heated in a deflocculating agent (10% potassium hydroxide, KOH) and sieved at 150 µm and 50 µm. The retents of the two sieves were then washed into separate pots and safranin stain was added. Chitinous remains of cladocera from a sub-sample were enumerated using a compound microscope and identified with reference to Flössner (1972), Frey (1958; 1959) and Alonso (1996). Counting of individuals followed the minimum number method: head shields, carapaces and post abdominal claws were tabulated separately, the count for each species being the number of the most numerous remain. These data are presented as relative abundance of chitinous remains.

Ephippial remains were separated and counted along with macrofossil remains using a binocular microscope, thus the counts are based on the analysis of at least 30 cm^3 of sediment and are expressed as numbers per 100 cm^3. The sedimentary cladoceran record, based in chitinous remains alone, is incomplete, with a greater diversity of littoral chydorids being preserved compared to planktonic cladocerans (Hoffman 1987; Hann et al. 1994). Planktonic cladocera, particularly large bodied species, are most susceptible to fish predation (Brooks & Dodson 1965). Furthermore, the larger species, such as *Daphnia* spp. and *Ceriodaphnia* spp. are keystone species for shallow lake ecosystem function and records of changes in their abundance are crucial in determining past ecosystem function. Recent developments in cladoceran based palaeolimnology have incorporated ephippia data (Jeppesen et al. 2001) and demonstrated that the sedimentary assemblage is a good reflection of the population that formed it (Davidson et al. 2007). Thus, in order to determine the past effects of fish and record shifts in ecosystem function it is vital that ephippia are enumerated. *Daphnia* ephippia were identified to the highest taxonomic resolution possible, with remains separated into three different groups. These were: *Daphnia hyalina* agg. consisting of a number of smaller bodied species, including *Daphnia longispina, D. hyalina, D. cucullata* and *D. galeata*; *D. pulex* and *D. magna.*, both of which can be identified to species. *Ceriodaphnia* spp. is the highest taxonomic resolution for the various *Ceriodaphnia* species.

In addition to presenting the cladoceran data as changes in the species composition over time, in a simple stratigraphic plot, the data were analysed using a recently developed palaeolimnological inference model (Davidson et al. in press). August macrophyte abundance and zooplanktivorous fish density are the two factors that have the greatest control on cladoceran communities. Thus, changes in the fossil assemblage in sediment cores reflect, to some degree, alterations in past macrophyte and fish abundance. The model was calibrated by analysis of cladoceran surface sediment assemblages against fish and macrophyte density from 39 shallow lakes (Davidson et al. in press). The model is presented within an ordination bi-plot (e.g. Figure 9), the distance between samples is an expression of the difference in cladoceran assemblages and therefore reflects different fish and macrophyte abundance the relative difference of which can be interpreted by the position of the sample relative to the vector (or arrow) representing fish or macrophyte density. Movement in the direction of the arrow represents an increase in the parameter, thus, movement between the samples in ordination space represent change in plant and fish density over time. There are absolute values of zooplanktivorous fish density and macrophyte PVI given by the lines and values that run at right-angles to the vectors, which are a guide to the likely past absolute values of macrophyte abundance and fish density in the Broads. The Trinity Broads are deeper than most of the sites within the calibration data set and thus the results should be treated with a little caution. They results are informative however, in particular reflecting large shifts in ecological function with changes in the balance and benthic to pelagic production.

Trinity Broads

The Trinity Broads system consists of a series of interconnecting shallow water bodies (Figure 1) the location of which are given in Table 1. The Broads were isolated from the main river by a sluice on Muck Fleet in 1868 (Jones, 1868). The Broads have not directly received sewage effluent, therefore diffuse inputs of nutrients from an agricultural catchment is chiefly responsible for eutrophication. Thus, whilst it is clear that these Broads have been impacted, and a number of restorative measures including fish manipulation have been attempted, they are thought to have been less impacted than other Broads (Jackson 1978). There are, however, observations from early last century which suggest that blue-green algal blooms (Gurney 1929) occurred at this site, whereas they were absent form Broads of the Thurne, Ant and Bure. Thus, the historical development of the Trinity system appears quite complex and more information is needed to assist the effective management of the system.

The Trinity Broads are generally deeper than Broads on the other river systems. Whatever the cause of this, be it initial depth, age or lower accumulation rates, the result may have been a distinct composition and abundance of the submerged flora compared with Broads from other river systems. There is a general movement of water through the sites from North to South and the report is structure this way, with Ormesby Great presented first and then in order of position North to South, with Filby Broad last. Limited results are presented for Lily Broad as the funding was limited to the analysis of five cores. Hameed (1989) suggests that Lily Broad never had a charophytes flora and it is thought to be different from the other sites and thus it was left out of the main analysis.

Figure 1. Map of the Trinity system

Licence Number – WU298506

Results

A summary of the location of sampling sites, water depth of coring location and core length are given in Table 1. The cores were collected in slightly deeper water than in previous studies in the Broads, particularly in Rollesby, Ormesby Little and Filby Broads. The choice of coring location benefited greatly from both sediment depth and water depth maps provided by Randall Surveys (2006).

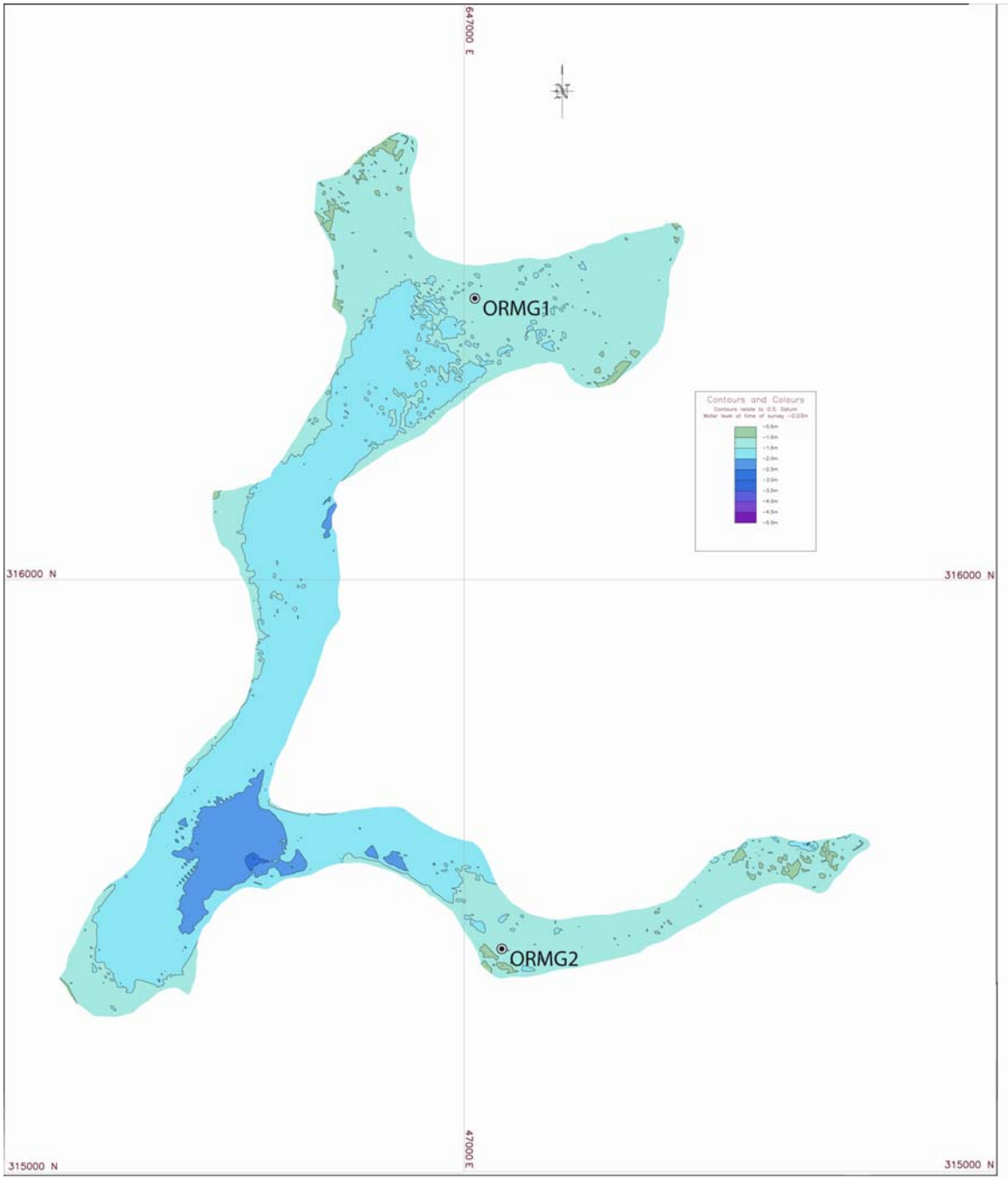
Table 1. Trinity Broads core location, water depth and core length

NAME	NGR	CORING DATE	SITE CODE	CORE CODE	WATER DEPTH AT CORE SITE (M)	CORING LOCATION	CORE LENGTH (CM)	CORE TYPE
Ormesby Great Broad	TG468163	07/03/07	ORMG	ORMG1	1.2 m	TG 47034, 16467	141	Fat piston
		07/03/07		ORMG2	1.1 m	TG 47134, 15398	150	Fat piston
Rollesby Broad	TG461150	07/03/07	ROLL	ROLL2	1.9 m	TG 46031, 14490	141	Fat piston
Lily Broad	TG454146	08/03/07	LYLI	LYLI1	1.3 m	TG 45616, 14477	140	Fat Piston
Ormesby Little Broad	TG463141	08/03/07	ORML	ORML1	2.0 m	TG 46190, 14035	150	Fat piston
Filby Broad	TG457133	08/03/07	FILBY	FILBY1	2.0 m	TG 46186, 13298	142	Fat piston

Ormesby Broad

Core location and water depth for the two cores taken from Ormesby Broad are shown in Figure 2 and Table1. The Broad is relatively deep, over 3 m at the deepest points and generally shelves steeply at the margins to over 1 m deep. Thus, very shallow marginal areas are mostly absent. ORMG1 was taken at the northern end of the Broad and ORMG2 in the Eastern Arm where sediment accumulation is thought to be greater.

Figure 2 Bathymetric map and coring locations of Ormesby Broad

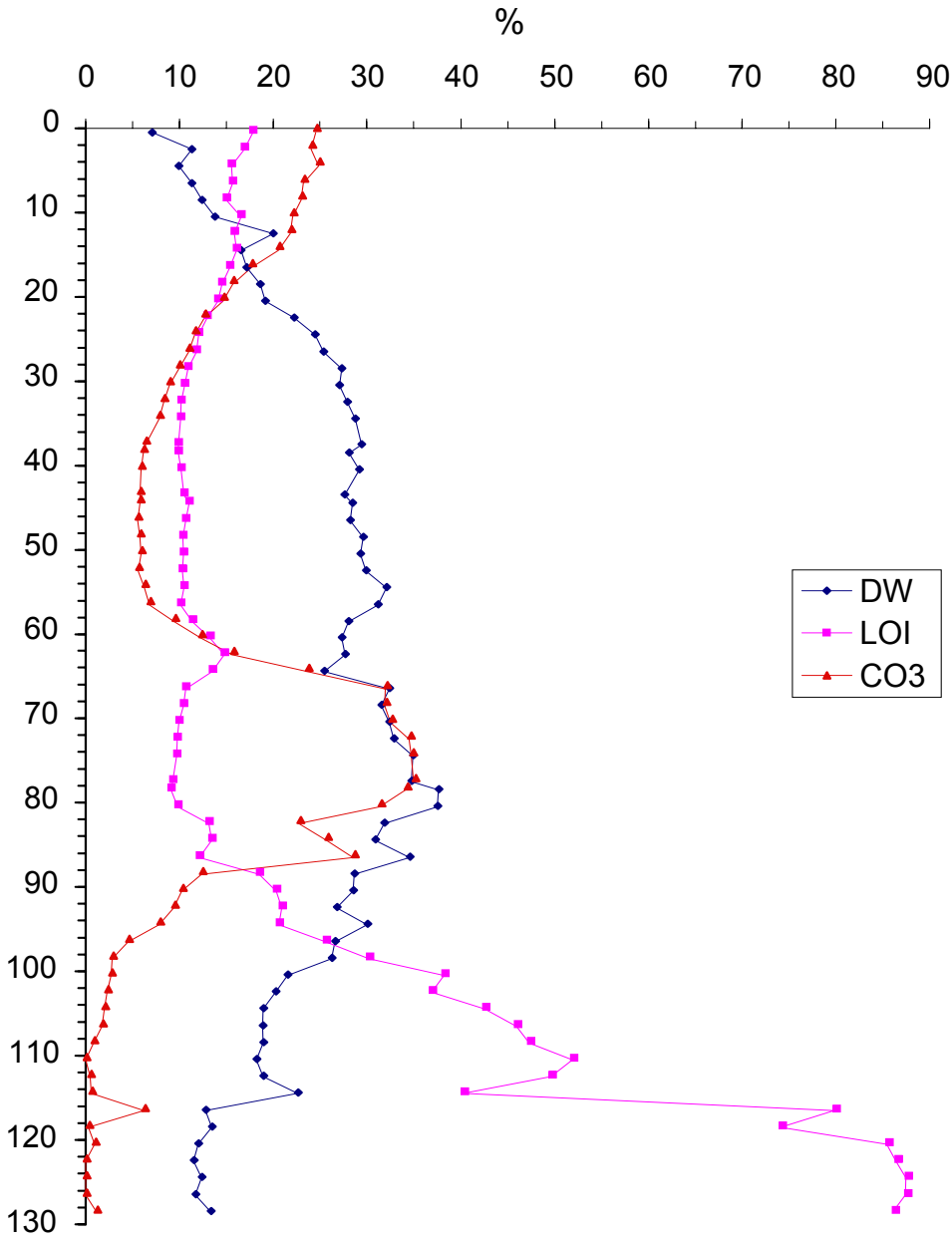


ORMG1 Core stratigraphy

ORMG1 had a number of distinguishing features which can be seen in Figures 3 and 4. The base of the core was peat, reflecting the origin of the Broads, characterised by very high organic content (LOI) (> 80%) and the absence of carbonate. Organic content declined gradually from 120 cm to around 10% at 80 cm, concomitant with this decline was an increase in dry weight (DW), rising

from 10 to 30%. Above 80 cm the values for both DW and LOI remained relatively constant to 40 cm, above which LOI slowly increased and DW gradually decreased. The carbonate profile is remarkable, after a slow increase from complete absence in the peat to around 5% at 100 cm there was a gradual, followed by a dramatic rise from 100 and 90 cm respectively, with levels reaching 35% between 90 and 65 cm. Carbonate levels then fell to between 5% and 10% between 60 and 40 cm, whereupon it increased steadily to 25% at the surface of the core.

Figure 3 Lithostratigraphy of ORMG1



The visible colour changes in the cores (Fig. 4) match the measured lithostratigraphy closely, with a peat base indicating that the entire lacustrine period of Ormesby Broad was covered by the core taken here. The high carbonate marl layer between 90 and 60 cm is recognisable by the light brown/marl colour, there follows a more gradual colour change from light brown marl to more organic dark brown sediments at the surface of the core.

Figure 4Stratigraphy of ORMG1

Depth (cm)	Sediment colour
0-6	**wet mid-brown**
6-50	**mid-brown**
50-60	**transition**
60-90	**light brown/marl**
90-105	**dark-brown**
117-129	**Peat**

ORMG1 Core chronology

The ORMG1 core shows a well-defined SCP concentration peak at 9 – 10cm (Figure 5a) which in this part of the UK is usually ascribed to 1970 ± 5 yrs. However, given the sampling interval of the core the peak could lie between 7 – 12cm. This suggests that the mean sediment accumulation rate for this upper section of the core is 0.189 – 0.324 cm yr^{-1} (0.257 cm yr^{-1} if the peak is actually at 9 – 10cm). The rapid increase in SCP concentration defined as the intercept between the slope of the two lines either side of the increase lies at c.30cm and this is usually ascribed the date of 1950 ± 10 yrs. This suggests that the accumulation rate in ORMG1 increased considerably between 1950 – 1970. The concentration profile falls to zero between 40 – 70 cm and this is probably related to the detection limit as a result of the more rapid sediment accumulation rate. The SCP record is therefore

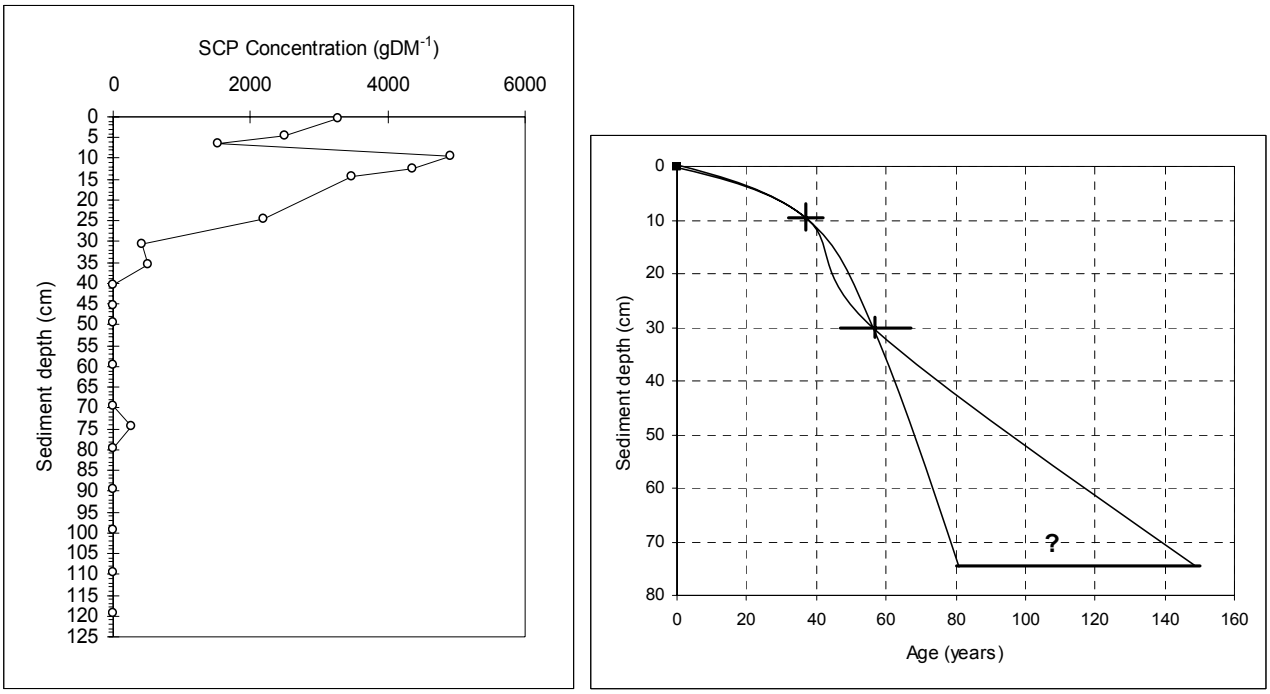
not complete and it is therefore not possible to employ the SCP cumulative percentage approach (Rose & Appleby 2005) to this core. However, the presence of SCPs was also determined at 74 – 75 cm indicating that this depth at least is post-1850. If this represents the earliest SCP presence in the mid-19th century (Figure 5b) then it would suggest that the 1950 – 1970 period represents a period of more rapid sediment accumulation and that the accumulation rates prior to and after this period are slower, and similar (Figure 5b). However, as it is unknown whether this presence of SCPs at 74 – 75cm is really the earliest record, it is only certain that this is equal to or younger than 1850. Hence it is possible that the more rapid sediment accumulation rate between 1950 and 1970 continues earlier than this (Figure 5b). There is therefore major uncertainty in the chronology prior to 1950. The best available chronology is therefore summarised in Table 2.

Table 2 Chronology for ORMG 1

Sediment depth (cm)	Age (years)	Date	± (years)
0	0	2007	0
10	38	1969	5
20	47	1960	10
30	58	1949	10

Figure 5 a) ORMG1 SCP concentration profile; b) Depth/age curve

a) b)



ORMG1 Biological data

Summary macrofossil results for ORMG1 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 6. Shifts in the animal macrofossil remains, in this case fish, macro-invertebrates, cladocerans, and molluscs can be seen in Figure 7.

Plant remains

110-60 cm (representing pre-1949)

A diverse array of *Potamogeton* species/species groups were identified in the lower section of the core (including *P. friesii* agg., *P. pusillus* agg., *P. obtusifolius* and *P. crispus*). All four

species/species groups occurred in the lowermost sample, however their prevalence within the core varied with *P. crispus* disappearing from the record after 85cm, *P. friesii* remains occurred until 65cm and *P. obtusifolius and P. pusillus* agg. occurred until 60cm and 55cm respectively. *Chara* oospores types B and C, and *Nitella* oospores all increased in abundance at 90cm and showed variable but very high abundances until 50cm achieving levels indicative of extensive *Chara* beds within Ormesby Broad at this time (Zhao et al. 2006). *Chara* oospores type A increased initially at 90 cm, declined between 90- 70 cm and rose again after 60cm, maintaining relatively high abundances later than oospores types B and C. *Ranunculus* sect. *Batrachium* fragments and seeds first occurred at 90cm and the fragments rose in abundance after 70cm. *Ceratophyllum* spines, most likely to be from *C. demersum* rather than the rarer *C. submersum,* were also found in one sample (70cm) in the lower section of the core . *Z. palustris* seeds were found in all the samples between 100- 60cm. Maximum species diversity of the water associated plants occurred at 70cm.

60-30 cm (representing pre-1949)
In this section of the core the *Potamogeton* species/species groups declined and disappeared almost completely from the sediment sequence by 50cm. *Chara* oospores type C and B also fell in numbers, *Nitella* oospores declined and were absent above 40cm. Whereas *Chara* oospores type A and *Ranunculus* sect. *Batrachium* fragments increased within this section. Remains of *Z. palustris* also increased at 60cm but declined to reach minimal abundances at 30cm. *Nymphaeaceae* trichoschlereids also peaked at 60cm. This may indicate an increase in *Nymphaeaceae* at that time, however, it may be that this reflects the presence of a large piece of *Nymphaeaceae* leaf within the sieved sample.

30-0 cm (1949 to the present)
Remains of submerged and floating macrophytes were rare in this section of the core. *Chara* oospores A, B and C were present in very small numbers. *Ranunculus* sect. *Batrachium* fragments were also present throughout this section. *Z. palustris* seeds increased to maximum levels at *ca.* 1969 AD but declined again in the subsurface core sample (1cm). *Nymphaeaceae* trichoschlereids also increased in the subsurface sample.

The plant macrofossil remains in ORMG1 suggest that there have been profound changes to the submerged flora of the site. There has been a shift from a phase with diverse *Potamogeton-Chara*, with at least four species of *Potamogeton*, through a *Chara-Ranunculus* phase to a *Zanichellia-Nymphaeaceae* phase. The contemporary flora of the site is dominated by fine leaved *Potamogeton* species and it is therefore unusual that there are no fine leaved *Potamogeton* remains in the surface sediment. Zhao et al. (2006) found that the leaf remains of fine *Potamogeton* species were particularly patchy in their distribution, perhaps as they tend to raft on die-back. Furthermore, the short growing season of the fine-leaved Potamogeton species may allow more time for the break down of the leaf material. The fact that there are very abundant remains of *P. pusillus* agg. in the surface of ORMG2 suggests the latter explanation is less likely.

Figure 6 Summary stratigraphy for selected plant macrofossils for ORMG1

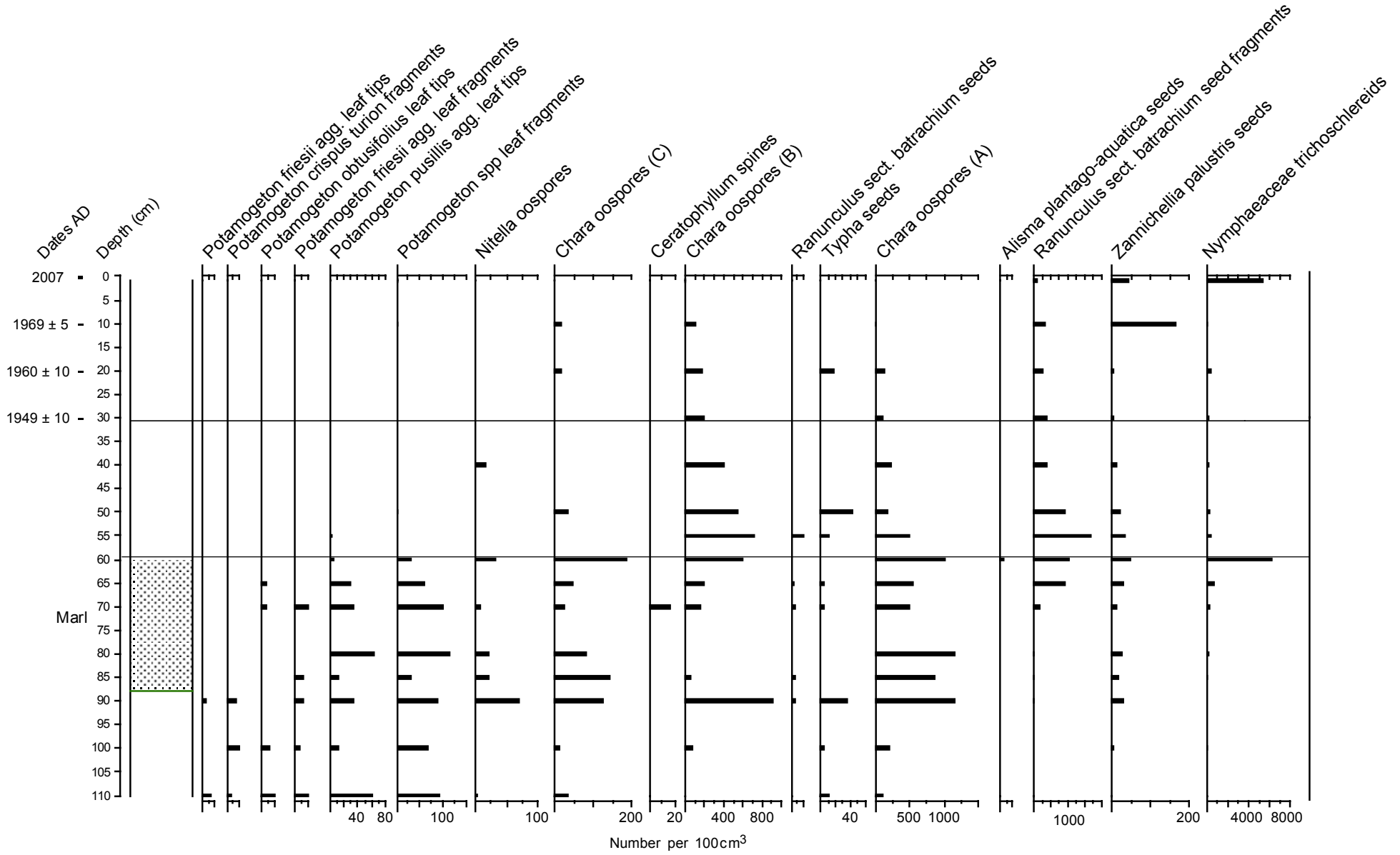
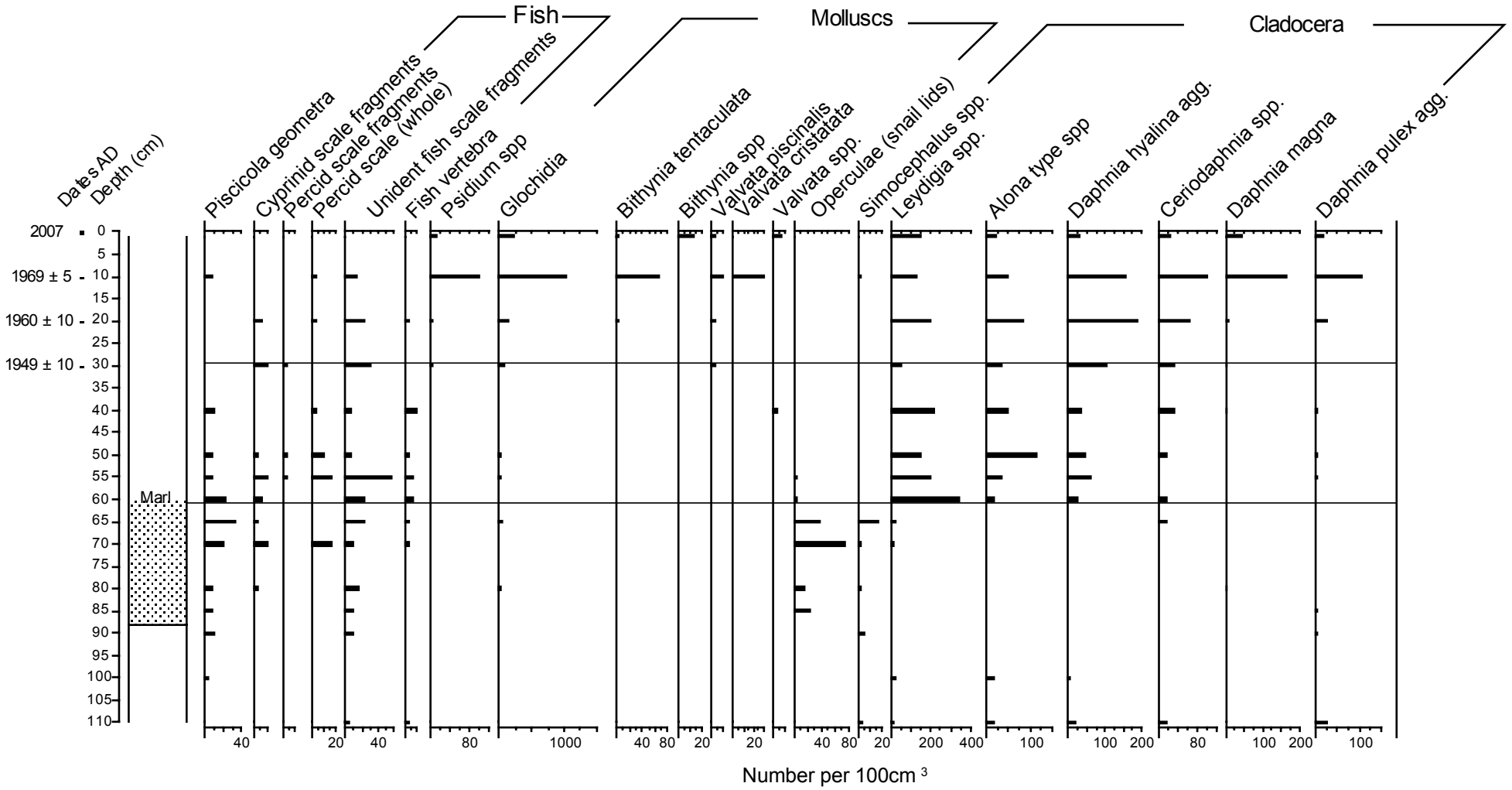


Figure 7 Summary stratigraphy of animal macrofossil for ORMG1



Animal and cladoceran remains

The stratigraphy of selected animal remains from the macrofossil analysis displayed a similar zonation to the plant macrofossil remains (Figure 7) as did the cladoceran sub-fossil stratigraphy (Figure 8). The chitinous sub-fossil cladoceran profile was dominated by the small-bodied pelagic cladoceran *Bosmina longirostris* which had over 40% on most samples, the other co-dominant species was *Chydorus sphaericus*. Notwithstanding the numerical dominance of these two taxa there were significant changes in the stratigraphy of animal remains along the length of the core. From the base of the core to 60 cm the diversity of cladocerans was higher with a number of macrophyte associated species present (Whiteside 1970; Hann 1989), of particular note were *Camptocercus rectirostris*, *Phrixura rostrata*, *Graptoleberis testudinaria* and *Alonella nana*. There were also numerous animal remains in the macrofossil data including the occurrence of the large plant associated *Simocephalus* spp. ephippia, along with abundant mollusc remains, in this case the operculae of prosobranch molluscs.

There was a significant shift in the cladoceran and invertebrate remains coincident with the changes in plant remains above 60 cm depth where there was such a dramatic change in carbonate concentration in the sediments. Between 60 cm and around 25 cm the number and diversity of cladoceran taxa present declined and the dominance of *B. longirostris* increased. In addition, whilst sporadically present in very small numbers in the bottom section of the core, the ephippia of large pelagic cladoceran species, such as *Daphnia hyalina* agg., *Daphnia pulex* and *Ceriodaphnia* spp. were consistently present in larger numbers above 60 cm. The ephippia of *Alona* type chydorids and of *Leydigia* spp. were also more numerous in this zone.

The final period of the core between 25 cm and the surface had further changes with the continued increase in the ephippial abundance of all large bodied pelagic cladocerans (*D. hyalina* & *D. pulex*) and the addition of *Daphnia magna* in large numbers, in particular in the sample from 10 cm. There was also the reappearance of *Pleuroxus aduncus* and *Pleuroxus uncinatus*. A number of mollusc species appear in this phase with both prosobranch and pulmonate species represented, there may be some issues of preservation of the snail shells at lower levels in the core and thus these data should, perhaps, be treated with caution. They do, however, indicate a degree of recovery in the invertebrate community.

The records of fish for the site were chiefly scales of cyprinid and percid species. In addition, vertebrae were found and the remains of the fish leech *Piscicola geometra* is also an indication that fish were present. All these remains occurred more frequently and were more numerous below 50 cm in ORMG1.

The results of placing the sedimentary cladoceran assemblages from both ORMG1 & 2 in the inference model can be seen in Figure 9. The model indicates a period of relative stability of macrophyte cover but perhaps increasing zooplanktivorous fish density in the basal zone below 60 cm. Above 60 cm there is a large movement in ordination space suggesting profound changes in the ecological functioning which the model suggests is a decline in August macrophyte abundance relatively early in the record, perhaps 1850. The system again appears stable with little variation until the model then indicates a decline in zooplanktivory between 29 and 20 cm, there are then quite large changes in the final three samples, perhaps reflecting instability and changes in the dominant components of the fish community in the past decades.

Figure 8 Summary stratigraphy for selected sub-fossil cladoceran remains in ORMG1

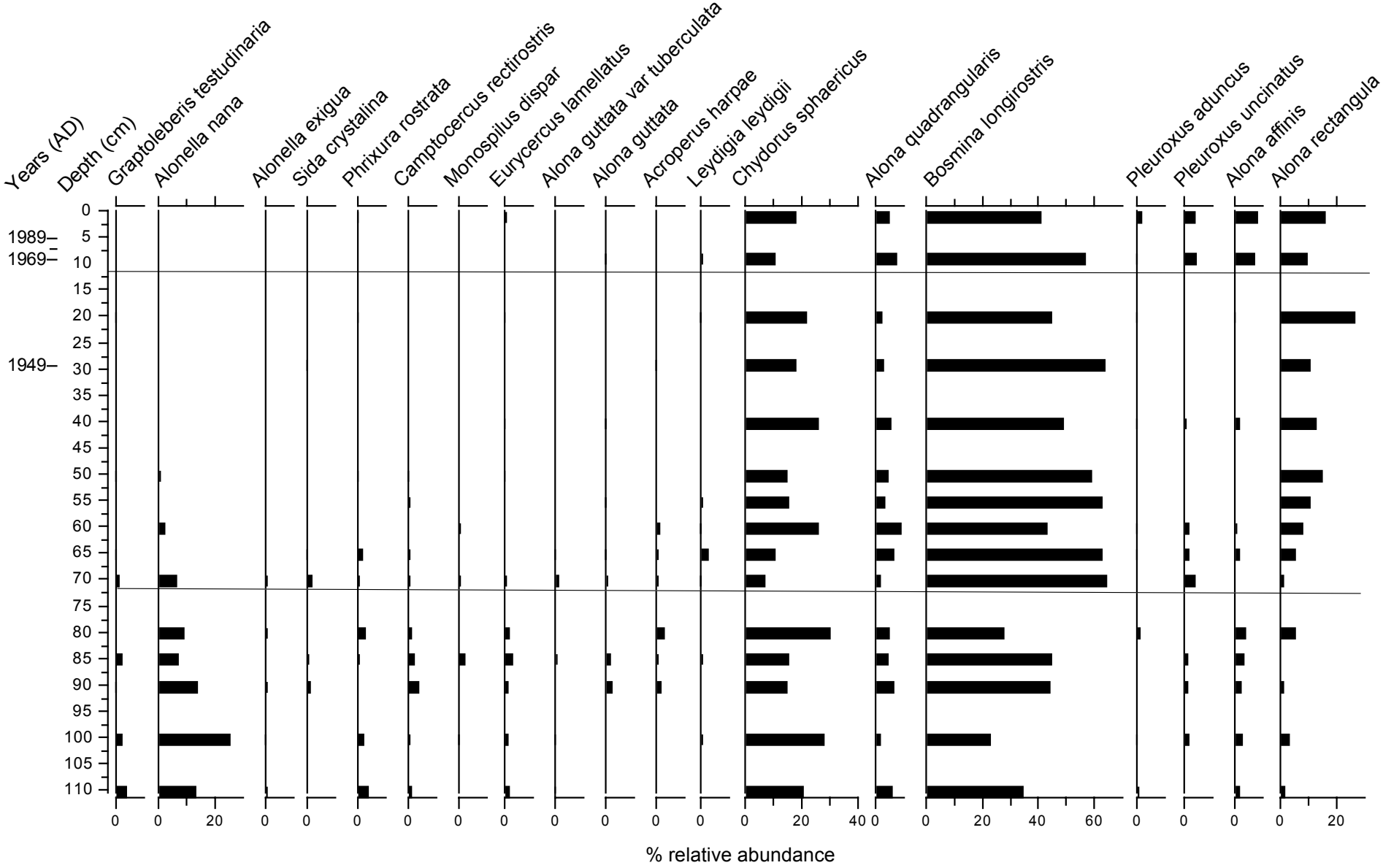
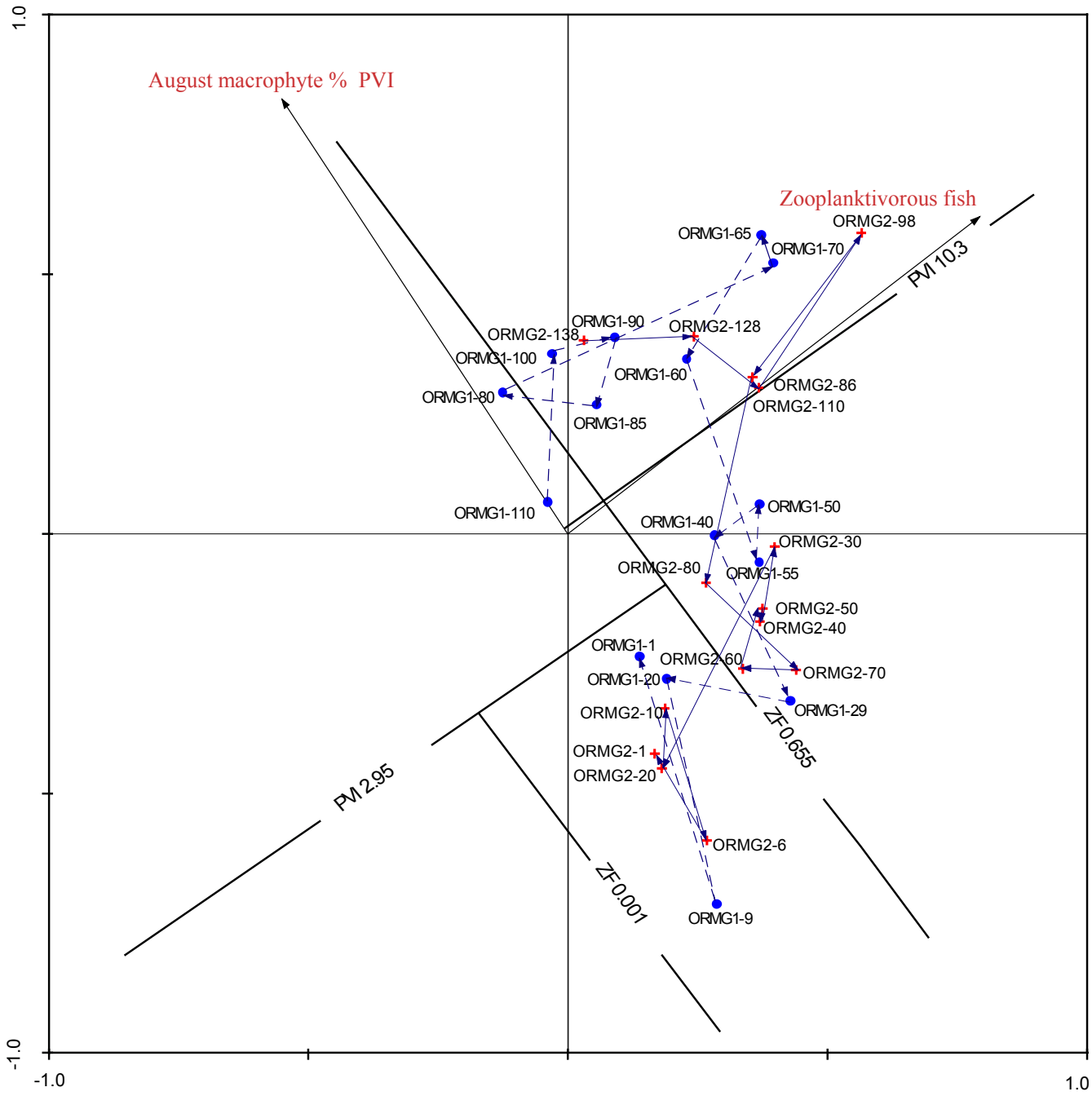


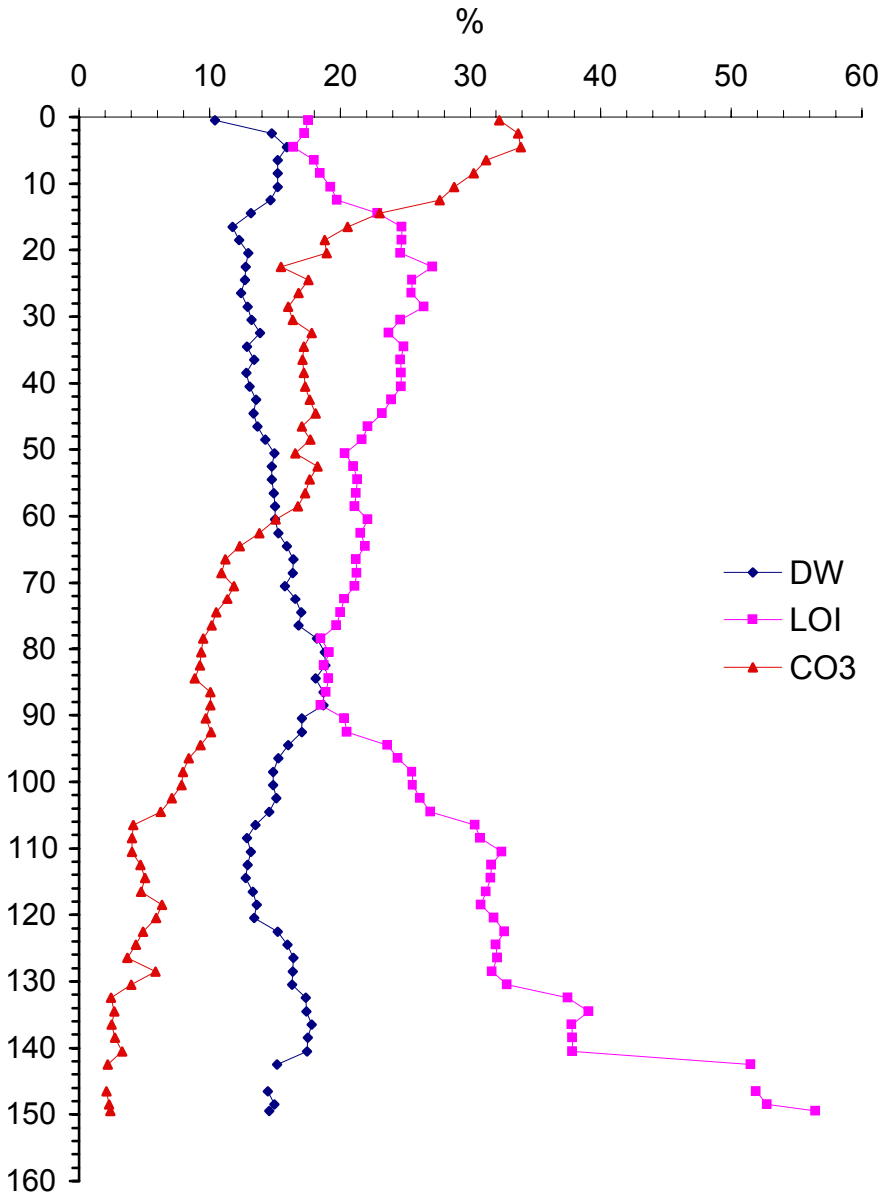
Figure 9 Time tracks of ORMG1 & 2 cladoceran samples reflecting changes in zooplanktivorous fish density and August macrophyte density



ORMG2 Core stratigraphy

The core ORMG2 was taken in the Eastern Arm of Ormesby Broad the details are given in Table 1 and Figure 2. The lithostratigraphy of ORMG2 can be seen in Figures 10 and 11. There were a number of changes in sediment composition from the peat at the base of the core, reflected in very high organic content (LOI) of 60%. From 140 cm there was a gradual decrease in LOI to 20% at 90 cm. From 90 cm to 20 cm there was a gradual increase in LOI to about 25% thereafter LOI fell to just under 20% at the surface. The percentage dry weight (DW) remained relatively constant along the length of the core varying between 10 and 20%. Carbonate content increased gradually from the base of the core to 20 cm from very low values of around 2% to 18% at 20 cm. From 20 cm to the surface there was a sharp rise in carbonate to >30 %.

Figure 10 Lithostratigraphy of ORMG2



The visible changes in sediment stratigraphy coincided relatively closely to the measured lithostratigraphic measurements. The peat at the base of the core indicates that the sequence covers the entire record of the broad from its origins as a flooded peat digging. This first lacustrine period after the peat was characterised by a marl coloured sediments which had relatively high levels of organic matter. Whilst these sediments were marl in colour, in contrast to this zone in ORMG1 they were relatively carbonate poor. From around a metre to the surface of the core the sediments became darker in colour as organic matter increased.

Figure 11 Stratigraphy for ORMG2

Depth (cm)	Sediment colour
0-70	dark-brown
70-90	mid-brown
90-140	light brown/marl
140-160	dark brown/peat

ORMG2 Core chronology

The ORMG2 core shows a well-defined SCP concentration peak at 14 – 15 cm (Figure 12a) which in this part of the UK is usually ascribed to 1970 ± 5 yrs. However, given the sampling interval of the core the peak could lie between 13 – 16cm. This suggests that the mean sediment accumulation rate for this upper section of the core is 0.351 – 0.432 cm yr^{-1} (0.392 cm yr^{-1} if the peak is actually at 14 – 15cm). The rapid increase in SCP concentration is more difficult to define in this core, though extrapolation of the upper sediment accumulation rate defined by the SCP peak would place 1950 at 20 – 24cm which seems reasonable. Further extrapolation of this rate would place 1850 at 55 – 68cm. A continuous SCP record is observed in ORMG2 down to 64-65 cm and SCPs are again

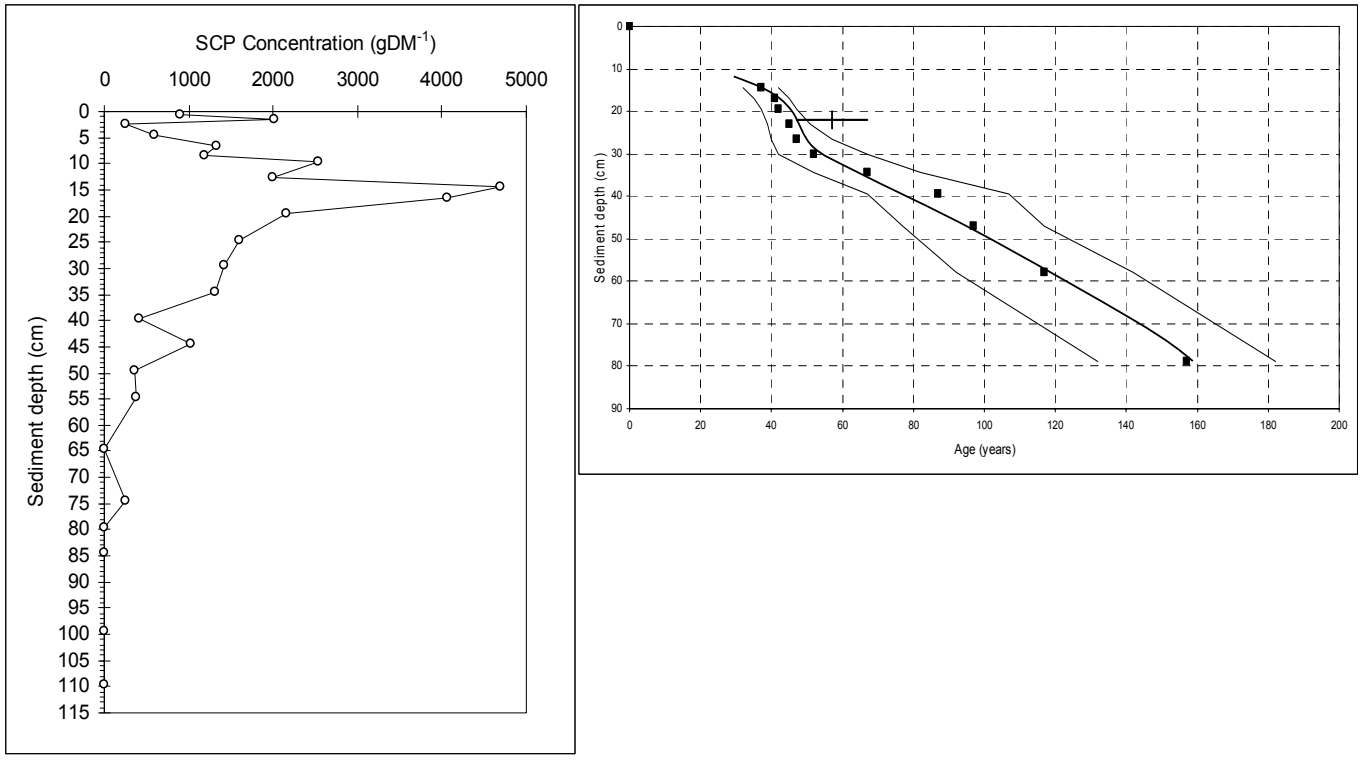
observed at 74-75cm. This therefore suggests that the full SCP record is likely to be present in ORMG2 and we can apply the SCP cumulative percentage approach (Rose & Appleby 2005) to this core. The SCP cumulative percentage approach sets the SCP concentration peak at 100% and calculates an inventory for all SCPs below this point. A date, based on a number of previously dated cores for the region, can then be allocated to each 10-percentile of the curve. Figure 11b shows the depth/age curve for ORMG2 based on this approach and shows an acceleration in sediment accumulation rate in the late-1950s /1960s. The sediment accumulation rate before and after this period is slower. This would appear to be in agreement with the ORMG1 core. The best available chronology is therefore summarised in Table 3.

Table 3 Chronology for ORMG 2

Sediment depth (cm)	Age (years)	Date	± (years)
0	0	2007	0
10	25	1982	5
20	47	1960	10
30	56	1951	10
40	80	1927	15
50	103	1904	20
60	125	1882	20
70	145	1862	25

Figure 12 a) ORMG2 SCP concentration profile; b) Depth/age curve

a) b)



ORMG2 Biological data

Plant remains

138-70 cm (Pre 1862)

The lowermost sample (138 cm) contained numerous *Potamogeton* species/species groups including *P. friesii* agg., *P. pusillus* agg., *P. obtusifolius* and *P. crispus.* Of note is the record of *Potamogeton compressus,* which is now an extremely rare species in the Broads. All of the *Potamogeton* species declined towards the top of the section. *Chara* oospores type A and B were very abundant and *Chara* C and *Nitella* oospores were present throughout this section. Remains of *Ranunculus* sect. *Batrachium* seed fragments and *Nymphaeaceae* trichoschlereids increased to a maximum abundance at 98 cm and then decreased towards the top of the section. Remains of *Z. palustris, Typha* spp., *Alisma plantago-aquatica, N. lutea* and *Callitriche* spp. seeds also occurred at low abundances. Numbers of water-associated plants were greatest in the lowermost sample (138cm) of the core and remained high until 86cm.

70-20 cm (1862 to 1980)

Oospores of all the *Chara* morphotypes and those of *Nitella* declined and where present were in very low numbers after 1862 disappearing completely from the record in the top sample. Likewise the diversity of *Potamogeton* remains declined after 1862. The abundance of *Ranunculus* sect. *Batrachium* seed fragments and *Nymphaeaceae* trichoschlereids declined towards the top of the core.

20–0 cm (1980 AD to present)

The uppermost samples contained abundant *P. pusillus* agg. and unidentified *Potamogeton* leaf tips (most likely *P. pusillus* agg. but the leaves were too small to make a definitive identification). In contrast to ORMG1 this reflects the contemporary macrophyte community. *Z. palustris* seed remains increased to a maximum abundance of 176 per 100 cm^3 seeds at 6cm. The uppermost sample also contained numerous remains of an unidentified filamentous algal species.

Animal and cladoceran remains

The changes in animal remains roughly corresponded with the changes in plant remains (Figure 14 & 15). The base of the sequence contained a number of plant associated species, although fewer than ORMG1, including *Alonella nana*, *G. testudinaria* and *C. rectirostris*, there were also the ephippia of *Ceriodaphnia* spp., *Leydigia* and *Chydorid* spp and the sporadic occurrence in low numbers of *D. hyalina* agg. In this basal section of the core snail operculae were also relatively numerous. The next zone from 80 to 20 cm displayed an increase in the abundance of *D. hyalina* and *Daphnia magna* appeared, and was present consistently in the record thereafter. The more plant associated chydorid species disappeared and *B. longirostris* increased in proportion to around 60%. There was a slight decline in the abundance of *Ceriodaphnia* spp. and *Leydigia* spp. ephippia. Above 20 cm there was a further change in assemblage with large bodied pelagic species, all the *Daphnia* groups, becoming more numerous and a number of snail species appearing in the record. In addition the large-bodied plant associated chydorid *E. lamellatus* increased in proportion in the uppermost samples as do the smaller *Pleuroxus* species. This may reflect the recent increases in plant cover.

The cladoceran based inference model showed very similar patterns to ORMG1 with the same three basic zones. The exception being that the initial shift in function, which the model suggests is a decline in plant abundance, happened at 80 cm rather then 60 cm which was the case in ORMG1. The dating in ORMG2 is less ambiguous than ORMG1 and thus a date of around 1850 can be ascribed to this shift. Thereafter there was a period of relative stability until 30 cm, which corresponds to *circa* 1950, where there was a shift that may reflect a decline in the abundance of zooplanktivorous fish and perhaps a shift to more benthivorous fish species.

Figure 13 Summary stratigraphy for selected plant macrofossils in ORMG2

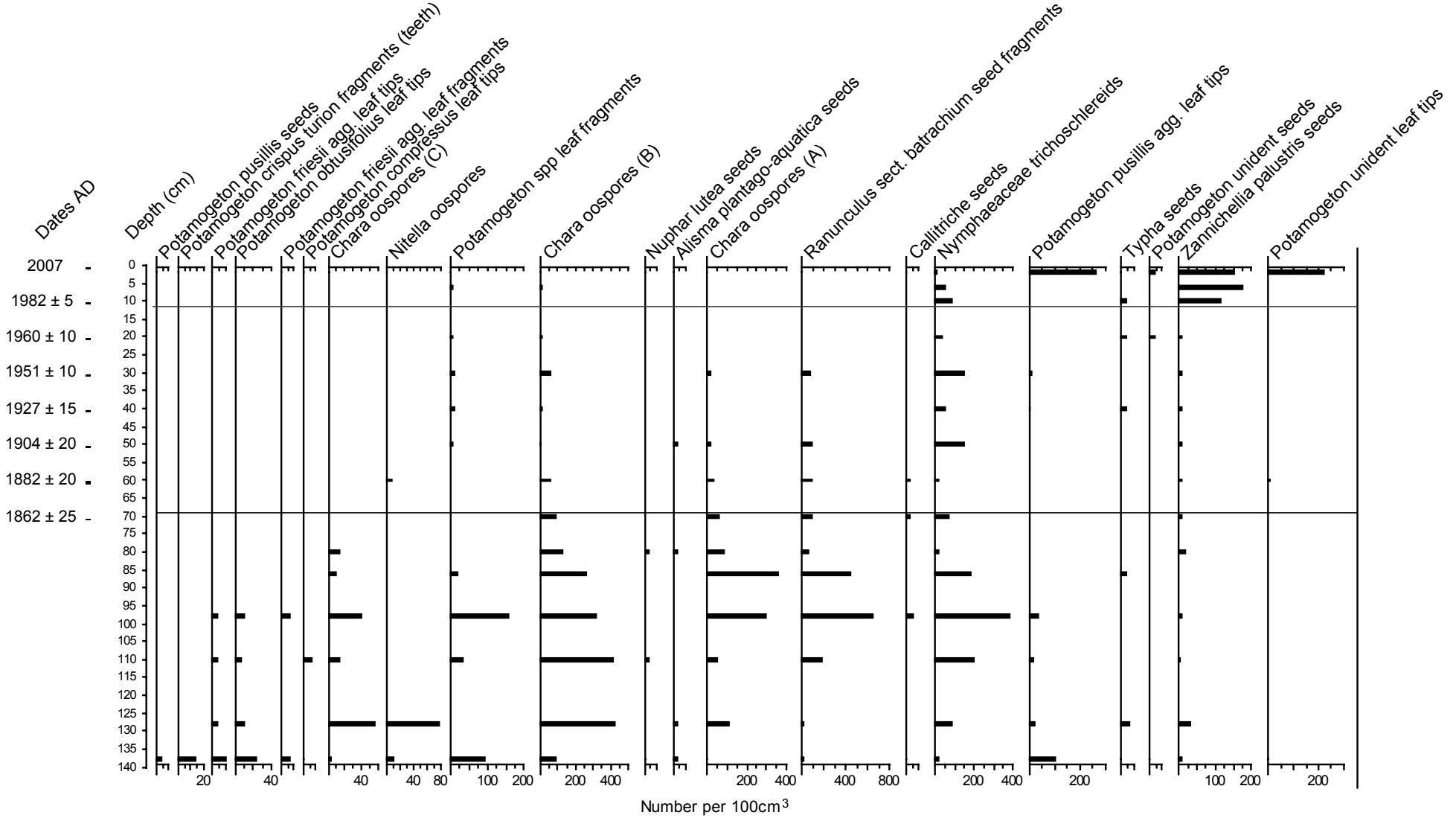


Figure 14 Summary stratigraphy for selected animal remains from ORMG2

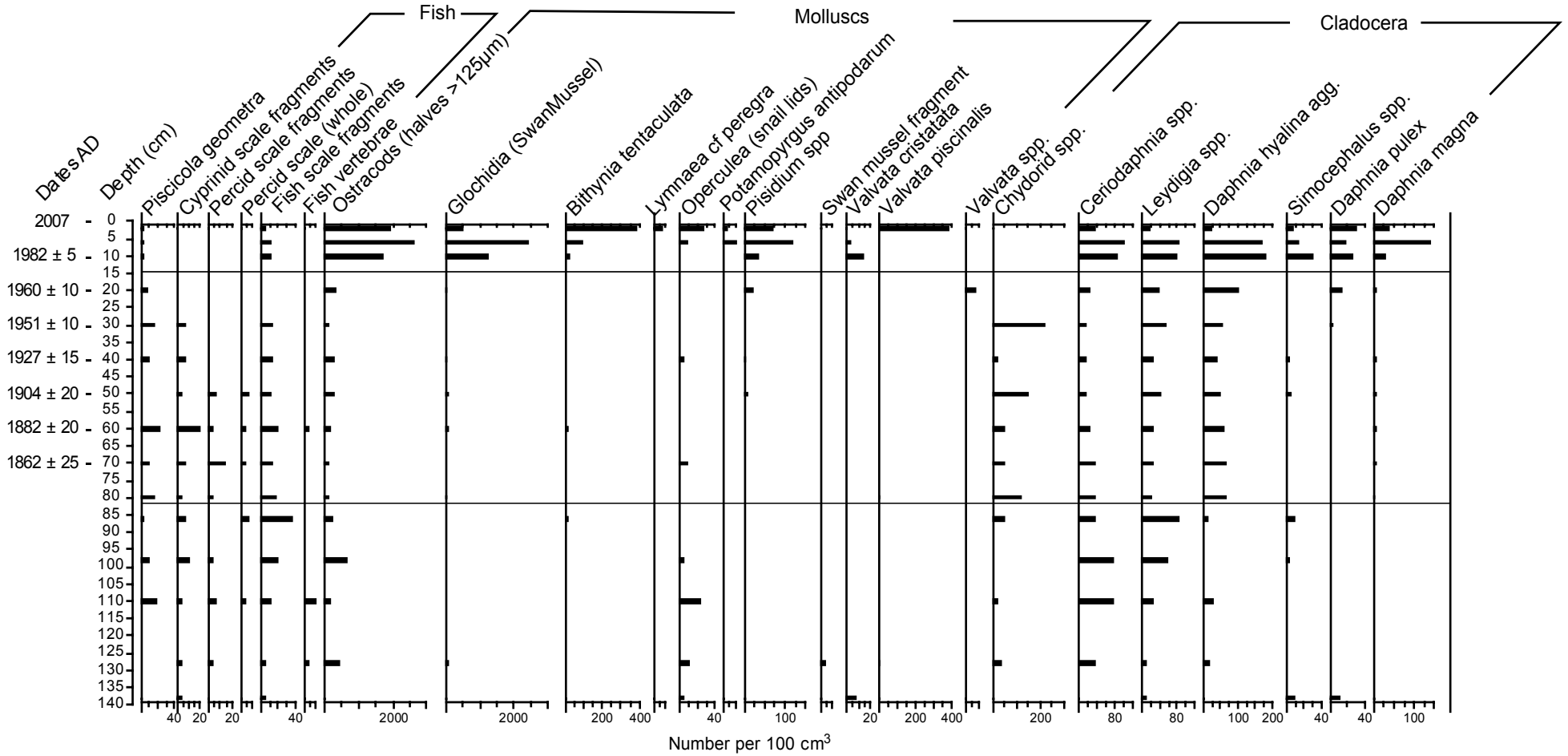
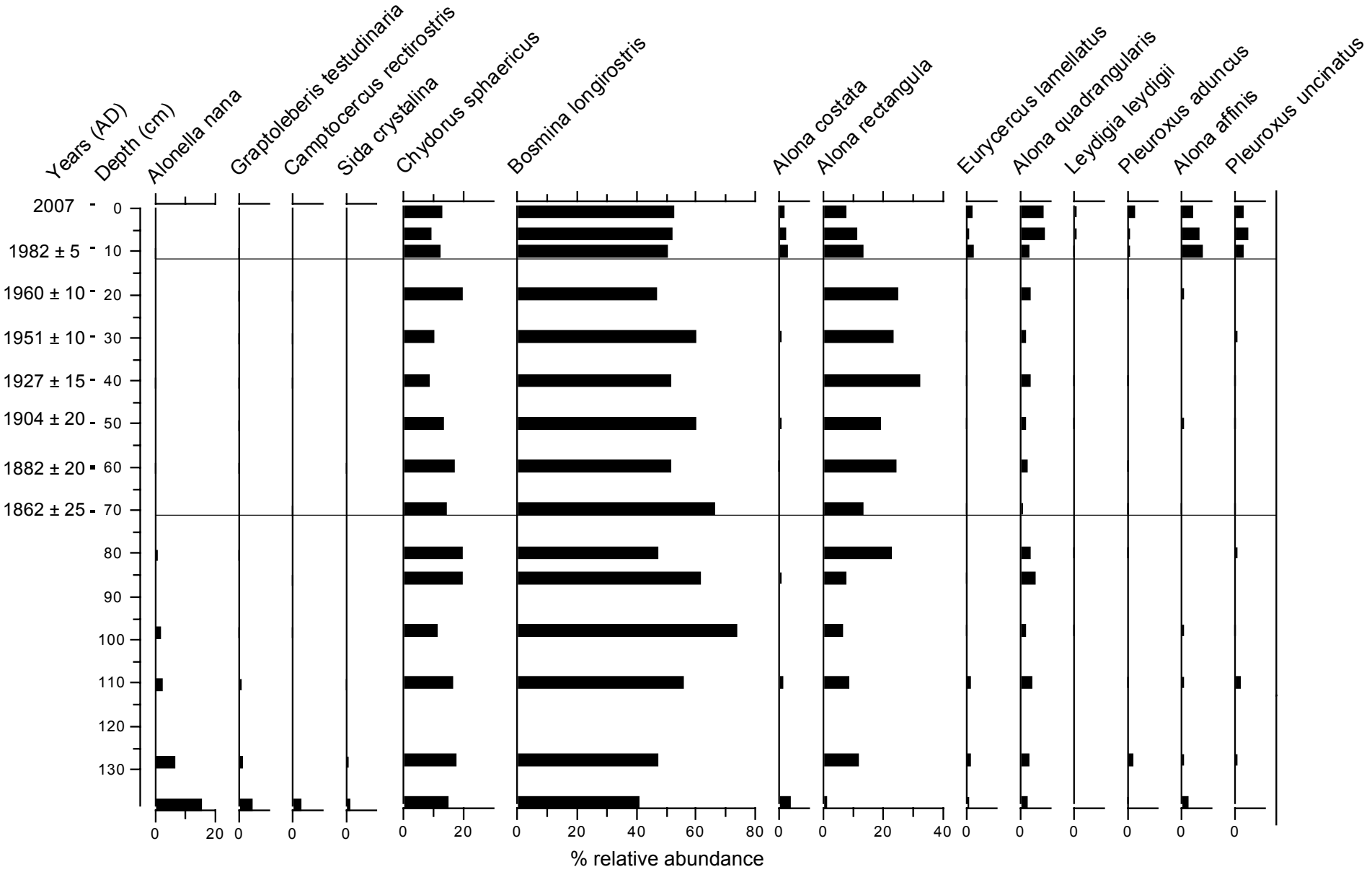


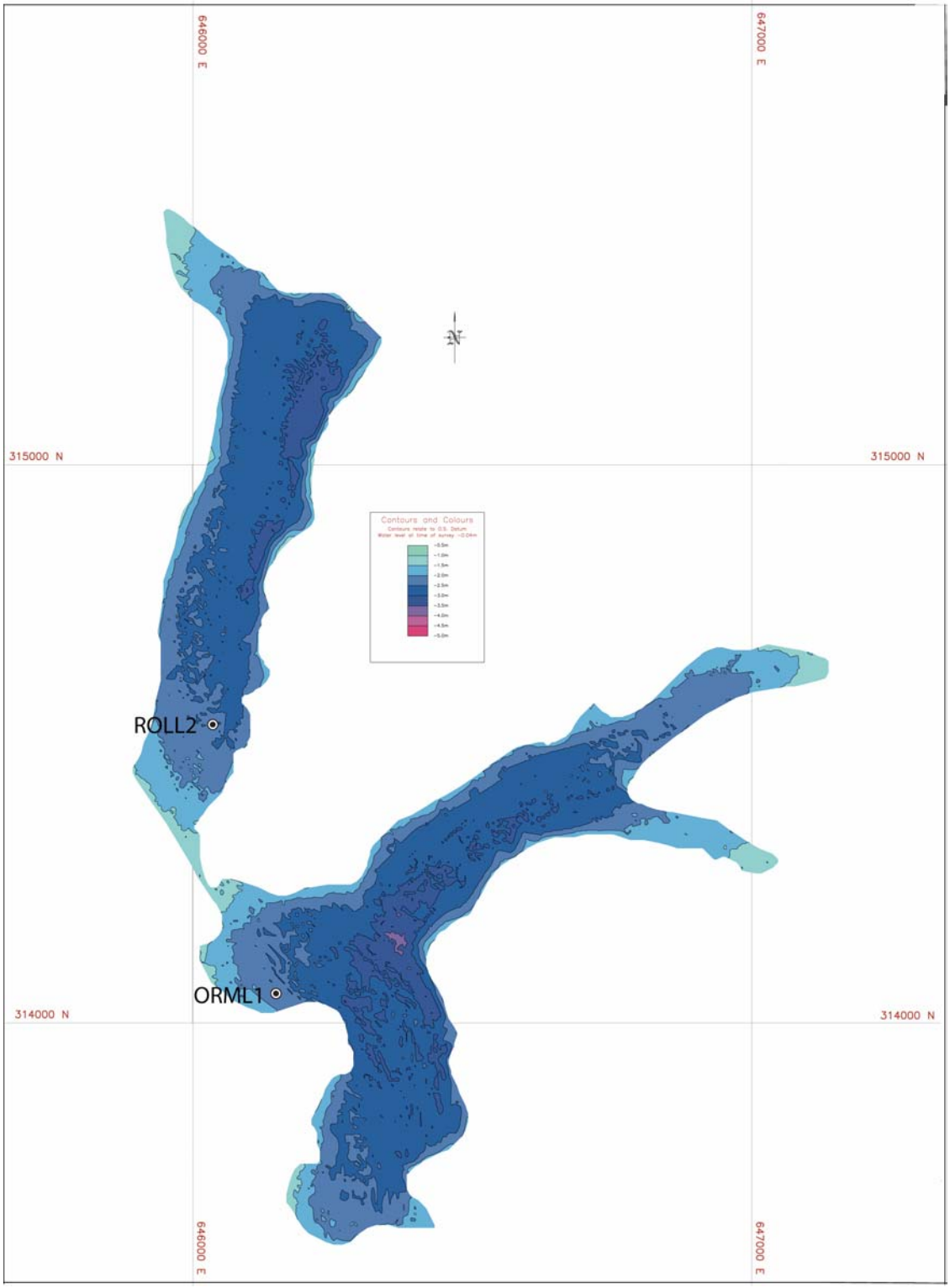
Figure 15 Summary stratigraphy for sub-fossil cladocerans from ORMG2



Rollesby Broad

The location of the Rollesby Broad core (ROLL2) can be seen in Figure 16 and the details of water depth and core length are given in Table 1.

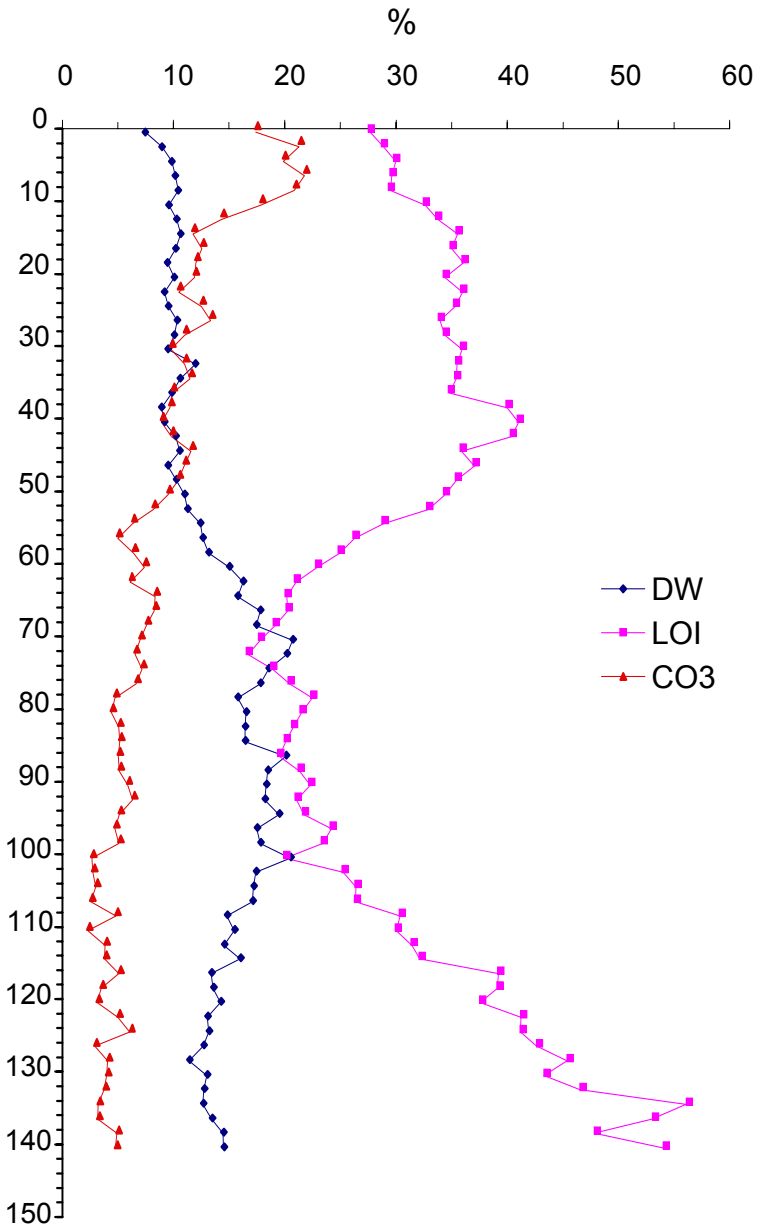
Figure 16 Bathymetric map and coring locations of Rollesby and Ormesby Little Broads



ROLL2 core lithostratigraphy

As in the two Ormesby Broad cores there base of the sequence had very high LOI values around 60% which indicate that the basal peat layer was reached in ROLL2 (Figure 17 & 18). There was a steady decline in LOI to 20% at 100 cm then a period of stability up to 60 cm, followed by a subsequent rise up to around 40% to 40 cm. Thereafter there was a slight decline to the surface with final values for LOI of around 30%. Percentage dry weight (DW) increased from the base to 70 cm from 15% to 20%, there was then a steady decline to the surface. Carbonate showed no real change between the base of the core and 60% with perhaps a slight increase, there was then a more significant steady rise from 60 cm to the surface, from 5% to 20%.

Figure 17 Lithostratigraphy of ROLL2



The changes in colour in the core matched the changes in the measured values LOI and carbonate quite closely. There was a period of light brown/marl like sediment after the basal peat, again the reference to marl is based on colour rather than an elevated carbonate content. The carbonate levels at this time were actually rather low. This was followed by a mid-brown layer of sediment to 60 cm which thereafter was darker brown.

Figure 18 Stratigraphy of ROLL2

Depth (cm)	Sediment colour
0-60	dark-brown
61-105	mid-brown
105-140	light brown/marl
140-149	dark brown/peat

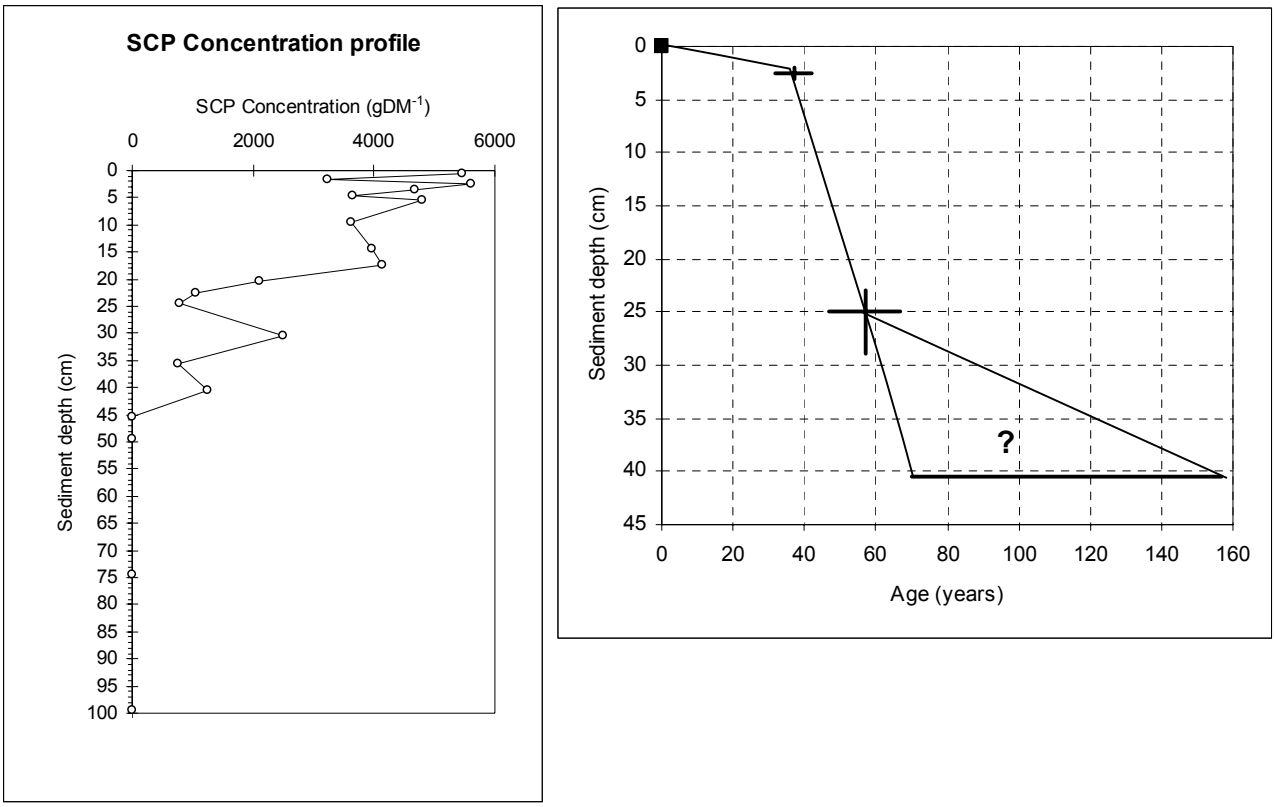
ROLL2 Core chronology

At first glance the SCP concentration profile for ROLL2 seems a little noisy in the surface 5 cm but otherwise looks like a reasonable record (Figure 19a). However, unlike any of the other cores considered in this Trinity Broads study, none of the usual dating features can be unambiguously identified. There are three SCP concentration peaks, in the surface sample, at 2-3cm and at 5-6 cm. If the first of these is the peak usually ascribed to 1970 ± 5 then this suggests that the most recent 37 years of sediment accumulation is missing from the core. If either of the other peaks represent 1970 ± 5 then the sediment accumulation rate for the site is very slow at the surface and has decreased dramatically at some point as an extrapolation of these rates show no indication of the rapid

increase feature at the relevant depths and '1850' falls well within the depth of the observed profile. Similarly, the rapid increase in SCP concentration could be identified at c. 25cm or possibly at the start of the SCP record (i.e. a move from below to above the limit of detection). However, extrapolation of either of the rates fails to agree with any feature in the profile that could be considered the SCP concentration peak. However, it is quite possible, as seen at other sites, that there has been considerable changes in sediment accumulation rates that may explain this so this cannot be ruled out. Further, if the rapid increase feature is at either of these identified points in the profile then the profile has been truncated, which seems quite likely given observations at other sites. If the profile were to be interpreted so that the observed SCP concentration peak is at 1970 ± 5 and the rapid increase is at c. 25cm then the situation is as it appears in Figure 19b. This implies a major change in sediment accumulation rate in the last 30 – 40 years. Below this depth the sediment accumulation rate may continue back in time at this rate or slow down again pre-1950 depending on whether the start of the SCP record relates to the earliest possible (1850) or a more recent date which seems more likely. A limit on this most recent date is only that the sediment record is considered conformable (Figure 19b). The only certainty in the interpretation of this ROLL2 profile is that sediment above 40 – 41cm is more recent than 1850. For this reason no further chronology is suggested here.

Figure 19 a) ROLL2 SCP concentration profile; b) Depth/age curve

a) b)



ROLL2 Biological data

Figures 20 and 21 are summaries of the stratigraphy of the plant and ephippia remains and chitinous cladoceran remains respectively. The species plotted in the diagrams were selected on the grounds of abundance and relevance to the investigation. The ambiguity of the dating of the core means that sediments below 40 cm maybe either older than 1950 or 1850, thus this point is referred to as 1950/1850.

Plant remains

115-40 cm (pre-1950/1850)

Within the lower section of the core (115-60 cm) remains of *Ranunculus* sect. *Batrachium* seed fragments, *Chara* oospores A and B and *Nymphaeaceae* trichoschlereids dominated. *Ranunculus* sect. *Batrachium* seed fragments and *Chara* oospores B reached maximum abundances at 100cm and *Chara* A and *Nymphaeaceae* trichoschlereids were most abundant at 80cm. Other remains present before 1950/1850 AD were *Typha* and *Callitriche* spp. seeds, *P. obtusifolius* leaf tips, *Stratiodes aloides* spines, and *Nitella* oospores. The species richness of water associated plant remains peaked at 80 cm.

40-0 cm (Post 1950/850)

Species richness fell above 40 cm reaching minimal diversity in the uppermost sample (1cm). *Chara* oospores B, *Nitella* oospores and *Ranunculus* sect. *Batrachium* seed fragments declined dramatically in the upper zone. *Potamogeton* remains were absent in the samples representing 1950/1850 AD to the present day. *Typha* spp. seeds and *Nymphaeaceae* trichoschlereids remained relatively stable after 1950/1850 with a small decrease in trichoschlereids in the uppermost sample.

Cladoceran remains

There were changes in the animal stratigraphy which, to some extent mirrored the changes in the plant macrofossil remains. The chitinous cladoceran remains did not show such a high degree of change compared to the Ormesby Broad cores with dominance by *B. longirostris* along the length of the core (Figure 21). The base of the sequence had a slightly higher diversity of cladocerans with a number of plant-associated species. The ephippia data (Figure 20), however, showed a greater degree of change, with the presence of benthic species *Leydigia* spp. and plant associated species *Simocephalus* spp. from the basal section to 60 cm. Thereafter, the presence and abundance of these two species declined and the abundance of pelagic species, in particular *D. hyalina* agg. and *Ceriodaphnia* spp. increased. From 20 cm to the surface, in common with the cores from the other Broads in the system, there was a sharp rise in numbers of large pelagic cladocerans, in particular species taxa such as *D. pulex* and *D. magna* increasing in abundance.

The results of the application of the samples to the sub-fossil cladoceran model (Figure 22) display similar results to the cores from Ormesby Broad, the changes were however less dramatic. The cladoceran assemblage of ROLL2 has the same basic pattern of a period of stability in the basal sequence, followed by a relatively dramatic change above 40 cm, the date of which is ambiguous. This is in agreement with the changes in plant remains and suggests a change in species composition and the model indicates a decline in August macrophyte abundance. ROLL2 was, however, distinct from the other cores in that the location in ordination space of both the basal sample and the surface sediment assemblage (Figure 22) are different form the other sites in the Trinity system. Whilst the surface sediment assemblages of ORMG1 & 2, ORML1 and FILBY1 cluster together the surface of ROLL2 is less proximal, perhaps suggesting the Rollesby Broad functions slightly differently form the other Broads in the system.

Figure 20 Summary stratigraphy of plant and cladoceran ephippia remains for the core ROLL2

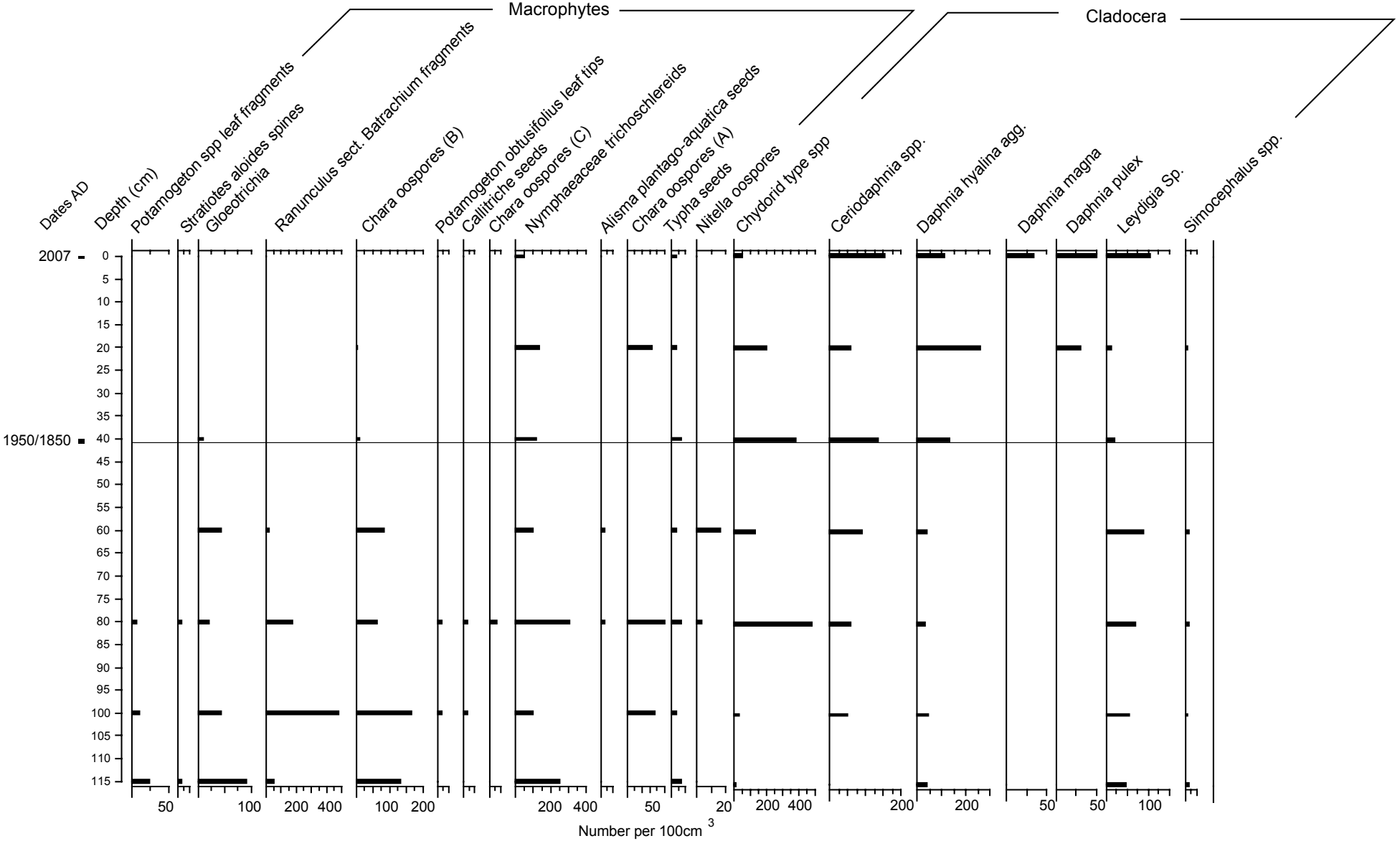


Figure 21 Summary stratigraphy of sub-fossil cladoceran remains for the core ROLL2

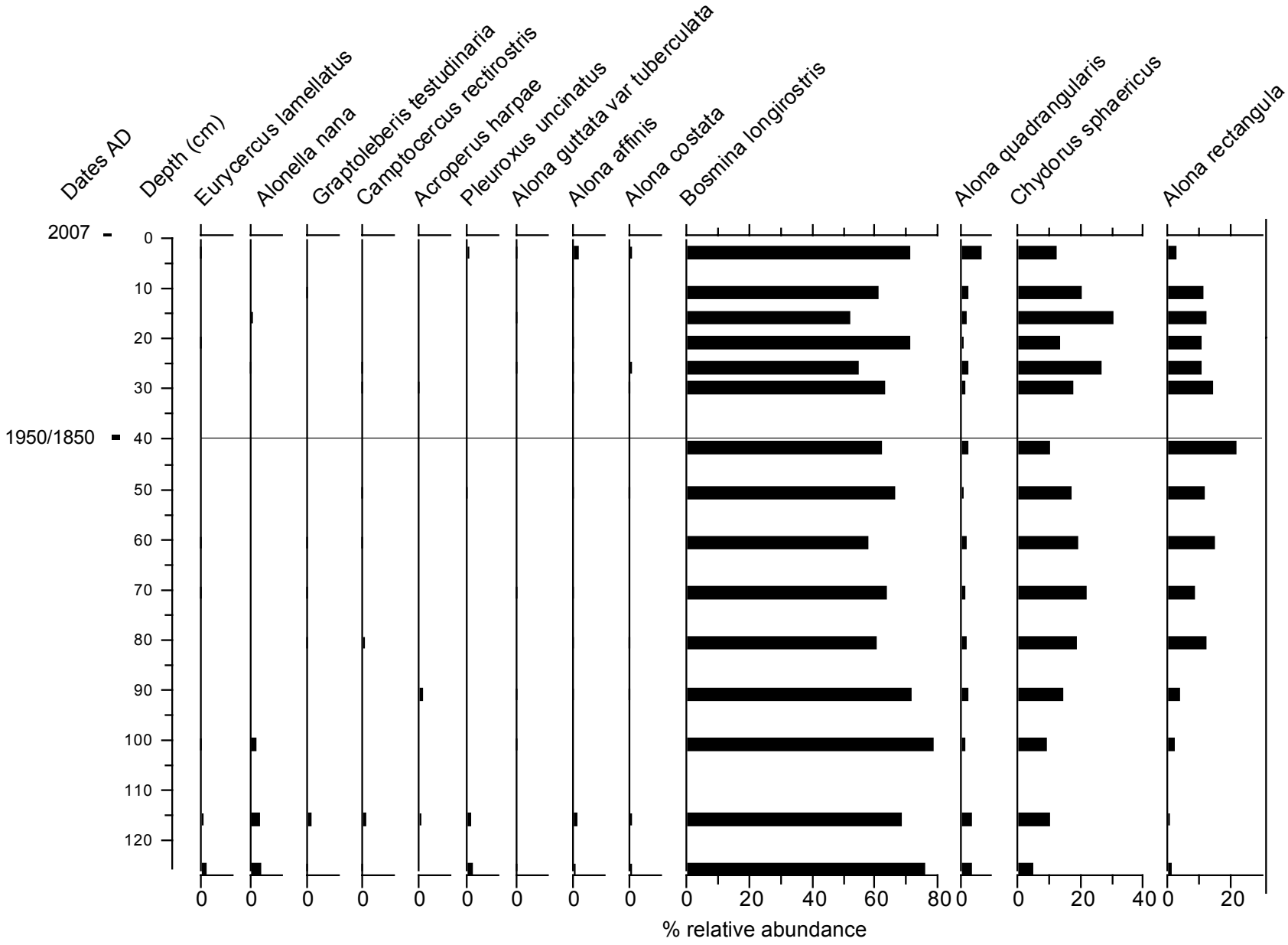
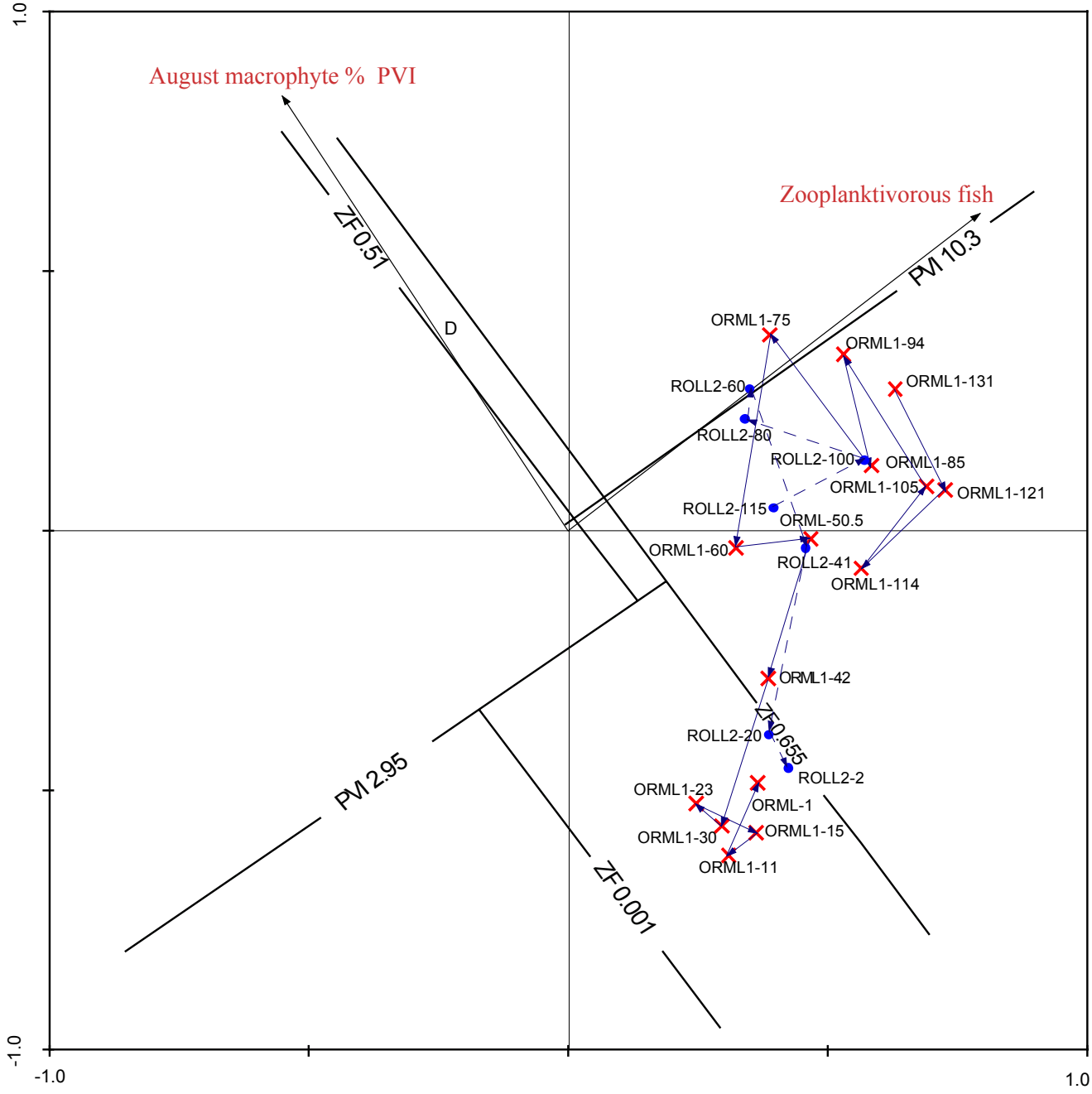


Figure 22 Time tracks of ROLL2 and ORML1 cladoceran assemblages placed in model reflecting changes in zooplanktivorous fish density and August macrophyte density



Ormesby Little Broad

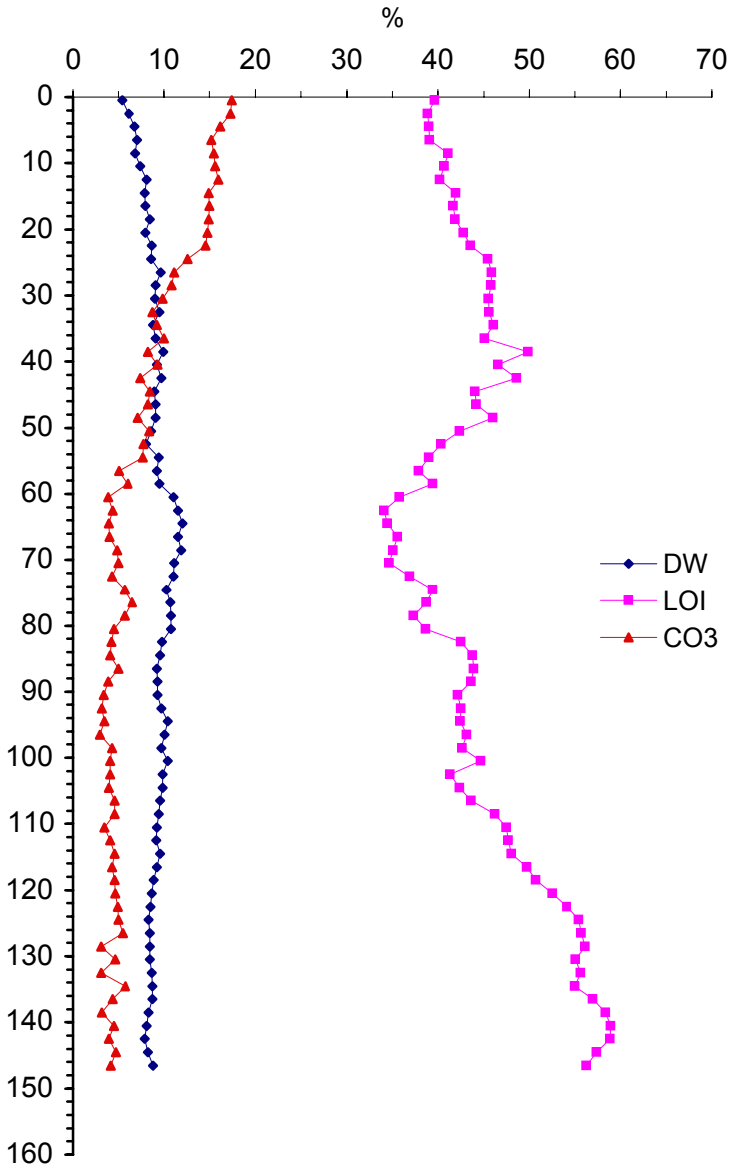
The bathymetry and core location of ORML1 is shown in Figure 16 and the details of location water depth and core length in Table 1.

ORML1 Core stratigraphy

The lithostratigraphy of ORML1 showed less variation than the other cores in this study (Figure 23). Organic content of the sediment (LOI) was uniformly high throughout the core. The basal peat, corresponding to the flooding of the peat digging was perhaps not reached for ORML1 although the base of the core was in excess of 50%. There was a steady decline to around 30% at 70 cm followed by a rise to just under 50 % at 40 cm and then slight decline to 40% at the surface. Dry weight

(DW) remained relatively constant along the length of the core and carbonate was constantly low to 60% and then rose steadily to the surface from there.

Figure 23 Lithostratigraphy of ORML1



The colour changes in the core match the LOI profile relatively closely (Figure 24) with a change in colour at 60 cm from red brown to dark brown. The core did not appear to have reached the basal peat, however the length of the core suggests that a large majority lake's history is represented by the core.

Figure 24 Stratigraphy of ORML1

Depth (cm)	Sediment colour
0-60	**dark brown**
61-150	**red-brown**

ORML1 Core chronology

The ORML1 core (Figure 25a) shows two well-defined SCP concentration peaks at 9 - 10 cm and 24-25 cm. However, given the sampling intervals these peaks could be between 7 – 12 cm and 23 – 30cm respectively. If the former peak is the feature usually ascribed to 1970 ± 5 yrs then the mean sediment accumulation rate for this upper section of the core is 0.189 – 0.324 cm yr^{-1} (0.257 cm yr^{-1} if the peak is actually at 9 – 10 cm). If the latter peak is the feature usually ascribed to 1970 ± 5 yrs then the mean sediment accumulation rate for this upper section of the core is 0.622 – 0.811 cm

yr^{-1} (0.662 cm yr^{-1} if the peak is actually at 24 – 25 cm). Unusually, the rapid increase in SCP concentration, defined as the intercept between the slope of the two lines either side of the increase, appears to be more clearly defined in ORML1 than the SCP concentration peak. Here, it lies at c. 35cm and this is usually ascribed the date of 1950 ± 10 yrs. Given this depth/date then either there has been a major change in sediment accumulation rate above this, or the SCP concentration peak should be the lower 24 – 25cm one. It is assumed that the latter case is more likely. The first presence of SCPs is at 74 – 75cm although there is also a 'zero' value above this. Considering the accumulation rates represented by the depth/date of the rapid increase feature and the SCP concentration peak, it is probable that this represents a slightly truncated SCP profile, or a change in sediment accumulation rate in this lower section. Therefore it is not possible to employ the SCP cumulative percentage approach (Rose & Appleby 2005) to this core. The depth of 74 – 75 cm therefore represents a date after 1850, but it is uncertain when exactly this is. Figure 24b shows these dating features plotted on a depth/age curve. The SCP peak and rapid increase features imply a reasonably constant accumulation rate. Below this depth there are several possibilities. First (represented by the darker line) the sediment accumulation rate continues through the core such that the SCPs at 74 – 75cm represent a presence at almost 120 years ago. Second, that sediment accumulation rate is slower below 1950s and that the SCPs at 74 – 75cm represent an age between 120 and 150 years ago (extreme case represented as thinner line on Figure 24b). Third, that sediment accumulation rate is more rapid below 1950s and the SCPs at 74-75 represent an age less than 120 years. Table 4 provides the chronology for ORML1 assuming the continuation of the depth/age curve prior to 1950s, while Table 5 provides the chronology for ORML1 assuming that the SCPs at 74 – 75 cm are at 1850.

Table 4 Chronology for ORML1 assuming continuation of sediment accumulation rate (values in italics are less certain and need to be treated with caution)

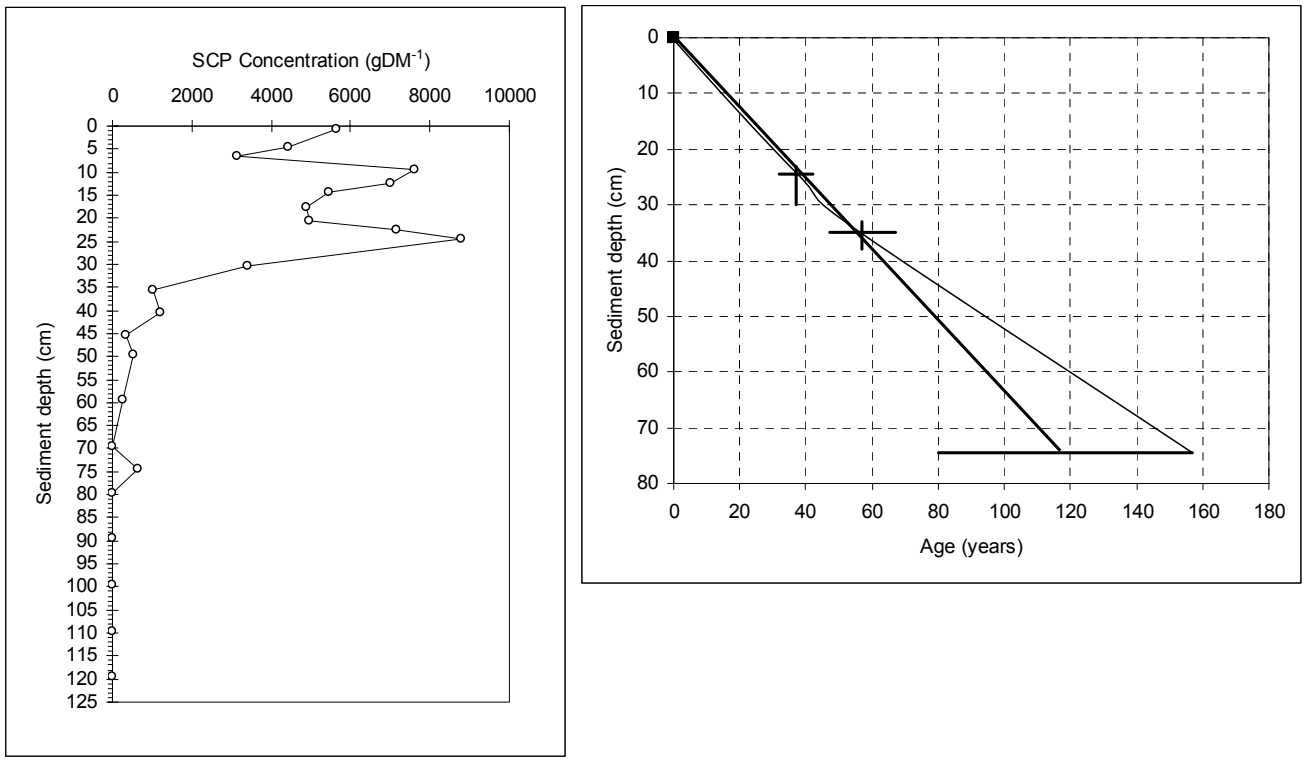
Sediment depth (cm)	Age (years)	Date	± (years)
0	0	2007	0
10	19	1988	5
20	34	1973	5
30	50	1957	10
40	65	1942	15
50	*80*	*1927*	*15*
60	*95*	*1912*	*20*
70	*112*	*1895*	*25*

Table 5 Chronology for ORML1 assuming SCPs at 74 – 75cm are at maximum age (values in italics are less certain and need to be treated with caution)

Sediment depth (cm)	Age (years)	Date	± (years)
0	0	2007	0
10	19	1988	5
20	34	1973	5
30	50	1957	10
40	65	1942	15
50	*96*	*1911*	*20*
60	*120*	*1887*	*25*
70	*147*	*1860*	*25*

Figure 25 a) ORML1 SCP concentration profile; b) Depth/age curve

a) b)



ORML1 Biological data

Plant remains

In the samples representing the period before 1895 (70-130 cm) several *Potamogeton* species were present (including *P. friesii* agg., *P. pusillus* agg., and *P. obtusifolius*) as were *Chara* oospores A, B and C (Figure 26). Morphotypes A and C first occurred within the sediment record at a slightly later date (at 105 cm and 75 cm respectively) in comparison to oospores type B, present from 130cm onwards. *Nitella* oospores were found in only one sample in this core section at 75 cm. *Ranunculus* sect. *Batrachium* seed fragments were abundant during the earliest part of the record (130-105 cm) but their quantity was sporadic and declined after their peak abundance at 105cm. *Nymphaeaceae* trichoschlereids were also present at 130cm reaching maximum abundances at 115cm, after which they declined and remained relatively stable throughout the pre 1895 AD period. Small amounts of *Typha* spp, *Alisma plantago- aquatica* and *Z. palustris* seeds, along with *S. aloides* spines also occurred in the pre 1895 AD section of the core. The diversity of the water associated plants peaked at 85 cm within this core.

70- 0 cm (1895-present)

Chara oospores types A and B declined in the sediments representing 1895 to the present day (70-2cm). *Chara* oospores type C reached maximum abundance at 23cm and *Nitella* oospores also exhibited a second peak within the record at 30cm. However, oospores of *Chara* A and C and *Nitella* did not occur after *ca*.1988 (10 cm) and *Chara* oospores type B only occurred within the uppermost sample at a count of 3 suggesting that abundances of *Chara* and *Nitella* species were relatively rare within Ormesby Little Broad after *ca*.1973. No *Potamogeton* species leaf fragments or seeds were found in the sediment representing 1895 AD to the present day and remains of *Z. palustris* and *S. aloides* were also absent after 1895 AD. *Callitriche* spp seeds first occurred at 60 cm (*ca*.1912 AD) but declined thereafter and were absent in the sediments representing 1957 AD to the present day (30-0 cm). *Nymphaeaceae* trichoschlereids remains were present throughout the whole post 1895 AD period, decreasing in abundance at 60 and 40 cm (*ca*. 1912 and 1942

respectively) but increasing again in the uppermost sample. In general the uppermost sample was almost completely devoid of submerged or floating leaved macrophytes remains.

Animal remains

The animal remains from the macrofossil samples (Figure 27) and the chitinous cladoceran samples (Figure 28) showed very similar stratigraphies to the plant remains and the lithostratigraphy. There was, however, a dramatic change in the composition of animal remains at 30 cm. As with the other cores the base section had more plant associated species in the chitinous remains. Ephippia from the benthic *Leydigia* spp., plant associated *Simocephalus* spp. were more abundant in the lower section and *D. hyalina* was also present in relatively high numbers at the base. Above 60 cm there was a decline in the abundance of *B. longirostris* and an increase in the proportion of *C. sphaericus*. Above 30 cm, which is post-1950 there was a significant increase in large bodied pelagic cladocerans including *D. magna* and *D.* pulex.

Above 30 cm there was an increase in *Pisidium* remains and the first appearance and proliferation of the glochidia which are likely to be from the swan mussel (*Anodonta cygnea*). Fish remains were relatively abundant along the length of the core, they did, however, become less abundant in the top 30 cm. In particular, the larger remains of scales, identifiable as either percid or cyprinid (Davidson et al. 2003) were more abundant below 30 cm. Thereafter the remains were dominated by the small fragments, which could not be identified.

The application of the cladoceran based model to the sedimentary sequence of ORML1 (Figure 22) revealed a pattern of change similar to the other Trinity cores. There was period of relative stability from the base of the sequence to 50 cm, although there was also quite a large shift between 75 and 60 cm, with a trajectory suggesting decreasing August macrophyte abundance. Above 50 cm there was a large change in assemblage to 30 cm again suggesting a decline in August macrophyte abundance. Above 30 cm, around 1950, there has been very little change in cladoceran assemblage, suggesting that in Ormesby Little Broad ecological function has remained relatively constant since that time.

Figure 26 Summary stratigraphy of plant remains from ORML1

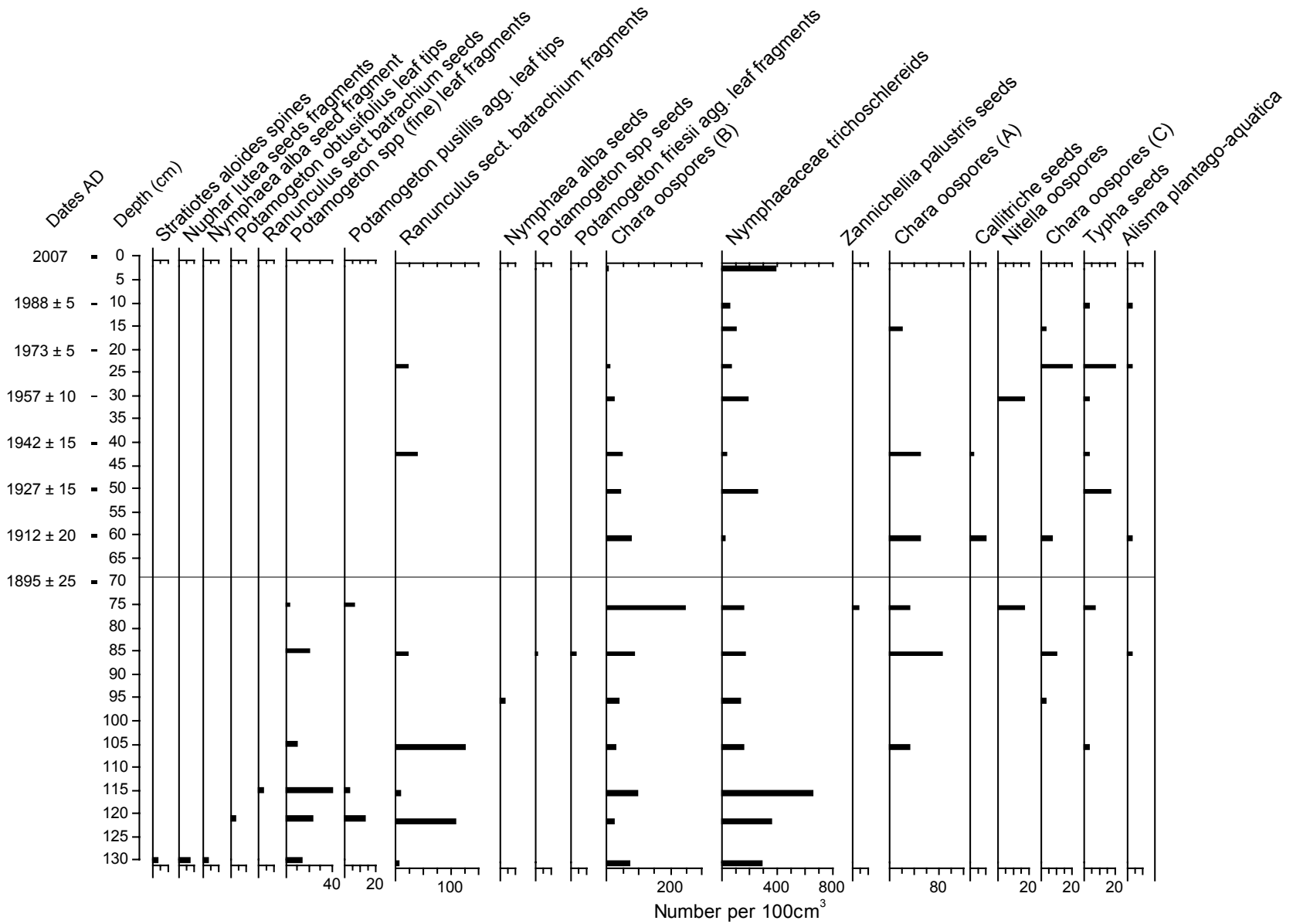


Figure 27 Summary stratigraphy of animal macrofossil remains from ORML1

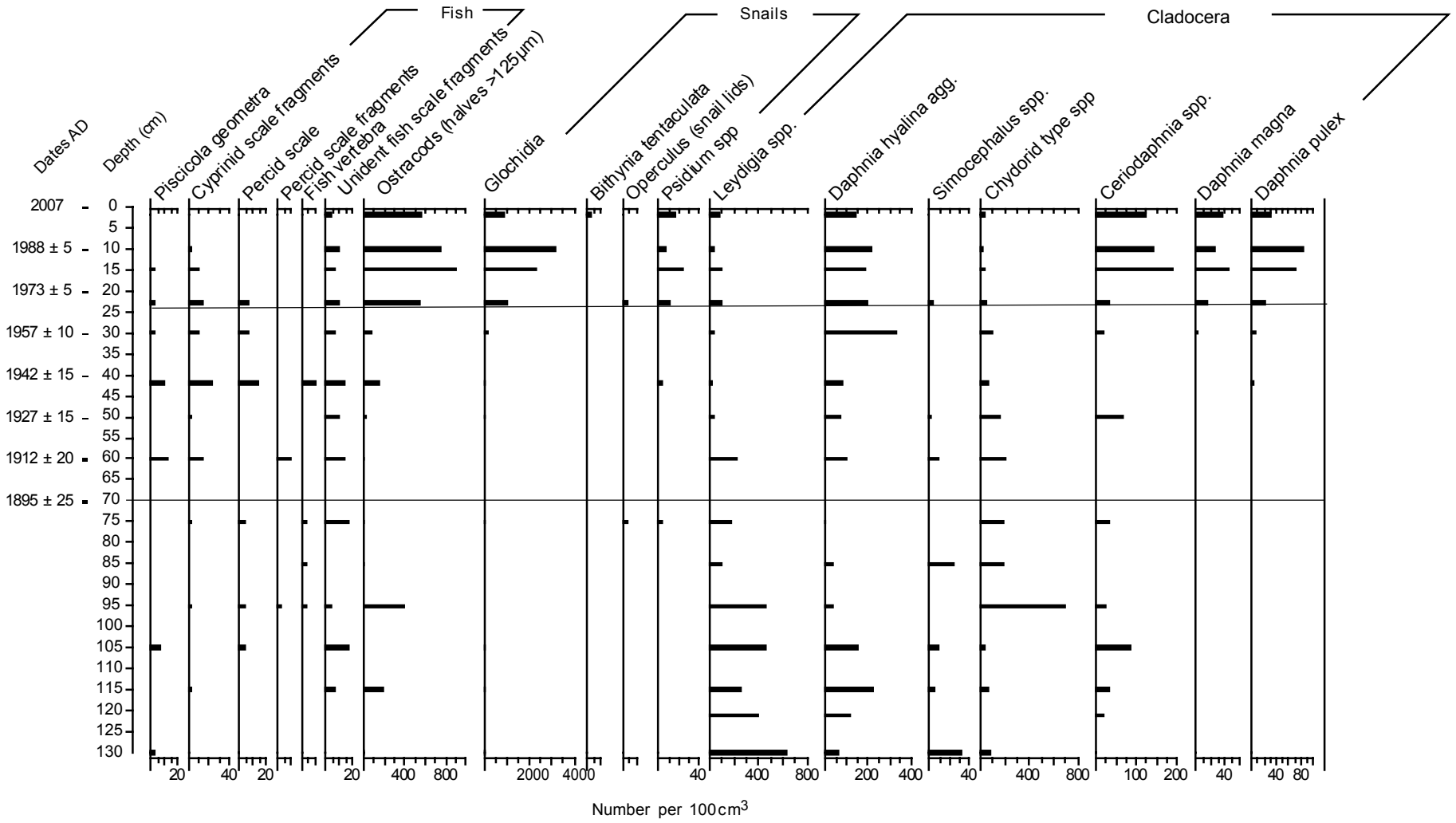
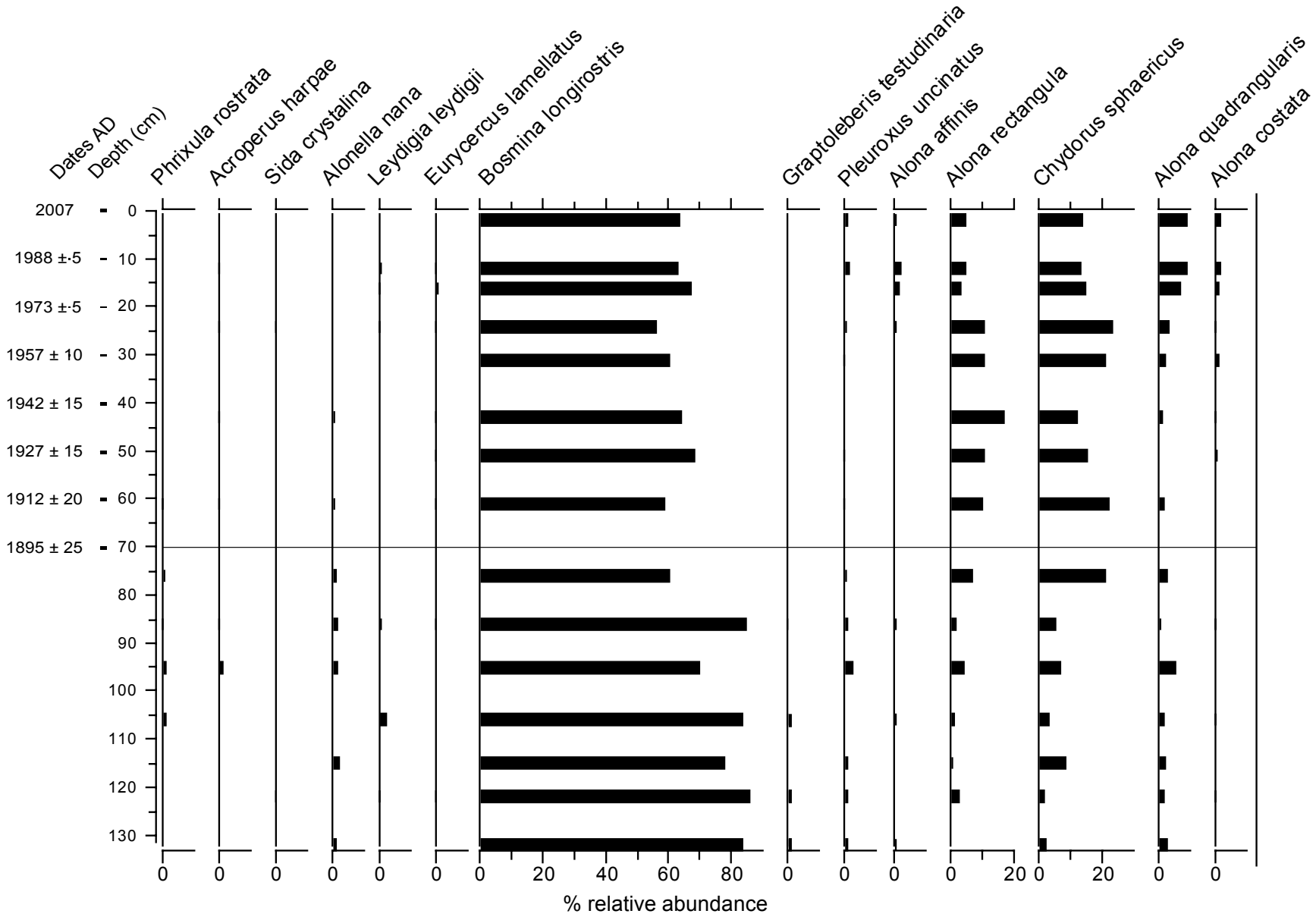


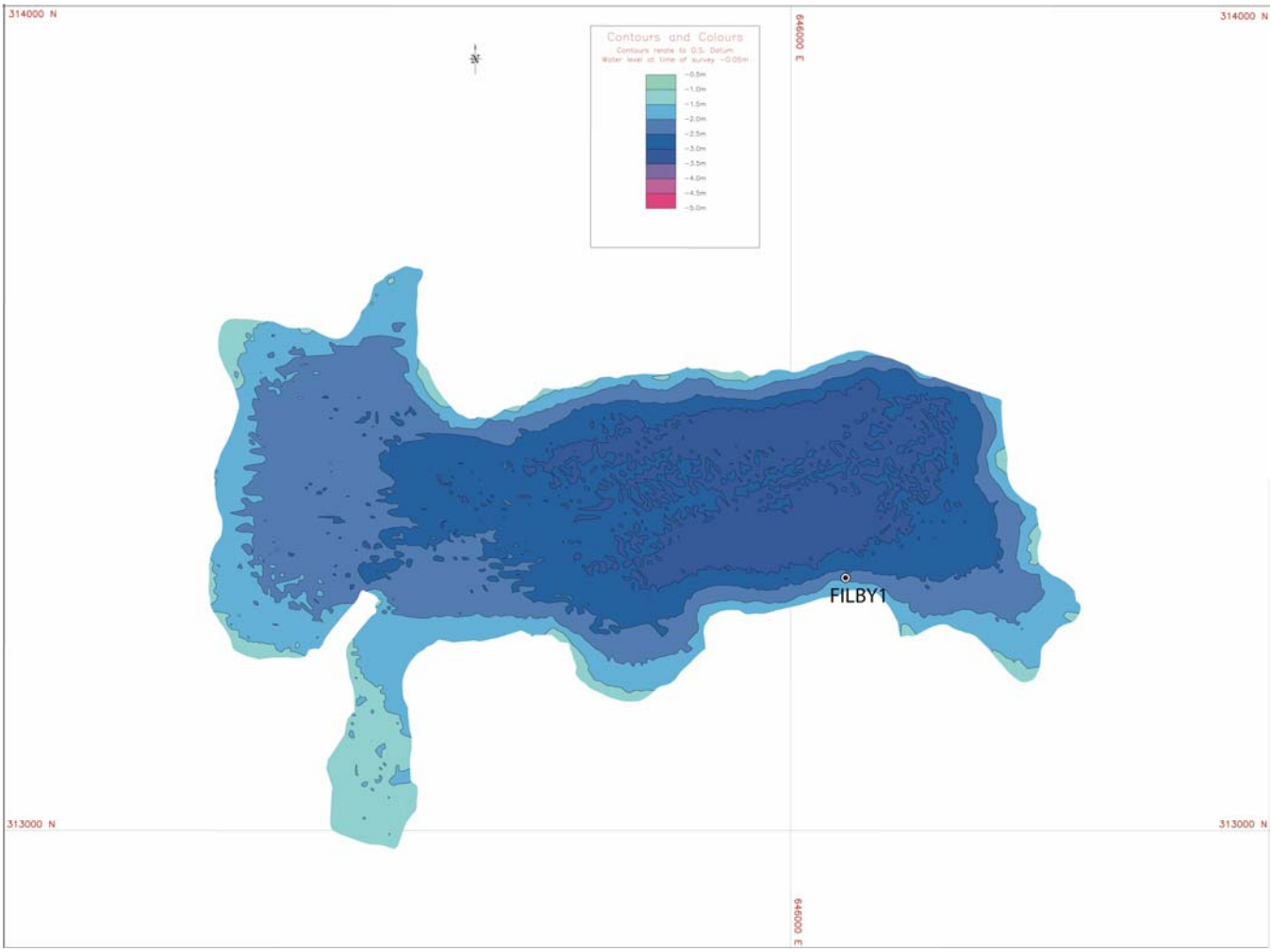
Figure 28 Summary stratigraphy of chitinous cladoceran remains from ORML1



Filby Broad

The water depth and coring location of FILBY1 can be seen in Figure 29 with full details in Table 1.

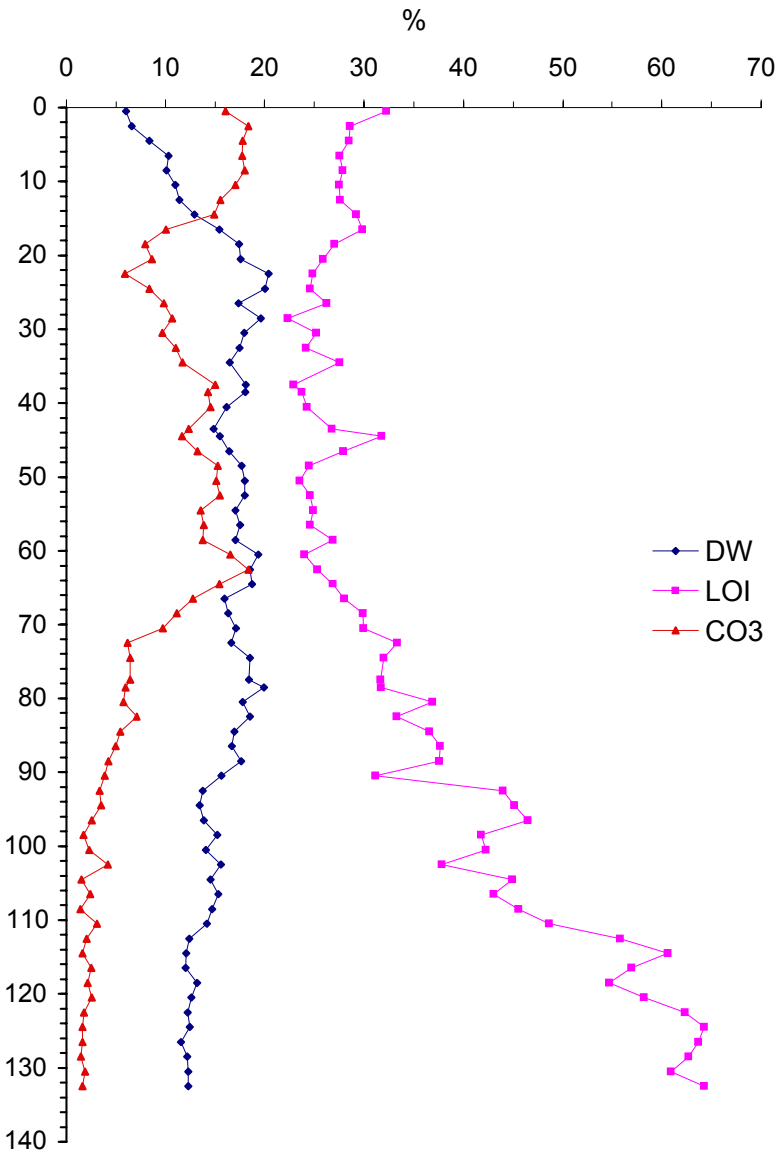
Figure 29 Bathymetric map and coring location for FILBY1



FILBY1 Core lithostratigraphy

The core FILBY1 had a base of peat indicating that the core covers the entire life of the Broad (Figure 30). There was a steady decline organic content (LOI) from the base to around 60 cm, thereafter, it was relatively constant to the surface with perhaps a slight increase in the top 20 cm. The dry weight (DW) increased very gradually between the base and 20 cm, after which there was a decline to the surface as water content increased towards the surface of the core. Carbonate increased slowly from almost total absence at the base to 70 cm, where it increased quite sharply to 20% at 60 cm. Thereafter carbonate fell slowly to around 5% at 20 cm and then increased to the surface of the core.

Figure 30 Lithostratigraphy of FILBY1



The changes in the sediment colour along the length of the core (Figure 31) roughly corresponded to changes in LOI and carbonate concentration. The peat base was followed by a rich dark brown section corresponding to the initial lacustrine phase of the lake. There followed a section with lighter-brown sediments from 80 cm to 30 cm before a final transition to darker brown sediment more common in enriched lakes.

Figure 31 Stratigraphy of FILBY1

Depth (cm)	Sediment colour
0-30	dark-brown
30-80	light brown
80-120	dark rich brown
120-142	Peat

FILBY1 Core chronology

The FILB1 core shows a well-defined SCP concentration peak at 9 – 10cm (Figure 32a) which in this part of the UK is usually ascribed to 1970 ± 5 yrs. However, given the sampling interval of the core the peak could lie between 8 – 12cm. This suggests that the mean sediment accumulation rate for this upper section of the core is 0.216 – 0.324 cm yr^{-1} (0.257 cm yr^{-1} if the peak is actually at 9 – 10cm). The rapid increase in SCP concentration defined as the intercept between the slope of the

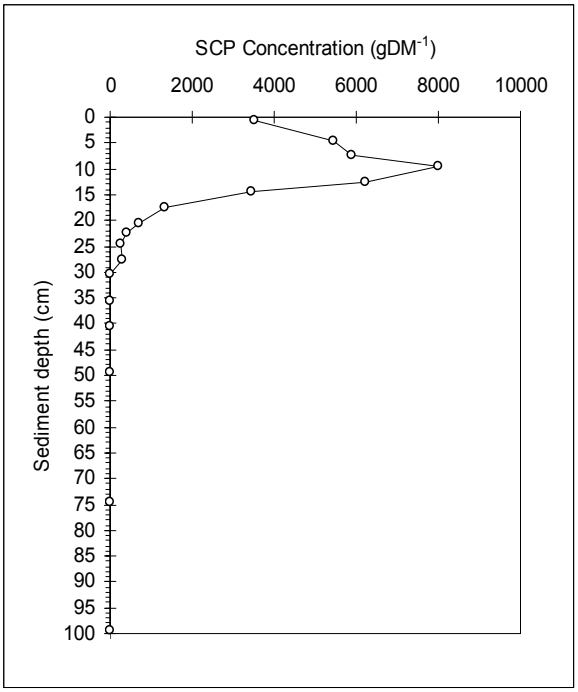
two lines either side of the increase lies at 18 – 20cm and this is usually ascribed the date of 1950 ± 10 yrs. Plotting these two sets of data (Figure 32b) suggests that the accumulation rate in FILBY1 has decreased over this period. Extrapolation of the basal accumulation rate suggests that the start of the SCP record at 27 – 28 cm occurs in the 1930s. This implies that the record has been truncated and the start of the record at this depth/date is defined by when the SCP concentration exceeds the detection limit of the technique for the first time. This truncation of the record also indicates that it is not possible to employ the SCP cumulative percentage approach (Rose & Appleby 2005) to this core. The best available chronology is therefore that represented by Figure 32 and summarised in Table 6.

Table 6 Chronology for FILB 1 (values in italics extrapolated)

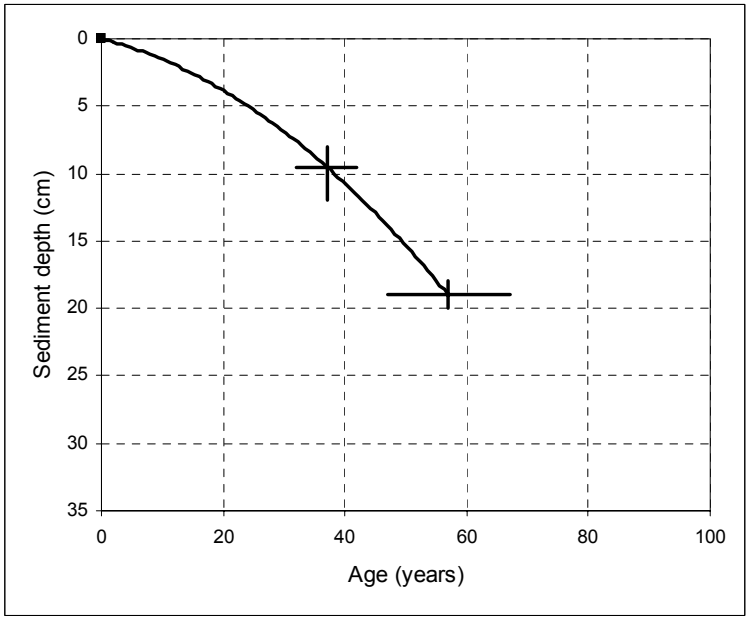
Sediment depth (cm)	Age (years)	Date	± (years)
0	0	2007	0
5	24	1983	5
10	38	1969	5
15	49	1958	10
20	60	1947	15
25	*69*	*1938*	*20*
30	*79*	*1928*	*20*

Figure 32 a) FILBY1 SCP concentration profile; b) Depth/age curve

a)



b)



FILBY1 Biological data

The plant and animal macrofossils (Figures 33 & 34) and the chitinous cladoceran remains (Figure 35), all display roughly the same stratigraphy with aquatic remains sparse in the bottom-most sample. There was then a long period from the 120 to 30 cm which, whilst there was some variation, particularly at about 90 cm in the cladoceran record, had relatively similar assemblages of both plants and animals. Above 30 cm there was a profound shift away from diverse submerged vegetation and charophytes to a more pelagic community of invertebrates.

Plant remains

120- 30 (cm Pre 1928)

The lowermost sample (120 cm) contained few submerged or floating macrofossils suggesting that this sample corresponds to a peat layer prior to the formation of the Broad proper. At 100 cm leaf remains of many *Potamogeton* species/species groups occurred (including *P. friesii* agg., *P. pusillus* agg., and *P. obtusifolius*) and increased throughout this section reaching maximum abundance at 50 cm. As the *Potamogeton* species declined *Chara* oospores A, B and C increased and became dominant within the record, but numbers were already high and remained so throughout this zone. All three *Chara* morphotypes increased at the same time within this core, unlike ORMG1 and ORMG2 where the dominance of *Chara* A was slightly delayed in comparison to types B and C. *Nitella* oospores first occurred within the record at 100 cm and persisted in similar numbers throughout the zone. Remains of *Nymphaeaceae* trichoschlereids also first occurred at 50cm. *Z. palustris* seeds were present throughout this section of the core increasing around 80-70 cm and 50cm. *Typha* spp, *Alisma plantago- aquatica,* and *Callitriche* spp. remains occurred sporadically throughout this section of the core.

30-10 cm (1928 to 1970)

Remains of *Ranunculus* sect. B*atrachium* seed fragments increased at *ca.* 1928 (30cm) but then declined at 15cm, around 1958. Numbers of *Chara* oospores A, B and C and *Nitella* oospores remained high throughout the period between 1928- 1958 AD. After 1958 AD all types of *Chara* and *Nitella* oospores fell. The abundance of *Potamogeton* remains was low in the upper section of the core in comparison to the pre 1928 AD sediment section. Species diversity was highest within FILBY1 at 20cm (*ca.* 1947 AD), but is also high at 30cm (*ca.* 1928 AD), 50cm and 70cm.

10-0 cm (1970 to present)

The diversity of the water associated plants was lowest in the uppermost sample. Very few species were represented with only *Z. palustris*, *Potamogeton* spp. and *Nymphaeaceae* trichoschlereids present.

Animal remains

As with the plant macrofossil remains, remains aquatic fauna were rare in the bottom-most sample. The cladoceran community changed at about 90 cm in the core with a shift from benthic and plant associated taxa, such as *Leydigia* spp., *Alonella nana* and *C. rectirostris* to more pelagic species, in particular *B. longirostris.* At 60 cm there was a further increase in the abundance of the pelagic species *D. hyalina*. Then at 30 cm there was a further increase all the *Daphnia* species numbers and a significant increase in the proportion of *C. sphaericus*.

Fish remains were relatively common in FILBY1, identifiable larger remains were common between 30 and 10 cm representing 1920 to around 1970. In this period, the data suggest that Perch were plentiful and that cyprinids were also abundant, unfortunately which species of cyprinid they were is not possible to determine.

Figure 33 Summary stratigraphy of plant macrofossil remains from FILBY1

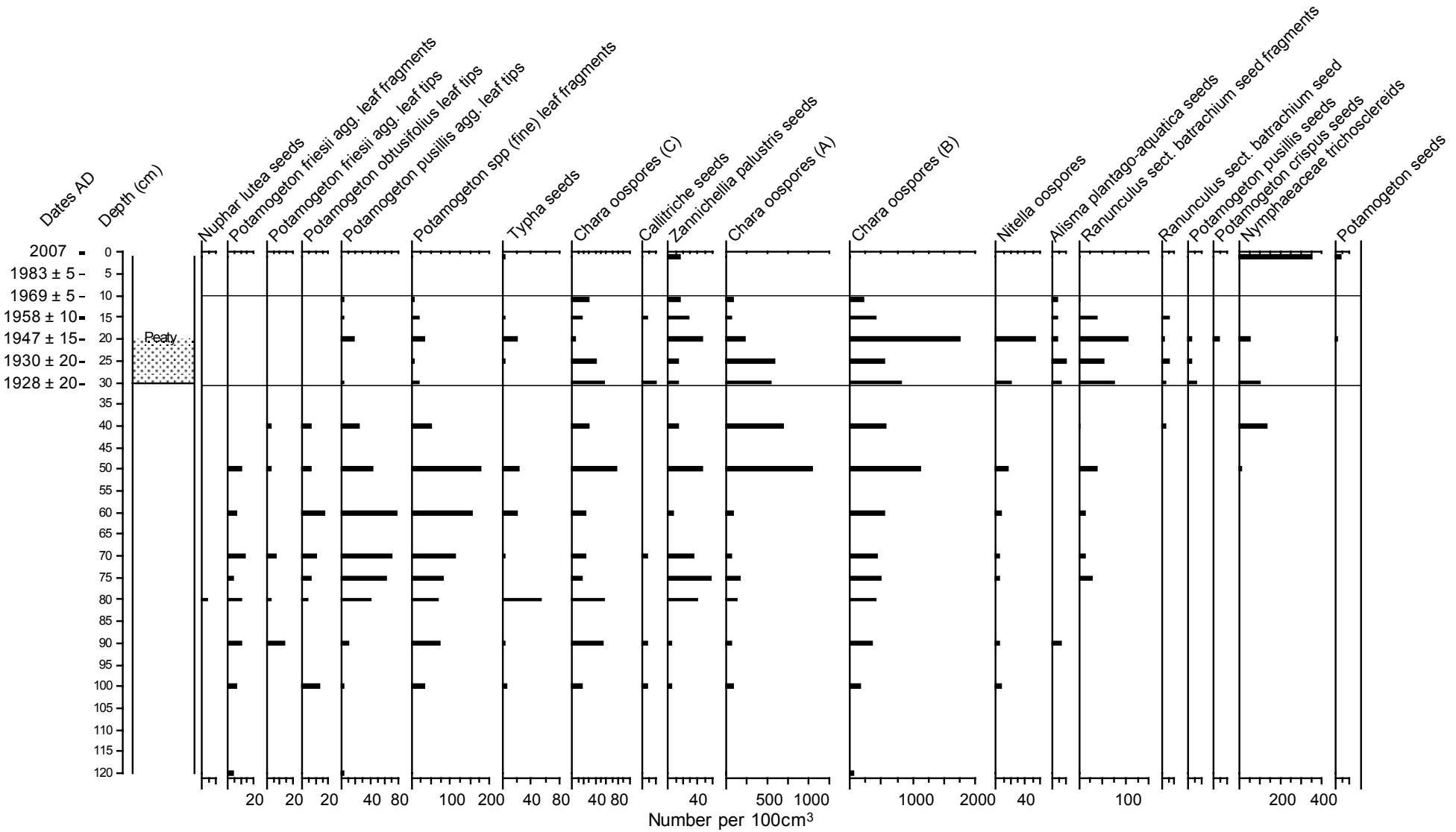


Figure 34 Summary stratigraphy of animal macrofossil remains from FILBY1

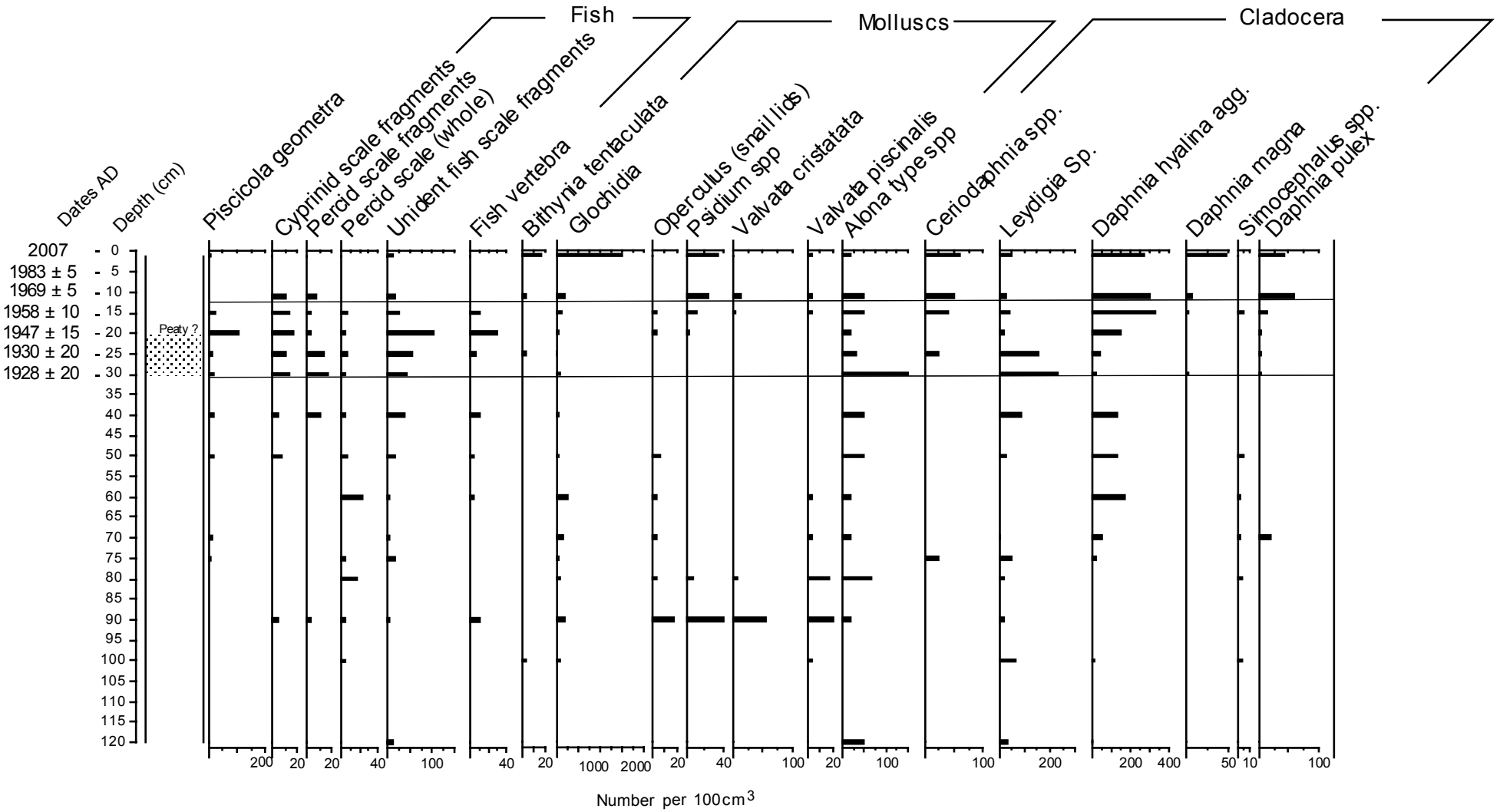
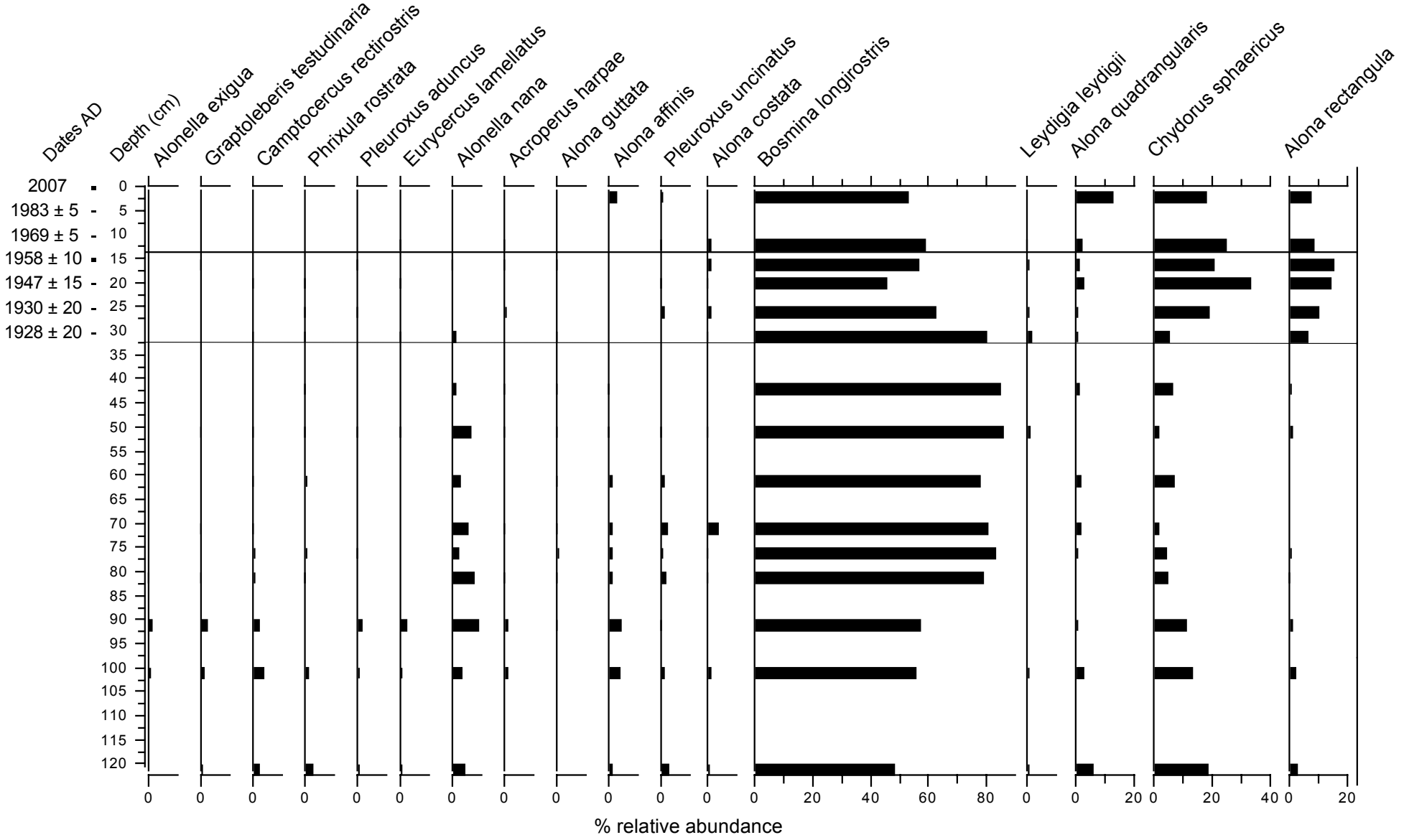
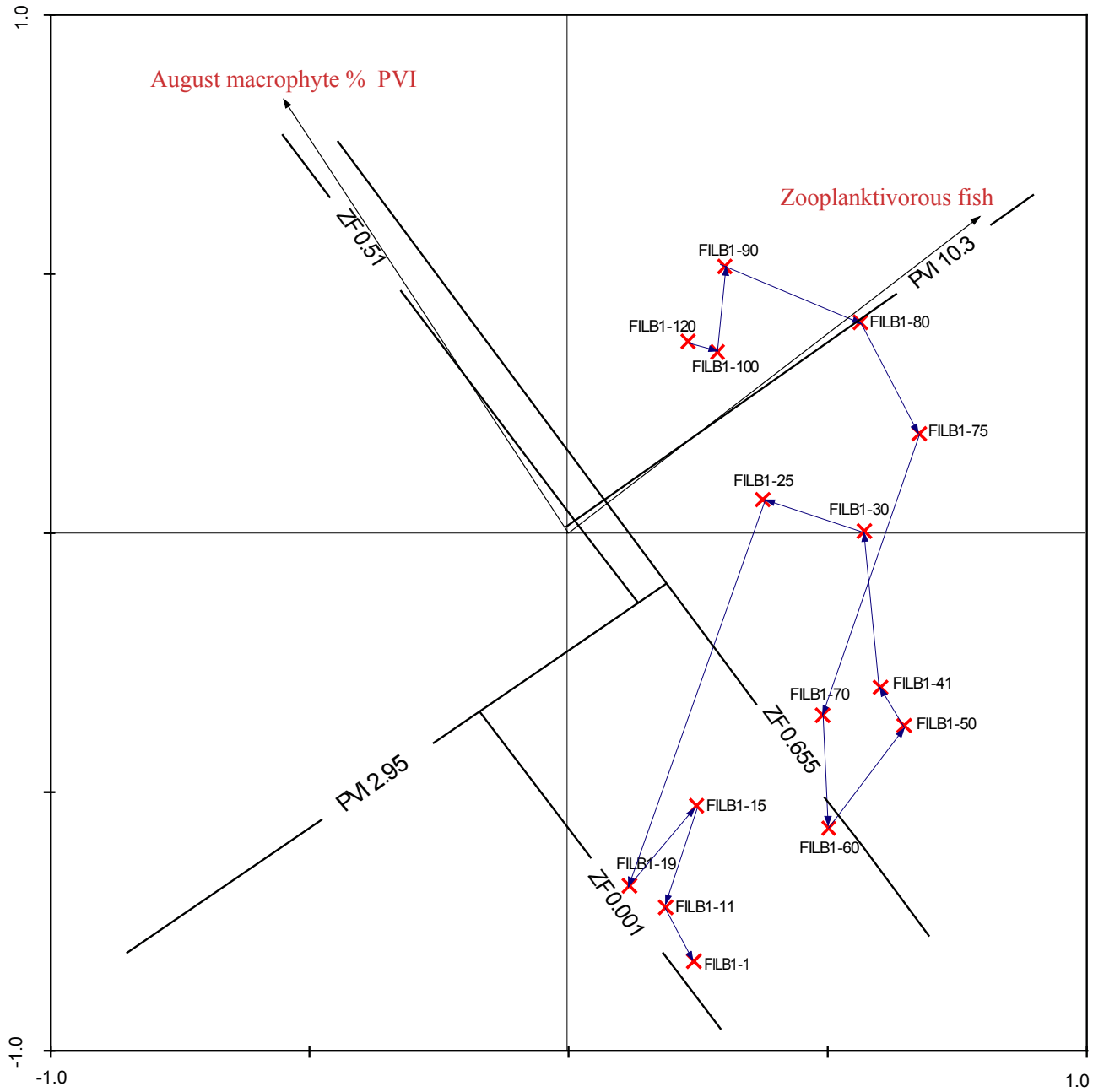


Figure 35 Summary stratigraphy of chitinous cladocerans from FILBY1



The application of the cladoceran data to the model suggests there have been a series of changes with three zones in the history of the site (Figure 36). The basal sequence corresponds to high August macrophyte cover in August, most likely with a diverse assemblage and the overwhelming dominance of benthic production in the system, with very little plankton. Above 90 cm there was a shift in function perhaps linked to increased nutrients, but the macrofossil record at this point suggested increasing macrophyte cover as *Chara* oospore numbers start to increase reaching high numbers. There was quite a lot of variation between the samples, but there was a period of relative stability between 60 and 30 cm. Thereafter, the increase in *D. hyalina* along with *D. magna* and *D. pulex* drove the movement in ordination space, suggesting a decline in fish predation, but increases in phytoplankton providing increased food for the larger bodied zooplankters may also explain this change. The position of the samples in ordination space from FILBY1 suggest in simple terms that Filby, of all the Trinity Broads, has changed the most as there is the greatest distance between the samples representing the basal and surficial cladoceran assemblage.

Figure 36 Time tracks of FILBY1 cladoceran assemblages placed in model reflecting changes in zooplanktivorous fish density and August macrophyte density



Lily Broad

A core from was taken from Lily Broad was taken and details are given in Table 1.

LYLI1 Core Lithostratigraphy

The profile of LYLI1 is not rich in distinguishing features (Figure 37). There was a steady decline in LOI from nearly 80% in the peat base to around 35% in the surface sediments. The dry weight (DW) of the core was almost constant with a slight decline in the wetter uncompacted surface sediments. Carbonate varied little from the base to 20 cm where is rose gradually to the surface sediment.

Figure 37 Lithostratigraphy of LYLI1

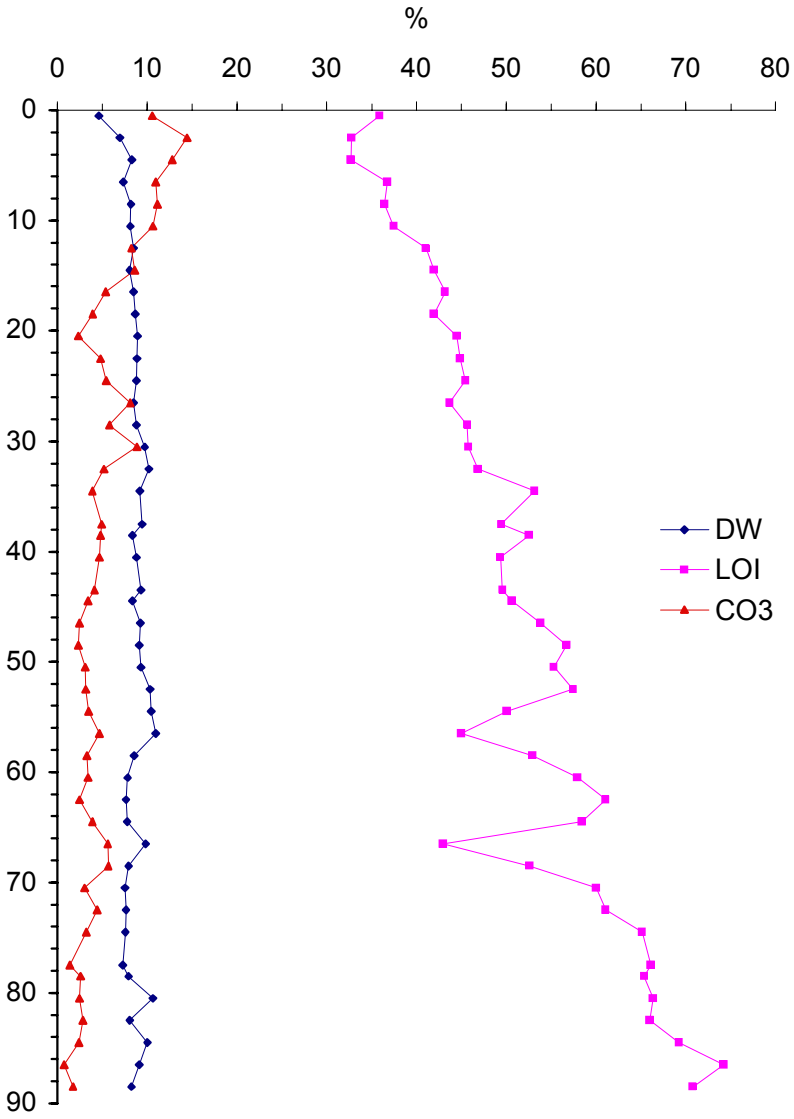


Figure 38 Stratigraphy of LYLI1

Depth (cm)	Sediment colour
0-50	dark-brown
50-70	dark brown with vegetation present
70-120	dark brown
120-142	peat

Comparison Trinity Broads accumulation with other Broads

Table 7. Comparison of accumulation rates for Broads with dated sediments presented as cm yr^{-1} from Rose et al. 2005.

Site		Pre-1960	Post 1960	contemporary	date
Ormesby Broad	Hameed thesis		0.266		1986
Martham Broad	MART1	Na	0.3	Na	1995
Rollesby Broad	ROLL1	0.51	0.51	0.51	1995
Upton Broad	UPTO1 (central)	0.38	0.63	0.63	1995
	UPTO3 (edge)	na	1.25	1.64	2003
Wroxham Broad	WROX1	1.3	1.3	1.3	1995
	WROX2	0.8	0.8	0.8	2000
Barton Broad	BART9	~ 0.5	1.3	1.38	2001
Hickling Broad	HICK1	0.13	0.30	0.55	2002
Calthorpe Broad	CALT	0.17	0.30	0.93	2003
Salhouse Broad	SALG1	0.85	0.85	1.48	2003
Barnby Broad	BARB4	0.29	0.56	0.77	2003
Current study					
			Post 1970		
Ormesby Broad	ORMG1		0.189 – 0.324		2007
	ORMG2		0.351 – 0.432		2007
Ormesby Little Broad	ORML1		0.588		2007
Rollesby Broad	ROLL2		na		
Filby Broad	FILBY1		0.216 – 0.324		2007

Rose et al. (2005) reported that only one of the cores they analysed had a radiometric record reaching the mid-19th century. Thus, establishing good chronologies from these sites has proven problematic, the time period covered is shorter than might be expected and the analysis of changes in sediment accumulation rates at the sites is similarly restricted. In particular the pre-1960 dates should be treated with some caution. The SCP dating presented here for the Trinity Broads had a number of ambiguities and the accumulation rates are therefore given as ranges for post 1970 rather than precise values. Notwithstanding the vagaries of radiometric and SCP dating techniques it is clear that the Trinity Broad system has a lower accumulation rates than Broads in other river catchments. Furthermore, the estimation of accumulation rate for Ormesby Broad from the ORMG1 core indicates little to no change in accumulation rate from the core taken as part of the Hameed Ph.D. study (Hameed 1989). ORMG2 had a higher rate of accumulation, but was taken in the Eastern arm of the Broad, suggesting higher accumulation rates in this area. The accumulation rate for pre-1960 for the other cores may give an indication of what a 'natural' rate of sediment accretion may be for Broads in general. This suggests that currently the Trinity Broads have slightly elevated accumulation rates compared with 'natural' background rates, but that they are low compared to other Broads.

Discussion and interpretation of results

Core lithostratigraphy

The percentage of organic matter (LOI) profiles from some of the cores in this study, combined with the biological results may provide an insight into how the Broads functioned in their 'reference' period towards the base of each core. It is interesting that there was not a sharp transition from the peat base to much less organic lake sediment, rather there was a gradual decline

in organic content. This may suggest that the organic matter from the peat was re-worked into the water column and contributed nutrients and energy to system. Nutrients would have been at a premium at that time and the nutrients in the system may have come from the utilisation of sediment associated nutrients by epipelic algae, macrophytes and benthic invertebrates. This is speculative but interesting in that there may have been a process of oligotrophication occurring which was perhaps truncated by the onset of cultural eutrophication.

A major difference between all the cores was the profile of ORMG1 which has an increase in carbonate to over 40% between 90 and 60 cm. These values are akin, or even greater, than those of marl lakes (Wetzel 1970). Whether marl was precipitated in the water column due to elevated pH in the summer months or whether the precipitate was associated with an extensive *Chara* community is difficult to say. It is clear, however, that this northern area of Ormesby Broad was not only functioning in a different way to the other Broads, but also to other areas of the same Broad, reflected by the lack of a 'Marl' phase in ORMG2. This may have been biologically or chemically (spring or in-flow water quality) driven.

Changes in ecosystem structure and function

The adaptations of the standard macrofossil methods applied here, i.e. the use of two sieve sizes and maximising the volume of sediment analysed from the larger fraction, appear to have produced reliable data. The number and diversity of, in particular, plant remains compares favourably with both published data (e.g. Odgaard & Rasmussen 2001; Davidson et al. 2005) and with other palaeolimnological studies of similar sites (e.g. Davidson & Appleby 2003). A number of studies have demonstrated that the analysis of plant macrofossils in sediments is unlikely to reconstruct all historically present species as rare taxa and those which leave fewer remains (e.g. *Potamogeton* species) are likely to be under-represented (Davis 1985; Dieffenbacher-Krall & Halteman 2000). The method has, however, been shown to provide a reliable means with which to track changes in the dominant components of the submerged vegetation of shallow lakes (Davidson et al. 2005).

In addition to sub-fossils of aquatic vegetation, those left by animals, such as fish, molluscs and cladocerans can shed light on past changes in the ecological structure and function of shallow lakes (Jeppesen et al. 2001). Cocoons of the fish leech *P. geometra* may provide information on plant abundance as they require not only fish, on which they feed, but also plant surfaces to which the cocoons are attached (Odgaard & Rasmussen 2001). Thus, in addition to the direct information provided by the remains of the actual plants these animal remains provide complementary information on both plant abundance and wider changes in ecological functioning.

The data generated here demonstrates, with little room for doubt, that the alteration of the flora and fauna of the Trinity Broads since their formation has been profound. There were differences in the records between the different Broads, for examples *S. aloides* was only found in Rollesby and Ormesby Little Broad and the abundance of charophyte remains also varied quite considerably. Notwithstanding the between core variation, the same general pattern was displayed across all the sites. The ancestral community of the Trinity Broads was characterised by a flora of diverse *Potamogeton* species including *P. obtusifolius, P. crispus, P. compressus* and perhaps *P. friesii*. *P. pusillus* agg., was also abundant in the cores, this is potentially quite a diverse group, covering *P. pusillus, P. berchtoldii* and perhaps *P. trichoides*. In addition, there was also a diverse community of charophytes consisting of a number of species of *Chara* and *Nitella* (which may have included *Nitellopsis*). The ecological function revealed by the cladoceran assemblages at this stage was one dominated by benthic species which reflects low nutrient levels and very little primary production in the pelagic zone (Vadeboncoeur et al. 2003). The other palaeolimnological studies of the Trinity system confirm this. At Rollesby (Bennion et al. 2001) and Ormesby and Lily Broad (Hameed 1989) diatoms were analysed in dated sediment cores and the assemblage was dominated by benthic taxa during this period with minimal plankton. It is, however, unlikely that plankton was

completely absent, as unlike other more shallow Broads, the cladoceran data, particularly the presence of such a high proportion of *Bosmina longirostris*, suggest that there has always been an algal plankton at some time of the year in all the Trinity Broads. Furthermore, in the cores from Rollesby and Ormesby Little Broads, *D. hyalina* agg. was present in relatively large numbers at this time, further suggesting the presence of some phytoplankton. Whether or not plants grew across the entire bed of these deeper Broads is an interesting question. Some species of *Chara* and in particular *Nitella* are known to grow in deeper water being more tolerant of water pressure and lower light climate in some instances, for example, in less impacted systems *Chara* and *Nitella* may be recorded growing at well over 5 m water depth (Schwarz et al. 1996). Towards the end of this period of the Broads' development *Ranunculus* sect. *Batrachium* usually appeared, typically in relatively high numbers. In studies in other Broads, *R.* sect. *Batrachium* has rarely been found in the numbers it occurred here (e.g. Davidson et al. 2005; Ayers & Sayer in press). This suggests that the Trinity Broads had a different flora from Broads in other river valleys and this important facet of regional beta diversity appears to have been lost. Another notable difference is the absence of remains of *Myriophyllum spicatum* which has been a common feature in other macrofossil studies, but was absent from the cores studied here.

The cladoceran analysis and the model application identify a change in ecological function relatively early in the records of all the sites. This was concurrent with an alteration in the plant macrofossil record. The change in macrophyte flora was characterised by a decline in the diversity and abundance of *Potamogeton* remains and of *Chara* and *Nitella* numbers. *N. alba* and *N. lutea* generally persisted and *R.* sect. *Batrachium* also tended to decline in numbers. These changes in assemblage are generally associated with increasing nutrient levels (Blindow 1992; Egertson et al. 2004). The timing of these changes varied between the sites with Ormesby Broad the earliest impacted and Filby Broad the most recently affected. ORMG1 and ORMG2 show the first impacts of eutrophication from around 1850 whereas Filby Broad apparently, although the cladocerans indicate some earlier change, maintained a healthy and abundant charophyte community until the 1950s. Historical records suggest that Filby Broad was historically the least enriched sites with a record for *Littorella uniflora* (Trimmer, 1866), a plant characteristic of more upland oligotrophic sites and now long absent from the Broads. This system wide late-19th to early-20th century change in function recorded by each core is reflected by an increase in the proportion of pelagic zooplankton, in particular *D. hyalina* agg. this shift implies an alteration in the principal location of primary production from the benthic to the pelagic zone (Vadebonceour et al. 2003). This accords well with other palaeolimnological studies which recorded an increase in the proportion of planktonic diatoms relative to benthic at this time (Hameed 1989; Bennion et al. 2001). Further confirmation of this change comes from the historical observations of Gurney (1929), which presumably relate to the years just prior to publication, where he noted "Ormesby has the richest plankton of the whole region. There is so great a development of phytoplankton in the summer that there is a striking 'water bloom' which lasts from about the end of April to the end of June. At times the water seems to be covered with a coat of green paint." This may refer to Ormesby Broad itself, but there is also reference to blooms in the 'Ormesby group'. Gurney goes on to state the "Daphnia abound, but it is difficult too determine to which species it should be referred". The *D. hyalina* guild is notoriously difficult to separate and thus the palaeo results here tally well with Gurney's observations. The plankton blooms are most likely blue-green algal blooms, with the characteristic paint covered appearance of species such as *Aphanizomenon* spp. These observations agree well with the palaeo findings of a change in function and an increase in the proportion of planktonic production but sit slightly at odds with the current ideas on shallow lakes being phytoplankton or macrophyte dominated (Scheffer et al. 1993). It seems that there may have been a period of coexistence of submerged plants with, at least periodic, phytoplankton blooms. There are a number of reasons why blue green blooms occur, including excessive grazing by *Daphnia*, which agrees with the Gurney observation of plentiful *Daphnia*, also nitrate limitation and longer retention times may contribute the dominance of blue-green algae (Shapiro 1973; Ferber et al. 2004). There

are some contemporary observations of blue-green blooms at sites where nutrient levels are low, retention time long and macrophytes relatively abundant (Sayer & Davidson unpublished data).

The final change indicated by the palaeolimnological data presented here is more contemporary and corresponds to a further shift towards the dominance of pelagic production. This is reflected in all the cores by an increase in numbers of *Daphnia* with the appearance and proliferation of *D. pulex* and *D. magna*. These species are large bodied and very effective grazers of phytoplankton, with *D. magna* in particular, generally avoiding plants where possible (Lauridsen & Lodge 1996). The larger bodied species are most vulnerable to fish predation (Brooks & Dodson 1965) and their presence in high numbers indicates that zooplanktivory was low and phytoplankton abundant for at least part of the year. The resolution of the study makes it difficult to determine how the biomanipulation of Ormesby Broad fits in with these changes. The fact that a similar pattern is observable across all the Broads might indicate that the changes in the fish community have been occurring naturally and were helped along by the biomanipulation. However, the seasonality of fish abundance and the inter-annual variability in populations are not recorded by these palaeo-data, which are likely to reflect longer term trends. The fish scale data indicates there has been a decline in the fishery, suggesting a reduction in the number of larger individuals, in particular of perch, but also perhaps of larger cyprinids. The macrofossil record in the surface sediments reflects the current dominance of the Broads by fine-leaved *Potamogeton* species, the notable exception being their absence from ORMG1 surface sediments. The ORMG2 data may well reflect the partial recovery of the system since the biomanipulation of Ormesby Broad. Recent work across a range of shallow lakes in Norfolk has identified the pattern of early season growth of fine-leaved *Potamogeton* species with a crash in the population in July as a phenomenon of moderately enriched shallow lakes (Sayer et al. in press-b). Thus, the current 'state' of Ormesby appears to be plant dominated for the first period of the growing season and turbid for the later months. Thus, the key to future management is the extension of the plant dominated period over the entire growing season. It may be that the species of submerged plant formerly abundant at the site, e.g. *Chara* and *Ranunculus* sect. *Batrachium*, are needed if the site is to maintain plant cover over the entire growing season.

An interesting feature of this study, combined with historical observations, is a new perspective on former flora and the timing and nature of eutrophication related changes across the system. The data presented here along with historical observation suggest that Filby Broad was formerly had the lowest nutrient concentrations, supporting *L. uniflora* (Trimmer 1868). Historically, during the early 'pre-impact', prior to 1850 period, the sediments of the all the Broads would have been sinks for phosphorus. Thus, as water moved through the system, from North to South, nutrients may have become more and more scarce. The data here suggest that eutrophication affected the system in sequence from Ormesby Broad down the chain of Broads to Filby. The timing of change at the different sites suggests that each Broad in turn provided some resistance to enrichment to its neighbour below in the chain. At some point, in Ormesby Broad the data suggest it was in the mid-19th century, the sediments of each Broad stopped being sinks for phosphorus and its buffering capacity ceased, and at this point the effects of nutrient enrichment cascaded down to the next site. The tipping point for each site would have been where the sediments became sources of phosphorus, most probably in the late summer months. Finally instead of phosphorus declining down the system the opposite situation now prevails where each Broad contributes phosphorus from its sediment, in late summer, and Filby Broad at the end of the chain is the most impacted site.

Management recommendations

It is clear from contemporary monitoring, and suggested by the palaeolimnology data, that Ormesby Broad has improved in quality in terms of macrophyte cover and species richness over the past decade. How much of this change is due to the biomanipulation of the system is moot. It is, however, beyond question that abundant zooplanktivorous fish impact the abundance of grazing

cladocerans and this effect cascades down to phytoplankton abundance which is likely to increase algal crop and negatively impact submerged plants. It is, therefore, vital that the low levels of zooplanktivorous fish are maintained and to this end that the monitoring of the fish population continues.

The Trinity system appears to be ecologically relatively unstable reflected by the relatively large degrees of variation in macrophyte cover both within a single year and also between years in Ormesby Broad. The other Broads in the system have low abundances, but in some case, Ormesby Little Broad, relatively high species richness, Filby, in particular has very low plant cover. This apparent instability may result in slight differences between years in weather, or whatever it is that drives good and bad plant years, will have quite a profound effect on the system, i.e. the site is not resilient. The focus of management should be to re-establish this resilience which is likely to consist of extending the period of plant cover to the whole summer and increasing the diversity of submerged macrophyte species present. The existence of relatively long-term monitoring data is invaluable in this situation in order to identify any trends or step changes in the chemical and biological status of the sites, it is, therefore, vital that the monitoring programme is continued.

Dredging is an often mentioned management option and may be successful where water depth needs to be re-established. The Trinity system, however, retains good depth and it is likely it is, in part, their current depth that is limiting light penetration and preventing the return of some species of macrophyte. Dredging, at Filby, for example, would increase water depth and although it may reduce nutrient levels, through removal of phosphorus rich sediment, it would mean light climate would need to improve even more markedly for the successful re-establishment of plants. Other ideas for restoration include supplementing the seed bank of, for example, Ormesby Little Broad, with an inoculum from another site. I would suggest that the seed bank of any site intended for an inoculum is assessed prior to any management. The major factors preventing the greater proliferation of those plants present in the Broads needs to be ascertained, these are likely to include light climate, reduced by water turbidity. In addition, the role of sediment structure and chemistry may be crucial in restricting the abundance existing species and retarding the establishment of new species. Establishing the role these two factors play in preventing the establishment of abundant growth of plants may provide valuable information for the restoration of the system.

The long-term perspective of the work presented here highlight the fact that when considering the restoration of the Trinity Broads it should be borne in mind that lakes do not recover from nutrient enrichment instantly. However, where nutrients levels have been consistently reduced the biology of shallow lakes has been shown to positively respond to these reductions (Jeppesen et al. 2005). There may, however, be a lag in response, in particular, where the reduction of nutrients in the sediment one of the factors preventing recovery.

Two measures which are important to maintaining the system on its current trajectory of improvement are:
1. The continued reduction of nutrient input, both point, where they still exist and diffuse, through promotion of catchment sensitive farming;
2. Ensuring that a significant zooplanktivorous fish population is not permitted to re-establish.

Key recommendations for activities in the Trinity System are

- **The reduction of nutrients entering the site. Identifying and reducing any remaining point sources, especially septic tanks.**
- **Promotion of catchment sensitive farming, to reduce diffuse nutrient enrichment to a minimum.**
- **Monitoring of the site is paramount in order to have as much information on seasonal and inter-annual variation. This monitoring should include, where possible, the**

monthly assessment of a suite of chemical and biological parameters – crucially phytoplankton crop (and composition if possible), zooplankton, at least two macrophyte survey in early June and August and fish.

- **Further research into the nature of phosphorus release from the sediments**
- **Further research into the light requirements and germination conditions of the species identified in this study as formerly dominant at the site.**
- **Further research into the viability of the seed bank across the system**
- **Investigation of new restoration techniques for stabilising sediments, such as breaks to water flow, to reduce localised sediment resuspension and the use of organic binding materials.**

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